BENEFICIAL USE OF RECYCLED MATERIALS

IN CONTROLLED LOW STRENGTH MATERIALS

by

CLAIRE SARAH GEMPERLINE

B.S. Civil Engineering, University of Colorado Denver, 2008

A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado Denver

in partial fulfillment

of the requirements for the degree of

Master of Science, Structural Engineering

Civil Engineering

2011

This thesis for the Master of Science degree by

Claire Sarah Gemperline

has been approved

by

____

Dr. Stephan A. Durham

____

Dr. Kevin L. Rens

____

Dr. Rui Lui

Date ________________

Gemperline, Claire Sarah (M.S. Civil Engineering)
Beneficial Use of Recycled Materials in Controlled Low Strength Materials
Thesis directed by Dr. Stephan A. Durham

ABSTRACT

Controlled low-strength material (CLSM) is a self-compacting, flowable, low strength, cementitious material used primarily as backfill and void fill. CLSM is primarily used as a replacement of compacted soil in cases where the application of the later is difficult or impossible. Strength requirements are low in comparison to typical structural concrete. This enables the use of low cost, abundant, industrial by-products for the production of CLSM. The use of industrial by-products in CLSM is the focus of this Thesis.

This thesis explains that the two most important properties of a CLSM are the flowability and compressive strength. The flowability of CLSM must allow efficient placement without segregation, while the compressive strength must provide structural support but allow for easy excavation. Consequently, there are minimum and maximum performance criteria for both consistency and strength. This research investigated the effects of using recycled materials in CLSM on the fresh and hardened CLSM properties. A total of six materials were used to create 18 mixtures that were batched and tested. The cementitious materials investigated were Class C fly ash and spray dryer ash; and the aggregates tested were bottom ash, crushed glass, recycled concrete fines, and crumb rubber. The results showed that in most cases, CLSM with acceptable strength and flowability properties can be made using these recycled materials.

The following were observed for mixtures that achieved typical CLSM consistency requirements.

- Compressive strength increased as the Class C fly ash content increased from 90 to 100 percent of the total cementitious content.
- Compressive strength decreased as the amount of SDA content increased from 90 to 100 percent of the total cementitious content. It is possible that reduction in strength is due to sulfate attack.
- Strength increased as the aggregate fraction of bottom ash was changed from 25 percent to 75 percent, but decreased as the fraction was changed from 75 to 100 percent. It is unclear if this is due to a concurrent increase in water to cement ratio caused by adding water during batching to maintain acceptable consistency.
- The crumb rubber aggregate mixtures exhibited low unit weight, a tendency for segregation, low strength, the lowest modulus of elasticity measured, and was the most ductile during compression testing.
- Waste glass mixtures exhibited consistency and mixing characteristics similar to C 33 sand. The compressive strength increases as the fraction of glass in the mixtures increased. Finely crushed concrete as aggregate demonstrated similar fresh CLSM properties as bottom ash. Strengths for the mixtures tested were too low to be considered useful in common CLSM applications. It is likely that the low strengths are a consequence of high water to cementitious ratios.
- Typically the strains at yield were less than 1.5 percent except for crumb rubber mixtures. The yield strains of crumb rubber mixtures were typically greater than 1.5 percent indicating greater ductility than other mixtures.

This abstract accurately represents the content of the candidate's thesis. I recommend its publication.

Approved: Dr. Stephan A. Durham

Signed____________________________________
Dr. Stephan A. Durham

DEDICATION

I dedicate this thesis to my family and friends for continually supporting me; my mother and father for showing me that giving up isn’t an option, and never doubting me and my abilities; and my brothers, sister, and sister-in-law’s for the inspiration to become an engineer.

ACKNOWLEDGMENT

I would like to thank my academic advisor, Dr. Stephan A. Durham, for his patience, support, and the never-ending encouragement over the years. I would like to thank Dr. Rui and Dr. Rens for their support and participating on my committee. I would like to thank Dr. Rutz for contributing to my education at the University of Colorado at Denver. I would like to thank Dr. N.Y. Chang for his guidance, support and kindness through the years. I would also like to thank Adam Kardos, Andrea Soils, Zack Ballard, Matthew Gemperline, and Derek Chan for their support and much appreciated help during my research.

I would like to thank Mr. David Neel for the support, materials, and knowledge he contributed; all of which was essential to the success of this thesis. I would like to thank Mr. Amster Howard for sharing his knowledge and experience on the topic of controlled low strength materials. It was by his suggestion that I was encouraged to explore this topic. I would like to thank MCG Geotechnical Engineering, Inc. for financial support, which allowed me to perform this thesis and continue with my academic career.

Additionally, I would like to thank the faculty and staff of the University of Colorado Denver Civil Engineering Department for their support and guidance throughout my academic career.

TABLE OF CONTENTS

FIGURES

Figures

TABLES

Tables

1. Introduction

Engineering applications for controlled low-strength material (CLSM) are continually being discovered. CLSM has been shown to improve structural performance and expedite the construction process in multiple applications. Examples include the use of CLSM as embedment material to support buried flexible pipe and as backfill for retaining walls. Besides having practical engineering application, CLSM can help to fulfill the national commitment to effectuate sustainable development by making valued use of common waste materials. This thesis demonstrates that CLSM can be manufactured using industrial waste and recycled materials and thereby reduce the need to use rapidly disappearing natural aggregates and mineral resources. Furthermore, it is herein demonstrated that the desired strength, flowability and flexural characteristics of CLSM can be obtained by the selective use and proper proportioning of recycled materials.

Controlled low-strength material (CLSM) is defined by American Concrete Institute (ACI) Committee 229 as a self-compacted cementitious material used primarily as a backfill in place of compacted fill. CLSM is also known by other names including flowable fill, unshrinkable fill, controlled density fill, flowable mortar, flowable fly ash, fly ash slurry, plastic soil-cement, K-Krete, and soil-cement slurry (ACI 1999).

CLSM is commonly specified and used in lieu of compacted fill in various applications, especially for backfill, utility bedding, void filling, and bridge approach support. Backfill applications include backfilling foundation walls, such as retaining walls; or to fill both shallow and deep trenches. Utility bedding involves the use of CLSM as a bedding material for buried water conveyance pipe, electrical conduits, and other similar utilities where gravity flow of CLSM into hard-to-reach places poses an advantage. Void-filling applications include the filling of sewers, tunnels, shafts, basements, or other underground structures. Bridge approach applications use CLSM as either a sub-base for the bridge approach slab or as a structural backfill against wing-walls or other bridge foundation elements (ACI 1999).

CLSM is commonly described as a material constructed of aggregate and cementitious material that results in a compressive strength of 1200 psi (8 MPa) or less. Generally, CLSM applications require unconfined compressive strength of 200 psi (1.4 MPa) or less. The lower strength requirement is to provide easy excavation in the event the CLSM must be removed, for example, in the event a buried pipeline requires excavation for repair or replacement. A flowable nature to the material is generally desired in order to facilitate placement in voids beneath foundations, under overhanging constructions, and in the annular space around buried pipes.

The American Concrete Institute ACI 229 committee describes CLSM as a family of mixtures used in a variety of applications. The advantages associated with its use include: reduced labor, reduced equipment costs, faster construction, and the ability to place material in cramped spaces by gravity flow (ACI 1999).

CLSM constructed using industrial by-products, such as fly ash and foundry sand, have the positive effects of reducing landfill demand and supporting the civil demand for sustainable development. The world's need for sustainable development and reduction of the waste burden on landfills supports the need for this research and development.

The purpose of this thesis is to 1) determine if CLSM can be created using spray dryer ash (SDA) as the principle cementations material, 2) add to the growing body of knowledge regarding approximate mix proportions for CLSM manufactured using crushed glass, bottom ash, crushed concrete and crumb rubber as a portion or all of the aggregate, and 3) measure and compare the rate of strength increase and the modulus of elasticity (MOE) of CLSM manufactured from the above materials. The research presented herein investigates the effects that the materials discussed above have on the fresh and hardened properties of CLSM. Various proportions of the recycled materials were used in CLSM mixtures. The mixtures for this research project consisted of aggregates proportioned by volume and cementitious material proportioned by mass. The control mix was a typical CLSM comprised of fine sand; cementitious material consisting of 90 percent Class C fly ash and 10 percent cement; and a water to cementitious ratio (w/cm) of 1.25. The test program has two components 1) the cementitious materials investigation, and 2) the aggregate investigation.

Portland cement was mixed with either Class C fly ash or SDA using sand as a fine aggregate. The compositions were as follows:

- Class C fly ash mixtures included fly ash as 90, 95 and 100 percent of the cementitious material.
- SDA mixtures included SDA as 90, 95 and 100 percent of the cementitious material.

Sand was replaced with either crumb rubber, bottom ash, recycled concrete or crushed glass. Regarding aggregate compositions:

- The aggregates were substituted for the sand with 25, 75 and 100 percent replacement.
- All mixtures to investigate aggregates used cementitious material comprised of 90 percent Class C fly ash, and 10 percent portland cement.

All mixtures were designed to have 630 lbs/yd^3 cementitious material except SDA mixtures which was designed to have 750 lbs/yd3 cementations material.

The necessary CLSM requirement that it have a flowable consistency was assured for all mixes by adjusting batch quantities during the batching process. A water to cement ratio (w/cm) of 1.25 was maintained to the extent practicable. Exceptions were necessary to achieve consistency requirements for CLSM and are noted herein. All mixtures were tested for fresh and hardened CLSM properties. The fresh CLSM properties tested included slump, unit weight and air content. The hardened CLSM properties examined were compressive strength, and modulus of elasticity. All testing conformed to American Society of Testing Materials (ASTM) testing standards and all data results, details and conclusion of findings from this research are included with this thesis.

This thesis is organized as follows: Chapter 2 presents a brief history and literature review; Chapter 3 provides a problem statement of the research; Chapter 4 describes the experimental plan; Chapter 5 discuses the experimental results and Chapter 6 presents the conclusion and recommendations.

2. Literature Review

The raw cementitious and aggregate materials being investigated are common industrial and/or recycled waste. This section begins by providing a brief summary of the nature and origin of each material, and the reasons for their selection. This is followed by a summary, by material, of pertinent research performed by others. Relevant material properties and CLSM investigation considerations are also included.

2.1 Nature of the Investigated Cementitious and Aggregate Materials

The composition of early CLSM mixtures was restricted to cement, water, and mineral aggregates such as sand and gravel. All these materials in their purest forms are very costly, draw heavily on natural resources and/or are created by manufacturing processes that consume large amounts of energy and thereby are associated with environmentally significant and undesirable CO_2 emissions. Therefore, it is beneficial if sources of CLSM aggregate and cementitious material are derived from less costly sources and sources that are less environmentally damaging in their production. The following discussion presents a brief summary of the materials selected for research and the rationale for their selection.

2.1.1 Cementitious Material

The production of cement, commonly known as portland cement (PC), requires a significant amount of energy and the use of an ever-diminishing supply of raw materials. The production of portland cement accounted for about 3.4 percent of global CO_2 emissions in 2000, and the United States is the world's third largest cement producer with production occurring in 37 states (Marland, 2003). Carbon dioxide (CO_2) is a green house gas, and is believed to be a main contributor to global climate change. Portland cement production is a key source of CO_2 emissions, due in part to the significant reliance on coal and petroleum coke to fuel the kiln for clinker production. Portland cement production is a contributor to green house gases (EPA, 2004).

The concrete industry has been using coal fly ash to make high quality concrete for many years. Fly ash is a waste by-product of coal combustion that has found use in a wide range of construction applications, including use as a partial replacement to cement in concrete. It's has been well established that the use of fly ash with portland cement promotes long-term strength, durability, and increases workability of concrete.

Fly ash is readily available at a relatively low cost. In 2001, 52 percent of the electricity in the United States was produced by coal fired electric utilities (ACAA, 2011). Fly ash is used mostly in portland cement concrete, but its use in CLSM has grown considerably in recent years. Fly ash is used in combination with portland cement in this study to create a common CLSM mix for comparison to more innovative mixtures. It is also used in constant mixture ratio with portland cement for mixtures that investigate aggregate selection effects on CLSM.

A rarely used industrial by-product is spray dryer ash (SDA). In 2005 the United States reported that 1,427,263 short tones of dry flue gas desulfurization (FGD) material were produced and of that 159,198 short tons (or 11.15 percent) were beneficially used (ACAA, 2005). Fly ash and SDA is known to have pozzolanic characteristics. Pozzolans are siliceous or aluminsiliceous material that, in finely divided form and in the presence of moisture, chemically reacts with the calcium hydroxide released by the hydration of portland cement to form calcium silicate hydrate and other cementitious compounds (PCA, 2005). Pozzolans are generally categorized as supplementary cementitious materials or mineral admixtures. Because spray dryer ash and fly ash have pozzolanic characteristics, their use as cementitious material replacement in CLSM mixtures is expected to result in desired strength and consistency.

2.1.2 Aggregates

The replacement of CLSM aggregate with recycled materials is becoming increasingly popular. Aggregate is primarily a granular filler material within a CLSM mixture.

Large amounts of industrial waste having a granular nature accumulate every year in all industrial countries. These materials are, in general, unsuitable for use in the construction industry due either to their high content of very fine particles; or due to their poor mechanical properties. Sand is primarily used as aggregate in CLSM mixtures. However, the availability of aggregate sources has decreased. From the environmental perspective, the mining of aggregate generates significant quantities of undesirable CO_2 from equipment emissions.

The use of recycled materials as aggregate is expected to eliminate these emissions and thereby improve environmental quality. There are a variety of recycled materials that could be suitable aggregate for use in CLSM. Recycled concrete, bottom ash, crumb rubber, and crushed glass all have promising characteristics, are readily available, are low cost, and their use is environmentally friendly. They are selected for use in this study for these reasons.

2.1.2.1 Recycled Concrete Fines

Aggregate size particles of recycled concrete are created by crushing waste concrete originating from demolition of civil constructions such as buildings, sidewalks, streets, etc. Crushed concrete is separated into different size ranges for reuse in various applications. . However, the very fine fraction is not as desirable, demand is low, and interest in its potential use as CLSM is increasing (Achtemich, 2009). The use of the crushed concrete fines in CLSM is expected to reduce potential harmful effects on the environment in two ways. First, it will reduce the disposal of fine crushed concrete and thereby reduce the use of valuable and limited landfill space. Second, potential leaching of trace chemicals from crushed concrete into nearby water sources would be eliminated by encapsulation of these undesirable components in a cemented matrix.

2.1.2.2 Crushed Waste Glass

Crushed glass has recently gained attention as a potential aggregate substitute in CLSM due to availability and low cost. Glass bottles are typically reused to make more bottles, but when the glass can't be reused the glass is stockpiled and then disposed in landfills. Therefore, finding a use for such glass would provide environmental benefit by reducing landfill demand. Aggregate replacement with crushed glass will likely be increase in future CLSM applications.

2.1.2.3 Bottom Ash

Bottom ash is another by-product of burning coal and is a common waste produce from coal-fired power plants. It does not have the strong pozzolanic properties of fly ash and SDA. However, its larger size, low cost, and abundance makes is a good candidate for CLSM aggregate. Bottom ash is composed of the large and small noncombustible particles that cannot be carried by the hot gases and therefore settle at the bottom of the furnace in a solid or partially molten condition (Hardjito, 2011). Bottom ash is commonly sluiced from the furnaces and often disposed in ponds. During this process the particles are pulverized to sizes predominantly between 75 microns and 25 millimeters. Bottom ash has successfully been used as an aggregate in CLSM mixtures. Its availability, and low cost make it attractive as an aggregate source. However, little information is available regarding proper CLSM mix proportions. It is investigated here to increase this body of knowledge.

2.1.2.4 Crumb Rubber

Hard aggregate is essential to create high strengths for structural concrete. However CLSM is a low strength material by definition. This suggests that sources of “soft” aggregate, such as crumb rubber, may be successfully used in CLSM.

Crumb rubber is created by grinding scrap tires. The United States produces nearly 300 million scrap tires per year (Rubber Manufacturers Association 2006). Of these scrap tires, 14 percent are placed in landfills or dumped in stockpiles. Hence, crumb rubber is a readily available and low cost material and therefore an attractive CLSM aggregate replacement.

A literature review was performed to locate results of previous research related to the use of Class C fly ash, spray drier ash, bottom ash, recycled crushed glass, recycled concrete and/or crumb rubber in CLSM. The results of this review are presented next.

2.2 Historical use of CLSM

Soil-cement has been a widely used material in geotechnical-engineering practices for a long time. Flowable CLSM is relatively new and is different from conventional soil-cement in that soil-cement generally is not flowable and requires compaction.

In 1964 the U.S. Bureau of Reclamation (BOR) used CLSM in what is thought to be its first major application (Adaska, 1997). The BOR referred to the mixture as “plastic soil-cement”, and applied it as pipe bedding to over 320 miles of the Canadian River Aqueduct Project pipeline in northwestern Texas (Adaska, 1997). The soil used in the mixture as aggregate consisted of local sand deposits. The estimated cost of this project was 40 percent less than expected using conventional backfilling techniques. Also, estimates suggested use of the soil cement increased productivity from 120 meters to 305 meters of pipe placed per shift. Since then, CLSM has become a popular material for projects such as structural fill, foundation support, pavement base, and conduit bedding (Du, Folliard, Trjo, 2011).

The introduction of CLSM caught the attention of Detroit Edison Company, who worked cooperatively with Kuhlman Corp., a ready-mix concrete producer in Toledo, Ohio in the early 1970s. Together they created an alternative to compacted granular fill which utilized fly ash and a concrete batching technique. This new backfill material, called “flowable fly ash”, was used in several applications in the late 1970s (Funston, 1984). The mixture consisted primarily of fly ash and 4 to 5 percent cement. Water was added to attain the desired workability. In the Belle river project, it was estimated that more than $1 million was saved by using this new material (Funston, 1984). What made this material unique and impressive was that is remained cohesive when being placed and could be shaped in unsupported steep slopes above or underwater (Funston, 1984).

In 1977, four patents from a company known as K-Krete Inc. were issued to Brewer et al. (Larsen, 1993). The typical K-Krete mixture was 1305 to 1661 kg of sand, 166 to 297 kg of fly ash, 24 to 119 kg of cement, and up to 0.35 to 0.40 m^3 of water per cubic meter of the product. The four patents included mixture design, backfill technique, pipe bedding, and dike construction practice. These patents were sold to Contech, Inc. in Minneapolis, MN, who later ceded the patent rights to the National Ready Mix Concrete Association (NRMCA) with the stipulation that those rights may not be used in a proprietary manner (Larsen, 1993). Since then, ready-mixed concrete producers and contactors have used similar materials to K-Krete without patent-rights conflicts. Similar materials have been developed and used throughout the United States and Canada. "However, the lack of a centralized source for obtaining and disseminating information within the marketplace appeared to cause confusion and reluctance on the part of the engineering community to use these materials" (Du, Folliard, Trejo, 2011). The ACI Committee 229 was establishing in 1984 under the title "Controlled Low-Strength materials (CLSM)." In 1994, the committee published a report called "Controlled Low Strength Materials (CLSM)," which has been referenced widely. It was revised in 1999 (Du, Folliard, Trejo, 2011).

Shortly following the development of the ACI Committee 229, different designs were studied. Different types of mix designs were created for CLSM that utilized recycled waste to reduce the cost. Currently there are five ASTM testing standard available for CLSM. These are:

- ASTM D 4832 Standard Test Method for Preparation and Testing of Controlled Low Strength (CLSM) Test Cylinders

- ASTM D 6023 Standard Test Method for Density (Unit Weight), Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low-Strength Material (CLSM).
- ASTM D 6024 Standard Test Method for Ball Drop on Controlled Low Strength Material (CLSM) to Determine Suitability for Load Application.
- ASTM D 5971 Standard Practice for Sampling Freshly Mixed Controlled Low-Strength Material
- ASTM D 6103 Standard Test Method for Flow Consistency of Controlled Low-Strength Material (CLSM).

2.3 CLSM Development Research

This section discusses the research related to the use of recycled materials in CLSM. Each material being researched is independently discussed and typical material properties are presented.

2.3.1 Fly Ash

2.3.1.1 Production

Fossil fuel electric power generation produces a majority of coal combustion residuals (CCRs). In 2009 coal generated electricity supplied approximately 45 percent of the electricity consumed in the United States (EPA, 2011). Other industries, such as commercial boilers and mineral and grain processors that use coal as a fuel source, also produce small quantities of CCRs. The American Coal Ash Association (ACAA, 2011) estimates that between 100 million and 500 million tons of fly ash has accumulated in United States landfills since the 1920s when the disposal of large quantities of fly ash in landfills began. This is likely a very low estimate considering that: 1) the 2008 Kingston fly ash spill alone dumped 4,200,000 m^3 of fly ash into the Emory and Clinch Rivers in Tennessee, which was only a minor portion of the material that had been previously retained in an 84 acre area behind a dike (en.wikipedia.org, 2011); and 2) there are many similar waste fly ash disposal sites in the United States (en.wikipedia.org, 2011).

Coal combustion residuals are produced by coal burning power plants and industrial boilers. The coal-fueled electric power industry generated approximately 72.4 million tons of coal fly ash (EPA, 2011). Coal combustion produces various forms of CCRs that are categorized by the process in which they are generated. Fly ash is one of many CCRs that can be used as ingredients in the manufacturing of portland cement. Exhaust gases leaving the combustion chamber of a power plant entrain particles during the coal combustion process. To prevent fly ash from entering the atmosphere, power plants use various collection devices to remove it from the gases that are leaving the stack (EPA, 2011). Fly ash is the finest of coal ash particles. The use of fly ash in the United States started in the early 1930s and today fly ash has multiple uses; one use is to increase cement production. During cement production, fly ash can be added to the raw material feed in clinker manufacturing to contribute specific required constituents, such as silica, alumina, and calcium. Fly ash can also be used in non-combustion applications as well. Fly ash's most common, and most valued, use is as a supplementary cementitious material in concrete. It is used as a substitute or a partial replacement for portland cement in concrete mixes. The benefits of using fly ash in concrete are greater workability, higher strength, and increased longevity.

Coal will continue to be an important fuel source in coming years; therefore the quantity of fly ash produced and its beneficial reuse will also increase. In 2008, 42.3 million tons of coal fly ash was disposed of in landfills, and 58 percent generated (EPA, 2011). The research conducted herein, among other things, increases the body of knowledge regarding the effects on the properties of a typical CLSM mixture containing cement and fly ash.

2.3.1.2 Physical, Chemical and Reactive Properties

There are two major ASTM specified classes of fly ash produced today: Class F and Class C. The assigned class depends on the chemical composition, which depends on the type of coal burned. Class F fly ash is typically produced from burning anthracite or bituminous coal, and Class C is normally produced from the burning of subbituminous coal and lignite (FHWA, 2011). The main components of bituminous coal fly ash (Class F) are silica, aluminum, iron oxide, and calcium oxide along with residual, unburned carbon (EPA, 2011). Lignite and subbituminous coal fly ashes (Class C) are characterized by higher concentrations of calcium and magnesium oxides and, when compared to Class F fly ash, have reduced percentages of silica and iron oxide and lower residual carbon content (EPA, 2011). Class C fly ash usually has cementitious properties in addition to pozzolanic properties due to free lime that causes it to gain strength when mixed with water alone. Class F is not as cementitious when mixed with water alone. Table 2.1 presents the compounds found in fly ash generated from the combustion of bituminous, subbituminous, and lignite coal. Table 2.2 presents the ASTM C 618 compositional requirements for Class C and Class F fly ashes.

Table 2.1 Overview of Fly Ash Constituent Compounds - Expressed in PPM (EPA, 2011)

Component	Bituminous	Subbituminous	Lignite
SiO_2	200,000 - 600,000	400,000 - 600,000	150,000 - 450,000
Al_2O_3	50,000 - 350,000	200,000 - 300,000	100,000 - 250,000
Fe_2O_3	100,000 - 400,000	40,000 - 100,000	40,000 - 150,000
CaO	10,000 - 120,000	50,000 - 300,000	150,000 - 400,000
MgO	0 - 50,000	10,000 - 60,000	30,000 - 100,000
SO_3	0 - 40,000	0 - 20,000	0 - 100,000
Na_2O	0 - 40,000	0 - 20,000	0 - 60,000
K_2O	0 - 30,000	0 - 40,000	0 - 40,000
Loss of Ignition	0 - 150,000	0 - 30,000	0 - 50,000

The fly ash used herein was Class C fly ash. Class C has pozzolanic and self-cementing properties desired for replacement of portland cement in the CLSM mix designs. ASTM notes that a typical cementitious design for a CLSM mix contains 10 percent of cement. For this reason, and also because the properties of portland cement are better controlled during manufacturing and therefore less variable, the control mix for research presented herein used 90 percent Class C fly ash and 10 percent portland cement. This mix proportion of cementitious materials was also used in all mixes designed to investigate the effects of aggregates on CLSM properties.

Table 2.2 Chemical Requirements ASTM C 618

Class	**F**	**C**
Silicon dioxide (SiO_2) plus aluminum oxide (Al_2O_3) plus iron oxide (Fe_2O_3)min, %	70	50
Sulfur trioxide (SO_3), max %	5	5
Moisture content, max, %	3	3
Loss of Ignition, max, %	6	6

Fly ash has a lower heat of hydration than portland cement; consequently its use will result in less heat build-up in massive placements. Large volume placements are common when using CLSM. Therefore, the control over heat build-up afforded by fly ash is often advantageous. The amount of heat generated is dependent upon the chemical composition of the cement. Hydration of tricalcium aluminate and tricalcium silicate is primarily responsible for high heat evolution. Typical portland cement heat generation is greatest shortly after adding water whereas fly ash heat generation is slower and lasts longer. This is because fly ash has a relatively low surface area relative to portland cement causing the pozzolanic reaction to be slow to start and the rate to increase several weeks after the start of hydration. For similar reasons, strength development is slower in mixtures using large quantities of fly ash. In 1996 Langan performed a study regarding the affects of fly ash during cement hydration and concluded that: 1) fly ash increases the initial hydration of cement; 2) retards hydration in the dormant and acceleration periods; and 3) accelerates hydration after the typical portland cement acceleration period. It was also found that fly ash retards cement hydration more significantly at high w/cm ratios. In the long run, fly ash amended concrete demonstrates higher strength and durability.

2.3.1.3 The Effects of Class C Fly Ash on CLSM Properties

2.3.1.3.1 Flow Consistency

A flowable consistency is a critical parameter for optimizing performance and placement characteristics of CLSM. Therefore it is critical that desired flow requirements are achieved. The flowability of a CLSM is dependent on the intended use of the material. The acquired flow characteristic targeted for this study was to create an 8 to 12 inch diameter footprint, a.k.a. “patty,” of the slumped material using test procedure ASTM D 6103. The 8 to 12 inch consistency criterion is suggested in ASTM D 6103 as a range typical of CLSM.

Research on CLSM containing fly ash has shown that the use of fly ash increases the workability of the mix. CLSM mix designs may have a large percentage replacement of cement by fly ash. Much more so than is common for typical portland cement concrete mixtures.

Katz and Kovler (2003) investigated the use of cementitious industrial by-products in CLSM mixtures. Three mix designs were used: one used 525 kg/m^3 (885 lb/yd^3) of fly ash and 53 kg/m^3 (89 lb/yd^3) of cement with a w/cm of 0.51; the second mix used 519 kg/m^3 (875 lb/yd^3)of fly ash and 96 kg/m^3 (162 lb/yd^3) of cement with a w/cm of 0.50; the third mix combined 951 kg/m^3 (1603 lb/yd^3) of fly ash and 45 kg/m^3 (76 lb/yd^3) of cement with a w/cm of 0.42. All three mixtures used sand as the fine aggregate. Water was added gradually until the desired workability was achieved. They observed that 10 percent less water was needed to achieve the flowability for the mixtures containing fly ash. The acquired consistency was measured by ASTM D 6103 and resulted in an 8 inch diameter flow footprint.

Du, Folliard and Trejo (2002) researched the effects of water demand on CLSM. Three sources of Class C fly ash three sources of Class F fly ash, three sources of fine aggregate, and Type I portland cement were used in their study. The water demand for their investigation was defined as the amount of water required to obtain a flow footprint diameter between 7.9 and 9.8 inches. Table 2.3 presents the mixture proportions and the acquired flowability for mixtures using either Class C or Class F fly ash.

Table 2.3 CLSM Mixtures Proportions and Fresh Properties (Du, Kolver, and Trejo, 2002)

Mixture	Type I cement (kg/m^3)	Fly ash type	Fly ash (kg/m^3)	Fine aggregate type	Water demand (kg/m^3)	Flow (mm)
Mixture 1	30	Class C	180	Sand	211	200
Mixture 2	60	Class C	180	Sand	206	200
Mixture 3	30	Class C	180	Sand	206	210
Mixture 4	60	Class C	180	Sand	205	250
Mixture 5	30	Class F	360	Sand	220	200
Mixture 6	60	Class F	360	Sand	216	216

*Mixture 3 is a replicate of mixture 1, and mixture 4 is a replicate of mixture 2.

The comparison of Class C verses Class F shows that Class F requires more ash to acquire the desired flow, where as Class requires less ash to achieve the same flow. This is likely caused by the fact that Class F fly ash, being less cementitious, acts in greater capacity as an aggregate than in the capacity of a cementitious material. This is expected because Class F fly ash does not possess the same chemical properties as Class C fly ash, as previously discussed in Section 2.3.1.2.

2.3.1.3.2 Bleeding and Segregation

The high water demand required for CLSM mix designs increases the bleeding and the risk of segregation of the fresh CLSM. High bleeding values have been commonly observed with mixes containing fly ash. The large bleeding values are expected for the fly ash mixes due to the spherical shape of the fly ash particles and their delayed setting (Ravina, 1990).

Katz and Kolver's (2003) research that was introduced in the previous section discusses the bleeding and segregation they observed. They noted that higher fly ash to cement ratios result in greater bleeding. Ratios of fly ash to cement of 500/50 and 1000/50 had bleeding percentages of 3.4 percent and 4.4 percent respectively. This observation is consistent with Ravina's work presented in the previous paragraph.

Du, Folliard and Trejo (2002) researched the effects of water demand on CLSM. Their research demonstrated the differences in bleeding between the Class F and Class C fly ash. A Class C fly ash to cement ratio of 180/60 demonstrated a bleeding percentage of 2.45 percent. A Class F fly ash to cement ratio of 360/30 had a bleeding percentage of 2.92 percent. Hence, the different classes of fly ash demonstrate similar bleeding characteristics using different cementitious material ratios.

2.3.3.3 Air Content

Information regarding air content of CLSM mixtures containing fly ash is very limited. Air content is commonly recorded, however seldom discussed unless air-entraining admixtures (AEA) were specifically used.

Du, Folliard and Trejo (2002) did not use air-entraining admixtures in their Class C fly ash mix design. The mixture had an average air content of 0.92 percent.

Naik (1991) evaluated the effects of Class C fly ash on CLSM mixtures. The mix designs that were analyzed consisted of cement, fly ash, water, sand and pea sized gravel. All mixtures were observed as having good workability with high slumps ranging from 7.5 inches to 9.25 inches. Air content ranged between 1.0 and 2.3 percent. Table 2.4 illustrates the mixture proportions and field test done by Naik (1991). Three out of the four mixtures (Mix 2, 3, and 4) show a linear trend when comparing air content and w/cm. The higher w/cm has the highest air content and the lowest w/cm has the lowest air content. It's noted that Mix 1 has the highest w/cm content and doesn't seem to fit the trend of the other mixtures with the air content. It is noteworthy that the highest slump was also associated with this sample. This suggests that air bubbles, as well as solid particles, are more mobile when slumps are high thereby allowing entrapped air to more easily exit the sample during mixing.

Table 2.4 Mixture Proportions and Field Test Data (Naik, 1990)

Mixture	**Mix 1**	**Mix 2**	**Mix 3**	**Mix 4**
Cement, lb/yd^3	70	81	96	129
Class C Fly Ash, lb/yd^3	118	159	195	239
Water, lb/yd^3	345	337	338	351
SSD Sand, lb/yd^3	1728	1611	1641	1543
SSD Pea Gravel, lb/yd^3	1778	1761	1813	1721
Slump, inch.	7.5	6.25	6.5	9.25
Air Content, percent	2.1	2.3	2.2	1
w/cm	1.84	1.4	1.16	0.95

2.3.1.3.4 Time of Set

The time required for the fly ash in CLSM to set is influenced significantly by the type of fly ash and the amounts of fly ash used in the mixture. In general, research has shown that in typical concrete mix designs fly ash retards cement hydration in dormant and acceleration periods. Furthermore, at higher w/cm ratios the retarding effect appears more significant than at the lower w/cm ratio's. CLSM mix designs have much higher w/cm ratios compared to typical concrete mixes (Langan, 1996). Therefore, it is expected that the time of set will be significantly delayed relative to that commonly observed for portland cement concrete.

Folliard, Du, and Trejo (2003) study on the effects of curing conditions on strength development of CLSM discussed the use of Class C fly ash in CLSM mix designs. It's noted that concrete containing Class C fly ash is generally more sensitive to curing temperature than Class F fly ash, mainly because of it inherently higher potential for reactivity. Also, the strength development of CLSM containing Class C fly ash was observed to be greatly affected by the curing temperature.

McCarthy discusses the mechanisms that might cause slower time of sets and emphasizes that CLSM strength development rate is dependent on the curing environment (McCarthy, 1984).

The Katz and Kolver (2003) study on the utilization of industrial by-products in CLSM mixtures showed that the greater the Class C fly ash to cement content the higher the setting time. The mix design with a fly ash to cement ratio of 20/1 had a setting time at 22 hours as opposed to the mix design with a fly ash to cement ratio of 10/1, which had a 7-hour-shorter setting time of 15 hours.

Some research has investigated the effect of Class C fly ash calcium oxide (CaO) content on the setting time of CLSM (Du, 2006). It was demonstrated that fly ash with high calcium oxide (CaO) content (greater than 25 percent) will lead to earlier setting and higher early strength than fly ash with lesser amounts of CaO. The study used the needle penetration test (ASTM C 403) to evaluate time of set of CLSM mixtures. A penetrometer approach was used herein to evaluate the time of set.

2.3.1.3.5 Strength

In general, research pertaining to the effects of Class C fly ash on strength is varied. Maintaining strength at a low level is a major objective for projects where later excavation is required. Some mixtures that are acceptable at early age continue to gain strength with time, making future excavation difficult. Also, some mixtures that would achieve a desirable long-term strength have a low short-term strength that adversely affects project schedules. For example, CLSM used in buried pipe backfill must achieve a minimum strength before additional fill is placed over the pipe. Therefore, strength needs depend significantly on the use. For the remainder of this discussion, strength will refer to the strength at 28 days unless otherwise noted.

CLSM strength is dependent on the fly ash/cement ratio and w/cm ratio. Katz and Kolver (2003) study on CLSM with Class C fly ash showed a high 28-day compressive strength. The mix designs with fly ash to cement ratio of 10/1 and w/cm ratio of 0.51 had a 3.5 MPa (508 lb/in^2) compressive strength. The mix design of 20/1 with a w/cm ratio of 0.42, all other things equal, had a 2.5 MPa (363 lb/in^2) compressive strength at 28 days. The mix with the highest strength was the 5/1 with a w/cm ratio of 0.50, which had a compressive strength of 7.3 MPa (1059 lb/in^2). In comparison, the mix designs used in this study targeted the creation of CLSM exhibiting less than 200 psi (1.4 MPa) compressive strength.

2.3.2 Spray Dryer Ash

2.3.2.1 Production

As previously discussed, fly ash is a by-product fossil fuel electric power generation and has numerous advantages for use in the concrete industry. Spray dryer ash is derived from the same source, however is less commonly used in the construction industry due to its high sulfur trioxide (SO_3) content.

Pulverized coal is generally burned during the production of energy. The volatile matter and carbon burn off during the combustion process leaving the coal impurities such as clays, shale, quartz, felspar, etc. mostly fused and remaining in suspension (Naik, 1993). The fused particles are carried along with the flue gas. When the flue gas approaches low temperatures, the fused substances solidify to form predominately spherical particles, which are called, fly ash (Naik, 1993). Sulfur dioxide is a gaseous product of coal combustion that enters the atmosphere and contributes to acid rain. Flue gas desulfurization (FGD) is employed to reduce sulfur dioxide emissions. When dry lime dust is used for this purpose as the sorbent a solid waste product known as spray dryer ash is produced. Butalia and colleagues implemented a laboratory-testing program to study the suitability of spray dryer ash as flowable fill (Butalia, 1999.). Butalia showed that the relationships between strength and w/cm ratio and cementitious material content are similar in direction to those for portland cement. That is, strength increases with increasing cement content and decreasing w/cm ratio. The researchers concluded that spray dryer ash is a potentially viable cementitious material for use in CLSM and that the mixture, with accelerators, can be controlled to provide desired early strength while limiting long term strength to make it "diggable" (Butalia, 1999.). It was also concluded that the load-displacement behavior, among other things, be further investigated. This thesis measures the Young's modulus of spray drier ash in response to the need for more research.

