# CONTROLLED LOW STRENGTH MATERIAL (CLSM) PRODUCED FROM LIMESTONE FINES AND OTHER BYPRODUCTS

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# CONTROLLED LOW STRENGTH MATERIAL (CLSM) PRODUCED FROM LIMESTONE FINES AND OTHER BYPRODUCTS

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## ABSTRACT

Controlled Low Strength Material (CLSM) or flowable fill mixtures are typically specified and used in lieu of compacted fill especially for backfill, utility bedding, void fill and bridge approaches. This study developed flowable fill mixtures containing only quarry fines, fly ash, synthetic gypsum and water, for different applications without any cement or good quality aggregates, to reduce costs significantly. The study used by-products of two industries, quarry fines and fly ash, to produce cheap cementitious CLSM mixtures that are flowable in their fresh state. Successful use of quarry fines in CLSM mixtures can reduce costs related to storage and disposal of fines, save dwindling landfill space, and generate additional revenue for quarries. This study also evaluated the use of synthetic gypsum obtained from industrial waste products.

The use of soil as a compacted fill is generally responsible for various issues related to differential settlement. Some of the most important causes of differential settlement are compression of poorly compacted embankment soils, poor material characteristics, non-homogeneity of embankment soils, and erosion of underlying soils. Considering limited

funds available to federal and state highway agencies, the developed group of mixtures should be economically feasible and it should provide a good, constant density, homogeneous support layer with low settlement.

# APPROVAL PAGE

The faculty listed below, appointed by the Dean of the School of Computing and Engineering have examined a thesis titled "Controlled Low-Strength Material (CLSM) Produced from Limestone Fines and Other Byproducts," presented by Harsh Shah, candidate for the Master of Science degree, and certify that in their opinion it is worthy of acceptance.

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# CHAPTER 1

# INTRODUCTION

## 1.1. General Overview

Controlled low-strength material (CLSM) is a relatively new technology whose use has grown in recent years. CLSM, often referred to as a flowable fill, is a highly flowable material in its fresh state typically comprised of water, cement, fine aggregates and often times , fly ash. Other by-product materials such as foundry sand, bottom ash, and chemical admixtures, including air-entraining agents, foaming agents, and accelerators have also been used successfully in CLSM. CLSM is typically specified and used in lieu of compacted fill in various applications especially for backfill, utility bedding, void fill, and bridge approaches. There are inherent advantages of using CLSM instead of compacted fill in these applications. These benefits include reduced labor and equipment costs (due to self-leveling properties and no need for compaction), faster construction, and ability to place material in confined places. The relatively low strength of CLSM is advantageous because it allows for future excavation, if required. Another benefit of CLSM is the utilization of by-product materials, such as fly ash and foundry sand, that would otherwise be deposited in landfills [1].

The use of soil as a compacted fill is generally responsible for various issues related to differential settlement. Some of the most important causes of differential settlement are compression of poorly compacted embankment soils, poor material characteristics, non-homogeneity of embankment soils, and erosion of soils under the approach slabs.

This study proposes to develop cheap CLSM mixtures out of quarry fines, fly ash, synthetic gypsum, and water for different applications, without using any cement or good quality aggregates. The study proposes the use of by-products of two industries, quarry fines and fly ash, to produce cheap cementitious CLSM mixtures that are flowable in their fresh state. This study also evaluates the use of synthetic gypsum obtained from industrial waste products. Considering limited funds available to federal and state highway agencies, the proposed group of mixtures should be economically feasible and it should provide a good, constant density, homogeneous support layer with low settlement.

## 1.2. Objective

The main objective of the proposed project is to research the use of a low strength flowable cementitious fill material, produced mainly from a by-product of the limestone aggregate industry, for different applications as an alternative to compacted embankment soils. The work also includes developing new mixture proportions, new mixing procedures, characterization of materials, evaluation of flowable fill mixtures, and analysis of the results.

## 1.3. Scope and Rationale

Particle-size distribution and absorption of quarry fines are important characteristics to assess the suitability of quarry fines in mineral based products and they depend on the source rock and the degree of applied processing. The limestone quarry fines were tested in the laboratory for size gradation, specific gravity, absorption coefficient, and unit weight; and the results were compared to those provided by corresponding quarries in Kansas City. Laboratory experiments were conducted to determine the specific gravity of synthetic gypsum and fly ash used in the study.

Mixtures were prepared changing three variables; amount of quarry fines, percentage of gypsum and weight ratio of water to fly ash. These variables were evaluated for their effects on engineering properties like flowability and setting time of flowable fill mixtures. Samples of fresh and hardened flowable fill mixtures were evaluated for material properties such as flowability, setting time, unit weight, unconfined compressive strength, modulus of elasticity, Poisson's ratio, dynamic modulus, and freeze thaw durability to understand the effects of mixture proportioning on these characteristics. Because flowable fill mixtures are expected to flow and fill excavation areas in the proximity of abutments that are inaccessible to large compaction equipment, flowability of the mixtures is an important characteristic. Setting time is another important characteristic since placement of formwork for any application cannot be started before the flowable backfill reached a minimum compressive strength value.

## 1.4. Significance

Quarry processes of aggregate production such as blasting, crushing, and screening of coarser grade aggregates produce waste residues, commonly known as quarry fines or quarry dust. Studies indicate that quarrying typically produces around 20-25% fines [2]. With over two billions of tons of aggregate produced in the United States, estimated waste fine production in 1995 was 200 million tons [3]. Amount of waste quarry fines rapidly increase at plants in stockpiles, using up valuable space. Successful use of quarry fines in flowable fill mixtures for different applications can reduce costs related to storage and disposal of fines, save dwindling landfill space, and generate additional revenue for quarries.

Using a cheap constant density fill material that can provide a continuous support with very low settlement can eliminate a high percentage of the problems and result in significant savings. A cheap, flowable fill material produced mainly from by-products may also cut construction time and costs because of the reduction of compaction operations.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1. Introdcution

### 2.1.1. Soil as Fill Material

Even though using soil as fill material is mainly responsible for the settlement over time, there has been no other widely used engineering solution or material developed to replace soil and solve this problem. The majority of the previous studies are based on syntheses of practice, identification of differential settlements, and soil improvement. The use of lightweight fill materials was also proposed as a means of reducing the vertical loading exerted on the soil, by various DOTs. Use of lightweight fill involved more stringent requirements for fill material specifications and inspection practice [4].

### 2.1.2. Characteristics of Controlled Low-Strength Material (CLSM)

#### 2.1.2.1. Background

American Concrete Institute (ACI) Committee 229, established in 1994, published a document on Controlled Low Strength Materials (CLSM). The document discusses use of a wide range of materials in CLSM such as Portland cement, fly ash, chemical admixtures, water, aggregates, and other non-standard materials based on availability and cost for specific applications. Necessary characteristics of mixtures for different applications including flowability, excavatability, and density should be evaluated. According to the document, currently CLSM is described using several terms including flowable fill, unshrinkable fill, controlled density fill, flowable mortar, plastic soil-cement, soil-cement slurry, K-Krete, and other various names. The ACI Committee 229 in its document states that controlled low-strength material is not similar to low strength concrete or compacted soil-cement. ACI

Committee 229 defines controlled low-strength materials as a group of mixtures with a compressive strength of 1200 psi or less at 28 days. Most current CLSM applications require unconfined compressive strengths with upper limit of 300 psi; necessary to allow for future excavation of CLSM. CLSM having compressive strengths of 50 to 100 psi can be used where future excavation with conventional digging equipment is likely desirable [5]. The ACI Committee 229 document has been referenced in many CLSM studies and has been revised in 2005 under the same title [1]. A book titled “The Design and Application of Controlled Low-Strength Materials (flowable fill)” was published later, in 1998, by the American Society for Testing and Materials (ASTM) [6].

The concept of “removability modulus” (RE) is a function of compressive strength and unit weight of the flowable fill and is based on the strength development of flowable fill mixes. The RE is expressed as, $RE = w^{1.5} X C^{0.5} X 19.53 X 10^{-6}$ (SI units); where, w = dry unit weight ($kg/m^3$) of hardened material and C = unconfined compressive strength (MPa) at 30 days. Based on this concept, any CLSM mixtures can be considered removable if its RE value is lower than 1.0. The concept of Excavability Index is a modification of the RE [7, 8].

#### 2.1.2.2. Advantages and Applications

Because of the hybrid nature of CLSM between soils and concrete, conventional geotechnical or concrete testing laboratories can be used for testing CLSM (9). Depending upon project requirements, locally available and more economical, non-standard materials or by-products can be used in CLSM mixtures [5]. Various advantages of CLSM are well cited in the literature. The main advantages of controlled low-strength materials can be stated as follows [10];

- readily available,

- easy to deliver, and place,
- versatile, strong and durable,
- easily excavatable, thus reducing equipment needs and leading to reduced excavating cost
- requires less inspection,
- allows fast return to traffic,
- will not settle,
- improved worker safety,
- allows all-weather construction,
- requires no storage, and
- allows use of by-product.

CLSM mixtures can be produced for different applications with different characteristics. The amount and type of materials used in CLSM production should be designed to obtain the required characteristics for its desired application [9]. CLSM has many applications which are well listed in the literature. Some of the main applications of CLSM include [5, 11];

- backfills (trench, bridge abutment, building excavation, hole or other cavity);
- structural fills for road base, mud jacking, uneven or nonuniform subgrades under foundation footings and slabs; insulating and isolation fills;
- pavement bases, subbases, and subgrades; conduit bedding for pipe, electrical, telephone, etc.;
- slope stabilization;

- erosion control especially where natural soil or non-cohesive granular fill has eroded away;
- void filling for tunnels shafts and sewers, basements and underground structures, under sidewalks and bridges

#### 2.1.2.3. Cost

Due to various advantages, the in-place cost of CLSM may be lower compared to conventional backfill materials, even though per cubic yard cost of CLSM is typically higher [5]. The cost of CLSM is influenced by the cost and local availability of materials, the mixing and transportation method, and the methods of placement [10]. However, the most important factor influencing the cost of CLSM is the cost of the filler material used in the mixtures [12]. This study proposes the use of a cheap filler material, quarry waste, that is, the by-product of the aggregate industry. Many case studies in the literature have reported that the use of CLSM has produced a high quality product with considerable related cost and time savings in different parts of the country [9, 13, 14].

#### 2.1.2.4. Potential Challenges

The use of CLSM is not currently as widespread as its potential might predict. CLSM is a cementitious material behaving more like a compacted fill and can be termed as somewhat a hybrid material. As a result, much of the information and discussions on its use and benefits have fallen outside the traditional specialties of concrete materials and geotechnical engineering. Despite the benefits and advantages over compacted fill, CLSM often lacks the level of attention it deserves by either group [1].

Several specifications (in some cases, provisional) governing the use of CLSM have been developed by many states. These specifications differ from state to state and moreover a variety of different test methods are currently being used to define the same properties. This lack of conformity on specifications and testing methods is an obstacle to widespread use of CLSM [1]. Whenever non-standard materials are used in CLSM, it is important to determine the characteristics of the mixture and test its suitability for specified application [5]. Each time a new mixture is proportioned, it is necessary to examine its fresh and hardened properties and long-term behavior for the intended application with suitable laboratory testing [15].

Other important technical challenges that deserve attention are [1];

- The excessive-long term strength gain often observed in the field making it difficult to excavate CLSM at later ages and thus leading to added cost and labor.
- The durability of CLSM subjected to freezing and thawing cycles.

## 2.2. Materials

One of the main advantages of CLSM is the possibility for use of wide range of locally available economical by-products to produce mixes. A survey of literature indicates that quarry fines, fly ash, and gypsum (not synthetic) have been used along with cement, sand, chemical admixtures or other such materials to produce flowable fill mixtures.

### 2.2.1. Quarry Fines

An estimated 1.2 billion tons of construction aggregates are produced in the United States annually. Quarry fines are by-products that are generated as a result of the production of crushed stone aggregates. Fine particles are produced by abrasion/ attrition of the rock as it comes into contact with other rock fragments. Apart from fine material, quarry fines also consist of a graded mix of coarse and medium sized particles, along with a clay/silt fraction (known as the ‘filler’ grade). Filler grade material is defined as material less than 0.075 mm

(75 microns) in size. The filler content has a significant impact on technical properties of quarry fines [16, 17].

Crushing of quarried rock is carried out in various stages. In general, the greater the number of crushing stages the higher the proportion of fines produced as a proportion of total plant throughput [16, 18]. The amount of fines generated varies from one crushing plant to another depending on the particular process used for crushing. The production of fines depends on nature of quarry, type of rock crushed, and type and size of aggregates produced. The production of fines in a typical quarry site is illustrated in Fig. 2.1 [17].

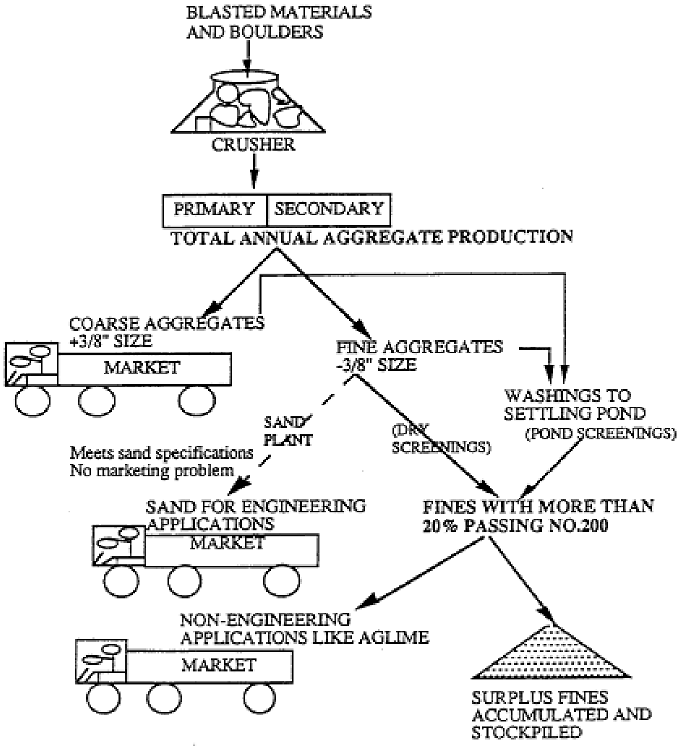


Figure 2-1: Crushed stone products and production of fines [52]

Fine grading and moisture content are two important properties of quarry fines that need to be considered before using them in any applications. Out of two, grading is considered as the most important property of the fines. Chemical composition of quarry fines is also an important material characteristic of quarry fines [17].

Currently quarry fines are used on a limited basis. Most aggregate specifications for concrete require materials not to have more than 10% passing No. 200 sieve to be acceptable. However, these gradation requirements may be overconservative. Due to their increasing quantities, proper disposal of quarry fines is a growing concern for stone industry and environmental agencies. To solve this problem it is important that industries responsible for generating quarry fines continue to seek alternative uses and markets to utilize quarry fines. This approach could minimize or eliminate costs related to storage and disposal of these materials; serve as a convincing demonstration of environmental awareness of the crushed stone industry; and generate additional revenue from the sale of these stockpiled fine materials [17].

One of the promising and potentially highest volume uses is in the application of ready mixed flowable fill. In order to be used in flowable fill, it is important to consider characteristics of quarry fines available, amount of available quarry fines, location of quarry with respect to markets, and market demand of the product [17]. Limited studies showed that use of quarry fines (up to 17%) in controlled low strength materials improved flexural strength, abrasion resistance, higher unit weight, and lowered permeability. Higher proportion of appropriately graded fines in flowable fill leads to improved flow characteristics and workability [16]. High-fines limestone screenings have been used as aggregate for CLSM, with the development of performance-enhancing admixtures [19, 20]. The literature search has mostly showed utilization of the quarry fines along with cement in various construction applications but there is very little information on the use of limestone quarry fines itself as cementitious material in preparing the flowable fills for backfilling. Some of the studies on the use of quarry fines in flowable fill are described in the following paragraphs:

At Haifa, Israel, CLSM mixes were prepared and tested using coarse sand, quarry waste (large proportions), cement, and water. Quarry waste consisted of fine material from an aggregate quarry that is unsuitable for the production of concrete. The properties of the fresh mix were governed by the amount of fine waste and the shape of its particles. The engineering properties, such as strength (0.5 MPa or 72.52 psi), volume change at early and late ages, bleeding, etc. were satisfactory despite the small amount of cement and the large amount of fine waste. The setting time and the total absorption increased significantly as the amount of quarry fines were increased [21].

At Izmir, Turkey, a research was conducted using mixtures of high volume fly ash, crushed limestone fine aggregate (filler), and a low percentage of pozzolana cement to study the strength properties of CLSM. Fine aggregate, basically limestone powder made up the major portion of a typical CLSM mixture. A non-standard fine crushed limestone fine aggregate (filler) rejected for concrete production and proven to be more economical had been used as a filler in all CLSM mixtures. CLSM mixtures with a low pozzolanic cement content and high Class C fly ash and limestone filler content were produced with excellent flowability and compressive strength values in the range of 0.85 MPa (123.28 psi) –1.15 MPa (166.79 psi) at 28 days [22].

A study in Malaysia in 2011, studied various engineering properties of CLSM made using industrial waste incineration bottom ash and quarry dust. The quarry dust consisted of excess fines and was considered as a waste material which was normally dumped in bulk quantities around the quarry plants and caused environmental pollution. Various mix proportions of CLSM were developed using bottom ash, quarry dust, cement and water. The addition of quarry dust reduced the water demand for constant flow consistency and did not seem to affect the setting time. The compressive strength at 28 days varied from 0.224 MPa (32.49 psi) to 11.416 MPa (1655.75 psi). It was observed that the addition of quarry dust increased the fresh density, hardened density and strength of CLSM. The addition of quarry dust made the CLSM more stable and enhanced the performance of the mixtures. The test results concluded that there was potential for the use of industrial waste incineration bottom ash and quarry dust in CLSM. Also, use of quarry dust in bulk quantities greatly mitigated the environmental problems caused by dumping of quarry dust in open lands [23].

In 1992, a special research report was prepared for the National Stone Association, after a study conducted at The University of Texas at Austin. A part of the study was to determine the suitability of the use of quarry fines as an alternative to the fine aggregates in the flowable fill concrete. The materials used were quarry fines, fly ash, Portland cement and water. The 3 day compression strength of the specimens varied from 0.086 MPa (12.42 psi) to 0.29 MPa (42 psi). The results were based on the performance criteria specified by the state agencies and the test results obtained by the actual testing of the flowable fill material using quarry fines rather than material specifications. Based on the results, it was concluded that flowable fill using quarry fines could emerge as an alternative to conventional backfilling methods and may be technically acceptable and economically advantageous [17].

In Tennessee a study investigated the effect of fine aggregate type on controlled low-strength materials (flowable fill). They developed a high-flow, rapid-set, non-excavatable controlled low-strength material for applications where time was critical. It was found that this type of CLSM could be produced with a wide variety of Tennessee fine aggregate types. Fine aggregate properties such as gradation and angularity dictated the mixture proportions required to achieve flow, air content, and bleeding characteristics and therefore indirectly influenced the time of set and compressive strength development [24].

Research by the Tennessee Technological University Department of Civil Engineering in collaboration with Rogers Group Inc., has shown that limestone screenings up to 21% finer than 75 micron can be used as aggregate to produce a flowable fill mix meeting National Ready-Mix Concrete Association performance recommendation [25].

Another study investigated the use of flowable fill mixes containing limestone fines where other aggregates are expensive or difficult to obtain. A well designed flowable fill mix (CLSM) with the proper air content (14-30%) provided the necessary strength, generated adequate flow, eliminated segregation, and greatly reduced bleeding. The material also proved to be economical compared to conventional aggregates [16].

### 2.2.2. Fly Ash

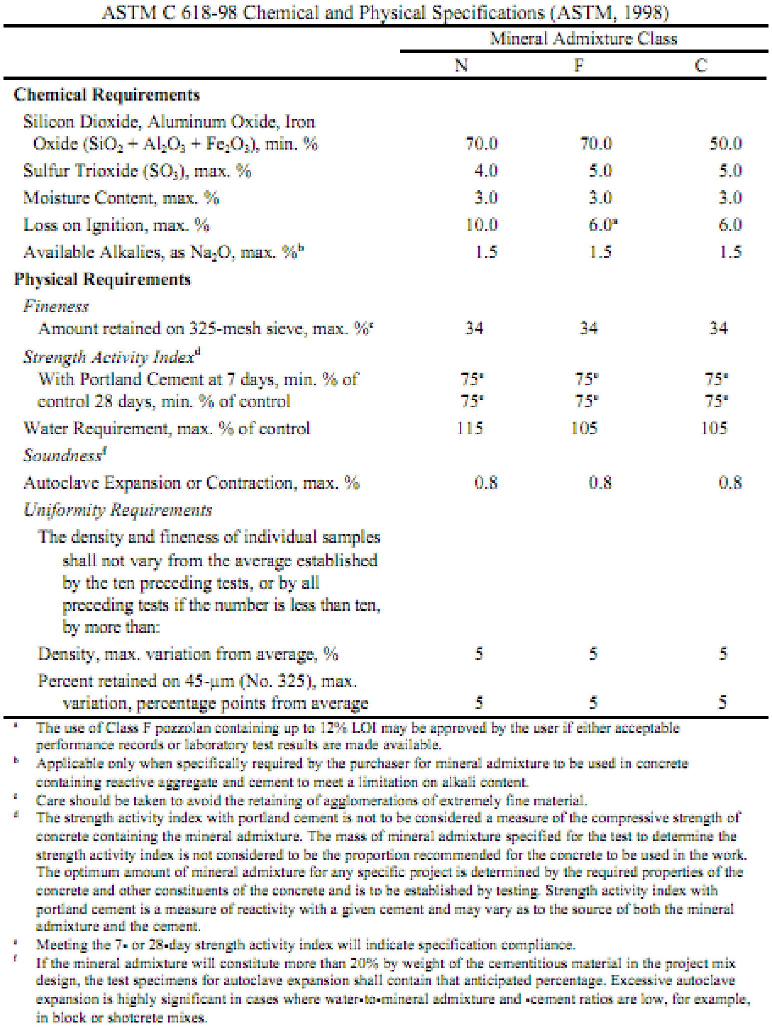
Coal is used as a major source of energy throughout the world. The energy production takes place when pulverized coal is burned [26]. Fly ash generally refers to the non-combustible mineral particles that are released from coal during combustion. These particles "fly" up and out of the boiler with the flue gases in coal-fired utilities [27]. The main constituents in fly ash are oxides, sulfates, phosphates, partially converted dehydrated silicates, and other residual inorganic particulate matter from combustion of coal [28]. The percentage of fly ash obtained upon combustion of pulverized coal depends on the type of boiler used by the coal-fired utilities [29].

Physically, fly ash is made up of fine and powdery particles. These particles are predominantly spherical, solid or hollow, and generally in an amorphous state [30]. The surface area of fly ash ranges between 300 to 500 $m^2/kg$. Generally, density of fly ash varies between 1.6 and 2.8 $g/cm^3$ [26]. Fly ash has a specific gravity between 2.1 to 3.0 [31]. Fineness (percent of material retained on a 0.045 mm or No. 325 sieve) is the characteristic of fly ash that influences its pozzolanic activity (reactivity with soluble calcium ions). The particle size distribution of most sources of coal fly ash is generally similar to that of a silt with a major fraction of particles (60 to 90 percent) being finer than 0.075 mm (No. 200 sieve). Fly ash particles are normally sized from 1 to 100 microns [32]. Ash from lignite or sub-bituminous coal is generally tan to beige in color, indicating low carbon content and the presence of lime or calcium [30].

Fly ash is also known as a pozzolan. This is because when fly ash combines with water and a free lime source such as calcium hydroxide, a pozzolanic reaction occurs to form the same calcium-silicate-hydrate that is found in commercially available cement [27, 33]. Fly ash as pozzolanic material can be grouped into three classes: N, F, and C. Class N refers to natural pozzolans, but Classes F and C differentiate between fly ashes of different chemical and physical properties. Most fly ashes are rich in $SiO_2$, $Al_2O_3$, and $Fe_2O_3$, and contain significant amounts of CaO, MgO, MnO, $TiO_2$, $Na_2O$, $K_2O$, and $SO_3$ [34]. Class F fly ashes (low-lime or low calcium fly ashes) are produced from burning anthracite or bituminous coal and generally contain 6-10% CaO. This class exhibits pozzolanic reactivity but lacks any self-cementitious behavior [34, 35, 36]. Class C fly ashes (high- lime fly ashes) are generated from burning lignite or sub-bituminous coal and typically contain higher concentrations of CaO (10 to 40%). Class C fly ash also exhibits both pozzolanic and self-cementitious behavior [29, 37, 34].

Specifications, provided by ASTM C 618 and AASHTO M295, noted in Tables 2.1 and 2.2, are very similar and specify limits for both chemical and physical characteristics of fly ash [38].

Table 2-1 ASTM C 618-98 Chemical and Physical Specifications [41]



ASTM C 618-98 Chemical and Physical Specifications (ASTM, 1998)

| | Mineral Admixture Class | | |
|---|---|---|---|
| | N | F | C |
| **Chemical Requirements** | | | |
| Silicon Dioxide, Aluminum Oxide, Iron Oxide ($SiO_2 + Al_2O_3 + Fe_2O_3$), min. % | 70.0 | 70.0 | 50.0 |
| Sulfur Trioxide ($SO_3$), max. % | 4.0 | 5.0 | 5.0 |
| Moisture Content, max. % | 3.0 | 3.0 | 3.0 |
| Loss on Ignition, max. % | 10.0 | 6.0[a] | 6.0 |
| Available Alkalies, as $Na_2O$, max. %[b] | 1.5 | 1.5 | 1.5 |
| **Physical Requirements** | | | |
| *Fineness* | | | |
| Amount retained on 325-mesh sieve, max. %[c] | 34 | 34 | 34 |
| *Strength Activity Index*[d] | | | |
| With Portland Cement at 7 days, min. % of | 75[e] | 75[e] | 75[e] |
| control 28 days, min. % of control | 75[e] | 75[e] | 75[e] |
| Water Requirement, max. % of control | 115 | 105 | 105 |
| *Soundness*[f] | | | |
| Autoclave Expansion or Contraction, max. % | 0.8 | 0.8 | 0.8 |
| *Uniformity Requirements* | | | |
| The density and fineness of individual samples shall not vary from the average established by the ten preceding tests, or by all preceding tests if the number is less than ten, by more than: | | | |
| Density, max. variation from average, % | 5 | 5 | 5 |
| Percent retained on 45-µm (No. 325), max. variation, percentage points from average | 5 | 5 | 5 |

[a] The use of Class F pozzolan containing up to 12% LOI may be approved by the user if either acceptable performance records or laboratory test results are made available.

[b] Applicable only when specifically required by the purchaser for mineral admixture to be used in concrete containing reactive aggregate and cement to meet a limitation on alkali content.

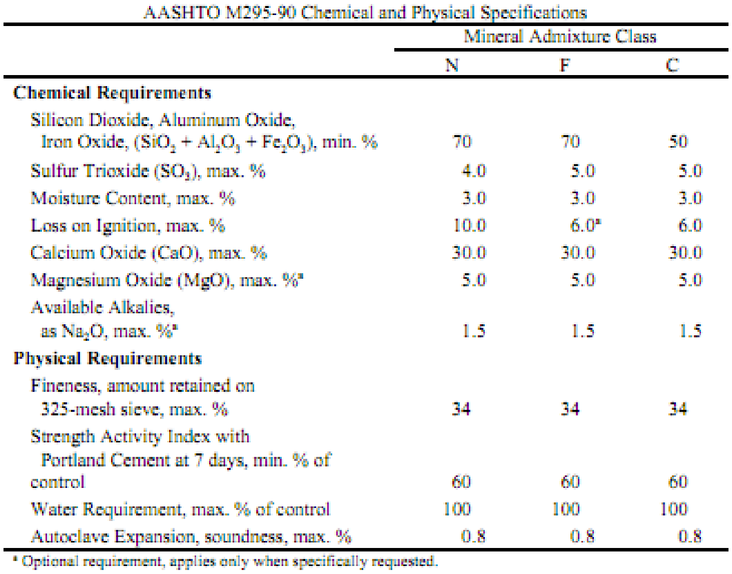
[c] Care should be taken to avoid the retaining of agglomerations of extremely fine material.

