Synthetic Lightweight Aggregate for Highway Construction

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Acknowledgments

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Executive Summary

The objective of this study was to develop a new product, Synthetic Lightweight Aggregate (SLA), from two materials, waste plastics, and fly ash, currently sent to the disposal facilities. SLA is being developed and evaluated for use in construction applications such as geotechnical lightweight fill, concrete masonry blocks, and lightweight concrete structures. SLA is produced by melt compounding high concentrations of fly ash from coal with various thermoplastics.

A. Production

In this study, a series of lightweight aggregate samples were produced using several different thermoplastics as binders at several fly ash-to-binder ratios. The SLA samples were produced using flexible thermoplastics, rigid thermoplastics, and mixed thermoplastics as binder. The fly ash used as filler contained various levels of carbon content ranging from less than 4% to more than 30%.

B. Physical Properties

The physical properties of the melt-compounded materials such as Izod impact, hardness, flexural, ad flammability, were evaluated to determine the relationship between variables such as the binder stiffness and the SLA stiffness as well as the filler concentration and the SLA physical properties.

The results of the study show that the SLA properties are influenced by both the fly ash concentration and the thermoplastic binder composition. However, as the fly ash concentration increases, the physical properties of the SLA become less dependent on the thermoplastic binder's properties. At fly ash concentrations of 80%, the physical properties of the SLA are fairly insensitive to the composition of the thermoplastic binder.

C. Application of SLA as a Geotechnical Fill and as a Concrete Aggregate

Samples of SLA were tested for their properties as a geotechnical fill and as a concrete aggregate. An expanded clay lightweight aggregate and a normal weight aggregate were used for comparison.

For geotechnical applications, the SLAs were tested for gradation, specific gravity, bulk density, absorption, 1-D compression (consolidation), and triaxial compression properties. The SLA exhibited a very high friction angle, high compressive strength, and a higher compressibility than normal fill.

Concrete made with SLA exhibited a lower compressive strength as compared with the control material. As fly ash contents of the SLA increased, all properties of the SLA concrete were improved. SLA concrete can satisfy the minimum strength of 170 kPa (2500 psi) required for structural lightweight concrete and non load-bearing concrete masonry units. The SLA concrete samples tested for compressive strength exhibited a low elastic modulus and a unique post

cracking ductile behavior. The concrete samples made with the SLA that contained the maximum amount of fly ash 80% showed an excellent freeze-thaw salt scaling resistance, surpassing concrete made with both natural and lightweight aggregate.

1.0 Research Objectives

The reuse of waste materials in building and highway construction has been a growing phenomenon since early 1980's. The high demand for construction materials and building products makes them favorable medium to reuse recyclable materials. Recent research has shown that synthetic aggregates can be developed from compounding coal fly ash and recycled high-density polyethylene, HDPE. [1,2]

One objective here was to develop a new product from two materials currently sent to the disposal facilities. The final product, lightweight synthetic aggregate, is a granular material to be used in construction industry for applications such as lightweight fill, pre-cast concrete elements, concrete structures, and insulation for utility pipelines.

The other objective was to test this product in accordance with the ASTM standard test methods and compare the test results with those of commercially available products in the market. Several samples of this synthetic aggregate (SLA) were tested for various physical properties such as static load bearing capacity, direct shear, and triaxial tests as geotechnical fill. Concrete specimens made with this product were tested for strength, modulus of elasticity, Poison's ratio, and salt scaling. We also to tested this product for long metal leachability concrete aggregate.

The Chelsea Center for Recycling and Economic Development, an agency affiliated with the Commonwealth of Massachusetts, funded the development part of this project. Within the scope of this project, we used various ash-to-plastic ratios, plastics of different thermal properties, and various production methods. We also evaluated the potential use of this aggregate in concrete masonry blocks.

2.0 Scope of Work

The scope of work included the following:

- Evaluate the formulations and a process for production of SLA using waste plastics and fly ash of various characteristics with a twin-screw extrusion process.

- Evaluate the physical, mechanical, and environmental characteristics of the developed aggregates.

- Evaluate the potential for use of SLA in concrete and for use as a construction aggregate in geotechnical applications.

- Determine if another thermoplastic or thermoplastic blends are suitable as binder for production of SLA. Specifically, evaluate the use of a lower cost, mixed post-consumer, thermoplastic that is typically placed in landfills (type 3 to 7).

The thermoplastic type numbers referred to here was developed by the Society for the Plastic Industry (SPI) in order to assist both consumers and sorters at post consumer waste recycling facilities. A type number ranging from 1 to 7 and a recycling symbol have been assigned by SPI to each of the major plastic resin types and that number is molded onto each plastic product. The major plastic resin types and their SPI numbers are presented in Table 1.

The fly ash used in this study was a class F fly ash, supplied by the US GEN New England generating from their Brayton Point Station in Massachusetts.

The SLA was produced and granulated in the laboratory of the Department of Plastics Engineering at the University of Massachusetts, Lowell (UMASS). A variety of plastics, production techniques, and formulations of ash-to-plastic ratio were used in order to optimize the production method. The physical characteristics such as flammability, flexural strength at failure, shear modulus, and impact resistance of the SLA were also determined at UMASS.

The produced SLA samples were delivered to the laboratory of the Department of Civil and Environmental Engineering at Tufts University, Medford, MA (Tufts). At Tufts, the SLA samples were tested for characteristics as construction material for both geotechnical applications and as aggregate in concrete.

For geotechnical aggregate applications, the SLA was tested for grade size distribution, specific gravity, minimum and maximum density, 1-D compression (consolidation), and triaxial compression. For concrete application, the SLA was tested for water absorption and specific gravity. Also at Tufts, the SLA was incorporated into several batches of concrete as total replacement for aggregate and partial replacement for coarse aggregate. Hardened specimens from these concrete were tested for strength in compression and tension, elastic modulus, Poison’s ratio, and fracture characteristics.

Table 1 - SPI Numbering System for Plastic Recycling

Acronym **Full Name**	**Typical Consumer Products**	**SPI Code**
PET Polyethylene Terephthalate	▪ Bottles: Soft drinks, honey, liquor, dish detergent, antacid, cold medicine, some oven food trays, and peanut butter jars. ▪ Currently Recycled	1 PETE
HDPE Natural High Density Polyethylene (without color)	▪ Jugs: milk, cider, distilled water and spring water bottles, juice (not clear), rubbing alcohol, and large vinegar. Grocery bags. ▪ Currently Recycled	2 HDPE
HDPE High Density Colored Polyethylene	▪ Bottles: laundry and dish detergent, fabric softener, saline solution, bleach, motor oil, and antifreeze. ▪ Currently Recycled	2 HDPE
PVC Polyvinyl Chloride	▪ Bottles: imported mineral water, salad dressing, salad and vegetable oil, floor polish, mouthwash, liquor, some translucent pharmaceutical bottles, bottle liners and cap coatings, blister pack "bubble" for batteries, tile and drainage pipes. ▪ Currently Not Recycled	3 V
LDPE Low Density Polyethylene	▪ Usually appears in flexible film bags for dry cleaning, bread, produce, trash, etc.; also some rigid items such as food storage containers and flexible lids, coatings, and recycling bins. ▪ Currently Not Recycled	4 LDPE
PP Polypropylene	▪ Battery cases, medical containers; oil additive containers, some dairy tubs; cereal box liners; bottle caps; rope and strapping; combs; snack wraps; bags; some yogurt cups and lids for containers (those that do not crack easily when bent). ▪ Currently Not Recycled	5 PP
PS & HIPS Polystyrene & High Impact PS	▪ Some yogurt cups and tubs, cookie and muffin trays, clear carry-out containers, vitamin bottles, most fast food cutlery, waste baskets, and audio cassette tapes. ▪ Currently Not Recycled	6 PS
Other Various Items	▪ Plastics other than the six most common or made of multiple layered resins, blends, or different parts (i.e., water cooler bottles, microwavable serving ware, most snack bags, and squeezable bottles for condiments, etc.). ▪ Currently Not Recycled	7 OTHER

3.0 Background

3.1 Recycling Overview

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 (such as fly ash from coal) or post consumer wastes such as plastic containers. These wastes, depending on the nature, must be handled and disposed in properly designed landfills.

An industrial or social strategy of using only raw materials and landfill all wastes is not sustainable because resources and landfill space are limited. As schematically diagramed in Figure 1, if industrial-related processes are seen as an ecosystem, the most sustainable ecosystem is one that minimizes both the input of limited resources and the output of waste materials. If waste production can be reduced via recycling and reuse of manufacturing by-products and post-consumer products, the ecosystem will become significantly more sustainable as less raw resources are required and fewer wastes are produced. Waste recycling and reuse are critical components for sustainable development since wastes are minimized, their reuse maximized, and natural resources left for the future generations.

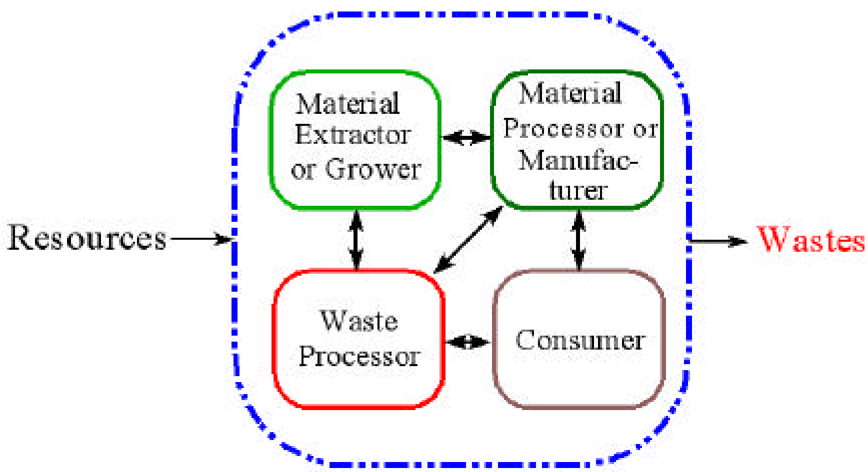


Figure 2 - Industrial System. [3]

3.2 Previous Research

The previous efforts that led to this project consisted of using post consumer plastics as a binding media to pelletize fly ash as aggregate for various potential construction applications. We chose the name of SLA for this product.

After measuring characteristics such as specific gravity, grain size distribution, and absorption, some samples of SLA were incorporated into Portland cement concrete and tested for compressive strength. The test results indicated that the concrete produced with SLA satisfies the strength requirements for structural lightweight concrete (170 kPa). In addition, the concrete specimens under compression exhibited a potentially beneficial, post-cracking creep or ductility not normally observed in ordinary concrete made with lightweight or normal-weight aggregates. Given the potential of SLA for other construction applications such as lightweight fill, several samples were also tested for shear strength, triaxial compression strength, and consolidation potential. We found that these measured attributes are comparable with those obtained from other granular materials used in geotechnical applications. Moreover the SLA was shown to be superior to other granular materials in some of the tested properties, including friction angle. Table 2 lists the lightweight aggregates produced by pelletization of fly ash by different research groups.

Table 2 - Synthetic Aggregates - Coal Combustion Fly Ash Primary Constituent

Aggregate	Manufacturing Process	Specific Gravity	Reference
Pelletized fly ash	Pan pelletizing and indurations	1.25	Terukina, et al., 1999(4)
Unsintered fly ash pellet	Disc pelletizing	2.12	Baykal and Doven, 1999(5)
Unsintered fly ash + cement pellet	Disc pelletizing	2.21	Baykal and Doven, 1999(5)
Unsintered fly ash + lime pellet	Disc pelletizing	2.14	Baykal and Doven, 1999(5)
Spray dryer ash	Disc pelletizing	1.73 -1.78	Wu, et al., 1999(6)
Pelletized fly ash with lime and bentonite	Pan pelletizing and sintered in a rotary kiln	1.7-2.0	Shigetomi, et al., 1999(7)
SLA (fly ash + waste plastics)	Twin-screw extrusion	1.9	Kashi, et al., 1999(1)

While recycled HDPE may be suitable for use in SLA from a performance standpoint, the costs involve in separation of HDPE from the waste stream and the high value of HDPE after separation limit economic viability for SLA application. However, other waste plastics or blends of waste plastics may be suitable as SLA binders and would economically be more viable alternatives.

4.0 Lightweight Aggregate

According to statistics compiled by the U.S. Bureau of Mines,[8] the United States produces about 2.1 billion tons of aggregate annually. The construction industry is the greatest consumer of aggregates using it in the manufacture of Portland cement concrete, bituminous (asphalt) concrete, plaster, grout, filter beds, railroad ballast, base course for roads, building foundation sub-base, drainage fill, etc.

Aggregates are a rock-like material of random shape and sizes. They are found in nature as sand, gravel, stones, or rock that can be crushed into particles. ASTM C125 and D8[9,10] 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.

Based on the specific gravity (S.G.) and bulk density,[11] aggregates are divided into:

- Lightweight aggregate (S.G. less than 2.2 and bulk density less than 1120 kg/m^3).
- Normal-weight aggregate.
- Heavyweight aggregate (S.G. more than 4.0).

Approximately 19 million tons of lightweight aggregates are used annually in the U.S.[8] Most lightweight aggregates are classified as natural lightweight aggregates or manufactured lightweight aggregates. Natural lightweight aggregates include pumice, scoria, and vermiculite, which are used for low density and strength concrete. Sintered ash, slag, and expanded slates, clays, and shale are examples of manufactured structural lightweight aggregates developed by pyro-processing (heating in a rotary kiln to temperatures up to 1300 °C), which expands the material to increase particle volume (air voids) and thus decrease aggregate density.

Lightweight aggregate is used in construction industry for variety of applications such as lightweight fill behind retaining walls and over utility pipelines in excavated trenches, masonry blocks, and structural concrete. Concrete made with manufactured lightweight aggregates should develop compressive strengths of at least 17 MPa (about 2500 psi) to be qualified for lightweight structural concrete.[11] This type of concrete is used in projects where lower deadweight loads are desirable.

5.0 SLA Raw Materials

5.1 Fly Ash

Fly ash is a finely divided residue produced from coal combustion. Approximately 60 million tons of coal fly ash is produced annually in the U.S.[12] About 10% of this coal fly ash is suitable to be used directly in Portland cement concrete as beneficial additive. 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 set by the ASTM C618 "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete."

Another 10% can be used in other areas of construction such as flow able and structural fill, filler in asphalt mixes, road base material, and in hazardous waste stabilization.[13] Unused fly ash is usually land disposed. Data from the American Coal Ash Association [12] indicates that since 1965 more than 950 million metric tons of fly ash has been sent to landfills throughout the U.S. Coal fly ash is exempt from hazardous waste regulations and is usually placed in landfills similar to the ones used for municipal solid waste.

However, the coal fired power generation facilities are under increasing regulatory requirements for NOx emission reductions. NOx control technologies will result in increased levels of carbon in fly ash. The ASTM C618 specification limits LOI (loss of free carbon on ignition) to 6%, largely because the higher LOI levels often result in discoloration and poor action of chemical additives such as air entrainment agent (AEA) and plasticizers in concrete. Air entraining agents (AEA) are used to produce small air bubbles in concrete during mixing, which provide freeze-thaw resistance in hardened concrete.

For the scope of this research, we used type F high carbon fly ash (fly ash that does not satisfy the requirements of ASTM C618 for the LOI of less than 6%) produced by the Salem Harbor and Brayton Point power plants in the Commonwealth of Massachusetts.

5.2 Waste Plastics

The preferred plastic material for use in the synthetic lightweight aggregate should be available in large quantities as post consumer waste with little or no resale value. The most likely material candidates for such an application are mixed waste plastics from both municipal and industrial waste streams. One possible material source is the relatively low-value post consumer SPI #3-7 stream. This material currently has no recycle application since any attempt to use different plastic resins together in a melt blending process requires expensive compatibilizers and that is if not more than two resins are involve.

A study was carried out by the research team at UMASS to evaluate the concentration of each plastic material in a typical bale of mixed waste plastics. A bale of recycle plastics described as SPI # 3-7 was obtained from a local material recovery facility (MRF). The bale consisted of many different thermoplastics materials collected as part of a recycling program after many of the HDPE and PET bottles and containers had been removed for recycling by the MRF. This material is sent to landfills or incinerators by the material recovery facilities as waste. The content of this bale was separated based on the type of plastic and each separate type was weighed in order to find a typical composition of plastics in the waste stream. The concentrations of different plastics found in the bale are presented in the Table 3.

Table 3 - Composition of Non-Recycled Mixed Plastics From a MRF

Material	Concentration by Weight (%)
PET (recycled bottle grade) # 1	30
HDPE (recycled blow molding grade) # 2	30
HDPE (injection molding grade) # 2	5
LDPE (extrusion grade) # 4	10
PP (injection molding grade) # 5	10
PS (injection molding grade) # 6	5
HIPS (injection molding grade) # 6	10

It should be noted that even though this was a type 3-7 bale, most of the material was either #1 (PET) or #2 (HDPE) that was either deemed unacceptable for recycling because of contamination or simply was not removed earlier.

Based on the results of this study, the concentrations of different plastics commonly found in the bale were determined and a simulated waste plastic composition was created based roughly on these concentrations. Clean, recycled materials (in 5 mm pellet form) were used where possible; however, some virgin materials were used to make up the mixed thermoplastics formulations. The pellets from each plastic type were weighed according to their concentrations to make one batch of mixture. The thermoplastics materials were put in a large drum. The material was initially hand mixed and then the drum was rolled and tumbled for 15 minutes to get a homogeneous mixture of different thermoplastics materials.

6.0 Production of SLA

6.1 Compounding Equipment

The SLA was manufactured using a laboratory scale twin-screw compounding extruder. The specific equipment used was a 30-mm Werner-Pfliederer inter-meshing; counter rotating twin-screw extruder (Figure 2) with a medium/high shear profile screw configuration.

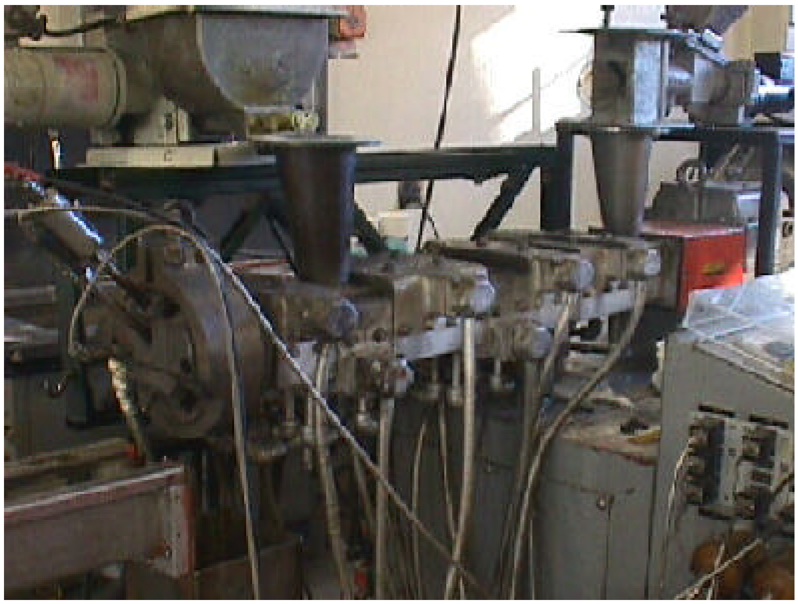


Figure 3 - Twin-Screw Extruder.

The thermoplastic binder material was starve-fed into the feed section of the twin screw using a single screw auger feeder. The relative feeder outputs were adjusted to control the filler concentration.

The extrudate produced was a flat strip about 50-mm wide and 9.5-mm thick. The melting temperature was slightly higher than normal temperature used for melting HDPE (200°C to 260° C). After compounding and cooling, the extrudate was granulated to produce the SLA (Figure 3) using a conventional thermoplastic granulator equipped with appropriate size screen.

Figure 4 - Extrudates Before and After Granulation.

6.2 Production Process Study (Melt Compounding)

In order to determine if mixed plastic from waste stream was a suitable binder material, a series of fundamental material formulation studies were conducted. This study was concentrated on the following variables:

- Molecular Weight of Thermoplastic Binder (MFR)
- Stiffness of Thermoplastic Binder
- The Composition of Thermoplastic

For this part of study, plastic binders of extreme viscosities and melting temperatures were used to investigate their impact on the production process and the final product. The mixture ratios (% fly ash) and binder types as well as production process equipment settings are listed in the Table 4.

We were able to produce aggregate with different thermoplastics used both individually as well as mixed (type 3 to 7) for the binder. In general, the more fluid the plastic, the easier it was to incorporate higher concentrations of fly ash in the mixtures. With a very fluid (high MFR) plastic, we were able to incorporate, as much as, 90% fly ash into the mixture. The carbon content in the fly ash did not affect the production process as we used both low (<4 %) and high (>15 %) carbon content fly ash in our productions.

Table 4 - Composition of SLA Produced

Plastic Resin	Fly Ash Content Percent		
HDPE	0	50	80
LDPE	0	50	80
PS	0	50	80
Mixed Plastic	0	50	80

7.0 Physical Properties of Extrudates

A number of tests were conducted on the specimens made from the formulations (Table 4) to determine their physical properties. The tests included flexural properties, impact resistance, hardness, flammability, and tension modulus at elevated temperatures. The tests conducted for this study were performed using standard test procedures. However, for some these tests the procedure was modified to suit the size of the sample or the unusually viscous nature of the material, as compared with usual plastic compounds that contain much lower concentration of fillers.

After compounding with the twin-screw and granulation, the granulated material was injection molded using a 22-ton Cincinnati Milacron injection-molding machine to make test specimens. Some of the produced specimens were shorter in length than the ASTM specifications require, however, this short flow length mold was used here to simplify the molding of the very viscous materials. Hence, to maintain consistency in size and shape, all the samples were molded in the same mold. After molding, the test samples were cut to a specific size using a band saw. The dimensions of the cut samples were 63.5-mm (length), 12.7-mm (width), and 3.2-mm (thickness).

7.1 Extent of Plastic Encapsulation

An ideal product is one in which the mixture of plastic and fly ash are homogeneous and a layer of polymer encapsulates each fly ash particle. In order to measure the degree of encapsulation, SLA made with different ratios of mixed plastic to fly ash were sieved to separate different particle sizes. Each size was then heated to 750 ºC for several hours. At this temperature the polymers and free carbon are volatilized. The residue left from this process consists of non-organic components that require much higher temperature to volatilize such as silicon oxides.

As evident in Figure 4, the total mass volatilized for each SLAs made with various ratios of fly ash to Mixed Plastics (MP), remains constant regardless of grain size down to about 300 ìm (No. 50 sieve). The total mass of material volatilized decreases for grain sizes less than 300 ìm. Regardless of plastic to ash ratio, the total mass lost to volatilization for the SLA particles passing No. 200 sieve (75 ìm) was about the same. This indicates that with the current co-compounding effort, the SLA particles, regardless of their size down to 300 ìm, have a homogeneous structure. For the finer SLA particle sizes however, fly ash or free carbon particles may not be completely encapsulated within the polymer. Lack of encapsulation may not be a serious draw back as in most applications such as in concrete and as structural fill because the SLA used must be coarser than No. 100 sieve.

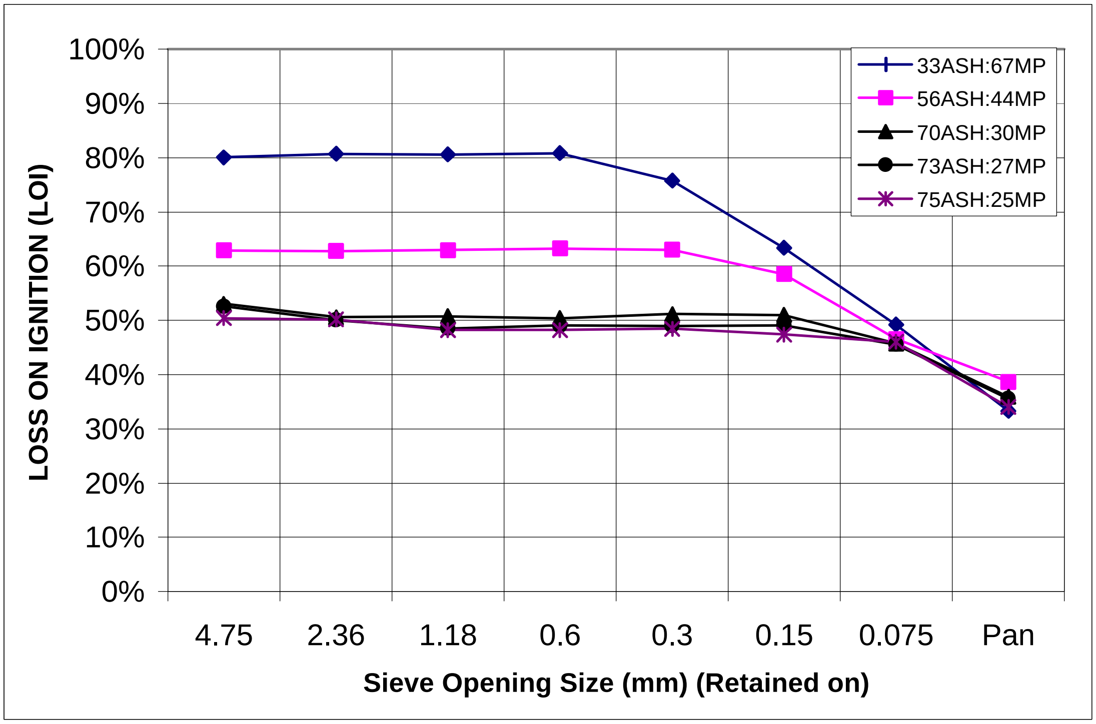


Figure 5 - Volatized Component As A Function of SLA Grain Size.