Spray drier ash has been used in the construction of stabilized road base, as a raw material for manufacturing of cement, in concrete and other cement-based materials, and for manufacture of wallboards (Siddique, 2010). Naik (1993) reported that significant amount of spray dryer ash can be used in concrete as well as masonry products.

2.3.2.2 Physical, Chemical and Reactive Properties

Spray dryer ash has low unit weight and good shear strength characteristics and thus hold promise for CLSM applications (Naik, 1993). Spray dryer ash by-products consists of primarily spherical fly ash particles coated with calcium sulfite/sulfate, fine crystals of calcium sulfite/sulfate, and unreacted sorbent composed of mainly $Ca(OH)_2$ and a minor fraction of calcium carbonate. The fly ash amount varies from less than 10 percent as much as 50 percent. The spray dryer by-products are higher in concentrations of calcium, sulfur, and hydroxide, and lower in concentrations of silicon, aluminum, iron, etc. than is typical for conventional Class C fly ash (Naik, 1993). Table 2.5 provides an example chemical composition of spray dryer ash.

Table 2.5 Spray Dryer Ash Chemical Composition (Naik, 1993)

Composition	Percent (%)
Al_2O_3	25.2
CaO	21.73
Fe_2O_3	3.26
MgO	0.84
K_2O	1.69
SiO_2	21.17
Na_2O	3.29
SO_3	17.5

There are several dry processes for cleaning up the SO_2 emissions from coal plants. The advance systems include atmospheric fluidized bed combustion (AFBC), lime-spray drying, sorbent furnace addition, sodium injection, and other clean-coal technologies such as integrated coal classification combined cycle (IGCC) process. This thesis uses a spray dryer ash (SDA) from a lime-spray drying process.

2.3.2.3 The Effects of Spray Dryer Ash on CLSM Properties

2.3.2.3.1 Flow Consistency

A flowable consistency is a very important CLSM property, and therefore it is essential to understand how SDA, among other components, affect this behavior. It is commonly accepted for typical concrete as well as CLSM mixtures that consistency is predominantly controlled by the amount of water in a CLSM mixture. A study evaluating the use of spray dryer ash in CLSM was conducted by Butalia, Wolfe, and Lee (Butalia, 1999). Their tests results were compared to typical CLSM mixtures. Table 2.6 presents the water content in percent along with a flow footprint diameter measure of consistency. The results demonstrate that an increase in water will cause an increase in flow.

Table 2.6 Flowability and Water Content (Butalia, Wolfe, & Lee 1999)

Mix #	W_c (%)		Flow (in)
	Initial	Mix	
1	20	65	6
2	20	72.5	8
3	20	77	13

In a subsequent study, Butalia, Wolfe, Zand, and Lee (2004) researched flowable fill using flue gas desulfurization materials (FGDs) produced from wet and dry desulfurization processes. The dry FGD material used in the laboratory tests was a spray dryer ash. The flow consistency from this test is presented in the following table, Table 2.7. The results demonstrate the same increase of flow consistency with increasing water content.

Table 2.7 Flowability and Water Content (Butalia, Wolfe, Zang & Lee 2004)

Mix #	Wc (%)	Flow (mm)
1	65	150
2	72.5	200
3	77	330

2.3.2.3.2 Bleeding and Segregation

Little is written concerning the effects that spray dryer ash has on bleeding and segregation. However, it is reasonable to assume that the bleeding and segregation of CLSM using spray dryer ash will be similar to CLSM manufactured using fly ash due to their similar physical properties. Fly ash and spray dryer ash have approximately the same spherical shape and also many similar chemical characteristics.

2.3.2.3.3 Air Content

Air content is another property that was tested in the Butalia, Wolfe, and Lee research. However it wasn't recorded or discussed in the available reference. No other literature was found on this subject.

2.3.2.3.4 Time of Set

Both of Butalia, Wolfe, and Lee's investigate the time of set for CLSM mixtures made using spray drier ash. For this research they used the penetration test in accordance with ASTM C 403: Time of Setting of Concrete Mixtures by Penetration Resistance. The first study, conducted in 1999, discusses how the penetration resistance values were less than 100 lb/in^2, and even after six days resistance values were less than 200 lb/in^2. Therefore, it was concluded that the mixes exhibited slow development of penetration resistance requiring approximately two to three weeks to reach 400 lb/in^2. The characteristic slow strength gain is common for normal CLSM mixtures. The penetration resistance characteristics of SDA CLSM mixtures show that SDA should be suitable for replacing conventional CLSM mixtures. The 2004 confirmed the results of the 1999 study. It was observed that spray dryer ash has a retarding effect on CLSM time of set but doesn't seem to be substantively different from that expected of a typical CLSM mixture.

2.3.2.3.5 Strength

The recommend value for 28-day CLSM strengths varies depending on the intended application. Rice (1997) recommended values for 28-day strengths range from 25 to 60 lb/in^2. The minimum specified strength is intended to provide sufficient support for construction and vehicular loads, whereas the maximum specified strength assures that the material can be excavated. A flowable fill having an unconfined compressive strength of 60 lb/in^2 has at least two to three times the bearing capacity of a well compacted earth backfill (FHWA, 1995). The result from the study conducted by Butalia, Wolfe, and Lee

(1999) data shows that the strength of the spray dryer ash CLSM mixes increases with curing time. It is also documented that as the water content increased the flowability also increased. However, as the flowability increased, the compressive strength decreased. The following table, Table 2.8 summarizes the characteristic of each mix and their measured compressive strengths.

Table 2.8 Flowability and Water Content (Butalia, Wolfe, & Lee 1999)

Mix #	W_c (%)		Flow (in)	Compressive Strength (lb/in^2)				
	Initial	Mix		7 (days)	14 (days)	28 (days)	60 (days)	90 (days)
1	20	65	6	10	27	35	38	51
2	20	72.5	8	8	25	27	31	34
3	20	77	13	5	18	18	24	27

It has been observed that Mixes 1 and 2 satisfied Rice's 28 day strength recommendations. Mixes 1 and 2 are likely usable in any kind of flowable fill applications. Mix 3's strength was less than 25 lb/in^2 at 28 days and likely has more limited applications.

Butalia, Wolfe, and Lee (1999) observed that although a 13-inch consistency provides good workability and placeablity, high moisture content in the spray dryer ash mix without any additive resulted in insufficient strength development. They concluded that a flowability range of 7 to 8 in. would provide sufficient strength and good flowability for most fill applications where spray dryer ash is used as a cementitious material in CLSM.

In the 2004 study by Butalia, the strength gain verses water content was evaluated and results show that compressive strength sufficient for most applications can be required for a large range of mix proportions. The strength depends chiefly on the cement and water content; the higher the cement content, the higher the strength. As the water content increased, the strength decreased.

2.3.3 Bottom Ash

2.3.3.1 Production

Bottom ash is another by-product of fossil fuel electric power generation. As discussed below, bottom ash is formed from burning coal. It consists of the heavier and larger particles in flue gas that falls to the bottom of the flue and typically ranges in size from fine sand to fine gravel. The annual production of bottom ash is 18 million tons and the annual use is 7 million tons (ACAA, 2007). In 2008 it was recorded that 10.4 million tons of bottom ash was landfilled and approximately 56 percent was generated. It's low cost and availability makes its use in CLSM desirable (ACAA, 2008).

Bottom ash is produced in a dry-bottom coal boiler from residue found in coal-fired electric power plants. Initially, coal is pulverized and blown into a burning chamber where it immediately ignites. About 80 percent of the unburned material, ash, is entrained in the flue gas and is captured and recovered as fly ash. The incombustible portion of this material not collected in the flue as fly ash is known as dry bottom ash. It drops down to a water-filled hopper at the bottom of the boiler or is impinge on the furnace walls (FHWA, 2011). When a sufficient amount of bottom ash drops into the hopper, it is removed by means of high-pressure water jets and conveyed by sluiceways either to a disposal pond or to a decant basin for dewatering, crushing, and stockpiling for disposal or use (FHWA, 2011).

2.3.3.2 Physical, Chemical and Reactive Properties

Bottom ash, like fly ash, is primarily composed of silica, alumina, and iron oxide; however, with smaller percentages of calcium and magnesium oxides, sulfates, and other compounds than fly ash. Bottom ash composition is controlled primarily by the source of the coal. Bottom ash derived from lignite or sub-bituminous coals has a higher percentage of calcium oxide (Class C fly ash) than the bottom ash from anthracite or bituminous coal (Class F fly ash) (www.tfhrc.gov). Table 2.9 shows detailed constituent sampling results for bottom ash as produced from the combustion of several types of coal mined from different locations.

Table 2.9 Overview of Bottom Ash Compounds, expressed in PPM (www.tfhrc.gov)

Coal Type	Bituminous			Sub-bituminous	Lignite
Location	**West Virginia**		**Ohio**	**Texas**	
Silicon Dioxide	536,000	459,000	471,000	454,000	700,000
Aluminium Oxide	283,000	251,000	283,000	193,000	159,000
Iron Oxide	58,000	143,000	107,000	97,000	20,000
Calcium Oxide	4,000	14,000	4,000	153,000	60,000
Magnesium Oxide	42,000	52,000	52,000	31,000	19,000
Sodium Oxide	10,000	7,000	8,000	10,000	6,000
Potassium Oxide	3,000	2,000	2,000	-	1,000

Bottom ash is a coarse, granular material collected from the bottom of a coal furnace. The physical characteristics of the residuals generated depend on the characteristics of the furnace. Typically, bottom ash is grey to black in color, and has a porous surface structure. Bottom ashes consist primarily of angular particles, the particles range in size from fine gravel to fine sand with very low percentages of silt-clay sized particles (particles less than 0.075 mm). The ash is usually a well-graded material, although variations in particle size distribution may be encountered in ash samples taken from the same power plant at different times. Bottom ash is predominantly sand-sized, usually with 50 to 90 percent passing a 4.75 mm (No. 4) sieve, 10 to 60 percent passing a 0.42 mm (No. 40) sieve, 0 to 10 percent passing a 0.075 mm (No. 200) sieve, and a top size usually ranging from 19 mm (3/4 in) to 38.1 mm (1-1/2 in) (FHWA, 2011).

Bottom ash has been used as a replacement for aggregate in structural concrete applications and in geotechnical applications, such as structural fills. The porous surface structure of bottom ash makes the material lighter than conventional aggregate and useful in lightweight concrete applications (EPA, 2011). Bottom ash may contain pyrites or "popcorn" particles that result in low specific gravities and high losses during soundness (i.e. freeze-thaw) testing. Due to an inherent salt content and in some cases low pH, this material may exhibit corrosive properties (FHWA, 1995). The specific gravity of dry bottom ash is a function of chemical composition with higher carbon content resulting in lower specific gravity. Bottom ash with a low specific gravity has a porous or vesicular texture, a characteristic of popcorn particles that readily degrade under loading or compaction. Table 2.10 lists the typical physical properties of bottom ash.

Table 2.10 Typical Physical Properties of Bottom Ash (FHWA, 1995)

Property	Bottom Ash
Specific Gravity	2.1 - 2.7
Dry Unit Weight	720 - 1600 (kg/m^3) (45 - 100 lb/ft^3)
Plasticity	None
Absorption	0.8 - 2.0%

Bottom ash does not possess the same pozzolanic and cementing properties as fly ash and, for this thesis, is investigated as an aggregate replacement for CLSM.

2.3.3.3 The Effects of Bottom Ash on CLSM Properties

2.3.3.3.1 Flow Consistency

Hardjito, Chuan, and Tanijaya (2011) examined the effects of bottom ash on the fresh CLSM properties. Their research focused on the practical use of bottom ash in CLSM for various construction purposes. Cement, water, sand and fly ash and bottom ash were studied. The research evaluated various cementitious material mixing proportions by 1) varying the percentage of cement in the cementitious material as 3, 6, 10 and 15 percent of total wet density and 2) varying the percentage of bottom ash in the aggregate as 0, 25, 50, 75, and 100 percent. All the material was placed in the mixer minus half of the water. After a minute or two of mixing, the remaining water was added and mixing continued an additional 15 minutes. Additional water was added, followed by mixing if the desired flowability was not initially achieved. Flowability was determined by using the inverted slump cone test. To perform this test, the CLSM mixture was loaded into the inverted slump cone until it was full. Then, the inverted slump cone was lifted up so that the CLSM flowed from the base and formed a circle (Hardjito, 2011). The diameter of the circle was measured with measuring tape. The diameter of the circle is considered acceptable if it is within the range of 475 mm to 750 mm (29.53 inches) (Hardjito, 2011). This diameter distance is considered adequate for most field applications of CLSM. The water content needed to achieve the flowability based on the fly ash to bottom ash ratio for 3, 6, 10, and 15 percent cement mix varied. The results showed that the required water content to achieve good flowability decreases gradually as the fly ash to bottom ash ration increases from 0:100 to 25:75 and then increases drastically as the fly ash to bottom ash ration increases from 25:75 to 100:0. It is speculated that this behavior is likely the consequence of effects related to the differences in particle size distributions, particle shapes, and pozzolanic natures of fly ash and bottom ash.

Du, Folliard, and Trejo (2002) also investigated the effects of bottom ash as an aggregate replacement of CLSM. The flowability or constituency of the CLSM specimens created was measured by the ASTM D6103. The experimental program of this particular study has been described in a previous section. To help better understand the behavior of the aggregate used in the experiment, the uncompacted void content was analyzed for the as-received condition and various size fractions. The researchers noted that such information is a valuable tool for assessing the shape and surface texture of aggregates.

Higher void contents, especially for as-received materials, suggest that additional fines in the fine aggregate or additional cementitious materials may be required to obtain the desired workability for conventional concrete. It is expected that higher void contents would have a similar effect on CLSM flowability, specifically increasing the water demand. Accordingly, the high percentage of void in the bottom ash suggests that it should need for more water and/or more cementitious material to affect the desired flowability. The researchers demonstrated that, compared to typical concrete sand, bottom ash required more water. The results are presented in Table 2.11 below. The flowability that was experienced in this study show that mixes using bottom ash, when compared to typical CLSM mixture design using sand, requires more water and/or more cementitious material to achieve desired flowability.

Table 2.11 CLSM Mixture Proportions and Fresh Properties (Du, Folliard, Trejo 2002)

Mixture	Type I cement (kg/m³)	Fly ash type	Fly ash (kg/m³)	Fine aggregate type	Water demand (kg/m³)	Flow (mm)	Total bleeding (%)
1	60	Class C	360	Bottom Ash	577	178	4.32
2	30	Class C	360	Bottom Ash	572	216	3.64
3	30	none	none	Bottom ash	582	127	4.35
4	60	none	none	Bottom ash	525	130	3.41
5	30	Class C	180	Concrete Sand	211	200	-
6	60	Class C	180	Concrete Sand	206	200	2.45
7	30	none	none	Concrete Sand	295	200	2.33
8	60	none	none	Concrete Sand	131	200	0.05

2.3.3.3.2 Bleeding and Segregation

Both bleeding and segregation were observed or calculated in the research done by Hardjito, Chuan, and Tanijaya (2011). During literature review, it was observed that the methods for measuring bleeding varied between researchers. Hardjito (2011). performed the bleeding test by measuring the difference in CLSM height following water evaporation. The bleeding test was measured in order to obtain the height reduction of the CLSM specimen; the reduced heights of CLSM specimens were measured on the third day after batching. The reduction of height over the total height of the CLSM specimen is considered as the percentage of bleeding. It was observed that the bleeding percentage of CLSM varies from 2.31 percent to 7.25 percent. The research demonstrates that the bleeding percentage of CLSM increases as the content of bottom ash is increased; and therefore concludes that the bottom ash does have porous properties and retains high initial moisture content. Hardjito, Chuan, and Tanijaya (2011) explain that the initial water content is predominantly water trapped in the pores of bottom ash, and that adds to the total available water of CLSM mixture. The result is high amounts of free water. Within this research no segregation was observed because fine aggregates and fillers were used in the mixtures and the cementitious material content was great enough to hold it in suspension. Fine particles have smaller voids between the particles, smaller diameter, and smaller mass and are therefore inherently less likely to segregate in a viscous paste.

2.3.3.3.4 Time of Set

The time of set for Hardjito, Chuan, and Tanijaya (2011) study was determined using a vicat penetrometer. The general procedure follows. After mixing, the CLSM was loaded in the penetrometer cast and water that collected on the surface due to bleeding was removed. The vicat needle was positioned and released. A reading of the penetration was recorded every 15 minutes.

The CLSM mixture was considered set when the penetration of the vicat needle was less than 0.98 inches (25 mm) in 15 minutes. The results on the vicat penetrometer method for their research was carried out for specimen with three percent cement content and six percent cement content. The results showed that the hardening time for the three percent cement mix varies from 5 to 6.5 hours, whereas the hardening time for six percent cement mix varies from 4 to 6 hours. It was observed that the overall results show that the hardening time increases with decreasing fly ash to bottom ash ratio.

The researchers noted that bottom ash was very porous and that water trapped in the pores prior to mixing is released during and after mixing causing excessive free water and bleeding of the specimen (Kasemchaisiri, Tangtermsirikul, 2006). It was also noted that although water due to bleeding was removed before the hardening time testing, there is still excessive free water trapped in the pores of bottom ash, thus causing the time for set to be slow. Hence, the hardening time increases as the bottom ash content increases.

2.3.3.3.5 Strength

The California Bearing Ratio (CBR) machine was used to measure the unconfined compressive strength the CLSM specimens in Hardjito, Chuan, and Tanijaya (2011) study. The compressive strength of CLSM was tested 3, 7, 28 and 60 days after batching.

The researchers concluded that higher quantity of cement used will produce CLSM with higher compressive strength. This result was true for bottom ash used as an aggregate as well as for other aggregates and was expected since using more portland cement in CLSM is expected to cause aggregate to be more effectively bonded together and better support the pozzolanic reaction of the fly ash. Also, higher cement content of CLSM would have higher strength, all other components equal, since it necessitates a lower water/cement ratio.

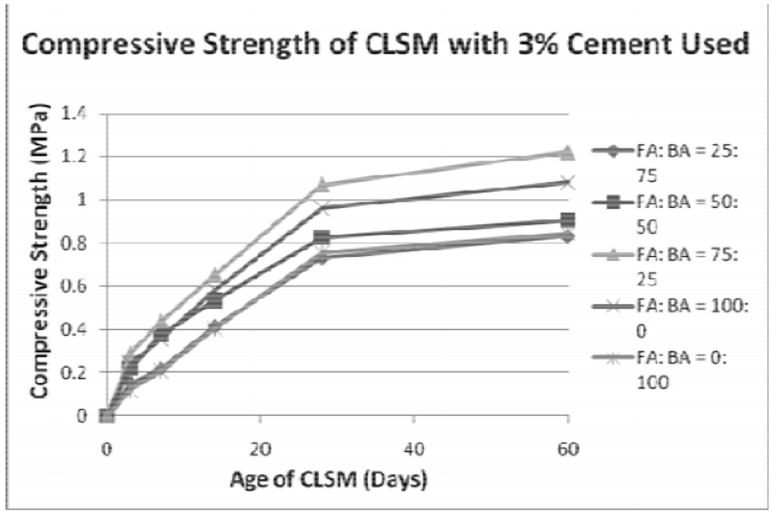


Figure 2.1 Compressive Strength of CLSM with 3% Cement Used (Hardjito, 2011)

The researchers concluded for the CLSM mixtures tested, that 3 percent cement in the cementitious material is suitable for general-purpose backfilling and future excavation purpose as it has low compressive strength. CLSM with 6 percent cement in the cementitious material is suitable for roadway trench backfilling; whereas CLSM mixture with 10 percent cement in the cementitious material is best used for structural backfill as it has higher compressive strength. The previous figure shows the different fly ash- bottom ash portions.

2.3.4 Crushed Waste Glass as Aggregate

Glass recycling is the process of turning waste glass into usable products. Waste glass is usually separated by chemical composition, and then, depending on the end use and local processing capabilities, might also have to be separated into different colors (Meyer, 2001). Glass retains its color after recycling and the most common colors are: colorless glass, green glass, and brown/amber glass. Glass contributes to a large amount of household and industrial waste due to its weight and density. However, of the materials being recycled today, glass is still one of the most difficult to reuse (Meyer, 2001). One of the major problems with glass recycling is the separation of clear and colored glass and removing all of the impurities. Post-consumer glass is often mixed –colored and containing contaminants such as plastics, metals, and organic matter. This reduces its value and complicates the ability to achieve the “cullet” specifications. Cullet is the term given to crushed waste glass ready to be melted. Because of difficulties achieving cullet specification the majority of crushed glass is landfilled. The recycling rate in 2007 was 23.7 percent (EPA 2007). Of the 13.6 million tons of waste glass generated that year, 10.36 million tons were landfilled and only 3.22 million tons were recycled (EPA 2007).

Closed-loop recycling is the process of collecting, sorting, transporting, beneficiating, and manufacturing glass back into bottles; is the most common form of glass recycling; and has costs embedded in each step of the process (Meyer 2001). Because the post-consumer glass is of mixed color, and much of it is broken, it cannot be easily recovered for closed-loop recycling. Therefore the disposal of the mixed broken glass as a waste residue from the recycling process causes a significant cost to recyclers.

Alternative solutions for disposing of mixed colored glass and glass-containing impurities have been difficult. The basic principle of environmental consciousness is violated when a potentially valuable resource is simply wasted or perceived to be underutilized, especially when it uses up increasingly scarce landfill space. Therefore, there has been a great interest in using crushed waste glass as a fine aggregate replacement. Past research has shown that a concrete mix containing crushed waste glass tends to lead to lower compressive strengths, and may be particularly susceptible to alkali-aggregate reactivity (ASR) when used with high alkali cements. Past studies took the approach of grinding the waste glass into a fine glass powder and incorporating it into concrete as a pozzolanic material. In laboratory experiments with powdered glass suppressed the alkali reactivity of coarser glass particles as well as that of a natural reactive aggregate. Consequently, the powdered glass undergoes beneficial pozzolanic reactions in the concrete and could replace up to 30 percent of cement in some concrete mixes with satisfactory strength development (Shayan 2002).

2.3.4.1 Production

Waste glass is produced through the glass recycling process, which primarily consist of post-consumer glass. Recycling companies collect the glass from households and commercial facilities, and then the glass is stockpiled at the recycling plant. There the glass is separated by color. Although all glass is made up of the same materials the type and quantity of the materials vary slightly with different types of glass, therefore having different melting points and chemical incompatibility (Shayan, 2002). In addition, glass will maintain its color after recycling (Shayan, 2002). Therefore, neither brown nor amber glass is used to manufacture clear glass, and it is important to separate the glass by color.

The process of recycling glass after the color sorting involves multiple segments of crushing to break the glass down into smaller particles. After the glass has successfully been crushed it travels by conveyor belt through a series of refinements. Magnets pull out metal, and air currents remove lightweight materials such as paper (www.es.anl.gov, 2011). Once the glass is crushed, it is typically conveyed to a screen designed to separate the broken glass, typically a 2 inch opening. After traveling along the conveyor belt and passing the screen, the glass is crushed and ready to be melted; at this point the material is known as “cullet.” However, other items passing through the screen include significant amount of contaminates such as paperclips, caps, tabs, etc. Some cullet suppliers use sophisticated equipment such as lasers to sort colors of crushed glass and further remove small contaminates. Scientists continue to develop mechanisms to improve materials sorting and, therefore, the quality of the cullet (www.es.anl.gov, 2011). The efficiency of this process comes down to how the glass is separated. Because, if the glass isn’t properly separated the colors get mixed and unsuitable for the use as containers then they are used for other purposes or sent to a landfill.

2.3.4.2 Physical and Chemical Properties

Waste glass comes in a variety of different compositions. The following is a description of the physical and chemical properties glass provides. Glass is considered to be a unique material with the molecular structure of a liquid and the physical characteristics of a solid. Glass sometimes is mistakenly called a super cooled liquid, but it’s actually a non-crystalline solid. The molecular structure of glass is irregular and randomly arranged. The chemical compositions of various types of glass are listed in Table 2.12. Glass is considered a brittle material due to its un-orderly crystalline structure (Shayan, 2002).

When used in concrete, the smooth nonporous surfaces of glass to not promote good bonding. The result is an increased potential for failure within the interfacial transition zone (ITZ) relative to other aggregates.

Table 2.12 Chemical Compositions of various color glass (Shayan, 2002)

Composition	Clear Glass	Brown Glass	Green Glass
SiO_2	72.42	72.21	72.38
Al_2O_3	1.44	1.37	1.49
TiO_2	0.035	0.041	0.04
Cr_2O_3	0.002	0.026	0.13
Fe_2O_3	0.07	0.26	0.29
CaO	11.5	11.57	11.26
MgO	0.32	0.46	0.54
Na_2O	13.64	13.75	13.52
K_2O	0.35	0.2	0.27
SO_3	0.21	0.1	0.07

The efficiency of glass manufacturing is dependent on the sorting of the various colors. When the glass colors get mixed, they become unsuitable for use as containers, and then must be used for other purposes or disposed in a landfill. Recycled waste glass is a mix of various colored glass and impurities. The waste glass that was used for this research was taken "as-is" and unwashed. Depending on the manufacturing plant, the material may or may not have been washed; therefore, it may contain some remnants of sugars or other organic contaminates. Other contaminates that weren't picked up by the magnet or vacuum during the crushing process are also present. Common contaminates are paper, metals, and aluminum caps.

The typical average specific gravity of soda-lime glass is 2.52 (en.wikipedia. org, 2011). Considering the fact that soda-lime glass comprises the majority of glass, it's probable to assume that the specific gravity of recycled glass is about 2.52. Therefore, the specific gravity of waste glass is generally less than that of natural aggregate. Consequently, it is reasonable to expect that using waste glass as aggregate would lessen concrete's unit weight. Glass is not a porous material; therefore, the expected absorption capacity is zero percent. However, impurities in the cullet may cause a slight absorption capacity. Different recycled glass processing facilities are likely to produce waste glass that has varying fineness modulus and particle size distributions. Therefore the use of crushed glass in CLSM may require carefully planned and implemented quality control.

2.3.4.3 The Effects of Waste Glass on CLSM Properties

2.3.4.3.1 Flow Consistency

Naik and colleagues at the University of Wisconsin-Milwaukee conducted research on the use of crushed waste glass in a CLSM (2000). Their mix design consisted of water, cement, fly ash, and various amounts of waste glass. The different mixtures contained glass with sand replacement levels of 30 percent to 75 percent by mass. They designed their mixtures to maintain a flow in the range of approximately 14 +/- 2 inches (355.6 mm) in accordance with ASTM D6103. ASTM D6103 notes that the average diameter of the patty is typically are 8 to 12 inches (203.2 to 304.8 mm). It was noted in the report that as the quantity of glass increased, the water required remained very similar to that of sand. The unit weight of the mixtures remained essentially unchanged because the sand and glass had similar values of specific gravity. The w/cm ratio changed based on the different glass proportions. Cement was the only cementitious material used in the study. Sand was the aggregate mixed with glass. The following Table 2.13 shows the flow consistency and the w/cm ratio of the mixtures contain 0 to 80 percent crushed waste glass.

Table 2.13 Flowability and Water to Cementitious ratio (Naik, 2000)

Mixture	Glass (%)	Flow (inch)	w/cm
1	0	13	0.45
2	30	13.5	0.44
3	75	12.25	0.91

The results indicated that as the quantity of glass was increased in these mixtures, more water was required to maintain the flow. The observation can be a result of the larger particle size and higher density of glass compared with that of fly ash.

2.3.4.3.2 Bleeding and Segregation

Naik (2000) observed bleeding while batching CLSM mixtures containing crushed glass. The mixtures containing crushed glass with only fly ash as the cementitious material experienced the most bleeding. He noted that decreasing the amount of fly ash and increasing glass content lead to increased bleeding and segregation, observed shortly after casting the CLSM test specimens. He further noted that this effect was greater at the higher glass and fly ash replacements. He concluded that this observation was attributable to the decreased amount of the cohesive material, i.e. fly ash, and increased amount of denser and larger size glass particles compared to fly ash particles. Similar results were obtained for CLSM containing waste glass, sand and cementitious material.

2.3.4.3.3 Air Content

Naik's (2000) research measured and reported air content for the fly ash and glass mixtures. These ranged from 0.6 to 2.1 percent. The 80 percent glass mixture had the highest percentage and the 60 percent glass mixture the lowest. The air contents for the sand and glass mixtures increased from 0.7 percent for mixtures having no glass to 1.9 percent for a mixtures having 75 percent glass. A relationship between air content and the two materials is not strongly supported by the data.

2.3.4.3.4 Time of Set

The setting and hardening characteristics of the CLSM mixtures used by Naik (2000) research was determined in accordance with ASTM D 6024. The time of set for the fly ash and crushed glass mixtures were increasingly delayed as glass increasingly replaced sand in the control mixture. This probably occurred due to the decrease in the cementitious materials content of the mixture. Figure 2.2 illustrates the results from the sand and glass mixture from the Niak (2000) study.

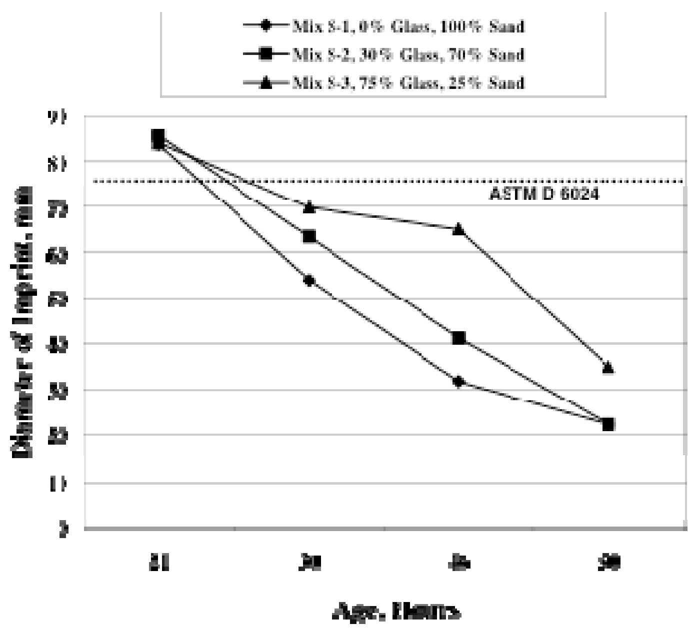


Figure 2.2 Setting and hardening Characteristics of Sand/Glass mixtures (Naik, 2000)

2.3.4.3.5 Strength

Naik's (2000) research showed that the compressive strength of the fly ash and glass mixtures increased with age. The rate of increase in compressive strength was the highest for the mixtures containing 60 and 80 percent glass. Naik explains that the typical CLSM mixtures behave like paste. However due to the coarse glass in some mixtures, the CLSM had the appearance and texture of concrete containing small aggregate. The compressive strength values of these mixtures with and without glass ranged from 60 to 90 lb/in^2 (0.4 to 0.6 MPa) at the age of 28 days. Figure 2.3 illustrates the results Naik's study on fly ash and glass mixtures.

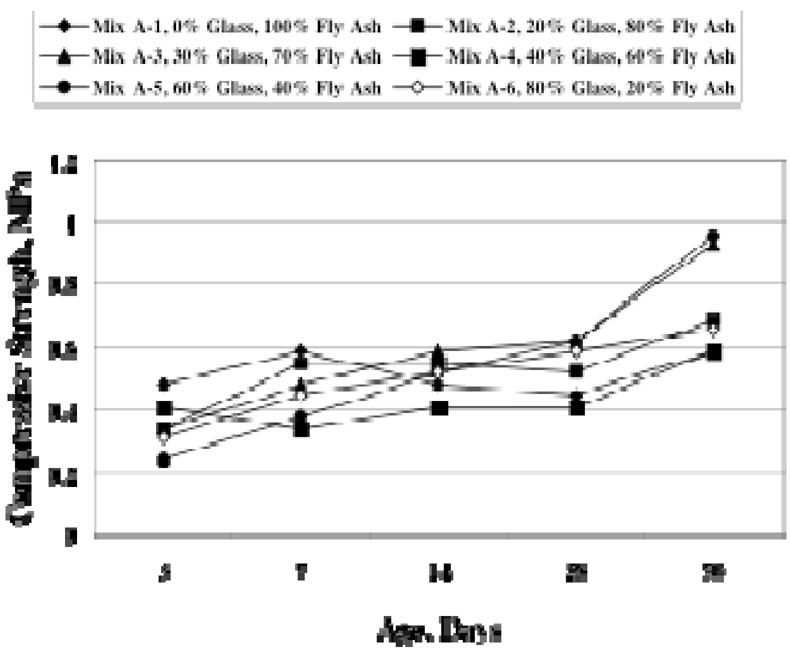


Figure 2.3 Compressive Strength of Glass/Fly ash CLSM Mixtures (Naik, 2000)

The compressive strength values of the CLSM mixtures containing glass and sand aggregate and portland cement had similar compressive strengths as

CLSM mixtures containing only glass and fly ash. Compressive strengths range from 20 to 85 lb/in^2 (0.15 to 0.6 MPa) at the 28 day age. Figure 2.4 illustrates the results from this study. The range of compressive strengths suggests that all CLSM mixtures are likely be excavatable.

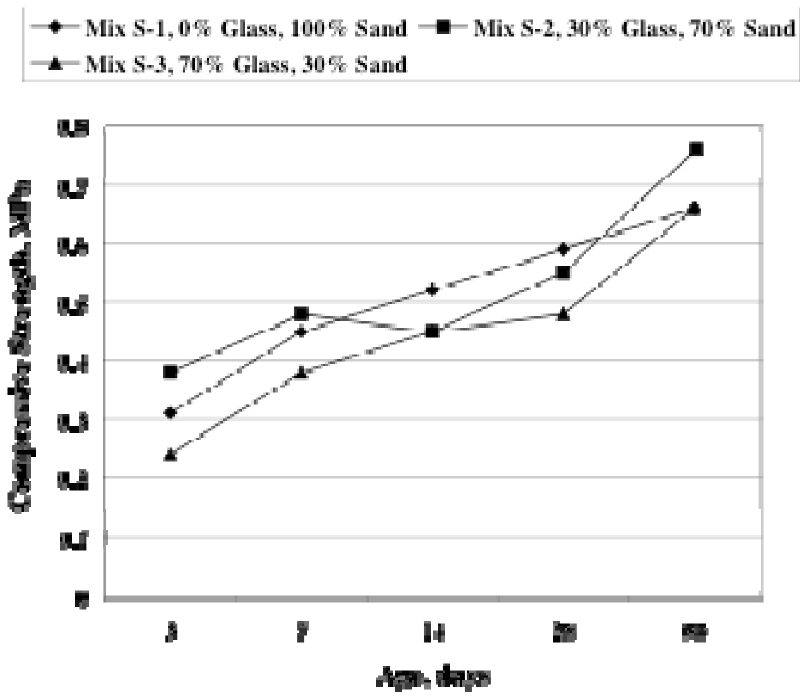


Figure 2.4 Compressive Strength of Sand/Glass CLSM Mixtures (Naik, 2000)

2.3.5 Recycled Concrete as Aggregate

2.3.5.1 Production

Recycled concrete used as aggregate is an example of a common construction waste that is produced from demolishing concrete. Recycling of concrete is a relatively simple process. For concrete to qualify for recycling it cannot contain trash or metal objects such as rebar.

The concrete is typically crushed to a reasonable size for transport at the construction site. At the recycling plant the concrete is crushed further by primary and secondary crushers and screened to remove any contaminates (PCA, 2011). The concrete is then graded and washed. The washed concrete is generally stockpiled according to particle size (NMAS). Materials that do not meet the recycling plant's requirements are either sent to another recycling plant or landfilled (PCA, 2011).

The use of recycled aggregate will decrease the need to consume virgin natural aggregate and simultaneously conserve landfill space. Unlike coarse recycled concrete, fine recycled concrete aggregate has been found to have limited use in structural concrete because it is more angular, porous, and weaker than natural aggregate. These characteristics affect the workability, ease of finishing and strength.

2.3.5.2 Physical, Chemical and Reactive Properties

The recycled concrete aggregate chemical and physical properties will vary greatly depending on the source of the demolished concrete. Recycled concrete aggregate can be purchased in various size ranges. The crushed concrete not only contains the originating concrete's coarse aggregate but also chunks of mortar, fine aggregates and cementitious paste. This paste will also be present in the coarse and fine aggregate in varying amounts. Chloride content may be high when the parent material is road concrete since residual chlorides salts used to melt snow and prevent icing may be present.