[d] The strength activity index with portland cement is not to be considered a measure of the compressive strength of concrete containing the mineral admixture. The mass of mineral admixture specified for the test to determine the strength activity index is not considered to be the proportion recommended for the concrete to be used in the work. The optimum amount of mineral admixture for any specific project is determined by the required properties of the concrete and other constituents of the concrete and is to be established by testing. Strength activity index with portland cement is a measure of reactivity with a given cement and may vary as to the source of both the mineral admixture and the cement.

[e] Meeting the 7- or 28-day strength activity index will indicate specification compliance.

[f] If the mineral admixture will constitute more than 20% by weight of the cementitious material in the project mix design, the test specimens for autoclave expansion shall contain that anticipated percentage. Excessive autoclave expansion is highly significant in cases where water-to-mineral admixture and -cement ratios are low, for example, in block or shotcrete mixes.

Table 2-2 AASHTO M295-90 Chemical and Physical Specifications [41]



AASHTO M295-90 Chemical and Physical Specifications

| | Mineral Admixture Class | | |
|---|---|---|---|
| | N | F | C |
| **Chemical Requirements** | | | |
| Silicon Dioxide, Aluminum Oxide, Iron Oxide, ($SiO_2 + Al_2O_3 + Fe_2O_3$), min. % | 70 | 70 | 50 |
| Sulfur Trioxide ($SO_3$), max. % | 4.0 | 5.0 | 5.0 |
| Moisture Content, max. % | 3.0 | 3.0 | 3.0 |
| Loss on Ignition, max. % | 10.0 | 6.0$^a$ | 6.0 |
| Calcium Oxide (CaO), max. % | 30.0 | 30.0 | 30.0 |
| Magnesium Oxide (MgO), max. %$^a$ | 5.0 | 5.0 | 5.0 |
| Available Alkalies, as $Na_2O$, max. %$^a$ | 1.5 | 1.5 | 1.5 |
| **Physical Requirements** | | | |
| Fineness, amount retained on 325-mesh sieve, max. % | 34 | 34 | 34 |
| Strength Activity Index with Portland Cement at 7 days, min. % of control | 60 | 60 | 60 |
| Water Requirement, max. % of control | 100 | 100 | 100 |
| Autoclave Expansion, soundness, max. % | 0.8 | 0.8 | 0.8 |

$^a$ Optional requirement, applies only when specifically requested.

Annually in the U.S. large quantities of fly ash is disposed of in landfills and surface impoundments. This creates additional strain on waste management options that are already approaching their capacity for safe and sanitary operation. There is still a great deal of uncertainty surrounding fly ash behavior in a landfill, in regards to heavy metal speciation and leachate impacts over extended periods of time. Additionally, as landfills are increasingly used, their maximum capacity is about to be approached. This results in rise in disposal cost of by-products like fly ash. The beneficial use of fly ash can prove to be an effective alternative based on the potential human health risks, environmental impacts, and economic costs associated with disposal of these by-products. Apart from minimizing or eliminating the cost and problems of disposal, beneficial use of fly ash helps to gain financial returns from product sales, replaces some scarce or expensive natural resources, and conserves energy required for processing or transporting the products for disposal. Based on these potential benefits, using fly ash in economically and environmentally sound applications should serve as an increasingly and mutually attractive option for utilities and coal combustion product (CCP) beneficial use industries alike [29, 37].

An overview of national trends in generation, disposal, and beneficial use of fly ash is shown in Figures 2-2 [39]. Approximately 80 million tons of ash residues are produced per year in U.S. [38].

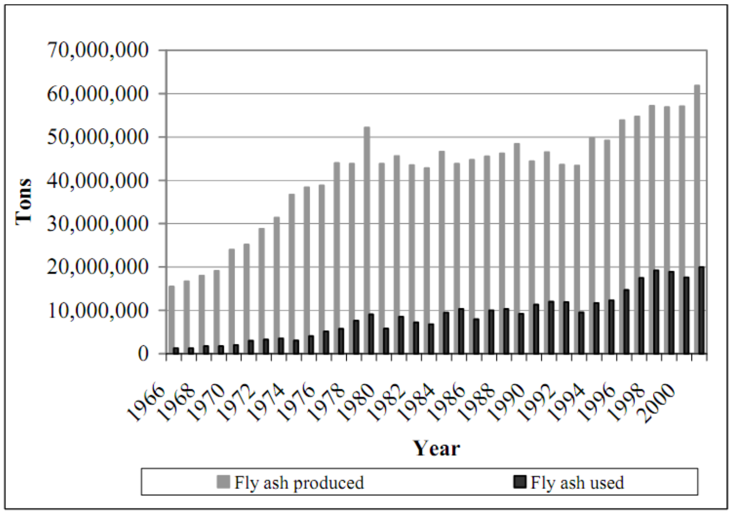


Figure 2-2: Fly ash production and beneficial use trends [42]

It has been determined that fly ash addition or partial substitution of portland cement may result in technical benefits including improved strength, durability, placement properties, improved sulfate resistance, lower heat of hydration, reduced creep and shrinkage, lower permeability, increased resistance to alkali reactivity, and enhanced workability [40, 41]. Literature indicates that flowable fill usually containing a mixture of fly ash, Portland cement, sand, and water has been used in construction and engineering applications [42]. Fly ash is well suited for use in flowable fill mixtures and considered as an economically desirable option for CLSM application. Fly ash does not need strict quality control or special processing prior to use in flowable fill applications as in other cementitious applications, such as concrete. Large quantities of fly ash have been used in flowable fill applications both as a fine aggregate and as supplement to or replacement for the cement. Due to its fine particle sizing and spherical particle shape, the flowability of flowable fill mix is enhanced on adding fly ash. The relatively low dry unit weight (890-1300 kg/cu. m) of fly ash assists in producing a relatively lightweight fill, and its pozzolanic or cementitious properties contribute to strength gain [43, 32].

Several studies that have used fly ash for flowable fills are given below;

A study conducted for the Wisconsin Department of Transportation compared the performance of bridge abutments constructed with flowable fill to those made with conventional granular backfill. The flowable fill used consisted of a mixture of foundry sands, Class C fly ash, cement and water. Initially it was observed that the cold weather and the saturated surrounding soils significantly lengthened the set time, reduced the rate of hydration and prevented the release of moisture. However, there did not appear to be any difference in performance between the granular backfill and the flowable fill after 10–11 months. In fact, from available data, it appeared that the use of flowable fill as backfill performed slightly better than the conventional granular fill. However, the difference was not significant. A similar study reported in literature indicated that flowable fill had better settlement properties under heavy traffic loading as compared to conventional backfill [44].

A study conducted using fly ash and cement to produce flowable fill as backfilling material for trenches, during the construction of Edison’s Belle River plant, indicated substantial cost savings in the overall project through the use of cement-stabilized ash [45].

An existing case history proves that flowable fill using fly ash has been successfully used as a backfilling material to replace pockets of soft material of an underlying soil layer. The material also lead to cost and time savings [46].

A study conducted has shown that fly ash can be used as a replacement of up to 100% of sand in producing Controlled Low Strength Materials (CLSM) which can be used for various backfilling applications [47, 48, 49].

A research conducted by American Electric Power Company has lead to development of a new type of patented flowable fly ash fill that is made entirely from coal combustion by-products and water [50].

### 2.2.3. Synthetic Gypsum

The literature shows that pure or regular gypsum has been used as an ideal building material. It is abundant, economical, fire resistant, strong, versatile and can have other environmental benefits, in terms of reducing waste delivered to landfills [51]. Waste gypsum used with other secondary materials to make Controlled Low Strength Materials for trench or mine backfill has showed a good performance for the desired application [52]. Studies showed that phospho gypsum, a by-product in the production of phosphoric acid in the manufacture of fertilizers used along with class C fly ash to prepare mixes of flowable fill has provided adequate flowability, strength and stability characteristics [53, 54]. Cement, quarry fines, and red gypsum or plaster board gypsum have been used as flowable backfill materials in the roads and have proved to be ideal replacements of granular backfill materials [55].

The production of synthetic gypsum is based on a simple chemical reaction between sulphuric acid ($H_2SO_4$) and lime ($Ca(OH)_2$) or limestone ($CaCO_3$) [56]. Research has shown that synthetic gypsum generated as a by-product in flue-gas desulfurization (FGD) systems from coal-fired electric powerplants can be suited for use in flowable fill mixtures or CLSM [29]. The literature search indicated that synthetic gypsum produced by processing waste products from cement or concrete industry had never been used to produce flowable fill mixtures till date.

### 2.2.4. Water

Several studies indicate that water quality has been a matter of concern in civil engineering construction and hence, most specifications require the use of potable water. The chemical composition of potable water is known and well regulated. Depending on situations and local availability, many other water types which are unacceptable for drinking may be satisfactorily used in construction [57, 58, 59].

The literature search indicated that not much research work was performed on the effect of water quality on the properties of flowable fills [60]. The water to be used in CLSM does not have special requirements. As a general rule, any water that is suitable for concrete will work well for CLSM [1].

A research was conducted at The Sultanate of Oman, for studying the potential use of groundwater and oily production water in flowable fills. The Sultanate of Oman lies in an arid region where fresh water sources are scarce. Owing to large scale oil production activities and treated wastewater, the region consists of abundant quantities of non-fresh water supplies. The use of non-fresh water yielded lower compressive strength in comparison with tap water. However, such water types still generated an acceptable 28-day strength requirement of 0.35 MPa (50.76 psi) – 3.5 MPa (507.36 psi) for flowable fill mixes. In general, the slump values obtained for most of the mixes did not show significant difference [60].

### 2.2.5. Chemical Admixtures

Air-entraining agents are the most commonly used chemical admixtures in CLSM, according to several studies. In few cases, set accelerators have been used to increase the speed of construction and to minimize subsidence. The air-entrainment in CLSM is intended to obtain low density, reduced segregation and bleeding, improved frost resistance, and lower material costs. Also, air-entrainment may be used to limit long-term strength gain to allow for future excavatability [1]. Recently available air entraining admixtures specifically designed for CSLM mixtures, apart from entraining large percentages of stable air bubbles in CLSM also allow the use of higher amounts of fines in CLSM production. The use of high amount of fines in CLSM can not only lead to reduced cost of CLSM for ready mixed concrete producers and the end users but also provide economical and environmental advantages to the aggregate producers [9].

## 2.3. Mixture Proportions

Currently, there isn't a standard mixture proportioning method that has been widely adopted for CLSM. Several studies have focused on CLSM mixture proportions, but most CLSM producers have adopted mixtures based on past experience with locally available materials. It is difficult to find a standard approach to mixture proportioning because of a variety of by-product and non-standard materials typically being used in CLSM [1]. Proportioning of CLSM is mostly done on trial and error basis until a mixture with the required characteristics for the desired application can be obtained. For CLSM material, the use of performance specifications is considered more logical than the use of descriptive specifications [9].

## 2.4. Batching, Mixing, Transportation and Placement

CLSM is typically batched, mixed, and transported in similar manner as concrete. Various mixing procedures have been described in the literature. Based on several studies, description of batching, mixing, transportation, and placement pertaining to CLSM can be done with following statements [1, 9, 32];

### 2.4.1. Batching and Mixing

Flowable fill materials can be batched and mixed in pugmills, turbine mixers, or central-mix concrete plants. There is no standard mixing procedure for CLSM, and mixing type varies with CLSM types. It is important to mix CLSM thoroughly, because of the amount of fines included and the fact that CLSM does not usually contain coarse aggregate. The coarse aggregate usually assist in breaking up cement clumps and dispersing the mixture.

### 2.4.2. Transportation

Flowable fill materials are most commonly transported to the site and discharged using ready-mix concrete trucks.

### 2.4.3. Placement

Flowable fill may be placed in any way that concrete can be placed, that is, by means of pumps, conveyors, chutes, boxes, buckets, or tremie. Several lifts or layers are generally advisable for placement of relatively deep backfills. The high fluidity of CLSM affects several aspects of placement and construction. CLSM can be directly placed without the need of compaction or vibration.

## 2.5. Curing

Normally, there are no requirements for the curing of flowable fill. Although during hot weather conditions, it may be recommended to cover the exposed surfaces of flowable fill in order to minimize evaporation and subsequent development of shrinkage cracking [32].

## 2.6. Standard Test Methods

Despite the production and use of CLSM, since early 1970's, the ACI Committee 229, established in 1984, was the key to real development and research of this material. ACI published the initial provisions and specifications which were later accepted as standards by ASTM [9]. A few important CLSM properties are routinely measured by the state DOTs and commercial testing laboratories, and these properties may be measured with different test method [61]. Some methods mentioned in ASTM and AASHTO that are applicable for soil, cement and concrete also serve as potential methods for CLSM [1]. Test methods which are widely used to test some important CLSM properties are as follows [1, 9].

### 2.6.1. Compressive Strength

- ASTM D 4832, "Preparation and Testing of Controlled Low-Strength Material (CLSM) Test Cylinders"
- AASHTO T 22, "Compressive Strength of Cylindrical Concrete Specimens"
- AASHTO T 106, "Compressive Strength of Hydraulic Cement Mortar"

### 2.6.2. Flow

- ASTM D 6103, "Standard Test Method for Flow Consistency of Controlled Low-Strength Material"
- ASTM C 939, "Flow of Grout for Preplaced-Aggregate Concrete (Flow Cone Method)"
- ASTM C 143, "Standard Test Method for Slump of Hydraulic-Cement Concrete"

### 2.6.3. Unit Weight Yield and Air Content

- ASTM D 6023, “Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Controlled Low Strength Material”
- AASHTO T 12, “Unit Weight, Yield, and Air Content (Gravimetric) of Concrete”

### 2.6.4. Setting and Hardening Time

- AASHTO T 197, “Time of Setting of Concrete Mixtures by Penetration Resistance”
- ASTM D 6024, “Test Method for Ball Drop on Controlled Low Strength Material to Determine Suitability for Load Application”
- ASTM C 403, “Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance”

### 2.6.5. Freezing-and-Thawing Resistance

- AASHTO T 161, “Standard Test Method for Resistance of Concrete to Freezing and Thawing”
- ASTM D 560, “Standard Test Methods for Freezing and Thawing of Compacted Soil-Cement Mixtures”

## 2.7. Research Significance

The literature survey indicated that quarry fines, fly ash, synthetic gypsum and water have been used in combination with some other by-products and portland cement to produce controlled low-strength mixtures. However, combination of only waste materials like limestone quarry fines, fly ash, synthetic gypsum, and water without portland cement to produce flowable fills, for different applications has not been studied in the literature. The proposed material can prove to be more economically feasible and environmentally beneficial with proper engineering properties to conventional backfilling materials. It can also be a source of additional revenue for companies which are currently spending large amount of money for dumping these by-products or waste products in landfills. Landfilling of these materials also leads to various environmental problems and is also currently an issue of rising concern among various protection agencies and industries. A sustainable and durable backfilling material with superior engineering properties, for different applications will in long-term have a positive effect on safety and economy of transportation infrastructure.

# CHAPTER 3

# MATERIALS, MIXTURE PROPORTIONS AND TEST PROCEDURES

## 3.1. Introduction

This chapter describes the materials mixture proportions and test procedures utilized in this study. Component materials used in the flowable fill include limestone quarry fines, Class C fly ash, synthetic gypsum, and water. The mixture proportions used for trial mixes and follow-up mixes to study the important engineering properties of flowable fill have been presented in this chapter. Particular emphasis was placed on parameters like flow diameter, setting time, compressive strength, and freeze-thaw resistance because of their importance in CLSM specifications. Additionally properties like elastic modulus, Poisson's ratio and dynamic modulus were evaluated. The effects of an air-entrainment agent, Darafill, on flow diameter, setting time, compressive strength and freeze-thaw resistance of mixtures were also evaluated.

## 3.2. Materials

### 3.2.1. Quarry Fines

The limestone quarry fines were obtained from Kansas City area limestone aggregate producers. Reports were obtained from Martin Marietta Materials for different quarries in Missouri namely Greenwood, Ottawa, Peculiar, Sunflower, and Parkville quarries. Based on fineness modulus, specific gravity, absorption, and strength; the limestone fines from Sunflower quarry and Parkville quarry were selected for this study. The overall acceptability for both quarry fines was rated as undesirable for use in concrete following Missouri state specifications. The section 1005 of Missouri Standard Specification for Highway Construction covers aggregates to be used for concrete construction. Table 3.1 shows the sieve analysis results for both quarry fines. The physical and chemical properties for Sunflower quarry fines and Parkville quarry fines are presented in Table 3.2 and Table 3.3, respectively. The sieve analysis results and properties of both quarry fines shown in these tables are obtained from manufacturers reports. In tables 3.2 and 3.3 various properties of quarry fines were classified as excellent, acceptable, marginally acceptable, or undesirable based on section 1005 of the Missouri Standard Specification for Highway Construction.

The following paragraph provides more information on the properties shown in Tables 3.2 and 3.3. AASHTO M 6/M 80 and ASTM C 33, "Specifications for Aggregates in Concrete" provides detailed description on the use of normal-weight aggregates in concrete. Aggregates must be resistant to breakdown and disintegration from weathering (wetting/drying and freezing/thawing) or they may break apart and cause premature distress. Durability and soundness are terms typically given to an aggregate's weathering resistance characteristic. Generally, AASHTO T 104 or ASTM C 88, the "Standard Test Method for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate" is used for soundness testing of aggregates to be used in concrete. The soundness test determines an aggregate's resistance to disintegration by weathering and, in particular, freeze-thaw cycles. The sulfate soundness could be considered a measure of tensile strength or elastic accommodation. The aggregate samples are subjected to repeated immersion in either sodium sulfate or magnesium sulfate solution. The formation of salt crystals in the aggregate's water permeable pores creates internal forces that apply pressure on aggregate pores and tend to break the aggregate. The test is supposed to mimic the formation of ice crystals in the field and could therefore be used as a surrogate to predict an aggregate's freeze-thaw performance. Depending upon the type of soundness test used, the sodium sulfate loss is typically between about 0 and 15 percent, while the magnesium sulfate loss is typically between about 0 and 30 percent. The fine aggregate angularity (FAA) test is an indirect method of assessing the angularity of fine aggregate. AASHTO T 304 or ASTM C 1252, the “Standard Test Method for Uncompacted Void Content of Fine Aggregate” indirectly measures the angularity of fine aggregate using the aggregate’s uncompacted void content. The higher the measured uncompacted void content, the more angular the material. Typical test values for crushed concrete aggregates range from 38 to 50 percent voids. Durability factor (DF) is a measure of the change (with time) in the property of a material as a result of exposure to an influence which has the potential of causing deterioration; usually expressed as a percentage of the property before exposure. Durability factor is measured using AASHTO T 161 or ASTM C 666, the “Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing.” A DF > 60 % indicates a PCC that has good freeze-thaw resistance. However, in places where freeze-thaw conditions are dominant, a DF of minimum 75 % is essential based on maximum aggregate size produced that meets durability requirements. Fine aggregate shall produce a mortar having a seven-day compressive strength of at least 90 percent of a control mortar developed at the same proportions, using standard Ottawa sand in accordance with AASHTO T 106, the “ Standard Method of Test for Compressive Strength of Hydraulic Cement Mortar (Using 50-mm or 2-in. Cube Specimens).” Deleterious materials are defined as materials that are extraneous to the parent material and may include alkali, mica, coated grains, soft and flaky particles. Micas (muscovite, biotite, and chlorite) are commonly found in certain rocks used for aggregate (e.g. granite, gneiss) and discrete mica flakes may be released when aggregate is crushed. Free mica is undesirable in concrete aggregates as it will increase the water demand. It also leads to reduced compressive strength. ASTM C33 does not specify the limits for discrete mica content in aggregates but a maximum content of 1 % mica has been suggested for sand. The amount of clay lumps and friable particles in concrete aggregates is measured using AASHTO T 112, the “Standard Test Method for Clay lumps and friable particles in aggregates.” These are the materials finer than the 75-µm (No. 200) sieve, especially silt and clay, present as loose dust and may form a coating on the aggregate particles. Even thin coatings of silt or clay on aggregate particles can be harmful because they may weaken the bond between the cement paste and aggregate. If certain types of silt or clay are present in excessive amounts, water requirements may increase significantly. The clay lumps and friable particles in concrete aggregates should be less than 0.5 %. Usually Methylene Blue Value (MBV) is used to estimate the amount and type of harmful clays present. ASTM C 295, the “Standard Test Method for Petrographic Examination of Aggregates for Concrete” can be used to measure MBV. In general, fines with MBV greater than 5 mg/g (on <#200 fraction) warrants further investigation. The amount of organic impurities in aggregates for concrete can be measured using AASHTO T 21, the “Standard Test Method for Organic impurities for fine aggregates in concrete.” The presence of organic impurities in aggregates for concrete is limited to 1.5 to 2 %.

Table 3-1 Results for Sieve Analysis of Fines

| | **Source** | |
|---|---|---|
| | **Sunflower quarry** | **Parkville quarry** |
| **Sieve No.** | **% Passing** | **% Passing** |
| 3/8" | 100.0 | 100.0 |
| #4 | 84.4 | 99.1 |
| #8 | 50.8 | 75.1 |
| #16 | 31.2 | 50.6 |
| #30 | 22.3 | 36.7 |
| #50 | 17.4 | 27.8 |
| #100 | 14.6 | 22.0 |
| #200 | 12.6 | 18.4 |

Table 3-2 Properties of fines from Sunflower quarry, MO

| **Properties** | **Results** | | | **Classification according to MODOT specification for concrete aggregates** |
|---|---|---|---|---|
| Fineness Modulus | 3.79 | | | ↓ |
| | Bulk dry ($g/cm^3$) | Bulk SSD ($g/cm^3$) | | |
| Specific Gravity | 2.52 | 2.59 | | → |
| Absorption Coefficient | 2.69 | | | → |
| Methylene Blue Value | 3 mg/g | | | ↑ |
| Organic Impurities | 1 % | | | ↑ |
| Fine Aggregate Angularity | 48.9 % | | | ← |
| Sodium Sulfate Soundness | 3.7 % | | | → |
| Clay Lumps and Friable Particles | 0.5 | | | → |
| Mica Content | 0 | | | ↑ |
| | 3-day (psi) | 7-day (psi) | 28-day (psi) | |
| Mortar Cube Strength | 2734 | 4547 | 4995 | ↓ |
| Control Mortar Strength | 3251 | 5085 | 6948 | NA |
| Magnesium Sulphate Soundness | 7.38 % | | | NA |
| Durability | 75 % | | | NA |

↑ denotes Excellent → denotes Acceptable ← denotes Marginally Acceptable
↓ denotes Undesirable NA denotes Not Applicable

Table 3-3 Properties of fines from Parkville quarry, MO

| **Properties** | **Results** | | | **Classification according to MODOT specification for concrete aggregates** |
|---|---|---|---|---|
| Fineness Modulus | 3.79 | | | ← |
| | Bulk dry (g/cm$^3$) | Bulk SSD (g/cm$^3$) | | |
| Specific Gravity | 2.53 | 2.58 | | → |
| Absorption Coefficient | 1.87 | | | → |
| Methylene Blue Value | 6 mg/g | | | → |
| Organic Impurities | 1 % | | | ↑ |
| Fine Aggregate Angularity | 46.3 % | | | → |
| Sodium Sulfate Soundness | 1.84 % | | | ↑ |
| Clay Lumps and Friable Particles | 2.4 % | | | ↓ |
| Mica Content | 0 % | | | ↑ |
| | 3-day (psi) | 7-day (psi) | 28-day (psi) | |
| Mortar Cube Strength | 2994 | 4377 | 6475 | → |
| Control Mortar Strength | 3251 | 5085 | 6948 | NA |
| Magnesium Sulphate Soundness | 8.72 % | | | NA |
| Durability | 78 % | | | NA |

↑ denotes Excellent → denotes Acceptable ← denotes Marginally Acceptable
↓ denotes Undesirable NA denotes Not Applicable

### 3.2.2. Fly Ash

The flowable fill mixtures in this study were prepared using Class C fly ash meeting ASTM C 618 and AASHTO M 295 specification requirements. LaCygne plant of Kansas City Power and Light Company (KCPL) was the source of fly ash. The results of chemical and physical analysis performed on fly ash by Lafarge North America-Kansas City Performance Center (KCPC) are shown in Table 3.4 and Table 3.5, respectively. The results shown are taken as average values from three laboratory reports submitted by Lafarge based on different composite dates.

### 3.2.3. Synthetic Gypsum

The synthetic gypsum supplied by the Lafarge Sugarcreek Plant at Kansas City was obtained at the plant from utilizing waste products.

### 3.2.4. Water

Regular laboratory tap water was used for this study to prepare all the flowable fill mixtures.

Table 3-4 Chemical analysis of Class C fly ash

| | | **Specifications (% wt.)** | |
|---|---|---|---|
| **Chemical Composition** | **% wt.** | **ASTM C 618 Class C** | **AASHTO M 295 Class C** |
| $SiO_2$ (silicon dioxide) | 37.93 | | |
| $Al_2O_3$ (aluminum oxide) | 19.71 | | |
| $Fe_2O_3$ (iron oxide) | 5.84 | | |
| $SiO_2+Al_2O_3+Fe_2O_3$ | 63.47 | 50 Min. | 50 Min. |
| CaO (calcium oxide) | 25.16 | | |
| MgO (magnesium oxide) | 4.80 | | |
| $SO_3$ (sulfur trioxide) | 1.27 | 5.0 Max. | 5.0 Max. |
| Moisture content | 0.09 | 3.0 Max. | 3.0 Max. |
| Loss On Ignition | 0.37 | 6.0 Max. | 5.0 Max. |
| $Na_2O$ (sodium oxide) | 1.66 | | |
| $K_2O$ (potassium oxide) | 0.45 | | |

Table 3-5 Physical analysis of Class C fly ash

| | | Specifications (% wt.) | |
|---|---|---|---|
| **Physical Composition** | **% wt.** | **ASTM C 618 Class C** | **AASHTO M 295 Class C** |
| Fineness, amount retained on #325 sieve | 12.5 | 34 Max. | 34 Max. |
| variation, points from average | 1.25 | 5 Max. | 5 Max. |
| Density, Mg/m$^3$ | 2.65 | | |
| variation from average | 1.12 | 5 Max. | 5 Max. |
| Strength Activity Index with Portland Cement at 7 days of cement control | 95.7 | 75 Min. | 75 Min. |
| Water Requirement % of cement control * | 94 | 105 Max. | 105 Max. |
| Soundness, autoclave expansion or contraction | 0.03 | 0.8 Max. | 0.8 Max. |

* Control cement = Sugar Creek T I/II

## 3.3. Test Procedures and Mixture Proportions

### 3.3.1. Characterization and Gradation of Materials

Sieve analysis was performed to determine the gradation of quarry fines. Quarry fines were delivered in 5 gallons buckets. Three samples of quarry fines were taken from three different buckets. The samples were taken from the top, middle, and bottom layer of the buckets for both Sunflower and Parkville quarry fines. The sieve analysis was performed using ASTM C 136 – 06, the “Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates”. Fineness modulus was calculated for both types of quarry fines based on respective sieve analysis results.

Specific gravity of both types of quarry fines was determined following ASTM C 128-07a, the “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate.” Three samples from the top, middle, and bottom of the same bucket were tested and the average value was calculated for each type of quarry fines. The specific gravities of both types of quarry fines measured in the laboratory were slightly lower than the materials report obtained from the manufacturer. Our laboratory results were used for all mix designs in this study. Absorption coefficient for Sunflower fines and Parkville fines was also determined using ASTM C 128-07a. The absorption coefficients determined in the laboratory for both type of quarry fines were slightly higher than the absorption coefficients provided by the manufacturer’s materials report. Thus, for all mix designs, the absorption coefficients determined in the laboratory using ASTM standards were used. Specific gravity of fly ash and synthetic gypsum was also determined following ASTM C 128-07a and used for mixture design calculations.

### 3.3.2. Initial Mixture Designs

Initial mixture designs were prepared based on CLSM mixtures found in the literature to obtain a flow range of 175 to 250 mm (7.00 to 9.75 in). These initial mixtures were also used to work out the details of mixing procedures and flow measurements.