7.2 Flexural Properties

Flexural properties were determined in accordance with ASTM D790-95,[(14)] modified for shorter specimens. This modification resulted in a span length/depth ratio of 13:1, which is a little less than the recommended 16:1. The crosshead speed used was 1.3 mm/min as recommended by the standard.

The purpose of this test was to determine the flexural properties of fly ash filled thermoplastics and mixed plastics formulations; specifically initial bending modulus or stiffness and outer fiber strain at break. A three-point loading apparatus with a center loading on a simply supported beam was used. Initial bending modulus and outer fiber strain at break (if less than 5% outer fiber strain) were determined. All tests were carried out at 23°C and 50 % relative humidity. The values reported in Figure 5 for the initial bending modulus are the averages of five replicates.

As shown in Figure 5, the initial bending modulus of all the formulations increased with the increase in fly ash concentration. The increase in flexural modulus showed that, as the filler concentration increased, it became harder to bend the samples. However, looking at the values for the mixed plastic, the initial bending modulus value depended very little on the homogeneity of the base thermoplastic matrix. In other words, the lack of compatibility in the base plastics did not hamper the binding properties of the polymers that are required for pelletizaton of fly ash.

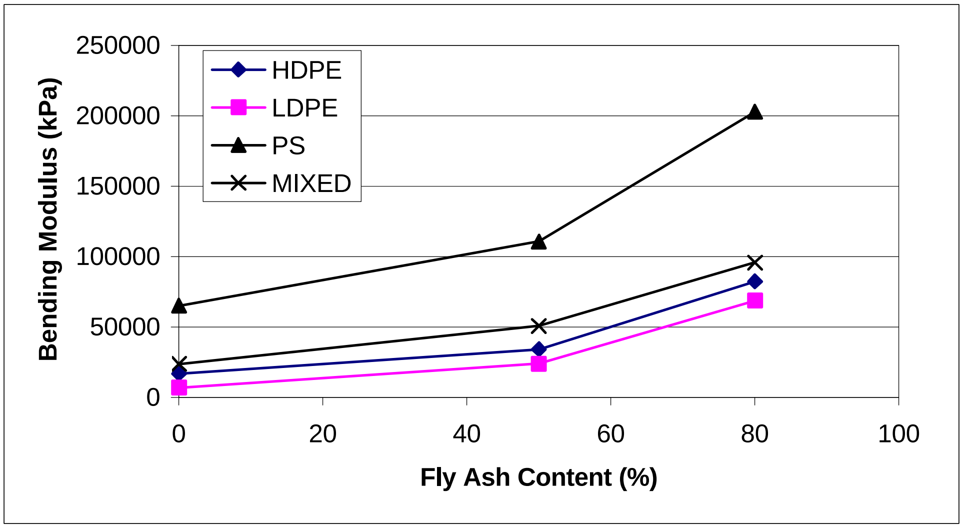


Figure 6 - Initial Bending Modulus of the Fly Ash/Plastic Mixes.

7.3 Izod Impact Resistance

The purpose of the Izod Impact Resistance (ASTM D 256-93a[15]) test was to determine the notched Izod impact resistance or toughness of plastic-fly ash composites to breakage by energy exerted from standardized pendulum-type hammers. These pendulums were mounted on a standardized machine and the specimens were fractured with one pendulum swing.

The samples used for this test were 63.5 mm in length and the nominal thickness of the samples was 3 mm in accordance with the test protocol. The testing speed was 3.35 m/sec. The specimens were notched on the strike side by a notching machine equipped with a 45° by 0.025 mm radius cutter. This notch acts as a stress concentration point, which promotes a brittle fracture. The results obtained from this test reported the energy absorbed per unit width of the specimen. All tests were carried out at 23°C and 50% relative humidity. The values reported in Figure 6 are the average of five replicates.

Amongst the base plastics, LDPE had the highest resistance followed by HDPE, PS, and mixed plastics. The formulations with lower than 50% fly ash, this trend continued. However, it can be concluded from this test that the addition of fly ash to the plastics made the extrudates more brittle. As a result, the notched impact resistance value decreased with additional amount of fly ash. Also, it is noticed that the impact resistance values for the 80% fly ash filled formulations of different thermoplastics were more or less the same irrespective of the base thermoplastic matrix. One conclusion from this test was that when fly ash content exceeds 50% of the compound mass by weight, the impact resistance of the product was nearly independent of the base thermoplastic material.

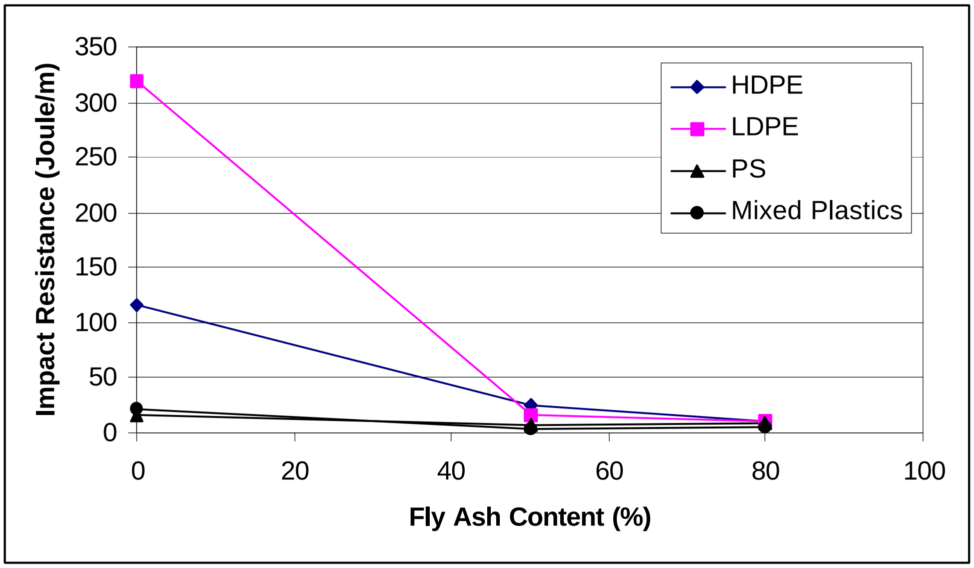


Figure 7 - Notched Izod Impact Resistance.

7.4 Hardness Test

The Hardness test (ASTM D 2240-97[16]) is also appropriate for rigid materials such as metals if the Shore D durometer with a sharper indenter is used. Because the high stress values associated with the Rockwell hardness test intended for rubbery materials caused the SLA specimens made with 80% fly ash content to fracture, the Shore D hardness test for hard plastics was used for this study.

The purpose of this test was to determine the indentation hardness of fly ash filled thermoplastic and mixed plastics formulations. The durometer instrument provides a relative indication of hardness from 0-100.

The test method was based on the penetration of a specific type of indenter when forced into the material under specified conditions. The tests were carried out at 23 °C and 50% relative humidity. The values reported in Figure 7 are an average of five replicates.

It was concluded from this test that the hardness of the compound increased with the addition of fly ash in the formulations. For example, the addition of 50% fly ash to the LDPE formulation increased its hardness by 20%. The addition of 80% fly ash to the LDPE formulation increased the hardness number by 40%. Similarly, for the formulations of different thermoplastics compounds evaluated, the hardness value increased with higher fly ash content.

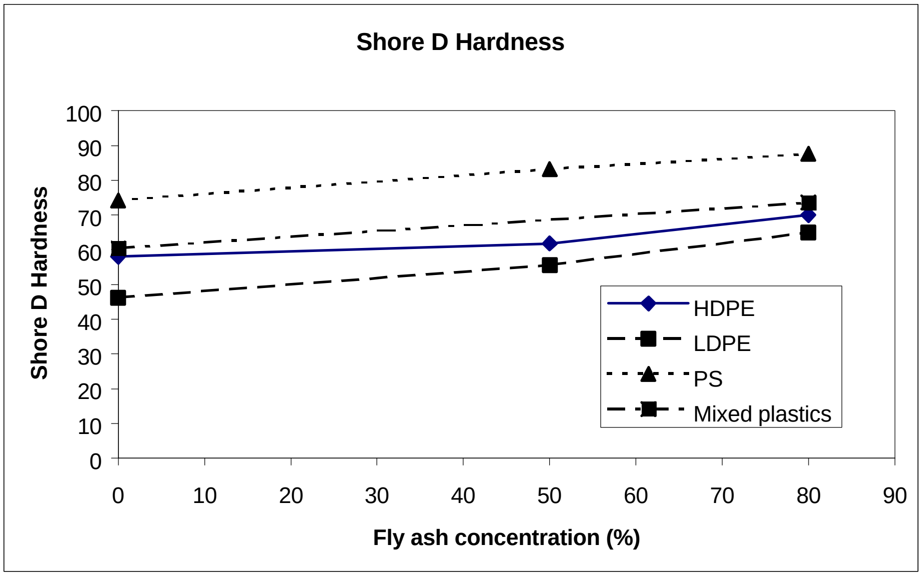


Figure 8 - Shore D Hardness of the SLA.

7.5 Flammability Test

The purpose of the Flammability Test (ASTM D 3713–78[(17)]) was to characterize the response of a plastic to an ignition source consisting of a small flame of controlled intensity applied to the base of a standard sample being held in a vertical position. The samples used for this test had the same sample dimensions as for all the other tests in this study.

The equipment used for this test included a propane burner for igniting the end of the samples, a stand for holding the samples, and a cotton bed beneath the samples, as shown in Figure 8. The propane burner was used as an ignition source and the intensity of the flame was maintained constant for all the samples. The observations reported from this test are:

- Time taken to ignite
- Self extinguishing characteristics
- Rate of flame spread
- Dripping characteristics
- Smoke comments

Results of this test may be used as elements of a fire risk assessment for a particular end use. The test results reported in Table 5 are average of six to eight replicates.

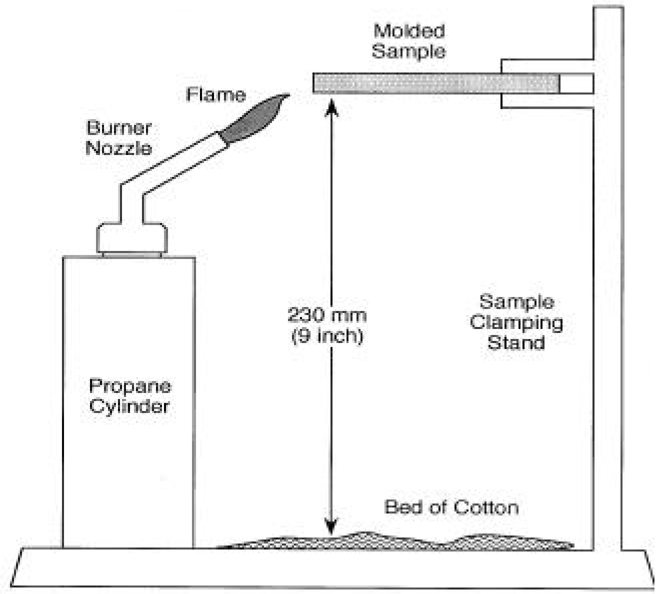


Figure 9 - Diagram Showing Apparatus Set Up for the Flammability Test.

In order to determine the effect of fly ash concentration on the base thermoplastics materials, six observations were made to reflect the flammability characteristics of the blends. The six observations made were as follows:

a. How much time did it take to ignite?
b. Did it self-extinguish?
c. How much time did it take to burn to the specified length (38 mm)?
d. How long did it burn if it stopped before reaching the specified length?
e. Did it drip? If yes, did the cotton burn which was kept exactly below the sample?
f. Comments on smoke.

The results of these observations are summarized in Table 5.

The test was useful in evaluating the effect of fly ash on flammability characteristics of the different compounds. Fly ash as a filler can act as a flame retardant. However, the SLA made with the fly ash that had more than 15% carbon content ignited and burned faster than polymer alone. The high carbon in the composition of SLA may have increased flammability. Thus, it was observed that the samples of fly ash filled LDPE took less time to ignite than the time required to ignite samples without fly ash. Also, the time taken to burn the specified lengths of fly ash filled LDPE was less than the time it took to burn LDPE and mixed plastic without fly ash.

Table 5 - Flammability Test Observations

Material	Time to Ignite (sec)	Self Extinguished	Burn Rate (mm/sec)	Length Burned (mm)	Drip Characteristics	Smoke
HDPE + 0% Fly Ash	10	No	0.9525	38	Drips, Cotton burns	White
HDPE + 50% Fly Ash	10	No	1.171	38	Drips, Cotton burns	Black
HDPE + 80% Fly Ash	10	No	1.153	38	Drips, Cotton burns	Black
LDPE + 0% Fly Ash	10	Yes	1.00	19	Drips, Cotton burns	White
LDPE + 50% Fly Ash	5	No	0.622	38	Drips, Cotton burns	Black
LDPE + 80% Fly Ash	5	No	0.846	38	No drip	Black
PS + 0% Fly Ash	10	No	1.587	38	Drips, Cotton burns	Black
PS + 50% Fly Ash	5	No	2.116	38	No drip	Heavy black
PS + 80% Fly Ash	5	No	1.730	38	No drip	Heavy black
Mixed + 0% Fly Ash	10	No	1.360	38	Drips, Cotton burns	Black
Mixed + 50% Fly Ash	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluated
Mixed + 80% Fly Ash	10	No	3.175	38	No drip	Black

7.6 Dynamic Mechanical Properties in Torsion

The purpose of the Dynamic Mechanical Properties in Torsion (ASTM D 5279-95[18]) test was to determine the effect of temperature on the shear modulus of the fly ash filled thermoplastic formulations (80% fly ash to 20% plastic). The data collected from this study can be used to identify the thermo-mechanical properties of filled formulations.

The tests were started at room temperature from which the temperature rose at the rate of 3 °C/min. The sample was clamped between two jaws. The lower jaw remained stationary while the upper jaw oscillated at the strain rate of 6 radian/sec.

The values reported from this test (Figure 9) show a decrease in shear modulus as temperature increased. The initial forced oscillatory strain rate for all the samples was constant at 0.002 radian/sec. However, for 80% fly ash filled samples of PS the strain rate had to be reduced to 0.1 radian/sec because the material proved to be very stiff for that setting and the machine was overloaded.

The shear modulus for the base plastic, without fly filler, yield from 140,000 kPa for LDPE to 1000,000 kPa for PS. Addition of 80% fly ash as filler increases the shear moduli by a minimum factors of between 2 and 7. At low temperatures, the peak shear modulus values for HDPE, PS and mixed plastics values are similar. These results further confirm our assumption that, at such a high concentration of filler (fly ash), the properties of the extrudates depend less on the base plastic matrix. The multiple transitions (Figure 9) for the mixed plastic formulation are probably because of the variety of thermoplastics materials present.

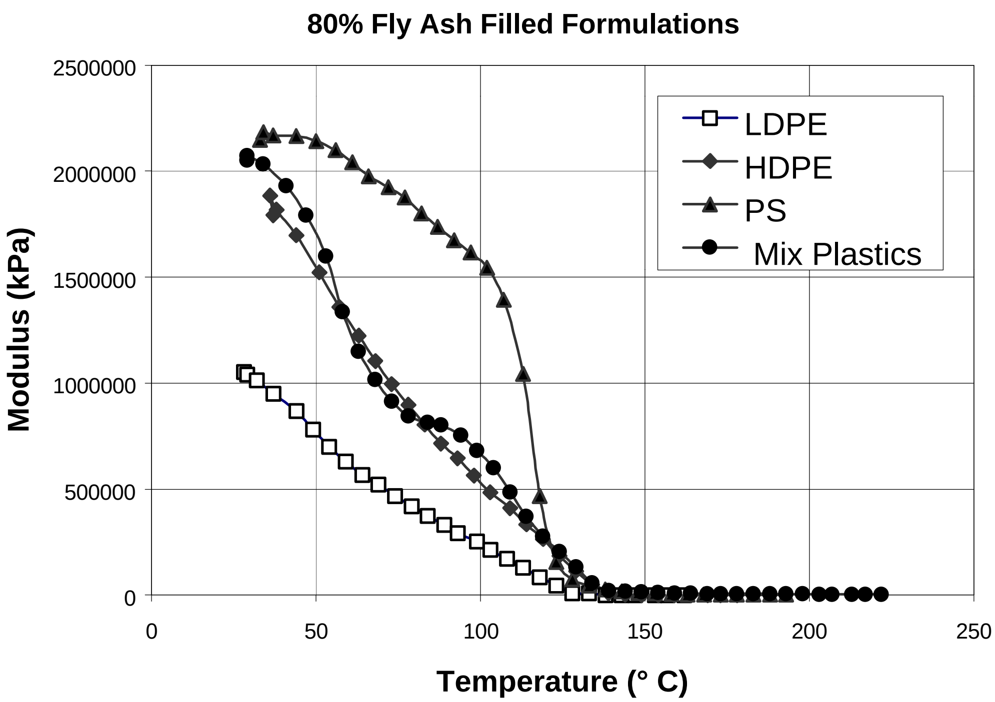


Figure 10 - Effect of Temperature on Shear Modulus.

8.0 Use of SLA for Geotechnical Applications

The SLA has the potential to be used for geotechnical applications such as lightweight fill and insulating materials placed over and around pipelines in excavated trenches. Lightweight aggregates are routinely utilized as backfill behind water front structures, retaining walls and bridge abutments as well as drainage layers in landfill caps. Beneficial properties of lightweight aggregates include reduced dead weight, high internal stability, high thermal resistance, and sound dampening qualities.

We conducted several tests to compare SLA properties with those of other granular materials currently used as lightweight aggregates for geotechnical applications. For this comparison, we obtained samples of aggregate from three manufacturers of lightweight aggregate, Buildex, Soilite, and Norlite. These companies manufacture and market lightweight aggregate made from expanded clay and shale for both geotechnical and concrete applications.

Six different SLA samples were produced so that the variances in mechanical properties between different fly ash compositions, polymer (binder) variations, and polymer to fly ash ratios could be evaluated. Aggregates produced in the laboratory of UMASS and their abbreviations used herein are presented in Table 6.

Table 6 - List of the SLA Produced

Fly Ash Content (%)	Type*	Plastic Content (%)	Plastic Type	Abbreviation
80	LC	20	2HDPE:1PP	80:20LC
70	LC	30	2HDPE:1PP	70:30LC
80	HC	20	2HDPE:1PP	80:20HC
60	HC	40	2HDPE:1PP	60:40HC
66	HC	33	HIPS	66:33 HIPS
35	HC	65	HIPS	35:65HIPS
70	LC	30	HDPE	70:30HDPE
80	LC	20	HDPE	80:20HDPE

* LC- Low Carbon Fly Ash (<4%) HC- High Carbon Fly Ash (>15%)

Table 7 lists the geotechnical tests performed in the laboratory of Tufts University on samples of SLA and the control aggregates.

Table 7 - List of Geotechnical Tests Performed

Material	Testing Program					
	Specific Gravity	Loose Bulk Density	Grain Size Analysis	Direct Shear	1-D Compression	Triaxial CIDC
80:20 LC	X	X	X		X	X
70:30 LC	X	X	X			
80:20 HC	X	X	X		X	X
60:40 HC	X	X	X		X	X
66:33 HIPS	X	X	X		X	X
35:65 HIPS	X	X	X		X	X
70:30 HDPE	X		X	X	X	
80:20 HDPE	X		X	X	X	
Buildex	X	X	X		X	X
Norlite	X	X	X		X	
Solite	X	X	X		X	
Natural Sand	X	X	X			X

8.1 Specific Gravity and Loose Bulk Density

The objective was to investigate the impact of varying composite formulation on the specific gravity and density of the lightweight aggregates. The specific gravity indicates the unit weight of solid as compared with water. Loose bulk density indicates the unit weight of aggregates in a loose state.

The specific gravity tests were conducted in accordance with ASTM D 854-92,[19] as well as ASTM C 128-93.[20] The ASTM D 854-92 is used for measuring the specific gravity of soils in geotechnical applications and ASTM C 128-93 method is used for measuring specific gravity of aggregate for concrete application. The specific gravity values obtained by ASTM D 854[19] method are higher than the ones obtained from method ASTM C 128.[20] For ASTM D 854[19] the sample is saturated to a higher degree by applying vacuum pressure to the submerged specimens. Aggregates in ASTM C 128 are saturated by simple submersion in water without vacuum pressure.

The test results are tabulated in Table 8 and the specific gravity results are displayed in Figure 10. Carbon residue in the fly ash is lighter in weight as compared with other components of fly ash; therefore, the specific gravity of the SLA made with high carbon fly ash is lower by about 15%.

Table 8 - Aggregates Physical Properties

Aggregate	Specific Gravity ASTM C 128-93	Specific Gravity ASTM D 854-92	Loose Bulk Density Kg/m^3
80:20 LC	1.61	1.86	770
70:30 LC	1.37	1.67	700
80:20 HC	1.32	1.59	700
60:40 HC	1.14	1.27	540
66:33 HIPS	1.39	1.51	640
35:65 HIPS	1.25	1.25	600
70:30 HDPE	-	1.64	-
80:20 HDPE	-	1.86	-
Buildex	1.28	1.95	640
Sand	2.63	2.63	1420

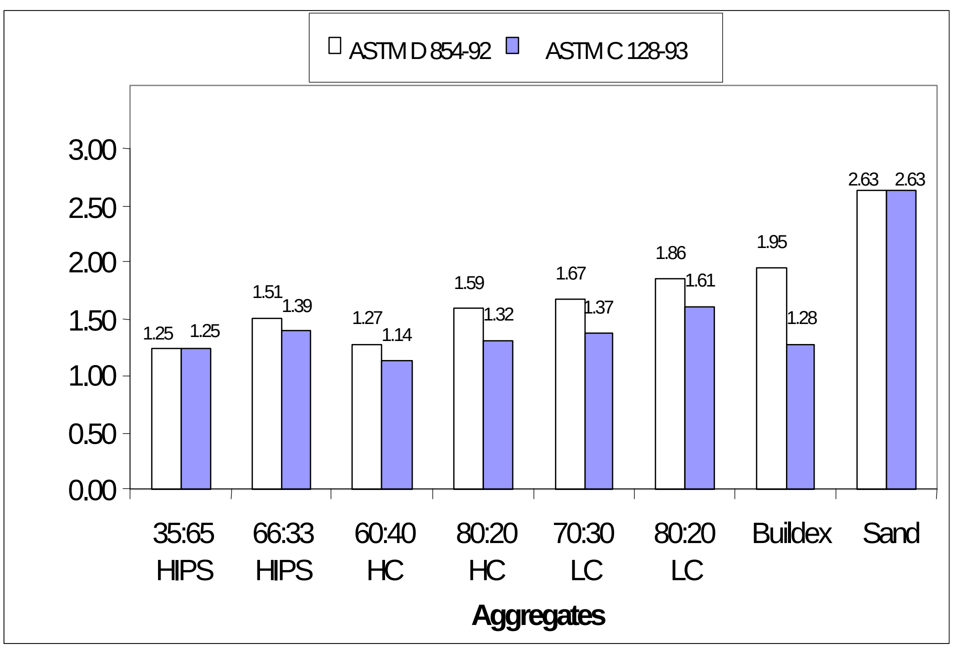


Figure 10- Specific Gravity of Specified Aggregates.

8.2 Grain Size Analysis

The grain size distribution or gradation of aggregate or soil is determined by sieve analysis. Soils can be classified as widely graded, narrowly graded, or gap graded. A material classified as widely graded has a significant mass of particles retained across a range of sieve sizes compared to a narrowly graded sand that has the majority particles retained on only a few sieves. Gap graded refers to a soil that is retained on the extremes of the sieve spectrum and not on the intermediate sieves. The SLA with high fly ash contents had more fines than comparable aggregates with lower fly ash contents. The grain size distribution is depicted in Figure 11.