Cementitious paste and mortar contained in crushed concrete used as aggregate reduces the specific gravity and increases the porosity of cementitious mixtures. Higher porosity of recycled concrete aggregate leads to a higher absorption (PCA, 2011). The absorption capacity of crushed concrete will usually be higher than that of common sand and gravel due to the increased porosity of the mortar chunks and cementitious paste surrounding the aggregate. Typical range for absorption content is between 3 and 10 percent and increases as the crushed concrete aggregate size decreases (www.cement.org, 2002). The physical appearance of recycled concrete is more angular than crushed rock. Because of this characteristic it expectedly exhibits workability problems.

2.3.5.3 The Effects of Recycled Concrete as Aggregate on CLSM Properties

2.3.5.3.1 Flow Consistency

Achtemichuk, Hubbard, Sluce, and Shehata (2009) examined the effects of fine recycled concrete aggregate on the properties of CLSM. The workability was evaluated using the slump flow test (ASTM D 6103). It was concluded that with fine recycled concrete aggregate the CLSM design was mainly for applications that involve narrow areas such as small trenches, or bedding for conduits with small spacing, because the plastic properties of these mixtures are very important. The mix designs consisted of fly ash, water and crushed concrete as aggregate. Table 2.14 shows the mix proportions of the CLSM and their fresh CLSM properties. The minimum flowability for this research was 5.9 in (150 mm).

Table 2.14 Mix Proportions of CLSM with Fine Recycled Concrete Aggregate (Achtemichuk, 2009)

Fly Ash (%)	w/cm	Slump flow (mm)
5	2.65	120
10	1.25	119
15	0.83	132
20	0.63	108
30	0.5	141

2.3.5.3.2 Bleeding and Segregation

Segregation during the batching of RCA CLSM mixtures was a concern expressed by Achtemichuk (2009) and avoided by adjusting water to cementitious material ratio as needed to maintain approximately the same consistency in all tests.

2.3.5.3.3 Air Content

Air content was not specifically discussed in the Achtemichuk document.

2.3.5.3.3 Time of Set

Achtemichuk (2009) found that the fine crushed concrete used in their study contained 0.08 percent alkalis, which were attributed, in part, to activating the pozzalonic reaction with fly ash and slag which were used in their study as cementitious material. They attributed the high surface area fine crushed concrete as helping accelerate the release of alkalis from cement paste, thereby accelerating set time.

2.3.5.3.5 Strength

Achtemichuk (2009) used fly ash mixed with various percentages of slag as cementitious materials when batching, using fine crushed concrete as the sole aggregate. Some mixtures having acceptable strength ranges resulted. As noted earlier, the water content was adjusted to regulate consistency; therefore the w/cm ratios for all tests varied, as did the cementitious material content.

2.3.6 Recycled Crumb Rubber as Aggregate

2.3.6.1 Production

Crumb rubber generally consists of particles ranging in size from 4.75 (No. 4 Sieve) to less than 0.075 (No. 200 Sieve). Methods commonly used to convert scrap-tires into crumb rubber are: (i) cracker mill process, (ii) granular process and (iii) micro-mill process (Siddique, 2009). The cracker mill process tears apart or reduces the size of tire rubber by passing the materials between rotating corrugated steel drums. This process produces irregularly shaped torn particles having large surface area. The size of these particles varies from 5 to 0.5 mm (No. 4 – No. 40 Sieve) and is known as crumb rubber. Crumb rubber can be sieved to produce a wide range of particle sizes. In 2001, about 281 million scrap tires were generated in the United State and roughly 75 percent of these tires were reused in some type of secondary market (Rubber Manufacturers Association 2006). Civil engineering applications, in which tires are shredded for applications such as leachate collection in landfills or for highway embankments, accounted for about 15 percent of scrap tires.

A nominal crumb rubber process is designed to process passenger tires and truck tires in separate batches and can alter the mesh size of output depending on customer specifications and market requirements. A magnetic metal removal and fiber screening system are incorporated, and metal and fiber fragments removed at various stages of the process are conveyed to central container for later sale or disposal (Sunthonpagasit, 2002). The first part of this process is visual inspection and sorting, and is important to ensure that the scrap tires are suitable for processing. Passenger tires and truck tires are separated; tires containing rims are de-rimmed. The tires are then put on a conveying system to reduce the whole tires through shredding and granulating down to various sizes, and then classified into three groups: coarse, mid-range, and fine size. Not all recycled crumb rubber plants reduce the size of the material to 40 to 80 mesh. Typically 30 mesh is the smallest size created because smaller sizes are more difficult to isolate.

2.3.6.2 Physical, Chemical and Reactive Properties

A tire is a composite of complex elastomer formulations, fibers and steel/fiber cord. Tires are made of plies of reinforcing cords extending transversely from bead to bead, on top of which is a belt located below the thread. Table 2.15 lists typical types of materials used in manufactured tires.

Table 2.15 Typical Materials used in Manufacturing Tire (Rubber manufacturer's Association, 2006)

1) Synthetic rubber
2) Natural rubber
3) Sulfur and sulfur compounds
4) Phenolic resin
5) Oil
(i) Aromatic
(ii) Naphthenic
(iii) Paraffinic
6) Fabric
(i) Polyester
(ii) Nylon
7) Petroleum waxes
8) Pigments
(i) Zinc oxide
(ii) Titanium dioxide
9) Carbon black
10) Fatty acids
11) Inert materials
12) Steel wires

Crumb rubber is finely ground tire rubber from which the fabric and steel belts have been removed. It has a granular texture and ranges in size from very fine powder to sand-size particles. Tire chops consist of tire pieces that are roughly shredded into 1- 12 inches (2.5-30 cm) lengths (Pierce, 2002).

Pierce and Blackwell (2002) researched the characteristics of crumb rubber:

> According to Humphrey (1999), some of the advantageous properties of tire chips in civil engineering applications include low material density, high bulk permeability, high thermal insulation, high durability, and high bulk compressibility. When mixed with mortar or concrete, research has shown that both compressive strength and unit weight decreases with increasing rubber content (Goulias, 1998). Incorporating fly ash in rubber

mixtures further reduces unit weight (Fattuhi, 1996). Increasing rubber content also reduced modulus of elasticity (Fedroff, 1996) and improves ductility (Goulias, 1998). Due to its low specific gravity and unit weight crumb rubber can be considered a lightweight aggregate for use in concrete manufacturing. Fattuhi (1996) suggest that concrete rubber mixtures could be used for trench filling and pipe bedding, which are common applications for CLSM. However, research on mixing crumb rubber in CLSM has minimal amount of literature.

2.3.6.3 The Effects of Recycled Crumb Rubber as Aggregate on CLSM Properties

2.3.6.3.1 Flow Consistency

Pierce, and Blackwell (2002) investigated the performance of CLSM mixes using crumb rubber exclusively as aggregate in CLSM. No sand was added to the mixtures. The crumb rubber was a No. 30 mesh. A general-purpose fluidizing agent commonly used for cement-sand grouts was added to three of the nine mixtures tested to improve flowability. It was noted the higher w/cm ratios tend to increase flowability and bleeding. Table 2.16 lists the average flowability measured for the nine mixtures studied. Consistency was measured in accordance with ASTM D 6103. Only two of the nine mixtures met the criterion of a spread diameter of 8 to 12 inches (203.2 to 304.8 mm). Mixtures 1, 2 and 3 contained fluidizing agents the researchers noted that flowability increased by 40 percent when fluidizing agent was added and all other things equal. It was concluded that Mixtures 4 and 8 could be used as CLSM in select applications that do not require significant flowability. This contingency was in recognition that any flow resulting in less than an 8 inch diameter footprint does not achieve the ASTM minimum consistency requirement, being too stiff. Flowability increased consistently with an increasing w/cm ratio. It is noteworthy that Pierce and Blackwell (2002) CLSM crumb rubber mixtures required a w/cm ratio between 1.75 and 3 to meet flowability requirements and that a fluidizing agent was effective in increasing flowability.

Table 2.16 Flowability and Bleeding

Mixtures	Flowability (cm)	Bleeding (% volume)
1	0	1.3
2	20.3	1.9
3	23.9	3.7
4	16.8	4.3
5	35	10.1
6	36.3	13.8
7	31.8	9.5
8	16.8	4.6
9	>60	29.9

A study done by Wu and Tsai (2008) concluded that rubberized CLSM is essentially not flowable without the addition of sand. No fluidizing agents were used in their study. Wu and Tsai's (2008) study indicated that, despite different w/cm ratios, the rubberized CLSM without the addition of sand exhibited poor workability and was unable to achieve a preferable flowability of 20 cm (8 inches). They drew the conclusion that rubber fines are poorly graded sand-like porous materials with higher permeability and that water exchange with the pores leads to a lower flowability.

2.3.6.3.2 Bleeding and Segregation

Segregation is often a concern when dealing with lightweight aggregate and incorporating it into cement-based materials. Because of crumb rubbers low specific gravity, it can be considered a lightweight material. As discussed in the previous section, Pierce and Blackwell (2002) used the admixtures to increase flowability of the mixture. Because the admixture reduced water content it also helped to control segregation. High water contents were observed to result in segregation. This was noted during consistency testing as an observed surface layer of crumb rubber that developed on the surface of the tested material as it flowed. (Pierce and Blackwell, 2002).

Bleeding depends primarily on the mixture of water content. Pierce and Blackwell associated observations of increased bleeding with increased w/cm ratios. To help control bleeding the mixing time and speed was increased.

2.3.6.3.3 Air Content and Unit Weight

No information was found in literature regarding the air content of CLSM that uses crumb rubber as aggregate. However, unit weight measurements by Wu and Tsai (2008) yielded unit weights for CLSM that ranged from 5.5 to 11.6 kN/m^3 (35 to 74 lb/ft^3). These values are only about 25 to 50 percent of that of a standard CLSM or a compacted earth fill (Wu, Tsai 2008). Pierce and Backwell's (2002) investigation shows similar results. The reduction in unit weight is primarily a function of the increase in crumb rubber content.

2.3.6.3.4 Time of Set

The Pierce and Blackwell (2002) investigation revealed that all mixtures set within 24 hours. They defined set time as the earliest time for which there was penetration resistance using a pocket penetrometer. ASTM recommends a minimum equivalent strength of 20 lb/in^2 after three days of curing. It was recorded that all but one of their mixtures met this requirement.

Table 2.17 Flowability, Bleeding and Initial Hardening Time for All Mixtures

Mixtures	Flowability (cm)	Bleeding (% volume)	Time to Reach 140 kPa (20psi)
1	0	1.3	1
2	20.3	1.9	2
3	23.9	3.7	6
4	16.8	4.3	1
5	35	10.1	1
6	36.3	13.8	1
7	31.8	9.5	1
8	16.8	4.6	2
9	>60	29.9	1

2.3.6.3.5 Strength

Pierce and Blackwell (2002) concluded that CLSM mixed with crumb rubber can achieve sufficient strength for practical applications. Table 2.18 shows the strengths achieved by Pierce and Blackwell. Note that Mixture 9 was not analyzed due to a high bleeding factor. The data collected showed that the measured compressive strengths generally fell between 30 and 300 lb/in^2, which is common for most standard CLSM. However, mixtures with strengths greater than 200 lb/in^2 are not expected to be excavatable (ACI, 1999). Research is not definitive regarding the influence of crumb rubber content on strength. At a w/cm ratio of 3, strength is greatest when the crumb rubber content is 29 percent. Strength is consistently lower at both higher and lower rubber contents, suggesting that there may be an optimum for a given w/cm ratio. The most determinable influence on strength of cement-based material is the w/cm ratio. Based on Pierce and Blackwell's measurements, strength generally decreases as the w/cm ratio increases from 1.5 to 2.

Table 2.18 Average Compressive Strength (Pierce, & Blackwell 2002)

Mixtures	7-Day (kPa)	14-Day (kPa)	28-Day (kPa)
1	179	228	269
2	-	566	766
3	331	359	483
4	932	1449	2601
5	-	897	1021
6	97	469	676
7	718	897	1194
8	114	1525	-

3. Problem Statement

3.1 Statement

The public, industries and government have become increasingly interested in green design and engineering in particular is moving towards more sustainable development. The world is in a transition of improving the disposal and usage of waste products from solid waste materials to by-products of the coal and mining industry. Electricity is one of the most versatile and therefore the most desirable forms of energy. The U.S. consumes the largest amount of the total electrical power consumption in the world. In 2007, the world consumed 495 quadrillion Btu., and of the total, the U.S. consumed 21% (energy.gov, 2011). Electric power consumption is comprised of commercial, industrial, residential and transportation users. The U.S. Department of Energy states that industrial use is half of what the world consumes in electric power (energy.gov, 2011). Recycling has a significant positive effect by reducing the amount of energy needed to make products with new materials. When recyclables go to the landfill, more materials must be mined, harvested or refined to replace the discarded item. Concrete construction is one of the largest users of natural resources. The recycling of concrete, asphalt and other solid waste materials is a great opportunity to reduce mining, and the use of virgin materials, and minimize landfill use.

Recycling also has economic benefits, landfill space costs money for state and local governments, which do not receive a financial return on this investment. Recycling, on the other hand, produces income that not only offsets the cost of establishing recycling facilities, but also generates significant income through tax revenues for local, state and federal governments. The use of concrete has become a sustainable approach to construction. With the economy changing and the critical need for environmental conservation, builders are moving towards a more sustainable and innovative solutions that meet engineering challenges while reducing labor, material cost and environmental impact. It is for these reasons that the use of flowable fill also known as Controlled Low Strength Material (CLSM) was chosen for further research.

CLSM is a self-compacting low strength material with a flowable consistency that is used as an economical fill or backfill materials as an alternative to compacted granular fill. CLSM is not concrete, nor is it used to replace concrete. CLSM is also known as unshrinkable fill, controlled density fill (CDF), flowable mortar, soil cement slurry, plastic cement and was known for a while as “K-Krete.” CLSM is a self-leveling material that does not require compaction or vibration and is placed with minimal effort. When hardened the material provides adequate strength. The ingredients may vary, but typically consist of a mixture of soil (used as aggregate), cementitious material, and water. The contributions of these admixtures are selected to reduce the cement quantity, to improve the flow characteristics of the mixture and/or to optimize the use of readily available materials. Like many other concrete products, CLSM has many green benefits when made using industrial waste products.

The focus of this research is to create mix designs of CLSM that will provide the use of recycled materials that are a potentially low-cost source of aggregate. The use of these recycled materials will reduce the amount of waste materials that end up in landfills. To fully understand the effects that recycled materials have on the fresh and hardened properties of CLSM, the percentages of recycled materials used ranged from 25% replacement to 100% replacement. CLSM ideal applications are: backfill, trenches, pipe bedding, excavated tanks, sub-bases, slope stabilization, and pavement base. These applications and others require the CLSM have an acceptable compressive strength. CLSM compressive strengths in some cases must be low enough for future excavation. The ultimate strength, modulus of elasticity and fresh concrete properties were examined for all mix designs. The main purpose for this research is to investigate the advantages and disadvantages of the different percent replacement of recycled materials, determine if they are beneficial, and conclude if specific mixtures will result in usable CLSM.

4. Experimental Plan

4.1 Design Summary

The objective of this thesis is to evaluate innovative uses for common waste materials in CLSM mixtures. To this end, the following two goals are established.

1) Determine if there is potential for CLSM to be manufactured using spray drier ash (SDA) as the principle cementitious material by evaluating rate of strength increase and attainment of common CLSM strength and flowability requirements for several mixtures.
2) Measure and compare the compressive strength, and the modulus of elasticity of CLSM mixtures manufactured using select combinations of Class C fly ash, portland cement, SDA, crushed glass, bottom ash, recycled concrete and crumb rubber; and thereby add to the growing body of knowledge regarding appropriate mix proportions for CLSM manufactured using these materials.

A standard CLSM mixture is made up of water, cement, and fine aggregate. The ingredients that were subject to replacement with the above listed recycled waste materials include cement and fine aggregate.

The research presented herein investigates the effects that the materials discussed above will have on the fresh and hardened properties of CLSM. Various proportions of the recycled materials were used in CLSM mixtures. The mixtures for this research project consisted of aggregates proportioned by volume and cementitious material proportioned by mass. A typical CLSM is described in ASTM D 4832 and was selected as the control mix. It was comprised of fine sand with the cementitious material consisting of 90 percent Class C fly ash and 10 percent cement with a water to cement ratio (w/cm) of about 1.25.

The test program has two components 1) the cementitious materials investigation, and 2) the aggregate replacement investigation. Literature review provided information necessary to determine which waste materials may be successfully applied to CLSM and mixture proportions likely to be successful.

Portland cement was mixed with either Class C fly ash or SDA using sand as a fine aggregate.

- Class C fly ash mixes included fly ash as 90, 95 and 100 percent of the cementitious material.
- SDA mixes included SDA as 90, 95 and 100 percent of the cementitious material.

The sand used as control mix aggregate was replaced with either crumb rubber, bottom ash, recycled concrete or crushed glass.

- The aggregates were substituted for the sand with 25, 75 and 100 percent replacement.
- All mixes to investigate aggregates used cementitious material comprised of 90 percent Class C fly ash, and 10 percent portland cement.

All mixes other than the SDA mixes were designed to have 630 lbs/yd^3 cementitious material and to the extent practicable maintained a w/cm ratio of 1.25. The SDA mix was designed to have 750 lbs/yd^3 cementitious material. As needed, measured quantities of either water or dry mixture were added during batching to achieve flowability requirements for CLSM. This changed some mixture proportions slightly and is discussed in Chapter 5. All mixtures were tested for fresh and hardened CLSM properties. The fresh concrete properties tested included slump, unit weight and air content. The hardened CLSM properties examined were compressive strength and modulus of elasticity. A penetrometer test was used to evaluate set time for SDA mixtures. All testing conformed to ASTM testing standards with exceptions presented in Chapter 5; and all data results, details, conclusions, and findings of this research are included with this thesis.

A successful CLSM must have properties defined by specific standards. The standards of the Colorado Department of Transportation (CDOT) for typical CLSM are herein adopted for this research with the exceptions noted below. Mixtures that achieve the CDOT strength and consistency standards are deemed successful.

To evaluate the effects of these recycled materials the fresh and hardened CLSM properties of each mixture are measured and compared to each other, CDOT and ASTM standards. A CDOT CLSM mixture is a low strength structural material that can be used in multiple structural backfill applications. CDOT states that structural backfill shall be composed of non-organic mineral aggregates and soil from excavations, borrow pits, or other sources (CDOT, 2011). CDOT also notes that fine aggregate and fly ash that do not meet the requirements subjected in their specification manual may be used as long as testing indicates its use is acceptable for the application. The mixtures main concern is its flowability. The flowability requirement of a CDOT mixture is to achieve a flow consistency that results in at least a 6 inch (152.4 mm) diameter patty of fresh mixture when tested in accordance with ASTM D6103. Table 4.1 shows the other specific requirements for a CDOT CLSM mixture. Table 4.2 shows the ASTM specifications for comparison. The CDOT removability modulus (RM) and is calculated as follows:

$$RM = \frac{W^{1.5} \times 104 \times C^{0.5}}{10^6} \quad \text{(Equation 1)}$$

W=unit weight (pcf)

C=28-day compressive strength (psi)

It is expected that CLSM achieving the RM standard can be excavated with common equipment.

Table 4.1 Colorado Department of Transportation (CDOT) Structural Backfill Specifications (CDOT, 2011)

28-Day Compressive Strength minimum	Flow Consistency	Air Content
(lb/in^2)	(inches)	(percent)
50	6	2 to 3

Table 4.2 ASTM Standards Specifications

28-Day Compressive Strength maximum	28-Day Compressive Strength typical value	Flow Consistency	Air Content
(lb/in^2)	(lb/in^2)	(inches)	(percent)
1200	50 to 100	8 to 12	entrapped .5 to 3; air entraining 15-25

The remainder of this section is organized as follows. Section 4.2 presents properties of the materials used in this thesis; Section 4.3 presents the experimental design; and Section 4.4 presents the CLSM batching, curing, and general testing procedures.

4.2 Material Properties

The cementitious materials used in this study are spray drier ash, Class C fly ash, and portland cement. The aggregates used in this study are fine sand (C 33 Sand), crushed glass (recycled glass), crumb rubber, bottom ash and crushed concrete. The properties of each are discussed in this section.

4.2.1 Class C Fly Ash

The Class C fly ash was obtained from the Pawnee Plant (Boral), just east of Denver, Colorado. Class C fly ash was chosen rather than Class F because Class C has stronger pozzolanic character thought to be needed to successfully replace cement without significantly changing the total unit mass of the cementitious material. The Class C fly ash was tested by the supplier in accordance with ASTM C 618 and the results of this testing are shown in Table 4.3.

Table 4.3 Pawnee Class C Fly Ash Physical and Chemical Properties

Pawnee Class C Fly Ash			
Chemical Properties		**Test Results**	**ASTM C 618 Specifications**
Silicon Dioxide (SiO_2)	(%)	30.3	
Aluminum Oxide (Al_2O_3)	(%)	17.2	
Iron Oxide (Fe_2O_3)	(%)	6.66	
Sum of SiO_2, Al_2O_3, Fe_2O_3	(%)	54.16	70.0/50.0 min.
Calcium Oxide (CaO)	(%)	29.13	
Magnesium Oxide (MgO)	(%)	7.45	
Sulfur Trioxide (SO_3)	(%)	2.85	5.0 max
Sodium Oxide (Na_2O)	(%)	2.26	
Potassium (K_2O)	(%)	0.31	
Total Alkalies (as Na_2O)	(%)	2.46	
Physical Properties		**Test Results**	**ASTM C 618 Specifications**
Moisture Content	(%)	0.02	3.0 max
Loss of Ignition	(%)	0.4	6.0 max
Amount Retained on No. 325 Sieve	(%)	13.41	34 max
Specific Gravity	-	2.77	-
Autoclave Soundness	(%)	0.15	0.8 max
SAI, with portland Cement at 7 Days	(%) of Control	101.9	75 min.
SAI, with portland Cement at 28 Days	(%) of Control	97.8	75 min.
Water Required	(%) of Control	95	105 max
Loose, Dry Bulk Density	(lb/ft^3)	72.03	-

4.2.2 Portland Cement

Type I-II portland cement was supplied by Holcim Cement Company, located in Florence, Colorado. The cement was tested by the supplier in accordance to ASTM C 150 and the results are shown in Table 4.4.

Table 4.4 Holcim Type I-II Cement Physical and Chemical Properties

Holcim Type I-II Portland Cement			
Chemical and Physical Properties		**Test Results**	**ASTM C 150 Specifications**
Silicon Dioxide (SiO_2)	(%)	19.6	-
Aluminum Oxide (Al_2O_3)	(%)	4.7	6.0 max
Iron Oxide (Fe_2O_3)	(%)	3.2	6.0 max
Calcium Oxide (CaO)	(%)	63.4	-
Magnesium Oxide (MgO)	(%)	1.5	6.0 max
Sulfure Tioxide (SO_3)	(%)	3.4	3.0 max
Carbon Dioxide (CO_2)	(%)	1.4	-
Limestone	(%)	3.7	5.0 max.
Calcium Carbonate ($CaCO_3$) in Limestone	(%)	84	70 min.
C_3S	(%)	59	-
C_2S	(%)	11	-
C_3A	(%)	7	8.0 max
C_4AF	(%)	10	-
$C_3S + 4.75\ C_3A$	(%)	92	100 max
Loss of Ignition	(%)	2.6	3.0 max
Blaine Fineness	cm^2/g	414	2600 - 4300
Air Content of PC Mortar	(%)	6.3	12 max
Specific Gravity	(%)	3.15	-

4.2.3 Spray Dryer Ash

The spray dryer ash was obtained from the Comanche Plant near Pueblo, Colorado. The spray dryer ash that was used in this research was chosen because of its abundance resulting from a general lack of industrial applications. The spray dryer ash was tested by the supplier in accordance with ASTM C 618 and the results of this testing are shown in Table 4. 5.

Table 4.5 Chomanche Spray Dryer Ash Physical and Chemical Properties

Chomanche Spray Dryer Ash			
Chemical Properties		**Test Results**	**ASTM C 618 Specifications**
Silicon Dioxide (SiO_2)	(%)	26.21	
Aluminum Oxide (Al_2O_3)	(%)	15.22	
Iron Oxide (Fe_2O_3)	(%)	4.37	
Sum of SiO_2, Al_2O_3, Fe_2O_3	(%)	**45.8**	70.0/50.0 min.
Calcium Oxide (CaO)	(%)	30.31	
Magnesium Oxide (MgO)	(%)	3.99	
Sulfur Trioxide (SO_3)	(%)	**12.68**	5.0 max.
Sodium Oxide (Na_2O)	(%)	1.45	
Potassium (K_2O)	(%)	0.28	
Total Alkalis (as Na_2O)	(%)	1.63	
Physical Properties			
Moisture Content	(%)	1.72	3.0 max.
Loss of Ignition	(%)	2.47	6.0 max.
Amount Retained on No. 325 Sieve	(%)	11.11	34 max.
Specific Gravity	-	2.57	-
SAI, with Portland Cement at 7 Days	(%) of Control	107.9	75 min.
SAI, with Portland Cement at 28 Days	(%) of Control	-	75 min.
Water Required	(%) of Control	99.2	105 max.

The spray dryer ash however, did not meet the ASTM C 618 cementitious materials specifications by not possessing the minimum allowable sum of SiO_2, Al_2O_3, Fe_2O_3 and also by exceeding the sulfur trioxide standard.

4.2.4 (Virgin) Fine Aggregate

The fine aggregate was obtained by the University of Colorado Denver from Bestway Concrete and other sources located in the Colorado area. The material properties and gradation analyses were determined by WestTest Laboratories located in Denver, Colorado. The sand was determined to meet the ASTM C 136 requirements for C 33 Fine Aggregate. The materials properties data and complete gradation for the sand is included in Appendix B. The specific gravity for the C 33 sand is 2.63 and the absorption capacity is 0.7 percent. The fine aggregate will be referred to as "C 33 Sand" for the remainder of this thesis.

4.2.5 (Recycled) Fine Aggregate

The bottom ash, crushed waste glass, recycled concrete fines, and the crumb rubber used to replace aggregate in the control mix were from various sources and were tested by methods indicated in Table 4.6 prior to use in the CLSM mixtures.

Table 4.6 Testing of Recycled Materials

Fine Aggregate	Test Type Performed	ASTM Method
Bottom Ash	Specific Gravity & Absorption Capacity	ASTM C 128
	Sieve Analysis (Gradation)	ASTM C 136
Crushed Waste Glass	Specific Gravity & Absorption Capacity	ASTM C 128
	Sieve Analysis (Gradation)	ASTM C 136
Recycled Concrete Fines	Specific Gravity & Absorption Capacity	ASTM C 128
	Sieve Analysis (Gradation)	ASTM C 136
Crumb Rubber	Specific Gravity & Absorption Capacity	ASTM C 128
	Sieve Analysis (Gradation)	ASTM C 136

4.2.5.1 Crushed Waste Glass

The crushed waste glass was obtained from Rocky Mountain Bottling Co., owned by Miller-Coors. The waste glass was mainly produced from beer bottles with various colors such as clear, amber and green. The glass was collected from the hopper after it had traveled along a conveyor belt and had undergone multiple crushing's. The crushed glass also had impurities removed by a vacuum and magnets. The waste glass was used "as received" from the plant, i.e. no washing took place. It was observed that the waste glass contained a few foreign objects such as batteries and screws. These were removed from the material prior to batching by a physical separation process. That is, the crushed glass was passed through a 3/8 inch sieve to remove the undesirable objects.

Testing was performed on the waste glass to determine the absorption capacity, specific gravity and fineness modulus. Table 4.7 shows the properties of the waste glass and compares them to the same C 33 Sand properties.

Table 4.7 Fine Aggregate Properties of Waste Glass and C 33 Sand

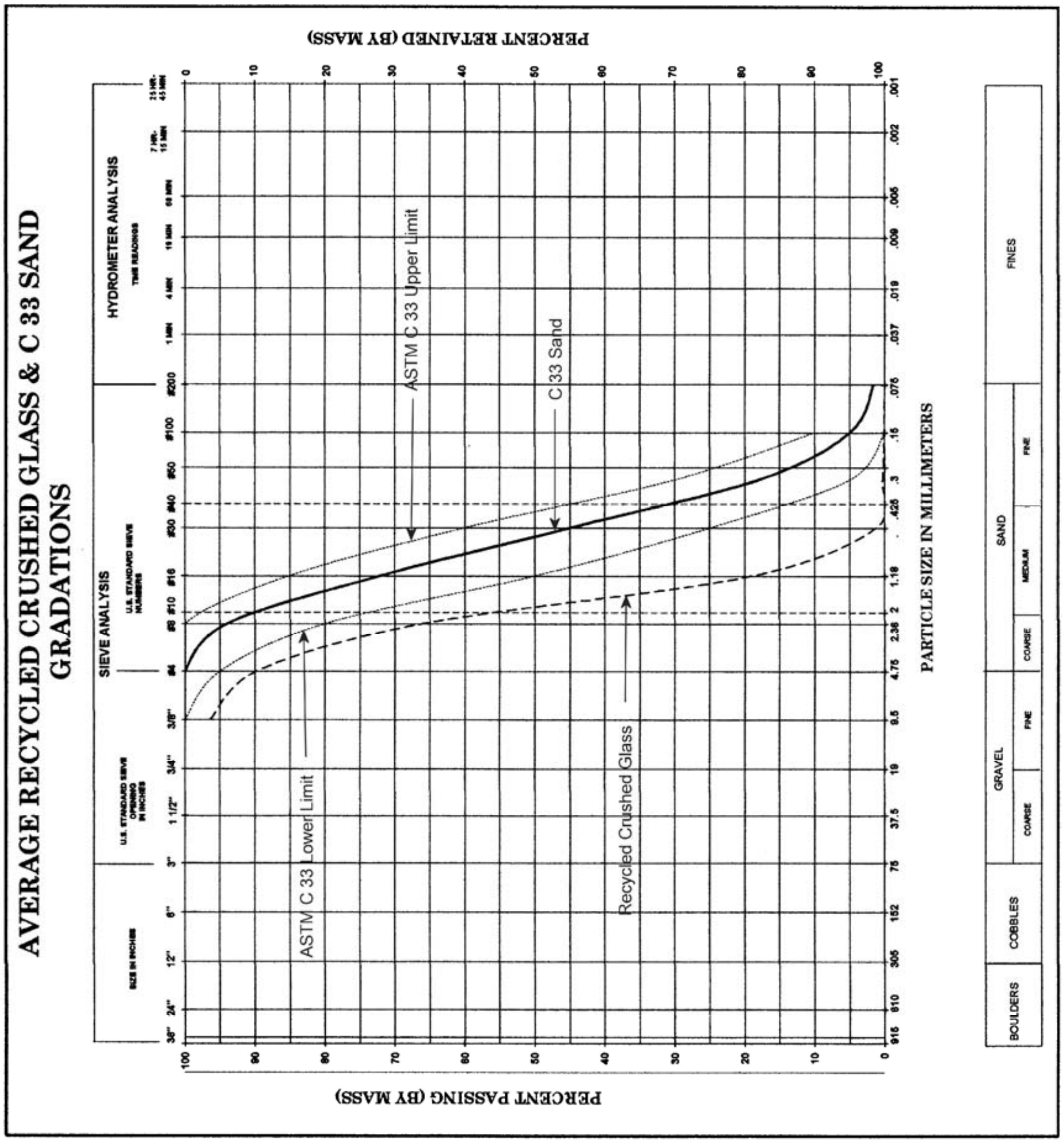
Aggregate Property	Waste Glass	C 33 Sand
Absorption Capacity, (%)	0.02	0.7
Specific Gravity	2.50	2.63
Fineness Modulus	4.37	2.67

The absorption for both aggregates is low, with the waste glass adsorption registering lower than the C 33 Sand. This can be expected because glass is not porous and therefore does not retain water. A comparison of the specific gravity of the waste glass to the C 33 Sand also indicates the specific gravity of the glass is slightly lower than the sand.

Gradation analyses were performed on three independent representative sample of waste glass. ASTM C 702: Standard Practice for Reducing Samples of Aggregate to Testing Size was followed to obtain representative samples. This required the waste glass to be thoroughly mixed; the pile iteratively split into smaller piles; and two suitable piles combined for a sieve analysis. The splitting was iterated until the two piles combined for the testing had the proper combined weight for the analysis. The particle size distributions were consistent with all three samples and are presented in Appendix B. The average of the gradation analyses for the waste glass is shown alongside the gradation for the C 33 Sand on Figure 4.1. The plot is a representation of the average of three-gradation analysis performed. The waste glass specimens did not achieve the requirements of ASTM C 136 C 33 aggregate due to excess materials retained on the 8, 16, and 30 sieves. The No. 200 sieve was added to the standard sieve stack because the amount of fines in CLSM aggregate is a concern. CDOT specification regarding fine aggregate states that 100 percent must pass the 1 inch sieve and no more than 10 percent pass the No. 200 sieve. The waste glass meets this standard.

The fineness modulus (FM) for waste glass is much higher than the C 33 Sand. The FM for fine aggregate is required for mix proportioning since sand gradation has the largest effect on workability. In general, finer sand (lower fineness) has a greater number of particles available to improve workability. The fineness modulus for fine aggregate should lie between 2.3 and 3 (Mindness, 2003). The FM is used to check the consistency of grading when relatively small changes are to be expected; but it should not be used to compare the grading of aggregates from two different sources. Based on the test results, the waste glass is coarser than the C 33 Sand. However, adequate workability was anticipated because the crushed glass is a uniform relatively fine aggregate.

Figure 4.1 Average Crushed Glass & C 33 Sand Gradation Analysis



4.2.5.2 Bottom Ash

Bottom ash was obtained from the Pawnee Plant (Boral), just east of Denver, Colorado. The bottom ash and Class C fly ash were acquired from the same production process. The bottom ash was taken from the bottom of the boiler and included some material removed from the furnace walls. Larger pieces were removed by passing the material over a 3/8 inch sieve. Testing was performed on the bottom ash to determine the physical properties. Table 4.8 shows the properties of the recycled concrete alongside the same property measurements for the C 33 Sand for comparison.

Table 4.8 Fine Aggregate Properties of Bottom Ash and C 33 Sand

Aggregate Property	Bottom Ash	C 33 Sand
Absorption Capacity, (%)	7.08	0.7
Specific Gravity	2.6	2.63
Fineness Modulus	4.9	2.74

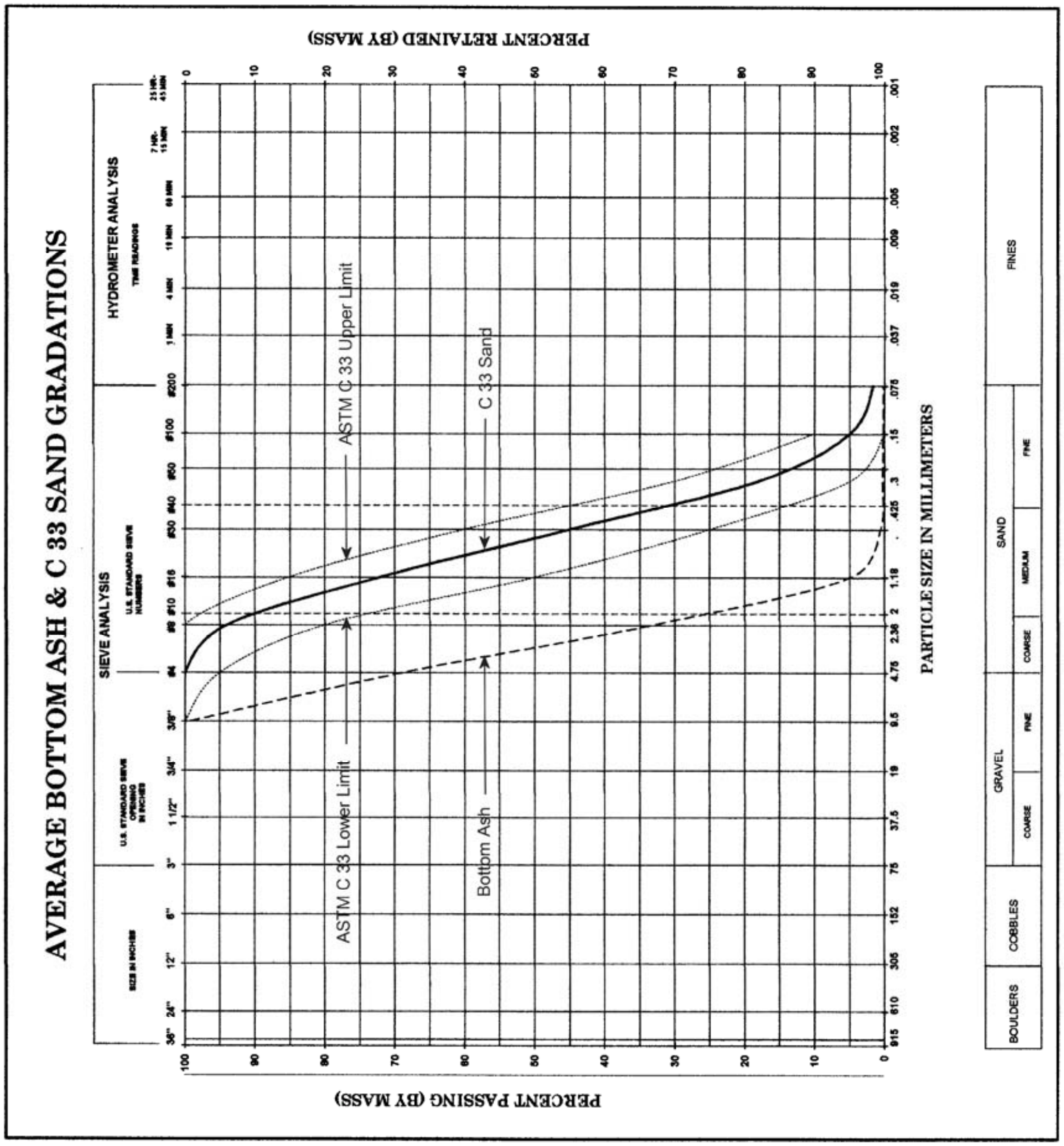
The bottom ash and the C 33 Sand have similarities and differences. The specific gravities are very similar. However, the absorption capacities of the two materials are significantly different. Bottom ash has a higher absorption capacity due to its porous structure and angular shape. Water is absorbed and retained in the porous bottom ash.