Experiments were performed with initial mixture designs to check the flow diameter range and the change of flow over time. The flow diameter was measured following ASTM D6103 – 04, the “Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)” using test set up shown in Figure 3.1. Tables 3.6 and 3.7 show the initial mixture designs used in this study with Sunflower and Parkville quarry fines.

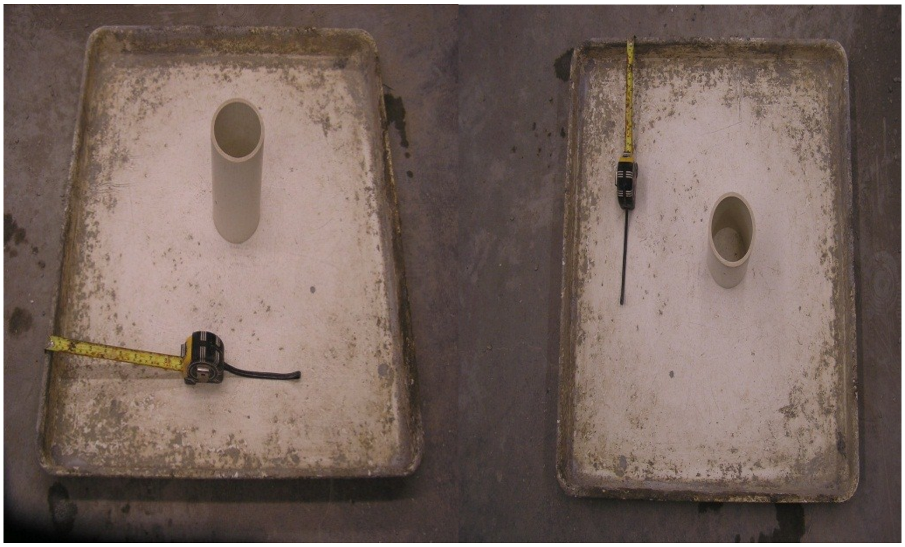


Figure 3-1: Apparatus used to measure flow diameter

Table 3-6 Initial Mixture Designs with Sunflower Quarry Fines

| **Mix Identity** | **Fly ash (kg/m$^3$)** | **Gypsum (kg/m$^3$)** | **Quarry Waste (kg/m$^3$)** | **Water (kg/m$^3$)** | **Quarry Fines % by weight of binder*** |
|---|---|---|---|---|---|
| D1-S | 790 | 80 | 430 | 476 | 50 |

**binder = Fly ash + Gypsum*

Table 3-7 Initial Mixture Designs with Parkville Quarry Fines

| **Mix Identity** | **Fly ash (kg/m$^3$)** | **Gypsum (kg/m$^3$)** | **Quarry Waste (kg/m$^3$)** | **Water (kg/m$^3$)** | **Quarry Fines % by weight of binder*** |
|---|---|---|---|---|---|
| D1-P | 790 | 80 | 430 | 478 | 50 |

**binder = Fly ash + Gypsum*

#### 3.3.2.1. Mixing Procedure

All CLSM mixtures were prepared following a modified ASTM C 305-06, the "Standard Practice for Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency" procedure because of the nature of the mix. A lower capacity (0.000262 m$^3$)

Hobart mixer and a large capacity (0.008579 $m^3$) Hobart HL 200 mixer were used based on the quantity of the mixes desired. The small mixer and the large mixer used in the experiments are shown in Figure 3.2. The following procedure was used throughout the study for all mixtures:

1. Place all the mixing water in the bowl.
2. Thoroughly mix fly ash and gypsum, and then put the mixture in the bowl.
3. Start the paddle for 30 seconds at low speed and stop.
4. Let the mix rest for 15 seconds but during these 15 seconds add quarry fines uniformly in the bowl. Scrape down into the batch any material that may have collected on sides of the bowl during this period.
5. Start the paddle for 90 seconds at low speed and stop.

Note: Final mixing duration of 90 seconds in step 5 was modified in some trials to evaluate the effect of mixing time on flow and setting time of mixtures.

Figure 3-2: Small (left) and large (right) mixers used in the experiments

### 3.3.3. Effect of Gypsum Content on Flow and Setting Time

A series of mixtures with constant water to fly ash ratio and varying amounts of gypsum were prepared to evaluate the effect of gypsum content on flow and setting time of mixtures. The water to fly ash ratio was kept at 0.61. The gypsum percentage was varied in the range of 0, 5, 10, 13, 15, and 20 % by weight of the overall fly ash amount present in the mix. The amount of quarry fines was reduced with an increase in the gypsum amount. With an increase in the gypsum percentage, there was a decrease in the ratio of water to fly ash and gypsum. The mix designs used for this evaluation are shown in Table 3.8.

The flow diameters were measured after mixing for 90 seconds and 30 minutes time intervals using the same mix according to ASTM standard D6103 – 04. The setting time was measured after mixing for 30 min. (fresh mix) using two methods, needle penetration (ASTM C807-08, the “Standard Test Method for Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle”) and pocket penetrometer (C403/C 403M- 06, the “Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance ”). For needle penetration, fresh mix was poured in Vicat’s apparatus and a 2 mm needle was used as shown in Figure 3.3. Fresh mix was also placed in 4 x 8 in. cylindrical mold for pocket penetrometer reading. A typical pocket vane shear (VS) tester is shown in Figure 3.4.

Table 3-8 Mixture proportions with varying amount of gypsum and fines

| **Mix Identity** | **FA (kg/m$^3$)** | **G (kg/m$^3$)** | **QW (kg/m$^3$)** | **W (kg/m$^3$)** | **W/FA** | **G % of FA by weight** | **W/ (FA+G)** |
|---|---|---|---|---|---|---|---|
| D2-S | 790 | 0 | 540 | 476 | 0.61 | 0 | 0.61 |
| D3-S | 790 | 40 | 490 | 476 | 0.61 | 5 | 0.58 |
| D4-S | 790 | 80 | 430 | 476 | 0.61 | 10 | 0.55 |
| D5-S | 790 | 100 | 400 | 476 | 0.61 | 13 | 0.54 |
| D6-S | 790 | 120 | 380 | 476 | 0.61 | 15 | 0.53 |
| D7-S | 790 | 160 | 330 | 476 | 0.61 | 20 | 0.50 |
| D2-P | 790 | 0 | 540 | 478 | 0.61 | 0 | 0.61 |
| D3-P | 790 | 40 | 490 | 478 | 0.61 | 5 | 0.58 |
| D4-P | 790 | 80 | 430 | 478 | 0.61 | 10 | 0.55 |
| D5-P | 790 | 100 | 400 | 478 | 0.61 | 13 | 0.54 |
| D6-P | 790 | 120 | 380 | 478 | 0.61 | 15 | 0.53 |
| D7-P | 790 | 160 | 330 | 478 | 0.61 | 20 | 0.50 |

S – Sunflower quarry fines, P – Parkville quarry fines

FA – Fly ash, G – gypsum, QW – Quarry Waste, W – Water

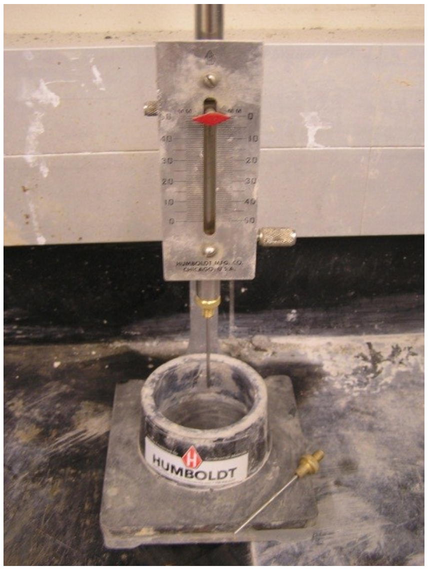


Figure 3-3: Vicat's apparatus used to measure the setting time

Figure 3-4: A typical vane shear tester

### 3.3.4. Evaluation of Fresh and Hardened Properties of CLSM Mixtures

#### 3.3.4.1. Experimental Design

Based on the results obtained from initial mixtures, researchers decided to evaluate mixtures with four gypsum contents measured as percent by weight of fly ash. The gypsum percentages by weight of fly ash selected were 0, 10, 15, and 20 %. Various mixtures were prepared with different water to fly ash ratios for each percentage of gypsum. For each gypsum percentage, the water to fly ash ratios of 0.61, 0.80 and 1 were evaluated. For each mixture, tests were conducted to measure flow, setting time, weight, unconfined compressive strength, elastic modulus and Poisson's ratio. Table 3.9 shows mixture proportions used in the study. Mixture proportion with water to fly ash ratio of 0.50 and 15 % gypsum showed zero flow diameter and did not allow samples to be cast for various testing. The detailed description of test methods used to study the fresh and hardened CLSM properties is provided in following sections.

Table 3-9 Mixture proportions with varying amount of gypsum and water to fly ash ratios

| Mix Identity | FA ($kg/m^3$) | G ($kg/m^3$) | QW ($kg/m^3$) | W ($kg/m^3$) | W/FA | G % of FA by weight |
|---|---|---|---|---|---|---|
| S1' | 560 | 0 | 540 | 560 | 1 | 0 |
| S2' | 560 | 0 | 800 | 448 | 0.80 | 0 |
| S3' | 560 | 0 | 1050 | 342 | 0.61 | 0 |
| P1' | 560 | 0 | 540 | 563 | 1 | 0 |
| P2' | 560 | 0 | 810 | 451 | 0.80 | 0 |
| P3' | 560 | 0 | 1070 | 344 | 0.61 | 0 |
| S1" | 560 | 60 | 460 | 560 | 1 | 10 |
| S2" | 560 | 60 | 730 | 448 | 0.80 | 10 |
| S3" | 560 | 60 | 980 | 342 | 0.61 | 10 |
| P1" | 560 | 60 | 470 | 563 | 1 | 10 |
| P2" | 560 | 60 | 740 | 451 | 0.80 | 10 |
| P3" | 560 | 60 | 990 | 344 | 0.61 | 10 |
| S1 | 560 | 80 | 430 | 560 | 1 | 15 |
| S2 | 560 | 80 | 690 | 448 | 0.80 | 15 |
| S3 | 560 | 80 | 940 | 342 | 0.61 | 15 |
| *S4 | 560 | 80 | 1080 | 280 | 0.50 | 15 |
| P1 | 560 | 80 | 430 | 563 | 1 | 15 |
| P2 | 560 | 80 | 700 | 451 | 0.80 | 15 |
| P3 | 560 | 80 | 960 | 344 | 0.61 | 15 |
| *P4 | 560 | 80 | 1110 | 282 | 0.50 | 15 |
| S01 | 560 | 110 | 390 | 560 | 1 | 20 |
| S02 | 560 | 110 | 650 | 448 | 0.80 | 20 |
| S03 | 560 | 110 | 900 | 342 | 0.61 | 20 |
| P01 | 563 | 110 | 390 | 563 | 1 | 20 |
| P02 | 560 | 110 | 660 | 451 | 0.80 | 20 |
| P03 | 560 | 110 | 920 | 344 | 0.61 | 20 |

S – Sunflower quarry fines, P – Parkville quarry fines
FA – Fly ash, G – Gypsum, QW – Quarry Waste, W – Water

* *The mixture proportion with water to fly ash ratio of 0.50 and 15% gypsum showed zero flow diameter and did not allow casting of samples for various testing. Therefore water to fly ash ratio of 0.61 was used instead of the water to fly ash ratio of 0.50 for various testing.*

Mixture proportions in Table 3.9 were designed to maximize the use of quarry fines at different gypsum contents. Fly ash content was kept constant and the change in water content was adjusted through changes in quarry fines content.

### 3.3.4.2. Fresh CLSM Properties

#### 3.3.4.2.1. Flowability

To measure flow of the test mixtures, ASTM D6103 – 04, the “Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)” was followed. This method uses a 3 x 6 in. plastic cylinder, with the bottom removed. The cylinder is raised vertically and quickly and the diameter of the forming spread is measured as flow diameter. For each mixture proportion, flow values were measured immediately after mixing the materials for 90 seconds. The same mixture was then further mixed for 30 minutes and the flow value was measured again. Flow values were reported as the average value of two flow diameters measured in perpendicular directions.

#### 3.3.4.2.2. Setting Time

The initial setting time was measured after mixing the materials for 30 minutes using ASTM C807-08, the “Standard Test Method for Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle”. For needle penetration, fresh mix was poured in Vicat’s apparatus and a 2 mm needle was allowed to penetrate the mix. The readings were repeated till the needle showed a penetration depth of 10 mm or less indicating the initial setting time of the mix. This test is carried out to find the rate at which the backfilling material sets to allow for follow up work to be resumed.

### 3.3.4.3. Hardened CLSM Properties

One particular issue with measuring the hardened properties of CLSM was the handling of cylinders at early ages. It is very important to carefully handle CLSM test cylinders especially when stripping the molds because of the relatively low strength at early ages (compared to concrete). Because of the large number of specimens cast in the program plastic molds served to provide an economical option. Before casting CLSM cylinders for hardened properties, the plastic cylinder molds were cut lengthwise and taped back together using electrical tape. This approach has negligible impact on the shape and size of CLSM specimens. Figure 3.5 shows a typical plastic mold prepared for casting in the study. After mixing the CLSM for 30 minutes cylinders were filled and tapped lightly on the sides to remove large entrapped air voids. A total of nine 3 x 6 in. cylindrical samples were cast to study the hardened properties of CLSM mixes at various ages following casting. Plastic lids were then placed firmly on the cylinders and the specimens were covered with wet clothes to minimize evaporation. Three samples were tested for compressive strength at 1 day. The electrical tape was stripped and the CLSM specimens were removed from the cylinders. Conventional stripping tools were not used due to the possibility of damage to the specimens. After seven days of curing in the molds at laboratory, all remaining specimens were removed from the molds in the same way. Three out of remaining six specimens were tested for compressive strength at 7 days. After fifty-six days of curing in the room temperature without the molds, the testing was performed on the last three samples. Figure 3.6 shows three samples at 56 days before testing.

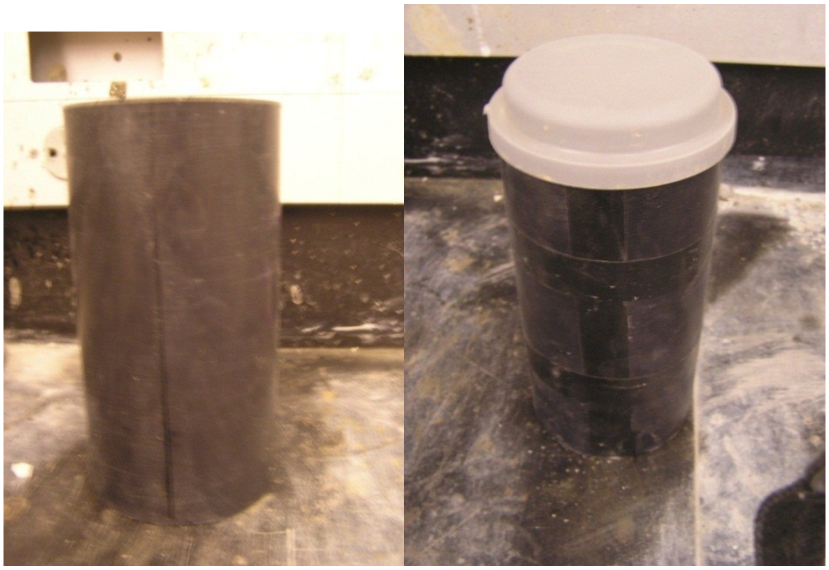


Figure 3-5: Cut and tapped plastic cylindrical mold

Figure 3-6: Samples at 56-days of curing

### 3.3.4.3.1. Weight

The mass of hardened samples was measured using a low capacity balance of 0.01 gram accuracy prior to subjecting the samples to unconfined compressive strength testing at 56 days. The weights were calculated using the measured mass and the volume of cylinders. Cylinders were assumed to have the volume of a 3 x 6 in. cylinder.

### 3.3.4.3.2. Unconfined Compressive Strength

ASTM D 4832, the “Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders” provides little guidance on load rate for compressive strength testing. The method states only to “Apply the load at a constant rate such that the cylinder will fail in not less than 2 min.,” and hence, is vague in defining the load rate. Compression tests were performed on a relatively low-load capacity Humboldt soil testing frame (100 kN load cell) (Figure 3.7). The use of a low capacity load cell to test CLSM samples is necessary to meet the accuracy requirements of ASTM Standard D 4832. The machine was connected to a HM-2325A MiniLogger which displayed the load and displacement values. For this study, the loading frame was set to ‘Triaxial 1.4 inches.’ The set up provided with the least available strain rate in the loading frame. The stress-strain curves were automatically logged to data files on a computer using Humboldt testing software. Three cylinders were tested for unconfined compressive strength at ages of 1, 7 and 56 days.

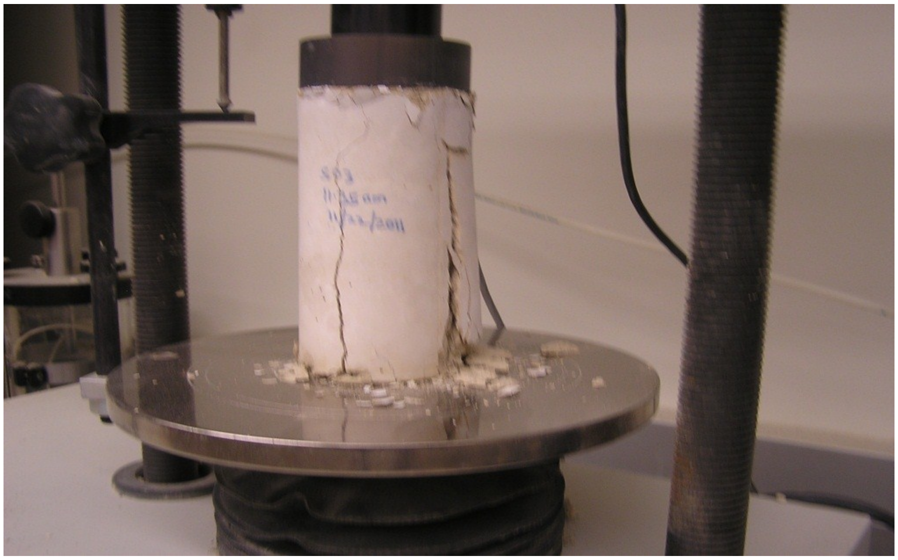


Figure 3-7: Testing for unconfined compressive stress

#### 3.3.4.3.3. Elastic Modulus and Poisson’s Ratio

Modulus of elasticity and Poisson’s ratio of CLSM samples was measured based on the procedure of ASTM C 469, the “Standard Test Method for Static Modulus of Elasticity and Poisson Ratio of Concrete in Compression,” with some modifications due to the nature of CLSM. The Humboldt geotechnical unconfined compression frame (same as used for compression testing) was used in combination with an extensometer to determine the elastic modulus and Poisson’s ratio of the samples as shown in Figure 3.8. The extensometer had two high accuracy LVDTs to measure the horizontal and vertical deformations. The elastic modulus and Poisson’s ratio was obtained for the samples at 7 days. Elastic modulus and Poisson’s ratio testing was performed on the same samples used for unconfined compressive strength. One sample out of the three was first tested to failure to measure the approximate strength. The remaining two samples were first tested for elastic modulus and Poisson’s ratio, based on the strength result of the first sample. Samples were loaded up to 30 - 40 % of the maximum load value (of initial tested sample) while being tested for elastic modulus and Poisson’s ratio. The elastic modulus and Poisson’s ratio was calculated from the slopes of load-horizontal displacement and load-vertical displacement curves which were automatically logged to data files on desktop computer. The load and displacement curves were obtained as a result of loading and unloading the samples.

### 3.3.5. Freeze-Thaw Testing

#### 3.3.5.1. Freeze-Thaw Resistance without using Air Entrainment

ASTM D 560, the “Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures,” a method designed to measure the freeze-thaw resistance of soil-cement mixtures, was used with some modifications. The samples were not oven-dried either

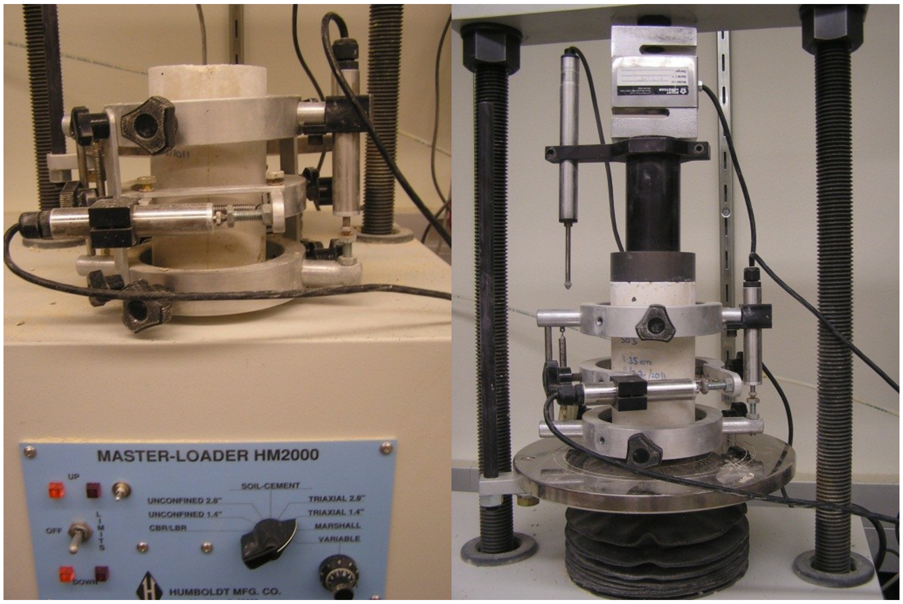


Figure 3-8: Testing for elastic modulus

before or after freeze-thaw resistance testing. One freeze-thaw cycle involved cycling between 10 $^0$F (-12 $^0$C) and 73.4 $^0$F (23 $^0$C). The samples were frozen on a wet cloth and were thawed in a bucket partially filled with water and a closed lid. Samples were kept above the water surface. This allowed the samples to thaw in a high humidity environment with minimal moisture loss. The time period for freezing and thawing were 12 hours and 10 hours, respectively for all cycles. Mass loss and dynamic modulus (ASTM C 215, “Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens”) were used to measure freeze-thaw damage. Only mixtures with higher gypsum content, i.e. 15 % and 20 %, and with water to fly ash ratios of 0.61 and 0.80 were tested for freeze-thaw resistance. A total of three 4 x 5 in. cylinders were cast for each mixture. Again, plastic cylinders served as the best economical option for molds. The preparation of molds and removal of the specimens from molds was done in a similar manner as explained in the testing of hardened properties of CLSM. After mixing the CLSM for 30 minutes, cylinders were filled and tapped lightly on the sides to remove large entrapped air voids. Plastic lids were then placed firmly on the cylinders and the specimens were kept for twenty-four hours under wet towels at 73.4 $^0$F (23 $^0$C). Wet towels were removed after twenty-four hours. After seven days of curing in molds at room temperature all specimens were removed from molds and curing was continued till twenty-eight days in the same room. After twenty-eight days, one out of three samples of each mixture was completely immersed in a bucket filled with water for twenty-four hours to saturate. The other two samples were continued to be cured in the same room. Initial readings for mass and dynamic modulus were taken for the saturated sample and the two unsaturated samples. Mass loss and loss of dynamic modulus were measured based on these initial values. The mass loss was measured after cleaning loose particles from thawed specimens with a wire scratch brush. The dynamic modulus was measured using a non-destructive testing (NDT) method. The instrument consisted of a Resonant Frequency Tester, a test bench for transverse resonance measurement, a miniature accelerometer as a receiver and a hardened steel ball to generate the vibrations on the sample by a mechanical impact. In order to obtain the resonance frequency of the sample, the received signal is analyzed in the time domain and the frequency spectrum is displayed on the instrument's screen. The samples were supported at a distance of 0.224 times the length from each ends. Figure 3.9 and Figure 3.10 show the setups for freezing and thawing of samples respectively. Figure 3.11 shows the test set up for the dynamic modulus measurement. The unsaturated samples were exposed up to 12 cycles unless they suffered severe damage and testing was stopped earlier. The samples were then kept for curing in the same room. Saturated samples were exposed up to 45 cycles (more than 12 cycles as requested by the standard) to observe the loss in mass and dynamic modulus over prolonged number of cycles. Figure 3.12 shows two saturated samples (S02 and P02) after exposure of

44 freeze-thaw cycles. The S02 sample contains mixture with 20 % gypsum by weight of fly ash, W/FA ratio of 0.80, and with Sunflower quarry fines. The P02 sample contains mixture with 20 % gypsum by weight of fly ash, W/FA ratio of 0.80, and with Parkville quarry fines. More pictures are provided in Appendix A.

The two unsaturated samples were kept at the same room temperature after completion of freeze-thaw testing and were tested for unconfined compression strength at 56 days using the same unconfined compression testing set up described earlier. The test was performed to check the decrease in the unconfined compressive strength of samples at fifty-six days after being subjected to freeze-thaw cycles. Results were compared to the unconfined compressive strength of the respective mixtures at fifty-six days that were not subjected to freeze-thaw testing. Figure 3.13 shows the unconfined compressive testing of a 4 x 5 in. freeze-thaw sample.

Figure 3-9: Set up for freezing of samples

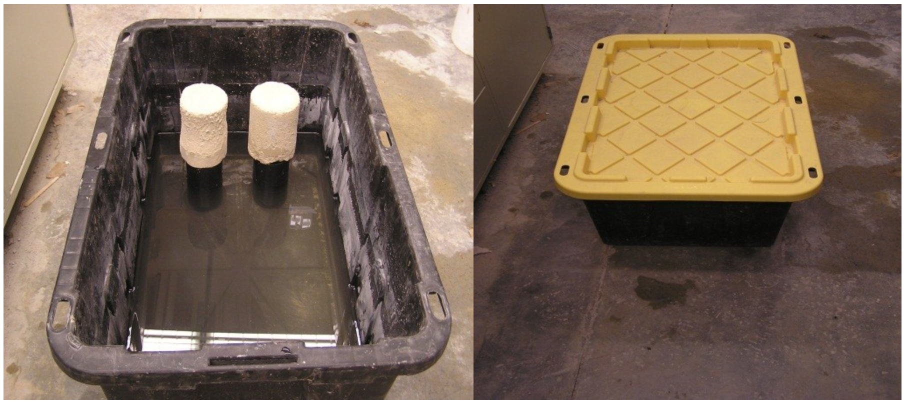


Figure 3-10: Set up for thawing of samples

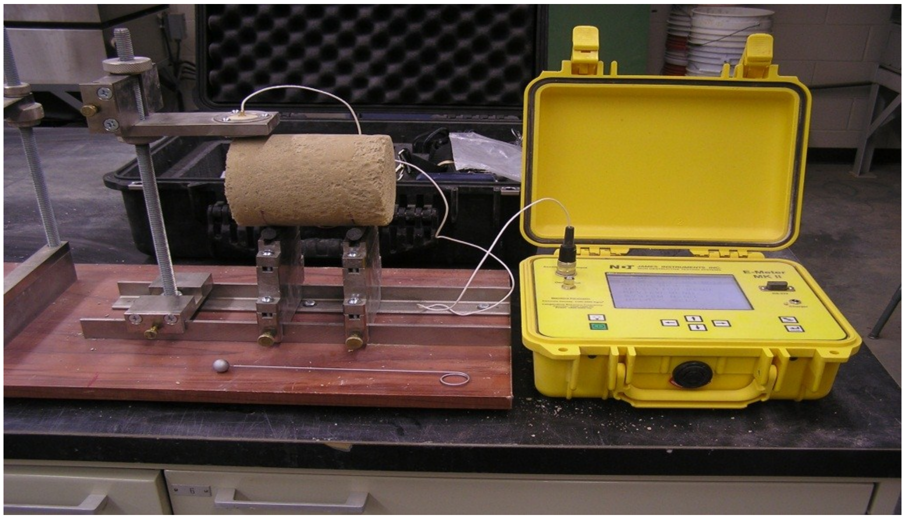


Figure 3-11: Testing for the dynamic modulus

Figure 3-12: Samples with Sunflower quarry fines (left) and Parkville quarry fines (right) after 44 freeze-thaw cycles (20 % gypsum by weight of fly ash and W/FA ratio of 0.8)

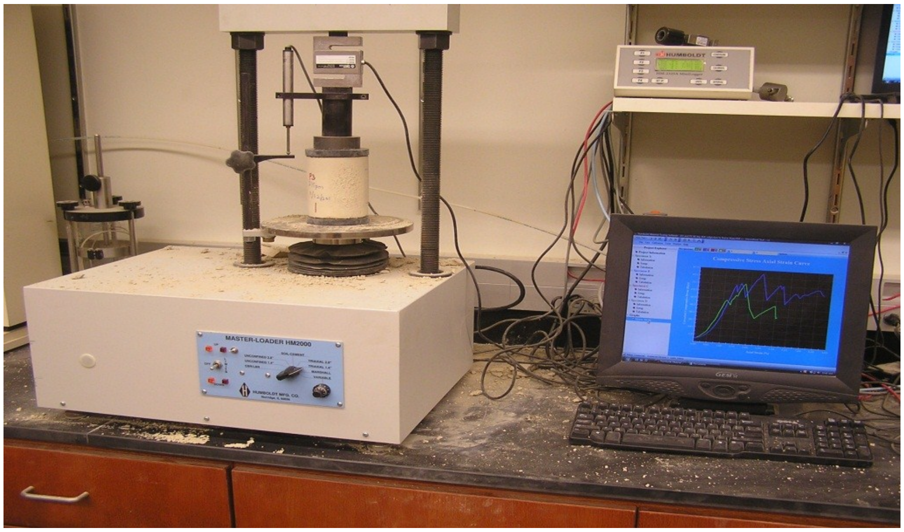


Figure 3-13: Testing for 56-day unconfined compressive stress after subjecting the samples to 12 freeze-thaw cycles

#### 3.3.5.2. Freeze-Thaw Resistance with Air Entrainment

The chemical admixture Darafill (Dry) was used to entrain air in CLSM mixtures. Darafill is specifically manufactured for use in CLSM and is used based on the volume of overall mix (that is 0.17 kg for 0.75 $m^3$ of CLSM) following manufacturer's recommendations. As with the non-air entrained testing program, the mixture proportions with higher gypsum content, i.e. 15 % and 20 %, and with water to fly ash ratios of 0.61 and 0.80 were used to study freeze-thaw resistance. The intended purpose was to study the effect of air entrainment in CLSM in terms of freeze-thaw resistance.