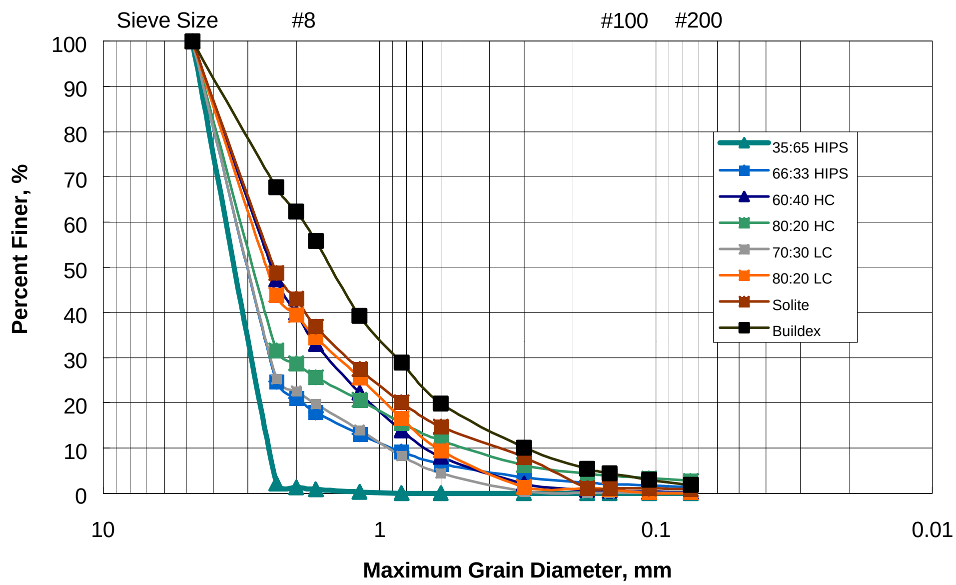


Figure 11 - Grain Size Distribution of Aggregates.

The synthetic lightweight aggregates are manufactured material and an adjustment to the opening size of the screen on the granulator can control their grade size distribution. An accurate measurement of grade distribution was necessary in order to have comparable samples and test results for various aggregate used in this study.

8.3 One-Dimensional Compression (Consolidation) Testing

The One-Dimensional Compression (Consolidation) test is a modification of the ASTM D 2435-90.[22] One-dimensional compression testing was conducted on the materials specified in Table 6. The consolidation rings were filled with a predetermined mass of aggregate such that the initial void ratio of the sample was approximately 1.0. The initial mass of aggregate to be placed inside the consolidation ring was determined by assuming that the sample would occupy the known volume of the ring. Using this calculated volume a sample of aggregate was weighed to satisfy the initial void ratio requirement. After the sample was placed in the consolidation ring the actual sample height was measured to determine the initial void ratio.

In order to achieve a relatively similar initial void ratio some aggregate samples were slightly compacted by hand. The 35:65 HIPS sample required no compaction.

Loads were applied to the load frame at one-hour time intervals until a total load of 1239 kPa was applied. The maximum load was maintained for 48 hours after which the sample was unloaded at one-hour time intervals. One-dimension compression test results are displayed in Figure 12.

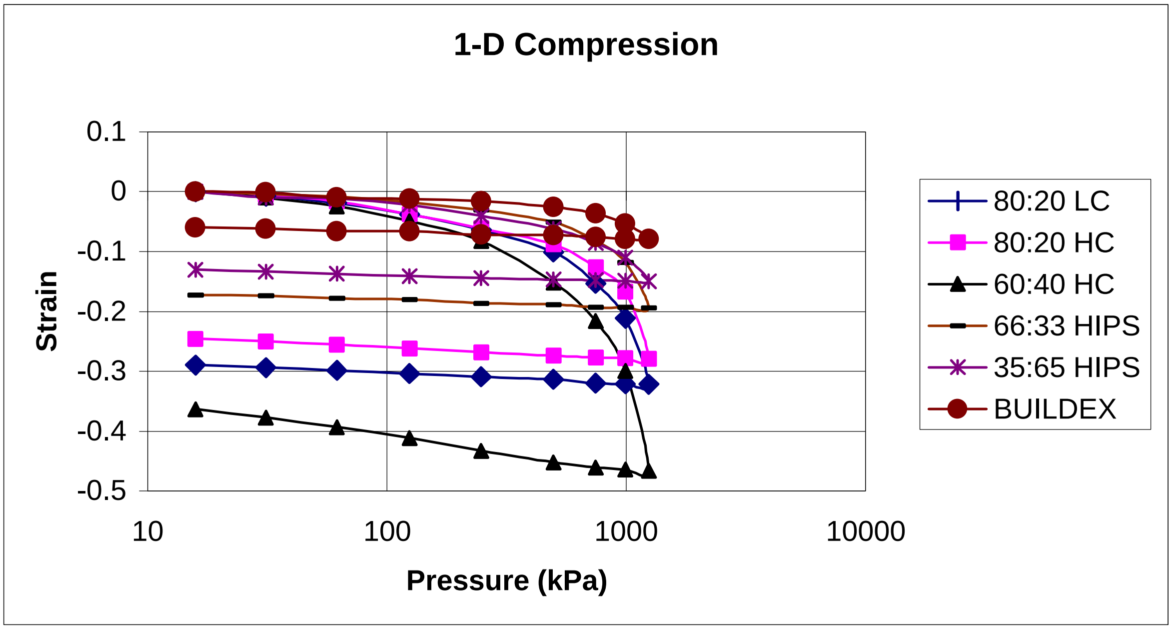


Figure 12 - Plot of 1-D Compression Tests for Aggregates.

Apparent in Figure 12 are the stiff response of Buildex (a lightweight aggregate made with expanded clay) to the loading and comparatively compressible response of the SLAs. Plastic content, type, and carbon content of ash affect the response of the composite aggregate to confined one-dimension compression. The SLAs containing HIPS resin are much stiffer than SLAs with the HDPE- PP resin blend. This is a reflection of the resin properties, HIPS has a higher flexural modulus than the HDPE-PP blend.

Although granular materials are non-cohesive by nature, several of the samples compressed in the settlement chamber exhibited cohesive behavior. See Figure 13 for photos of the samples after removal from the settlement chambers. Aggregates with high fly ash to resin ratios, i.e., both the 80:20 LC and the 80:20 HC, retained the shape of the settlement chamber after removal. The 70:30 LC showed some degree of binding and the 60:40 HC aggregate and both of the HIPS aggregates exhibited no binding in the consolidometers.

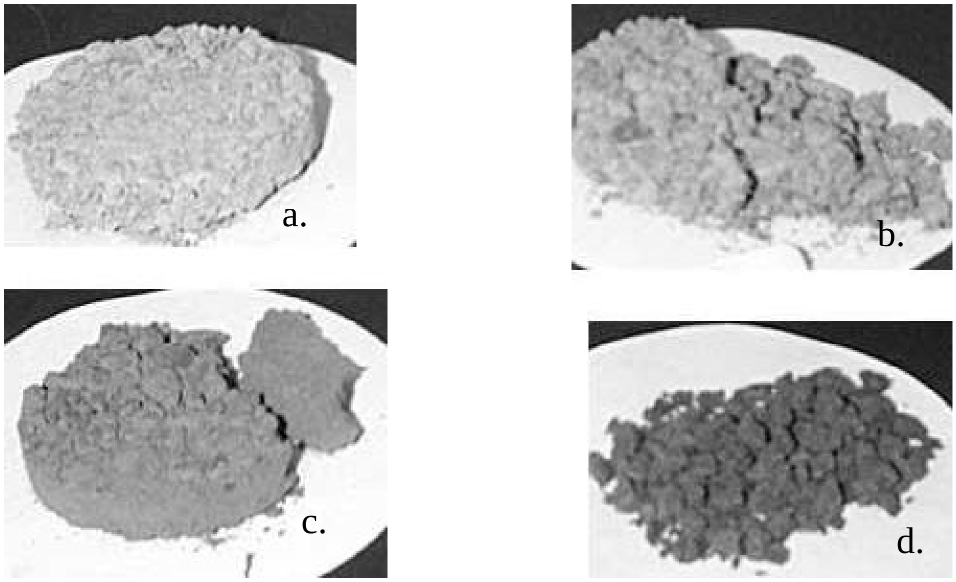


Figure 13 - SLA Samples After Removal From Consolidation Cells:
a) 80:20 LC; b) 70:30 LC; c) 80:20 HC, and d) 60:40 HC.

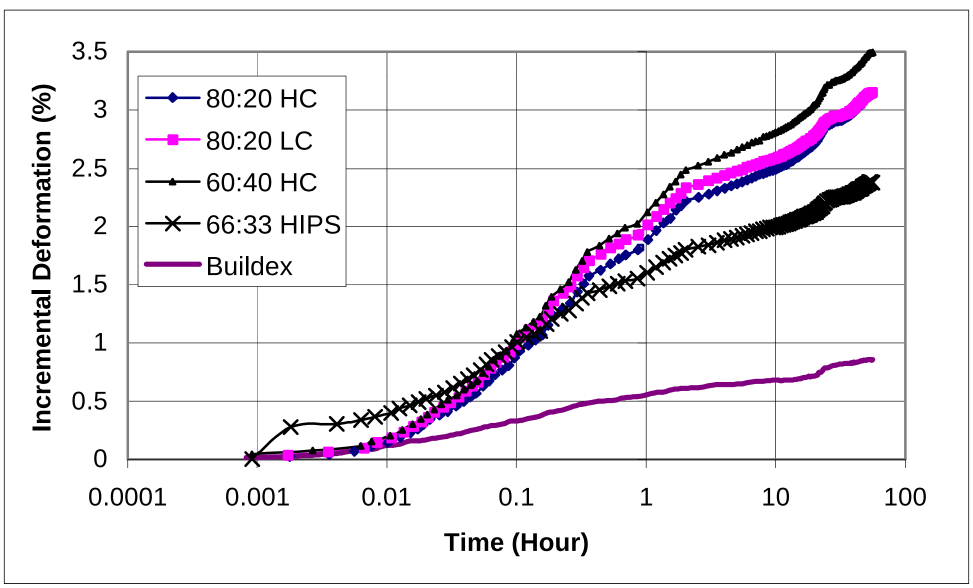


Figure 14 - Consolidation Under 1250 kPa of Constant Pressure for ~56 Hours.

Figure 14 depicts the strain and creep properties of SLAs and a lightweight aggregate tested under constant pressure for approximately 56 hours. The SLAs tend to creep more because of their polymer content. Plastic resins are viscoelastic by nature, and consequently will experience viscous flow under loading. Comparatively the plot for Buildex is less steep than slope of the SLAs.

8.4 Triaxial Testing

To establish shear and compressive strengths as well as friction angle of granular soils, SLA samples were tested using Confined Isotropic Drained Compression (CIDC), similar to the standard method specified by the ASTM D 2850.[23] Triaxial testing was conducted on the SLAs as well as on one of the lightweight aggregates (Buildex) and on natural sand. The tests were conducted at three confining pressure of 50, 100, and 200 kPa. The stress-strain and p-q curves for each material are included in the Appendix A.

The combined graphical presentation of the triaxial CIDC tests results (Figures 15, 16, and 17) reveal the effects of plastic resin type and the ratio of fly ash-to-plastic on the strength of these materials. The SLA samples containing HIPS typically reached higher strengths than the other aggregates including natural sand and Buildex.

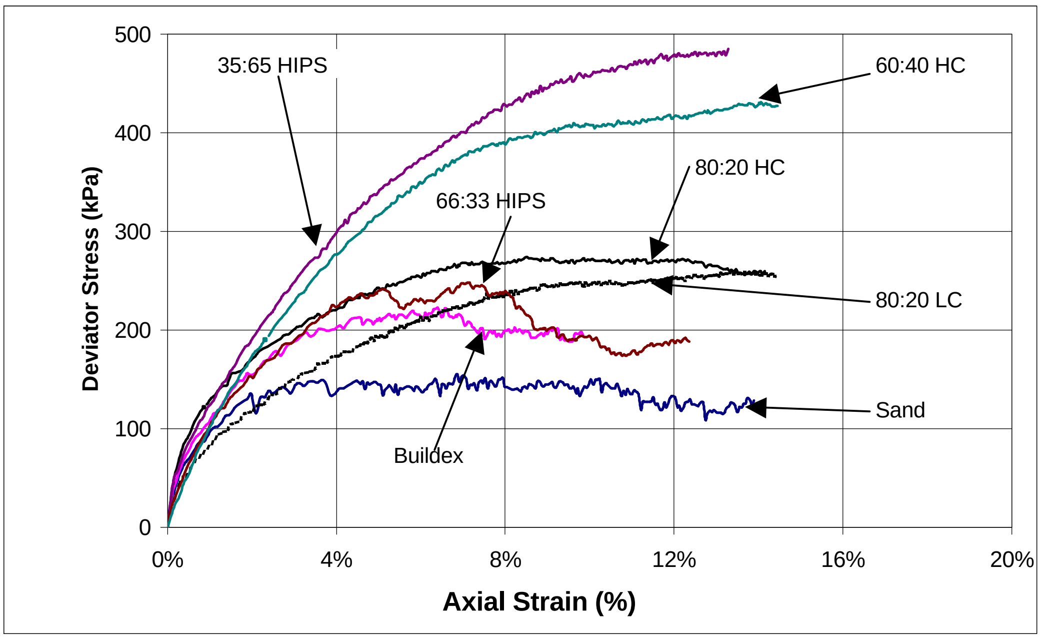


Figure 15 - Triaxial Stress-Strain Curve of the Aggregates (50 kPa Confining Pressure).

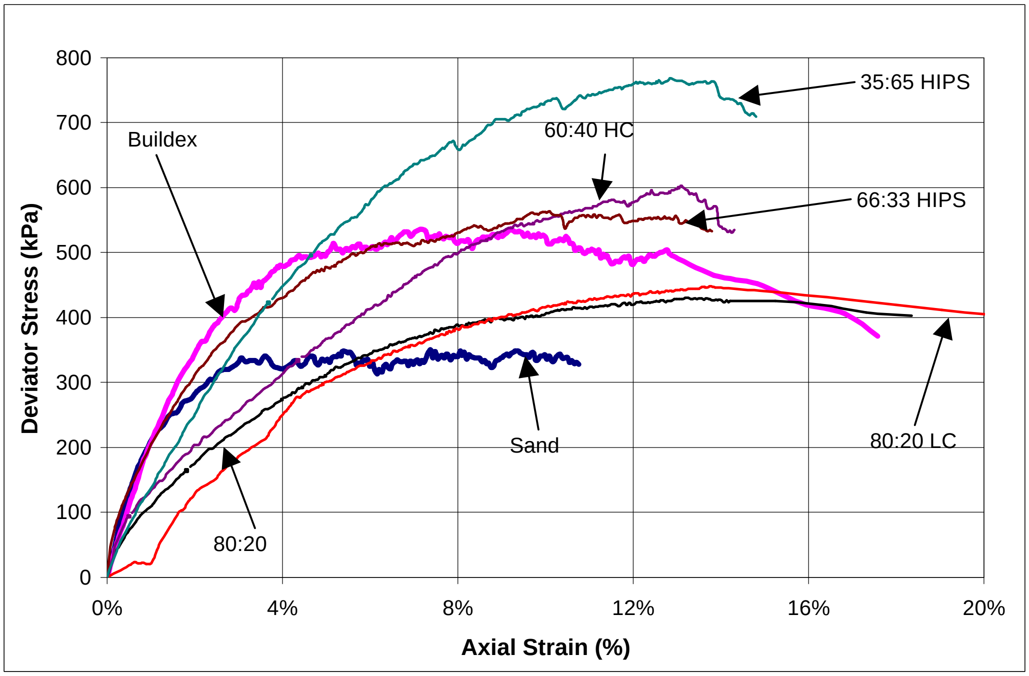


Figure 16 - Triaxial Stress-Strain Curve of the Aggregates (100 kPa Confining Pressure).

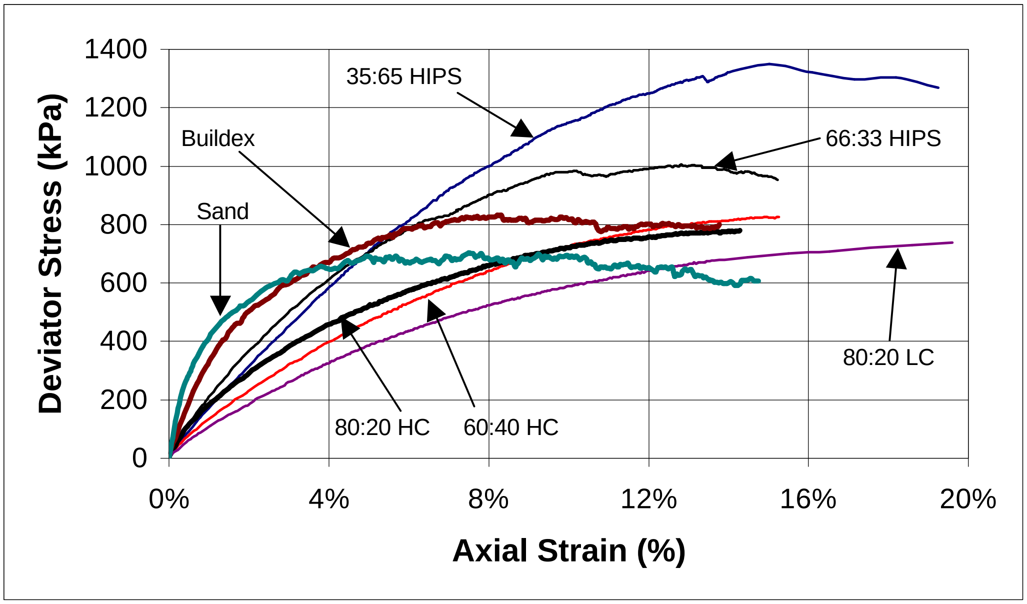


Figure 17 - Triaxial Stress-Strain Curve of the Aggregates (200 kPa Confining Pressure).

Based on these tests we also calculated the friction angle for each one of the specimens at peak strength. Figure 18 shows the average peak strength envelope for all tests on a p-q plot. The friction angle for each specimen is shown in Figure 19.

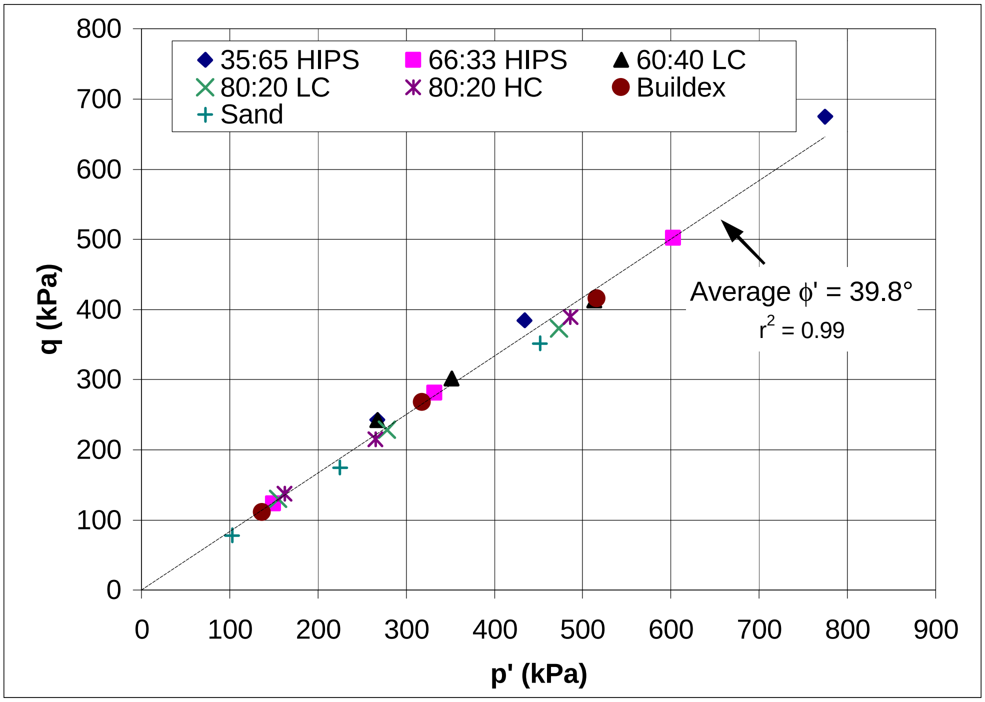


Figure 18. Failure Points of p-q Curves.

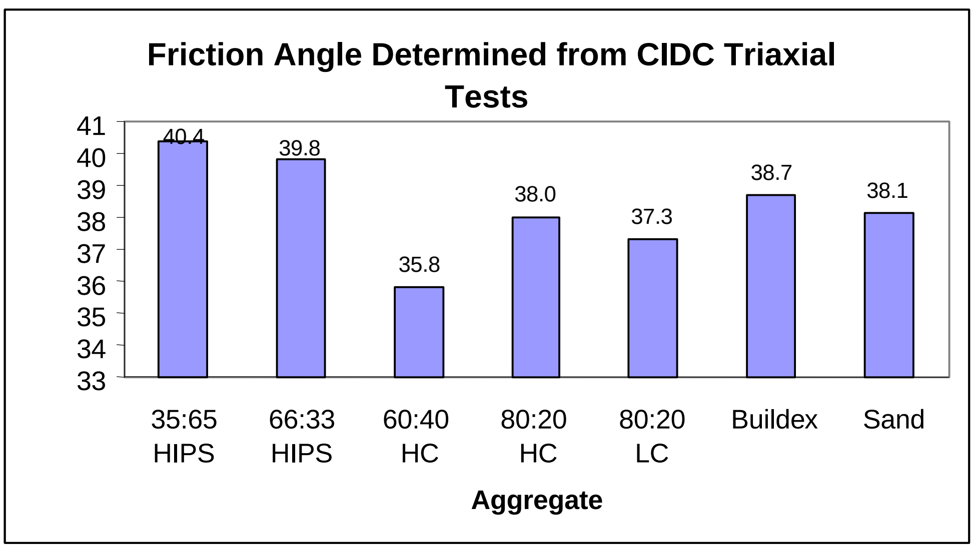


Figure 19 - Friction Angle of Aggregates Determined From the Slope of p-q Plots.

Increasing the ash content led to an increase in the friction angle of the HDPE-PP resin. The friction angle for the SLAs with an ash-to-plastic ratio of 80:20 is similar to that of natural sand and lightweight aggregate Buildex.

The strength characteristics of the synthetic composite aggregates indicate that they have the potential to be used as an alternative to natural or other lightweight aggregates for geotechnical applications.

8.5 Direct Shear Tests

Direct shear tests were performed on dry SLAs, Normal Weight Aggregate (NWA), expanded clay lightweight aggregate (LWA) and palletized HDPE specimens at various normal stresses. A Wynkam-Ferrance direct shear device with 6.25 cm diameter specimens was used for all tests.

Figure 20 shows a plot of the peak shear stress versus applied normal stress for the various materials. The figure also shows failure envelopes for each material. The failure envelopes for these data indicate that the aggregates listed from strongest to weakest are LWA, 70:30 SLA, 80:20 SLA, NWA, and HDPE. Table 9 lists the friction angles calculated from the failure envelopes for the test aggregates. Note that Table 9 does not include apparent cohesion or the y-axis intercept, which with the friction angle would define the failure envelope.

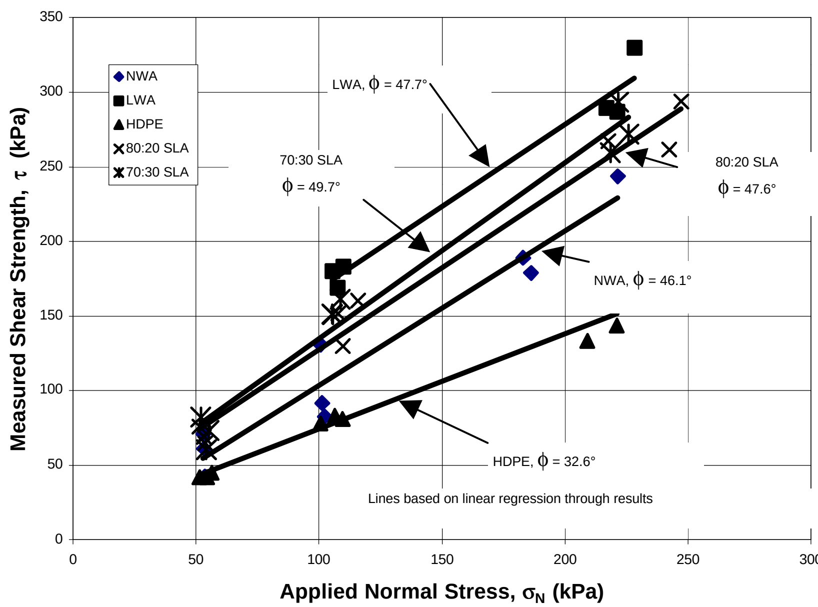


Figure 20 - Summary of Direct Shear Test Results.