Three separate gradations were performed on the bottom ash after the larger particles were removed by hand. ASTM C 702: Standard Practice for Reducing Samples of Aggregate to Testing Size was used to obtain a representative sample as previously described. The results of the three gradation analyses are presented in Appendix B. Figure 4.2 illustrates the comparison of the average bottom ash gradation to that of the C 33 Sand.

Three separate gradations were performed on the bottom ash, after the larger particles were removed by hand. Before performing these gradations, the bottom ash had to be sampled properly. ASTM C 702: Standard Practice for Reducing Samples of Aggregate to Testing Size was followed for sampling. All of the bottom ash that was obtained was dumped and mixed together, then separated into four piles. The piles were repeatedly broken down until two suitable piles were obtained for testing. Figure 4.2 illustrates the comparison of the bottom ash to the C 33 sand. The practical distribution plot is an average of three separate gradations. The gradation analysis for all three specimens did not meet the requirements of ASTM C 136 due to excess material retained on the No. 4, No. 8, and No. 16 sieves. These results were consistent for all three samples. The results are summarized in tables in Appendix B.

The fineness modulus (FM) for bottom ash is much higher than the C 33 sand. Therefore, based on the test result, bottom ash is a coarser material than the C 33 sand, and may cause workability issues. However, for the CLSM mixtures this may also not be a problem because the only aggregate being used in a fine aggregate.

Figure 4.2 Average Bottom Ash & C 33 Sand Gradation Analysis



4.2.5.3 Recycled Concrete (RCA)

Recycled concrete was obtained from Allied Recycled Aggregate, located north of Denver, Colorado. The aggregate was taken from a large waste pile that was designated as recycled concrete fines. The aggregate was shoveled into buckets from several locations on the large pile. The concrete originated from the demolition of facilities and structures such as roads, buildings, driveways, sidewalks, etc. Therefore the material in the pile may have been heterogeneous with regard to material properties. The recycling plant doesn't accept any material that contains foreign objects such as rebar. The recycled concrete fines are considered a waste product that result from sieving crushed concrete to obtain the larger, more valuable particles. Testing was performed on the recycled concrete to determine the physical properties. Table 4.9 shows the properties of the recycled concrete fines as well as the C 33 Sand fine aggregate for comparison. The fineness modulus is derived from the average of the three gradation tests.

Table 4.9 Fine Aggregate Properties of Recycled Concrete Fines and C 33 Sand

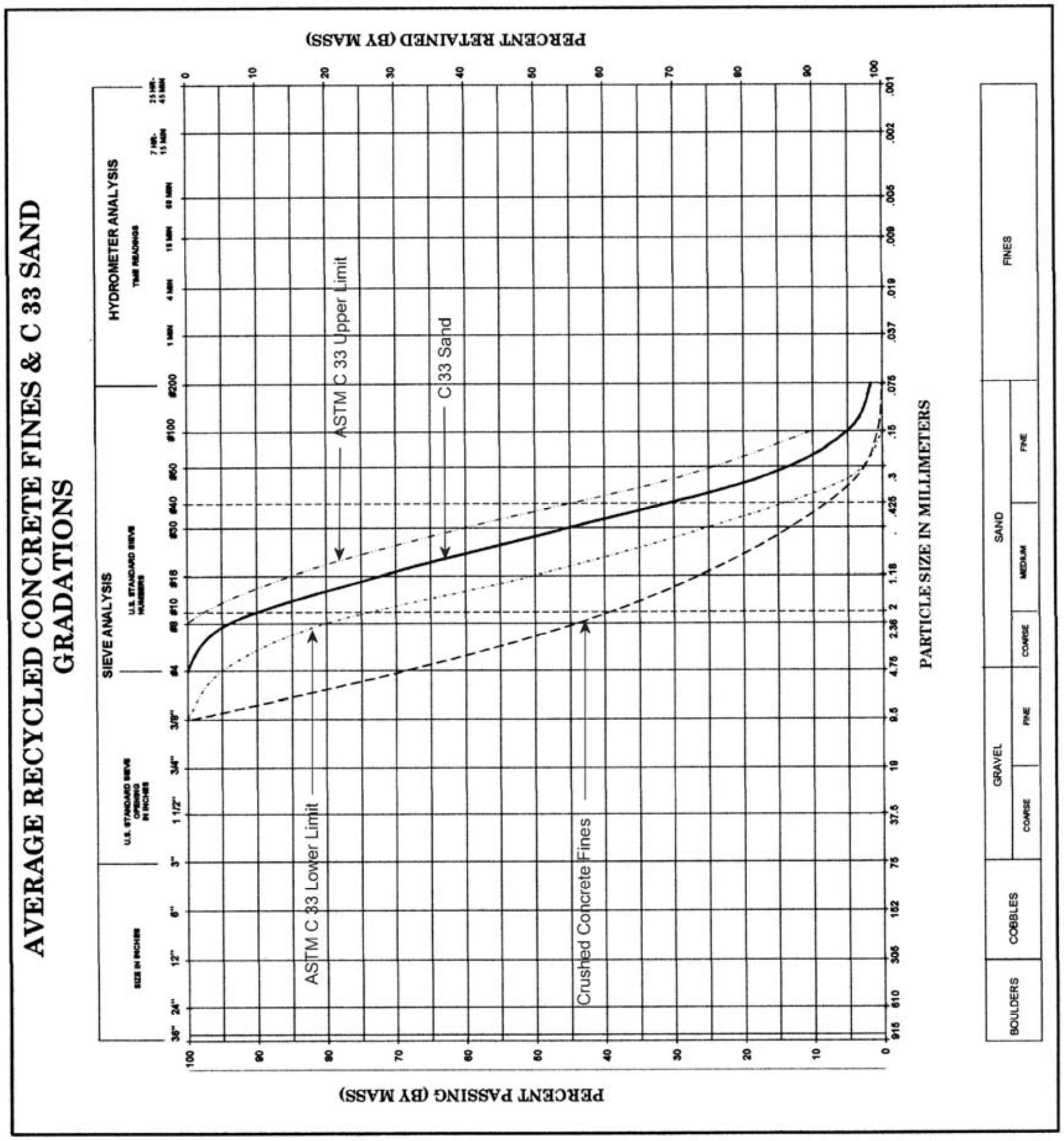
Aggregate Property	Recycled Concrete Fines	C 33 Sand
Absorption Capacity, (%)	9.7	0.7
Specific Gravity	2.62	2.63
Fineness Modulus	4.44	2.74

The specific gravity of the recycled concrete and the C 33 sand are similar. However, the absorption capacity and the fineness modulus show that the recycled concrete fines have a high absorption capacity, and higher fineness modulus than the C 33 sand. The high absorption capacity could be a result of the porous mortar coating on the larger particles and included mortar particles.

The high absorption results suggest CLSM may have a higher water demand than the control mixture. The large number for the fineness modulus indicates a coarse material. This may have a significant effect on the CLSM workability. However, only fine, uniformly graded material is used so workability and segregation issues were not anticipated.

Three separate gradations were performed on the recycled concrete fines. ASTM C 702: Standard Practice for Reducing Samples of Aggregate to Testing Size was used to obtain representative samples for gradation analyses. The three gradation test results are presented in Appendix B. The average gradation curve for the recycled concrete is shown with the gradation curve for the C 33 Sand on Figure 4.3. The gradations for all three specimens did not meet the requirements of ASTM C 136 for C 33 aggregate due to excess material retain on the number 4, 8, 16 and 30 (only two samples) sieves.

Figure 4.3 Average Recycled Concrete Fines & C 33 Sand Gradation Analysis



4.2.5.4 Crumb Rubber

The crumb rubber selected for this study was obtained from North West Rubber Colorado, Inc. located in Louviers, Colorado. The rubber is identified as tire crumb (styrene-butadiene rubber (SBR), poly Butadiene (PBD) & natural rubber). The crumb rubber is a blend of various rubbers, carbon black and oils. The rubber that was obtained is free of all metals and is 100 percent recycled tire and comes in varies sizes. The crumb rubber that was used in this thesis was collected and tested by Adam Kardos (UCD graduate student) and the results of his testing are shown in Table 4.10 alongside the test results representing C 33 Sand.

Table 4.10 Fine Aggregate Properties of Crumb Rubber and C 33 Sand

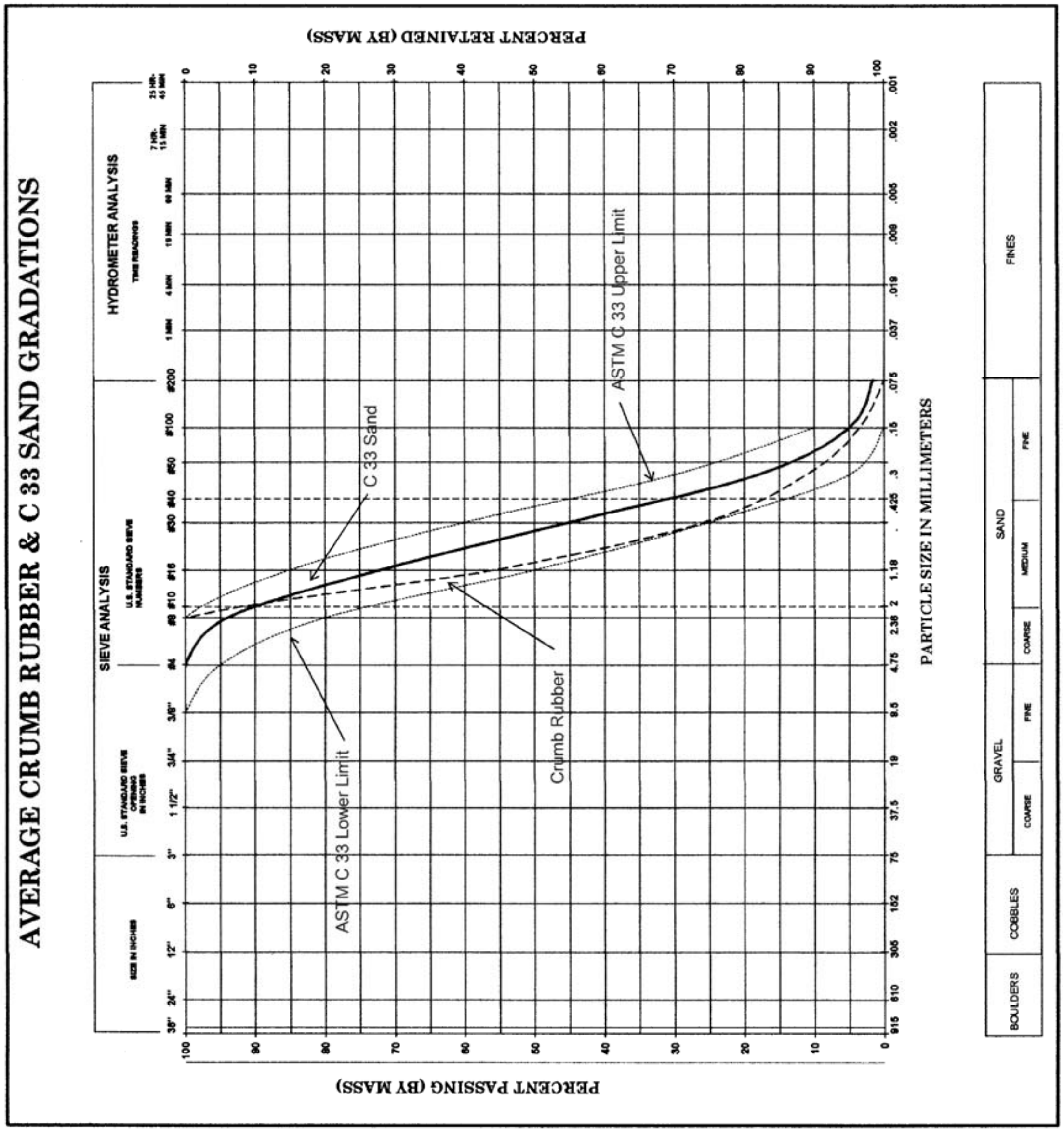
Aggregate Property	Crumb Rubber	C 33 Sand
Absorption Capacity, (%)	0	0.7
Specific Gravity	1.07	2.63
Fineness Modulus	3.05	2.74

*Note: Crumb rubber results were tested and obtained from Adam Kardos, UCD Masters Candidate, 2011.

Crumb rubber and C 33 sand have minor similarities. Crumb rubber is not a porous material therefore has no absorption capacity while C 33 Sand has a slight absorption capacity. The specific gravity of crumb rubber is lower than that of C 33 sand and is only slightly greater than that of water (specific gravity water = 1.0). When used in concrete, crumb rubber is generally considered a lightweight concrete aggregate due to its low specific gravity. The fineness modulus is also higher than the C 33 sand; this could be indicative of a decrease in workability in CLSM mixtures. It was anticipated that crumb rubber could have some trouble with both segregation and workability due to the combination of mixtures having high w/cm ratios and low crumb rubber specific gravity and high fineness modulus.

The gradation was determined as the average of analyses on two separate representative crumb rubber samples. Adam Kardos performed the gradation analyses as part of his more in-depth research study on the use of crumb rubber in concrete mixtures and the results are summarized in the tables in Appendix B. Figure 4.4 shows the average gradation curves of the crumb rubber alongside the curve for the C 33 sand. It can be seen on the figure that the two particle size distributions are very similar.

Figure 4.4   Average Crumb Rubber & C 33 Sand Gradation Analysis



4.3 Experimental Design

The test program has two components 1) the cementitious materials investigation, and 2) the aggregate replacement investigation.

4.3.1 Cementitious Materials Investigation Design

For the cementitious material investigation, the aggregate was sand and cementitious material was portland cement combined with either Class C fly ash or SDA in specific proportions. Theses mixtures are summarized as follows.

- Class C fly ash mixes included fly ash as 90, 95 and 100 percent of the cementitious material by mass.
- SDA mixes included SDA as 90, 95 and 100 percent of the cementitious material by mass.

4.3.2 Aggregate Replacement Investigation Design

For the Aggregate Replacement Investigation, the fly ash 90 percent mixture as described above is the control mix and all investigated aggregates were substituted for the C 33 sand in proportions described below. The C 33 sand was systematically replaced with, bottom ash, crumb rubber, crushed glass, or recycled concrete (RCA), in specific proportions. These mixtures are summarized as follows.

- The aggregates were substituted for the sand with 25, 75 and 100 percent replacement by volume.
- All mixes used cementitious material comprised of 90 percent Class C fly ash, and 10 percent portland cement.

The targeted mix proportions are presented in Table 4.11 and Table 4.12. All mixtures were designed to have 630 lbs/yd^3 cementitious material except the SDA mixtures, which were designed to have 750 lbs/yd^3 cementitious material. The targeted w/cm ratio was 1.25. Water or additional dry mixture components were added during batching as necessary to achieve consistent flowability that achieved the CDOT requirement for CLSM. Additionally, air content was not controlled and deviated from the value presumed for design. As a consequence, the mixture proportions actually achieved were different than those targeted. The mix proportions achieved are presented and discussed in Chapter 5.

All mixtures were tested for fresh and hardened CLSM properties. The fresh concrete properties tested included slump, unit weight and air content. The hardened CLSM properties examined were compressive strength, and modulus of elasticity. All testing conformed to ASTM testing standards and all data results, details and conclusion of findings of this research are included with this thesis.

Table 4.11 CLSM Mixture Design Matrix by % Replacement

Mix #	Mixture ID	w/cm	Cementitious Content (lb)	Type of Cement	%Portland Cement	%Class C Fly Ash	%SDA	%Bottom Ash	%Crumb Rubber	%Crushed Glass	%RCA	%Sand	Air Content (%)
1	FA-90	1.25	630	Type II	10	90	-	-	-	-	-	100	1
2	FA-95	1.25	630	Type II	5	95	-	-	-	-	-	100	1
3	FA-100	1.25	630	Type II	0	100	-	-	-	-	-	100	1
4	SDA-90	1.25	750	Type II	10	-	90	-	-	-	-	100	1
5	SDA-95	1.25	750	Type II	5	-	95	-	-	-	-	100	1
6	SDA-100	1.25	750	Type II	0	-	100	-	-	-	-	100	1
7	BA-25	1.25	630	Type II	10	90	-	25	-	-	-	125	1
8	BA-75	1.25	630	Type II	10	90	-	75	-	-	-	25	1
9	BA-100	1.25	630	Type II	10	90	-	100	-	-	-	0	1
10	CR-25	1.25	630	Type II	10	90	-	-	25	-	-	75	1
11	CR-75	1.25	630	Type II	10	90	-	-	75	-	-	25	1
12	CR-100	1.25	630	Type II	10	90	-	-	100	-	-	0	1
13	RCG-25	1.25	630	Type II	10	90	-	-	-	25	-	75	1
14	RCG-75	1.25	630	Type II	10	90	-	-	-	75	-	25	1
15	RCG-100	1.25	630	Type II	10	90	-	-	-	100	-	0	1
16	RCA-25	1.25	630	Type II	10	90	-	-	-	-	25	75	1
17	RCA-75	1.25	630	Type II	10	90	-	-	-	-	75	25	1
18	RCA-100	1.25	630	Type II	10	90	-	-	-	-	100	0	1

Table 4.12 CLSM Mixture Design Matrix (lb/yd^3)

Mix #	Mixture ID	w/cm	Cementitious Content (lb/yd3)	Type of Cement	Portland Cement (lb/yd3)	Class C Fly Ash (lb/yd3)	SDA (lb/yd3)	Bottom Ash (lb/yd3)	Crumb Rubber (lb/yd3)	Crushed Glass (lb/yd3)	RCA (lb/yd3)	Sand (lb/yd3)	Air Content (%)
1	FA-90	1.25	630	Type II	63	567	-	-	-	-	-	1725	1
2	FA-95	1.25	630	Type II	32	599	-	-	-	-	-	1721	1
3	FA-100	1.25	630	Type II	0	630	-	-	-	-	-	1717	1
4	SDA-90	1.25	750	Type II	75	-	675	-	-	-	-	245	1
5	SDA-95	1.25	750	Type II	38	-	713	-	-	-	-	233.16	1
6	SDA-100	1.25	750	Type II	0	-	750	-	-	-	-	1504	1
7	BA-25	1.25	630	Type II	63	567	-	421.3	-	-	-	1294	1
8	BA-75	1.25	630	Type II	63	567	-	1264	-	-	-	431.14	1
9	BA-100	1.25	630	Type II	63	567	-	1685	-	-	-	0	1
10	CR-25	1.25	630	Type II	63	567	-	-	177	-	-	1293	1
11	CR-75	1.25	630	Type II	63	567	-	-	531	-	-	431	1
12	CR-100	1.25	630	Type II	63	567	-	-	708	-	-	-608	1
13	RCG-25	1.25	630	Type II	63	567	-	-	-	410	-	1294	1
14	RCG-75	1.25	630	Type II	63	567	-	-	-	1230	-	431	1
15	RCG-100	1.25	630	Type II	63	567	-	-	-	1640	-	0	1
16	RCA-25	1.25	630	Type II	63	567	-	-	-	-	430	1293	1
17	RCA-75	1.25	630	Type II	63	567	-	-	-	-	1084	361	1
18	RCA-100	1.25	630	Type II	63	567	-	-	-	-	1371	0	1

4.3.1 Mixture Batching

The mixtures in this research were all batched following the guidelines in ASTM D 4832: Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders. All of the waste materials were stored in buckets with lids to help maintain the moisture content. For each batching episode, the aggregate moisture content was determined the day before batching and the batching weights adjusted accordingly.

The batching procedure was similar for all mixtures except for the occasional need to add water or dry mixture to achieve proper flow consistency. The materials were mixed in the following order. First the aggregate and half of the water were combined and mixed in a rotating drum or in a wheelbarrow using a shovel. Then the cementitious materials and the remaining water were incrementally added and mixed. The material was mixed for an additional fifteen to twenty minutes in the drum mixer, or in the wheel barrow sometimes by hand using a shovel and other times using a hand-held-drill paddle mixer. The flow consistency was determined following mixing by method ASTM 6103. If the mixture did not achieve the necessary flow consistency, a 6 inch (152.4 mm) or greater diameter footprint, then additional materials were mixed into the batch, in proper proportion when possible, to effectuate the desired consistency. Dry mixture added to the batch was always added in the same proportion as was used initially. However, water added to a batch was not accompanied by the addition of cementitious material necessary to maintain the original w/cm ratio.

Immediately following mixing and consistency testing the samples were cast in 4 inch (101.6 mm) diameter, 8 inch (203.2 mm) long, lubricated plastic molds and capped.

4.3.2 Curing

Curing was in accordance with ASTM D 4832: Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders. This standard requires all samples be placed at room temperature for 4 days, and then moved to a curing environment. The curing environment was a humidity controlled room with a relative humidity maintained at 90 percent. Because there was some concern that the facility may not efficiently maintain a 90 percent relative humidity the specimens (in the molds) were placed in the humidity room, wrapped in wet burlap and then wrapped in plastic. The test specimens were not removed from the molds until the day of testing. On the day of testing the cylinders are carefully removed from the molds and air-dried for 4 hours prior to testing.

4.4 CLSM Testing

Fresh and hardened CLSM properties were examined. The fresh CLSM properties were examined immediately after batching. The fresh properties examined included slump, unit weight and air content. The hardened CLSM properties evaluated, the compressive strength and modulus of elasticity, were examined beginning 4 days after batching and continued through 28 days of age. The SDA samples were additionally evaluated to determine set time using a penetrometer.

For the SDA mixtures, a pocket penetrometer was used to estimate the compressive strength at 8, 16 and 24 hours after batching. The procedure used was ASTM C 403: Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance; however, a standard soil penetrometer was used rather than the penetrometer prescribed by the method.

The loading system monitored the loading rate and displacement rate and made adjustments automatically to create a smooth loading condition. The system controlled the loading rate so that the maximum load is achieved in an acceptable time, after which a slow post-failure strain rate allowed measurement of post-failure loads. The equipment settings were adjusted with the intent to achieve the ultimate strength of the material in two or three minutes. The machine output was an electronic file containing force, time, and axial displacement data. This information was used to calculate stress, strain and time to failure as discussed in Chapter 5. Table 4.13 summarizes the fresh and hardened CLSM properties tested.

Table 4.13 Fresh and Hardened CLSM Properties Tested

Fresh CLSM Tests	**Standard Followed**	**Time of Testing**
Flow Consistency	ASTM D 6103	When Batched
Unit Weight	ASTM C 138	When Batched
Air Content	ASTM C 231	When Batched
Hardened CLSM Tests	**Standard Followed**	**Time of Testing**
Compressive Strength	ASTM C 39	4, 7, 14, & 28 Days (12-cylinders)
Early Compressive Strengths for SDA	ASTM C 403	8, 16, & 24 Hours (6-cylinders)
Modulus of Elasticity	ASTM C 469	28 Days (3-cylinders)

5. Experimental Results

5.1 General

Experimental results and significant observations are presented in this chapter. This chapter presents the measured fresh and hardened CLSM properties. The mixture designations presented in the mixture design matrix in Chapter 4 will be used throughout the remainder of this thesis.

5.2 Fresh Concrete Properties

The fresh CLSM properties tested included slump, unit weight and air content. The results of the fresh CLSM properties are included in Table 5.1 and Table 5.2. Table 5.1 contains the recycled cementitious replacements fresh properties and Table 5.2 contains the recycled aggregate replacements fresh properties.

Table 5.1 Fresh CLSM Properties For Cementitious Replacements

Mixture Identification		Flow Consistency (in. x in.)	Air Content (%)	Measured Unit Weight (lb/ft^3)
1	FA-90	10 x 10	0.1	116.9
2	FA-95	9 x 9	0.1	122.3
3	FA-100	10 x 10	0.1	120.1
4	SDA-90	10 x 10.5	0.2	123.9
5	SDA-95	9.5 x 10	0.2	125.5
6	SDA-100	8.5 x 10	0.2	131.5

Table 5.2 Fresh CLSM Properties For Recycled Fine Aggregate Replacements

Mixture Identification		Flow Consistency (in. x in.)	Air Content (%)	Measured Unit Weight (lb/ft^3)
7	BA-25	10.5 x 9.5	0.6	129.3
8	BA-75	10 x 10.5	0.7	124.3
9	BA-100	10 x 10	1.3	119.9
10	CR-25	8.5 x 10	1.5	107.6
11	CR-75	10 x 9.5	7.5	77.1
12	CR-100	6.5 x 7.5	8.5	74.5
13	RCG-25	10.5 x 10	6	125.3
14	RCG-75	9.5 x 10	5.5	122.3
15	RCG-100	10.5 x 10.5	2	122.5
16	RCA-25	9.5 x 9.5	0.2	117.9
17	RCA-75	10 x 10	0.5	114.5
18	RCA-100	10 x 9.5	0.9	110.8

5.2.1 Flow Consistency

As discussed in earlier chapters, a fluid CLSM consistency is desired for placement as backfill and/or structural fill. For uniformity, the water content of CLSM mixtures was adjusted during batching to ensure each batch attained approximately the same consistency. The flow consistency test was in accordance with ASTM D 6103: Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM). ASTM D 6103 defines flow consistency for CLSM as the diameter of a patty created following vertical lifting of a flow cylinder containing the fresh CLSM within a specified time. The flow cylinder is a tube that is 6 inches long and a 3 inch inside diameter. The test method is applied to flowable CLSM with a maximum particle size of ¾ inch or less. This procedure is a standard method for measuring fluidity of CLSM mixtures. The target flow consistency is based on the application of the material. Typical flow diameters are 7 to 12 inches (ASTM). For this research the target patty diameter was 9.5 in. to 10.5 in. Figure 5.1 illustrates a patty from the FA-95 mixture.

Figure 5.1 Picture of a flow patty

Because the material must be fluid and the target was to meet a specified flow consistency, water was added or removed from the design mixture during batching. This sometimes resulted in significant variation of the w/cm ratios from those originally targeted.

Expectedly, the finer aggregates demonstrated a higher water demand than the more coarse aggregates due to a higher surface area.

Summaries of the measured flow consistencies are presented in Table 5.2 for the cementitious materials investigation and Table 5.3 for aggregate investigation. The average of the minimum and maximum patty diameter measurements are visually portrayed on Figures 5.2 and Figure 5.3 for comparison. Figure 5.2 represents the results from the cementitious materials investigation, and Figure 5.3 represents results of the aggregate investigation.

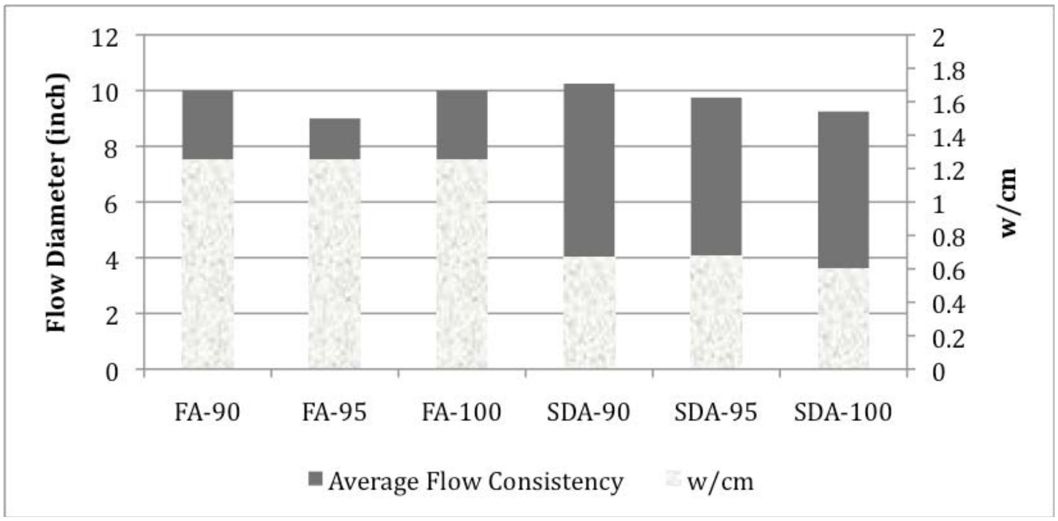


Figure 5.2 Average Cementitious Flow Diameters

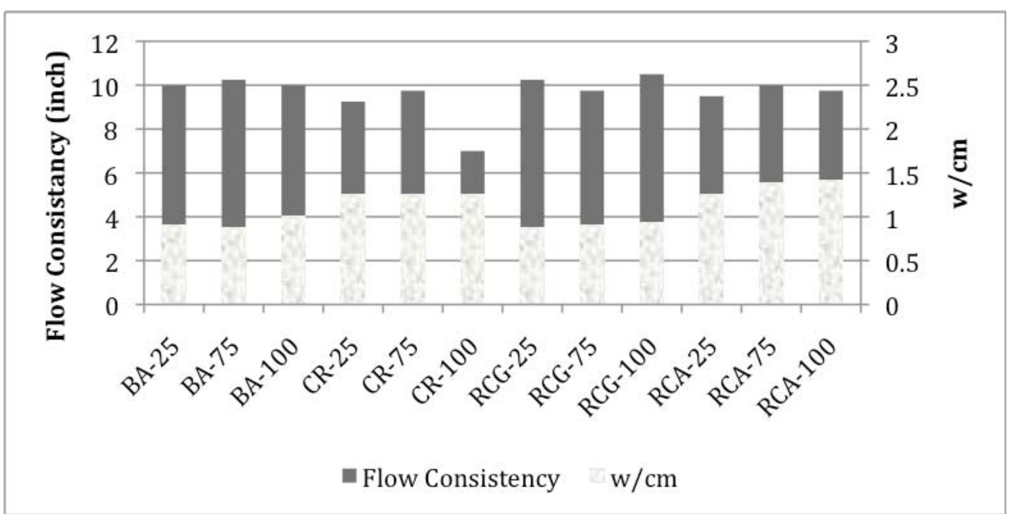


Figure 5.3 Average Aggregate Flow Diameters

All consistency measurements were within the ASTM range of 7 to 12 inches and above the CDOT minimum value of 6 inches. The CR-100 mixture had the least flowable consistency of all mixtures.

Table 5.3 Cementitious Mixtures Average Flow Consistency and w/cm ratio

Mixture Identification		**Average Flow Consistency Diameters (inch)**	**Water to Cementitious Material Ratio (w/cm)**
1	FA-90	10	1.25
2	FA-95	9	1.25
3	FA-100	10	1.25
4	SDA-90	10.25	0.67
5	SDA-95	9.75	0.68
6	SDA-100	9.25	0.6

The mix designs targeted a cementitious content of 630 lb/yd^3, except that 750 lb/yd^3 was targeted for the SDA. Table 5.3 presents the batched cementitious materials content for the mixtures. Adjusting the water or aggregate and cementitious material during batching to achieve constant consistency resulted in batches having varying volumes and consequently varying cementitious materials content and w/cm.

It is expected that strength of CLSM will increase with increasing cementitious material content. The variations in cementitious material content were reasonably minor except for the SDA mixture. Although the cementitious material content varied significantly for SDA, the cementitious material content did not vary significantly within or between other sets. Therefore, comparisons of the effect on CLSM properties of changing cementitious material content is more significant for comparisons involving SDA mixtures than with any other mixtures.

The mixture designs targeted a water to cement ratio of 1.25. However, as seen on Tables 5.3 and 5.4 and Figures 5.2 and 5.3 the batched w/cm ratios for the mixtures varied significantly. It is seen that in order to achieve a consistent flow the w/cm ratio generally decreased, the exceptions being Mixtures 17 and 18. Note that the variation of w/cm within data sets is less than the w/cm between data sets. Consequently, the effect of varying w/cm on measured CLSM properties is more pronounced for comparisons between data sets than for comparisons within data sets.

The water demand was the same for all fly ash mixtures. Likewise, the water demand for the SDA 90 percent and 95 percent replacement mixtures were the same but the water demand for the 100 percent SDA mixture was slightly lower.

The water demand increased as the percentage of aggregate replacement increased for all materials except crumb rubber. Crumb rubber water demand water demand was constant for all mixtures. The water demand increased for the RCA mixtures as the RCA content increased. This is a result of high absorption capacity of the RCA and the greater amount of fines in the mixture. The RCG water demand also increases as the RCG content increases. This is thought to be a result of abortive impurities that are within the RCG. RCG was used "as received" therefore the more used the more likely impurities will be present. BA doesn't show a distinct trend for water demand. BA-100 has the highest water demand, which is a result of BA higher absorption capacity. CR water demand kept constant however, the consistency wasn't as consistent as the other materials. The high water demand caused the CR to float as oppose to disperse within the mixture, causing the flow consistency to be lower than the others.

Table 5.4 Aggregate Mixtures Average Flow Consistency and w/cm ratio

Mixture Identification		Average Flow Consistency Diameter (inch)	Water to Cementitious Material Ratio (w/cm)
7	BA-25	10	0.91
8	BA-75	10	0.88
9	BA-100	10	1
10	CR-25	9.25	1.25
11	CR-75	9.75	1.25
12	CR-100	7	1.25
13	RCG-25	10.25	0.88
14	RCG-75	9.75	0.91
15	RCG-100	10.5	0.94
16	RCA-25	9.5	1.25
17	RCA-75	10	1.38
18	RCA-100	9.75	1.42

5.2.2 Air Content

Air content was not a controlled variable in this research. The air content presumed in all mixture designs was 1 percent. This was a typical value obtained from literature review. Air content was measured in accordance with ASTM C 231 for each fresh batch to determine the value actually attained.

Deviation of the air content from 1 percent resulted in deviation of densities and cementitious content from design values. Higher air contents resulted in a larger batch volume and consequently decreased density and cementitious material content. Air content also likely affected consistency with high air content resulting in a more fluid mixture. However, the data collected was insufficient to discern this relationship.

The cementitious replacements tests, which included mixtures of Class C fly ash or SDA (Mixtures 1-6) with C 33 sand, had the lowest measured air contents. These low air contents may have been caused by longer mixing times for these two mixes. This rationale is also supported by the observation that the crushed concrete (RCA) mixture designs (Mixtures 16, 17 and 18) were mixed for a longer period than other aggregate investigation mixtures and had the lowest air contents.

The air contents varied with the materials used. The BA, RCA and CR mixtures all demonstrated increased air content as their respective masses were increased. The crumb rubber (CR) mixtures showed a large increase in material to air content with increased crumb rubber content. It is speculated that air encapsulated in the rubber during its manufacturing is the prime contributor of air. The RCG mixtures (Mixtures 13, 14, and 15) demonstrate a different trend from the other recycled aggregate replacements, i.e. the air content decreases as the RCG content increases. It is speculated that, unlike the air in pores of sand aggregate, the encapsulated air in crushed glass would not be measured by ASTM C 231 and as a result the air content of the mixtures would decrease as increasingly more sand is replaced with crushed glass.