##### 3.3.5.2.1. Fresh and Hardened Properties

The fresh properties like flow diameter and setting time were measured using the same procedures described earlier. Specimens were also cast, cured, and tested in the similar manner as mentioned in the earlier section for studying the hardened properties like weight, unconfined compressive strength, and elastic modulus (at 56 days); except the use of air entrainment in the mixture proportions.

#### 3.3.5.2.2. Freeze-Thaw Resistance with Air Entrainment

Similar casting and testing procedures as described for the freeze-thaw resistance without air-entrainment was followed, except the use of air entraining agent in the mixture. The curing of one saturated and two unsaturated samples was also done in the same way as described for the freeze-thaw resistance without air entrainment. The samples were also subjected to unconfined compression testing following same steps. The results were compared to the unconfined compressive strength of the corresponding mixtures at fifty-six days that were not subjected to freeze-thaw testing. It should be noted that in addition to being subjected to freeze-thaw cycles samples also had different geometries (3 x 4 in. versus 4 x 5 in.). Pictures of freeze-thaw testing of samples with air entrainment and the related unconfined compression testing are provided in Appendix B.

# CHAPTER 4

# RESULTS AND DISCUSSIONS

## 4.1. Introduction

In this section, results from the testing program described in chapter 3 are provided. Also detailed discussions on the test results are included in this section. Specifically, the results of tests on the characterization and gradation of materials; initial mixture designs; fresh and hardened properties; and freeze-thaw testing results are presented. Results and discussions provided in this chapter are based on a laboratory study on the behavior of flowable fills made out of quarry fines, fly ash, synthetic gypsum and water. These results will help predict the behavior of these flowable fills in field applications, however large scale field testing to correlate the results is still necessary.

## 4.2. Characterization and Gradation of Materials

The results of sieve analysis performed in the laboratory using ASTM C 136 – 06, the "Standard Test Method for Sieve analysis of fine and Coarse Aggregates" for both Sunflower quarry fines and Parkville quarry fines are shown in Figures 4.1 and 4.2. Both types of quarry fines can be considered as finely graded as per the standard ASTM C 136 – 06. The percentages of fines passing through sieve # 200 (0.075 mm) for the top, middle, and bottom layer of Sunflower quarry fines are 16.56, 17.68, and 19.53, respectively. The percentages of fines passing through sieve # 200 (0.075mm) for the top, middle, and bottom layer of Parkville quarry fines are 17.42, 18.09, and 15.77, respectively. The average percentage of fines passing through sieve # 200 (0.075 mm) according to laboratory results is 17.92 and 17.09 for Sunflower quarry fines and Parkville quarry fines, respectively. According to the report obtained from Martin Marietta Materials, the percentage finer than sieve # 200 was

12.6 for Sunflower quarry fines and 18.4 for Parkville quarry fines. Thus, both Sunflower quarry fines and Parkville quarry fines had more than 10 % of fines passing sieve # 200 (0.075mm); and can be considered as undesirable for use as concrete aggregates according to ASTM C 33, the "Standard Specification for Concrete Aggregates."

Based on the results of sieve analysis, the fineness modulus is calculated as the sum of percentage of sample retained on each of a specified series of sieves divided by 100. The results of fineness modulus for the top, middle, and bottom layer of each quarry fines are shown in the Table 4.1. The average fineness modulus is 3.05 and 3.15 for both Sunflower quarry fines and Parkville quarry fines, respectively. According to the report obtained from Martin Marietta Materials, the fineness modulus is 3.79 for both Sunflower quarry fines and Parkville quarry fines. The laboratory results indicated that the material was finer than indicated by the report obtained from respective quarry tests.

The laboratory results for absorption coefficient and specific gravity of both types of

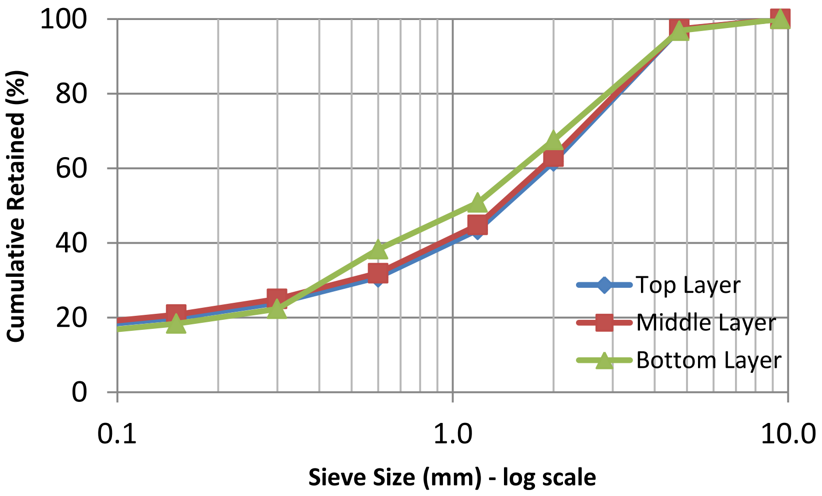


Figure 4-1: Result of sieve analysis for Sunflower quarry fines

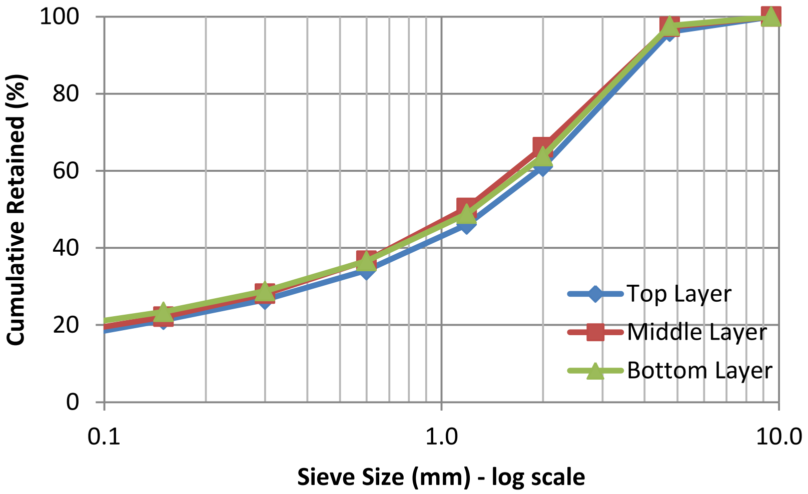


Figure 4-2: Result of sieve analysis for Parkville quarry fines

Table 4-1 Results of Fineness Modulus

| **Layer** | **Fineness Modulus (F.M.)** | |
|---|---|---|
| | **Sunflower fines** | **Parkville fines** |
| Top | 3.15 | 3.23 |
| Middle | 2.99 | 3.17 |
| Bottom | 3.01 | 3.06 |
| **Average** | **3.05** | **3.15** |

quarry fines were determined in accordance with ASTM 128 – 07a, the "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate". The average values of specific gravity were calculated based on the values of specific gravity from top, middle, and bottom layer of a bucket for both types of quarry fines. Based on average specific gravity, the absorption coefficient was calculated for both Sunflower quarry fines and Parkville quarry fines. These values were slightly different than the values in the report obtained from Martin Marietta Materials for Sunflower quarry fines and Parkville quarry fines. According to the report, the specific gravity and absorption coefficient for Sunflower quarry fines were 2.59 g/cm$^3$ and 2.69 respectively, and the specific gravity and absorption coefficient for Parkville quarry fines were 2.58 g/cm$^3$ and 1.87. Laboratory testing showed slightly lower values for specific gravity and the absorption coefficients were 3.51 and 2.45 for Sunflower and Parkville fines, respectively. Higher absorption coefficients are in line with higher fine percentage determined. Hence, values for specific gravity and absorption coefficient obtained in the laboratory were used in the study.

The laboratory results for specific gravity of synthetic gypsum and fly ash determined in accordance with ASTM 128 – 07a, are shown in Table 4.2. These values for specific gravity of fly ash and gypsum obtained in the laboratory were used in the study.

Table 4-2 Result for Specific Gravity of Fly Ash and Synthetic Gypsum

| **Material** | **Specific gravity ($g/cm^3$) [pci]** |
|---|---|
| Fly ash | 2.66 [0.096] |
| Synthetic gypsum | 1.77 [0.064] |

## 4.3. Initial Mixture Designs

Initial mixture designs that were described in chapter 3 were used to fix mixing procedures and to determine the testing procedures for flow diameter and setting time. One of the initial studies was to look at the effect of mixing time on flow of CLSM mixtures. Table 4.3 and Table 4.4 show the average flow values measured after three different mixing times for mixes prepared with Sunflower and Parkville fines, respectively. After mixing the materials for 90 seconds, the mixtures obtained were very soupy in nature. When the materials were mixed for 15 minutes, the measured flow values decreased substantially compared to the flow values after 90 seconds. However, increase of mixing time from 15 to 30 minutes did not change the flow values substantially. Both flow values obtained after 15 or 30 minutes mixing were within the desired range of flow (175 to 250 mm) [7.00 to 9.75 in.]

Table 4-3 Result for Initial Trial (Sunflower Fines)

| **Mix Identity D1** | **After 90 seconds** | **After 15 minutes** | **After 30 minutes** |
|---|---|---|---|
| **Flow diameter (mm) [in]** | 615<br>[24.25] | 230<br>[9.00] | 210<br>[8.25] |

Table 4-4 Result for Initial Trial (Parkville Fines)

| **Mix Identity D2** | **After 90 seconds** | **After 15 minutes** | **After 30 minutes** |
|---|---|---|---|
| **Flow diameter (mm) [in]** | 620<br>[24.50] | 235<br>[9.25] | 210<br>[8.25] |

## 4.4. Effect of Gypsum on Flow and Setting Time

A series of mixtures with changing gypsum contents were evaluated to consider the effect of gypsum on flow and setting time of CLSM. Table 4.5 shows results of changing amount of gypsum on flow value after 90 seconds and 30 minutes of mixing and initial setting time measured using needle penetration and pocket penetrometer. The plot of change in gypsum % by weight of fly ash versus flow value is shown in Figure 4.3. The plot of change in gypsum % by weight of fly ash versus initial setting time measured using needle penetration and pocket penetrometer is shown in Figure 4.4. In general, it can be seen that there was no consistent increase or decrease in flow values with increase in the amount of gypsum. However, the graph shows again the substantial difference based on mixing duration as was discussed in the earlier section. Evaluation of Figure 4.4 shows that pocket penetrometer, although a good method for cementitious mixtures, was not a suitable method for the low strength mixtures considered in this study. It was decided to use the Vicat needle for the remainder of the study to measure setting time. Although very small, Figure 4.4 Vicat results show an increase with increasing gypsum content which is similar to findings in literature. The mix with 0 % gypsum by weight of fly ash with both types of quarry fines showed flow values within the desired range of 175 to 250 mm (7.00 to 9.75 in.) after mixing for 30 minutes and showed comparatively higher initial setting time. The mix with 5 % gypsum by weight of fly ash with both types of quarry fines did not give desired flow value within the range of 175 to 250 mm (7.00 to 9.75 in.) after mixing for 30 minutes and also showed comparatively lesser initial setting time measured using both methods. The results obtained using 13 % and 15 % gypsum by weight of fly ash were most likely similar for both types of quarry fines in terms of flow values obtained after mixing for 90 seconds and 30 minutes.  The mixes with 0, 10, 15, and 20 % gypsum by weight of fly ash were evaluated in this study for further testing. The mix with 20 % gypsum by weight of fly ash showed substantially varying results with Sunflower quarry fines and Parkville quarry fines for initial setting time using pocket penetrometer method. This may be due to high flowability and low strength of the mix.

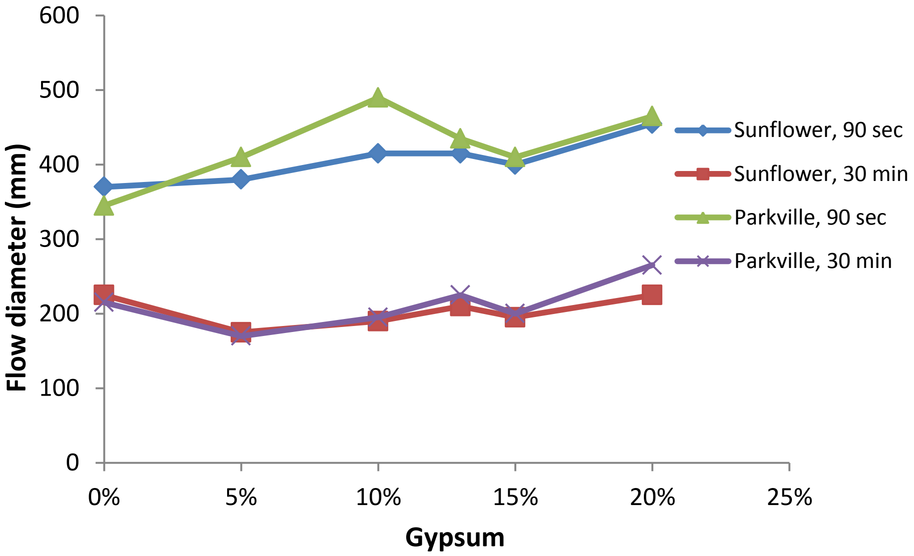


Figure 4-3: Plot of gypsum quantity and flow diameter

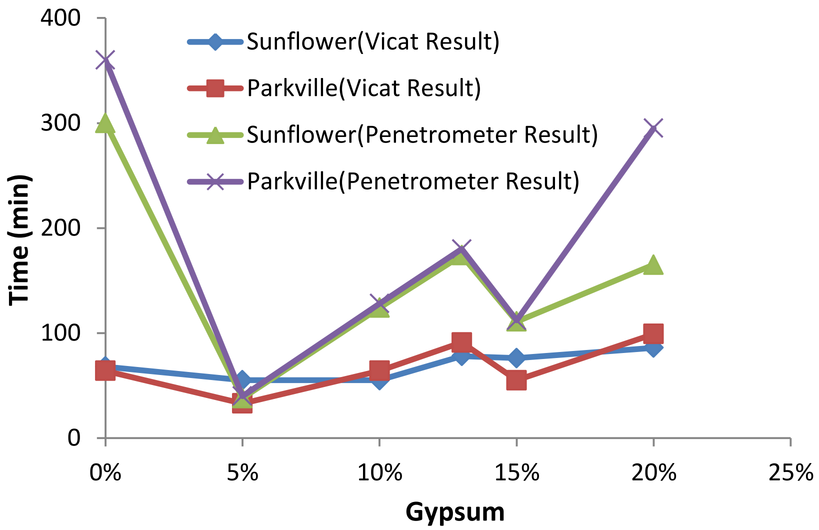


Figure 4-4: Plot of gypsum quantity and initial setting time

Table 4-5 Results for Fixing Gypsum Quantity

| Mix Identity | G % of FA by weight | Flow diameter after 90 seconds (mm) [in] | Flow diameter after 30 minutes (mm) [in] | Setting Time (min) | |
|---|---|---|---|---|---|
| | | | | Needle Penetration | Pocket Penetrometer |
| D5-S | 0 | 370 [14.50] | 225 [8.75] | 68 | 300 |
| D6-S | 5 | 380 [15.00] | 175 [7.00] | 55 | 38 |
| D7-S | 10 | 415 [16.50] | 190 [7.50] | 55 | 124 |
| D8-S | 13 | 415 [16.25] | 210 [8.25] | 78 | 174 |
| D9-S | 15 | 400 [15.75] | 195 [7.75] | 76 | 111 |
| D10-S | 20 | 455 [17.00] | 225 [9.00] | 86 | 165 |
| D5-P | 0 | 345 [13.50] | 215 [8.50] | 64 | 360 |
| D6-P | 5 | 410 [16.00] | 170 [6.75] | 33 | 40 |
| D7-P | 10 | 490 [19.50] | 195 [7.50] | 64 | 128 |
| D8-P | 13 | 435 [17.00] | 225 [9.00] | 91 | 180 |
| D9-P | 15 | 410 [16.00] | 200 [8.00] | 55 | 112 |
| D10-P | 20 | 465 [18.50] | 260 [10.25] | 99 | 295 |

G – Gypsum FA – Fly ash S – Sunflower quarry fines P – Parkville quarry fines

## 4.5. Fresh and Hardened Properties of Flowable Fill Mixtures

This section shows the results of fresh and hardened properties of CLSM mixtures like flow diameter, initial setting time, weight, unconfined compressive strength, elastic modulus, and Poisson’s ratio. The results are shown for mixtures with 0, 10, 15, and 20 % gypsum by weight of fly ash, and water to fly ash ratios of 0.61, 0.80, and 1 with both Sunflower quarry fines and Parkville quarry fines.

### 4.5.1. Flowability and Setting Time

Tables 4.6, 4.7, 4.8, and 4.9 show flow value and initial setting time for mixtures with 0, 10, 15, and 20 % gypsum by weight of fly ash, and with both types of quarry fines. The results are shown for W/FA of 0.61, 0.80 and 1 for each gypsum percentage by weight of fly ash. The flow value obtained after mixing the materials for both 90 seconds and 30 minutes are shown for each W/FA. The flow values are the average of two perpendicular readings as discussed in Chapter 3. It can be seen that flow values both after 90 second and 30 minutes increased with the increase in the W/FA for a given gypsum percentage by weight of fly ash. The setting time also increased with the increase in W/FA for a given gypsum percentage by weight of fly ash. The mixture with 0 % gypsum by weight of fly ash, and W/FA of 0.61, 0.80, and 1 showed comparatively lesser flow values than the mixtures with higher gypsum content. Also, the mixture with 0 % gypsum by weight of fly ash showed comparatively lesser initial setting time. This decrease in initial setting time could be explained as a form of flash set. Flash set is rapid and early loss of workability due to inadequate amount of form of calcium sulfate not available to control the calcium aluminate hydration which leads to rapid stiffening. The fly ash used in this study is a Class C fly ash with high alumina content. Results show presence of gypsum and W/FA ratio affect flow values and initial setting time of the mixture. Results of flow values and setting time obtained with both Sunflower and Parkville quarry fines followed similar trend. Flow diameter and setting time increased with increasing W/FA ratio at each gypsum level as shown in Figures 4.5, 4.6, 4.7, and 4.8. Flow diameter increased with increasing gypsum content at W/FA of 1. However, at the same W/FA (0.61 and 0.80) increasing the gypsum content most likely did not have an effect between 10, 15 and 20% for flow values. For setting time, at the same W/FA increasing the gypsum content most likely did not have an effect between 10, 15 and 20%.

Table 4-6 Result for Flow Diameter and Setting Time with 0% Gypsum without Air Entrainment

| **Type of Quarry Fines** | **Flow diameter after 90 sec. (mm) [in]** | **Flow diameter after 30 min. (mm) [in]** | **Setting Time (min)** | **W/FA** |
|---|---|---|---|---|
| Sunflower | 510 [20.25] | 435 [17.00] | 297 | 1 |
| Sunflower | 200 [8.00] | 190 [7.50] | 234 | 0.80 |
| Sunflower | 180 [7.00] | 175 [7.00] | 20 | 0.61 |
| Parkville | 525 [20.75] | 375 [14.75] | 312 | 1 |
| Parkville | 210 [8.25] | 195 [7.75] | 284 | 0.80 |
| Parkville | 225 [8.75] | 155 [6.25] | 30 | 0.61 |

Table 4-7 Result for Flow Diameter and Setting Time with 10% Gypsum without Air Entrainment

| **Type of Quarry Fines** | **Flow diameter after 90 sec. (mm) [in]** | **Flow diameter after 30 min. (mm) [in]** | **Setting Time (min)** | **W/FA** |
|---|---|---|---|---|
| Sunflower | 620 [24.50] | 555 [21.75] | 1380 | 1 |
| Sunflower | 635 [25.00] | 460 [18.00] | 420 | 0.80 |
| Sunflower | 400 [15.75] | 210 [8.25] | 40 | 0.61 |
| Parkville | 625 [24.50] | 530 [20.75] | 1260 | 1 |
| Parkville | 635 [25.00] | 465 [18.25] | 480 | 0.80 |
| Parkville | 365 [14.50] | 205 [8.00] | 60 | 0.61 |

Table 4-8 Result for Flow Diameter and Setting Time with 15% Gypsum without Air Entrainment

| Type of Quarry Fines | Flow diameter after 90 sec. (mm) [in] | Flow diameter after 30 min. (mm) [in] | Setting Time (min) | W/FA |
|---|---|---|---|---|
| Sunflower | 640 [25.25] | 585 [23.00] | 1560 | 1 |
| Sunflower | 575 [22.50] | 455 [18.00] | 420 | 0.80 |
| Sunflower | 365 [14.50] | 230 [9.00] | 55 | 0.61 |
| Parkville | 640 [25.25] | 585 [23.00] | 1440 | 1 |
| Parkville | 610 [24.00] | 410 [16.00] | 390 | 0.80 |
| Parkville | 385 [15.25] | 210 [8.25] | 60 | 0.61 |

Table 4-9 Result for Flow Diameter and Setting Time with 20% Gypsum without Air Entrainment

| Type of Quarry Fines | Flow diameter after 90 sec. (mm) [in] | Flow diameter after 30 min. (mm) [in] | Setting Time (min) | W/FA |
|---|---|---|---|---|
| Sunflower | 645 [25.50] | 635 [25.00] | 1500 | 1 |
| Sunflower | 610 [24.00] | 420 [16.50] | 360 | 0.80 |
| Sunflower | 360 [14.25] | 210 [8.25] | 90 | 0.61 |
| Parkville | 645 [25.50] | 620 [24.25] | 1440 | 1 |
| Parkville | 610 [24.00] | 405 [16.00] | 420 | 0.80 |
| Parkville | 330 [13.00] | 210 [8.25] | 80 | 0.61 |

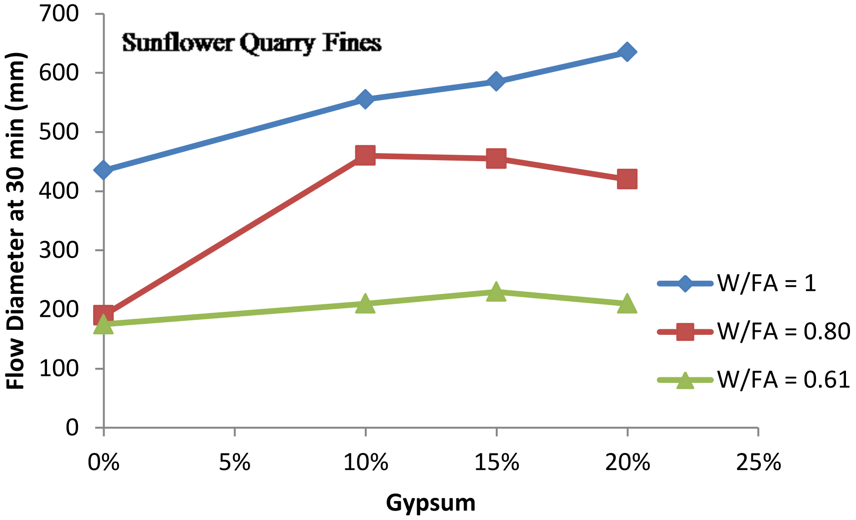


Figure 4-5: Plot of gypsum and flow diameter with varying W/FA for Sunflower quarry fines

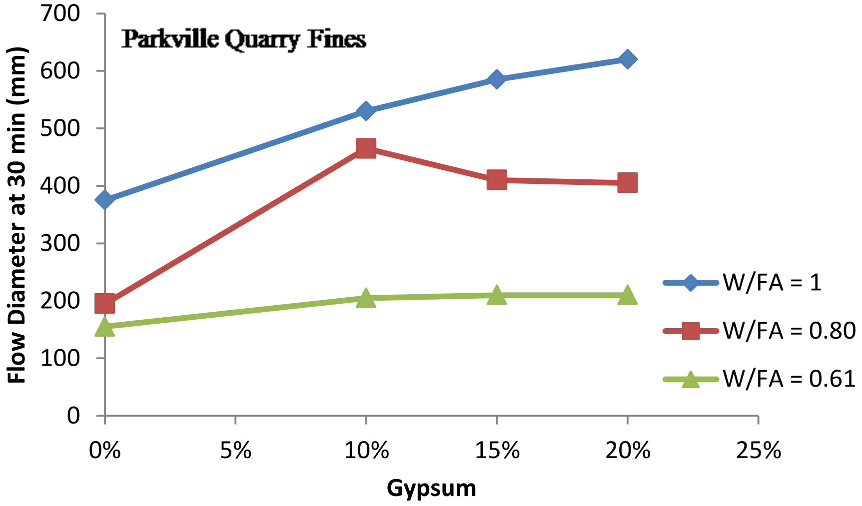


Figure 4-6: Plot of gypsum and flow diameter with varying W/FA for Parkville quarry fines

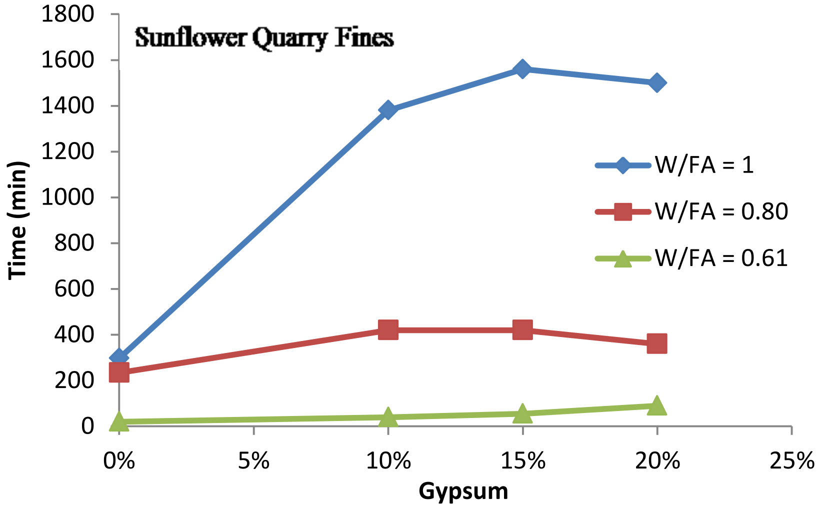


Figure 4-7: Plot of gypsum and initial setting time with varying W/FA for Sunflower quarry fines

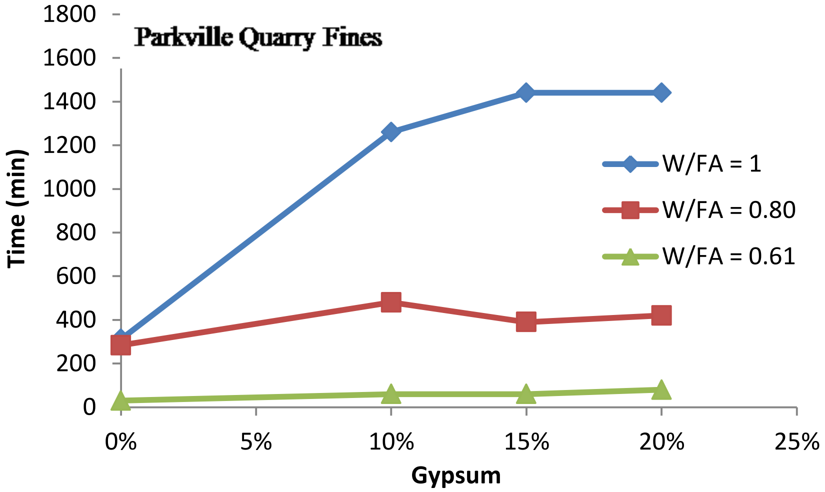


Figure 4-8: Plot of gypsum and initial setting time with varying W/FA for Parkville quarry fines

### 4.5.2. Weight

Tables 4.10, 4.11, 4.12, and 4.13 show the results of weight for CLSM mixtures with 0, 10, 15, and 20 % gypsum by weight of fly ash, respectively. Tables show mixtures with both types of quarry fines. The results are shown for W/FA of 0.61, 0.80, and 1 for each gypsum percentage by weight of fly ash. Weight was calculated for samples at ages of 1, 7 and 56 days by weighing them before compressive strength testing and assuming a perfect 3 x 6 in. cylindrical volume. The values shown in Tables are the average of three samples. Figures 4.9, 4.10, 4.11, and 4.12 show the change in average weights over time for the CLSM mixtures with 0, 10, 15 and 20 % gypsum by weight of fly ash, respectively. Figures 4.13, 4.14, 4.15, 4.16, 4.17, and 4.18 show the change in average weights over time for CLSM mixtures with the same W/FA. The error bars in Figures 4.9 through 4.18 show the standard deviation at each age. The weight decreased substantially at 56 day compared to weights at 1 day and 7 day. This may be due to the loss of water from the samples since they were cured at the laboratory temperature. CLSM is a hybrid backfill material and is not cured like concrete in the field, which is why the samples were cured at laboratory and were allowed to dry over time. The samples also showed traces of gypsum on the surface at later ages. For a given percentage of gypsum by weight of fly ash, the weight also decreased with an increase in W/FA of the mixture. A linear trend line represents an average value of weight for a given mixture at different ages. Results of weight obtained with both Sunflower and Parkville quarry fines followed similar trend. For mixtures with same W/FA, weight decreases with an increase in gypsum by weight of fly ash.