Table 9 - Friction Angle by Direct Shear Test

Aggregate	Relative Density	Particle Shape	Friction Angle Degrees
HDPE	Medium	Rounded	32.6°
70:30 SLA	Medium	Subangular	49.7°
80:20 SLA	Medium	Subangular	47.6°
Normal-Weight	Medium	Subangular	46.1°
Lightweight (Norlite)	Medium	Subangular	44.5°

9.0 Use of SLA in Structural Concrete

9.1 Lightweight Concrete

Lightweight aggregate (LWA) concrete is popular for use by the construction industry due to the improved physical properties it offers relative to normal weight aggregate concrete, specifically, reduced dead weight, higher insulating values, and sound dampening qualities. The use of lightweight concrete in structure may also result in lower overall costs due to the reduced weight on the foundation, and other structural elements. While lightweight concrete may cost more per cubic yard than normal weight concrete, the structure may cost less as a result of reduced dead weight and lower foundation costs.

The motivation for reducing the weight of constructed systems dates back several thousand years. In the case of lightweight concrete, early applications include portions of the Pantheon that were constructed with pumice aggregate concrete.[24] With the advent of artificially made LWAs early in the twentieth century, it became possible to obtain lightweight concrete with compressive strength comparable to normal weight concrete. This type of lightweight concrete has been used recently for the design of building structures as well as for bridge deck pavement and, in a more limited role, for entire bridge superstructures.[25] The original LWAs were composed of natural materials that were extracted from the earth. As demand for LWAs increased, other common rock and soil were altered, usually by elevated temperatures, to produce an alternative LWA.

In accordance with the ACI 213R-87[11], there are three classes of lightweight concrete based on their unit weight and compressive strength. Table 10 presents the approximate 28-day, air-dry unit weight range of three types of lightweight aggregate concrete along with the 28-day strength and the use for which each type is generally associated. The ranges given in Table 10 for both unit weights and compressive strengths are not precise and should only be used as guidelines.

Table 10 - Lightweight Concrete Classifications (ACI 213R-87)

Class of Concrete	Unit Weight (Kg/m^3)	Compressive Strength (MPa)	Use
Low Density	Less Than 800	0.69 to 6.89	Insulation
Moderate Strength	800 to 1400	6.89 to 17.24	Structural Fill
Structural	1400 to 1850	More than 17.2	Structural Applications

9.2 Concrete Material and Mixes

Twenty-two batches of concrete and one batch of mortar were made. The same source of Type I Portland cement and fine aggregates were used for all batches. The coarse aggregates used were a normal-weight coarse aggregate (NCA), an expanded clay lightweight aggregate (ECLWA), and several SLAs. The SLAs had different compositions such as different fly ash-to-plastic ratios and different plastic resin types (HDPE, LDPE, PS, and MP).

The normal weight fine aggregate (FA) was natural river sand with a maximum aggregate size of 4.75 mm and a fineness modulus of 2.72. The aggregate gradation, given in Table 11, met the gradation requirements of ASTM C33. The bulk specific gravity and absorption for both fine and coarse aggregates were determined per ASTM C127 and C128 respectively and are given in Table 12.

Table 11 - Gradation of Fine Aggregates

Sieve Size	Percent Passing	
	Actual	ASTM C33 Requirements
No. 4 (4.75 mm)	99	95-100
No. 8 (2.36 mm)	94	80-100
No. 16 (1.18 mm)	74	50-85
No. 30 (600 μm)	43	25-60
No. 50 (300 μm)	16	10-30
No. 100 (150 μm)	4	2-10

Table 12 - Aggregate Properties

Property	Aggregate					
	FA	NCA	ECLWA	0/100 (HDPE)	35/65 (HDPE)	80/20 (HDPE)
Bulk Specific Gravity $_{(SSD)}$	2.47	2.66	1.56	0.91	1.09	1.60
Absorption (%)	1.1	1.4	10.9	0.3	1.2	19.3
Unit Weight[a] (kg/m^3)	-[b]	1543	800	490	-[b]	-[b]

[a] Dry Rodded [b]Properties not determined

The natural coarse aggregate was sub-rounded granite with a maximum nominal aggregate size of 9.5 mm, and the lightweight aggregate was an ECLWA having a maximum aggregate size of 9.5 mm.

To evaluate a wide range of possibilities, concrete mixes with the following variables were examined:

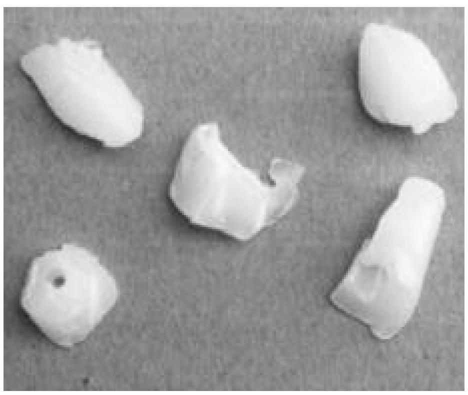
- The effect of SLA with different fly ash-to-polymer ratio on the mechanical properties of concrete.
- The effect of polymer type on the mechanical properties of concrete.
- The effect of water to cement ratio on the mechanical properties of concrete.

9.3 Effect of SLA With Different Polymer-to-Fly Ash Ratio

The five types of coarse aggregates used are shown in Figure 24. The SLAs with lower fly ash contents tend to be more angular and have smoother surfaces due to the ductility of the plastic and the manner in which the granulator cuts the aggregate from the larger extruded material. In the co-polymer pelletization process used for the production of the SLA, incorporation of 80 percent fly ash into the polymer matrix was the limit above which we were not able to get a homogeneous material. With the highest fly ash content, 80 percent by mass, the aggregate produced had rounder edges and rougher surface texture with exposed small internal air voids. The lower angularity of 80:20 SLA may be due to its brittleness that caused it to break rather than be cut by the granulator.

a) Normal Weight Aggregate

b) Expanded Clay Lightweight Aggregate



c) 0/100 SLA

d) 35/65 SLA

e) 80/20 SLA

Figure 24 - Photos of Aggregates.

The normal weight, ECLWA, and 0/100 coarse aggregates had gradations satisfying the requirements of ASTM C33[26] as size 8 aggregate. The 35/65 and 80/20 aggregates originally had higher fineness modulus and subsequently had to be sorted by sieving and recombined to provide a gradation satisfying the requirements of ASTM C33 as size 8 aggregate. The actual gradations of the coarse aggregates used in the concretes are given in Table 13.

The bulk specific gravity and absorption for all five coarse aggregate types were determined per ASTM C127[27] and C128[20] and are presented in Table 12. From Table 12, the high absorption of the 80/20 aggregate is indicative of high porosity, or entrapped air, associated with incorporation of high volumes of fly ash into the plastic. Although the 80/20 has higher absorption than the 0/100 and the 35/65, the density of the SLAs increases with higher fly ash contents. The 80/20 SLA has a similar bulk specific gravity to that of the expanded clay lightweight aggregate (ECLWA) used in this study.

The dry rodded unit weight was determined for the natural, ECLWA, and pure HDPE coarse aggregate following the ASTM C29[28] procedure and are given in Table 12. Only the dry rodded unit weight from the normal weight coarse aggregate (NCA) was used for the initial mix design in this study.

Table 13 - Gradation of Coarse Aggregates

Sieve Size	Percent Passing					
	NCA	ECLWA	0/100	35/65	80/20	Requirement*
1/2"	100	100	100	100	100	100
3/8"	95.7	98.1	100	100	100	85-100
No. 4 (4.75 mm)	13.8	30.4	25.6	30	30	10-30
No. 8 (2.36 mm)	0.4	6.7	2.5	0	0	0-10
No. 16 (1.18 mm)	0	1.1	0.6	0	0	0-5
No. 50 (300 µm)	0	0	0	0	0	0
No. 100 (150 µm)	0	0	0	0	0	0

*ASTM C33[10] Gradation requirement for size 8 coarse aggregate.

In order to evaluate the effect of SLA made with different plastic-to-fly ash ratio on the mechanical properties of concrete, five batches of concrete and one batch of mortar were made. These batches are designated as NCA, ECLWA, 0/100, 35/65, 80/20, and batch M.

Batch NCA was made as control, and batches ECLWA, 0/100, 35/65, and 80/20 SLAs were proportioned similar to the batch NCA replacing the natural aggregates with identical volumes of lightweight expanded clay and SLAs. The mortar (batch M) had the same mix proportions as batch NCA with the exception that there was no coarse aggregate. The coarse aggregates were all in air-dry condition at the time of mixing. For all five batches of concrete, the weight ratios of cement-to-fine aggregates were identical and the volume fraction of the coarse aggregate was 0.30.

The mix water was adjusted during mixing to achieve a consistent workability (slump) for all five mixes with a target slump between 60 and 90 mm. Mix proportions and the slump for the mortar and the five batches of concrete are given in Table 14. The relatively smaller masses of lightweight expanded clay and SLA coarse aggregates in their respective batches can be attributed to their lower densities in comparison to the normal weight coarse aggregate. The weights for the aggregates given are in the saturated surface dry (SSD) condition; however, the water-cement ratios given may not be completely accurate due to the aggregates not reaching full saturation.

The five batches of concrete were mixed per ASTM C192.[29] From each batch, three-100 x 150 mm cylinders for splitting tension tests, three 100 x 200 cylinders for compression and modulus of elasticity tests, two 200 x 250 x 90 mm salt scaling specimens, and three notched beams for fracture tests were cast. The notched beams were used for determining fracture properties of the concrete and were 560 mm long by 130 mm high by 50 mm wide. The cylinders and beams were covered with plastic sheets to prevent moisture loss after casting, de-molded after 18 hours, and placed in a 100 percent humidity room. The salt scaling specimens were cast and cured following ASTM C672,[30] with the exception that the specimens were moist cured for 28 days instead of 14 days, prior to air drying for an additional 14 days.

Table 14 - Mix Proportions

Properties	Batch					
	NCA	**ECLWA**	**0/100**	**35/65**	**80/20**	**M**
Cement (kg/m^3)	428	415	418	428	402	617
Water (kg/m^3)	208	221	227	219	195	300
Coarse Aggregate, SSD (kg/m^3)	786	441	275	318	515	-[a]
Fine Aggregate, SSD (kg/m^3)	901	875	873	893	856	1300
Unit Weight (kg/m^3)	2323	1953	1792	1858	1969	2217
w/c	0.49	0.53	0.54	0.51	0.49	0.49
Slump (mm)	76	64	89	76	64	-[a]

[a]Property not determined.

9.3.1 Effect on Unit Weight

The unit weights of the hardened concrete were determined per ASTM C642[31] and are provided in Table 14. The unit weights of the concretes made with ECLWA and the SLAs are approximately within the range of ACI 213R-R87[11] for structural lightweight concrete (1400 to 1850 kg/m^3). An increase in fly ash content of the manufactured aggregates results in aggregate and concrete with higher unit weights. The concretes made with the ECLWA and the 80/20 SLA had similar bulk specific gravities and nearly identical unit weights.

9.3.2 Effect on Compressive Strength

The compressive strength (f'_c), elastic modulus in compression (E_{cc}), and Poisson ratio (ν), were determined per ASTM C39[(32)] and C469[(33)] by testing 100 x 200 mm cylinders from the five batches of concrete and the mortar. The cylinders were capped with sulfur capping compound per ASTM C617[(41)] 24 hours prior to testing. Using a fully computerized compression machine, the stresses and strains (both axial and lateral) up to and beyond peak stresses were measured for each specimen.

Figure 25 shows typical stress versus axial and lateral strain responses for the five batches of concrete and mortar. As fly ash content in the SLA increases, the compressive strength and axial and lateral strains at peak load also increase. With respect to compressive strength, concretes made with 0/100 and 35/65 SLAs did not satisfy the ACI requirement for structural lightweight concrete as structural lightweight concrete. In accordance with the ACI requirement, structural lightweight concrete must have a minimum 28-day compressive strength of 17.2 mPa (2500 psi). The compressive modulus of elasticity also increases as the ratio of fly ash to plastic increases. The ACI equation to predict the modulus of elasticity is:

$$E_c = K_E W_c^{3/2} \sqrt{f_c^{'}}$$

Where W_c is the unit weight of the hardened concrete in kg/m^3 and ACI specifies the constant K_E =0.043 $MPa^{1/2}/(kg/m^3)^{3/2}$. From the measured elastic modulus, unit weight, and compressive strength, K_E was calculated for each batch of concrete using this expression. Results are provided in Table 15.

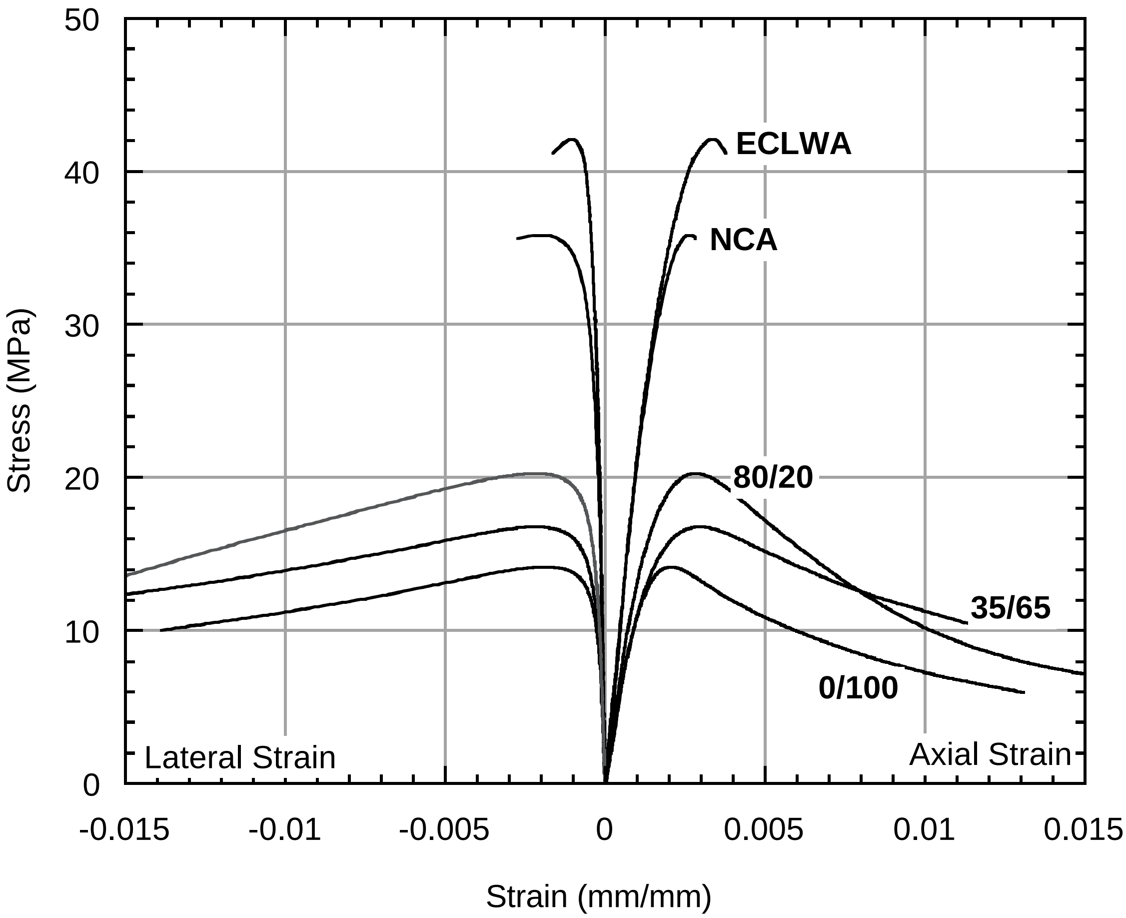


Figure 25 - Compressive Stress Versus Axial and Lateral Strains.

The most notable observation made in these test data was the ductility exhibited by the concrete batches made with 0/100, 35/65, and 80/20 SLAs. As can be seen in Figure 25, strains on the magnitude of greater than one percent were obtained while the specimens maintained approximately 50 percent of their respective peak loads. Complete results from the compression tests are given in Table 15.

To determine the modulus of elasticity of the coarse aggregates (E_a), the Hirsch-Dougill model[34,35] is applied. The Hirsch-Dougill model is a two phase elastic model that separates the concrete into its two constitutive components, in this case the mortar and the coarse aggregate,[36] and can be used to determine the elastic moduli of the natural, ECLWA, and synthetic coarse aggregates from the following equation:

$$\frac{1}{E_c} = X\left(\frac{1}{V_m E_m + V_a E_a}\right) + (1 - X)\left(\frac{V_m}{E_m} + \frac{V_a}{E_a}\right)$$

Where E_m and E_a are the elastic moduli of the mortar and coarse aggregate, respectively, and the constant X = 0.50 assuming isotropic conditions.[35] The volume fractions for the mortar and coarse aggregates are V_m=0.70 and V_a=0.30 for the five batches of concrete. Using

E_m=26.3 GPa determined from mortar specimens, the elastic moduli of elasticity for the five aggregates were calculated and are presented in Table 15. These results demonstrate that the synthetic aggregates have a significantly lower modulus of elasticity than the normal weight and ECLWAs. The moduli of elasticity values significantly increase as the fly ash content in the SLAs increase.

Typical Poisson's ratios (ν) for gravel are in the range of 0.3 to 0.4, whereas the HDPE in the manufactured aggregates has a typical range of 0.2 to 0.3.[37] This leads to the conclusion that batches NCA and ECLWA should have a higher Poisson ratios than the batches of concrete using the synthetic aggregates; however, the opposite is observed. Poisson ratio values for the five batches of concrete may be found in Table 15; for the SLAs, the Poisson ratio of the concretes is highest for pure HDPE (0/100) and decreases with increasing fly ash content.

9.3.3 Effect on Tensile Properties

The splitting tensile strength, f_{sp}, was determined in accordance with ASTM 496[33] by testing 100 x 150 mm cylinders from the five batches of concrete. With the splitting tension tests, aggregate fracture was observed in specimens made from concrete batches NCA, ECLWA, and 80/20 while pull-out of the aggregates were found for concrete batches 0/100 and 35/65. It is suspected that the NCA, ECLWA, and 80/20 SLA has better bond to the cement paste due to their rougher surface texture and their significantly higher values for E_a. The splitting tensile strengths, f_{sp}, are reported in Table 15. Lower strengths were found in concretes using the synthetic aggregates due to the lower elastic modulus (E_a) of the SLAs. Similar to the compressive strength, the tensile strengths increased in the concrete made with the SLAs as the fly ash content in the aggregates increased.

The following ACI relationship[38] may be used to predict the splitting tensile strength, f_{sp}, of lightweight concrete:

$$f_{sp} = K_{sp}\sqrt{f_c^{'}}$$

Where K_{sp} is an empirically derived constant for which ACI specifies a conservative value of K_{sp} = 0.56 $MPa^{1/2}$ for design. For each batch of concrete the values of K_{sp} calculated from the measured values of f_{sp} and f'_c are presented in Table 15. Confirming the conservatism, the measured K_{sp} for the ECLWA is larger than the 0.56 values given by ACI. In comparison, the values for K_{sp} for batches 0/100, 35/65, and 80/20 were significantly lower than K_{sp} for ECLWA, although they compare favorably with K_{sp} given by ACI. This indicates that a new K_{sp} value would not need to be determined for concrete using SLAs. Furthermore, differences in K_{sp} between batch ECLWA and the batches made with the SLAs are more likely caused by inaccuracy of the relationship over such a large compressive strength range than differences in aggregate type.

Table 15 - Results from Compression and Splitting Tension Tests

Property	Batch					
	NCA	ECLWA	0/100	35/65	80/20	M
f'_c (MPa)	35.5 ± 1.0	42.5 ± 0.4	14.2 ± 0.5	16.7 ± 0.6	20.1 ± 0.2	38.3 ± 0.6
E_{cc} (GPa)	21.8 ± 0.1	22.1 ± 0.2	12.6 ± 0.8	13.0 ± 0.3	14.4 ± 0.5	26.3 ± 0.0
K_E ($MPa^{1/2}/(kg/m^3)^{3/2}$)	0.033	0.039	0.044	0.040	0.037	0.041
E_a (GPa)	14.3	15.0	3.7	3.9	4.8	-[a]
Poisson's Ratio (ν)	0.20 ± 0.01	0.20 ± 0.01	0.26 ± 0.00	0.24 ± 0.01	0.24 ± 0.01	0.21 ± 0.01
f_{sp} (MPa)	3.4 ± 0.3	4.4 ± 0.0	2.1 ± 0.1	2.4 ± 0.1	2.5 ± 0.1	-[a]
K_{sp} ($MPa^{1/2}$)	0.57	0.67	0.56	0.59	0.56	-[a]

[a]Property not determined.

9.3.4 Effect on Fracture Properties

Notched beams from the five batches of concrete were tested following the RILEM testing procedures(39) for the Jenq-Shah two-parameter fracture model.(40) The Jenq-Shah two parameter fracture model describes the nonlinear fracture properties of concrete by two material constants: the fracture toughness constant (K_{IC}), and the critical crack tip opening displacement constant($CTOD_C$). The K_{IC} and CTODc factors correspond to the stress intensity and maximum crack tip opening at the peak load.

Prior to testing, a 40 mm notch was cut into the underside of each beam at center span using a diamond tip masonry blade. The setup for the fracture tests, schematically shown in Figure 26, had a single-point vertical load and a pair of LVDTs, one placed horizontally on each side of the beam at the level of the mouth of the notch. The average signal from the two LVDTs determined the Crack Mouth Opening Displacement (CMOD). The beam and the notch are shown schematically in Figure 26. The CMOD was increased at a rate of 0.024 mm/min until the maximum load was reached. The maximum load was reached when a load equivalent to 5 percent of the tensile strength were reached (95 percent of the beam's strength remained). Once at this level, the specimen was unloaded.

Figure 26 shows the CMOD versus load plot for the ECLWA and 80/20 specimens, and numerical results from the notched beam fracture tests are reported in Table 16. In Figure 26, the initial steeper slopes of the load vs. CMOD curve (inverse of the initial compliance) are due to the higher elastic modulus, E_{cf}, of the ECLWA concrete. The relative linearity of the pre-peak curve with the ECLWA is indicative of small amounts of pre-critical crack growth which further translate to smaller critical crack tip opening displacements, $CTOD_c$, for concrete made with ECLWA as reported in Table 16.

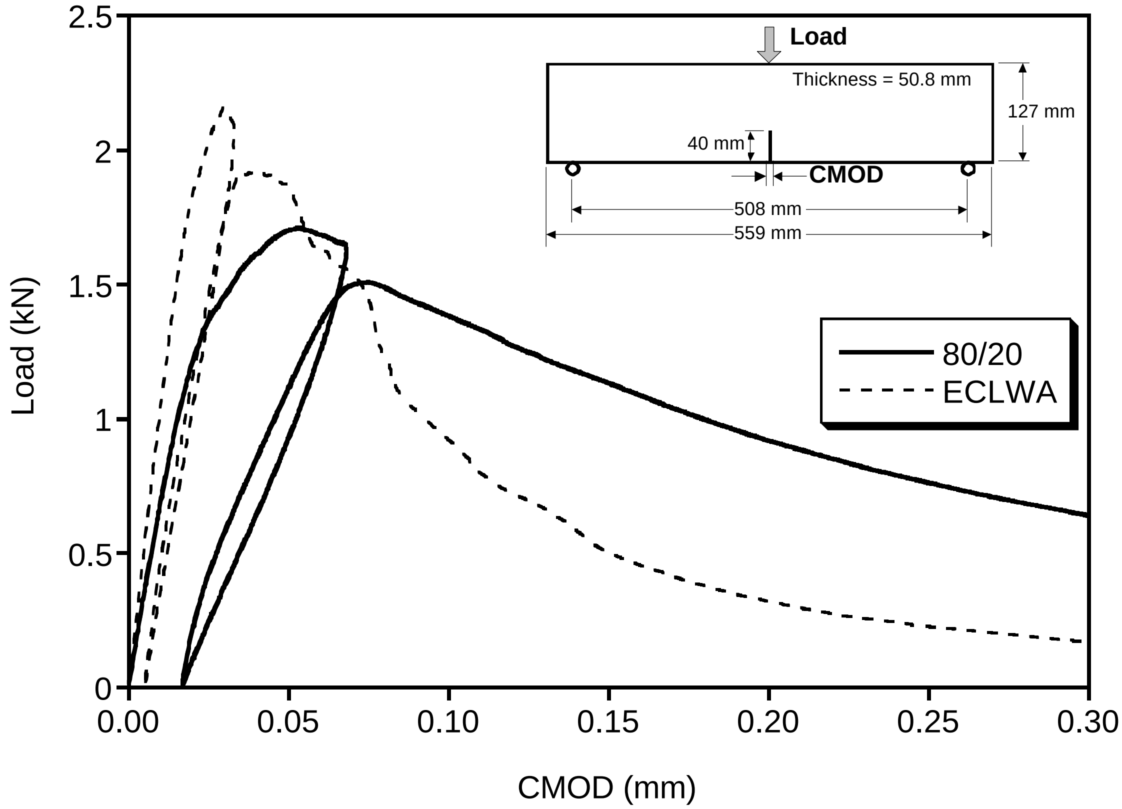


Figure 26 - Load Versus CMOD for Batches ECLWA and 80/20.