In practical applications the design air content for CLSM can be either high or low depending on its purpose. Higher air content could allow for lower strengths and ease of future excavation. High-entrained air content may be desirable and achieved with admixtures. Entrained air, and to some extent entrapped air, is expected to increase durability by reducing the effects of freeze/thaw, sulfate attack and alkali-silica reaction. The latter two considerations have significance to the use of SDA and crushed glass because SDA has a high SO_3 content and glass is considered a reactive aggregate subject to alkali-silica reaction. Investigation of the effect of air content on durability is beyond the scope of this research, but a good subject for subsequent research.

5.2.3 Unit Weight

The design theoretical unit weight and batched unit weight are presented for each cementitious investigation mixture on Table 5.5 and aggregate investigation mixture on Table 5.6. The design theoretical unit weights for the mixtures used for cementitious materials investigation were between 117.2 and 128.1 lb/ft^3 (1877 and 2052 kg/m^3) and for the aggregate investigation mixtures were between 78.7 and 130.4 lb/ft^3 (1261 and 2089 kg/m^3). As discussed in Sections 5.2.1 and 5.2.2, air content was not the same as presumed for design; water content was altered during batching to achieve desired CLSM consistency. Furthermore, as will be discussed in section 5.2.4, bleeding resulted in some water loss from the sampled portion of the mixture. Consequently, there are differences between design theoretical unit weights and respective measured unit weights.

The unit weight for each mixture was tested immediately after batching according to ASTM C 138 procedures, and the measurements are presented on Tables 5.6 and Table 5.7. The w/cm ratio was 1.25 by design for the cementitious materials. Both water and air have inherently lower unit weights than the designed CLSM mixtures. Therefore, the presence of either of these two materials in excess of the design quantities would be expected to result in a unit weight lower than that designed. Conversely, the absence of either of these two materials would be expected to result in a unit weight higher than that designed.

The difference between the design theoretical unit weight and the measured unit weight for each mixture is presented on Tables 5.5 or 5.6. The design theoretical unit weights presented in Tables 5.5 and 5.6 were calculated using batched w/cm ratios, however do not account for differences between the 1 percent design air content assumption and the subsequently measured air content. Therefore the differences seen in the design and batched unit weights reflect the effect of the differences between design water and air contents and water lost by bleeding during the sample preparation process. Design theoretical unit weights adjusted for proper air content are discussed and presented in the two paragraphs below.

Differences in mixture theoretical unit weights are most influenced by the specific gravity of the materials used when all other variables are equal. For example, the lowest unit weights were associated with the mixtures 10, 11 and 12 that used crumb rubber for aggregate. Unit weight of SDA mixtures, 4, 5 and 6 were greater than the similar fly ash mixtures 1, 2 and 3 due to the use of a greater cementitious materials content.

Table 5.5 Measured and Calculated Unit Weights and Air Content

Mixture Identification		Measured Air Content (%)	Measured Unit Weight (lb/ft^3)	Theoretical Unit Weight (lb/ft^3)	Difference from Theoretical (lb/ft^3)
1	FA-90	0.1	116.9	116.4	0.5
2	FA-95	0.1	122.3	116.2	6.1
3	FA-100	0.1	120.1	116.1	4
4	SDA-90	0.2	123.9	122.2	1.7
5	SDA-95	0.2	125.5	121.5	4
6	SDA-100	0.2	131.5	127.2	4.3

Table 5.6 Measured and Calculated Unit Weights and Air Content

Mixture Identification		Measured Air Content (%)	Measured Unit Weight (lb/ft^3)	Theoretical Unit Weight (lb/ft^3)	Difference from Theoretical (lb/ft^3)
7	BA-25	0.6	129.3	127.7	1.6
8	BA-75	0.7	124.3	127.6	-3.3
9	BA-100	1.3	119.9	124.1	-4.2
10	CR-25	1.5	107.6	107	0.6
11	CR-75	7.5	77.1	88.1	-11
12	CR-100	8.5	74.5	78.7	-4.2
13	RCG-25	6	125.3	130.4	-5.1
14	RCG-75	5.5	122.3	127.5	-4.2
15	RCG-100	2	122.5	125.5	-3
16	RCA-25	0.2	117.9	115.4	2.5
17	RCA-75	0.5	114.5	111	3.5
18	RCA-100	0.9	110.8	108.1	2.8

Air content plays a role in measured unit weights. In the design process the target air content of 1 percent was not always achieved. At the time of batching the air content was measured as discussed in Section 5.1. These air contents were used to adjust the design theoretical unit weights and these adjusted values are presented in Tables 5.7 and 5.8. There is no discernable pattern to the high and low differences in adjusted theoretical and measured unit weights and the differences were generally low in magnitude. Furthermore, the average difference is -0.6 lb/ft^3. These observations suggest that the batching was performed properly and likely exhibits only routine experimental error.

Table 5.7 Cementitious Measured & Air Adjusted Theoretical Unit Weights

Mixture Identification		Measured Air Content (%)	Measured Unit Weight (lb/ft^3)	Air Adjusted Theoretical Unit Weight (lb/ft^3)	Difference from Air Adjusted Theoretical (lb/ft^3)
1	FA-90	0.1	116.9	117.4	-0.5
2	FA-95	0.1	122.3	117.3	5
3	FA-100	0.1	120.1	117.2	2.9
4	SDA-90	0.2	123.9	123.2	0.7
5	SDA-95	0.2	125.5	122.3	3.2
6	SDA-100	0.2	131.5	128.1	3.4

Table 5.8 Aggregate Measured & Air Adjusted Theoretical Unit Weights

Mixture Identification		Measured Air Content (%)	Measured Unit Weight (lb/ft^3)	Air Adjusted Theoretical Unit Weight (lb/ft^3)	Difference from Adjusted Theoretical (lb/ft^3)
7	BA-25	0.6	129.3	128.2	1.1
8	BA-75	0.7	124.3	127.9	-3.6
9	BA-100	1.3	119.9	123.7	-3.8
10	CR-25	1.5	107.6	106.4	1.2
11	CR-75	7.5	77.1	82.4	-5.3
12	CR-100	8.5	74.5	72.5	2
13	RCG-25	6	125.3	124.4	0.9
14	RCG-75	5.5	123.2	121.7	-1.5
15	RCG-100	2	122.5	124.2	-1.7
16	RCA-25	0.2	117.9	116.3	1.6
17	RCA-75	0.5	114.5	111	3.5
18	RCA-100	0.9	110.8	108	2.8

Several factors may have played in any discrepancies among the unit weights and air content. Some errors may have occurred while performing the test. Improper consolidation or even air content measurement will cause significant difference between measured and theoretical unit weights.

5.2.4 Bleeding and Segregation

Water used for flowability in excess of that needed for hydration is generally absorbed by the surrounding soil or released to the surface as bleed water. For this study the presence of bleed water was noted but not measured. Because CLSM has high water demand, high bleeding and segregation of water and/or aggregate from the mixtures were a concern. All mixtures had some bleeding. The most notable bleeding was observed when mixtures contained bottom ash or crushed glass.

Bleeding was expected because research has been proven that large amounts of bleeding are expected of fly ash because of the spherical shape of the fly ash particles and their delayed settings and fly ash was used in all mixtures except for the SDA mixtures 4, 5 and 6. Furthermore, waste glass has a very smooth surface, low surface area and is generally hydrophobic, which are characteristics that can be expected to be associated with excess bleeding.

Segregation of aggregate was notable when performing consistency tests on crumb rubber mixtures. In these batches the crumb rubber (specific gravity – 1.07) had a slight tendency to float to the top of the patty. The effects of segregation on sample preparations were minimized by continuously mixing the material during sample preparation and no segregation within samples was observed. All other aggregates appeared homogenous during batching.

5.2.5 Set Time

Observations of the material after 24 hours of batching showed that all the mixtures were set. However, SDA was the only material that was tested to determine penetration resistance using a pocket penetrometer. To meet initial load bearing capacity requirements, ASTM C 403 recommends a minimum equivalent strength of 20 lb/in^2 (1.41 kg/cm^2) after three days of curing. The SDA mixtures were tested by the pocket penetrometer 8, 16 and 24 hours after batching. Table 5.9 shows the results from this test regarding only the SDA mixtures. All the mixtures achieved more than 20 lb/in^2 (1.41 kg/cm^2) after 24 hours of testing. Later day strengths are presented in Table 5.12.

Table 5.9 Penetrometer Test for SDA Mixtures

Mixture Identification	8 hours (lb/in^2)	16 hours (lb/in^2)	24 hours (lb/in^2)
4	7	14	35
5	10	21	37
6	7	7	35

5.3 Hardened CLSM Properties

Hardened CLSM testing was performed on all mixtures at 4, 7, 14 and 28 days after batching. The compressive test determined compressive strength and modulus of elasticity. Furthermore, SDA set time was evaluated by penetrometer tests performed at 8, 16 and 24 hours after batching.

5.3.1 Compressive Strength

The compressive strength for all mixtures was tested according to ASTM C 39 procedures at 4, 7, 14, and 28 days after batching. Three 4 inch by 8 inch (101.6 mm by 203.2 mm) cylinders were tested at each of the ages specified. The procedure was performed generally as follows.

On the day of testing, the plastic and wet burlap that covered the specimens during curing was taken off, and the test specimens were removed from their molds. The specimens were air-dried for 4 hours in accordance with ASTM D 4832, and then tested for the compressive strength according to ASTM C 39. ASTM C 39 requires capping test specimens to ensure a level-loading surface and to avoid point loads. This was not done for testing performed in this research because the material was reasonably soft, thereby allowing a smooth surface to be created by gentle block sanding or trimming. The machine used for the compressive strength was a load rate controlled machine that measured load and displacement on very short time intervals, and adjusted the displacement rate as needed to create a constant loading rate. Furthermore, the load control system automatically sensed the failure condition and tested the specimens at an approximately constant displacement rate following specimen failure. The compressive strength is calculated by dividing the ultimate load at failure (lb) by the initial cross-sectional area of the cylinder (in^2). The calculated ultimate strength is then recorded as a pressure (lb/in^2). The specimen compressive strengths are presented in Table 5.12 and Table 5.13.

Some compressive strengths were lower than would typically be used in CLSM applications such as buried pipe backfill. The results of the compressive tests suggest that CLSM mixed with Class C fly ash, spray dryer ash, bottom ash, waste glass, recycled concrete fines, and crumb rubber can achieve sufficient strength to meet CDOT and ASTM CLSM standards. Figure 5.4 shows a photograph of one 4 in diameter by 8 inch (101.6 mm by 203.2 mm) cylindrical specimen being tested by the MTS compression testing machine.

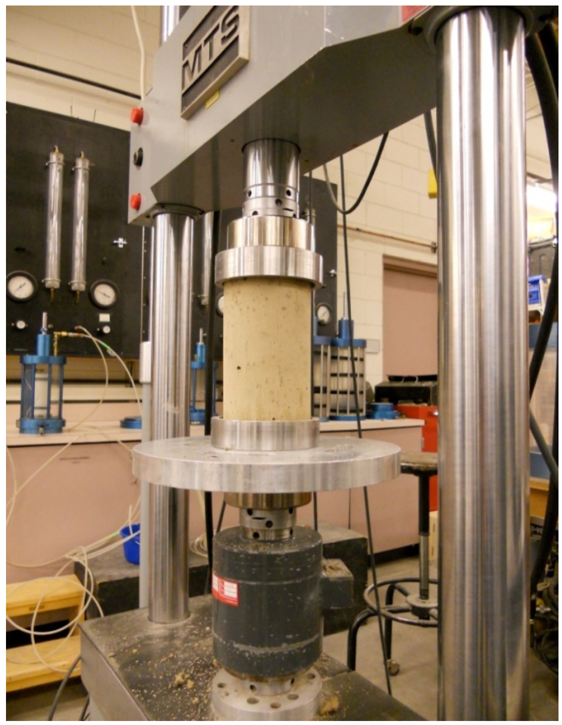


Figure 5.4 Photo of a CLSM in the MTS testing machine

All specimens were tested until the maximum load was achieved and fracturing, similar to that shown in Figure 5.5, was visible. Table 5.12 provides the average compressive strengths of three specimens representing each mixture at each testing age for the cementitious material and aggregate material investigations respectively.

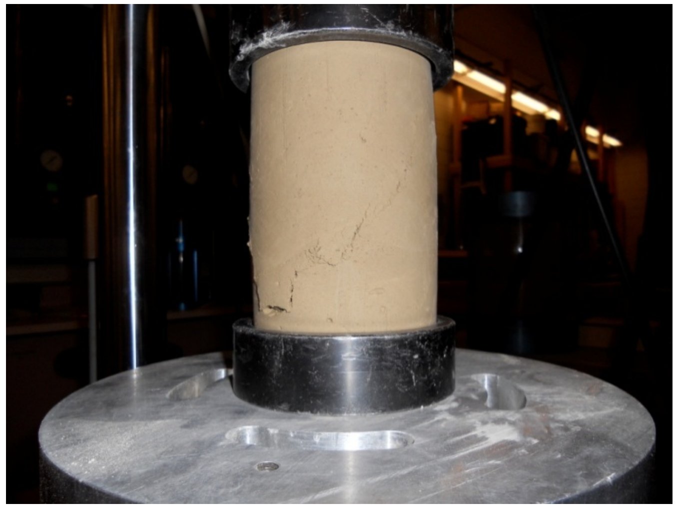


Figure 5.5 Photo of fractured test specimen

Table 5.12 shows that the maximum measured compressive strengths for all three SDA mixtures (Mixtures 4, 5 and 6) and the 100 percent Class C fly ash mixture (Mixture 3) fall within the 30 lb/in^2 and 300 lb/in^{2}range, which ACI presents as common for CLSM mixtures. The exceptions are Mixtures 1 and 2, which contained 10 and 5 percent, portland cement.

Interestingly, Class C fly ash and spray dryer ash have different strength at similar percentage cementitious material replacement despite having other similar physical and chemical characteristics. The results show a trend towards increasing strength with increasing fly ash content and decreasing strength with increasing SDA content. Sulfate attack might be the cause for decrease in strength with increase SDA percentage. The percent sulfate in the SDA is 12.68 percent (Chemical Analysis see Appendix B). Consequently, sulfate attack is more likely to occur as the percent SDA is increased. Internal sulfate attack occurs when a source of sulfate is incorporated into the concrete when mixed (Mindess, 2003). Delayed ettringite formation (DEF) occurs in concrete where hydration has resulted in high temperatures within the concrete (Mindess, 2003). A key contributor to DEF is the curing environment. High curing temperature breaks down the mineral ettringite, which contains sulfate, as well as alluminate (Mindess, 2003). After cooling, the sulfate is again available to form ettringite and this formation is associated with an increase in volume. The expansion results from the formation of macrocyrstalline ettrignite in pore spaces (Mindess, 2003). DEF, is usually limited to cases in which the cement has an SO_3 to Al_2O_3 ratio above 0.5 and the concrete is exposed to significant moisture (Mindess, 2003). DEF is still not fully understood, but it does appear that damage from another cause (e.g. alkalis silica reaction (ASR) or thermal gradients) is a necessary component for DEF to cause harmful expansions (Mindess, 2003). The likelihood of DEF can be reduced by controlling the cement composition, using pozzolands and entrained air, and limiting the maximum curing temperature to 70^0C (158^0F) and, to the extent possible, prevent exposure to moisture (Mindess, 2003). Because the spray dryer ash used with in this research has an SO_3 to Al_2O_3 ratio of 0.833 and is exposed to significant moisture and elevated temperatures during curing, it is possible that DEF is responsible for strengths decreasing with increasing SDA content.

The w/cm ratio represents the most significant factor in determining the strength of cement-based materials. For the cementitious replacement mixtures the w/cm ratio was consistently 1.25 for the fly ash mixtures and between 0.60 and 0.68 for the SDA mixtures. The SDA mixtures are notably stronger than the fly ash mixes, most likely due to the difference in w/cm, but also due in part to an increase in cementitious material content. Additional research is needed to identify and characterize the root cause.

The CDOT equation presented in Chapter 4 as Equation 1 is used to evaluate CLSM removability requirements. CLSM must be sufficiently soft to allow easy excavation. The value calculated is called the removability modulus.

Table 5.10 presents the calculated removability modulus for the cementitious replacement Mixtures 1 through 6. Table 5.11 shows the comparison of the removability modulus for each mixture compared to CDOTs specifications for recycled aggregate replacements. Equation 1 was used to calculate the removability modulus (RM).

Table 5.10 Removability Modulus for Cementitious Replacements (CDOT, 2011)

Mixture Identification		Removability Modulus (RM)	CDOT RM Standards
1	FA-90	0.4	< 1.5
2	FA-95	0.48	< 1.5
3	FA-100	1.5	= 1.5
4	SDA-90	2.58	> 1.5
5	SDA-95	1.19	< 1.5
6	SDA-100	1.06	< 1.5

Note that all but the SDA-90 and FA-100 material do not achieve the removability requirement. FA-100 is on the cusp of acceptable removability. Note however, the large exceedance of the maximum allowable value indicates that SDA-90 is clearly not considered removable by CDOT standard. Note that none of the crushed glass mixtures, two of the RCA mixtures and one of the bottom ash mixtures also did not achieve the CDOT removability requirement.

Table 5.11 Removability Modulus for Recycled Aggregate Replacements (CDOT, 2011)

Mixture Identification		Removability Modulus (RM)	CDOT RM Standards
7	BA-25	3.2	> 1.5
8	BA-75	5.2	> 1.5
9	BA-100	4.6	> 1.5
10	CR-25	1.0	< 1.5
11	CR-75	0.6	< 1.5
12	CR-100	0.7	< 1.5
13	RCG-25	2.7	> 1.5
14	RCG-75	2.9	> 1.5
15	RCG-100	3.4	> 1.5
16	RCA-25	1.8	> 1.5
17	RCA-75	1.5	= 1.5
18	RCA-100	1.2	< 1.5

Individual strength gain curves for each mixture are plotted and shown in Figures 5.6 through 5.12. Each individual mixture is plotted with the control mixture FA-90 for comparison.

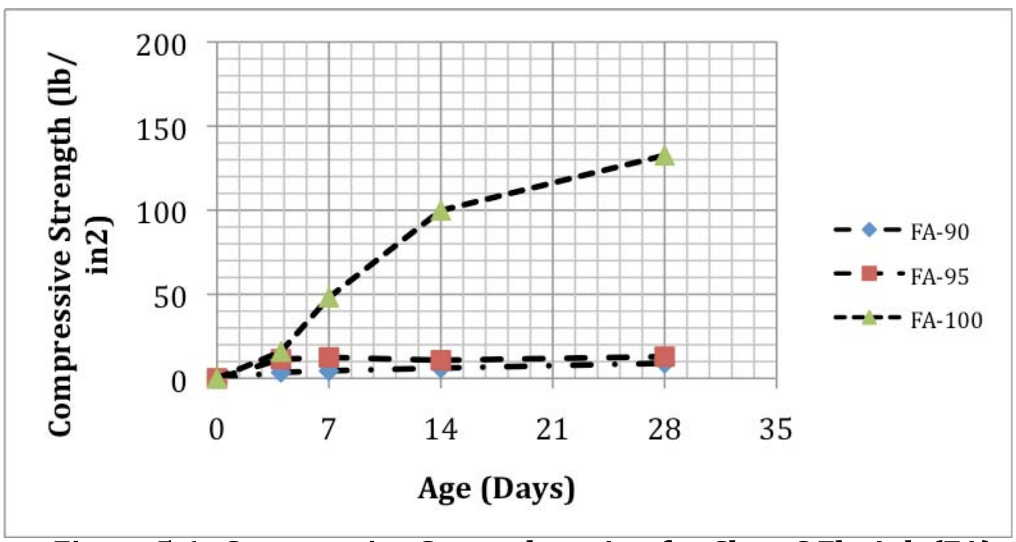


Figure 5.6 Compressive Strength vs. Age for Class C Fly Ash (FA)

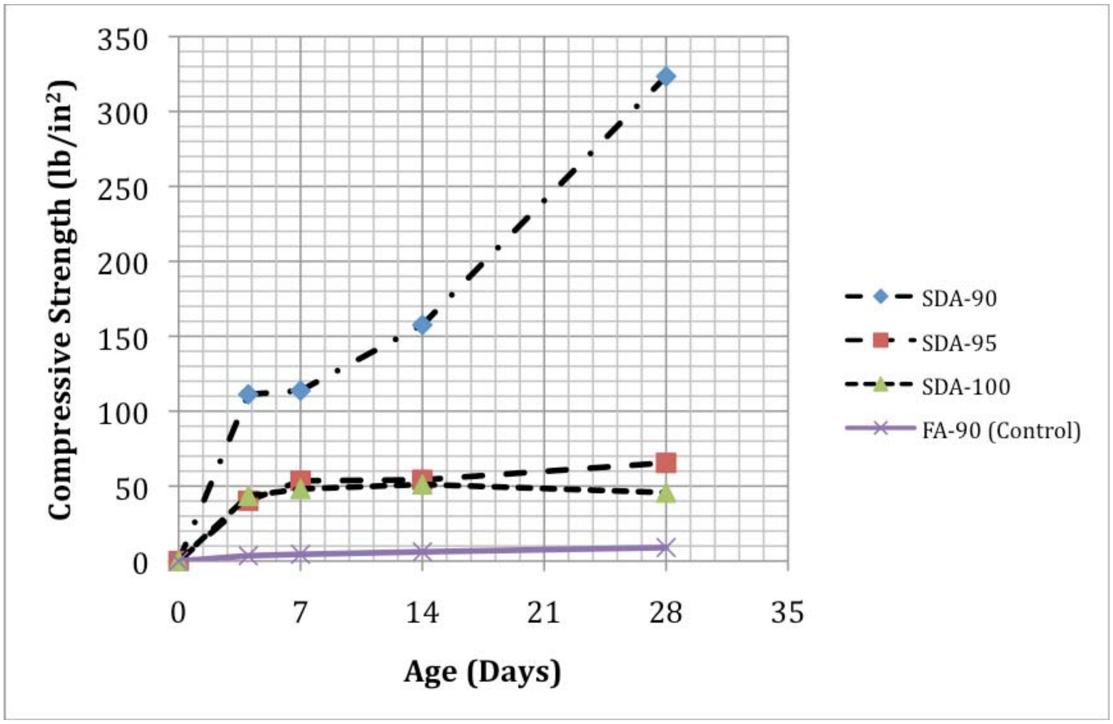


Figure 5.7 Compressive Strength vs. Age for Spray Dryer Ash (SDA)

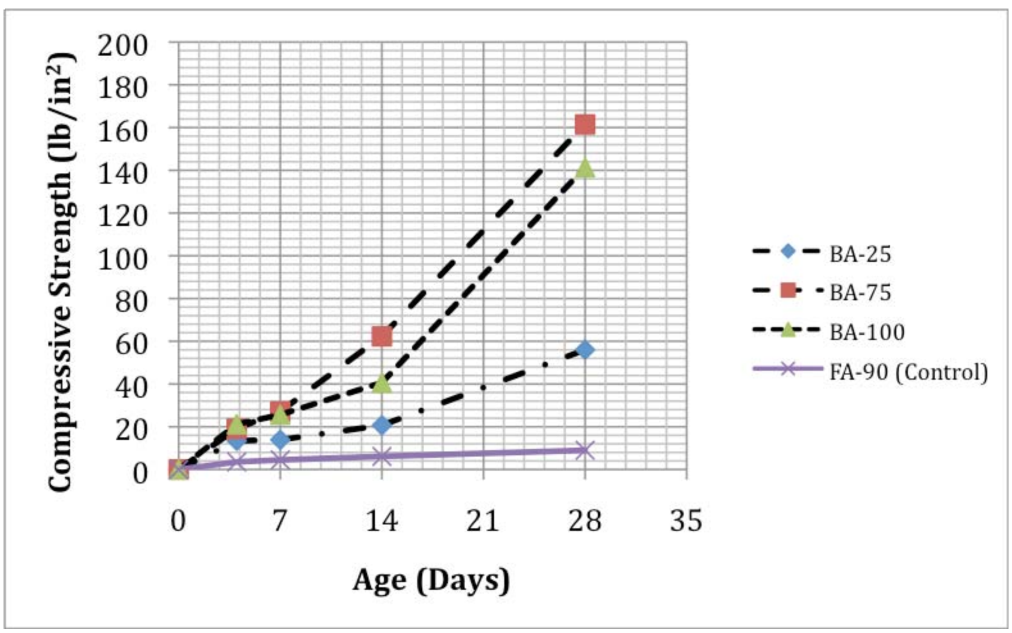


Figure 5.8 Compressive Strength vs. Age of Bottom Ash (BA)

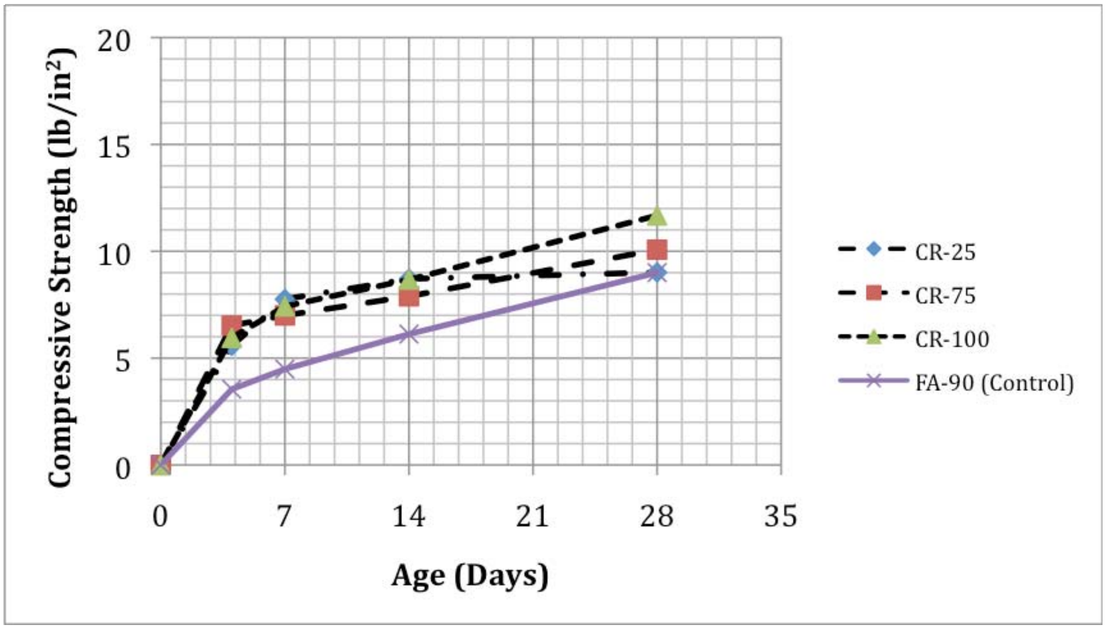


Figure 5. 9 Compressive Strength vs. Age for Crumb Rubber (CR)

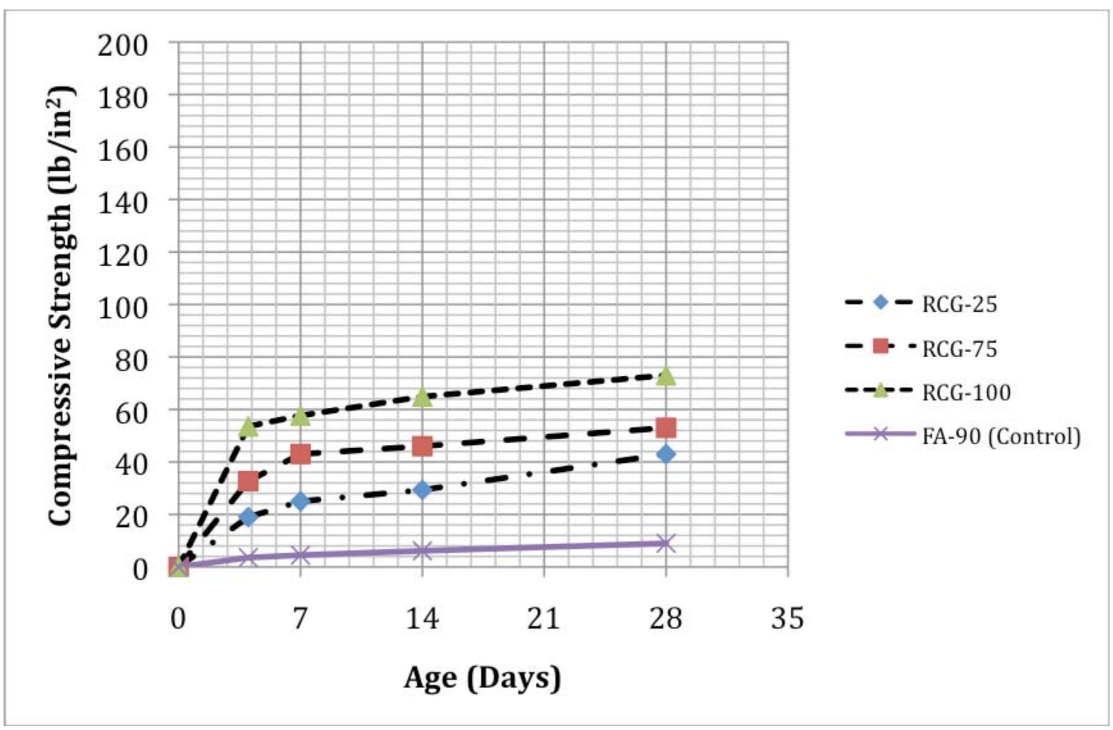


Figure 5.10 Compressive Strength vs. Age of Recycled Crushed Glass (RCG)

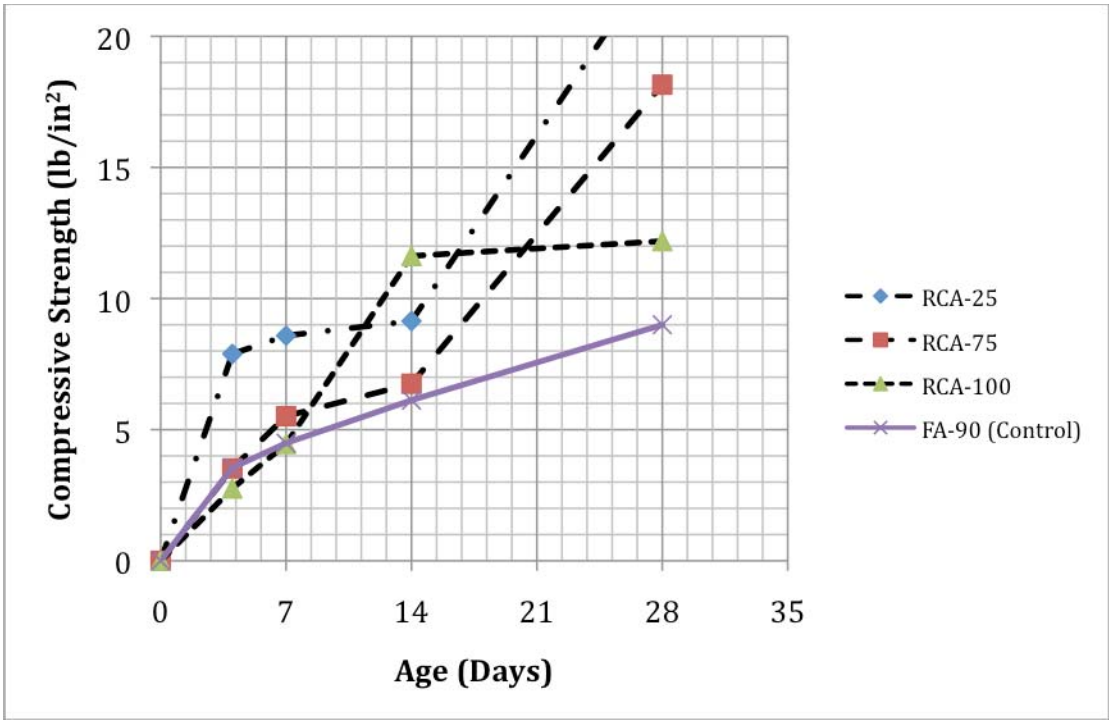


Figure 5.11 Compressive Strength vs. Age for Recycled Concrete Aggregate (RCA)

Table 5.12 shows that the crushed glass and the bottom ash mixture maximum compressive strengths fall within the 52 lb/in² and 141 lb/in² range. However, mixtures containing crumb rubber and crushed concrete had maximum measured compressive strengths less than 20 lb/in². This low strength is attributed to the fact that these tests had w/cm ratios ranging between 1.25 to 1.42, the highest used in testing. It is hypothesized that using higher cement content and a lower w/cm content will result in compressive strengths above 30 lb/in². Such experimentation is left to future research. The average of the three tests specimens are listed in Table 5.12

Table 5.12 Average Compressive Strength of Recycled Materials

Mixture Identification		Average Compressive Strengths (psi)							
		Measured Compressive Strengths (lb/in^2)	**4 day**	Measured Compressive Strengths (lb/in^2)	**7 day**	Measured Compressive Strengths (lb/in^2)	**14 day**	Measured Compressive Strengths (lb/in^2)	**28 day**
1	FA-90	4		5		6		7	
		3	**4**	4	**5**	6	**6**	11	**9**
		4		5		2*		8	
2	FA-95	12		12		12		14	
		10	**11**	11	**11**	13	**13**	14	**13**
		11		11		12		11	
3	FA-100	16		30		84		137	
		26	**21**	37	**48**	97	**100**	130	**133**
		5*		78		118		130	
4	SDA-90	12		98		157		368	
		10	**111**	90	**114**	157	**158**	222	**323**
		11		153		158		257	
5	SDA-95	48		83		71		84	
		33	**40**	40	**54**	36	**54**	58	**66**
		39		37		56		54	
6	SDA-100	39		49		75		48	
		42	**43**	43	**48**	41	**51**	43	**46**
		49		52		36		43	
7	BA-25	10		15		22		54	
		16	**13**	15	**14**	20	**21**	58	**56**
		14		11		20		25*	
8	BA-75	15		24		9		167	
		24	**19**	29	**27**	45	**50**	147	**161**
		18		29		55		171	
9	BA-100	17		22		55		146	
		23	**21**	25	**26**	41	**41**	136	**141**
		24		30		26		77*	
10	CR-25	6		8		9		9	
		5	**6**	7	**8**	8	**9**	10	**9**
		6		3*		9		9	
11	CR-75	6		8		7		10	
		7	**7**	7	**7**	8	**8**	8	**10**
		7		7		8		12	
12	CR-100	6		7		8		13	
		5	**6**	9	**7**	9	**9**	12	**12**
		6		7		9		11	
13	RCG-25	17		20		29		33	
		21	**19**	29	**25**	25	**29**	54	**43**
		19		26		34		43	
14	RCG-75	32		46		46		49	
		33	**33**	42	**43**	40	**44**	54	**53**
		34		41		45		54	
15	RCG-100	60		68		63		79	
		53	**54**	55	**58**	67	**65**	75	**73**
		48		50		10*		66	
16	RCA-25	8		8		10		25	
		8	**8**	9	**9**	9	**9**	22	**23**
		2*		8		8		23	
17	RCA-75	3		6		7		18	
		4	**4**	6	**6**	7	**7**	18	**18**
		3		6		3*		17	
18	RCA-100	3		4		12		13	
		3	**3**	5	**4**	12	**12**	13	**12**
		3		5		10		11	

*Note: strength disregarded due to, unduly low compressive strength caused by unacceptably rapid loading.

The material strength is also influenced by the bond strength between the aggregate, and the cementitious matrix. The aggregates in this study are C 33 sand bottom ash, crumb rubber, crushed glass and crushed concrete. Bond strength was not directly evaluated in this study; rather it was indirectly evaluated, among other things, by changing the percentage of the total aggregate represented by these materials. To this end, the following interpretation of the results of compression tests on the different aggregates is offered.

C 33 sand was the control aggregate and was present in all mixtures except those in which it was entirely replaced by one of the above aggregates. The following observations are made:

- The ultimate compressive strength decreased as the crushed concrete fraction of the aggregate increased. This may be the consequence of the mortar in the crushed concrete being weaker than the C 33 sand; it could be the consequence of poor bonding with friable surfaces of the crushed concrete; or it could be, and likely is, a consequence of the w/cm content increasing from 1.25 to 1.42 in response to water added to achieve consistency requirements.
- The ultimate compressive strength increased as the crushed glass fraction of the aggregate increased. This may be the consequence of angular glass fragments, which likely contained elongated shards, providing a better bond to the concrete and thereby causing the failure plane to preferentially break the glass aggregate rather than slide over the aggregate surface.
- The ultimate compressive strength of the crumb rubber mixtures was very low and a clear trend is indistinguishable.
- The ultimate compressive strength of bottom ash mixtures is highest for 75 percent replacement. This suggests that there may be an optimum

percent replacement for this material. It is unclear why an optimum value would exist. It is believed that it is more likely that the lower compressive strength associated with the 100 percent bottom ash mixture is due to it having a w/cm ratio that is 10 percent higher than the other two bottom ash mixtures. The unit weight is also the lowest of the three mixtures.