### 4.5.3. Unconfined Compressive Strength

Tables 4.14, 4.15, 4.16, and 4.17 show the results of unconfined compressive strength testing for mixtures with 0, 10, 15, and 20 % gypsum by weight of fly ash, respectively. Tables show mixtures with both types of quarry fines. The results are shown for W/FA of 0.61, 0.80, and 1 for each gypsum percentage by weight of fly ash and each result is average of three samples. Unconfined compressive strength and weight of each sample was recorded separately. Due to its low strength and nature CLSM mixtures were shown to have a high variation of compressive strength and the results of this study indicate similar findings [1, 9]. Figures 4.19, 4.20, 4.21, and 4.22 show the change in average compressive strength over time for the CLSM mixtures with 0, 10, 15 and 20 % gypsum by weight of fly ash, respectively. Figures 4.23, 4.24, 4.25, 4.26, 4.27, and 4.28 show the change in average compressive strength over time for CLSM mixtures with the same W/FA. The compressive strength did not differ with the type of quarry fines. For a given gypsum percentage by weight of fly ash, the compressive strength decreased with an increase in W/FA of the mix. The compressive strengths for all mixes with 0 % gypsum by weight of fly ash increased with age but were very low compared to results with 10, 15, and 20 % gypsum by weight of fly ash. The compressive strength increased most likely from 1 to 7 day, but from 7 to 56 day the compressive strength showed comparatively lesser increase or became stable. This may be due to the substantial decrease in the weight from 7 to 56 day due to drying as mentioned in the earlier section. The presence of gypsum in the mix influenced the compressive strength but most likely there was no difference found in compressive strength between mixtures with 10, 15 and 20 % gypsum by weight of fly ash.

### 4.5.4. Elastic Modulus and Poisson’s Ratio

Tables 4.18, 4.19, and 4.20 show the results of elastic modulus and Poisson’s ratio for mixtures with 10, 15, and 20 % gypsum by weight of fly ash, respectively. Figures 4.29 and

Table 4-10 Result of Weight with 0% Gypsum without Air Entrainment

| **Type of Quarry Fines** | **Weight** | | | **W/FA** |
|---|---|---|---|---|
| | **At 1 day ($g/cm^3$) [pcf]** | **At 7 day ($g/cm^3$) [pcf]** | **At 56 day ($g/cm^3$) [pcf]** | |
| Sunflower | 1.72 [107] | 1.67 [104] | 1.16 [73] | 1 |
| Sunflower | 1.85 [116] | 1.82 [114] | 1.47 [92] | 0.80 |
| Sunflower | 2.04 [128] | 1.96 [123] | 1.71 [107] | 0.61 |
| Parkville | 1.77 [111] | 1.59 [114] | 1.27 [79] | 1 |
| Parkville | 1.89 [118] | 1.85 [116] | 1.52 [95] | 0.80 |
| Parkville | 2.00 [124] | 1.98 [124] | 1.71 [107] | 0.61 |

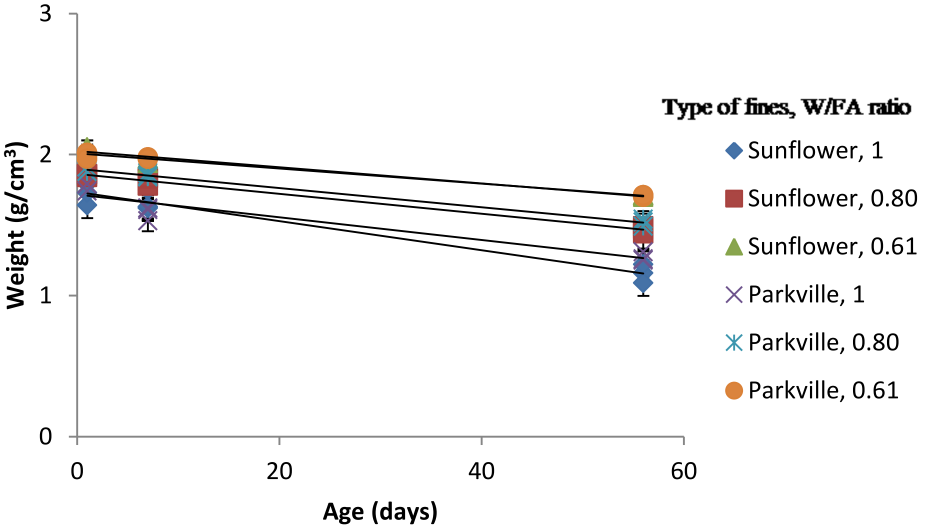


Figure 4-9: Plot of standard deviation in weight with 0 % gypsum without air entrainment

Table 4-11 Result of Weight with 10% Gypsum without Air Entrainment

| Type of Quarry Fines | Weight | | | W/FA |
|---|---|---|---|---|
| | At 1 day ($g/cm^3$) [pcf] | At 7 day ($g/cm^3$) [pcf] | At 56 day ($g/cm^3$) [pcf] | |
| Sunflower | 1.68 [105] | 1.70 [105] | 1.23 [76] | 1 |
| Sunflower | 1.89 [118] | 1.89 [118] | 1.50 [93] | 0.80 |
| Sunflower | 2.04 [128] | 2.02 [126] | 1.76 [111] | 0.61 |
| Parkville | 1.71 [107] | 1.65 [104] | 1.20 [74] | 1 |
| Parkville | 1.91 [119] | 1.91 [119] | 1.52 [95] | 0.80 |
| Parkville | 2.05 [128] | 2.02 [126] | 1.77 [111] | 0.61 |

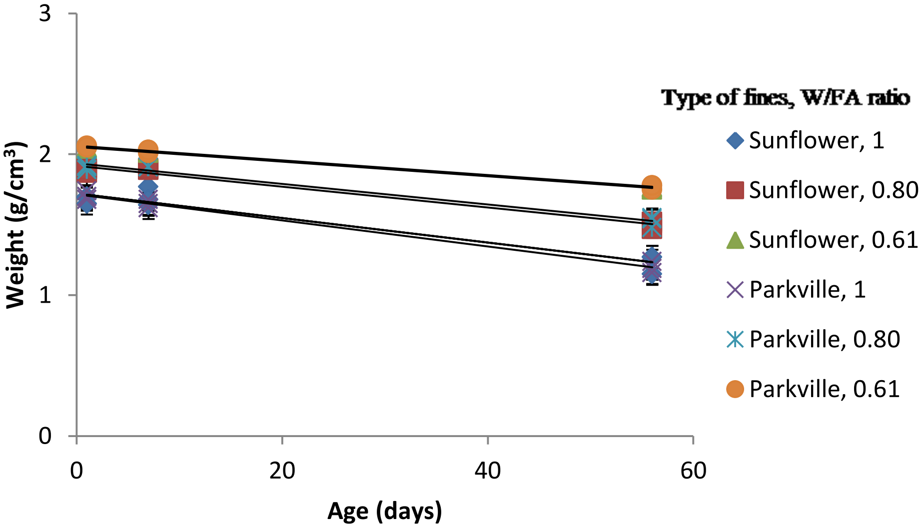


Figure 4-10: Plot of standard deviation in weight with 10 % gypsum without air entrainment

Table 4-12 Result of Weight with 15% Gypsum without Air Entrainment

| Type of Quarry Fines | Weight | | | W/FA |
|---|---|---|---|---|
| | At 1 day ($g/cm^3$) [pcf] | At 7 day ($g/cm^3$) [pcf] | At 56 day ($g/cm^3$) [pcf] | |
| Sunflower | 1.68 [105] | 1.75 [109] | 1.15 [73] | 1 |
| Sunflower | 1.88 [118] | 1.88 [118] | 1.56 [97] | 0.80 |
| Sunflower | 2.05 [128] | 2.03 [126] | 1.76 [111] | 0.61 |
| Parkville | 1.71 [107] | 1.73 [109] | 1.23 [76] | 1 |
| Parkville | 1.87 [118] | 1.90 [119] | 1.56 [97] | 0.80 |
| Parkville | 2.07 [130] | 2.04 [128] | 1.77 [111] | 0.61 |

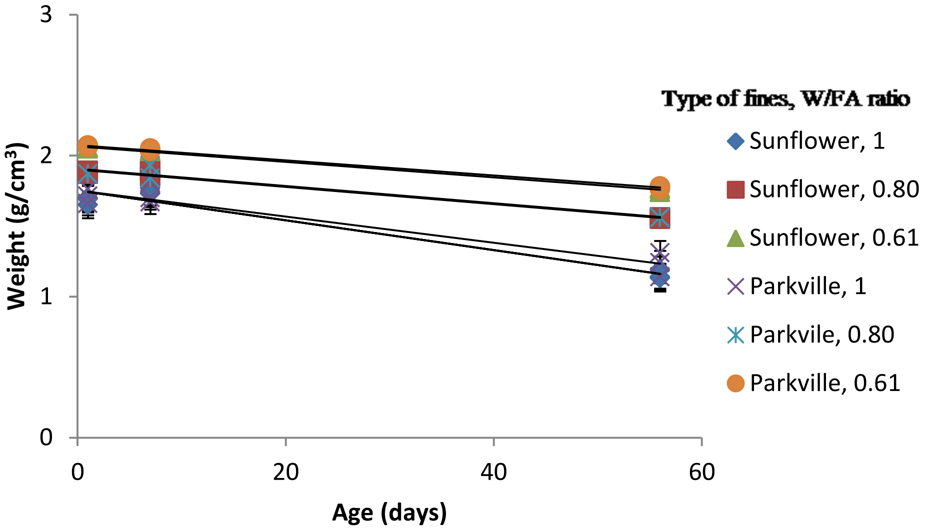


Figure 4-11: Plot of standard deviation in weight with 15 % gypsum without air entrainment

Table 4-13 Result of Weight with 20% Gypsum without Air Entrainment

| Type of Quarry Fines | Weight | | | W/FA |
|---|---|---|---|---|
| | At 1 day ($g/cm^3$) [pcf] | At 7 day ($g/cm^3$) [pcf] | At 56 day ($g/cm^3$) [pcf] | |
| Sunflower | 1.69 [105] | 1.67 [104] | 1.18 [73] | 1 |
| Sunflower | 1.87 [118] | 1.89 [118] | 1.48 [92] | 0.80 |
| Sunflower | 2.05 [128] | 2.04 [128] | 1.75 [109] | 0.61 |
| Parkville | 1.69 [105] | 1.67 [104] | 1.13 [71] | 1 |
| Parkville | 1.87 [118] | 1.88 [118] | 1.50 [93] | 0.80 |
| Parkville | 2.05 [128] | 2.04 [128] | 1.77 [111] | 0.61 |

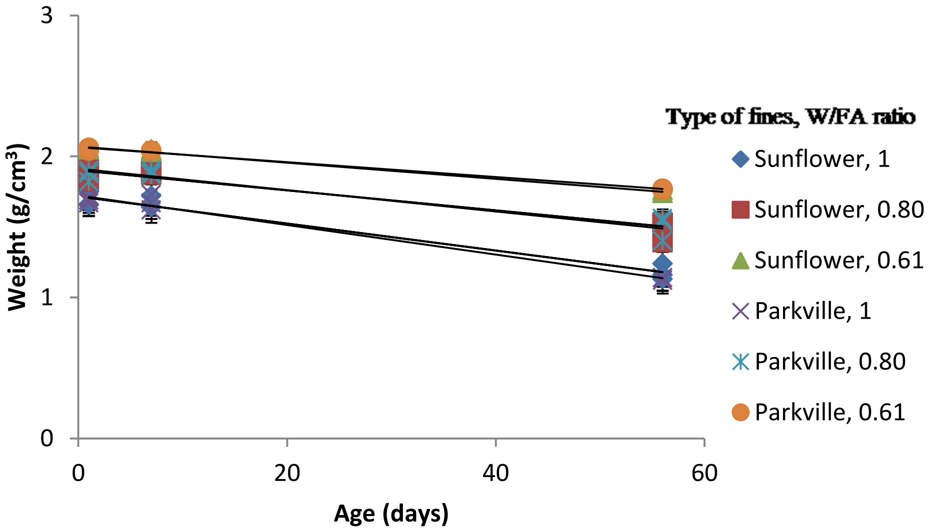


Figure 4-12: Plot of standard deviation in weight with 20 % gypsum without air entrainment

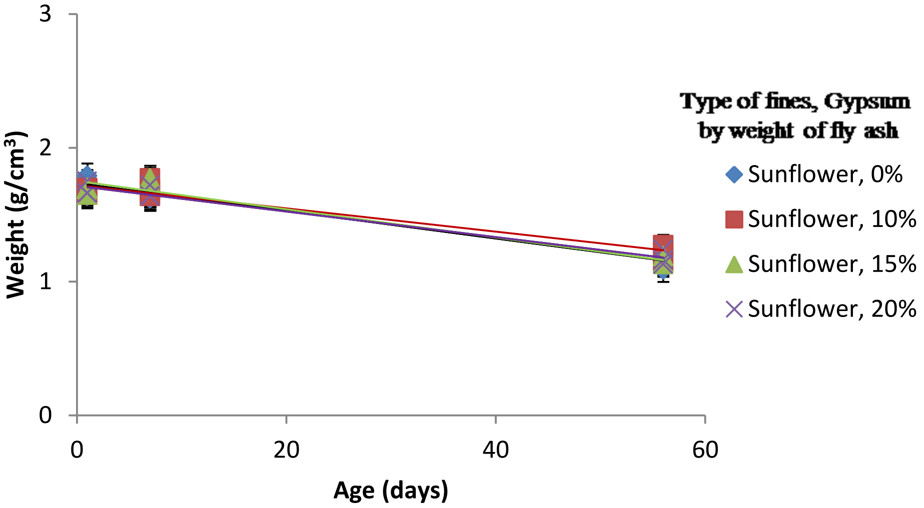


Figure 4-13: Plot of standard deviation in weight for Sunflower quarry fines with W/FA of 1 without air entrainment

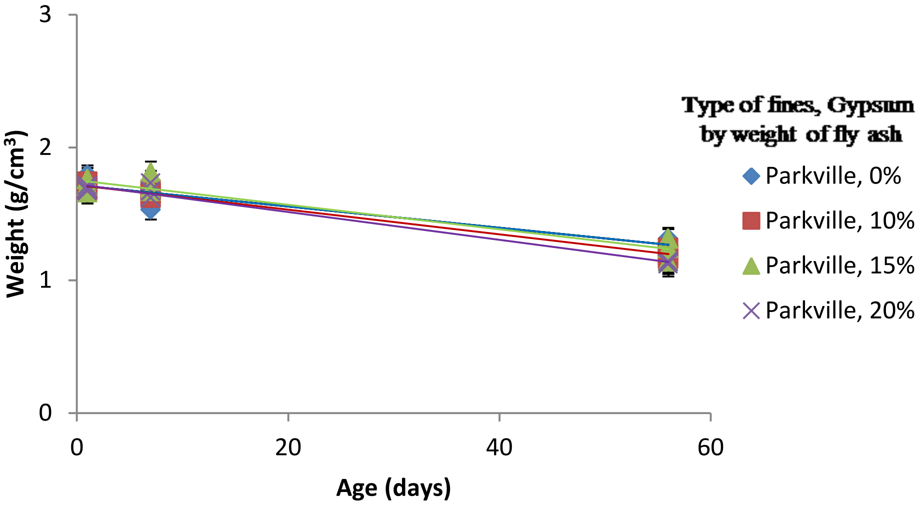


Figure 4-14: Plot of standard deviation in weight for Parkville quarry fines with W/FA of 1 without air entrainment

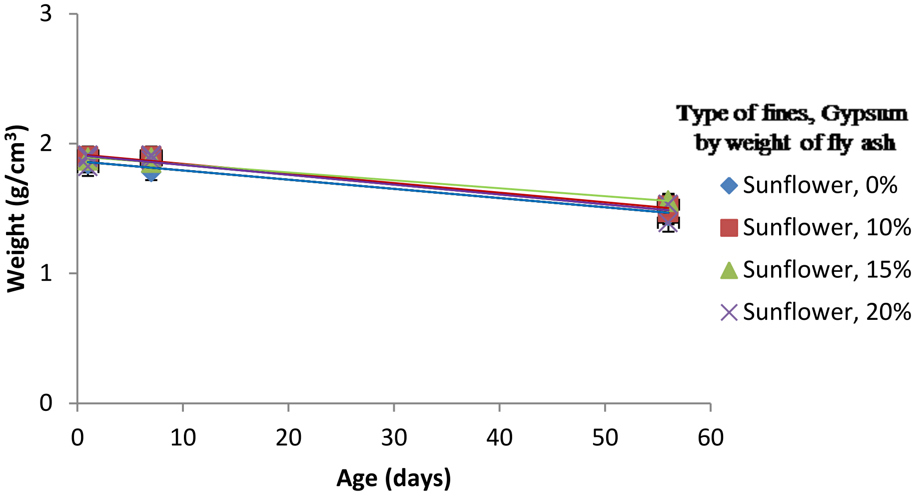


Figure 4-15: Plot of standard deviation in weight for Sunflower quarry fines with W/FA of 0.80 without air entrainment

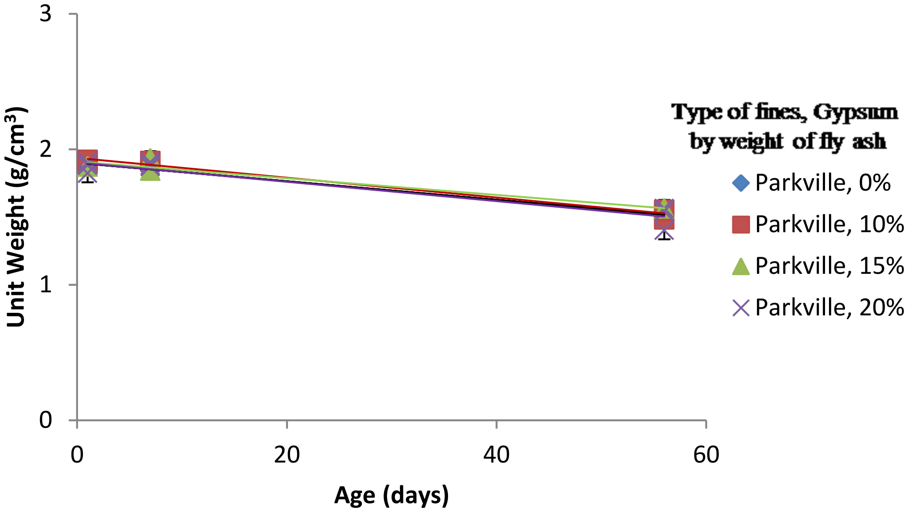


Figure 4-16: Plot of standard deviation in weight for Parkville quarry fines with W/FA of 0.80 without air entrainment

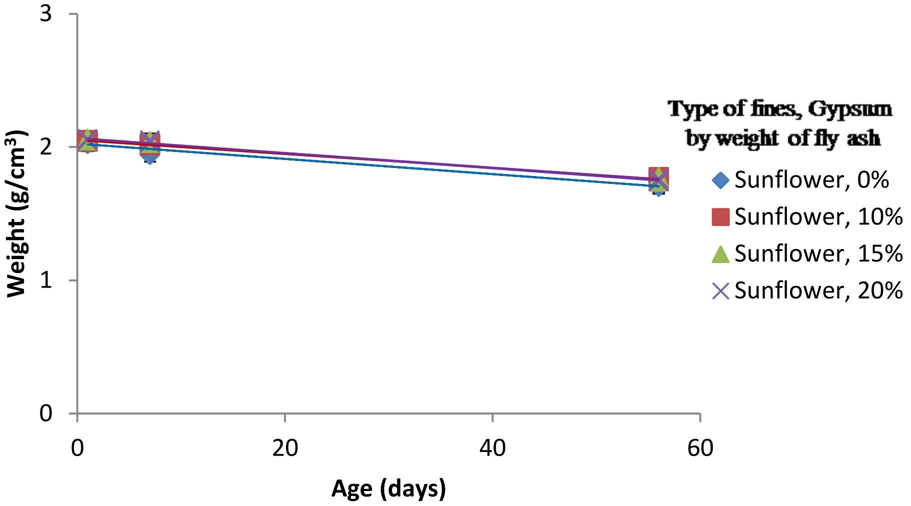


Figure 4-17: Plot of standard deviation in weight for Sunflower quarry fines with W/FA of 0.61 without air entrainment

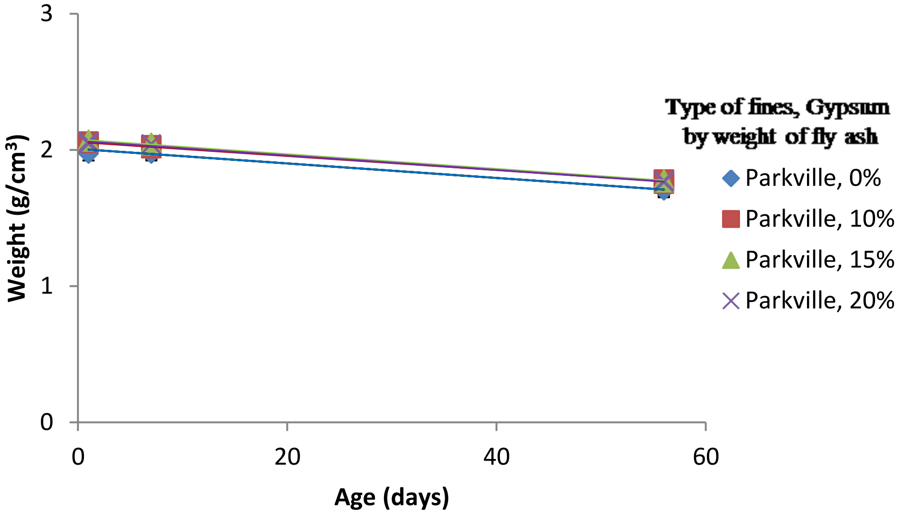


Figure 4-18: Plot of standard deviation in weight for Parkville quarry fines with W/FA of 0.61 without air entrainment

4.30 show the elastic modulus of samples with varying gypsum amount and different W/FA for Sunflower and Parkville quarry fines, respectively. Figures 4.31 and 4.32 show the Poisson’s ratio of samples with varying gypsum amount and different W/FA for Sunflower and Parkville quarry fines, respectively. Samples of mixture without gypsum could not be tested for elastic modulus and Poisson’s ratio due to their low strength at 7 days. The results are shown for W/FA of 0.61 and 0.80 for each gypsum percentage by weight of fly ash. Samples with W/FA of 1 were weak to obtain the elastic modulus and Poisson’s ratio. For a given percentage of gypsum by weight of fly ash, the value of elastic modulus and Poisson’s ratio increased with a decrease in W/FA. Similar results were obtained with both Sunflower and Parkville quarry fines. It could be seen that increasing the gypsum percentage by weight of fly ash from 10, 15, and 20 did not lead to consistent increase or decrease in the results of elastic modulus and Poisson’s ratio. According to Elson, typical value of elastic modulus of subgrade soil as homogeneous elastic material is considered within the range of 5 to 20 MPa (0.5 to 3 ksi). Also, according to Elson, the Poisson’s ratio of subgrade soil as homogeneous elastic material is considered within the range of 0.30 to 0.40 [62]. The value of elastic modulus of concrete is generally considered to be 27579.20 MPa (4,000 ksi) and the Poisson’s ratio of concrete is considered within the range of 0.15 to 0.20 [63].

## 4.6. Fresh and Hardened Properties with Air Entrainment

The results of flow diameter, setting time, unconfined compressive stress, elastic modulus, and Poisson’s ratio of samples with air entrainment are discussed in the following sections. The mixtures with 15 and 20 % gypsum by weight of fly ash and W/FA of 0.61 and 0.80 were evaluated with air entrainer as discussed in chapter 3. The results were compared to the fresh and hardened properties of the corresponding mixtures without air entrainment.