The same trend with regards to aggregate pullout versus aggregate fracture were observed in the fracture beam tests as were encountered in the splitting tension tests and can be seen in Figure 27. Aggregate pullout occurred in concrete specimens made with 0/100 and 35/65 SLAs. Aggregate fracture was observed in concretes made with NCA, ECLWA, and 80/20 aggregates.

Table 16 - Fracture Test Results

Property	Batch				
	NCA	ECLWA	0/100	35/65	80/20
K_{IC} (N/mm$^{3/2}$)	35.7 ± 5.0	25.1 ± 2.6	18.3 ± 2.3	22.6 ± 0.8	24.5 ± 0.2
$CTOD_c$ (mm)	0.0257 ± 0.007	0.0127 ± 0.005	0.0245 ± 0.003	0.0296 ± 0.004	0.0244 ± 0.001
G_{IC} (N/m)	52.3	27.4	27.8	39.6	39.2
f'_t (MPa)	2.99	3.17	1.67	1.94	2.36
E_{cf} (GPa)	24.4 ± 1.8	23.0 ± 1.5	11.6 ± 0.6	12.9 ± 0.7	15.3 ± 0.9
E_{cf}/E_{cc}	1.12	1.04	0.92	0.99	1.06

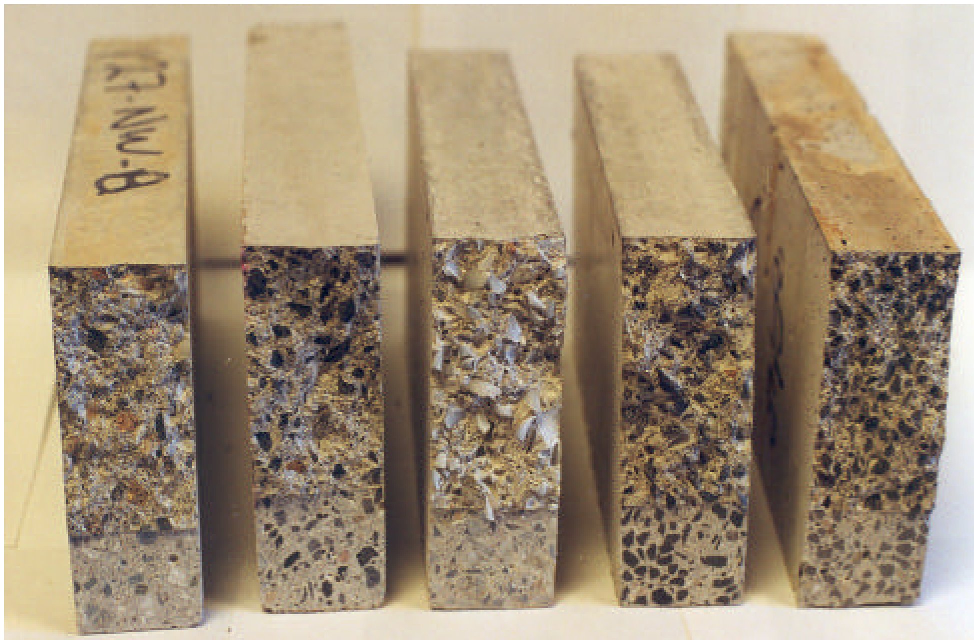


Figure 27 - Fractured Notched Beams (left to right: NCA, ECLWA, 0/100, 35/65, 80/20).

Differences in measured values of fracture toughness, K_{IC}, which is an indicator of a material's resistance to cracking, and critical crack tip opening displacement ($CTOD_C$), were significant. Concrete made with NCA had the largest fracture toughness. In the concrete made with the SLAs, the fracture toughness (K_{IC}) increased as the fly ash content of the SLAs increased. The toughness of the concrete made with the 80/20 SLA was approximately equivalent to that of the ECLWA concrete even though the ECLWA had considerably higher tensile strength.

Similar to the results from splitting tension tests, the ECLWA had the highest tensile strength (f'_t). However, its G_{IC} (the measure of energy required to completely fracture a material) was the lowest, indicating the brittleness of this material. Figure 26 shows a sudden decrease of the load as the crack mouth opens for the ECLWA, while the 80/20 SLA exhibited a considerable ductility. Further indication of the brittleness of the ECLWA concrete is its relatively small measured $CTOD_c$ in comparison with the other concretes, meaning very little crack bridging occurs with the ECLWA. The variation in the fracture energy (G_{IC}), from 27.4 N/m to 52.3 N/m is significant, implying that the required energy for creating a fracture surface is dependent on the type of coarse aggregate used in the concrete.

The elastic modulus determined from the notched fracture beam tests, E_{cf}, are given in Table 16. A comparison was made for the elastic modulus calculated based on the fracture tests and compression tests, E_{cf}/E_{cc}, and is also shown in Table 16. If a perfect bond between the mortar and aggregate exists, both methods will result in an identical value, therefore $E_{cf}/E_{cc}=1$. If the bond is poor, E_{cc} will be larger than E_{cf}, as is the case with concrete made with 0/100 and 35/65 SLAs, therefore $E_{cf}/E_{cc}<1$. Therefore it is concluded that the 0/100 and 35/65 aggregates provide poor bond and that there is separation between the aggregate and cement paste even within the elastic range, further supporting the conclusions drawn from the Poisson's ratio data from the uniaxial compression tests.

The modulus of elasticity of concrete from the fracture beam tests (E_{cf}) is determined using the beam geometry and the initial compliance factor (C_i). The C_i is the change in CMOD per unit change in load, or the inverse of the slope of a line fitted to the initial loading verses CMOD curve (Figure 26). The critical crack length (a_c), or crack length at peak load is determined using the unloading compliance (C_u). The unloading compliance is the slope of the line for the first unloading of the specimen in the loading verses CMOD curve. Using the critical crack length and the maximum load (P_{max}), the fracture toughness (K_{IC}), and critical crack tip opening displacement ($CTOD_C$), can be determined. The equations used to determine E_{cf}, a_c, K_{IC}, and $CTOD_C$ are given elsewhere.*[41,42]* Furthermore, the fracture energy, G_{IC} and the tensile strength, f'_t can be determined by;

$$G_{IC} = \frac{(K_{IC})^2}{E_{cf}}$$

$$f_t^{'} = 1.4705 \frac{(K_{IC})^2}{E_{cf}\, CTOD_C}$$

9.3.5 Salt Scaling Tests

Several specimens from the five batches of concrete were tested to evaluate salt scaling resistance following ASTM C672[30] procedure. A one-inch deep reservoir is made on the top surface of concrete block specimens by installing a wooden dike over the blocks. This reservoir is filled with a solution of calcium chloride and water. The blocks are then exposed to several cycles of freezing and thawing. After every five freezing and thawing cycles, the calcium chloride solution is replaced. During the solution replacement, the surface is visually inspected and the condition is rated from 0 to 5 (no scaling to severe scaling).

In order to have a more quantifiable mean of measurement, in addition to surface rating after every five freezing and thawing cycles, the scaled concrete surface was flushed with water over a 75 μm sieve. The residue left on the sieve was then oven dried, weighed, and added cumulatively to quantify the differences in the amounts of scaled material between the five batches of concrete. The surface rating data for the average of two specimens from each mix is reported in Table 17. The measured mass of the scaled material per unit area (kg/m^2) as a cumulative record of the material lost is shown in Figure 28.

Table 17 - Salt Scaling Visual Inspection Ratings

Cycles	Concrete Specimen				
	NCA	ECLWA	0/100	35/65	80/20
5	1	2	2.5	2	1
10	1	2.5	3	3	2
15	2	3	4	3	2
20	2	3.5	5	4	2
25	3	4.5	5	5	2
30	3	5	5	5	3
35	3	5	5	5	3
40	4	5	5	5	4
45	4	5	5	5	4
50	4	5	5	5	4

Note: Reported values are the average rating from two specimens.
0 No scaling
1 Very slight scaling
2 Slight to moderate scaling
3 Moderate scaling
4 Moderate to severe scaling
5 Severe scaling

The 80/20 concrete exhibited the best resistance to salt scaling, followed by batch NCA. The hydrophobic properties of the plastic in the 80/20 SLA may have inhibited water and chloride permeation hence contributing to its better performance. Specimen NCA exhibits similar performance against salt scaling.

The concrete specimens made with ECLWA, 35/65, and 0/100 aggregates demonstrated extremely poor resistance. The mortar aggregate bond appears to be the controlling factor for salt scaling resistance of concrete made with 0/100 and 35/65 SLAs; the weak interfacial zone may have provided a pathway for migration of water and chloride ions. Although stronger bond is present between the aggregate and paste with the ECLWA specimens, the aggregates themselves have high permeability allowing for the penetration of the chloride solution through the aggregate.

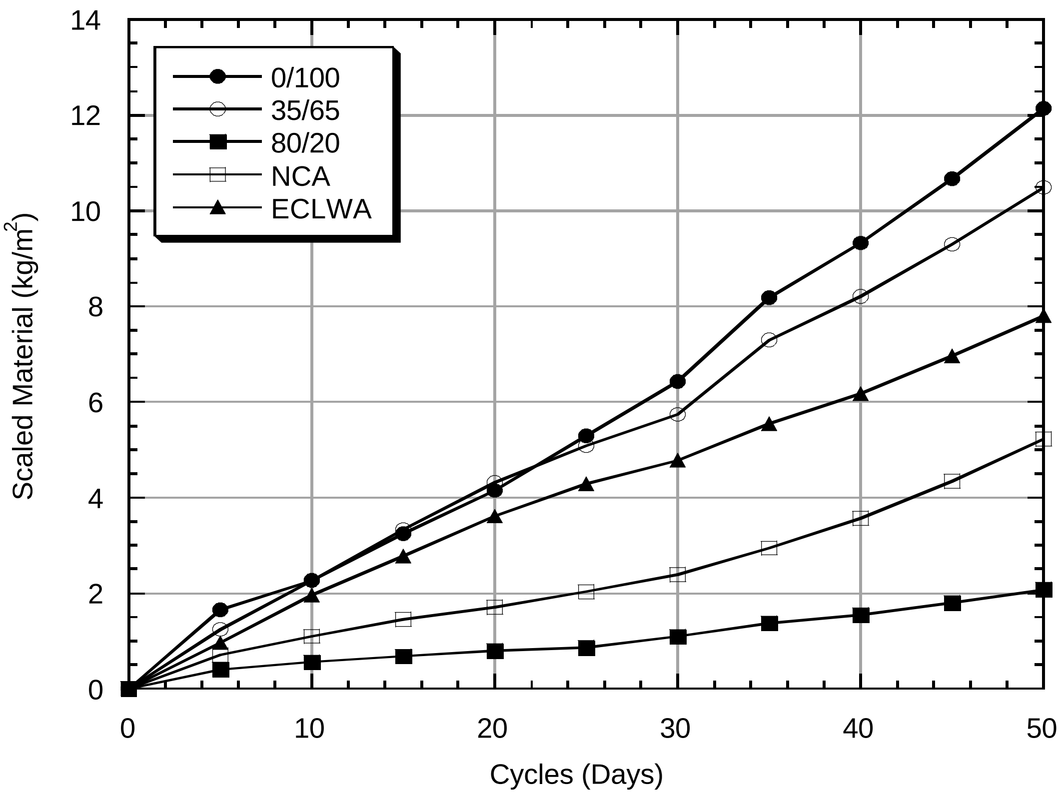


Figure 28 - Salt Scaling Performance of the Concretes.

9.4 Effect of Polymer Type on Concrete Mechanical Properties

Low-density polyethylene (LDPE) is harder and more brittle than high-density polyethylene (HDPE). Polystyrene (PS) is actually one of the hardest and the most brittle plastic in use. In order to examine the impact of polymer type on the physical properties of SLA and concrete, six batches of concrete were made using SLA coarse aggregate and natural sand for fine aggregate. The SLAs used were made with LDPE, HDPE, PS, and mixed plastics. The water to cement ratio (W/C) was 0.49 for all the mixes. The specimens from these batches were tested for unit weight, compressive strengths, and elastic modulus. The mixes were as follows:

- SLA made with 50% ash and 50% PS, designated as 50/50 PS.
- SLA made with 50% ash and 50% LDPE, designated as 50/50 LDPE.
- SLA made with 50% ash and 50% mixed plastics, designated as 50/50 MP.
- SLA made with 80% ash and 20% LDPE, designated as 80/20 LDPE.
- SLA made with 80% ash and 20% HDPE, designated as 80/20 HDPE.
- SLA made with 80% ash and 20% mixed plastics, designated as 80/20 MP.

9.4.1 Effect on Concrete Unit Weight

The effect of plastic resin type on the unit weight of concrete is shown in Figure 29. Regardless of fly ash to plastic ratio, the SLA made with mixed plastics resulted in concrete higher in unit weight.

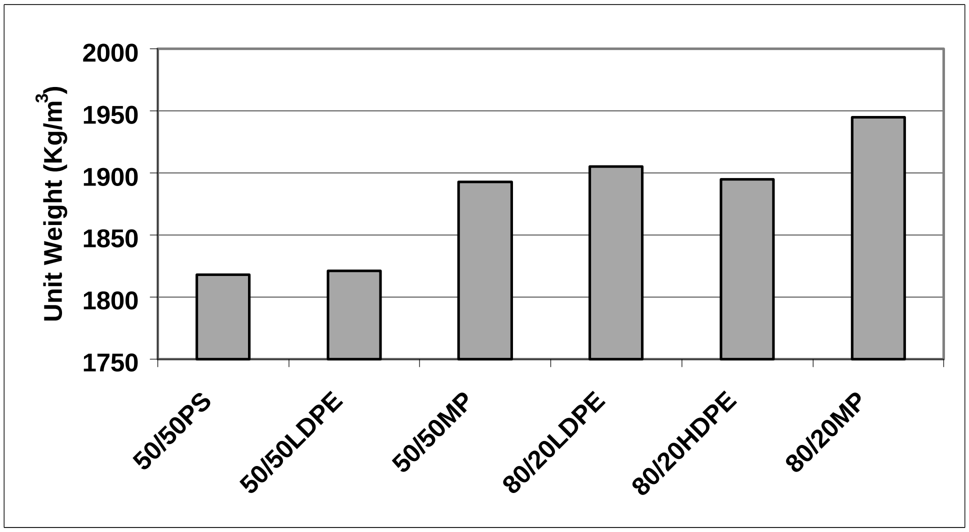


Figure 29 - Effect of Plastic Resin on the Concrete's Unit Weight.

9.4.2 Effect on Concrete Compressive Strength and Elastic Modulus

The concrete made with polystyrene (PS) and fly ash aggregate produced the highest compressive strength amongst the other mixes (Figure 30). The concrete made with 80/20 mixed plastics (MP) SLA, produced a higher strength than the mixes with similar fly ash to single plastic resin ratio. The compressive elastic modulus (E) for all the mixes was approximately similar (Figure 30). Concretes made with 50/50 MP and 80/20 HDPE and 80/20 MP satisfied the requirements of ACI 213-R87 for compressive strength (higher than 17.2 MPa).

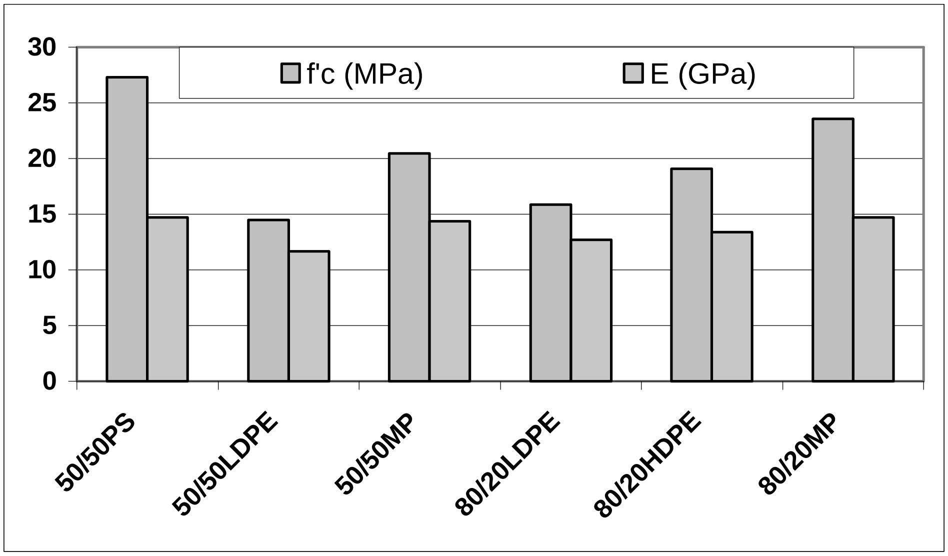


Figure 30 - Effect of Plastic Type on the Concrete's Compressive Strength and Elastic Modulus.

9.5 Effect of Aggregate on Concrete Mechanical Properties

In a typical concrete mix, 40 percent of concrete (by volume) is occupied by coarse aggregate, 30 percent is occupied by fine aggregate, and the remaining 30 percent is occupied by water, cement, entrapped or entrained air, and admixtures. In some lightweight concrete applications, LWA is only used as replacement for the coarse aggregate fraction rather than the total aggregate (coarse and fine) replacement.

In order to examine the potential of using SLA as only one of the two aggregate components in concrete, several batches of concrete were made using the following aggregate components:

1. SLA for both coarse and fine aggregates, designated as SLA/SLA.
2. SLA for coarse aggregate and normal weight for fine aggregate, designate as SLA/NW.
3. Normal weight coarse aggregate and SLA as fine aggregate, designated as NW/SLA.
4. Expanded clay as coarse aggregate and SLA as fine aggregate, designated as EC/SLA.
5. Expanded clay as coarse aggregate and normal weight as fine aggregate, designated as EC/NW.
6. Normal weight aggregate for both coarse and fine aggregate components as control, designated as NW/NW.

A water to cement ratio of 0.5 was used for all the mixes. Specimens made from these mixes were tested for unit weight, compressive strength, elastic modulus, and Poison's ratio. The results are presented in Table 18.

Table 18 - Test Results on Concrete with Different Aggregate Combinations

	Unit Weight (kg/m^3)	f'_c (MPa)	E (GPa)	μ
NW/NW	2323	41.3	28.3	0.21
EC/NW	1970	41.8	23.6	0.21
SLA/NW	1941	23.6	14.7	0.24
SLA/SLA	1571	16.0	5.0	0.26
NW/SLA	1794	21.3	9.5	0.25
EC/SLA	1570	23.0	8.9	0.24

9.5.1 Effect on Concrete Unit Weight

As indicated in Table 18 and Figure 31, the unit weights of concretes made entirely with lightweight aggregate (both coarse and fine components) are within the guidelines given by the ACI 213R-87(11) for structural concrete (Figure 32). The unit weights of concretes made with coarse lightweight aggregate and normal weight fine aggregate are slightly higher than the upper limit given by the ACI 213R-87 (1900 kg/m^3).

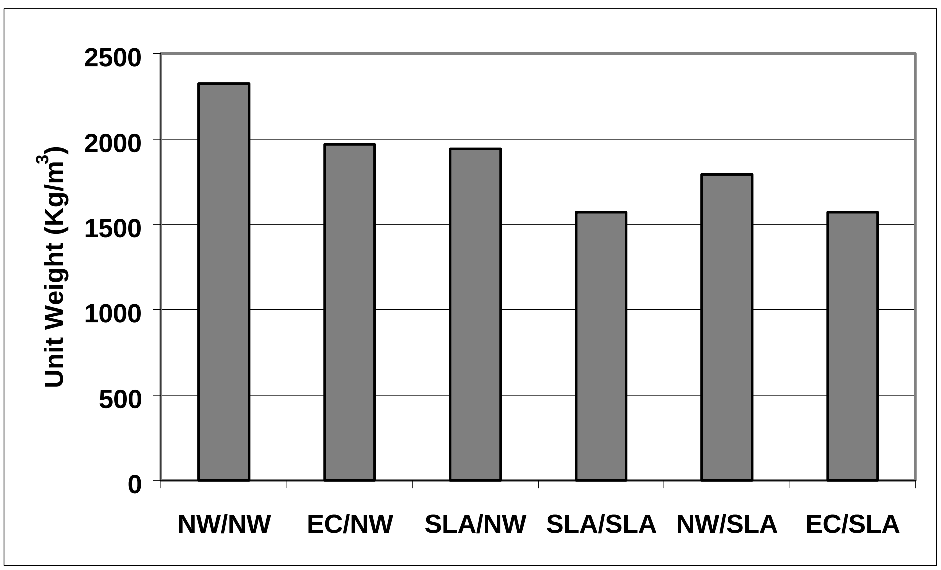


Figure 31 - Unit Weights of Concrete Made with Different Aggregates.

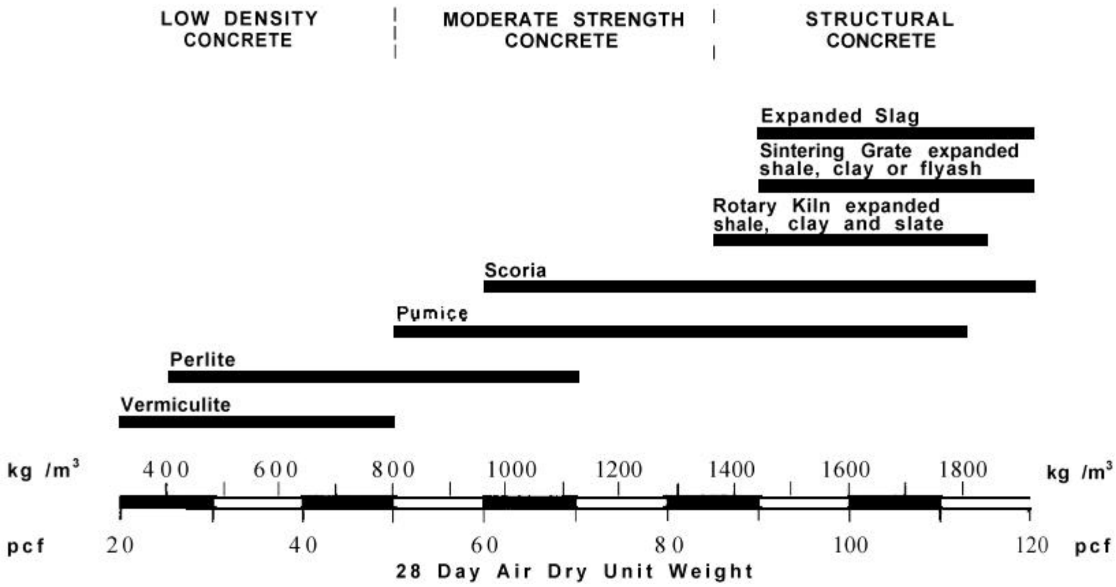


Figure 32[11] - Approximate Unit Weight and Use Classification of Lightweight Aggregate Concretes.

9.5.2 Effect on Concrete Compressive Strength and Modulus of Elasticity

The Figures 33 and 34 presents the compressive strength and elastic modulus of concrete made with different aggregate combinations. The compressive strength of concrete made entirely with SLA as both coarse and fine aggregate satisfies the requirement of moderate strength lightweight concrete (6.89 to 17.24 MPa). However, the concrete made with SLA as coarse aggregate and with normal weight fine aggregate had a compressive strength that satisfies the requirement of structural lightweight concrete (greater than 17.2 MPa).