5.3.2 Modulus of Elasticity

Axial stress and strain data were acquired during the compressive strength testing of each specimen. The secant modulus was calculated for each test. Mindess states that a practical measure of the modulus of elasticity (MOE) is the secant modulus, which is the slope of the secant between the origin and a point on the stress-strain curve (Mindess, 2003). The secant modulus inherently includes an element of nonlinearity, and clearly its value depends on the value of the level of applied stress chosen (Mindess, 2003). The secant modulus is often used in design since it simplifies the calculation of section properties (Mindess, 2003).

The specimen strain was calculated as the ratio of the axial displacement to the initial specimen length. Stress was calculated as the ratio of the applied axial load to the initial cross-sectional area of the specimen. The stress at 40 percent of the compression strength and the associated strain were determined for all test specimens and the MOE was calculated as the ratio of these values. These results are summarized in Table 5.13. The yield stress and yield strain were also estimated as the point of maximum curvature of the stress-strain plot as it deviates from approximate linearity. These values are presented in Table 5.13.

Note that, other than for all CR, and one RCA specimen, all specimens yielded between 0.6 and 1.5 percent axial strain. Crumb rubber was generally more ductile and generally yielded at greater than 2 percent strain.

The calculated MOE's appear directly proportional to the yield strengths as shown on Figure 5.12. A best-fit line that is forced through the origin is used to approximate each relationship. The slope of each line is a relative yield strain for the conditions represented. Because, for mixtures representing the same materials, a positive relationship exists between MOE and yield strength and yield strength is always very near the compressive strength, variables that influence the compressive strength will likewise influence the MOE and in the same manner. That is, if a previously discussed variable change increases compressive strength for mixture's representing the same materials, then it also increases MOE. The converse is also true. The MOE values are very low relative to values typical of concrete and more like those expected of very stiff or hard clays. This is reasonable to expect, considering CLSM is commonly used as a backfill substitute.

Table 5.13 28-day Compressive Strength, Yield Stress, Yield Strain; Strain at 40 percent Compressive Stress, and MOE

Mixture Identification		Compressive Strength 28-day (lb/in^2)	Stress at $0.4xf'_c$ (lb/in^2)	Corresponding Strain (in/in)	Modulus of Elasticity, MOE ($kips/in^2$)	Yield Stress (lb/in^2)	Yield Strain (in/in)
1	FA-90	9	3.39	0.002	2.15	8	0.006
2	FA-95	13	4.64	0.002	2.92	12	0.010
3	FA-100	133	52.99	0.003	18.59	122	0.009
4	SDA-90	323	112.97	0.006	20.85	219	0.010
5	SDA-95	66	26.17	0.009	10.99	60	0.012
6	SDA-100	46	18.17	0.001	16.68	42	0.007
7	BA-25	56	22.43	0.002	14.75	52	0.007
8	BA-75	161	65	0.008	11.92	153	0.013
9	BA-100	141	57	0.005	10.44	133	0.013
10	CR-25	9	3	0.006	0.64	8	0.046
11	CR-75	10	4	0.004	1.25	9	0.016
12	CR-100	12	5	0.005	0.99	9	0.016
13	RCG-25	43	17	0.005	4.54	41	0.01
14	RCG-75	53	21	0.007	10.02	49	0.009
15	RCG-100	73	30	0.005	4.87	68	0.011
16	RCA-25	23	9	0.003	2.85	22	0.015
17	RCA-75	18	5	0.003	1.93	17	0.014
18	RCA-100	12	4	0.005	0.97	11	0.027

The compressive strengths measured at different times after batching are presented in Figures 5.6 through 5.11 for fly ash, spray dryer ash, crumb rubber, crushed concrete, bottom ash and crushed glass respectively. The information presented in these figures, Table 5.13, and Figure 5.12 are used in the next two sections to explain relationships between the test variables.

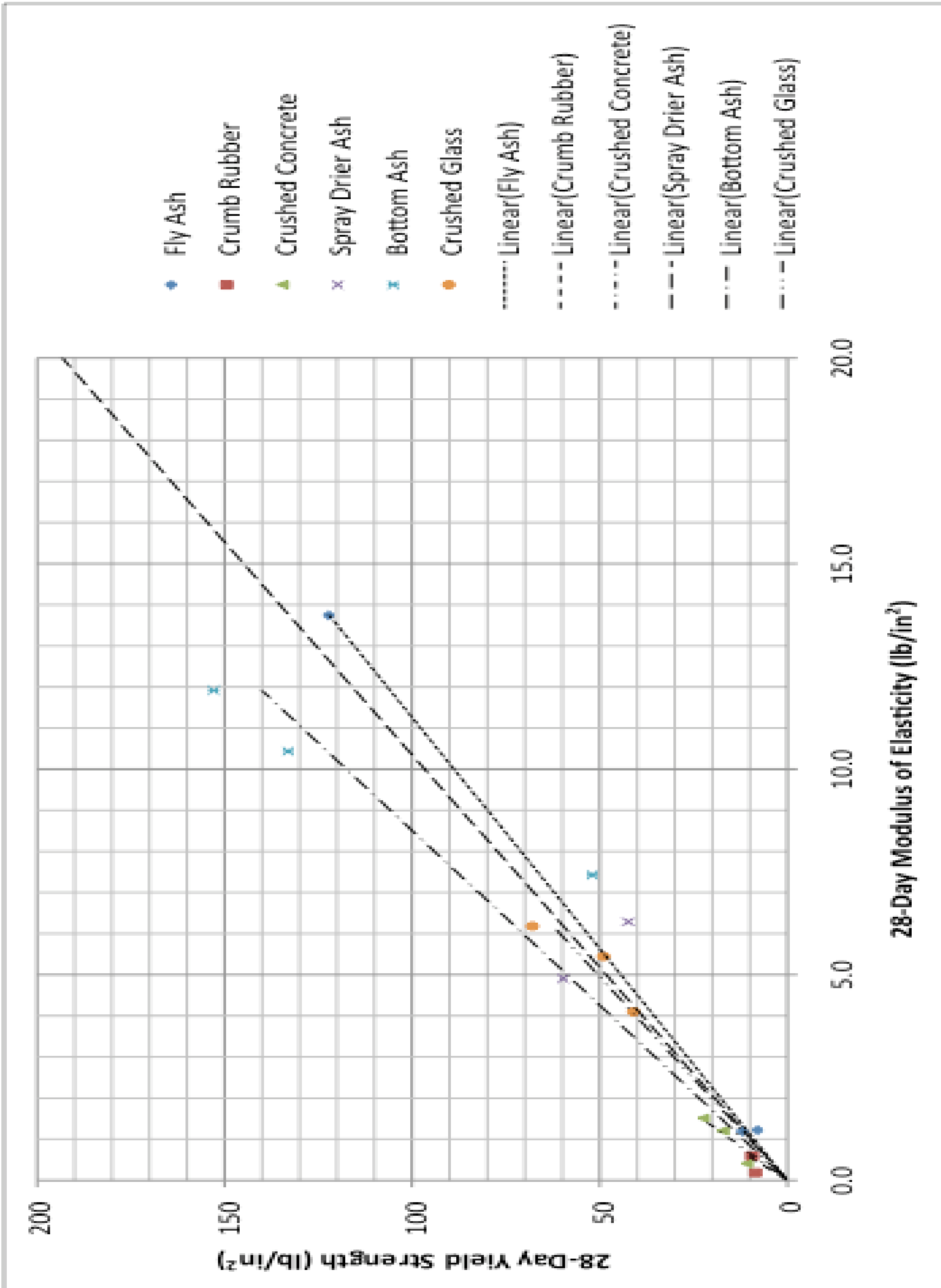


Figure 5.12 28 -Day Yield Strength vs. 28-Day MOE

5.3.2 Relationships Between Hardened Properties and Test Variables

5.3.2.1 Cementitious Materials Investigation

Table 5.13 show that strength and MOE increased with an increase in fly ash content. A much greater increase was realized when increasing the fly ash content from 95 to 100 percent than when increasing the fly ash content from 90 to 95 percent. In contrast, strength and MOE decreased as the SDA content was increased. A direct comparison of FA and SDA strengths is not appropriate because the two mixtures had very different cementitious material contents and w/cm ratios. As previously discussed SDA has a high SO_3 content suggesting a potential for sulfate attack. In other words, because SDA contains approximately 12 percent sulfate, it is speculated that the loss of SDA strength with increasing percent SDA may be due to sulfate attack.

5.3.2.2 Aggregate Investigation

Generally, the water content was varied to accommodate the need for a consistency that would result in a patty equal to approximately 10 inches (254 mm). This resulted in different w/cm ratios for many mixtures. Only the crumb rubber and crushed concrete mixtures were batched with the same w/cm (1.25) as the control sample FA-90. Therefore, these two mixtures will be compared to the control sample.

The water content generally did not vary much between mixtures used to investigate a specific aggregate. The calculated batched w/cm ratios are as follows: 1) BA varied between 0.88 and 1.0; 2) CR was 1.25 for all mixtures; 3) RCG varied between 0.88 and 0.94; 4) RCA varied between 1.25 and 1.42. The cementitious material contents generally varied over a small range for each aggregate. Except for a few situations noted in the next three paragraphs, these small variances in w/cm and cementitious material content did not prevent the development of general relationships relating hardened properties to percentage aggregate replacements.

Mixtures of bottom ash and crushed glass were very similar in density range, cementitious material content, water to cement ratio, and had the same 10/90 cement to fly ash ratio. Only the aggregate replacement ratios varied, therefore a comparison of measured strength and MOE properties for these two mixtures is appropriate. Figures 5.8 and 5.10 present the compressive strength test results for two mixtures and Figure 5.12 shows the relationship between modulus of elasticity and 28-day yield stress for all mixtures. The data is summarized in Table 5.13. The slope of each best-fit line (forced through the origin) on Figure 5.12 is a representation of the relative strain at yield for the respective test material and condition. It is observed on Figures 5.8 and 5.10 that the compressive strengths of both BA and RCG are about the same. It is possible that the BA-100 strength is lower than the BA 75 strength because the w/cm ratios for these mixtures were 1.0 and 0.68 respectively. Otherwise, the data appears to suggest that increased replacement of C 33 sand with RCG or BA results in increased strength. The MOE's for these two materials range from 4.54 to 10.2 kips/in^2 (4,540 to 10,200 lb/in^2) and 8.42 to 14.75 kips/in^2 (8,420 to 14,750 lb/in^2). Both materials yield at approximately the same strain as FA-90, as evidenced by data presented on Figure 5.12 and Table 5.13. All three-replacement ratios for both RCG and BA exhibit 28-day compressive strengths and consistency acceptable for use as CLSM in many common applications.

All crumb rubber mixtures were batched with the same w/cm ratio (1.25) as the control sample FA-90 and also had similar cementitious material contents (580 to 636 lb/yd^3). However, due to the low specific gravity and significant air content, unit weights of the crumb rubber mixtures (74.5 to 107 lb/ft^3) were significantly lower than those for the control sample (116.9 lb/ft^3). Figure 5.9 presents the results of compression tests on CR mixtures and Figure 5.6 presents the results of tests performed on FA. It is evident by comparison that replacing C 33 sand with crumb rubber in the FA-90 control mixture results in compressive strengths that equal or exceeds the control sample strength. It is observed on Figure 5.12 and Table 5.13 that the calculated crumb rubber MOE's are much lower than fly ash MOE's and that the relative strain at yield (slope of line on Figure 5.12) is much greater for the crumb rubber mixtures than for the fly ash mixtures. This is a consequence of crumb rubber being a flexible aggregate. The 28-day strengths (9 to 12 lb/in^2) are too low for most practical CLSM applications. However, it is expected that an acceptable compressive strength might be acquired without sacrificing workability by increasing the cementitious material content and slightly lowering the w/cm ratio. If that does not work, water reducing admixtures or small quantities of silica fume may be used in an attempt to further reduce w/cm or otherwise increase strength.

Crushed concrete mixtures were batched with w/cm ratio's ranging from 1.25 to 1.42 due to high water demand necessary to achieve CLSM consistency. The results of compressive tests on crushed aggregate mixtures are presented in Figure 5.11 and Table 5.13. Mixture RCA-25 was very similar in all aspects to the control sample FA-90 and had a w/cm of 1.25. Compressive strengths for RCA-25 were generally about twice that of the FA-90 mixtures. A single comparison is not sufficient to draw a meaningful conclusion about the strength or MOE effects that result from the replacement of C 33 sand with crushed concrete, but the data does suggest the effects may be moderate at high water content. In general the data suggests that increasing the crushed concrete content decreases the compressive strength. However, the w/cm ratio varied inversely with the compressive strength so it is not possible to determine if the observed decrease in strength is due to an increased crushed concrete content or an increased w/cm ratio. The MOE of crushed concrete is seen on Figure 5.12 and Table 5.13 to be generally less than that of fly ash samples and the relative strain at failure is greater. The large variance in both data sets does not permit a confident inference that replacement of C 33 sand with crushed concrete results in a weaker material. However, the presence of weak particles of mortar and cement paste in the crushed concrete used for aggregate support the possibility that a weaker CLSM with a lower MOE could result.

6. Conclusions and Recommendations

This paper presents the findings of an experimental laboratory investigation that used recycled materials to manufacture CLSM. A study was designed to test the effects of recycled materials, in varying amounts, on the fresh and hardened properties of CLSM. The tests were performed according to ASTM testing standards except as noted in previous discussion. The purpose of this research was to determine whether these recycled materials would have negative or beneficial effects on a CLSM. The materials used and the findings are discussed at length in Chapters 4 and 5 of this report respectively. This chapter presents a brief summary, conclusions and recommendations for future studies.

6.1 Summary

As the construction industry continues to recognize the importance of sustainable development, technologies such as applying CLSM as structural fill have come to the forefront as viable means of safely and efficiently using by-product and waste materials in infrastructure applications.

The results of this research showed that recycled materials can be incorporated into a CLSM mixture in proportions that achieve common minimum and maximum strength and consistency requirements. The use of recycled materials in CLSM has the environmental benefits of using materials most likely to occupy increasingly more valuable landfill space and decreasing greenhouse gas emissions. The use of recycled materials has the economic benefit of using low cost, readily available materials to effect sustainable development. CLSM strength and consistency requirements are dependent on specific project requirements. Herein these properties are compared to common

CLSM properties presented by CDOT and ASTM. The mixtures and associated test results provide a foundation for future designs using similar materials. The program is divided into two investigations: 1) cementitious materials investigation; and 2) aggregate investigation. The key findings of this research are summarized as follows.

Cementitious Materials Investigation:

- Compressive strength increased as the Class C fly ash content increased from 90 to 100 percent of the total cementitious content. All the designs achieved common CLSM mixture consistency. However, the strength of the 100 percent fly ash and 90 percent SDA mixture were too high to be considered excavatable and the 90 percent and 95 percent of fly ash mixtures were too weak to provide structural support needed for most common applications. However, because fly ash often demonstrates latent strength development, it is possible that the lower percentage mixtures will, with time, develop strength commonly sufficient for CLSM applications. The relative strain at yield of fly ash mixes was the lowest measured in this study at less than 1 percent strain. This indicates that the material is very brittle. It had the second highest MOE of all mixtures tested.
- Compressive strength decreased as the amount of SDA increased from 90 to 100 percent. This trend is opposite the trend observed as fly ash replaced portland cement. This trend reversal is possibly due to sulfate attack because SDA contains approximately 12 percent sulfate. Quick set times and rapid strength developments are sometimes advantageous characteristics for CLSM applications. The results of penetrometer tests performed on SDA specimens during the first 24 hours following batching describe the strength development during the time of set. Strengths

measured at 4, 7, 14 and 28 days establish the strength gain following the time of set. Penetrometer determined strengths and 4-day compressive strengths are similar to those presented in literature as acceptable for time-critical applications. All SDA mixes achieved common minimum strength requirements and consistency requirements. The strength of the 90 percent replacement mixture was too high to be considered excavatable. A lower, more acceptable strength would likely be obtained without sacrificing consistency by raising water to cementitious material content and adjusting the cementitious material content. The MOE's of SDA materials were generally the highest measured in this study.

Aggregate Investigation:

- All bottom ash mixtures attained strength and consistency commonly acceptable for CLSM. Strength increased as the aggregate fraction of bottom ash was changed from 25 percent to 75 percent, but decreased as the fraction was changed from 75 to 100 percent. It is unclear if the latter decrease is a consequence of adding more bottom ash to the mixture or due to a concurrent increase in water cement ratio caused by adding water during batching to maintain acceptable consistency. Bottom ash is coarser than the C 33 sand it replaced and consequently mixtures with increased bottom ash content demonstrated a tendency for greater segregation during consistency testing. Although segregation may have had some effect on the uniformity of test specimens the small amount of segregation observed and the use of constant mixing during the sample preparation process leads to the conclusion that segregation probably did not influence specimen representations of the mixtures. The workability of the mixtures was promising and the strength development appears to parallel that of typical CLSM mixtures.

- Crumb rubber aggregate replacement had varying effects. The mixture with 100 percent crumb rubber aggregate was difficult to work with and exhibited segregation during consistency testing. Unit weights were low due to the low specific gravity of crumb rubber. Strengths were approximately the same as measured for similar fly ash mixtures using C 33 sand for aggregate. The MOE for the crumb rubber mixtures were lower than the MOE of all other mixtures used in this research, as expected. This expectation is based on the realization that crumb rubber is the most compressible of all the aggregates studied. Strengths were generally too low for practical application as CLSM. However, it is thought likely that adjustment of the mix design to utilize a lower w/cm ratio and higher cementitious material content will effectuate the necessary increase in strength, reduce segregation, and improve workability. The unique properties of low MOE and light weight may result in crumb rubber mixtures being used in special structural fill applications.
- Waste glass used as a fine aggregate resulted in successful fresh and hardened CLSM properties for all mixtures. The consistency and mixing characteristics of the batches were not unlike C 33 sand, however, the material itself required some preprocessing. The waste glass "as received" was not crushed fine enough to eliminate glass shards. Also, there were bits of debris such as plastic and metal that were removed prior to use. All glass mixtures exhibited acceptable CLSM strength and consistency characteristics. The compressive strength increases as the fraction of glass in the mixtures increased. Strength gain is similar to that of bottom ash mixtures. MOE is similar to the bottom ash and is greater

than that of crushed concrete and crumb rubber. The crushed glass stiffness may be enhanced due to the presence of angular and elongated glass particles crossing prospective shear and fracture planes and that must be broken for the specimens to fail.

- Mixtures containing finely crushed concrete as aggregate demonstrated similar fresh CLSM properties as bottom ash. This material is coarser than C 33 sand and consequently, as the percent crushed concrete increased, slight segregation was noticed. The magnitude of segregation was small and thought inconsequential to sample preparation or use of the material as CLSM. Strengths were too low for the mixtures tested to be considered useful in common CLSM applications. However, it is likely that the low strengths are a consequence of high w/cm ratios. There was a general tendency for strength to decrease as the percent crushed concrete increased. However, the batched w/cm ratio also increased as the crushed concrete percentage was raised. This was a consequence of adding water during batching in order to maintain acceptable CLSM consistency. Therefore, the effect of increasing concrete percentage cannot be distinguished from the effect of changing w/cm.

As the construction industry continues to recognize the importance of sustainable development, technologies such as CLSM have come to the forefront as a viable means of safely and efficiently using industrial by-product and waste materials in infrastructure applications. This research has shown that the use of common recycled and waste materials in CLSM is feasible and produces materials with widely varying strength and modulus values. It was demonstrated that virgin materials such as sand and other quarried aggregates don't need to be used to create CLSM that have acceptable strength and consistency. Class C fly ash and spray dryer ash show significant promise as a replacement for portland cement in CLSM.

Table 6.1 presents a list of the most promising mixtures of the materials for achieving CLSM consistency and strength requirements and are based on tests performed herein.

Table 6.1 Mixtures that achieved CLSM Consistency and Strength

Air Content	Unit Weight (lb/ft3)	Cementitious Material Content (lb/yd3)	Water to Cementitious Material Ratio (w/c)	Percent Cementitious Material by Mass			Percent of Aggregate by Volume					
				Portland Cement	Class C Fly Ash	SDA	C 33 Sand	Bottom Ash	Crumb Rubber	Crushed Glass	Recycled Concrete	Concerns
0.1	117.3	635.7	1.25	<5	>95		100					Latent strength gain
0.2	122.3	999.1	0.60	5		95	100					Deterimintal due to sulfate attack
0.6	128.2	655.4	0.91	10	90		75	25				Segregation, and bleeding
8.5	72.5	>580	<1.2	10	90				100			Segregation and need to offset loss of strength due to high water demand by increasing cementitious material content.
5.5	121.7	578.2	0.91	10	90		25			75		Material cleanup may be required, alkili-silica reaction.
0.9	108	>635	<1.4	10	90						100	Workability, such as segregation.

Further investigation of these materials is needed to better understand relationships between design variables and material properties. Recommendations are presented in the next section.

6.2 Recommendations for Future Studies

The results of this research provide information useful for development of future CLSM studies. The following recommendations are offered.

All design mixes for this research had the same w/cm ratio and cementitious material content. However, water was adjusted during batching to create a mix that had acceptable consistency. This process resulted in significant changes to the water cement ratios and minor changes to the cementitious material contents. An alternative that adds both water and cement in prescribed proportion would result in the w/cm ratio remaining constant and make the cementitious material content the uncontrolled variable. This may be a preferred approach recognizing that w/cm appears to have a greater effect than cementitious material on strength and MOE. However, if large changes in consistency are required, adjusting water and cement content while maintaining the w/c ratio at the time of batching could result in unwieldy batches. Therefore a few small test batches may need to be performed prior to full-scale batching to approximate the w/c and cementitious material content needed to attain desired consistency. The results of tests presented in this thesis may be used to help select appropriate w/c and cementitious material contents for the materials and combinations tested.

Future studies that might attempt to optimize the mix proportions for each material used herein will find value in the presented results. The following should be considered. Optimizing the designs requires that the conditions of minimum and maximum strengths and minimum and maximum consistency be satisfied while minimizing or maximizing a controlled variable such as the cementitious material content. The results of this study may be used as a starting point. Increasing cementitious material or reducing w/c will cause an increase in strength. Conversely, reducing cementitious material or increasing w/c will cause a decrease in strength. Additionally, increasing or decreasing w/c is expected to increase or decrease flowability respectively. Also, the effect of increasing cementitious material content is expected to increase flowability if all other cementitious material proportions, aggregate proportions, and w/c remain equal. This expectation is based on the presumption that a paste consisting of only cementitious material and water would flow more readily than the same paste containing aggregate. The addition of air entraining admixtures may have a beneficial effect of reducing strength whereas the addition of admixtures that accelerate strength gain or increase long-term strength may also be useful.

Latent strength gain is generally not desirable for CLSM since it would either 1) necessitate that the CLSM not have necessary early strength or 2) result in a material that cannot be easily excavated in the long-term. Therefore a study of the long-term effect of latent strength gain needs further investigation.

Other long-term effects that should be investigated are sulfate attack, leaching of potential contaminants, and alkalis-silica reaction. The high SO_3 content in the SDA raises concern about sulfate attack; alkalis-silica reaction might be expected using glass as aggregate; and ashes from coal burning power plants have been associated with arsenic and other potentially toxic contaminants that could leach into groundwater. The understanding of these mechanisms on CLSM properties and practical applications is essential to understanding CLSM usefulness for specific applications.

CLSM used in shallow applications in northern latitudes may be subject to freeze-thaw cycles, which may affect durability. Therefore CLSM freeze-thaw behaviors should be investigated.

Finally, time-of-set and the rate of strength gain are concerns in applications where CLSM must be loaded soon after placement. Set-time was only investigated for SDA mixtures. A simple pocket penetrometer provided repeatable results of penetration resistance that can be used to make measurements necessary to allow comparison of time to set for various mixtures. The pocket pentrometer was easy to use and is recommended as a testing tool for use in future CLSM research.

BIBLIOGRAPHY

ACAA, (2005). Retrieved November 25, 2011, from 2005 Coal Product Production and Use Survey: http://www.acaa-usa.org.

ACAA. (2007). Retrieved October 12, 2011, from Advancing the Management and Use of Coal Combustion Products: http://www.acaa-usa.org.

ACAA. (2008). Retrieved October 12, 2011, from Coal Combustion Products (CCP) Production and Use Survey: http://acaa.affiniscape.com/associations/8003/files/2008_ACAA_CCP_Survey_Report_FINAL_100509.pdf

ACAA. (2011). Retrieved October 10, 2011, from Advancing the Management and Use of Coal Combustion Products: http://www.acaa-usa.org/

Achtemich, Hubbard, Sluce, and Shehata. (2009). *The utilization of recycled concrete aggregate to produce controlled low-strength materials without using Portland cement*. Ontario, Canada: Department of Civil Engineering, Ryerson University: Ryerson University.

ACI. (1999). *ACI Committee Report 229R-99, Controlled Low-Strength Materials*. Detroit: American Concrete Institute.

Adaksa, W. S. (1997). Controlled Low Strength Materials. *Concrete International*. Vol. 19.

ASTM D 4832. (2002). *Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders*. West Conshocken: American Society for Testing Materials

ASTM C 136. (2006). *Standard Analysis of Fine Aggregate and Coarse Aggre*gates. West Conshohocken: American Society for Testing Materials.

ASTM C 702. (2007). *Standard Practice for Reducing Samples of Aggregates to Testing Size*. West Conshohocken: American Society for Testing Materials.

ASTM D 5971. (2011). *Standard Practice for Sampling Freshly Mixed Controlled Low-Strength Material*. West Conshohocken: American Society for Testing Materials.

ASTM D 6023. (2011). *Standard Test Method for Density (Unit Weight). Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low-Strength Material (CLSM)*. West Conshohocken: American Society for Testing Materials.

ASTM D 6024. (2011). *Standard Test Method for Ball Drop on Controlled Low Strength Material (CLSM) to Determine Suitability for Load Application*. West Conshohocken: American Society for Testing Materials.

ASTM D 6103. (1997). *Standard Test Method for Flow Consistency of Controlled Low-Strength Material (CLSM)*. West Conshohocken: American Society for Testing Materials.

Butalia, T.S. (1999). *Evaluation of a dry FGD material as a flowable fill*. Ohio: Ohio State University, Department of Civil and Environmental Engineering.

Butalia, Wolfe, Zand, and Lee. (2004). "Flowable Fill Using Flue Gas Desulfurization Material." *Journal of ASTM International*.

C. Meyer, N.E. (2001). Concrete with Waste Glass as Aggregate. *International Symposium Concrete Technology Unit of ASCE and University of Dundee* (pp. 1-9). Columbia University.

Coloardo Department of Transportation (CDOT). (2011). *Structural Backfill (Controlled Low-Strenght Material)*. Specification No. 206.

Du (2006). "Rapid-Setting CLSM for Bridge Approach Repair: A Case Study." *ACI Materials Journal*, 312-318

Du, Folliard, Trejo (2002). "Effects of Constituent Materials and Quantities on Water Demand and Compressive Strength of Controlled Low-Strength Materials." *ACI Materials Journal*, 485-495.

Du, Folliard, Trejo. (2011). *Sustainable Development Using Controlled Low-Strength Materia*l. Austin: Department of Civil Engineering, University of Texas at Austin.

en.wikipedia.org. (2011). Retrieved August 3, 2011, from Wikipedia, the free Encyclopedia: http://en.enkipedia.org/wiki/Soda-lime_glass

en.wikipedia.org. (2011). Retrieved October 5, 2011, from Wikipedia, the free Encyclopedia: http://en.wikipedia.org/wiki/Kingston_Fossil_Plant_coal_fly_ash_slurry_spill

energy.gov. (2011). Retrieved September 3, 2011, from Energy.Gov: http://energy.gov/public-services/energy-economy

EPA. (2004). "EPA 430-R-04-003, Inventory of U.S. Greenhouse Gas Emissions and Sinks." Washington, DC: *U.S. Environmental Protection Agency.*

EPA. (2007). "Glass." Washington, DC: *U.S. Environmental Protection Agency*.

EPA. (2011). "Coal Combustion Residuals." Washington, DC: *U.S. Environmental Protection Agency.*

Fattuhi, N.I. (1996). "Cement-based materials containing shredded truck tyre rubber." *Construction and Building Materials*. 229-236.

Federal Highway Administration (FHWA). (1995). "Fly ash facts for highway engineers." *FHWA State of Practice National Review*

Federal Highway Administration (FHWA). (2011). "Infrastructure: Fly Ash." *FHWA State of Practice National Review*

Federal Highway Administration (FHWA). (2011). Retrieved October 6, 2011, from Federal Highway Administration. *Utilization of Recycled Materials in Illinois Highway Construction Bottom Ash:* http://www.fhwa.dot.gov/pavement/recycling/recbash.cfm

Federal Highway Administration (FHWA). (2011). Retrieved October 6, 2011, from Federal Highway Administration. *User Guidelines for Waste and Byproduct Materials in Pavement Construction:*

http://www.fhwa.dot.gov/publications/research/infrastructure/structures/97148/cbabs1.cfm

Fedroff, D. (1996). *Mechanical properties of concrete with ground waste tire rubber*. Transportation Research Board: Washington.

Folliard, Du, and Trejo. (2003). "Effects of Curing Conditions on Strength Development of Controlled Low-Strength Material." *ACI Materials Journal*, 80-86.

Funston, J.J. (1984). "Flowable Fly Ash, A New Cement Stabilized Backfill." *Civil Engineering, ASCE*.

Goulias, D.G. (1998). *Evaluation of rubber-filled concrete and correlation between destructive and non-destructive testing results*. Cement, Concrete Aggregate, 140-444.

Hardjito, Chuan, and Tanijaya. (2011). *Controlled Low Strength Materials (CLSM) Utilizing Fly Ash and Bottom Ash.* Indonesia, Surabaya, Department of Civil Engineering Petra Christian University: Petra Christian University.

Humphrey, D.N. (1999). *Civil engineering applications of tire shreds*. Proceeding of the Tire Industry Conference, Clemson University. 3-5 March.

Kardos, A. (2011). *The Beneficial Use of Crumb Rubber in Concrete Mixtures.* Denver: University of Colorado Denver.

Katz, A., Kovler, K. (2003). *Utilization of industrial by-products for the production of controlled low strength materials (CLSM)*. Israel: Department of Civil Engineering, National Building Research Institute.

Kasemchaisiri, and Tangtermsirikul. (2006). "A method to determine water retainability of porous fine aggregate for design and quality control of fresh concrete." *Construction and Building Materials.* 1322-133

Langan, B. W. (1996). *Effect of silica fume and fly ash on heat of hydration of Portland cement*. University of Calgary, Canada, Department of Civil Engineering: University of Calgary.

Larsen, R. L. (1993). “Sound Use of CLSMs in the Environment.” *Concrete International:* Vol. 15, No. 7.

Marland, G. (2003). *Global CO2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2000.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory: http://cdiac.esd.ornl.gov/ftp/ndp030/global00.ems

McCarthy, G.J. (1984). “Mineralogical Characterization of a Lignite Gasification Ash from a Low-BTU Fixed-Bed Gasifier I: X-Ray Phase Analysis.” *Cement and Concrete Research*, 479-484

Mindess, Y.D. (2003). *Concrete* (2nd ed.). (M. Horton, Ed.) Upper Saddle River, New Jersey, United States: Pearson Education, Inc.

Naik, R. T. (1991). *Controlled Low-Strength Materials (CLSM) Produced with High-Lime Fly Ash*. University of Wisconsin-Madison, Department of Civil Engineering. Madison: University of Wisconsin-Madison.

Naik, R.T. (1993). *Fly Ash Generation and Utilization*. University of Wisonsin-Madison, Department of Civil Engineering. Madison: University of Wisconsin-Madison.

Naik, R.T. (2000). *Use of Glass and Fly Ash in Manufacture of Controlled Low-Strength Materials*. University of Wisconsin-Madison, Department of Civil Engineering Madison: University of Wisconsin-Madison.

PCA. (2005). *Design and Control of Concrete Mixtures (14 ed.).* Skokie: Portland Cement Association.

Pierce, C.E. and Blackwell, M.C. (2002). *Potential of scrap tire rubber as lightweight aggregate in flowable fill*. South Carolina, Department of Civil and Environmental Engineering: University of South Carolina.

Ravina, D. (1990). *The Properties of Fresh Concrete and Compressive strength of Concrete with Mineral Admixture-Fly Ash and Blast Furnace Slage*. Technion Haifa, Israel. National Building Research Institute.

Rice, EK. (1997). *Comparing quick-set and regular CLSM thesis*. Ohio: The Ohio State University.

Rubber Manufacturers Association. (2006). Retrieved October 12, 2011, from Rubber Manufacturers Association: *Scrap Tire Markets in the United States*: http://www.rma.org/scraptires

Shayan, A. (2002). *Value-added Utilization of Waste Glass in Concrete*. ARRB Transport Research.

Siddiki, R. (2009). "Utilization of waste materials and by-products in producing controlled low-strength materials." *Resources, Conservation and Recycling*.

Siddiki, Z. N. (2010). "Use of Recycled and Waste Materials in Indiana." *Journal of the Transportation Research Board*, 78-85.

Sunthonpagasit, N. (2002). *Scrap tires of crumb rubber: feasibility analysis for processing facilities.* Washington, Department of Engineering and Applied Science: The George Washington University.

Wu, J and Tsai, M. (2008). "Potential Use of Recycled Rubberized CLSM as Bridge Approach Backfill." *ASCE Journal*

www.cement.org. (2011). Retrieved October 20, 2011, from Portland Cement Association. *Recycled Aggregate*: http://www.cement.org/tech/cct_aggregates_recycled.asp

www.es.anl.gov. (2011). Retrieved September 8, 2011, from Argonne National Laboratory, Energy Systems Division. *Recovery and Recycling of Glass Manufacturing Waste and Fiberglass Scrap:* http://www.es.anl.gov/Energy_systems/Process_Engineering/ Technologies/Documents/8- Glass%20Recycling-2003.pdf.

www.tfhrc.gov. (2011). Retrieved October 4, 2011, from Turner Fairbank Highway Research Center and the Federal Highway Administration. *User Guidelines for Waste and Byproduct Materials in Pavement Construction*: http://www.tfhrc.gov/hnr20/recycle/waste/begin.htm.