Table 4-14 Result of Compressive Strength with 0% Gypsum without Air Entrainment

| Type of Quarry Fines | Compressive Strength | | | W/FA |
|---|---|---|---|---|
| | At 1 day (kPa) [psi] | At 7 day (kPa) [psi] | At 56 day (kPa) [psi] | |
| Sunflower | 10.4, 11.5, 12.6<br>[1.5, 1.7, 1.8] | 19.7, 21.4, 21.4<br>[2.9, 3.1, 3.1] | 32.9, 32.8, 40.2<br>[4.8, 4.8, 5.8] | 1 |
| Sunflower | 15.3,15.9, 14.8<br>[2.2, 2.3, 2.2] | 18.7, 24.1, 23.0<br>[2.7, 3.5, 3.3] | 52.1, 44.1, 52.6<br>[7.6, 6.4, 7.6] | 0.80 |
| Sunflower | 24.1, 25.8, 30.1<br>[3.5, 3.7, 4.4] | 53.7, 58.1, 52.6<br>[7.8, 8.4, 7.6] | 114.1, 101.1<br>[16.6, 14.7] | 0.61 |
| Parkville | 12.7, 13.1, 13.7<br>[1.8, 1.9, 2.0] | 14.3, 13.7, 15.3<br>[2.1, 2.0, 2.2] | 34.5, 31.8<br>[5.0, 4.6] | 1 |
| Parkville | 15.3, 15.3, 15.9<br>[2.2, 2.2, 2.3] | 21.4, 25.2, 28.0<br>[3.1, 3.6, 4.1] | 65.0, 77.6<br>[9.4, 11.3] | 0.80 |
| Parkville | 21.9, 24.1, 23.6<br>[3.2, 3.5, 3.4] | 55.9, 68.6, 55.9<br>[8.1, 10.0, 8.1] | 151.6, 165.9<br>[22.0, 24.1] | 0.61 |

Table 4-15 Result of Compressive Strength with 10% Gypsum without Air Entrainment

| Type of Quarry Fines | Compressive Strength | | | W/FA |
|---|---|---|---|---|
| | At 1 day (kPa) [psi] | At 7 day (kPa) [psi] | At 56 day (kPa) [psi] | |
| Sunflower | 17.7, 16.6, 20.7<br>[2.6, 2.4, 3.0] | 220.7, 236.2, 241.1<br>[32.0, 34.3, 35.0] | 136.3, 134.9, 146.4<br>[19.8, 19.6, 21.1] | 1 |
| Sunflower | 60.7, 58.7, 60.1<br>[8.8, 8.5, 8.7] | 439.6, 552.2, 470.7<br>[63.8, 80.1, 68.3] | 215.5, 330.9, 396.9<br>[31.3, 48.0, 57.6] | 0.80 |
| Sunflower | 253.8, 236.4, 272.1<br>[36.8, 34.3, 39.5] | 1425.2, 1314.0, 1548.6<br>[206.7, 190.6, 224.6] | 1315.3, 1353.8, 1147.6<br>[190.8, 196.4, 166.5] | 0.61 |
| Parkville | 35.6, 25.6<br>[5.2, 3.7] | 210.5, 221.8, 229.4<br>[30.5, 32.2, 33.3] | 121.4, 124.9, 126.8<br>[17.6, 18.1, 18.4] | 1 |
| Parkville | 76.6, 69.6, 80.6<br>[11.2, 10.1, 11.7] | 475.1, 425.7, 467.1<br>[68.9, 61.7, 67.8] | 327.5, 347.7, 379.7<br>[47.5, 50.4, 55.1] | 0.80 |
| Parkville | 276.8, 286.9, 280.5<br>[40.2, 41.6, 40.7] | 1564.2, 1455.6, 1540.2<br>[226.9, 211.2, 223.4] | 1442.7, 1488.2, 1311.9<br>[209.3, 215.9, 190.3] | 0.61 |

Table 4-16 Result of Compressive strength with 15% Gypsum without Air Entrainment

| **Type of Quarry Fines** | **Compressive Strength** | | | **W/FA** |
|---|---|---|---|---|
| | **At 1 day (kPa) [psi]** | **At 7 day (kPa) [psi]** | **At 56 day (kPa) [psi]** | |
| Sunflower | 23.3, 17.6, 14.5<br>[3.4, 2.6, 2.1] | 193.1, 146.3, 186.3<br>[28.0, 21.2, 27.0] | 136.0, 135.5, 122.8<br>[19.7, 19.7, 17.8] | 1 |
| Sunflower | 42.3, 52.6<br>[6.1, 7.6] | 361.9, 513.8<br>[52.5, 74.5] | 406.3, 316.3, 463.7<br>[58.9, 45.9, 67.3] | 0.80 |
| Sunflower | 215.4, 272.0, 303.6<br>[31.2, 39.5, 44.0] | 1098.0, 1403.1, 1228.1<br>[159.3, 203.5, 178.1] | 1121.7, 1311.7, 1260.6<br>[162.7, 190.3, 182.8] | 0.61 |
| Parkville | 20.7, 26.5, 26.4<br>[3.0, 3.8, 3.8] | 241.4, 183.2, 207.7<br>[35.0, 26.6, 30.1] | 172.5, 190.1, 146.5<br>[25.0, 27.6, 21.3] | 1 |
| Parkville | 43.0, 28.7<br>[6.2, 4.2] | 376.1, 277.9, 361.9<br>[54.6, 40.3, 52.5] | 440.7, 387.8, 474.9<br>[63.9, 56.3, 68.9] | 0.80 |
| Parkville | 274.5, 295.4, 291.0<br>[39.8, 42.8, 42.2] | 1300.9, 1428.3, 1481.1<br>[188.7, 207.2, 214.8] | 1568.9, 1489.5, 1578.5<br>[227.6, 216.0, 228.9] | 0.61 |

Table 4-17 Result of Compressive Strength with 20% Gypsum without Air Entrainment

| **Type of Quarry Fines** | **Compressive Strength** | | | **W/FA** |
|---|---|---|---|---|
| | **At 1 day (kPa) [psi]** | **At 7 day (kPa) [psi]** | **At 56 day (kPa) [psi]** | |
| Sunflower | 30.4, 33.1<br>[4.4, 4.8] | 99.4, 89.3, 108.3<br>[14.4, 13.0, 15.7] | 147.3, 101.8, 156.0<br>[21.4, 14.8, 22.6] | 1 |
| Sunflower | 36.9, 34.7<br>[5.4, 5.0] | 482.3, 476.4, 325.9<br>[70.0, 69.1, 47.3] | 462.3, 415.8<br>[67.1, 60.3] | 0.80 |
| Sunflower | 273.9, 286.9, 320.0<br>[39.7, 41.6, 46.4] | 1150.3, 1225.5, 1241.8<br>[166.8, 177.7, 180.1] | 1715.9, 1245.0, 1295.9<br>[248.9, 180.6, 188.0] | 0.61 |
| Parkville | 27.1, 38.8<br>[3.9, 5.6] | 147.0, 85.1, 99.9<br>[21.3, 12.3, 14.5] | 134.3, 138.8, 178.8<br>[19.5, 20.1, 25.9] | 1 |
| Parkville | 54.4, 45.9, 47.3<br>[7.9, 6.7, 6.9] | 457.4, 409.5, 465.8<br>[66.3, 59.4, 67.6] | 501.3, 305.8, 375.8<br>[72.7, 44.4, 54.5] | 0.80 |
| Parkville | 203.7, 250.1, 249.0<br>[29.5, 36.3, 36.1] | 1021.1, 1018.4, 1101.4<br>[148.1, 147.7, 159.7] | 1610.6, 1535.4, 1240.2<br>[233.6, 222.7, 179.9] | 0.61 |

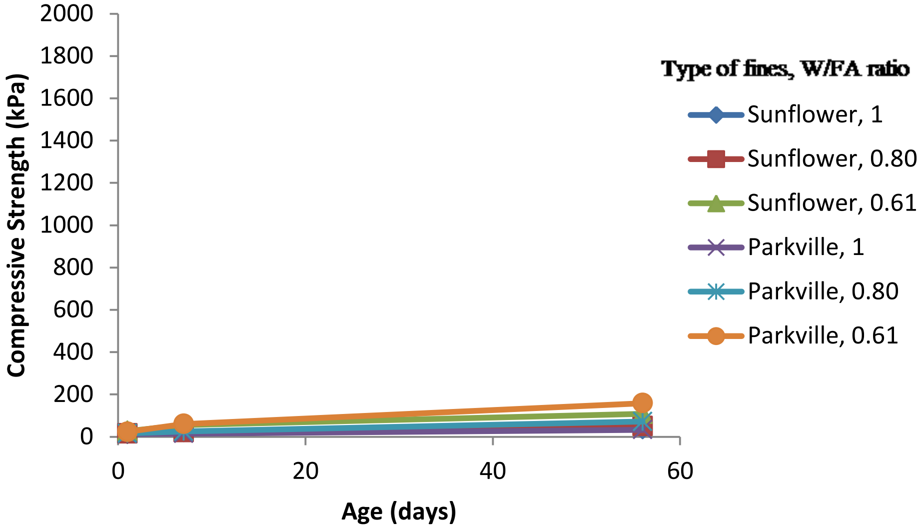


Figure 4-19: Plot of compressive strength result for 0 % gypsum without air entrainment

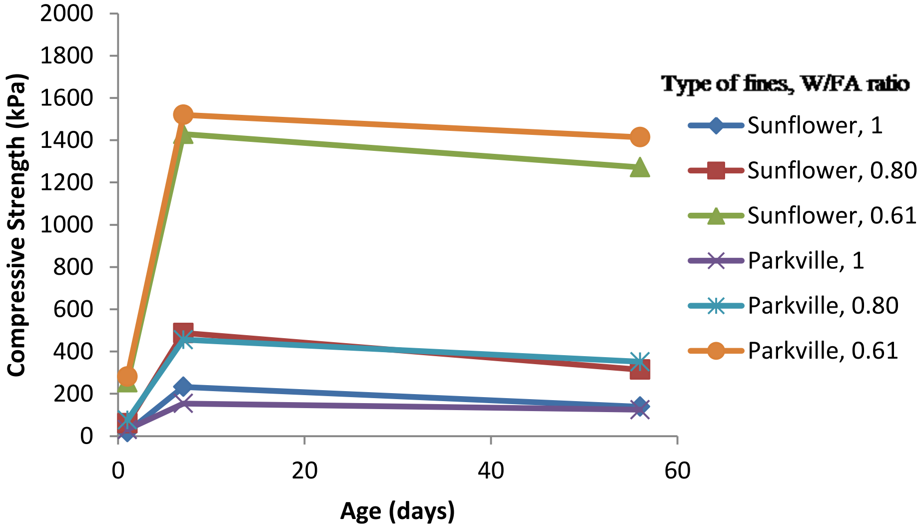


Figure 4-20: Plot of compressive strength result for 10% gypsum without air entrainment

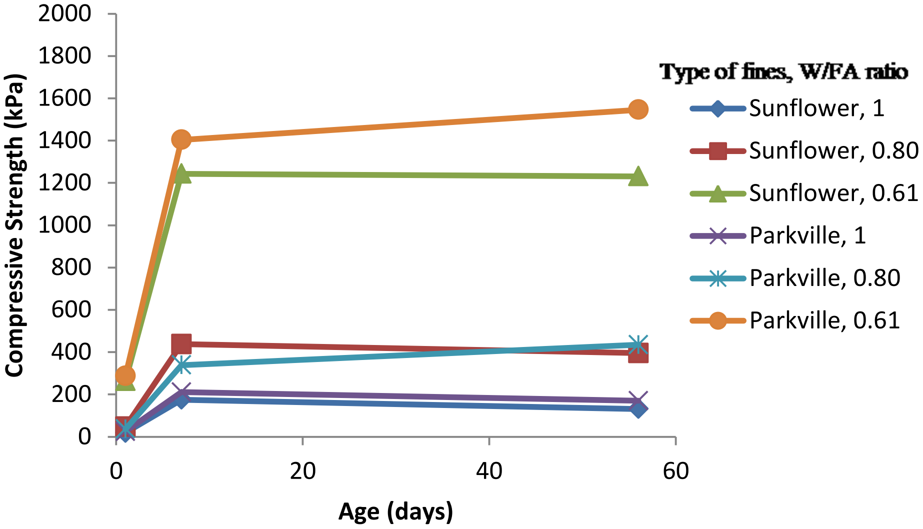


Figure 4-21: Plot of compressive strength result for 15 % gypsum without air entrainment

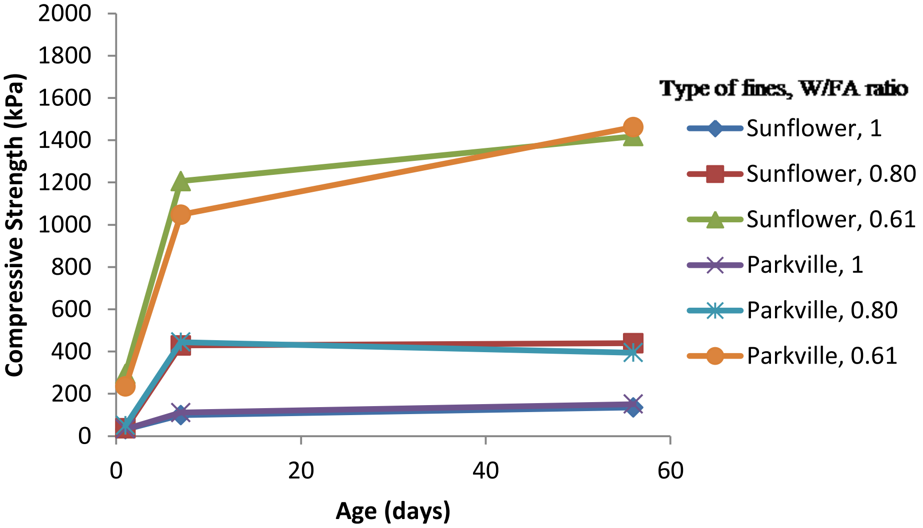


Figure 4-22: Plot of compressive strength result for 20% gypsum without air entrainment

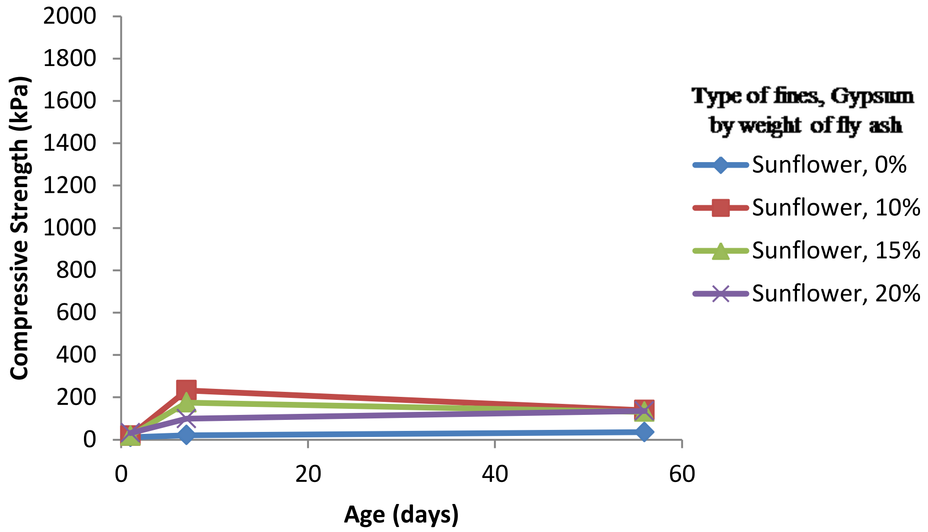


Figure 4-23: Plot of compressive strength result for Sunflower quarry fines with W/FA of 1 without air entrainment

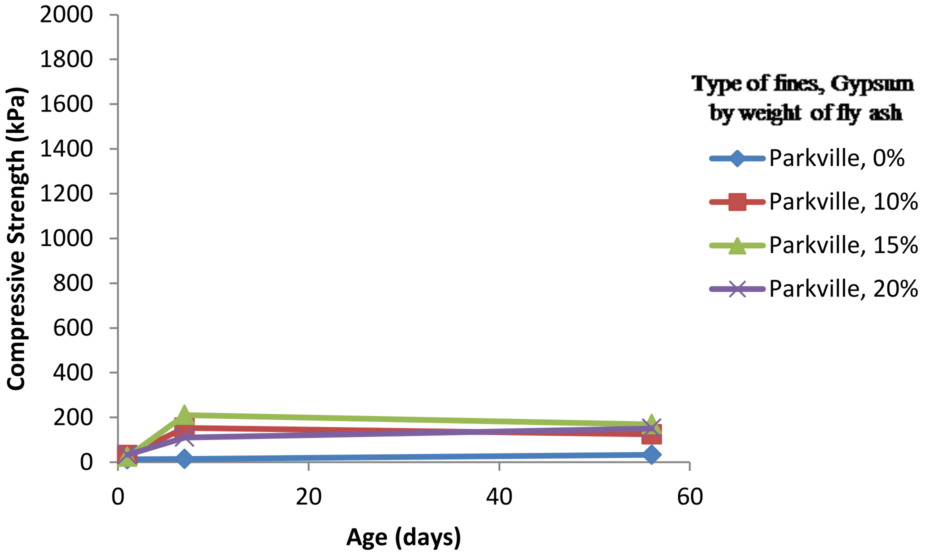


Figure 4-24: Plot of compressive strength result for Parkville quarry fines with W/FA of 1 without air entrainment

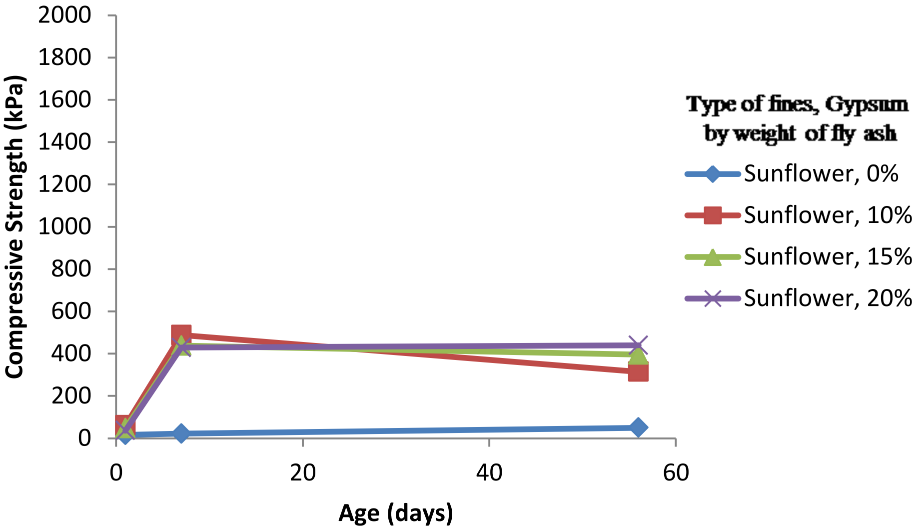


Figure 4-25: Plot of compressive strength result for Sunflower quarry fines with W/FA of 0.80 without air entrainment

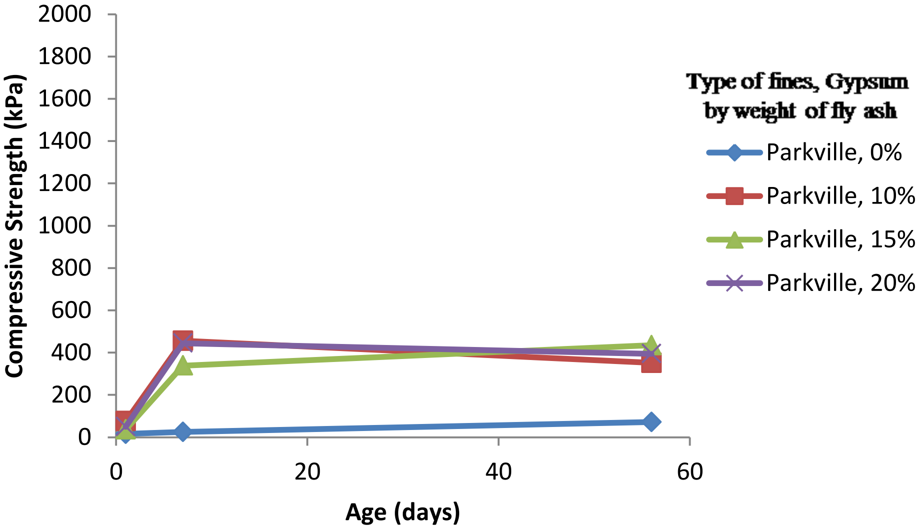


Figure 4-26: Plot of compressive strength result for Parkville quarry fines with W/FA of 0.80 without air entrainment

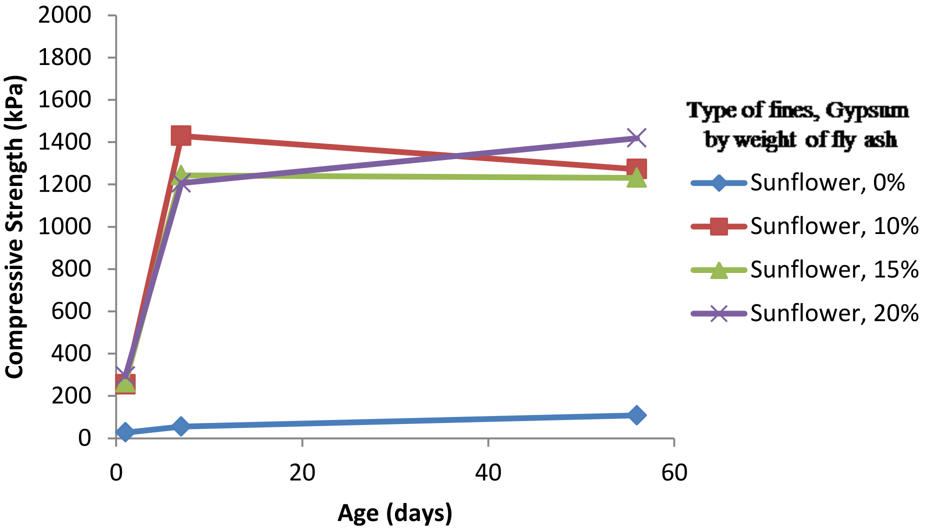


Figure 4-27: Plot of compressive strength result for Sunflower quarry fines with W/FA of 0.61 without air entrainment

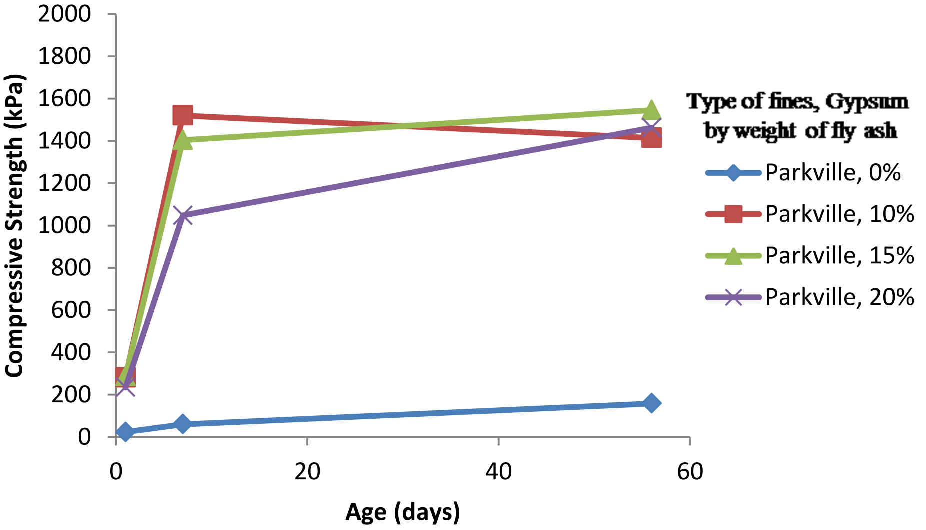


Figure 4-28: Plot of compressive strength result for Parkville quarry fines with W/FA of 0.61 without air entrainment

Table 4-18 Result of Elastic Modulus and Poisson's Ratio with 10% Gypsum without Air Entrainment

| Type of Quarry Fines | 7 day Elastic Modulus (MPa) [ksi] | Poisson's Ratio | W/FA |
|---|---|---|---|
| Sunflower | 689.48 [100] | 0.13 | 0.80 |
| Sunflower | 3102.66 [450] | 0.25 | 0.61 |
| Parkville | 1378.96 [200] | 0.21 | 0.80 |
| Parkville | 3102.66 [450] | 0.24 | 0.61 |

Table 4-19 Result of Elastic Modulus and Poisson's Ratio with 15% Gypsum without Air Entrainment

| Type of Quarry Fines | 7 day Elastic Modulus (MPa) [ksi] | Poisson's Ratio | W/FA |
|---|---|---|---|
| Sunflower | 1034.22 [150] | 0.17 | 0.80 |
| Sunflower | 2757.92 [400] | 0.24 | 0.61 |
| Parkville | 689.48 [100] | 0.19 | 0.80 |
| Parkville | 3102.66 [450] | 0.28 | 0.61 |

Table 4-20 Result of Elastic Modulus and Poisson's Ratio with 20% Gypsum without Air Entrainment

| Type of Quarry Fines | 7 day Elastic Modulus (MPa) [ksi] | Poisson's Ratio | W/FA |
|---|---|---|---|
| Sunflower | 689.48 [100] | 0.12 | 0.80 |
| Sunflower | 2413.18 [350] | 0.20 | 0.61 |
| Parkville | 689.48 [100] | 0.15 | 0.80 |
| Parkville | 2413.18 [350] | 0.22 | 0.61 |

The unconfined compressive strength results after subjecting the samples to 12 cycles of freeze-thaw testing were compared for samples with and without air entrainment. These results will provide an understanding of the effect of air entrainment on fresh and hardened

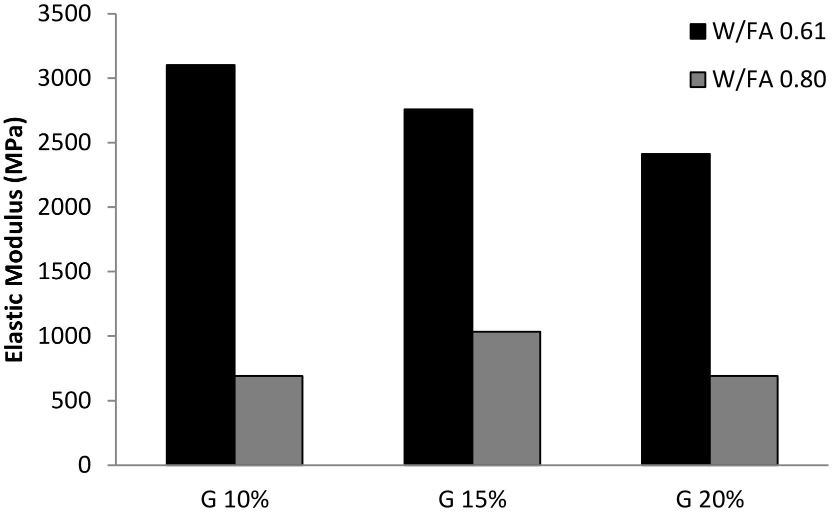


Figure 4-29: Plot of elastic modulus with varying gypsum amount and different W/FA without air entrainment for Sunflower quarry fines

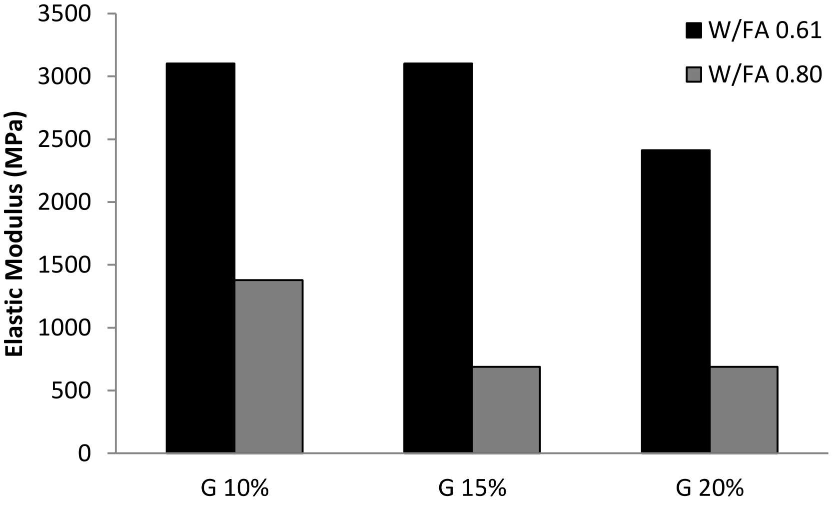


Figure 4-30: Plot of elastic modulus with varying gypsum amount and different W/FA without air entrainment for Parkville quarry fines

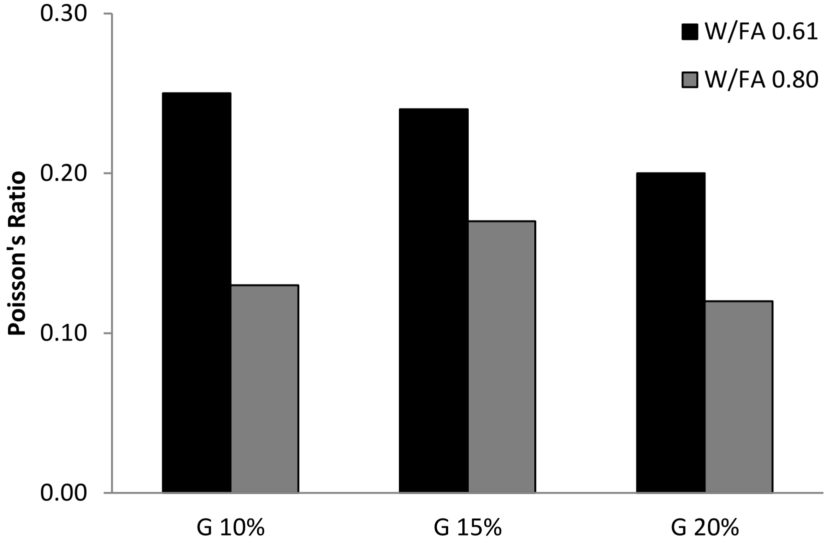


Figure 4-31: Plot of Poisson's ratio with varying gypsum amount and different W/FA without air entrainment for Sunflower quarry fines

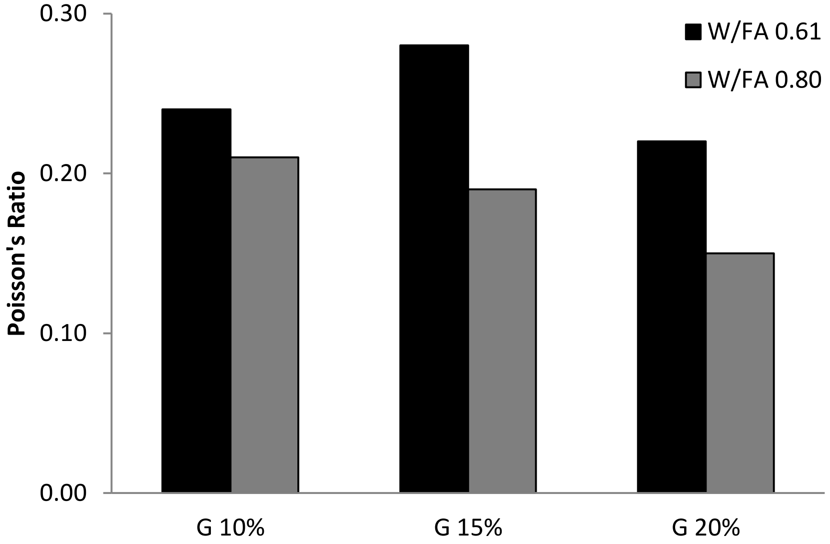


Figure 4-32: Plot of Poisson's ratio with varying gypsum amount and different W/FA without air entrainment for Parkville quarry fines

properties of CLSM.