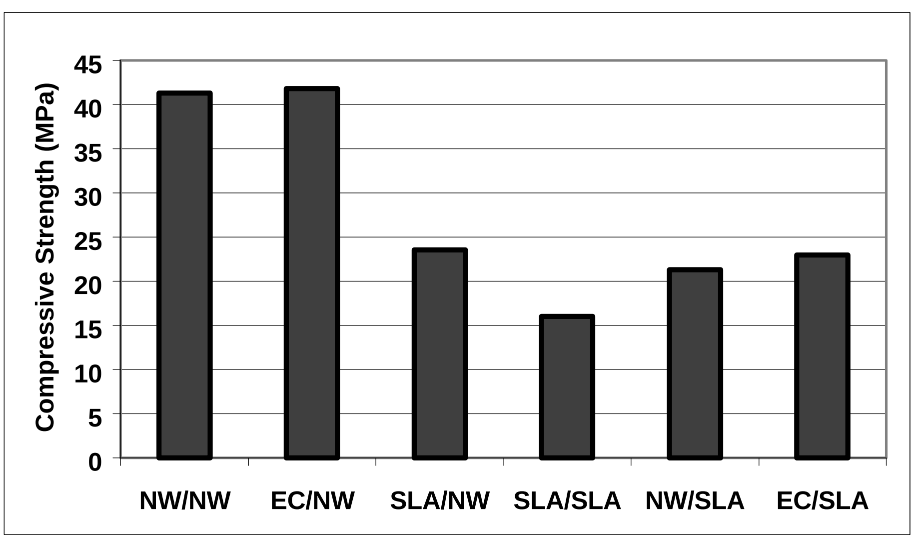


Figure 33 - Compressive Strength of Concrete Made with Different Aggregates.

The elastic modulus of concrete made with SLA was significantly lower than the other concretes (Figure 34). This is a clear indication of how soft this material is as compared with ordinary concrete. This figure also shows the significant affect that SLA fine aggregate had on the elastic modulus of the concretes made. The elastic moduli of concretes made with SLA as fine aggregate for both normal weight coarse aggregate (NW/SLA) as well as expanded clay lightweight coarse aggregates (EC/SLA) were less than half of the moduli for concretes that was made entirely with normal weight aggregate (NW/NW) or expanded clay coarse aggregate and normal weight fine aggregate (EC/NW).

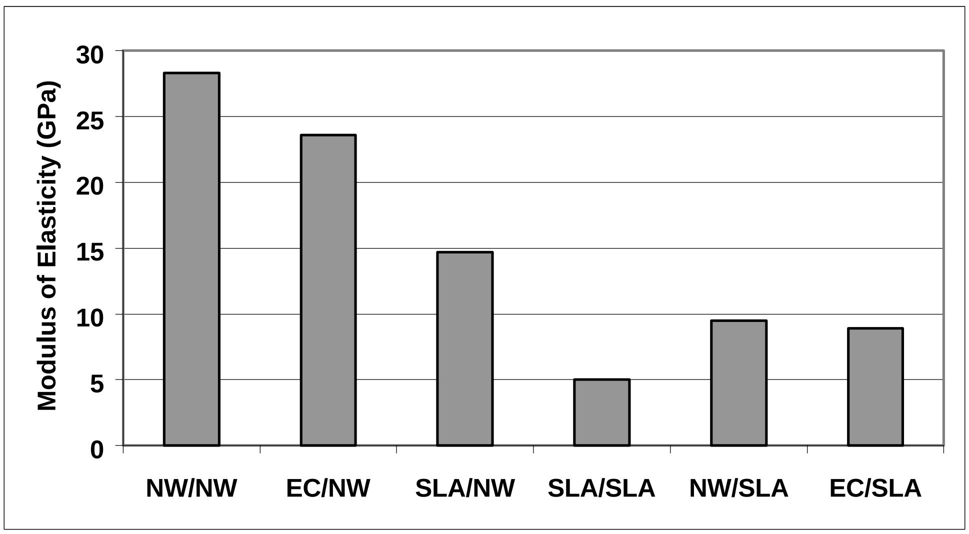


Figure 34 - Elastic Modulus of Concrete Made with Different Aggregates.

9.6 Effect of Water to Cement Ratio on Mechanical Properties of Concrete

Concrete strength typically increases with lower water-to-cement ratios. A study was conducted on the effect of water to cement ratio on concrete made with SLA for both coarse and fine aggregates as well as SLA only as coarse aggregate.

Several batches of concrete were made with varying water to cement ratios in the range of 0.35 to 0.48. The results of 28-day compressive strength tests on 4x8-inch cylinders from these batches are presented in Figure 35. The compressive strength of concretes made with SLA coarse aggregate and normal weight fine aggregate satisfied the minimum strength required for structural lightweight concrete, for the entire range of water-to-cement ratios. For the concretes made with SLA as both fine and coarse aggregates, a minimum water to cement ratio of 0.45 was required in order to have concrete with sufficient strengths to satisfy the ACI 213 guideline for structural lightweight concrete.

Figure 36 shows the effect of water-to-cement ratio on the elastic modulus of concrete made with SLA. The concrete made with SLA coarse aggregate, regardless of water to cement ratio, had higher elastic modulus as compared with the concrete made entirely with SLA.

The large difference between the elastic modulus emphasizes the significant affect that fine aggregate have on the modulus of elasticity of concrete.

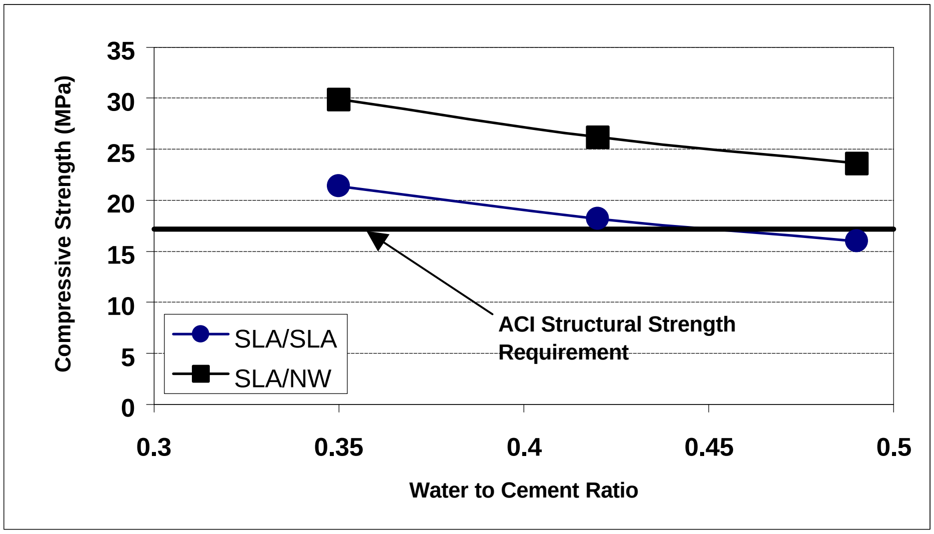


Figure 35 - Effect of Water to Cement Ratio on Compressive Strength of SLA Concrete.

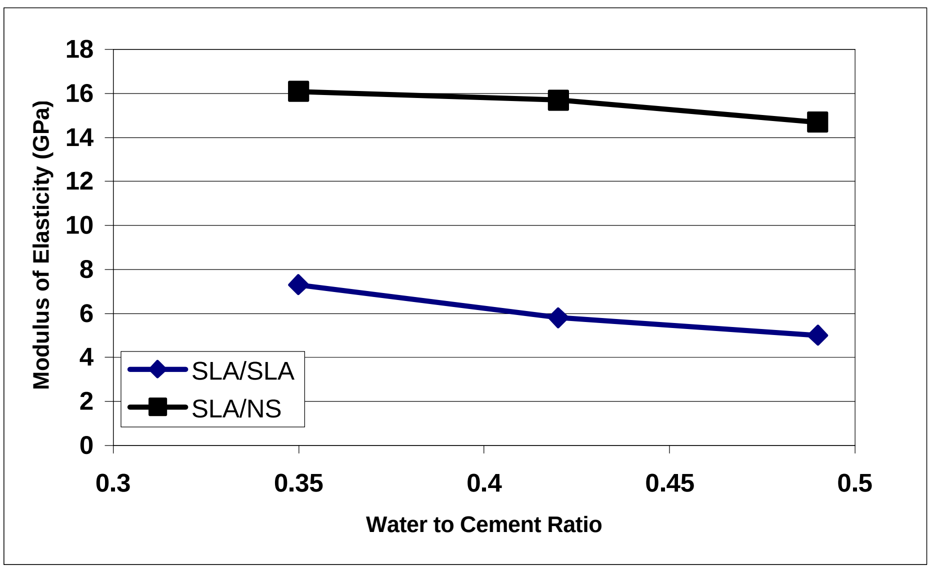


Figure 36 - Effect of Water to Cement Ratio on Elastic Modulus of SLA Concrete.

10.0 Environmental Study

10.1 Fly Ash Environmental Regulations

The U.S. Environmental Protection Agency (EPA) has concluded that coal combustion by-products including fly ash, bottom ash, and boiler slag produced by coal burning electric utilities do not warrant management as hazardous materials under Subtitle C of the Resource Conservation & Recovery Act (RCRA, 1976 Federal Register)[43]. On April 25, 2000 EPA issued the following regulatory determination:[44]

> The Environmental Protection Agency (EPA) has concluded that fossil fuel combustion wastes do not warrant regulations as hazardous under Subtitle C of the Resource Conservation and Recovery Act (RCRA). EPA is retaining the hazardous waste exemption for these wastes. However, the Agency has determined that national non-hazardous waste regulations under RCRA Subtitle D are needed for coal combustion wastes disposed in surface impoundments and landfills and used as minefilling. The agency also concluded beneficial uses of these wastes, other than for minefilling, poses no significant risk and no additional national regulations are needed.

10.2 Fly Ash Testing for Contaminants

The tests used to evaluate fly ash have been designed for wastes co-disposed in sanitary landfills. The most commonly used tests are the Toxicity Characteristics Leaching Procedure (TCLP) (EPA, 1990a), the ASTM leaching procedure (ASTM D 3987,[45] the EPA (EPA, 1990b), and the Synthetic Precipitation Leaching Procedure (SPLP) (EPA, 1990c). The TCLP[46] is the EPA regulatory leaching procedure, under RCRA, for the identification of wastes as hazardous when disposed in a sanitary landfill. The TCLP was developed primarily to simulate the leachability of an industrial waste co-disposed with sanitary refuse materials. The TCLP has also been adopted by many state regulatory agencies to provide leaching information on solid wastes (not hazardous) that are not federally regulated.

The scientific validity of these tests as generally applied to reused materials (versus disposed materials) has been questioned.[18] It is agreed within the by-product utilization industry that disposal regulations should not be generally applied to material in use applications. The main argument is that the by-products used in construction or similar applications will not experience the exposure condition imposed by the TCLP testing.[43] The ASTM E-50 committee, recently formed to deal with this issue, has begun to address the definition of coal combustion by-products including fly ash as resources versus waste.

10.3 TCLP Procedure

The leachability of eight inorganic metals; arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver, referred to as RCRA 8 metals, are generally the contaminants of concern for classification of metal bearing wastes as being hazardous or non-hazardous. Following the TCLP guidelines, a sample of the solid waste or material to be tested along with an extraction fluid solution (with a pH of 4.93 ± 0.05) are agitated in a rotating jar for 18 ± 2 hours. After agitation the solution is filtered and analyzed for trace metal elements using inductively coupled plasma-atomic emission spectrometry (EPA SW846 - 6010B) and manual cold-vapor technique (EPA SW846 - 7471A).

10.4 Coal Fly Ash and SLA Analysis

One desirable aspect of pelletizing fly ash with plastic is the encapsulation of many metal elements by the plastic binder. In order to measure the degree of encapsulation, samples of coal fly ash and 80:20 mixed plastic SLA were analyzed for both total metal concentration as well as leachable quantity through TCLP testing procedure. A commercial environmental lab in Massachusetts (AccuTest, Inc.) conducted the tests. The results are presented in Tables 19 and 25, as well as in Appendix B. The reportable concentrations limits (RC S1) shown in Table 19 are based on the Massachusetts Department of Environmental Protection (DEP) regulations for soil contamination at S1 sites.(47)

Table 19 - Total RCRA 8 Metals Content

Metals	Coal Fly Ash Content mg/kg	SLA Content mg/kg	Reduction %	RC S1* mg/kg
Arsenic	35.6	27.5	23	30
Barium	460	292	36	1000
Cadmium	<0.38	<0.37	ND	30
Chromium	35.7	30.4	15	1000
Lead	20.6	13.8	33	300
Mercury	0.70	0.25	64	20
Selenium	73.4	74.4	0	400
Silver	<0.48	<0.46	ND	100

*Reportable concentration for category S1 soil.

The S1 site according to the DEP is a soil category that has the highest exposure potential e.g. surficial soil in residential neighborhoods.(47)

Table 20 - TCLP Analysis for RCRA 8 Metals Leachability

Metals	Coal Fly Ash Content mg/l	SLA Content mg/l	Reduction %	Regulatory Level* mg/l
Arsenic	0.012	<0.010	<17	5.0
Barium	0.23	0.5	-117	100
Cadmium	0.0066	<0.0040	<39	1.0
Chromium	0.12	<0.010	<92	5.0
Lead	<0.010	<0.010	ND	5.0
Mercury	<0.00020	<0.00020	ND	0.2
Selenium	0.17	0.028	83	1.0
Silver	<0.0050	<0.0050	ND	5.0

*40CFR 261.24.

The regulatory levels shown in Table 20 are based on the Federal Regulations, 40CFR 261.24.

10.5 Discussion of Results

The results indicate that both total metals content and leachable metals (except for Ba, which is also present in Portland cement) were reduced by various degrees due to plastic binding effect. The SLA samples made with 80 percent fly ash and 20 percent mixed plastic is suitable for use as structural fill.

In the co-polymer pelletization process used for the production of the SLA, incorporation of 80 percent fly ash into the polymer matrix was the limit above which we were not able to get a homogeneous material. At this level of ash concentration, the matrix is very brittle and there is a potential of fly ash particles dislodging from the binders during agitation in the TCLP solution jars. It is our opinion that the SLA with lower ash content may do better in encapsulating metal elements of coal fly ash. Since the time of this analysis, we have discovered that even at 80 percent fly ash content, when the time of mixing during co-polymerization is increased, a more homogeneous material is produced. The data shown above is based on analysis on one SLA sample; therefore, further study is needed to establish the degree of encapsulation of metals by the polymer binder when lower amount of fly ash is used or when the time during production process is increased.

11.0 Conclusions

We showed that lightweight synthetic aggregates (SLA), a material used by construction industry in large volumes, can be produced from compounding coal fly ash and recycled waste plastics. The SLA is suitable for used as geotechnical fill, as well as in pre-cast or cast-in-place concrete. Based on the results of this study, the following conclusions can be drawn.

11.1 SLA Composition and Manufacturing

- The more fluid the plastic binder is, the easier it is to incorporate higher concentrations of fly ash in the mixtures.

- The carbon content in the fly ash does not affect the production process.

- The physical properties of SLA are influenced by both the fly ash concentration and the thermoplastic binder composition. However, as the fly ash concentration increases, the physical properties of the SLA become less dependent on the thermoplastic binder's properties. At fly ash concentrations of 80 percent, the physical properties of the SLA are relatively insensitive to the composition of the thermoplastic binder.

11.2 Geotechnical Properties of SLA

- The specific gravity of SLA made with 80 percent fly ash and 20 percent plastic binder is similar to the specific gravity of expanded clay. The specific gravity of the SLA decreased as much as 12 percent when fly ash with 30 percent carbon content was used.

- The SLA exhibited much softer (larger strain) behavior than expanded clay aggregate, when it was tested for one-dimensional compression (consolidation). Physical properties of the plastic binder do affect this property, as stiffer plastic binders produced stiffer SLA.

- The triaxial compression tests results from the SLA indicated that the compressive strength of SLA, regardless of its binder content and types, is higher than the strengths of both the natural sand and expanded clay.

- The friction angle of the SLA with 20 percent plastics and 80 percent fly ash is similar to the friction angles of natural sand or expanded clay.

- The strength characteristics of the SLA indicate that they have the potential to be used as an alternative to natural or lightweight aggregate for geotechnical applications.

11.3 Use of SLA in Structural Concrete

- The concretes made with the expanded clay lightweight aggregate and the 80/20 SLA had similar bulk specific gravities and unit weights (1400 to 1850 kg/m^3). The unit weights of concretes made with coarse lightweight SLA or expanded clay aggregate and normal weight fine aggregate are slightly higher than the upper limit given by the ACI 213R-87 for lightweight concrete (1900 kg/m^3).

- With respect to compressive strength, concretes made with 0/100 and 35/65 SLAs did not satisfy the ACI requirement for structural lightweight concrete. The compressive strengths of concrete made with SLA improved significantly as the fly ash content of SLA increased. The compressive strength of concrete made with 80/20 SLA, as both coarse and fine aggregate, with a water-to-cement ratio of lower than 0.45 did satisfy the requirement of structural lightweight concrete. However, the concrete made with SLA as coarse aggregate and normal weight fine aggregate had a compressive strength that satisfies the requirement of structural lightweight concrete even at water-to-cement ratio greater than 0.45.

- The concrete made with 80/20MP SLA produced a higher strength (both compressive and tensile) than the mixes with similar fly ash-to-single plastic resin ratio. The elastic modulus (E) for all the mixes, regardless of the type of plastic used for the manufacturing of SLA, was approximately similar.

- Similar to the compressive strength, the tensile strengths of SLA concrete increased as the fly ash content in the aggregates increased.

- Concretes made with 80/20 SLA exhibited a considerable ductility as compared with concretes made with expanded clay or normal weight aggregates.

- The 80/20 SLA concrete exhibited the best resistance to salt scaling as compared with all other specimens tested in this study.

11.4 Environmental Analysis of SLA

- Using EPA approved test methods for detection of total and leachable trace metals (8 RCRA) available, both the fly ash and SLA were tested and it is concluded that the plastic binder encapsulates the trace metals elements within the SLA particles to varying degrees at an 80/20-mix ratio.

12.0 Future Works

The bulk of the work reported herein concentrated on the production of SLA using fly ash and waste plastics in the municipal solid waste streams. Based on the results of this work, the research team plans to broaden the scope of SLA production to include waste plastics from other sources such as automotive and computer industries.

Portland cement concrete is used in variety of applications in transportation construction industry ranging from building and underground structures to bridge and pavements as well as sound and traffic barriers in highways and many more applications. Depending on the intended application of concrete, different properties are required and must be considered during the mix design. For example, constituents and mix ratios in concrete used for making masonry units are totally different from concrete used for construction of a highway pavement. Future work on the use of SLA shall concentrate on optimizing concrete mix design for each particular application.

For highway application, concrete using the fly ash/plastic aggregates (SLA) may be well suited for paving materials in some applications. The low elastic modulus will make the pavement more flexible, hence more fatigue resistant. The lightweight and excellent scaling resistance experienced in this study may make some of SLA concrete a candidate for bridge deck construction. Future research efforts should be concentrated on the experimental use of SLA concrete for pavements, bridge deck, and pre-cast concrete elements.

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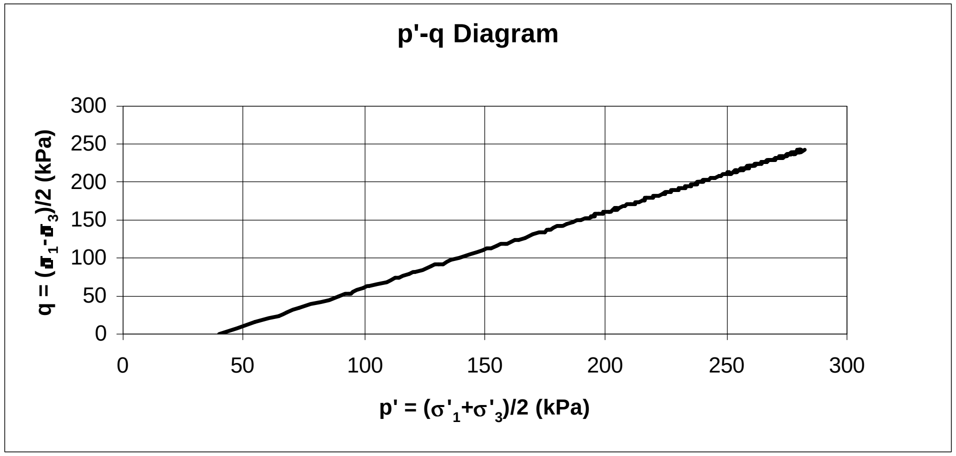
Appendix A

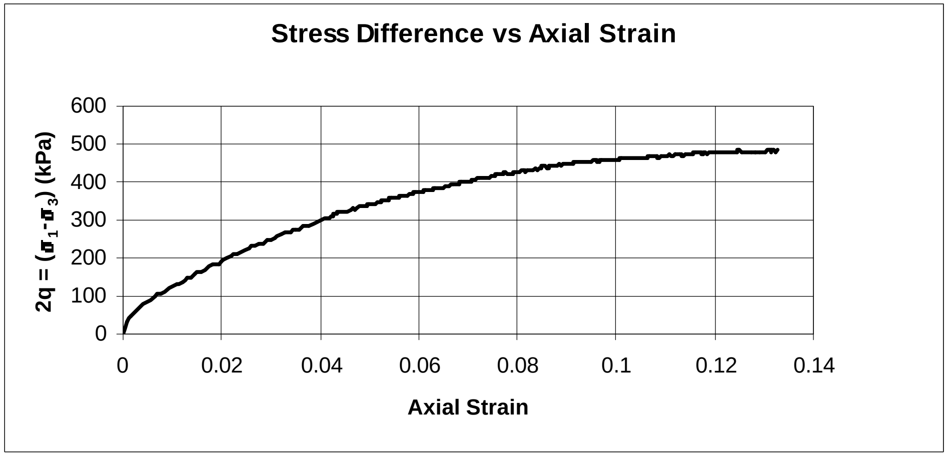
Triaxial Test Results
(Conducted by Tufts University)

Appendix B

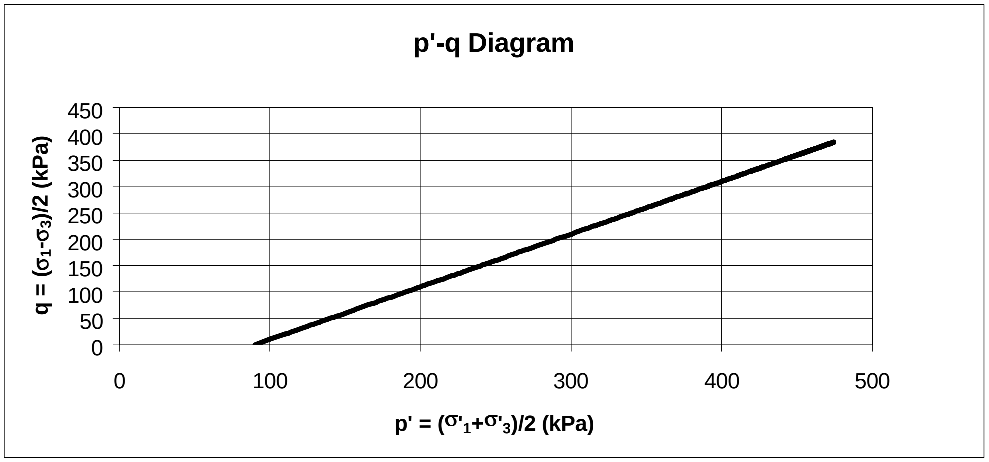
TCLP Test Results
(Conducted by AccuTest, Inc.)