APPENDIX A

CLSM Mixture Design: FA-90

CLSM Mixture Design (90% FA & 10% Cement & 100% C 33 Sand)

Batched on 9/21/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	63.0	0.32	0.012
FA	567.1	3.28	0.122
C 33 Sand	1724.8	10.51	0.389
Water	787.6	12.62	0.467
Air	0.010	0.27	0.010
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
FA	2.77	-
C-33 Sand	2.63	0.7

w/c	1.25
Unit Weight (pcf)	116.4
Cementitious material (lb)	630

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
Fly Ash Class C replacement (%)	90	567.06

Moisture Content

sand pan	504	sand +pan wt.		600
		dry wt. sand		556.4
C 33 Sand mc (%)	7.84	mc-ssd		0.07136089

Batch Weights (yd^3)

Cement	63	lb
FA	567	lb
C 33 Sand	1848	lb
Water	664	lb

Batch Weights (ft^3)

Batch size	2.52	cf
Cement	5.9	lb
FA	52.8	lb
C 33 Sand	172.2	lb
Water	61.9	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	8	0.47
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	2.01
	x 1.25	2.52

Fresh concrete tests		
Unit Weight	117	lb/ft^3
Bucket wt.	*7.6*	*lb*
Bucket + mix	*37*	*lb*
Bucket vol.	*0.249*	*ft^3*
Flow Consistency	10in. X 10in.	
Air	0.1	%

CLSM Mixture Design: FA-95

CLSM Mixture Design (95% Class C Fly Ash & 5% Cement & 100% C 33 Sand)

Batched on 9/21/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	31.5	0.16	0.006
Fly Ash Class C	598.6	3.46	0.128
C 33 Sand	1721.2	10.49	0.388
Water	787.6	12.62	0.467
Air	0.010	0.27	0.010
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
Fly Ash Class	2.77	-
C-33 Sand	2.63	0.7

w/c	1.25
Unit Weight (pcf)	116.3
Cementitious material (lb)	630

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
Fly Ash Class C replacement (%)	95	598.56

Moisture Content

sand pan	504	sand +pan wt.		600
		dry wt. sand		556.4
C 33 Sand mc (%)	7.84	mc-ssd		0.07136089

Batch Weights (yd^3)

Cement	32	lb
Fly Ash Class C	599	lb
C 33 Sand	1844	lb
Water	665	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	8	0.47
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	2.01
	x 1.25	2.52

Batch Weights (ft^3)

Batch size	2.52	cf
Cement	2.9	lb
Fly Ash	55.8	lb
C 33 Sand	171.8	lb
Water	61.9	lb

Fresh concrete tests

Unit Weight	122	
Bucket wt.	*7.6*	*lb*
Bucket + mix	*38*	*lb*
Bucket vol.	*0.249*	*cf*
Flow Consistency	9in x 9in	
Air	0.1	%

CLSM Mixture Design: FA-100

CLSM Mixture Design (100% Class C Fly Ash & 0% Cement & 100% C 33 Sand)

Batched on 9/21/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	0.0	0.00	0.000
Fly Ash Class C	630.0	3.64	0.135
C 33 Sand	1717.3	10.46	0.388
Water	787.7	12.62	0.468
Air	0.010	0.27	0.010
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
Fly Ash Class	2.77	-
C-33 Sand	2.63	0.7

w/c	1.25
Unit Weight (pcf)	116.1
Cementitious material (lb)	630

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
Fly Ash Class C replacement (%)	100	630.06

Moisture Content

sand pan	504	sand +pan wt.	600
		dry wt. sand	556.4
C 33 Sand mc (%)	7.84	mc-ssd	0.07136089

Batch Weights (yd^3)

Cement	0	lb
Fly Ash Class C	630	lb
C 33 Sand	1840	lb
Water	665	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	8	0.47
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	2.01
	x 1.25	2.52

Batch Weights (ft^3)

Batch size	2.52	cf
Cement	0.0	lb
Fly Ash	58.7	lb
C 33 Sand	171.4	lb
Water	62.0	lb

Fresh concrete tests

Unit Weight	120	
Bucket wt.	*7.6*	*lb*
Bucket + mix	*38*	*lb*
Bucket vol.	*0.249*	*cf*
Flow Consistency	10in x 10in	
Air	0.1	%

CLSM Mixture Design: SDA-90

CLSM Mixture Design (90%SDA & 10% Cement & 100% C 33 Sand)

Batched on 10/11/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	99.8	0.51	0.019
SDA	897.8	5.60	0.207
C 33 Sand	1637.4	9.98	0.370
Water	664.5	10.65	0.394
Air	0.010	0.27	0.010
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
SDA	2.57	-
C-33 Sand	2.63	0.7

w/c	0.67
Unit Weight (pcf)	116.4
Cementitious material (lb)	998

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
SDA replacement (%)	90	897.88

Moisture Content

sand pan	366.4	sand +pan wt.	461.2
		dry wt. sand	458.2
C 33 sand mc (%)	3.27	mc-ssd	0.02567974

Batch Weights (yd^3)

Cement	100	lb
SDA	898	lb
C 33 Sand	1679	lb
Water	622	lb

Batch Weights (ft^3)

Batch size	2.52	cf
Cement	9.3	lb
SDA	83.7	lb
C 33 Sand	156.5	lb
Water	58.0	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	8	0.47
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	2.01
	x 1.25	2.52

Fresh concrete tests

Unit Weight	124	lb/ft^3
Bucket wt.	*7.6*	*lb*
Bucket + mix	*38*	*lb*
Bucket vol.	*0.249*	*ft^3*
Flow Consistency	10.5in. X 10in.	
Air	0.2	%

CLSM Mixture Design: SDA-95

CLSM Mixture Design (95% SDA & 5% Cement & 100% C 33 Sand)

Batched on 10/11/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	47.7	0.24	0.009
SDA	939.5	5.86	0.217
C 33 Sand	1610.0	9.81	0.363
Water	666.9	10.69	0.396
Air	0.010	0.40	0.015
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
SDA	2.57	-
C-33 Sand	2.63	0.7

w/c	0.68
Unit Weight (pcf)	120.9
Cementitious material (lb)	987

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
SDA replacement (%)	95	937.86

Moisture Content

sand pan	366.4	sand +pan wt.	475.5
		dry wt. sand	468.2
C 33 Sand mc (%)	7.17	mc-ssd	0.06470923

Batch Weights (yd^3)

Cement	48	lb
SDA	940	lb
C 33 Sand	1714	lb
Water	563	lb

Batch Weights (ft^3)

Batch size	2.52	cf
Cement	4.4	lb
SDA	87.5	lb
C 33 Sand	159.7	lb
Water	52.4	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	8	0.47
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	2.01
	x 1.25	2.52

Fresh concrete tests		
Unit Weight	126	lb/ft^3
Bucket wt.	*7.6*	*lb*
Bucket + mix	*39*	*lb*
Bucket vol.	*0.249*	*ft^3*
Flow Consistency	9.5in. X 10in.	
Air	0.2	%

CLSM Mixture Design: SDA-100

CLSM Mixture Design (100% SDA & 0% Cement & 100% C 33 Sand)

Batched on 10/11/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	0.0	0.00	0.000
SDA	952.4	5.94	0.220
C 33 Sand	1909.5	11.64	0.431
Water	571.4	9.16	0.339
Air	0.010	0.27	0.010
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
SDA	2.57	-
C-33 Sand	2.63	0.7

w/c	0.60
Unit Weight (pcf)	127.2
Cementitious material (lb)	952

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
SDA replacement (%)	100	952.38

Moisture Content

sand pan	366.4	sand +pan wt.	475.5
		dry wt. sand	468.2
C 33 Sand mc (%)	7.17	mc-ssd	0.06470923

Batch Weights (yd^3)

Cement	0	lb
SDA	952	lb
C 33 Sand	2033	lb
Water	448	lb

Batch Weights (ft^3)

Batch size	2.52	cf
Cement	0.0	lb
SDA	88.7	lb
C 33 Sand	189.4	lb
Water	41.7	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	8	0.47
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	2.01
	x 1.25	2.52

Fresh concrete tests

Unit Weight	132	lb/ft^3
Bucket wt.	*7.6*	*lb*
Bucket + mix	*40*	*lb*
Bucket vol.	*0.249*	*ft^3*
Flow Consistency	8.5in. X 10in.	
Air	0.2	%

CLSM Mixture Design: BA-25

CLSM Mixture Design (90% Class C Fly Ash, 10% Cement, 25% Bottom Ash & 75% C 33 Sand)

Batched on 10/10/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	66.7	0.34	0.013
Fly Ash Class C	588.7	3.41	0.126
BA	544.4	3.39	0.126
C 33 Sand	1668.2	10.17	0.376
Water	594.9	9.53	0.353
Air	0.0	0.16	0.006
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
Fly Ash Class	2.77	-
BA	2.60	7.08
C 33 Sand	2.63	0.7

w/c	0.91
Unit Weight (pcf)	128.3
Cementitious material (lb)	655

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
Fly Ash Class C replacement (%)	90	567

Aggregate Replacement	Percent (%) by Volume (cf)	Weight (lb)
BA replacement (%)	25	177.09

Moisture Content

sand pan	395.5	sand +pan wt.	967.7
recycled material pan	295.7	RM + pan wt.	1017.4
		dry wt. sand	967.2
		RM wt. rock	1015.7

C 33 Sand mc (%)	5.00	mc-ssd	0.0477
BA mc (%)	4.92	mc-ssd	-0.0216

Batch Weights (yd^3)

Cement	67	lb
Fly Ash Class C	567	lb
Bottom Ash	533	lb
C 33 Sand	1748	lb
Water	527	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	0	0.00
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	1.55
	x 1.25	1.93

Batch Weights (ft^3)

Batch size	1.93	cf
Cement	4.8	lb
Fly Ash	40.6	lb
BA	38.2	lb
SC 33 Sand	125.2	lb
Water	37.8	lb

Fresh concrete tests		
Unit Weight	129	lb/ft^3
Bucket wt.	*7.6*	*lb*
Bucket + mix	*40*	*lb*
Bucket vol.	*0.249*	*ft^3*
Flow Consistency	10.5in. X 9.5in.	
Air	0.6	%

CLSM Mixture Design: BA-75

CLSM Mixture Design (90% Class C Fly Ash, 10% Cement, 75% BA & 25% C 33 Sand)

Batched on 10/16/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	66.2	0.34	0.012
Fly Ash Class C	596.1	3.45	0.128
BA	1648.0	10.28	0.381
C 33 Sand	562.3	3.43	0.127
Water	581.7	9.32	0.345
Air	0.0	0.19	0.007
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
Fly Ash Class	2.77	-
BA	2.60	7.08
C 33 Sand	2.63	0.7

w/c	0.88
Unit Weight (pcf)	127.9
Cementitious material (lb)	662

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
Fly Ash Class C replacement (%)	90	567

Aggregate Replacement		Percent (%) by Volume (cf)	Weight (lb)
BA replacement (%)		75	177.09

Moisture Content

sand pan	395.5	sand +pan wt.		967.7
recycled material pan	295.7	RM + pan wt.		1017.4
		dry wt. sand		967.2
		RM wt. rock		1015.7

C 33 Sand mc (%)	5.00	mc-ssd		0.0477
BA mc (%)	4.92	mc-ssd		-0.0216

Batch Weights (yd^3)

Cement	66	lb
Fly Ash Class C	567	lb
BA	1612	lb
Sand	589	lb
Water	590	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	0	0.00
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	1.55
	x 1.25	1.93

Batch Weights (ft^3)

Batch size	1.93	cf
Cement	4.7	lb
Fly Ash	40.6	lb
BA	115.5	lb
C 33 Sand	42.2	lb
Water	42.3	lb

Fresh concrete tests		
Unit Weight	124	lb/ft^3
Bucket wt.	7.6	*lb*
Bucket + mix	39	*lb*
Bucket vol.	0.249	*ft^3*
Flow Consistency	10in. X 10.5in.	
Air	0.7	%

CLSM Mixture Design: BA-100

CLSM Mixture Design (90% Class C Fly Ash, 10% Cement, 100% BA & 0% C 33 Sand)

Batched on 10/16/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	62.8	0.32	0.012
Fly Ash Class C	565.3	3.27	0.121
BA	2083.8	12.99	0.481
C 33 Sand	0.1	0.00	0.000
Water	628.1	10.07	0.373
Air	0.0	0.35	0.013
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
Fly Ash Class	2.77	-
BA	2.60	7.08
C 33 Sand	2.63	0.7

w/c	1.00
Unit Weight (pcf)	123.7
Cementitious material (lb)	628.1

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
Fly Ash Class C replacement (%)	90	567

Aggregate Replacement		Percent (%) by Volume (cf)	Weight (lb)
BA replacement (%)		100	177.09

Moisture Content

C 33 Sand pan	395.5	sand +pan wt.		967.7
recycled material pan	295.7	RM + pan wt.		1017.4
		dry wt. sand		967.2
		RM wt. rock		1015.7

C 33 Sand mc (%)	5.00	mc-ssd		0.0477
BA mc (%)	4.92	mc-ssd		-0.0216

Batch Weights (yd^3)

Cement	63	lb
Fly Ash Class C	567	lb
BA	2039	lb
C 33 Sand	0	lb
Water	673	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	0	0.00
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	1.55
	x 1.25	1.93

Batch Weights (ft^3)

Batch size	1.93	cf
Cement	4.5	lb
Fly Ash	40.6	lb
BA	146.0	lb
C 33 Sand	0.0	lb
Water	48.2	lb

Fresh concrete tests		
Unit Weight	120	lb/ft^3
Bucket wt.	*7.6*	*lb*
Bucket + mix	*37*	*lb*
Bucket vol.	*0.249*	*ft^3*
Flow Consistency	10in. X 10in.	
Air	1.3	%

CLSM Mixture Design: CR-25

CLSM Mixture Design (90% Class C Fly Ash, 10% Cement, 25% CR & 75% C 33 Sand)

Batched on 9/23/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	63.0	0.32	1.190
Fly Ash Class C	567.0	3.28	12.175
CR	177.1	2.63	9.753
C 33 Sand	1293.4	7.88	29.250
Water	787.5	12.62	46.838
Air	0.01	0.27	99.205
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
Fly Ash Class C	2.77	-
CR	1.08	0
C 33 Sand	2.63	0.7

w/c	1.25
Unit Weight (pcf)	106.4
Cementitious material (lb)	626.9

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
Fly Ash Class C replacement (%)	90	567

Aggregate Replacement		Percent (%) by Volume (cf)	Weight (lb)
CR replacement (%)		25.00	177.09

Moisture Content

sand pan	395.5	C 33 Sand +pan wt.		967.7
		dry wt. C 33 Sand		967.2
C 33 Sand mc (%)	5.47	mc-ssd		0.0477

Batch Weights (yd^3)

Cement	63	lb
Fly Ash Class C	567	lb
CR	177	lb
C 33 Sand	1355	lb
Water	726	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	0	0.00
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	1.55
	x 1.25	1.93

Batch Weights (ft^3)

Batch size	1.93	cf
Cement	4.5	lb
Fly Ash	40.6	lb
CR	12.7	lb
C 33 Sand	97.1	lb
Water	52.0	lb

Fresh concrete tests		
Unit Weight	108	lb/ft^3
Bucket wt.	*7.6*	*lb*
Bucket + mix	*34*	*lb*
Bucket vol.	*0.249*	*ft^3*
Flow Consistency	8.5in. X 10in.	
Air	1.5	%

CLSM Mixture Design: CR-75

CLSM Mixture Design (90% Class C Fly Ash, 10% Cement, 75% Crumb Rubber & 25% C 33 Sand)

Batched on 9/23/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	63.0	0.32	1.189
Fly Ash Class C	566.6	3.28	12.166
CR	530.8	7.88	29.232
C 33 Sand	430.9	2.63	9.745
Water	787.0	12.61	46.807
Air	0.01	0.29	99.138
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
Fly Ash Class	2.77	-
CR	1.08	0
C 33 Sand	2.63	0.7

w/c	1.25
Unit Weight (pcf)	82.4
Cementitious material (lb)	589

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
Fly Ash Class C replacement (%)	90	567

Aggregate Replacement	Percent (%) by Volume (cf)	Weight (lb)
CR replacement (%)	75	177.09

Moisture Content

sand pan	395.5	C 33 Sand +pan wt.		967.7
		dry wt. C 33 Sand		967.2
C 33 Sand mc (%)	5.47	mc-ssd		0.0477

Batch Weights (yd^3)

Cement	63	lb
Fly Ash Class C	567	lb
CR	531	lb
C 33 Sand	451	lb
Water	766	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	0	0.00
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	1.55
	x 1.25	1.93

Batch Weights (ft^3)

Batch size	1.93	cf
Cement	4.5	lb
Fly Ash	40.6	lb
CR	38.0	lb
C 33 Sand	32.3	lb
Water	54.9	lb

Fresh concrete tests		
Unit Weight	77	lb/ft^3
Bucket wt.	7.6	*lb*
Bucket + mix	27	*lb*
Bucket vol.	0.249	ft^3
Flow Consistency	9.5in. X 10in.	
Air	7.5	%

CLSM Mixture Design: CR-100

CLSM Mixture Design (90% Class C Fly Ash, 10% Cement, 100% CR & 0% C 33 Sand)

Batched on 9/23/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	62.9	0.32	1.188
Fly Ash Class C	566.3	3.28	12.160
CR	707.3	10.50	38.954
C 33 Sand	0.0	0.00	0.000
Water	786.5	12.60	46.781
Air	0.01	0.30	99.082
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
Fly Ash Class C	2.77	-
CR	1.08	0
C 33 Sand	2.63	0.7

w/c	1.25
Unit Weight (pcf)	72.5
Cementitious material (lb)	589

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
Fly Ash Class C replacement (%)	90	567

Aggregate Replacement		Percent (%) by Volume (cf)	Weight (lb)
CR replacement (%)		100.00	177.09

Moisture Content

sand pan	395.5	C 33 Sand +pan wt.		967.7
		dry wt. C 33 Sand		967.2
C 33 Sand mc (%)	5.47	mc-ssd		0.0477

Batch Weights (yd^3)

Cement	63	lb
Fly Ash Class C	567	lb
CR	707	lb
C 33 Sand	0	lb
Water	787	lb

Batch Weights (ft^3)

Batch size	1.93	cf
Cement	4.5	lb
Fly Ash	40.6	lb
CR	50.7	lb
C 33 Sand	0.0	lb
Water	56.3	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	0	0.00
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	1.55
	x 1.25	1.93

Fresh concrete tests		
Unit Weight	74	lb/ft^3
Bucket wt.	*7.6*	*lb*
Bucket + mix	*25*	*lb*
Bucket vol.	*0.249*	*ft^3*
Flow Consistency	6.5in. X 7.5in.	
Air	8.5	%

CLSM Mixture Design: RCG-25

CLSM Mixture Design (90% Class C Fly Ash, 10% Cement, 25% RCG & 75% C 33 Sand)

Batched on 10/10/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	61.3	0.31	1.190
Fly Ash Class C	551.5	3.19	12.175
RCG	570.9	3.66	13.965
C 33 Sand	1802.0	10.98	41.899
Water	536.4	8.60	32.800
Air	0.01	0.26	102.028
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
Fly Ash Class C	2.77	-
RCG	2.50	0.02
C 33 Sand	2.63	0.7

w/c	0.88
Unit Weight (pcf)	124.4
Cementitious material (lb)	584

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
Fly Ash Class C replacement (%)	90	567

Aggregate Replacement	Percent (%) by Volume (cf)	Weight (lb)
RCG replacement (%)	75	177.09

Moisture Content

sand pan	395.5	C 33 Sand +pan wt.	967.7
		dry wt. C 33 Sand	967.2

C 33 Sand mc (%)	5.00	mc-ssd	0.043
RCG (%)	1.63	mc-ssd	0.0161

Batch Weights (yd³)

Cement	61	lb
Fly Ash Class C	567	lb
RCG	580	lb
C 33 Sand	1879	lb
Water	450	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	0	0.00
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	1.55
	x 1.25	1.93

Batch Weights (ft³)

Batch size	1.93	cf
Cement	4.4	lb
Fly Ash	40.6	lb
RCG	41.6	lb
C 33 Sand	134.6	lb
Water	32.2	lb

Fresh concrete tests		
Unit Weight	125	lb/ft³
Bucket wt.	*7.6*	*lb*
Bucket + mix	*39*	*lb*
Bucket vol.	*0.249*	*ft³*
Flow Consistency	10in. X 10.5in.	
Air	6	%

CLSM Mixture Design: RCG-75

CLSM Mixture Design (90% Class C Fly Ash, 10% Cement, 75% RCG & 25% C 33 Sand)

Batched on 10/10/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	60.5	0.31	1.175
Fly Ash Class C	544.9	3.15	12.029
RCG	1692.2	10.85	41.393
C 33 Sand	593.6	3.62	13.801
Water	548.7	8.79	33.555
Air	0.01	0.28	101.953
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
Fly Ash Class	2.77	-
RCG	2.50	0.02
C 33 Sand	2.63	0.7

w/c	0.91
Unit Weight (pcf)	121.7
Cementitious material (lb)	578

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
Fly Ash Class C replacement (%)	90	567

Aggregate Replacement	Percent (%) by Volume (cf)	Weight (lb)
RCG replacement (%)	75	177.09

Moisture Content

sand pan	395.5	C 33 Sand +pan wt.		967.7
		dry wt. C 33 Sand		967.2
C 33 Sand mc (%)	5.00	mc-ssd		0.043
RCG (%)	1.63	mc-ssd		0.0161

Batch Weights (yd^3)

Cement	61	lb
Fly Ash Class C	567	lb
RCG	1719	lb
C 33 Sand	619	lb
Water	496	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	0	0.00
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	1.55
	x 1.25	1.93

Batch Weights (ft^3)

Batch size	1.93	cf
Cement	4.3	lb
Fly Ash	40.6	lb
RCG	123.2	lb
C 33 Sand	44.3	lb
Water	35.5	lb

Fresh concrete tests		
Unit Weight	122	lb/ft^3
Bucket wt.	7.6	*lb*
Bucket + mix	38	*lb*
Bucket vol.	0.249	ft^3
Flow Consistency	10in. X 9.5in.	
Air	5.5	%

CLSM Mixture Design: RCG-100

CLSM Mixture Design (90% Class C Fly Ash, 10% Cement, 100% RCG & 0% C 33 Sand)

Batched on 10/10/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	59.7	0.30	1.160
Fly Ash Class C	537.7	3.11	11.870
RCG	2226.7	14.27	54.467
C 33 Sand	0.0	0.00	0.001
Water	564.0	9.04	34.489
Air	0.01	0.27	101.987
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
Fly Ash Class	2.77	-
RCG	2.50	0.02
C 33 Sand	2.63	0.7

w/c	0.94
Unit Weight (pcf)	124.2
Cementitious material (lb)	591

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
Fly Ash Class C replacement (%)	90	567

Aggregate Replacement	Percent (%) by Volume (cf)	Weight (lb)
RCG replacement (%)	100	177.09

Moisture Content

sand pan	395.5	C 33 Sand +pan wt.		967.7
		dry wt. C 33 Sand		967.2
C 33 Sand mc (%)	5.00	mc-ssd		0.043
RCG (%)	1.63	mc-ssd		0.0161

Batch Weights (yd^3)

Cement	60	lb
Fly Ash Class C	567	lb
RCG	2227	lb
C 33 Sand	0	lb
Water	564	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	0	0.00
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	1.55
	x 1.25	1.93

Batch Weights (ft^3)

Batch size	1.93	cf
Cement	4.3	lb
Fly Ash	40.6	lb
RCG	159.5	lb
C 33 Sand	0.0	lb
Water	40.4	lb

Fresh concrete tests		
Unit Weight	122	lb/ft^3
Bucket wt.	*7.6*	*lb*
Bucket + mix	*38*	*lb*
Bucket vol.	*0.249*	*ft^3*
Flow Consistency	10.5in. X10.5in.	
Air	2	%

CLSM Mixture Design: RCA-25

CLSM Mixture Design (90% Class C Fly Ash, 10% Cement, 25% RCA & 75% C 33 Sand)

Batched on 9/26/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	64.3	0.33	1.221
Fly Ash Class C	578.6	3.35	12.498
RCA	349.7	2.14	7.987
C 33 Sand	1319.8	8.04	30.028
Water	803.5	12.88	48.084
Air	0.01	0.27	99.818
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
Fly Ash Class	2.77	-
RCA	2.62	9.7
C 33 Sand	2.63	0.7

w/c	1.25
Unit Weight (pcf)	116.3
Cementitious material (lb)	648

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
Fly Ash Class C replacement (%)	90	567

Aggregate Replacement	Percent (%) by Volume (cf)	Weight (lb)
RCA replacement (%)	25	177.09

Moisture Content

sand pan	395.5	C 33 Sand +pan wt.		967.7
		dry wt. C 33 Sand		967.2
C 33 Sand mc (%)	5.47	mc-ssd		0.0477
RCA mc (%)	7.83			0.0783

Batch Weights (yd^3)

Cement	64	lb
Fly Ash Class C	567	lb
RCA	377	lb
C 33 Sand	1383	lb
Water	741	lb

Batch Weights (ft^3)

Batch size	1.93	cf
Cement	4.6	lb
Fly Ash	40.6	lb
RCA	27.0	lb
C 33 Sand	99.0	lb
Water	53.0	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	0	0.00
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	1.55
	x 1.25	1.93

Fresh concrete tests		
Unit Weight	118	lb/ft^3
Bucket wt.	*7.6*	*lb*
Bucket + mix	*37*	*lb*
Bucket vol.	*0.249*	*ft^3*
Flow Consistency	9.5in. X 9.5in.	
Air	0.2	%

CLSM Mixture Design: RCA-75

CLSM Mixture Design (90% Class C Fly Ash, 10% Cement, 75% RCA & 25% C 33 Sand)

Batched on 9/27/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	64.1	0.33	1.217
Fly Ash Class C	576.8	3.34	12.460
RCA	1102.2	6.74	25.174
C 33 Sand	367.4	2.24	8.360
Water	887.4	14.22	53.102
Air	0.01	0.13	100.314
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
Fly Ash Class	2.77	-
RCA	2.62	9.7
C 33 Sand	2.63	0.7

w/c	1.38
Unit Weight (pcf)	111.0
Cementitious material (lb)	641

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
Fly Ash Class C replacement (%)	90	567

Aggregate Replacement	Percent (%) by Volume (cf)	Weight (lb)
RCA replacement (%)	75	177.09

Moisture Content

sand pan	395.5	C 33 Sand +pan wt.		967.7
		dry wt. C 33 Sand		967.2

C 33 Sand mc (%)	5.47	mc-ssd		0.0477
RCA mc (%)	7.83			0.0783

Batch Weights (yd^3)

Cement	64	lb
Fly Ash Class C	567	lb
RCA	1189	lb
C 33 Sand	385	lb
Water	870	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	0	0.00
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	1.55
	x 1.25	1.93

Batch Weights (ft^3)

Batch size	1.93	cf
Cement	4.6	lb
Fly Ash	40.6	lb
RCA	85.1	lb
C 33 Sand	27.6	lb
Water	62.3	lb

Fresh concrete tests		
Unit Weight	114	lb/ft^3
Bucket wt.	7.6	*lb*
Bucket + mix	36	*lb*
Bucket vol.	0.249	ft^3
Flow Consistency	10in. X 10in.	
Air	0.5	%

CLSM Mixture Design: RCA-100

CLSM Mixture Design (90% Class C Fly Ash, 10% Cement, 100% RCA & 0% C 33 Sand)

Batched on 9/27/2011

Mix Proportion (SSD)

Material	Weight	Volume (cf)	Volume Check
Cement	63.5	0.32	1.206
Fly Ash Class C	571.5	3.31	12.347
RCA	1381.4	8.45	31.551
C 33 Sand	0.0	0.00	0.001
Water	901.9	14.45	53.972
Air	0.01	0.47	99.078
		27.00	1.00

Material Properties

Material	S.G.	A.C
Cement	3.15	-
Fly Ash Class	2.77	-
RCA	2.62	9.7
C 33 Sand	2.63	0.7

w/c	1.42
Unit Weight (pcf)	108.1
Cementitious material (lb)	635

Suppl. Cementitious Mat.	Percent (%)	Weight (lb)
Fly Ash Class C replacement (%)	90	567

Aggregate Replacement	Percent (%) by Volume (cf)	Weight (lb)
RCA replacement (%)	100	177.09

Moisture Content

sand pan	395.5	C 33 Sand +pan wt.		967.7
		dry wt. C 33 Sand		967.2

C 33 Sand mc (%)	5.47	mc-ssd		0.0477
RCA mc (%)	7.83			0.0783

Batch Weights (yd^3)

Cement	64	lb
Fly Ash Class C	567	lb
RCA	1490	lb
C 33 Sand	0	lb
Water	902	lb

Testing Specimens Required

Compressive cylinders	18	1.05
RCIP cylinders	0	0.00
MOR	0	0.00
Unit weight	2	0.50
Permeameter slabs	0	0.00
Salt Ponding	0	0.00
MOE	0	0.00
F/T Beams	0	0.00
Split Cylinder	0	0.00
	Total	1.55
	x 1.25	1.93

Batch Weights (ft^3)

Batch size	1.93	cf
Cement	4.5	lb
Fly Ash	40.6	lb
RCA	106.7	lb
C 33 Sand	0.0	lb
Water	64.6	lb

Fresh concrete tests		
Unit Weight	114	lb/ft^3
Bucket wt.	*7.6*	*lb*
Bucket + mix	*36*	*lb*
Bucket vol.	*0.249*	ft^3
Flow Consistency	10in. X 10in.	
Air	0.5	%

APPENDIX B

Specific Gravity and Absorption Capacity of RCG Test #1 (10/07/2011)			
Wt. of Pycnometer and Water	PW =	1228.7	grams
Wt. of SSD Sample	S ssd =	510.4	grams
Wt. of Pyncometer, Water, and Sample	PWS =	1535	grams
Wt. of Bowl	B =	162.3	grams
Wt. Bowl and Dry Sample	BS dry =	672.8	grams
Wt. of Dry Sample	S dry =	510.5	grams
Results:			
Bulk Specific Gravity (Dry)	BSG dry=	2.50	
Bulk Specific Gravity (SSD)	BSG ssd=	2.50	
Absolute Specific Gravity	ASG =	2.50	
Absorption Capacity	AC =	-0.02	%

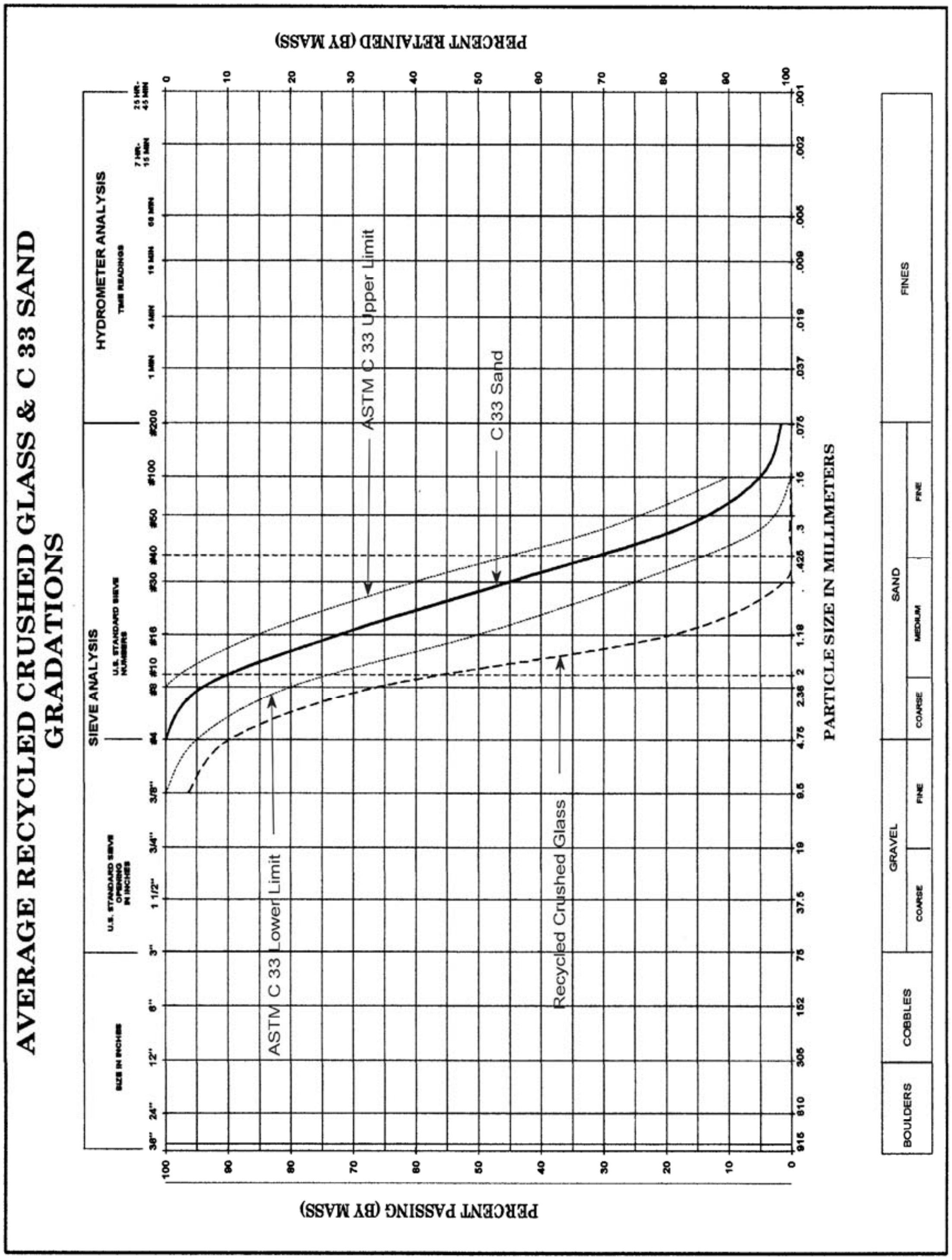
Specific Gravity and Absorption Capacity of RCA #1 (9/25/2011)			
Wt. of Pycnometer and Water	PW =	1228.7	grams
Wt. of SSD Sample	S ssd =	500	grams
Wt. of Pyncometer, Water, and Sample	PWS =	1510.7	grams
Wt. of Bowl	B =	230	grams
Wt. Bowl and Dry Sample	BS dry =	685.8	grams
Wt. of Dry Sample	S dry =	455.8	grams
Results:			
Bulk Specific Gravity (Dry)	BSG dry=	2.09	
Bulk Specific Gravity (SSD)	BSG ssd=	2.29	
Absolute Specific Gravity	ASG =	2.62	
Absorption Capacity	AC =	9.70	%
Moisture Content	MC =	7.83	%

Specific Gravity and Absorption Capacity of BA #1 (10/07/2011)			
Wt. of Pycnometer and Water	PW =	1228.4	grams
Wt. of SSD Sample	S ssd =	508.4	grams
Wt. of Pyncometer, Water, and Sample	PWS =	1520.8	grams
Wt. of Bowl	B =	230	grams
Wt. Bowl and Dry Sample	BS dry =	704.8	grams
Wt. of Dry Sample	S dry =	474.8	grams
Results:			
Bulk Specific Gravity (Dry)	BSG dry=	2.20	
Bulk Specific Gravity (SSD)	BSG ssd=	2.35	
Absolute Specific Gravity	ASG =	2.60	
Absorption Capacity	AC =	7.08	%

Waste Glass Aggregate Gradation #1 (9/28/2011)									
Sieve Size	**Sieve Size**	**Sieve Weight**	**Sieve & Sample Weight**	**Sample Weight**	**ASTM Maximum Allowable**	**Cumml. Sample Weight**	**Percent Retained**	**Cumml. Percent Retained**	**Percent Passing**
(Std)	*(mm)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(%)*	*(%)*	*(%)*
3/8"	9.50	547.40	637.10	89.70	670	89.70	5.40	5.40	94.60
#4	4.75	511.00	630.70	119.70	330	209.40	7.20	12.60	87.40
#8	2.36	493.70	861.00	367.30	200	576.70	22.10	34.69	65.31
#16	1.18	424.70	1217.00	792.30	200	1369.00	47.67	82.36	17.64
#30	0.60	395.60	673.90	278.30	200	1647.30	16.74	99.10	0.90
#50	0.30	371.20	382.10	10.90	200	1658.20	0.66	99.76	0.24
#100	0.15	347.40	350.60	3.20	200	1661.40	0.19	99.95	0.05
#200	0.08	334.50	335.20	0.70	-	1662.10	0.04	99.99	0.01
Pan	0.00	367.10	367.20	0.10	-	1662.20	0.01	100.00	0.00
Original Weight			Wo =	1666	grams				
Final Weight			Wf =	1662	grams				
Percent Loss			% Loss =	0.23	%				
Fineness Modulus			FM =	4.34	in.				

Waste Glass Aggregate Gradation #2 (9/28/2011)									
Sieve Size	**Sieve Size**	**Sieve Weight**	**Sieve & Sample Weight**	**Sample Weight**	**ASTM Maximum Allowable**	**Cumml. Sample Weight**	**Percent Retained**	**Cumml. Percent Retained**	**Percent Passing**
(Std)	*(mm)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(%)*	*(%)*	*(%)*
3/8"	9.50	547.40	577.60	30.20	670	30.20	1.85	1.85	98.15
#4	4.75	511.00	617.70	106.70	330	136.90	6.53	8.38	91.62
#8	2.36	493.70	791.70	298.00	200	434.90	18.24	26.61	73.39
#16	1.18	424.70	1266.70	842.00	200	1276.90	51.52	78.14	21.86
#30	0.60	395.60	726.90	331.30	200	1608.20	20.27	98.41	1.59
#50	0.30	371.20	388.90	17.70	200	1625.90	1.08	99.49	0.51
#100	0.15	347.40	354.60	7.20	200	1633.10	0.44	99.93	0.07
#200	0.08	334.50	335.50	1.00	-	1634.10	0.06	99.99	0.01
Pan	0.00	367.10	367.20	0.10	-	1634.20	0.01	100.00	0.00
Original Weight			Wo =	1624	grams				
Final Weight			Wf =	1634	grams				
Percent Loss			% Loss =	0.60	%				
Fineness Modulus			FM =	4.13	in.				