### 4.6.1. Flow Value and Setting Time

Tables 4.21 and 4.22 show flow diameter and initial setting time for air entrained mixtures with 15 % and 20 % gypsum by weight of fly ash, respectively. The results are shown for W/FA of 0.61 and 0.80 for each gypsum percentage by weight of fly ash and for both quarry fine types. Flow values obtained after mixing the materials for 90 seconds and 30 minutes are shown for each mixture. Similar to mixtures without air entrainment flow values both after 90 second and 30 minutes and setting time increased with the increase in the W/FA for a given gypsum percentage by weight of fly ash. Figures 4.33 and 4.34 show the comparison of flow diameter at 90 sec for mixtures with and without air entrainment for Sunflower and Parkville quarry fines, respectively. Figures 4.35 and 4.36 show the comparison of flow diameter at 30 min for mixtures with and without air entrainment for Sunflower and Parkville quarry fines, respectively. Figures 4.37 and 4.38 show the comparison of setting time for mixtures with and without air entrainment for Sunflower and Parkville quarry fines, respectively. Result shows that air entrainment generally has an increasing effect on the flow value, however it also increases the setting time, especially for mixtures with higher W/FA.

### 4.6.2. Weight

Tables 4.23 and 4.24 show weight of air entrained mixtures with 15 and 20 % gypsum by weight of fly ash, respectively. The results are averages of three samples for W/FA of 0.61 and 0.80 and for both quarry fines. It should be noted that air entrained samples with 15 % gypsum were too weak at 1 day and broke during the removal of molds, therefore their mass could not be determined. Evaluation of results showed similar trends as observed for the samples without air entrainment. All cured samples lost water over time and their mass decreased and weights were substantially lower at 56 days. Again similar to the samples without air entrainment, weights of mixtures with higher W/FA (0.80) were smaller compared to samples with W/FA of 0.61. Figures 4.39 and 4.40 show the change in average weights over time for the CLSM mixtures with 15 and 20 % gypsum by weight of fly ash, respectively. Figures 4.41 and 4.42 show the change in average weights over time for CLSM mixtures with the same W/FA. The error bars in Figures 4.39 through 4.42 show the standard deviation at each age. Figures 4.43, 4.44, 4.45 and 4.46 show that the weight of samples with air entrainment is lower compared to the average weight of samples without air entrainment for a given gypsum percentage by weight of fly ash and W/FA.

### 4.6.3. Unconfined Compressive Strength

Tables 4.25 and 4.26 show the unconfined compressive strength of air entrained mixtures with 15 and 20 % gypsum by weight of fly ash, respectively. The results are shown for W/FA of 0.61 and 0.80 for each gypsum percentage by weight of fly ash and for both quarry fines. Values of samples tested at each age are shown in Tables. Air entrained samples with 15 % gypsum and W/FA of 0.80 were too weak to be tested for unconfined compressive strength at 1-day. Figures 4.47 and 4.48 show the compressive strength development of air entrained mixtures with 15 and 20 % gypsum by weight of fly ash, respectively. Results indicate that the compressive strength increased with increased age up to 56 days. Similar to samples without air entrainment, the W/FA was an important variable and samples with W/FA 0.61 had higher compressive strength at all ages compared to samples with W/FA of 0.80. Similar to non-air entrained samples quarry type did not have a substantial effect on the compressive strength. Figures 4.49 and 4.50 show the compressive strength results of samples with the same W/FA. Results indicate that similar to the non-air entrained samples the gypsum content had an effect on the compressive strength. Samples with 20 % by weight of fly ash had higher compressive strength at the same W/FA values. Figures 4.51 and 4.52 compare the compressive strength results of air entrained and non-air entrained samples with 15 and 20 % gypsum, respectively. Both figures show that the strength of air entrained samples were lower at 1 and 7 days compared to samples without air entrainment. At 56 days however, results show that the average strength of air entrained samples were higher. The compressive strength of air entrained samples with 15 % gypsum by weight of fly ash and W/FA 0.61 increased most likely compared to the W/FA of 0.80 with same gypsum content. The compressive strength of air entrained samples with 20 % gypsum by weight of fly ash

Table 4-21 Result of Flow Diameter and Setting Time with 15% Gypsum with Air Entrainment

| **Type of Quarry Fines** | **Flow diameter after 90 sec. (mm) [in]** | **Flow diameter after 30 min. (mm) [in]** | **Setting Time (min)** | **W/FA** |
|---|---|---|---|---|
| Sunflower | 675 [26.50] | 455 [18.00] | 650 | 0.80 |
| Sunflower | 445 [17.50] | 235 [9.25] | 123 | 0.61 |
| Parkville | 620 [24.50] | 485 [19.00] | 601 | 0.80 |
| Parkville | 465 [18.25] | 220 [8.75] | 119 | 0.61 |

Table 4-22 Result of Flow Diameter and Setting Time with 20% Gypsum with Air Entrainment

| **Type of Quarry Fines** | **Flow diameter after 90 sec. (mm) [in]** | **Flow diameter after 30 min. (mm) [in]** | **Setting Time (min)** | **W/FA** |
|---|---|---|---|---|
| Sunflower | 665 [26.25] | 455 [18.00] | 437 | 0.80 |
| Sunflower | 450 [17.75] | 230 [9.00] | 100 | 0.61 |
| Parkville | 670 [26.25] | 400 [15.75] | 446 | 0.80 |
| Parkville | 455 [18.00] | 240 [9.50] | 111 | 0.61 |

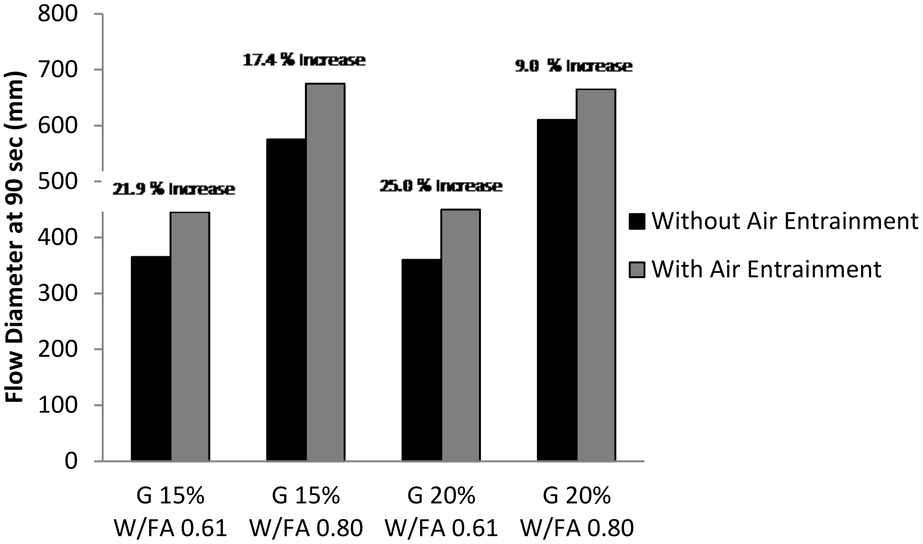


Figure 4-33: Comparison of flow diameter (at 90 sec) for mixtures with and without air entrainment for Sunflower quarry fines

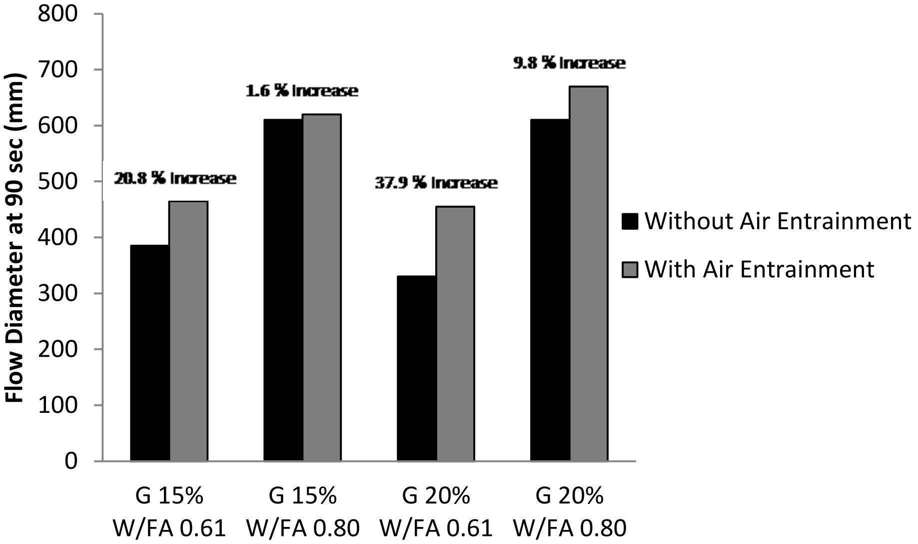


Figure 4-34: Comparison of flow diameter (at 90 sec) for mixtures with and without air entrainment for Parkville quarry fines

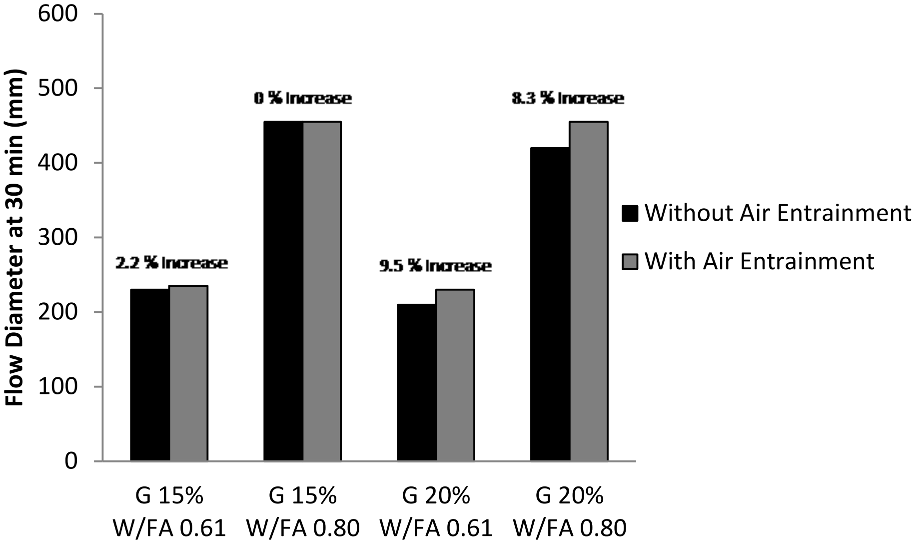


Figure 4-35: Comparison of flow diameter (at 30 min) for mixtures with and without air entrainment for Sunflower quarry fines

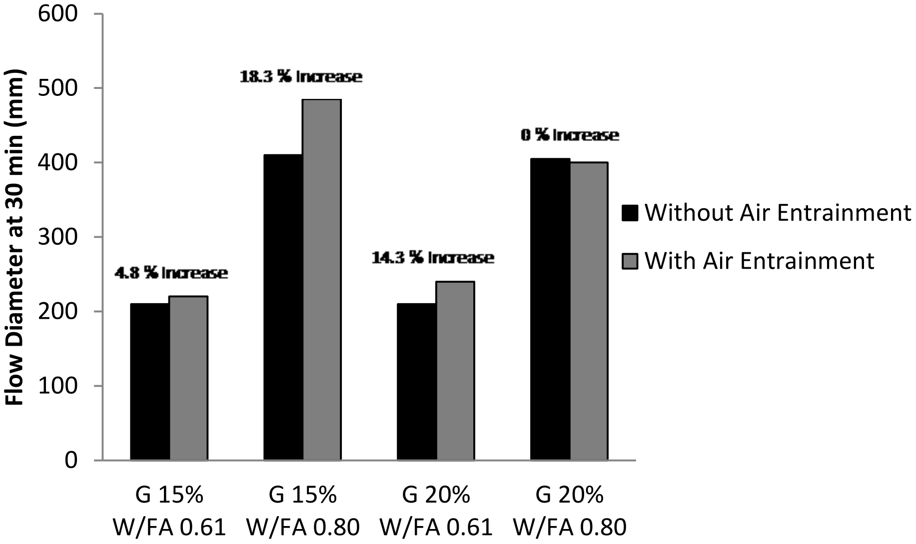


Figure 4-36: Comparison of flow diameter (at 30 min) for mixtures with and without air entrainment for Parkville quarry fines

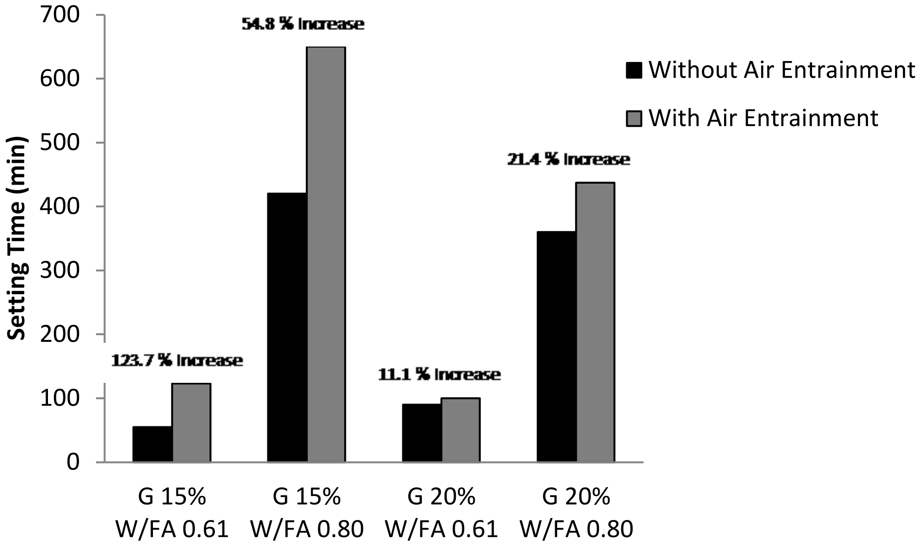


Figure 4-37: Comparison of setting time for mixtures with and without air entrainment for Sunflower quarry fines

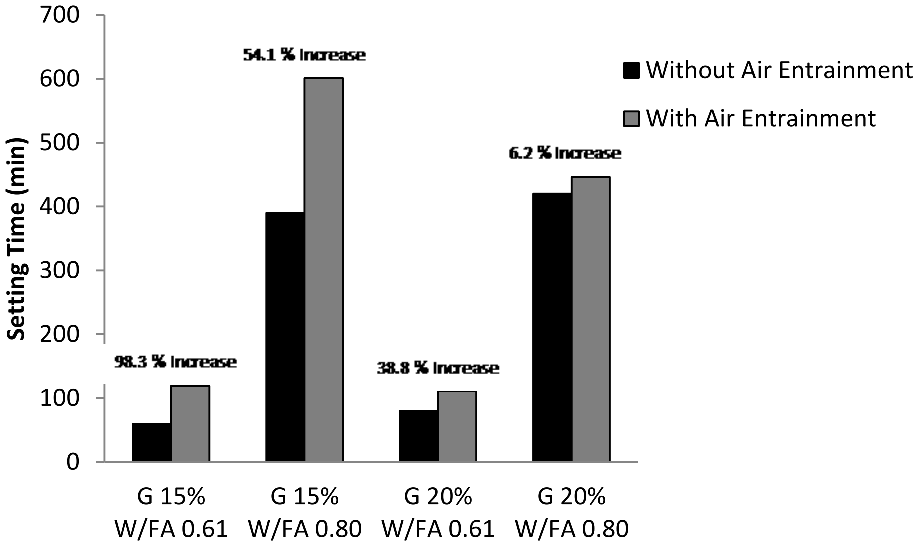


Figure 4-38: Comparison of setting time for mixtures with and without air entrainment for Parkville quarry fines

Table 4-23 Result of weight with 15% gypsum with Air Entrainment

| **Type of Quarry Fines** | **Weight** | | | **W/FA** |
|---|---|---|---|---|
| | **At 1 day ($g/cm^3$) [pcf]** | **At 7 day ($g/cm^3$) [pcf]** | **At 56 day ($g/cm^3$) [pcf]** | |
| Sunflower | - | 1.65 [104] | 1.70 [105] | 0.80 |
| Sunflower | 1.97 [123] | 1.89 [118] | 1.69 [105] | 0.61 |
| Parkville | - | 1.67 [104] | 1.30 [81] | 0.80 |
| Parkville | 2.00 [124] | 1.93 [121] | 1.70 [105] | 0.61 |

Table 4-24 Result of weight with 20% gypsum with Air Entrainment

| **Type of Quarry Fines** | **Weight** | | | **W/FA** |
|---|---|---|---|---|
| | **At 1 day ($g/cm^3$) [pcf]** | **At 1 day ($g/cm^3$) [pcf]** | **At 56 day ($g/cm^3$) [pcf]** | |
| Sunflower | 1.73 [109] | 1.71 [107] | 1.42 [88] | 0.80 |
| Sunflower | 1.98 [123] | 1.91 [119] | 1.69 [105] | 0.61 |
| Parkville | 1.69 [105] | 1.67 [104] | 1.42 [88] | 0.80 |
| Parkville | 2.01 [126] | 1.96 [123] | 1.72 [107] | 0.61 |

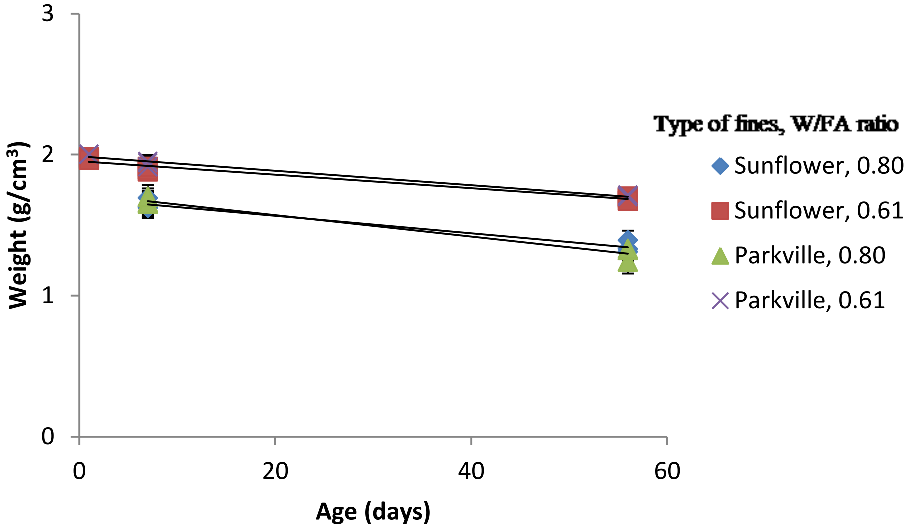


Figure 4-39: Plot of standard deviation in weight with 15 % gypsum with air entrainment

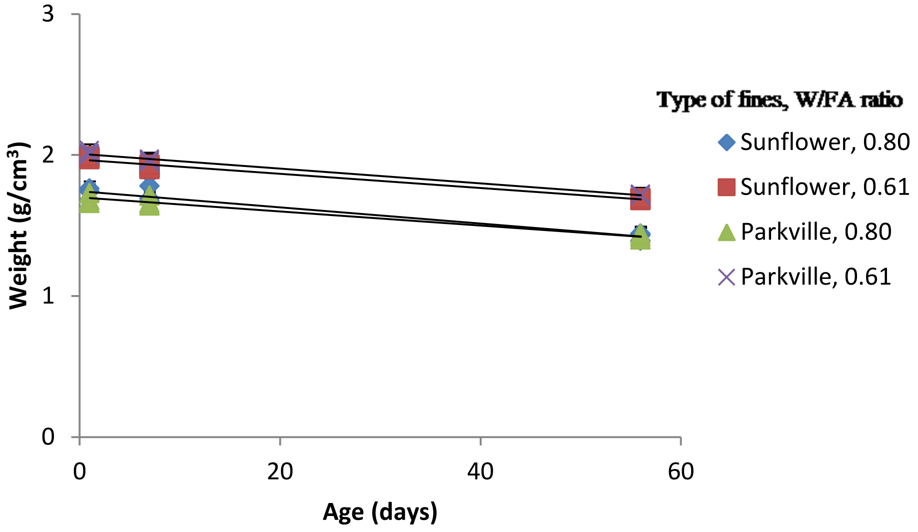


Figure 4-40: Plot of standard deviation in weight with 20 % gypsum with air entrainment

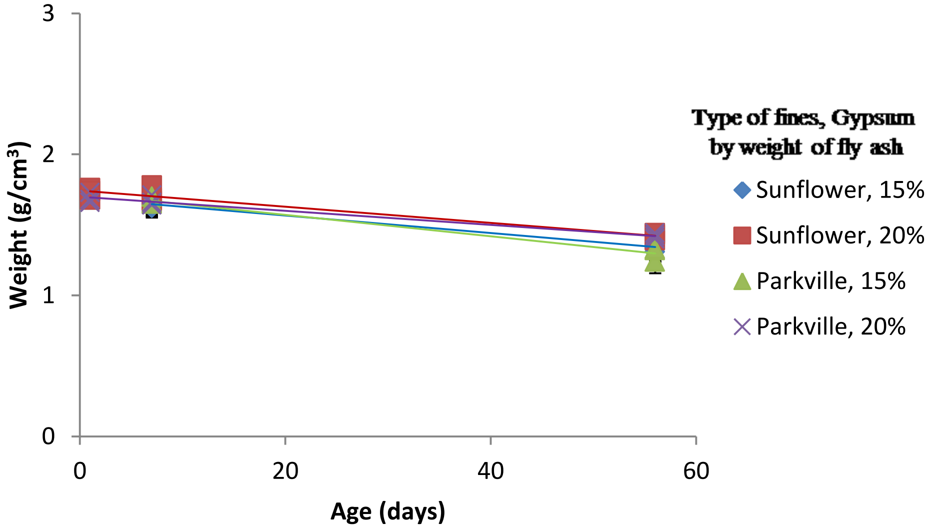


Figure 4-41: Plot of standard deviation in weight with W/FA of 0.80 with air entrainment

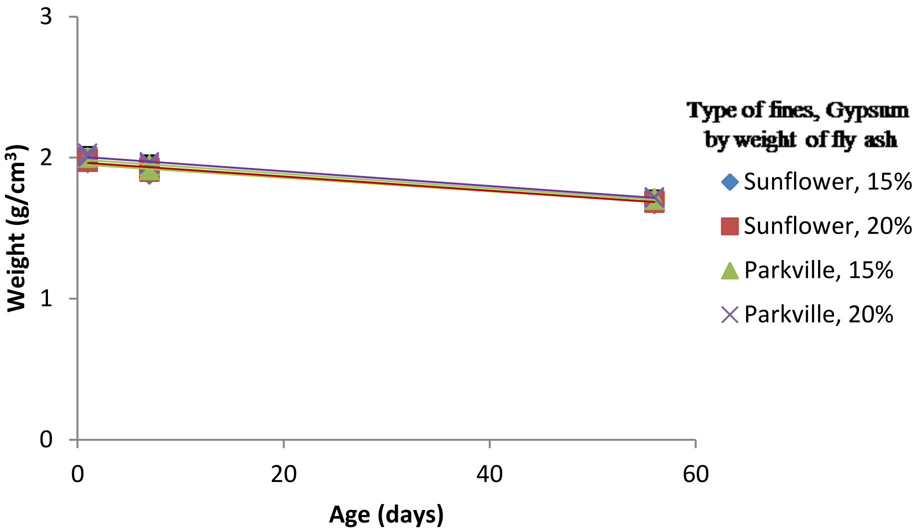


Figure 4-42: Plot of standard deviation in weight with W/FA of 0.61 with air entrainment

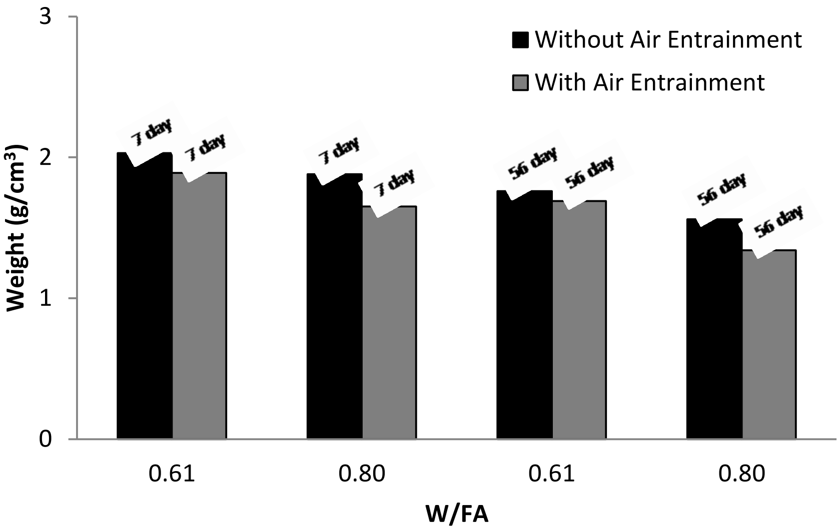


Figure 4-43: Comparison of weight results of air entrained and non-air entrained samples with 15 % gypsum and Sunflower quarry fines