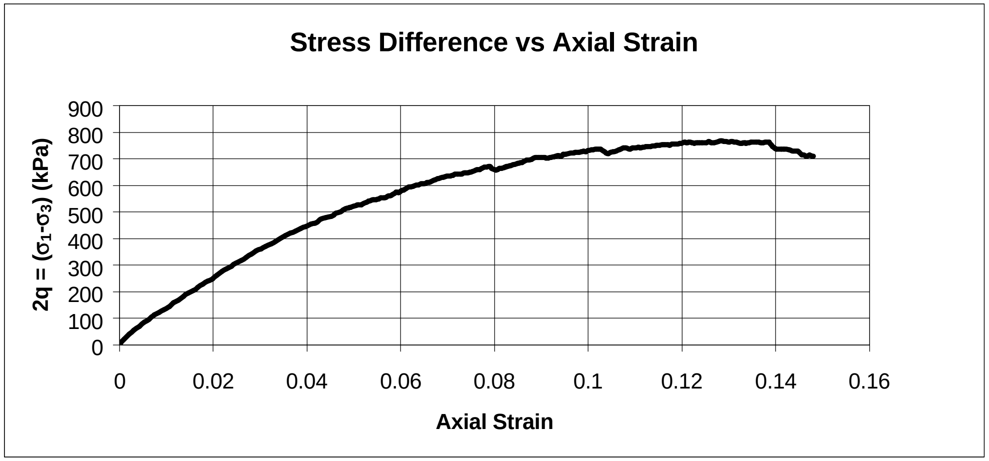
p'-q Diagram & Stress Difference vs Axial Strain for 35/65 HIPS at 50 kPa





p'-q Diagram & Stress Difference vs Axial Strain for 35/65 HIPS at 100 kPa





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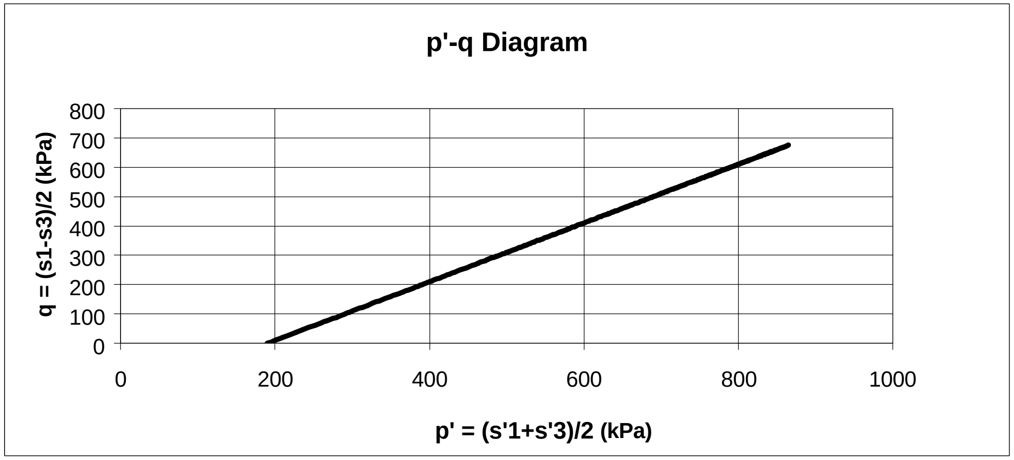
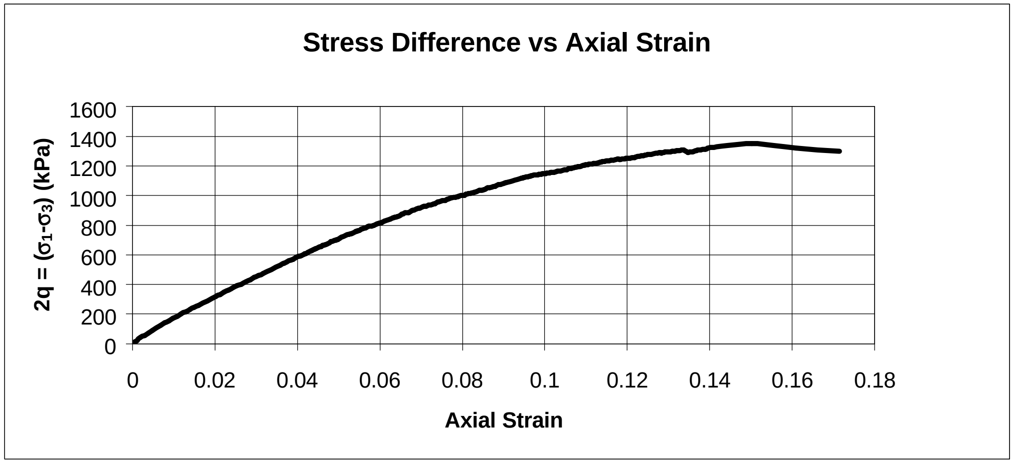
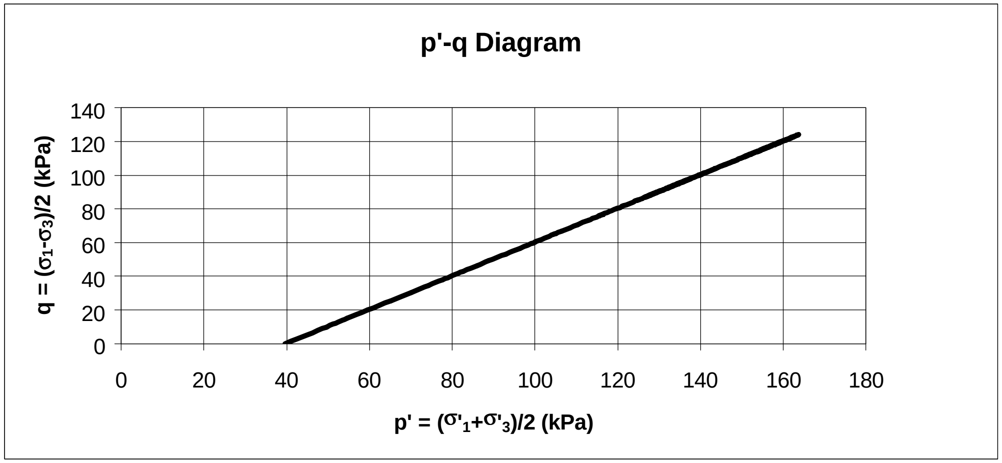
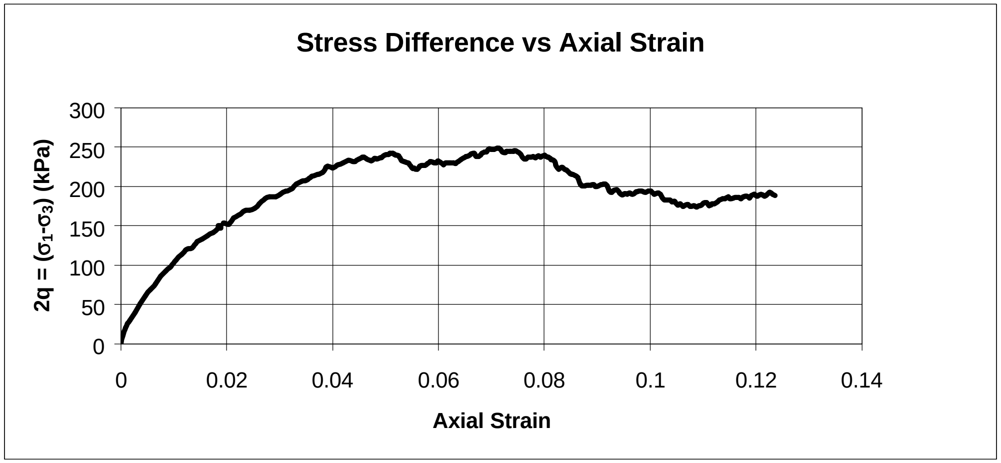




p'-q Diagram & Stress Difference vs Axial Strain for 66/34 HIPS at 50 kPa





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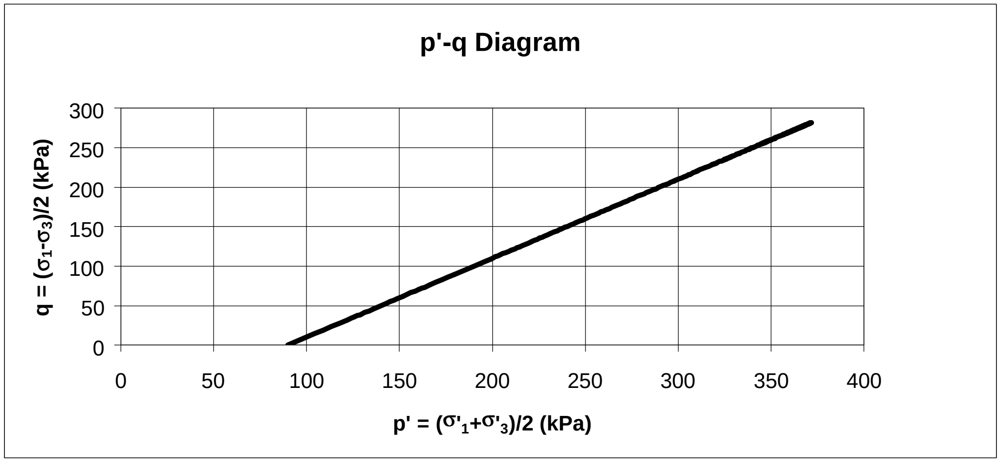

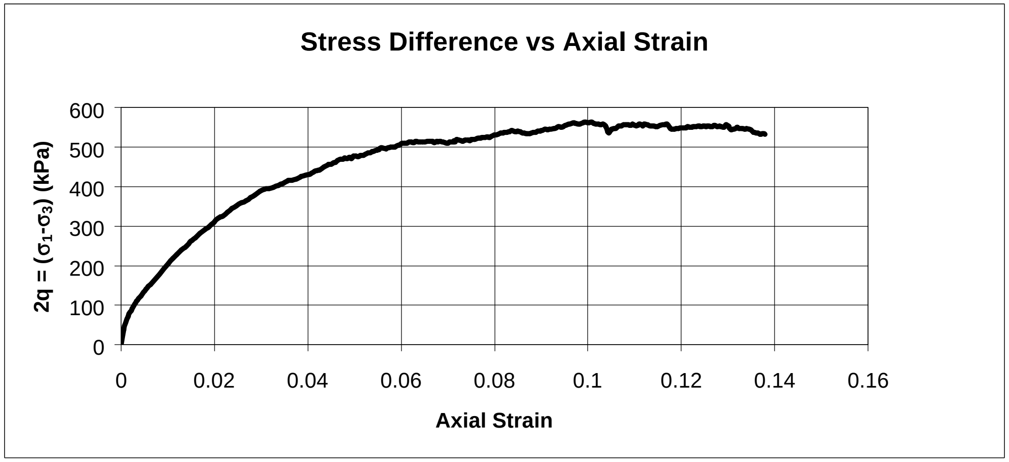

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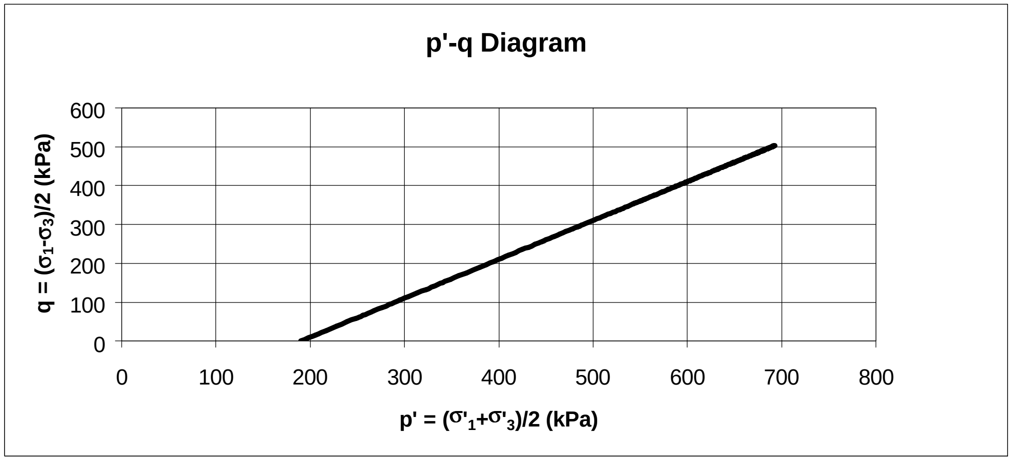
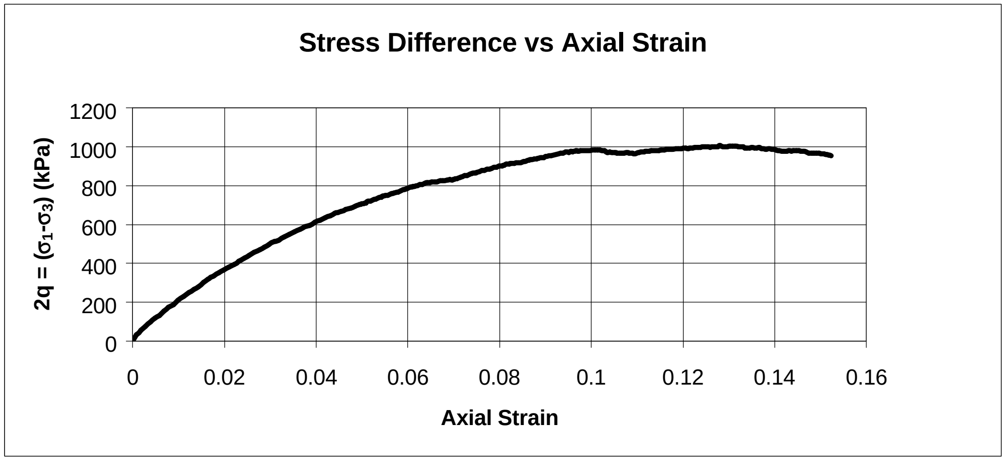
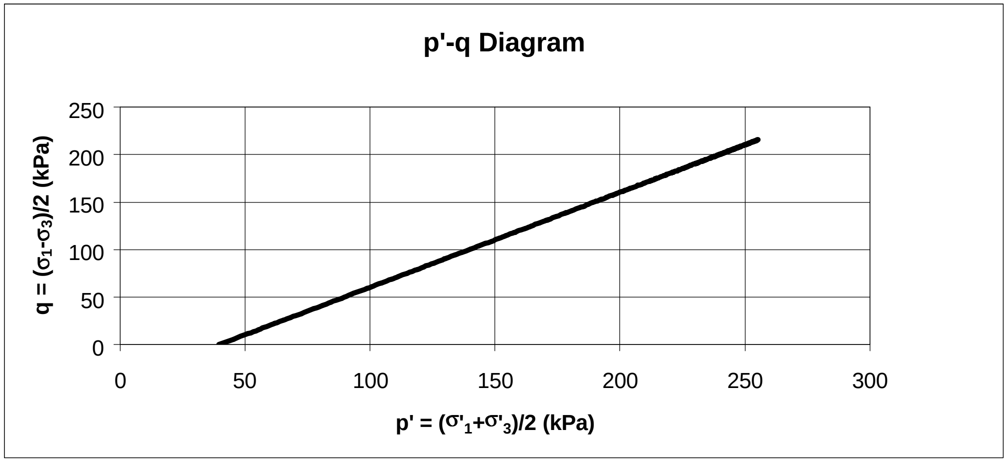
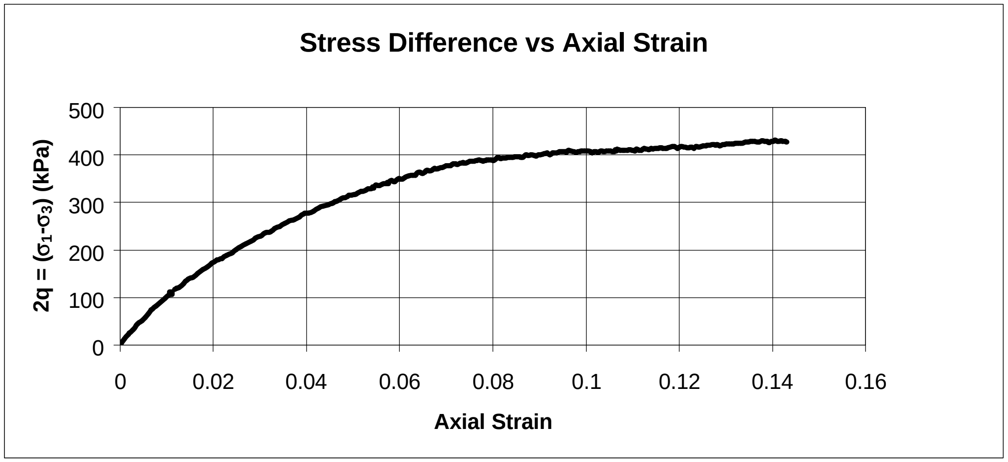




p'-q Diagram & Stress Difference vs Axial Strain for 60/40 HIPS at 50 kPa





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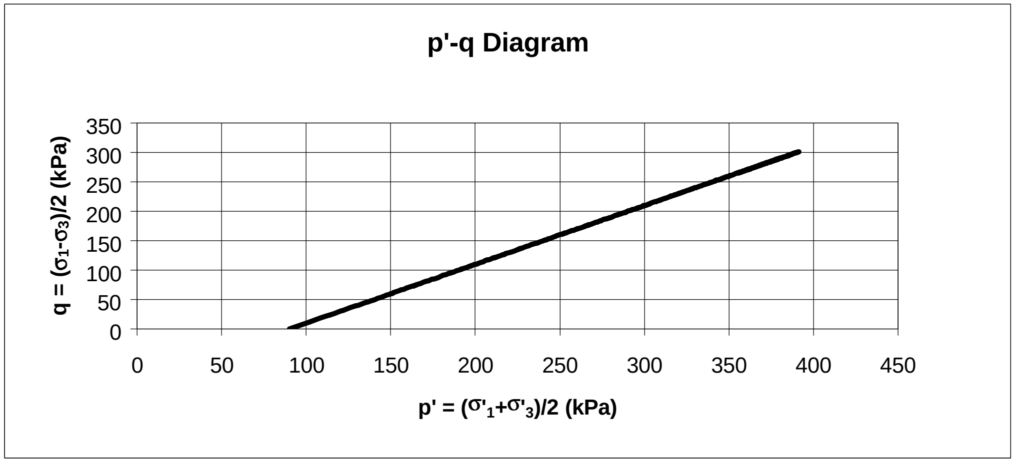

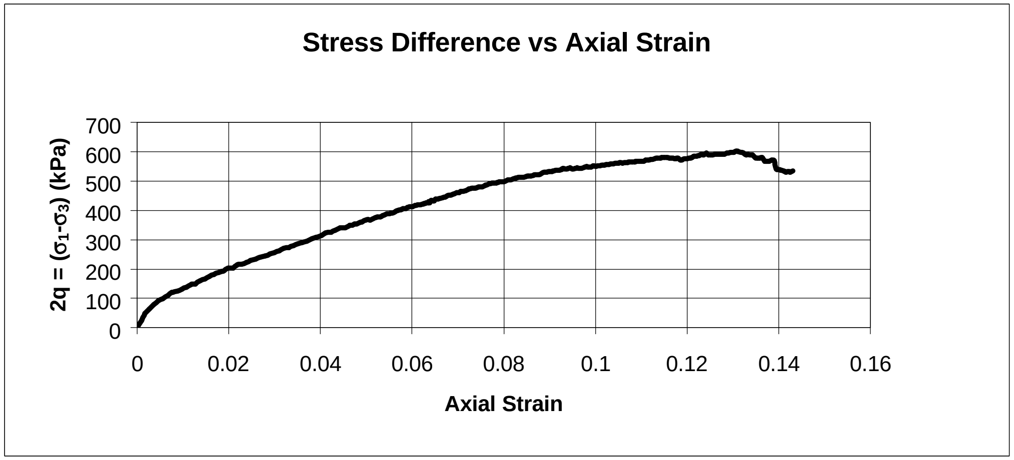

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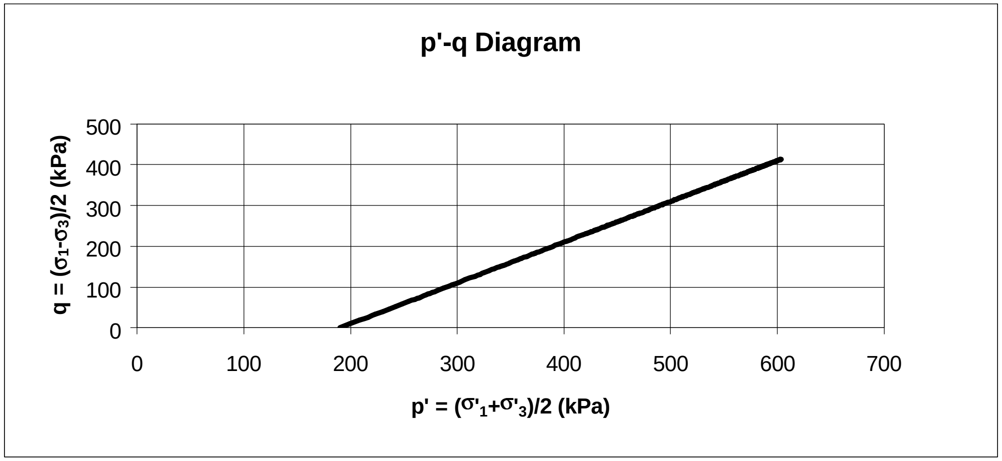

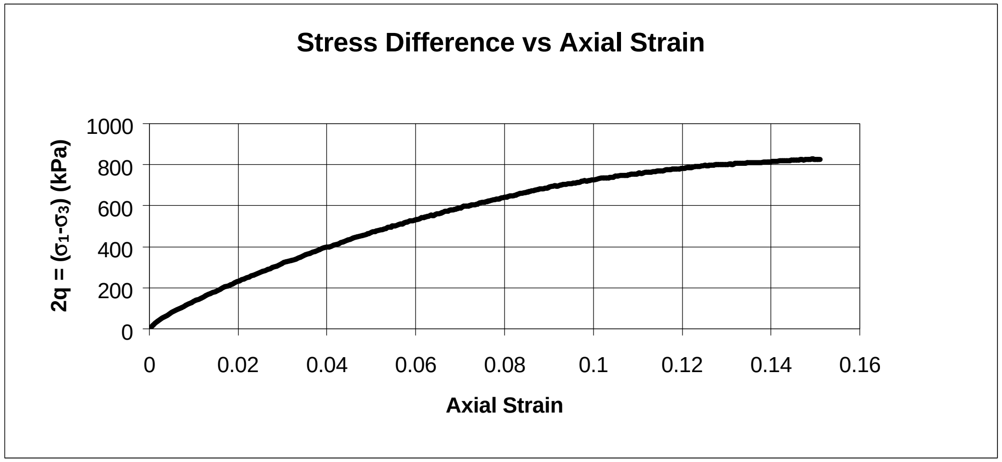

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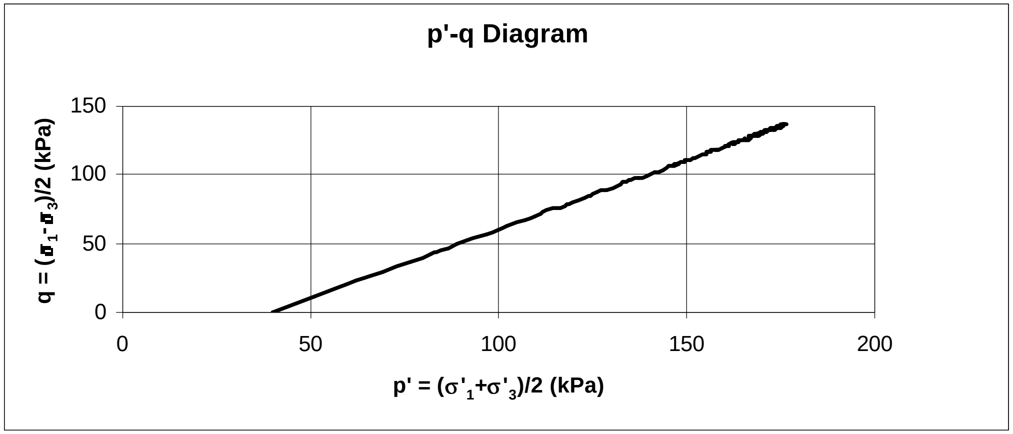

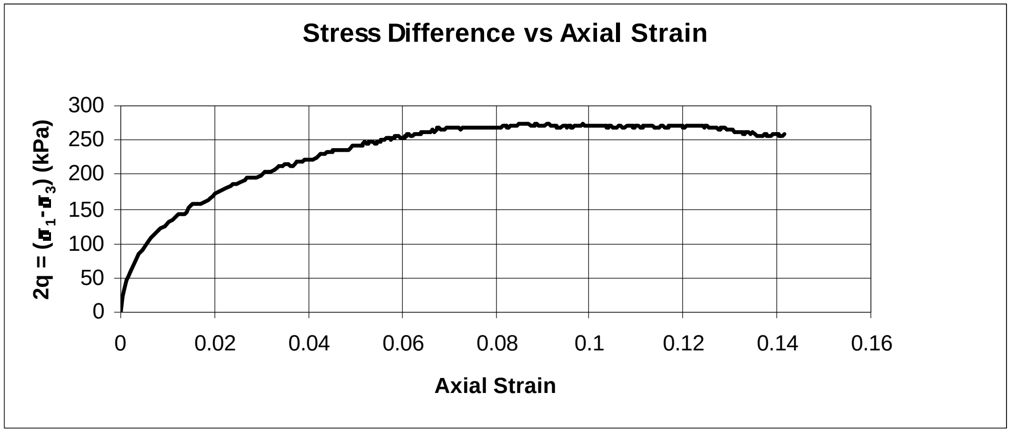

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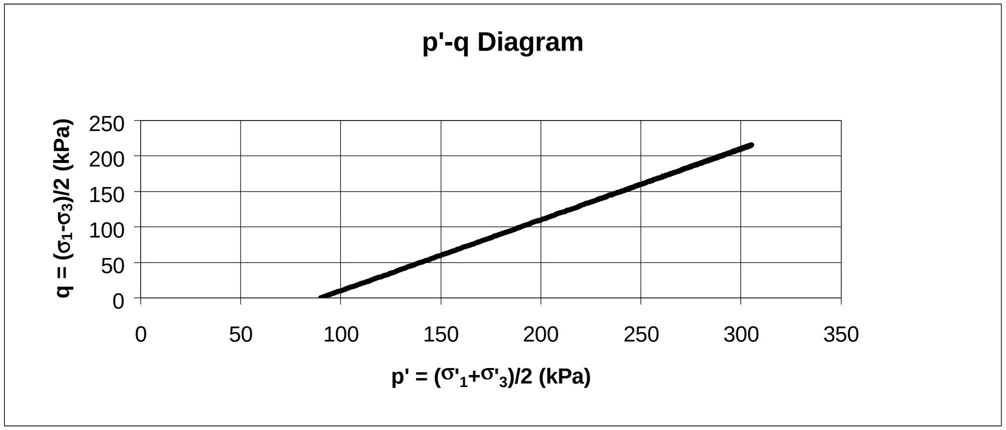