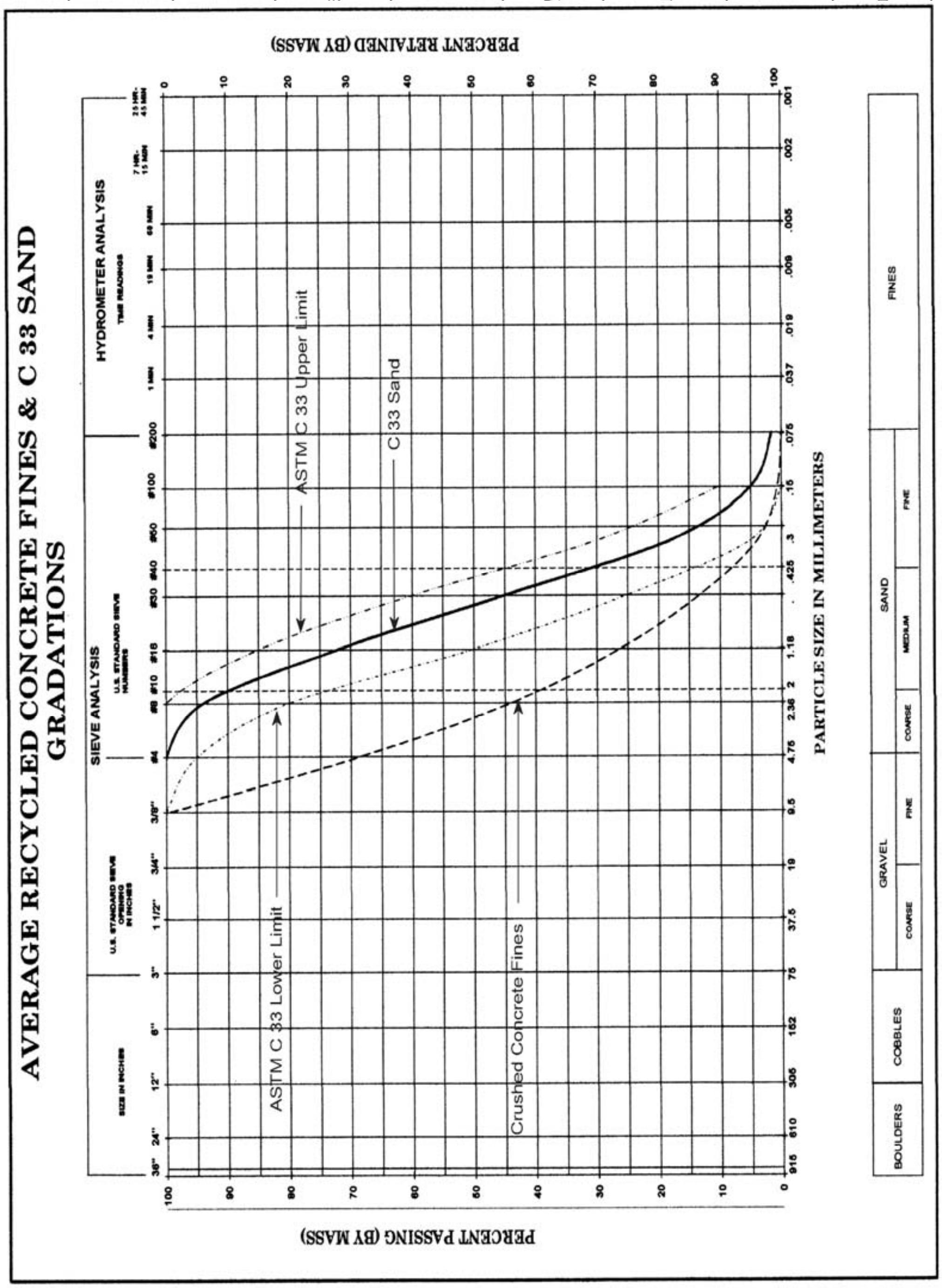
Waste Glass Aggregate Gradation #3 (9/28/2011)									
Sieve Size	Sieve Size	Sieve Weight	Sieve & Sample Weight	Sample Weight	ASTM Maximum Allowable	Cumml. Sample Weight	Percent Retained	Cumml. Percent Retained	Percent Passing
(Std)	*(mm)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(%)*	*(%)*	*(%)*
3/8"	9.50	547.40	608.30	60.90	670	60.90	3.65	3.65	96.35
#4	4.75	511.00	611.90	100.90	330	161.80	6.04	9.69	90.31
#8	2.36	493.70	1006.90	513.20	200	675.00	30.73	40.42	59.58
#16	1.18	424.70	1134.30	709.60	200	1384.60	42.49	82.91	17.09
#30	0.60	395.60	659.50	263.90	200	1648.50	15.80	98.71	1.29
#50	0.30	371.20	387.30	16.10	200	1664.60	0.96	99.68	0.32
#100	0.15	347.40	351.90	4.50	200	1669.10	0.27	99.95	0.05
#200	0.08	334.50	335.30	0.80	-	1669.90	0.05	99.99	0.01
Pan	0.00	367.10	367.20	0.10	-	1670.00	0.01	####	0.00
Original Weight			Wo =	1668.7	grams				
Final Weight			Wf =	1670	grams				
Percent Loss			% Loss =	0.08	%				
Fineness Modulus			FM =	4.35	in.				


AVERAGE RECYCLED CRUSHED GLASS & C 33 SAND GRADATIONS
SIEVE ANALYSIS
HYDROMETER ANALYSIS
ASTM C 33 Upper Limit
C 33 Sand
ASTM C 33 Lower Limit
Recycled Crushed Glass
PERCENT RETAINED (BY MASS)
PERCENT PASSING (BY MASS)
PARTICLE SIZE IN MILLIMETERS
BOULDERS
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
FINES

Recylcled Concrete Fines Aggregate Gradation #1 (9/28/2011)									
Sieve Size	**Sieve Size**	**Sieve Weight**	**Sieve & Sample Weight**	**Sample Weight**	**ASTM Maximum Allowable**	**Cumml. Sample Weight**	**Percent Retained**	**Cumml. Percent Retained**	**Percent Passing**
(Std)	*(mm)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(%)*	*(%)*	*(%)*
3/8"	9.50	547.40	558.40	11.00	670	11.00	0.68	0.68	99.32
#4	4.75	511.00	970.80	459.80	330	470.80	28.48	29.17	70.83
#8	2.36	493.70	879.90	386.20	200	857.00	23.93	53.09	46.91
#16	1.18	424.70	718.80	294.10	200	1151.10	18.22	71.31	28.69
#30	0.60	395.60	608.00	212.40	200	1363.50	13.16	84.47	15.53
#50	0.30	371.20	512.70	141.50	200	1505.00	8.77	93.24	6.76
#100	0.15	347.40	432.90	85.50	200	1590.50	5.30	98.53	1.47
#200	0.08	334.50	355.50	21.00	200	1611.50	1.30	99.83	0.17
Pan	0.00	367.10	369.80	2.70	-	1614.20	0.17	100.00	0.00
Original Weight			Wo =	1613.30	grams				
Final Weight			Wf =	1614.20	grams				
Percent Loss			% Loss =	0.00	%				
Fineness Modulus			FM =	4.30	in.				

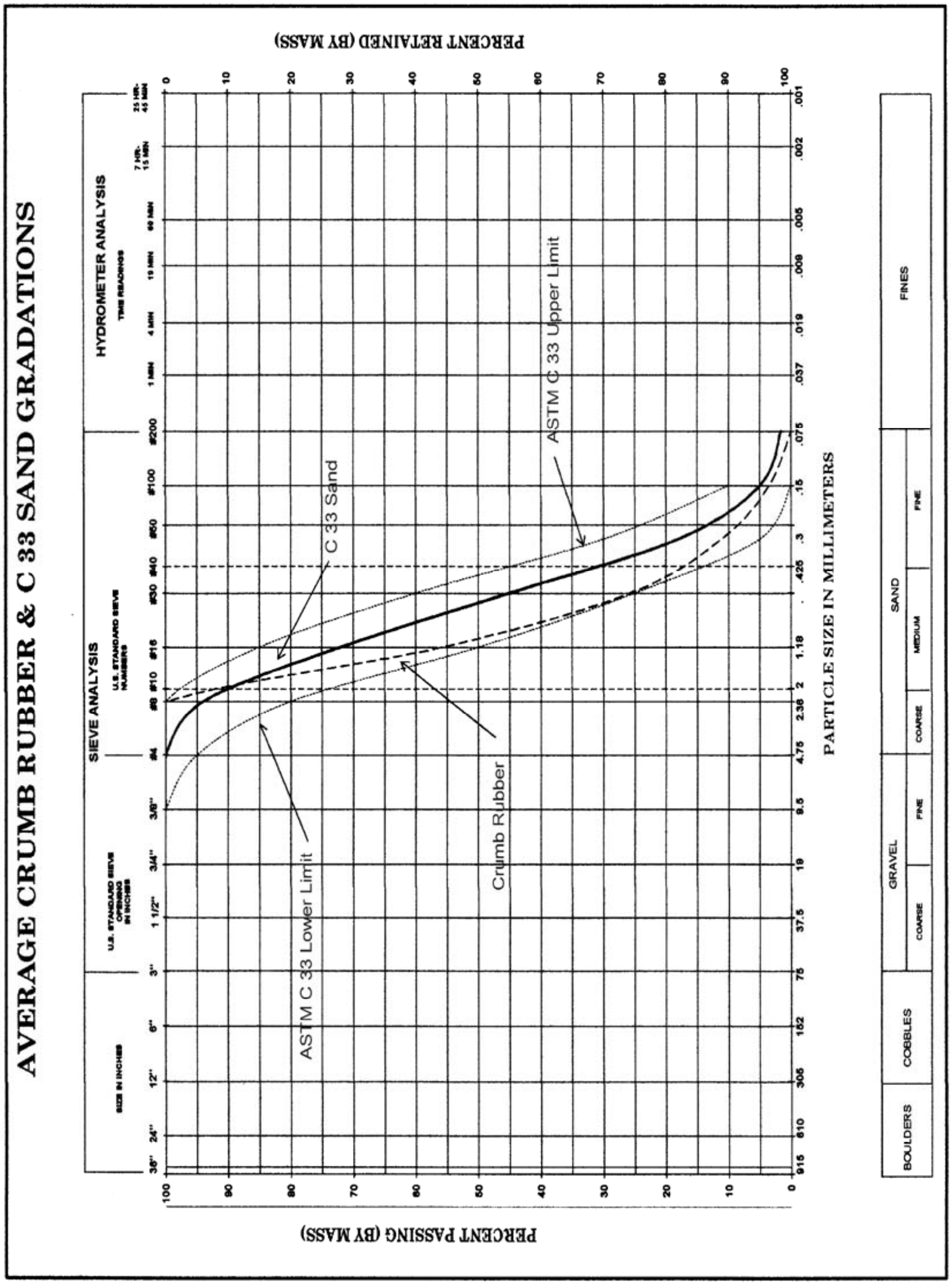
Recycled Concrete Fines Aggregate Gradation #2 (9/28/2011)									
Sieve Size	**Sieve Size**	**Sieve Weight**	**Sieve & Sample Weight**	**Sample Weight**	**ASTM Maximum Allowable**	**Cumml. Sample Weight**	**Percent Retained**	**Cumml. Percent Retained**	**Percent Passing**
(Std)	*(mm)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(%)*	*(%)*	*(%)*
3/8"	9.50	547.40	556.10	8.70	670	8.70	0.56	0.56	99.44
#4	4.75	511.00	990.10	479.10	330	487.80	30.92	31.48	68.52
#8	2.36	493.70	860.20	366.50	200	854.30	23.65	55.13	44.87
#16	1.18	424.70	706.10	281.40	200	1135.70	18.16	73.29	26.71
#30	0.60	395.60	621.00	225.40	200	1361.10	14.55	87.84	12.16
#50	0.30	371.20	519.90	148.70	200	1509.80	9.60	97.43	2.57
#100	0.15	347.40	382.50	35.10	200	1544.90	2.27	99.70	0.30
#200	0.08	334.50	338.80	4.30	200	1549.20	0.28	99.97	0.03
Pan	0.00	367.10	367.50	0.40	-	1549.60	0.03	100.00	0.00
Original Weight			Wo =	1544.10	grams				
Final Weight			Wf =	1549.60	grams				
Percent Loss			% Loss =	0.36	%				
Fineness Modulus			FM =	4.45	in.				

Recycled Concrete Fines Aggregate Gradation #3 (9/28/2011)									
Sieve Size	Sieve Size	Sieve Weight	...ve & Sample Weight	Sample Weight	...M Maximum Allowable	...mml. Sample Weight	Percent Retained	...ml. Percent Retained	Percent Passing
(.									(%)
3									99.56
									65.78
									39.81
#									23.16
#									11.88
#									2.36
#									0.26
#									0.04
I									0.00
Orig									
Fina									
Perc									
Fine									



Crumb Rubber Aggregate Gradation #1									
Sieve Size	**Sieve Size**	**Sieve Weight**	**Sieve & Sample Weight**	**Sample Weight**	**ASTM Maximum Allowable**	**Cumml. Sample Weight**	**Percent Retained**	**Cumml. Percent Retained**	**Percent Passing**
(Std)	*(mm)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(%)*	*(%)*	*(%)*
3/8"	9.50	792.30	792.37	0.07	670	0.07	0.01	0.01	99.99
#4	4.75	508.50	508.60	0.10	330	0.17	0.01	0.02	99.98
#8	2.36	493.50	497.07	3.57	200	3.73	0.48	0.50	99.50
#16	1.18	426.60	752.67	326.07	200	329.80	43.49	43.98	56.02
#30	0.60	395.60	621.40	225.80	200	555.60	30.11	74.10	25.90
#50	0.30	362.80	473.43	110.63	200	666.23	14.75	88.85	11.15
#100	0.15	347.00	404.50	57.50	200	723.73	7.67	96.52	3.48
Pan	0.00	367.20	393.30	26.10	-	749.83	3.48	100.00	0.00
Final Weight			Wf =	749.8	grams				
Fineness Modulus			FM =	3.05	in.				

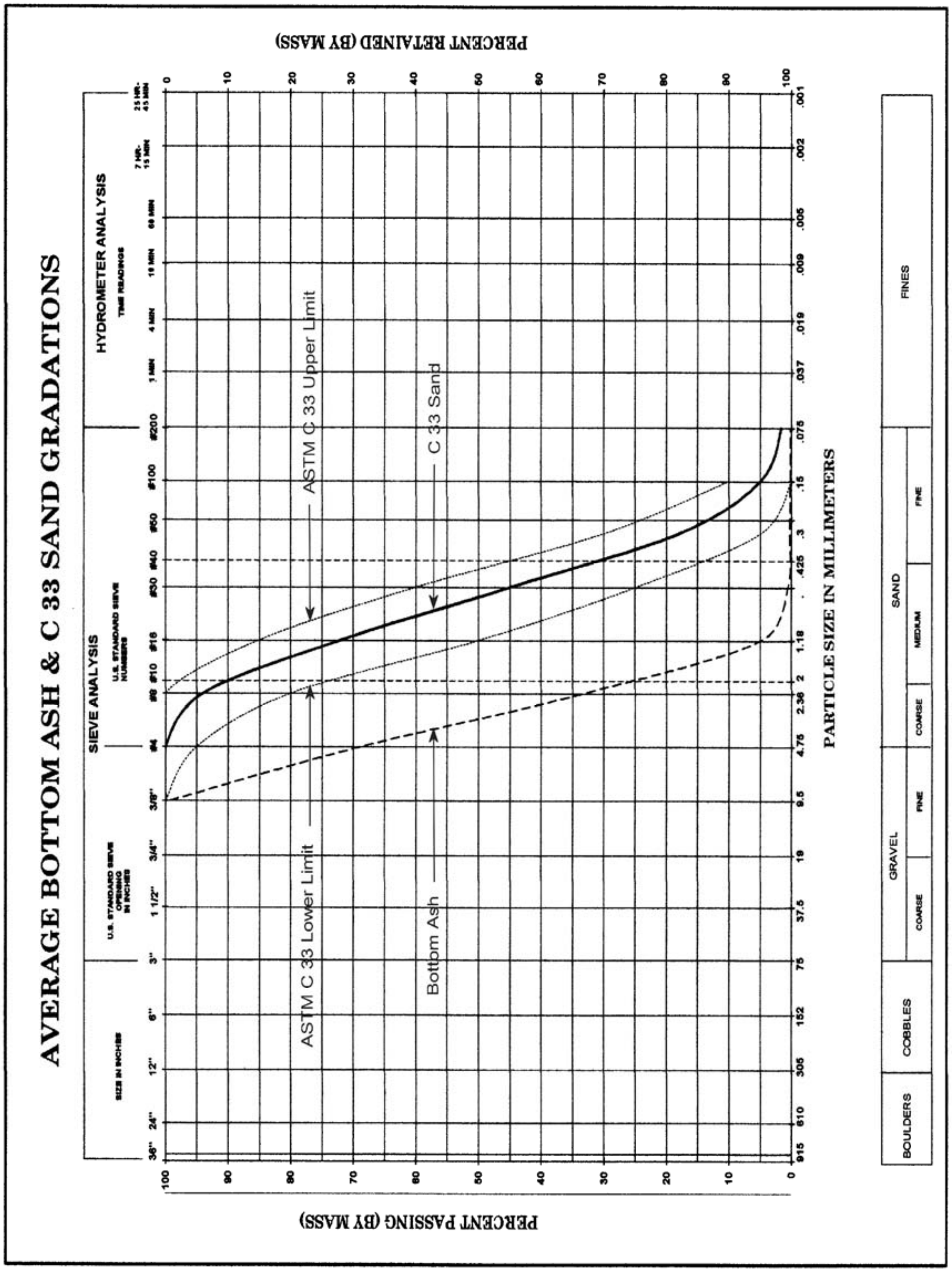
Crumb Rubber Aggregate Gradation #2									
Sieve Size	**Sieve Size**	**Sieve Weight**	**Sieve & Sample Weight**	**Sample Weight**	**ASTM Maximum Allowable**	**Cumml. Sample Weight**	**Percent Retained**	**Cumml. Percent Retained**	**Percent Passing**
(Std)	*(mm)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(%)*	*(%)*	*(%)*
3/8"	9.50	792.30	792.30	0.00	670	0.00	0.00	0.00	100.00
#4	4.75	508.50	508.60	0.10	330	0.10	0.01	0.01	99.99
#8	2.36	493.50	497.13	3.63	200	3.73	0.48	0.50	99.50
#16	1.18	426.60	757.37	330.77	200	334.50	44.07	44.56	55.44
#30	0.60	395.60	620.33	224.73	200	559.23	29.94	74.50	25.50
#50	0.30	362.80	470.97	108.17	200	667.40	14.41	88.91	11.09
#100	0.15	347.00	403.97	56.97	200	724.37	7.59	96.50	3.50
Pan	0.00	367.10	393.37	26.27	-	750.63	3.50	100.00	0.00
Final Weight			Wf =	750.63	grams				
Fineness Modulus			FM =	3.05	in.				


AVERAGE CRUMB RUBBER & C 33 SAND GRADATIONS
SIZE IN INCHES
U.S. STANDARD SIEVE OPENING IN INCHES
SIEVE ANALYSIS
U.S. STANDARD SIEVE NUMBERS
HYDROMETER ANALYSIS
TIME READINGS
PERCENT RETAINED (BY MASS)
PERCENT PASSING (BY MASS)
PARTICLE SIZE IN MILLIMETERS
ASTM C 33 Upper Limit
C 33 Sand
Crumb Rubber
ASTM C 33 Lower Limit
BOULDERS
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
FINES

Bottom Ash Gradation #1 (10/30/2011)									
Sieve Size	**Sieve Size**	**Sieve Weight**	**Sieve & Sample Weight**	**Sample Weight**	**ASTM Maximum Allowable**	**Cumml. Sample Weight**	**Percent Retained**	**Cumml. Percent Retained**	**Percent Passing**
(Std)	*(mm)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(%)*	*(%)*	*(%)*
3/8"	9.50	547.60	554.60	7.00	670	7.00	0.45	0.45	99.55
#4	4.75	511.10	958.90	447.80	330	454.80	28.74	29.19	70.81
#8	2.36	493.60	999.40	505.80	200	960.60	32.46	61.66	38.34
#16	1.18	424.70	907.80	483.10	200	1443.70	31.01	92.66	7.34
#30	0.60	395.80	483.20	87.40	200	1531.10	5.61	98.27	1.73
#50	0.30	371.20	383.40	12.20	200	1543.30	0.78	99.06	0.94
#100	0.15	347.30	352.30	5.00	200	1548.30	0.32	99.38	0.62
#200	0.08	334.50	335.50	1.00	200	1549.30	0.06	99.44	0.56
Pan	0.00	367.10	375.80	8.70	-	1558.00	0.56	100.00	0.00
Original Weight			Wo =	1533.70	grams				
Final Weight			Wf =	1558.00	grams				
Percent Loss			% Loss =	-0.02	%				
Fineness Modulus			FM =	4.81	in.				

Bottom Ash Gradation #2 (10/30/2011)									
Sieve Size	**Sieve Size**	**Sieve Weight**	**Sieve & Sample Weight**	**Sample Weight**	**ASTM Maximum Allowable**	**Cumml. Sample Weight**	**Percent Retained**	**Cumml. Percent Retained**	**Percent Passing**
(Std)	*(mm)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(%)*	*(%)*	*(%)*
3/8"	9.50	547.60	570.30	22.70	670	22.70	1.48	1.48	98.52
#4	4.75	511.10	977.30	466.20	330	488.90	30.49	31.98	68.02
#8	2.36	493.60	1094.90	601.30	200	1090.20	39.33	71.31	28.69
#16	1.18	424.70	819.20	394.50	200	1484.70	25.80	97.11	2.89
#30	0.60	395.80	439.60	43.80	200	1528.50	2.86	99.97	0.03
#50	0.30	371.20	371.70	0.50	200	1529.00	0.03	100.01	-0.01
#100	0.15	347.30	347.40	0.10	200	1529.10	0.01	100.01	-0.01
#200	0.08	334.50	334.40	-0.10	200	1529.00	-0.01	100.01	-0.01
Pan	0.00	367.10	367.00	-0.10	-	1528.90	-0.01	100.00	0.00
Original Weight			Wo =	1527.20	grams				
Final Weight			Wf =	1528.90	grams				
Percent Loss			% Loss =	0.00	%				
Fineness Modulus			FM =	5.02	in.				

Bottom Ash Gradation #3 (10/30/2011)									
Sieve Size	**Sieve Size**	**Sieve Weight**	**Sieve & Sample Weight**	**Sample Weight**	**ASTM Maximum Allowable**	**Cumml. Sample Weight**	**Percent Retained**	**Cumml. Percent Retained**	**Percent Passing**
(Std)	*(mm)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(grams)*	*(%)*	*(%)*	*(%)*
3/8"	9.50	547.60	550.90	3.30	670	3.30	0.30	0.30	99.70
#4	4.75	511.10	863.90	352.80	330	356.10	32.04	32.34	67.66
#8	2.36	493.60	875.80	382.20	200	738.30	34.71	67.06	32.94
#16	1.18	424.70	737.70	313.00	200	1051.30	28.43	95.49	4.51
#30	0.60	395.80	444.30	48.50	200	1099.80	4.41	99.89	0.11
#50	0.30	371.20	372.20	1.00	200	1100.80	0.09	99.98	0.02
#100	0.15	347.30	347.50	0.20	200	1101.00	0.02	100.00	0.00
#200	0.08	334.50	334.50	0.00	200	1101.00	0.00	100.00	0.00
Pan	0.00	367.10	367.10	0.00	-	1101.00	0.00	100.00	0.00
Original Weight			Wo =	1099.00	grams				
Final Weight			Wf =	1101.00	grams				
Percent Loss			% Loss =	1.00	%				
Fineness Modulus			FM =	4.95	in.				


AVERAGE BOTTOM ASH & C 33 SAND GRADATIONS
PERCENT RETAINED (BY MASS)
PERCENT PASSING (BY MASS)
SIEVE ANALYSIS
HYDROMETER ANALYSIS
PARTICLE SIZE IN MILLIMETERS
ASTM C 33 Upper Limit
ASTM C 33 Lower Limit
C 33 Sand
Bottom Ash
BOULDERS
COBBLES
GRAVEL
SAND
FINES

Boral Material Technologies

BORAL™

ASTM C 618 Ash Report

Title of the Project:	Comanche SDA	**Date Received:**	23-Feb-09
Contact Person:	David Neel	**Tested By:**	CC/JX
Project Number:	5130	**Report Date:**	03-Mar-09

CHEMICAL TESTS	**RESULTS**	**ASTM C 618**	**AASHTO M 295**
Comanche SDA split sample 1/09	**90223001**	**CLASS F/C**	**CLASS F/C**
Silicon Dioxide (SiO_2), %	26.21		
Aluminum Oxide (Al_2O_3), %	15.22		
Iron Oxide (Fe_2O_3), %	4.37		
Sum of SiO_2, Al_2O_3, Fe_2O_3, %	45.80	70.0/50.0 min.	70.0/50.0 min.
Calcium Oxide (CaO), %	30.31		
Magnesium Oxide (MgO), %	3.99		
Sulfur Trioxide (SO_3), %	12.68	5.0 max.	5.0 max.
Sodium Oxide (Na_2O), %	1.45		
Potassium Oxide (K_2O), %	0.28		
Total Alkalies (as Na_2O), %	1.63		

PHYSICAL TESTS	**RESULTS**	**ASTM C 618 CLASS F/C**	**AASHTO M 295 CLASS F/C**
Moisture Content, %	1.72	3.0 max.	3.0 max.
Loss on Ignition, %	2.47	6.0 max.	5.0 max.
Amount Retained on No. 325 Sieve, %	11.11	34 max.	34 max.
Specific Gravity	2.57		
Strength Activity Index with Portland Cement at 7 days, % of Control	107.9	75 min.*	75 min.*
Strength Activity Index with Portland Cement at 28 days, % of Control		75 min.*	75 min.*
Water Required, % of Control	99.2	105 max.	105 max.

By: ____________________

Diana Benfield
Quality Specialist

By: ____________________

Zhaozhou Zhang
Director, Research
and Laboratory Services

BORAL

ASTM C 618 TEST REPORT

Sample Number:	S-110405019	Report Date:	5/6/2011
		Sample Source:	Pawnee
Sample Date:	March 2011	Tested By:	jx

TESTS	RESULTS	ASTM C 618 CLASS F/C	AASHTO M 295 CLASS F/C
CHEMICAL TESTS			
Silicon Dioxide (SiO_2), %	30.30		
Aluminum Oxide (Al_2O_3), %	17.20		
Iron Oxide (Fe_2O_3), %	6.66		
Sum of SiO_2, Al_2O_3, Fe_2O_3, %	54.16	70.0/50.0 min.	70.0/50.0 min.
Calcium Oxide (CaO), %	29.13		
Magnesium Oxide (MgO), %	7.45		
Sulfur Trioxide (SO_3), %	2.85	5.0 max.	5.0 max.
Sodium Oxide (Na_2O), %	2.26		
Potassium (K_2O), %	0.31		
Total Alkalies (as Na_2O), %	2.46		
PHYSICAL TESTS			
Moisture Content, %	0.02	3.0 max.	3.0 max.
Loss on Ignition, %	0.40	6.0 max.	5.0 max.
Amount Retained on No. 325 Sieve, %	13.41	34 max.	34 max.
Specific Gravity	2.77		
Autoclave Soundness, %	0.15	0.8 max.	0.8 max.
SAI, with Portland Cement at 7 Days, % of Control	101.9	75 min.*	75 min.*
SAI, with Portland Cement at 28 Days, % of Control	97.8	75 min.*	75 min.*
Water Required, % of Control	95.0	105 max.	105 max.
Loose, Dry Bulk Density, lb/cu. ft.	72.03		

Meets ASTM C 618 and AASHTO M 295, Class C

The Class (C) Fly Ash from this plant meets the requirements of the MDOT and SCDHPT specifications.

* Meeting the 7 day or 28 day Strength Activity Index will indicate specification compliance.

Approved By: Diana Benfield

Diana Benfield
QC Specialist

Approved By: Brian Shaw

Brian Shaw
Materials Testing Manager

45 NE LOOP 410, SUITE 700 SAN ANTONIO, TEXAS 210.349.4069

WesTest

845 Navajo Street • Denver, CO 80204

SPECIALISTS TO THE PAVING INDUSTRY

Phone: 303.975.9959 • Fax: 303.975.9969 • Email:office@westest.net

January 3, 2011

Bestway Concrete
315 Frontier Court
Milliken, CO 80543

Attention: Mr. Dan Bentz

Subject: Laboratory Test Results
Brighton Pit
ASTM C 1260 Potential Alkali Reactivity of Aggregates
ASTM C 33 Fine Aggregate
ASTM C 33 Coarse Aggregate
WesTest Project No. 296411

Gentlemen:

Enclosed as Figures 1 and 2 are the results of potential alkali reactivity testing (mortar bar method), performed on aggregate sampled from the above-referenced source on December 15, 2011. The aggregate was prepared and tested in general accordance with ASTM Procedures. ASTM C 1260 defines the potential of an aggregate for deleterious expansion as follows:

Test Expansion	Classification	Potential for Deleterious ASR
< 0.10%	Innocuous	Low
0.10% to 0.20%	Inconclusive	Not Predictable
> 0.20%	Deleterious	High

Based on the test results of 0.06% expansion at 14 days in solution, 16 days after casting, the potential for deleterious alkali-silica behavior of this aggregate in concrete is considered low.

If you have any questions on the data presented, please contact us at your convenience.

Sincerely,
WesTest

Amy J. Hearon, P.E.

Reviewed by:
WesTest

Eric R. West, P.E.

SPECIALISTS TO THE PAVING INDUSTRY
845 Navajo Street
Denver, CO 80204
303.975.9959

LABORATORY TEST REPORT

POTENTIAL ALKALI REACTIVITY OF AGGREGATES
(MORTAR-BAR METHOD)
ASTM C 1260

CLIENT: Bestway Concrete
PROJECT NO.: 296411

REPORT DATE: January 3, 2011
SAMPLE ID: 2964A

AGGREGATE:
SOURCE: Brighton Pit
SIZE: ASTM C 33 Fine Aggregate

COMMENTS: Aggregate graded as per Section 8.2, Table 1

CEMENT:
SOURCE: Holcim
TYPE: I/II GU
AUTOCLAVE EXPANSION: 0.02%
ALKALIS CONTENT (as Na equivalent): 0.75%
COMMENTS: Cement data provided by Holcim

MIX WATER:
0.47 w/c ratio

EFFECTIVE GAUGE LENGTH = 250 mm

	12/16/10	12/17/10	12/20/10		12/23/10		12/27/10		12/31/10	
	Initial	Zero	3 Days		6 Days		10 Days		14 Days	
Specimen	Comparator Reading	Comparator Reading	Comparator Reading	Length Change	Comparator Reading	Length Change	Comparator Reading	Length Change	Comparator Reading	Length Change
A	-0.114	0.060	0.068	0.00%	0.100	0.02%	0.156	0.04%	0.220	0.06%
B	-0.134	0.040	0.052	0.00%	0.072	0.01%	0.128	0.04%	0.184	0.06%
C	-0.170	0.006	0.012	0.00%	0.034	0.01%	0.090	0.03%	0.152	0.06%
AVERAGE		0.035	0.044	0.00%	0.069	0.01%	0.125	0.04%	0.185	0.06%

MORTAR BAR EXPANSION

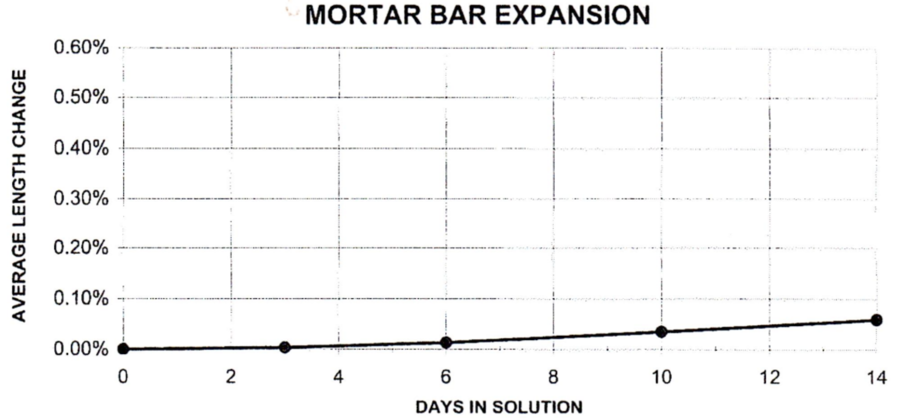


FIGURE 1

WesTest

Specialists to the Paving Industry

845 Navajo Street
Denver, CO 80204
303.975.9959, Fax 303.975.9969

LABORATORY TEST REPORT

CLIENT: Bestway Concrete
SOURCE: Brighton Plant
SAMPLED BY: Client
PROJECT: Brighton Plant Aggregate Testing

WesTest PROJECT NO.: 296411
REPORT DATE: January 17, 2011

MATERIAL DESCRIPTION	ASTM C 33 Fine Aggregate
DATE SAMPLED	December 7, 2010
SAMPLE LOCATION	Stockpile

Aggregate Physical Property and Quality Tests (ASTM C 33, AASHTO M 6 Specifications)

ASTM C 117 & C 136, AASHTO T 11 & T 27

SIEVE SIZE	% Passing	ASTM C 33 Spec.	AASHTO M 6 Spec.
1"			
3/4"			
1/2"			
3/8"	100	100	100
# 4	100	95 - 100	95 - 100
# 8	94	80 - 100	80 - 100
# 16	72	50 - 85	50 - 85
# 30	45	25 - 60	25 - 60
# 50	18	5 - 30	10 - 30
# 100	5	0 - 10	2 - 10
# 200	1.6	0 - 3	0 - 2
Fineness Modulus	2.67	2.3 - 3.1	2.3 - 3.1

ASTM C 128, AASHTO T 84,
Bulk Specific Gravity = 2.60, Bulk Specific Gravity (SSD) = 2.62, Apparent Specific Gravity = 2.65, Absorption = 0.7%

ASTM D 2419, AASHTO T 176,
Sand Equivalent Value = 93
Specification: 80 Min. (CDOT)

ASTM C 142, AASHTO T 112, Clay Lumps & Friable Particles
FINE AGG. = 0.0%, Specification: 3.0% Max.

ASTM C 123, AASHTO T 113, Lightweight Particles in Aggregate

SAMPLE WT.	LIQUID TYPE / SPECIFIC GRAVITY	LIGHTWEIGHT PARTICLES	SPEC.
285.3	$ZnCl_2$/2.0	0.0%	0.5% Max.
285.3	$ZnBr_2$/2.4	0.0%	3.0% Max.

ASTM C 88, AASHTO T 104, Sodium Sulfate Soundness, 5 Cycles

SIEVE SIZE	GRADING OF ORIGINAL SAMPLE	WEIGHT BEFORE TEST, g	PERCENT PASSING AFTER TEST	WEIGHTED PERCENT LOSS
Minus #100	5			
# 50 to # 100	13			
# 30 to # 50	27	100.0	2.1	0.6
# 16 to # 30	27	100.0	1.0	0.3
# 8 to # 16	22	100.0	1.6	0.4
# 4 to # 8	6	100.0	1.6	0.1
3/8" to # 4	0			
TOTAL	100	FINE AGG. TOTAL 100%		1
SPECIFICATION:				10 Max.

ASTM C 40, AASHTO T 21, Organic Impurities:
Less than Organic Plate No. 1
Specification: Organic Plate No. 3 or Less

COMMENTS:

MATERIAL SAFETY DATA SHEET

North West Rubber Colorado, Inc.
P.O. Box 128
7623 N. Lavaun Dr.
Louviers, CO 80131
Emergency Phone #: (303) 791-1030

I. IDENTIFICATION

Trade Name:	**Buffings**	CAS Number: 9003-55-8
Chemical Name:	Tire crumb [Styrene-Butadiene Rubber (SBR), Poly-Butadiene (PBD) & Natural Rubber]	
Generic Name:	Blends of various rubbers, carbon black & oils	
Chemical Family:	Rubber	

II. SPECIAL REGULATORY HAZARDS

Ingredient	CAS No.	Exposure Limit	OSHA (1910-1200)
Aromatic oil	64742-04-07	0.2 mg/m^3 as Benzene solubles (ACGIH)	Carcinogen
Carbon black:	1333-86-4	3.5 mg/m^3 (ACGIH)	NA

III. PHYSICAL DATA

Appearance and Odor:	Black, characteristic odor
Specific Gravity: (H_2O = 1)	1.15 - 1.18
Solubility:	Insoluble in water; soluble in petroleum distillates

Melting Point:	ND	Vapor Pressure @ 20° C:	NA
Boiling Point:	NA	Vapor Density: (air = 1):	NA
Other Data:	NA	Volatility @ 212° F:	1% maximum

IV. FIRE AND EXPLOSION HAZARD DATA

Flash Point: ND   Auto-ignition Temp: ND   Flammable limits in air: ND

Extinguishing Media: Water fog followed by coarse steam

Special Fire Fighting Procedures: Protect against inhalation of combustion product.

Unusual Hazards: Do not enter confined or enclosed space without proper protective equipment, i.e., self-contained breathing apparatus. Can ignite spontaneously if temperature exceeds 400° F.

NA = not applicable; ND = not determined.