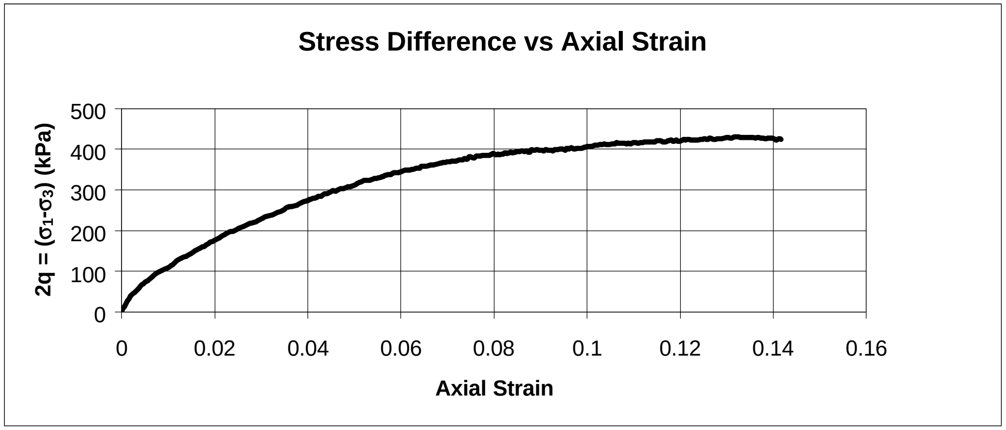

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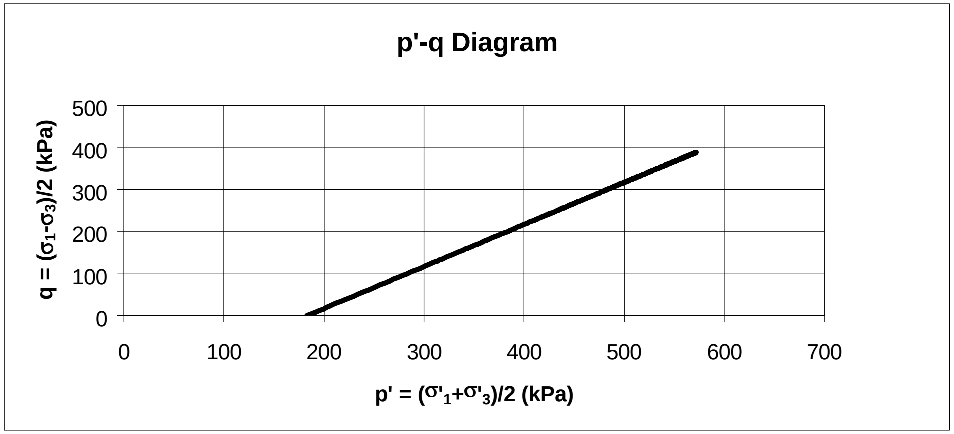

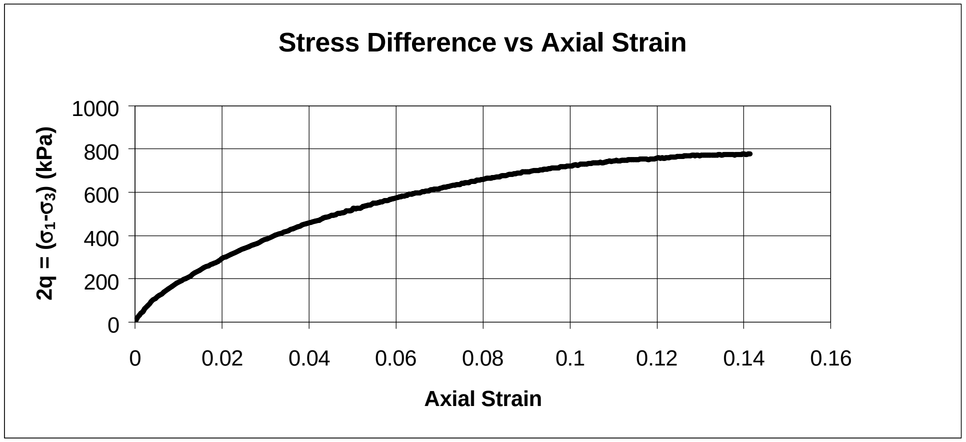

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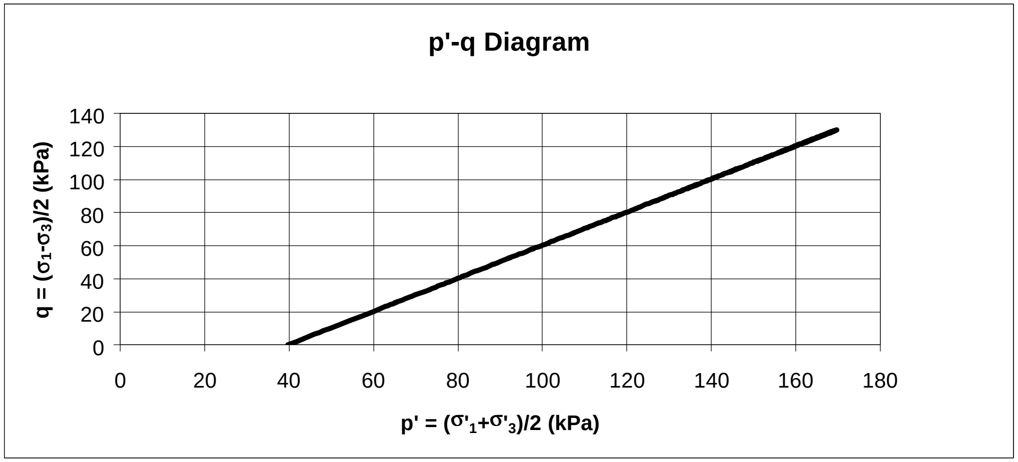

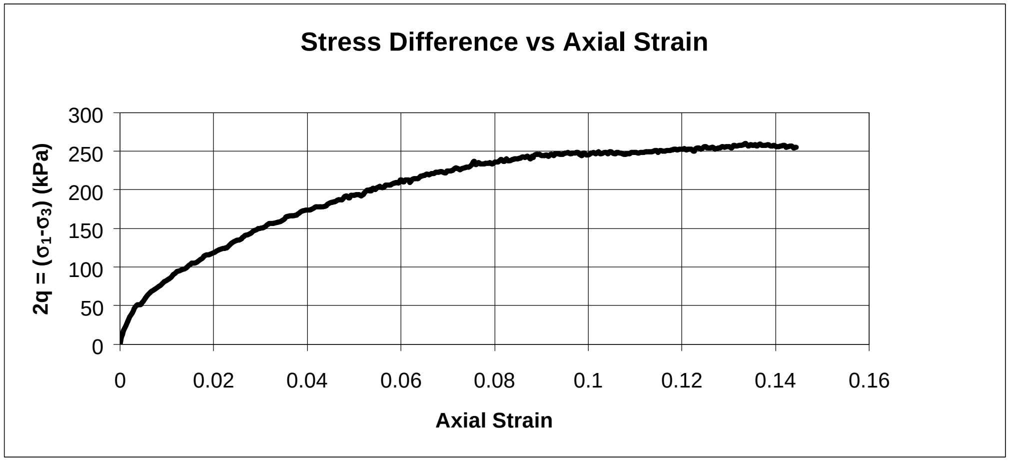

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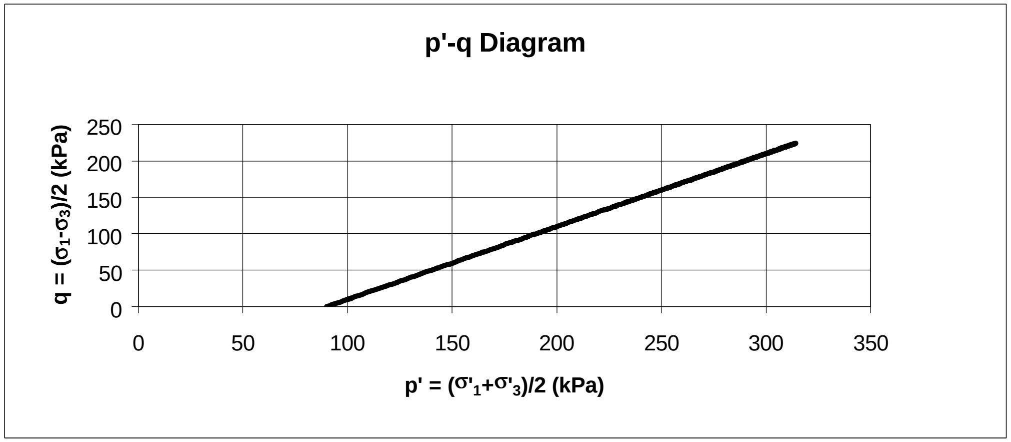

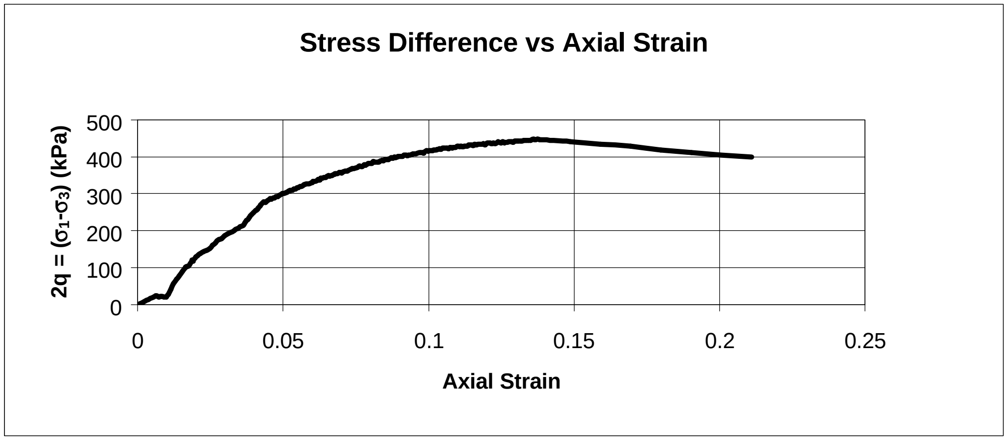

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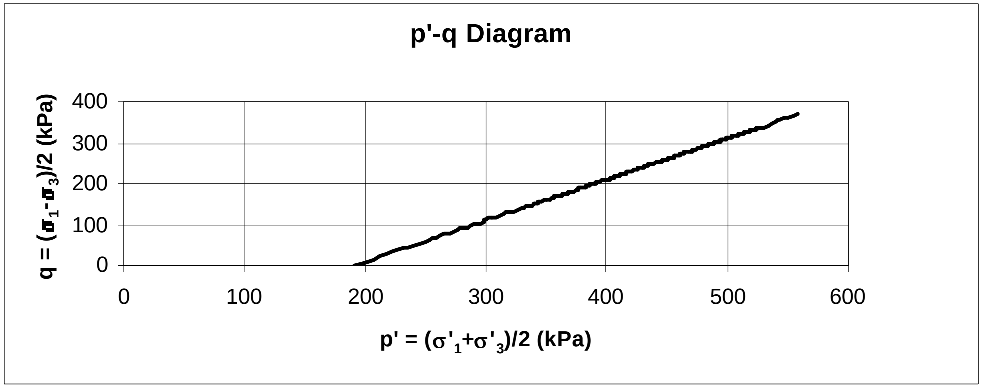

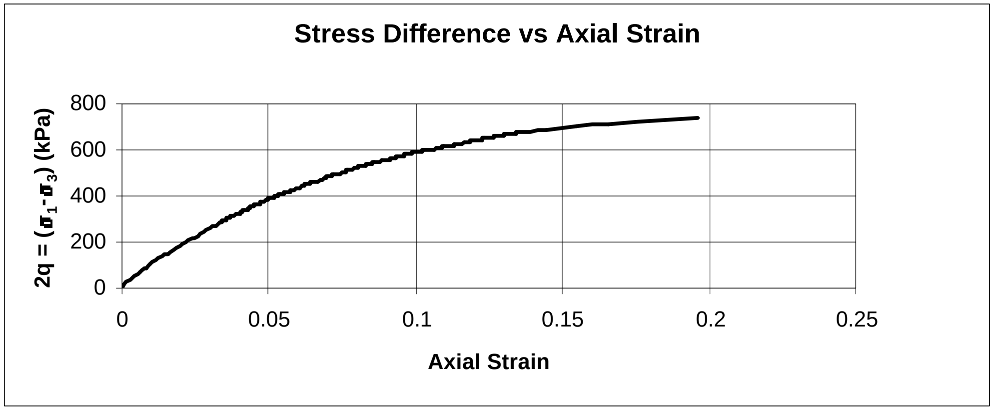

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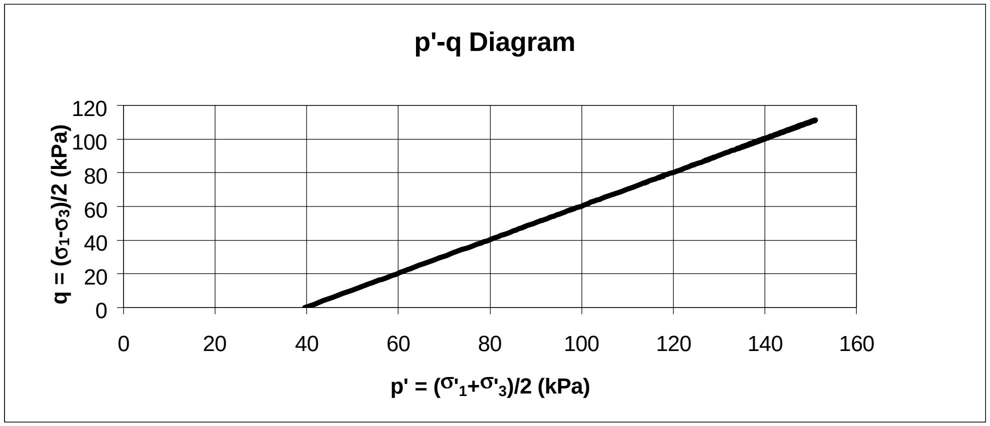

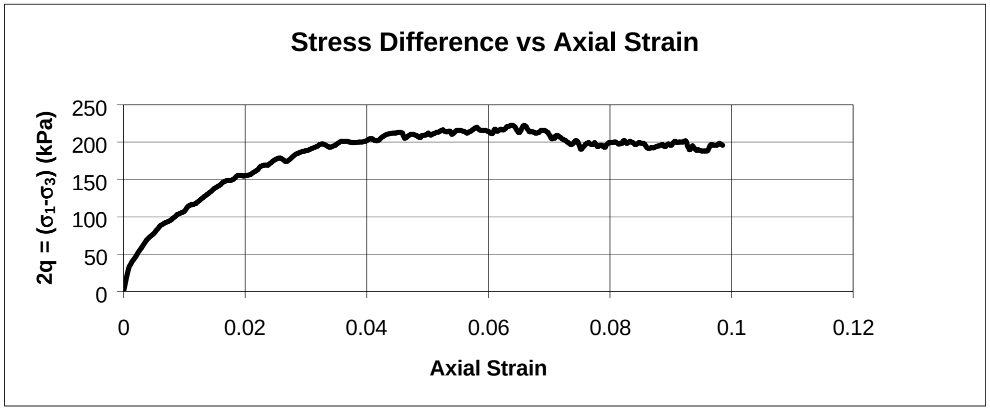

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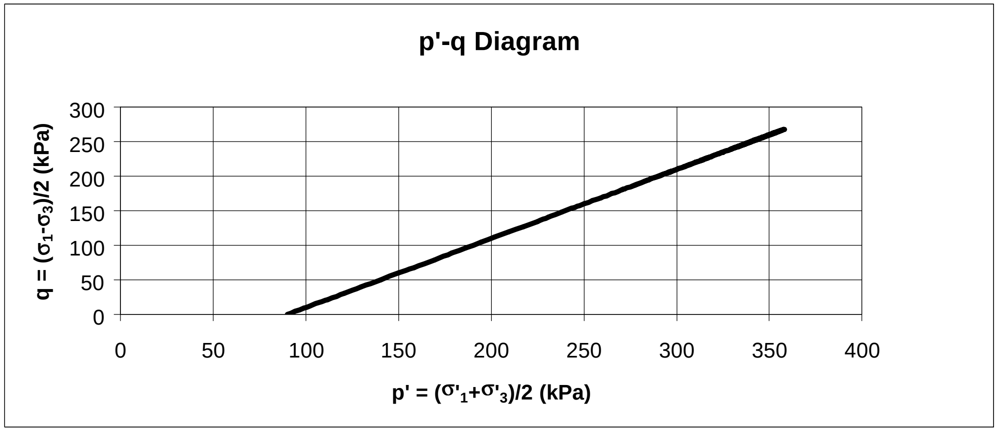

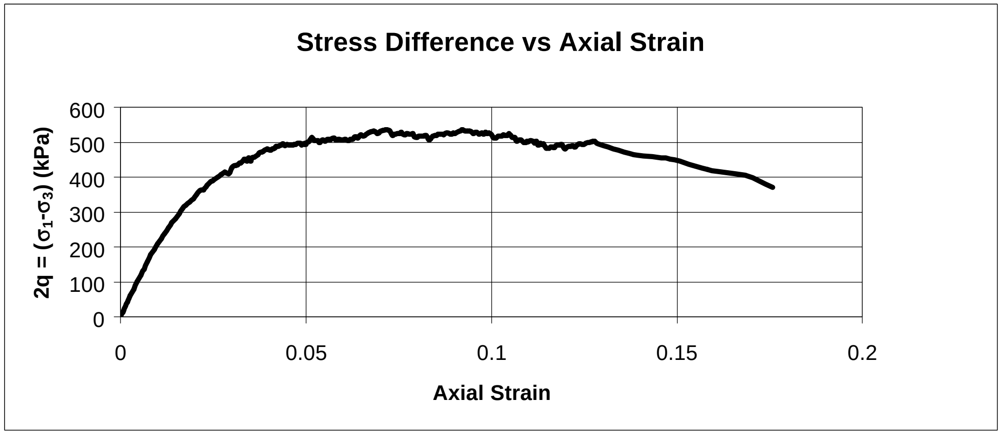

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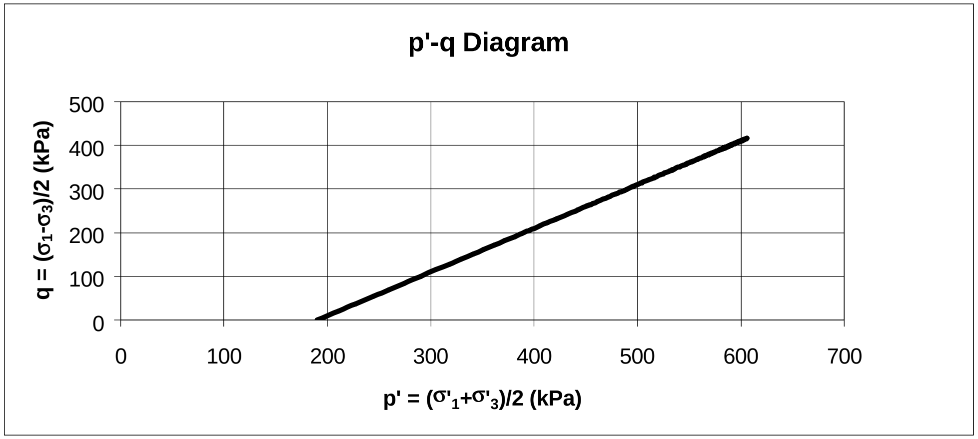
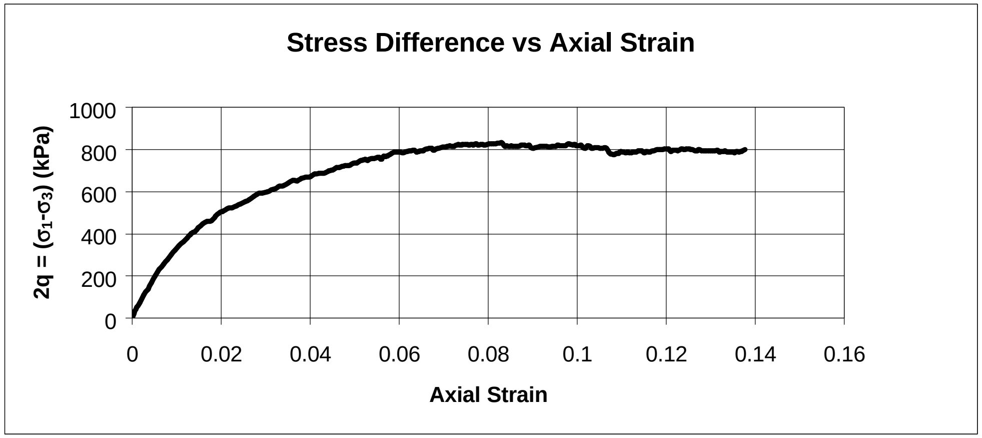
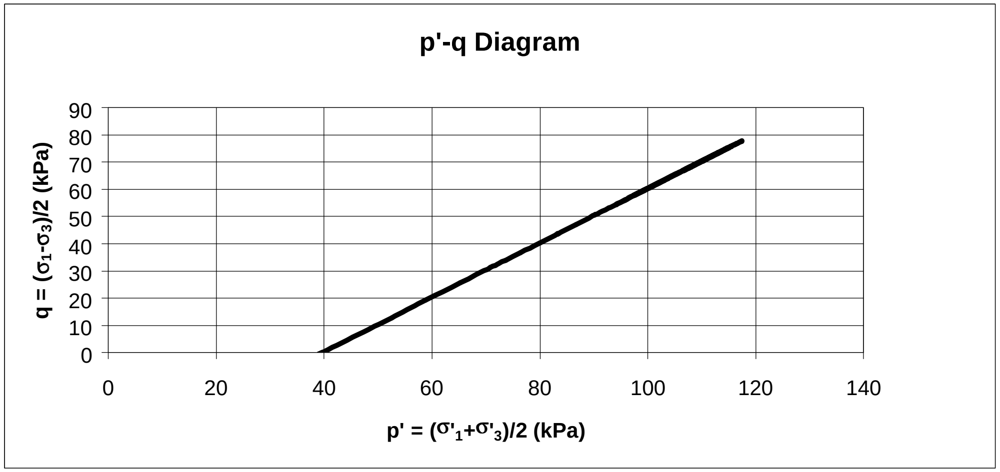
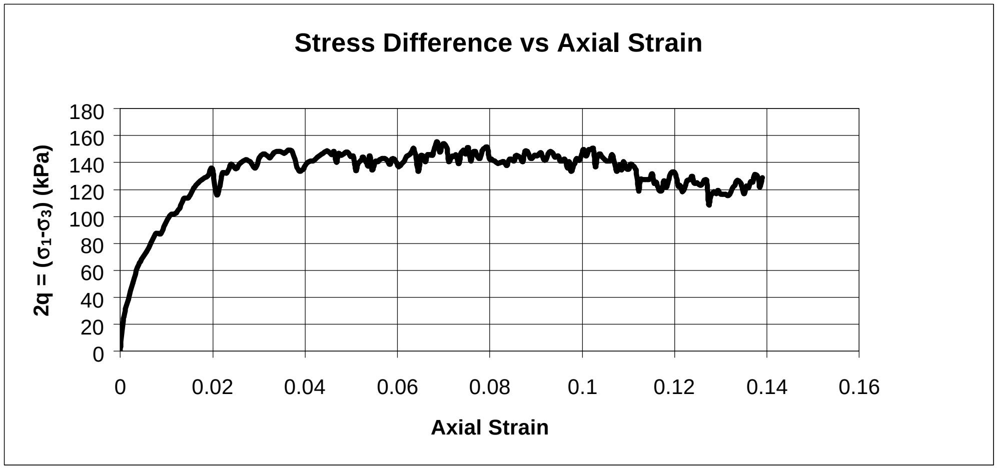




p'-q Diagram & Stress Difference vs Axial Strain for Sand at 50 kPa





p'-q Diagram & Stress Difference vs Axial Strain for Sand at 100 kPa