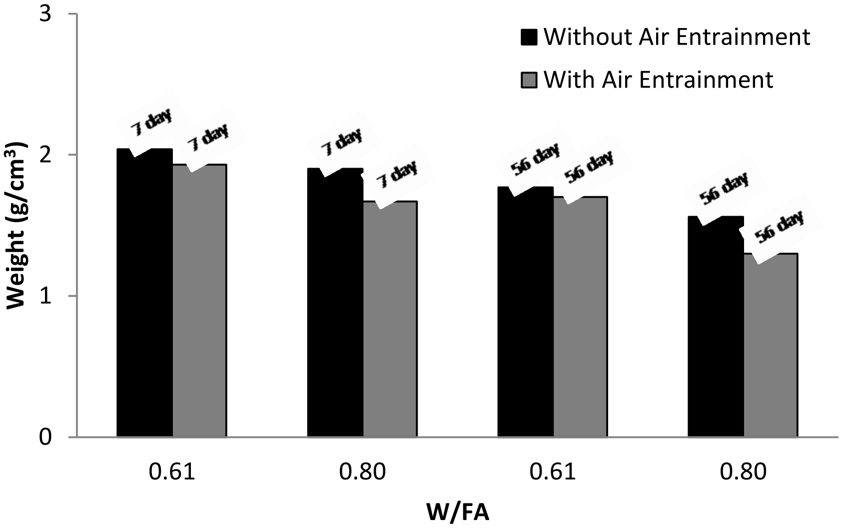


Figure 4-44: Comparison of weight results of air entrained and non-air entrained samples with 15 % gypsum and Parkville quarry fines

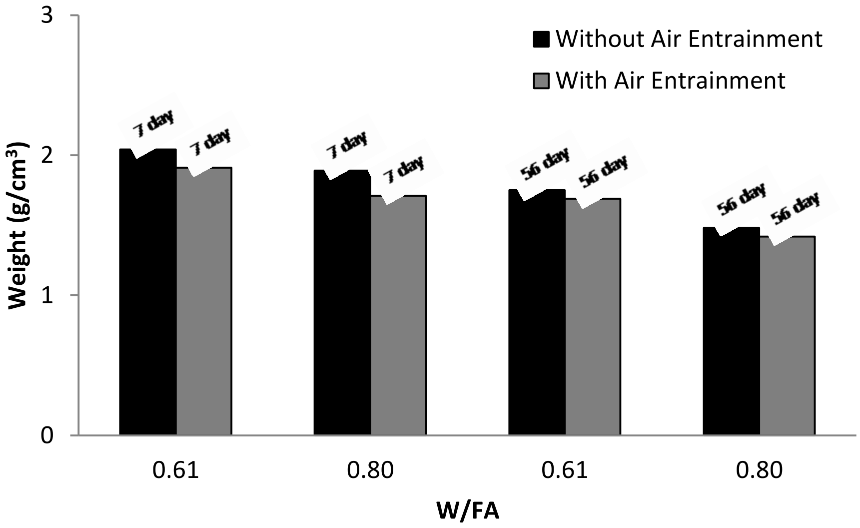


Figure 4-45: Comparison of weight results of air entrained and non-air entrained samples with 20 % gypsum and Sunflower quarry fines

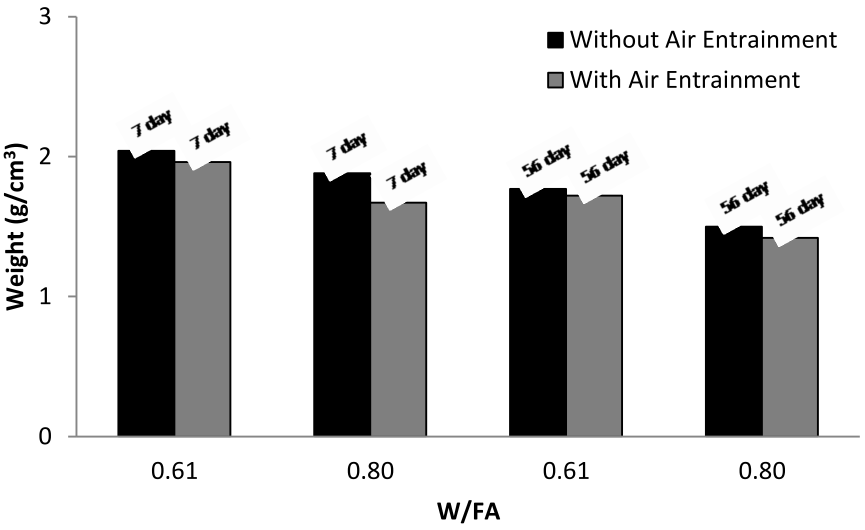


Figure 4-46: Comparison of weight results of air entrained and non-air entrained samples with 20 % gypsum and Parkville quarry fines

and both W/FA of 0.61 and 0.80 increased most likely. The results of unconfined compressive strength at 56 day with air entrainment were also higher to results of unconfined compressive strength obtained at 56 day for the respective mixture after subjecting the samples to 12 cycles of freeze-thaw testing with and without air entrainment (shown later in the following sections).

Table 4-25 Result of Compressive Strength with 15% Gypsum with Air Entrainment

| **Type of Quarry Fines** | **Compressive Strength** | | | **W/FA** |
|---|---|---|---|---|
| | **At 1 day (kPa) [psi]** | **At 7 day (kPa) [psi]** | **At 56 day (kPa) [psi]** | |
| Sunflower | -<br>- | 284.6, 255.2<br>[41.3, 37.0] | 374.2, 468.8, 418.3<br>[54.3, 68.0, 60.7] | 0.80 |
| Sunflower | 124.9, 123.5, 104.7<br>[18.1, 17.9, 15.2] | 718.8, 705.2, 841.9<br>[104.3, 102.3, 122.1] | 1520.1, 1475.0, 1778.7<br>[220.5, 213.9, 258.0] | 0.61 |
| Parkville | -<br>- | 268.4, 278.0, 269.7<br>[38.9, 40.3, 39.1] | 417.2, 399.7, 403.3<br>[60.5, 58.0, 58.5] | 0.80 |
| Parkville | 171.1, 186.2, 146.3<br>[24.8, 27.0, 21.2] | 998.1, 1077.7, 1031.4<br>[144.8, 156.3, 149.6] | 2119.0, 1711.3<br>[307.3, 248.2] | 0.61 |

Table 4-26 Result of Compressive Strength with 20% Gypsum with Air Entrainment

| **Type of Quarry Fines** | **Compressive Strength** | | | **W/FA** |
|---|---|---|---|---|
| | **At 1 day (kPa) [psi]** | **At 7 day (kPa) [psi]** | **At 56 day (kPa) [psi]** | |
| Sunflower | 24.7, 25.2. 16.7<br>[3.6, 3.7, 2.4] | 326.7, 387.1, 381.5<br>[47.4, 56.1, 55.3] | 591.7, 569.9, 661.5<br>[85.8, 82.7, 95.9] | 0.80 |
| Sunflower | 103.8, 164.5, 136.7<br>[15.1, 23.9, 19.8] | 798.9, 844.3, 928.9<br>[115.9, 122.5, 134.7] | 1736.3, 1494.1, 1354.2<br>[251.8, 21.6.7, 196.4] | 0.61 |
| Parkville | 16.2, 19.2, 12.5<br>[2.4, 2.8, 1.8] | 390.4, 331.9, 356.4<br>[56.6, 48.1, 51.7] | 596.7, 481.9, 521.7<br>[86.5, 69.9, 75.7] | 0.80 |
| Parkville | 202.3, 209.7<br>[29.3, 30.4] | 992.9, 963.4, 982.9<br>[144.0, 139.7, 142.6] | 1914.1, 1998.5, 1856.7<br>[277.7, 289.9, 269.3] | 0.61 |

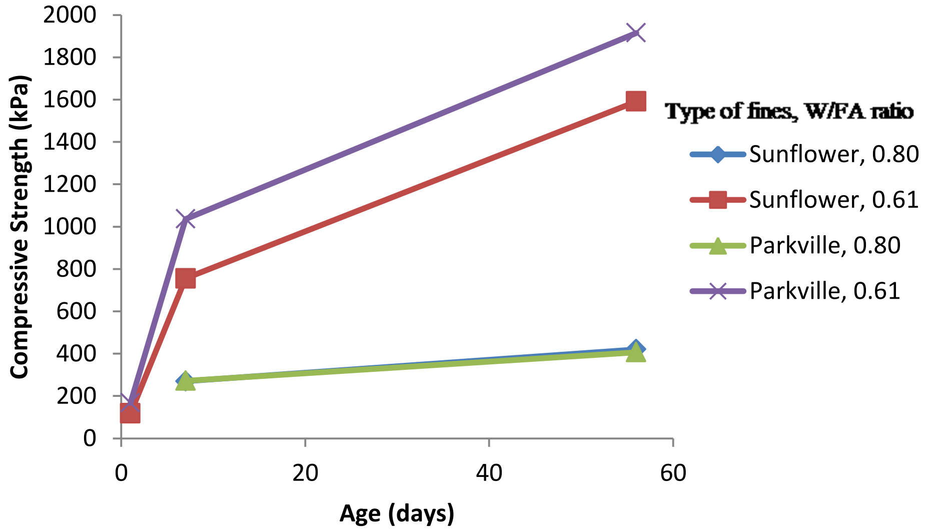


Figure 4-47: Plot of compressive strength result for 15 % gypsum with air entrainment

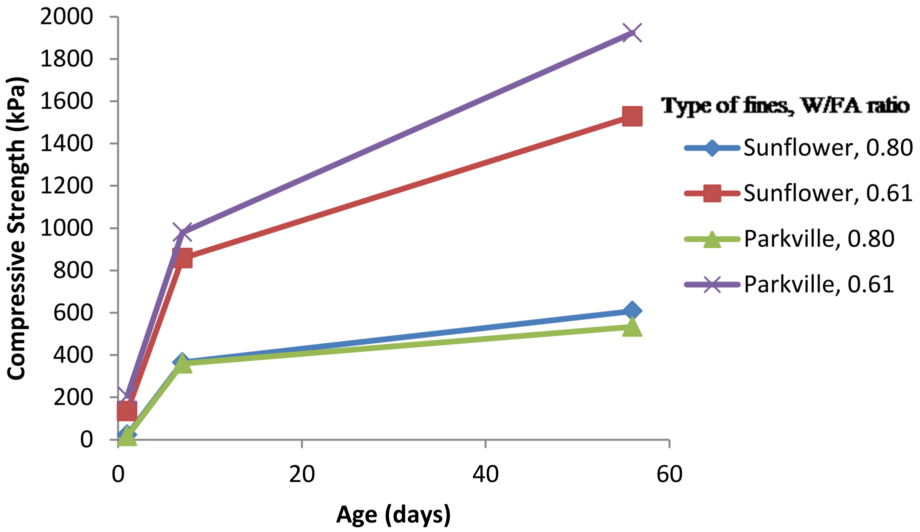


Figure 4-48: Plot of compressive strength result for 20 % gypsum with air entrainment

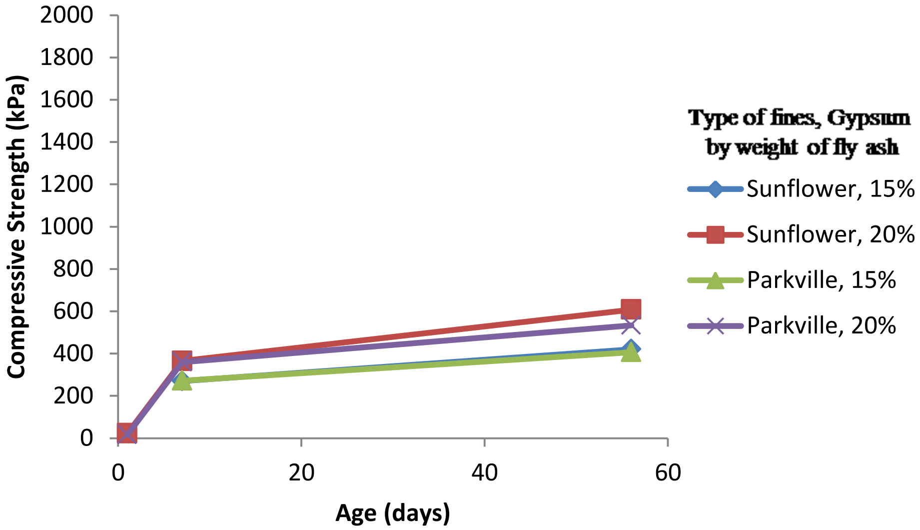


Figure 4-49: Plot of compressive strength result with W/FA of 0.80 with air entrainment

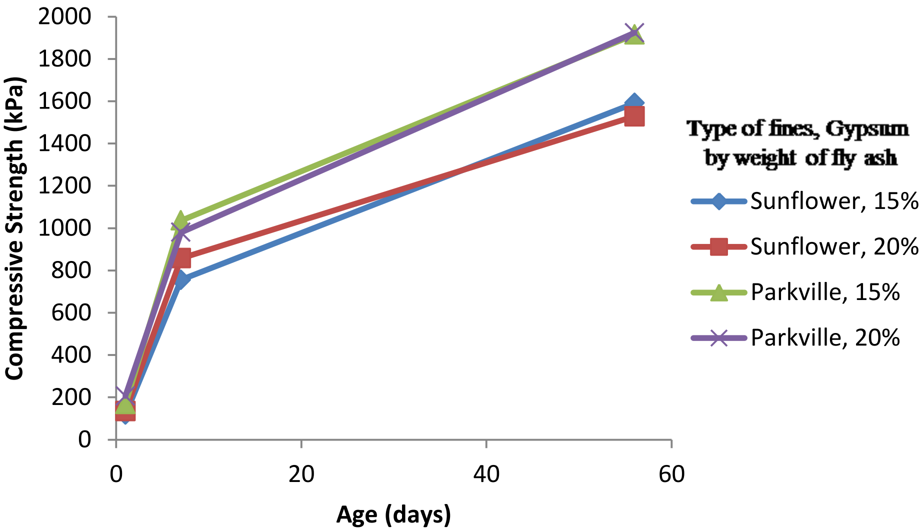


Figure 4-50: Plot of compressive strength result with W/FA of 0.61 with air entrainment

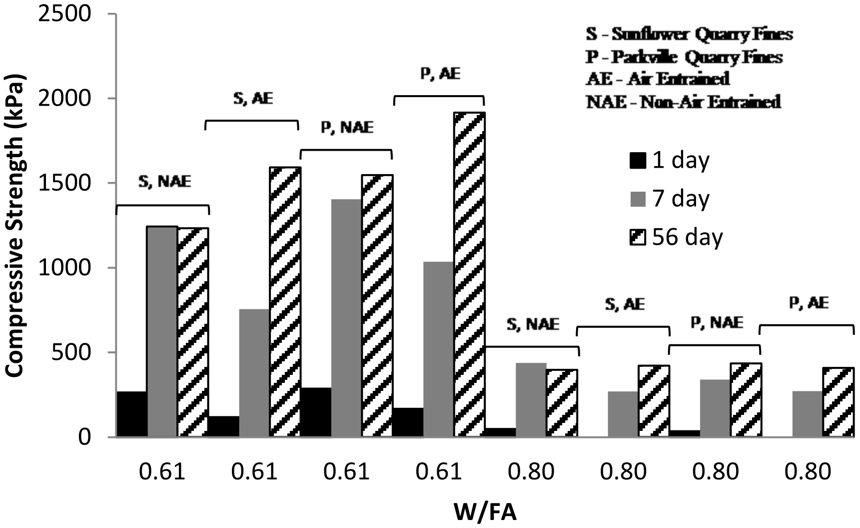


Figure 4-51: Comparison of compressive strength results of air entrained and non-air entrained samples with 15 % gypsum

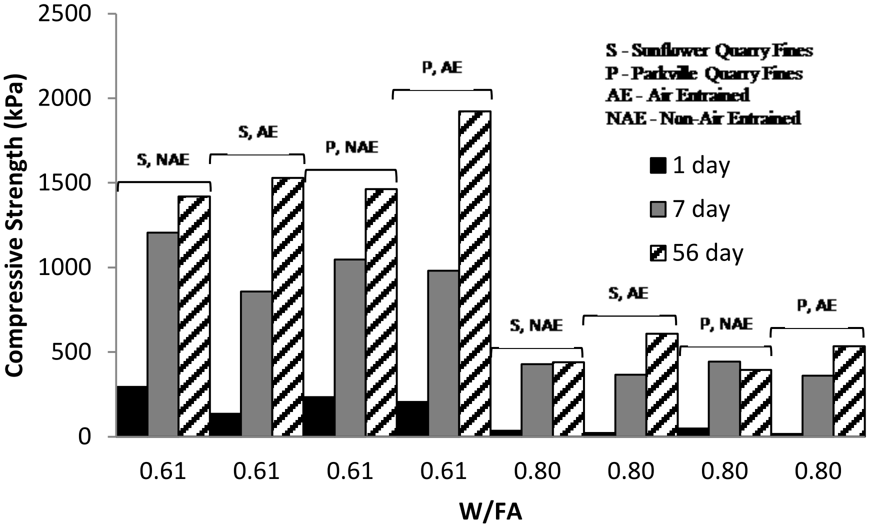


Figure 4-52: Comparison of compressive strength results of air entrained and non-air entrained samples with 20 % gypsum

### 4.6.4. Elastic Modulus and Poisson's Ratio

Table 4.27 and Table 4.28 show the results of elastic modulus and Poisson's ratio at 56 day for mixtures with 15 % gypsum and 20 % gypsum by weight of fly ash respectively, and with both types of quarry fines. The results are shown for W/FA of 0.61 and 0.80. Samples with W/FA of 1 were weak to obtain the results of elastic modulus and Poisson's ratio. The elastic modulus and Poisson's ratio increased with a decrease in the W/FA for a given gypsum percentage by weight of fly ash. Similar results were obtained for both Sunflower and Parkville quarry fines. It could be seen that increasing the gypsum percentage by weight of fly ash did not lead to consistent increase or decrease in the results of elastic modulus and Poisson's ratio. Figures 4.53 and 4.54 show the comparison of elastic modulus for mixtures with and without air entrainment for Sunflower and Parkville quarry fines, respectively. Results show that air entrainment has a decreasing effect or no effect on the elastic modulus of samples with W/FA 0.61, and with 15 and 20 % gypsum by weight of fly ash, respectively. Also results show that, air entrainment has an increasing effect or no effect on the elastic modulus of samples with W/FA 0.80, and with 15 and 20 % gypsum by weight of fly ash, respectively. Figures 4.55 and 4.56 show the comparison of Poisson's ratio for mixtures with and without air entrainment for Sunflower and Parkville quarry fines, respectively. Results show that air entrainment has a decreasing effect on the Poisson's ratio of samples.

### 4.7. Freeze-Thaw Testing

This section presents the results of freeze-thaw testing performed on CLSM samples following ASTM D 560. Results are shown in following sections separately for samples without air entrainment and for samples with air entrainment. The freeze-thaw results are evaluated for effects of different gypsum content and W/FA. The freeze-thaw resistance of samples was measured using two different methods: percentage mass loss of samples and

Table 4-27 Result of Elastic Modulus and Poisson's Ratio with 15% Gypsum with Air Entrainment

| **Type of Quarry Fines** | **56 day Elastic Modulus (MPa) [ksi]** | **Poisson's Ratio** | **W/FA** |
|---|---|---|---|
| Sunflower | 1034.22 [150] | 0.10 | 0.80 |
| Sunflower | 2068.44 [300] | 0.16 | 0.61 |
| Parkville | 1034.22 [150] | 0.10 | 0.80 |
| Parkville | 2413.18 [350] | 0.14 | 0.61 |

Table 4-28 Result of Elastic Modulus and Poisson's Ratio with 20% Gypsum with Air Entrainment

| **Type of Quarry Fines** | **56 day Elastic Modulus (MPa) [ksi]** | **Poisson's Ratio** | **W/FA** |
|---|---|---|---|
| Sunflower | 1034.22 [150] | 0.10 | 0.80 |
| Sunflower | 1723.70 [250] | 0.14 | 0.61 |
| Parkville | 1034.22 [150] | 0.11 | 0.80 |
| Parkville | 2413.18 [350] | 0.17 | 0.61 |

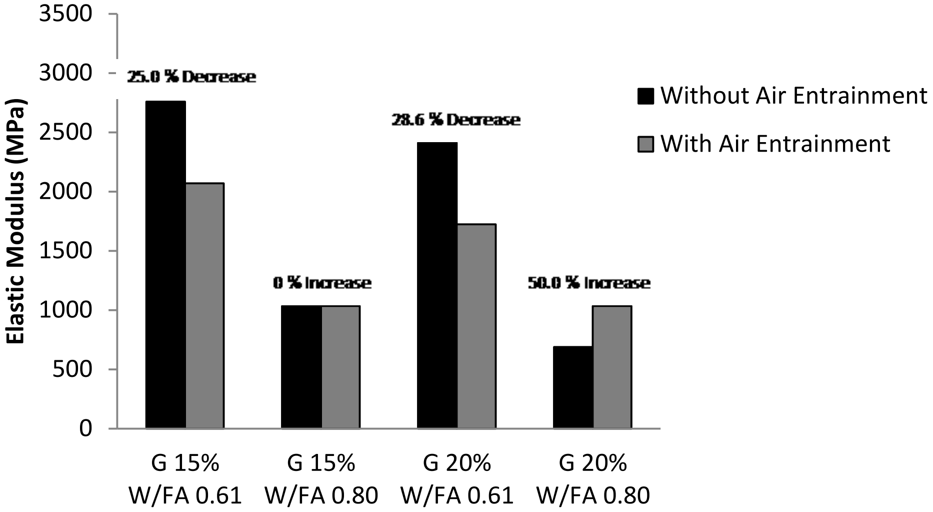


Figure 4-53: Comparison of elastic modulus for mixtures with and without air entrainment for Sunflower quarry fines

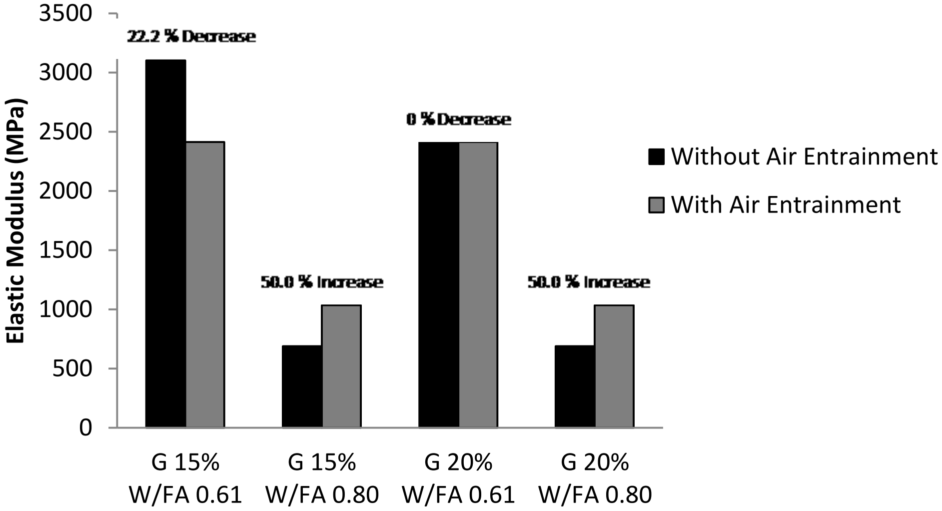


Figure 4-54: Comparison of elastic modulus for mixtures with and without air entrainment for Parkville quarry fines

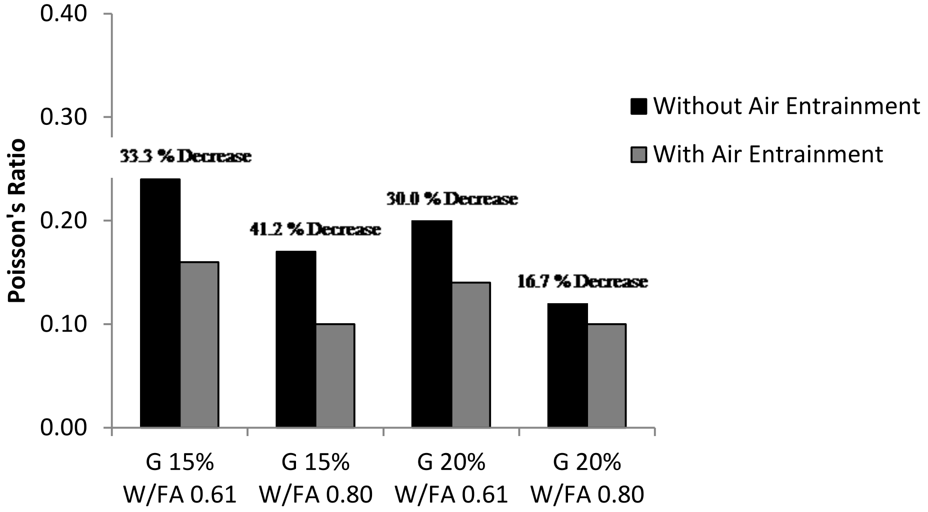


Figure 4-55: Comparison of Poisson's ratio for mixtures with and without air entrainment for Sunflower quarry fines

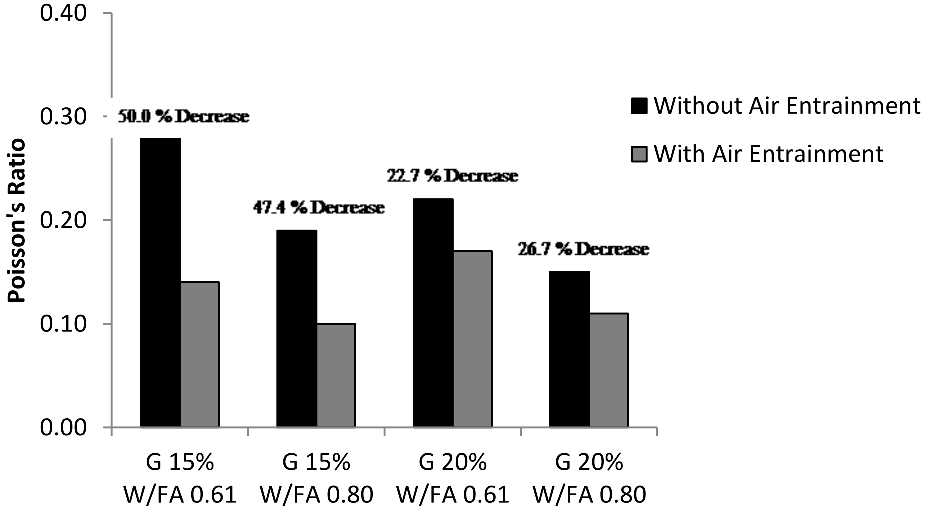


Figure 4-56: Comparison of Poisson's ratio for mixtures with and without air entrainment for Parkville quarry fines

percentage decrease in dynamic modulus of samples were monitored over freeze-thaw cycles. As described earlier in chapter 3, for each mixture two samples were tested in unsaturated state and one sample was kept saturated. The unsaturated samples were subjected to freeze-thaw testing for 12 cycles as requested by the standard. Saturated samples were exposed up to 45 cycles (more than 12 cycles as requested by the standard) to observe the loss in mass and dynamic modulus over prolonged number of cycles. It should also be noted that freeze-thaw testing was performed only with samples with 15 % and 20 % gypsum by weight of fly ash and at W/FA of 0.61 and 0.80. Other mixtures evaluated for strength in earlier sections were deemed too weak for freeze-thaw testing.

### 4.7.1. Freeze-Thaw Testing without Air Entrainment

Figure 4.57 shows mass of unsaturated samples as a percentage of initial mass versus number of cycles for mixtures with 20 % gypsum by weight of fly ash, and W/FA of 0.61 and 0.80. Results show that there was no substantial difference between the different quarry fines. The samples at both W/FA showed an initial increase in mass due to saturation, before they exhibited a mass loss due to freeze thaw deterioration. The gain of mass was higher for samples with higher W/FA. These samples were cured at laboratory environment and absorption of water during the freezing cycle is the reason for the initial increase in mass values. Evaluation of results showed that samples with lower W/FA (0.61) most likely did not show a mass loss. The samples with W/FA of 0.80 were at 92 % of their initial mass after 12 cycles of exposure. Figure 4.58 shows the results for the samples that were kept saturated from the beginning of the test. Due to initial saturation of the samples there was no initial mass loss increase. However, mass loss results were similar to unsaturated samples. Samples with higher W/FA showed higher mass loss values. After 12 cycles of exposure the saturated samples with W/FA 0.61 and 0.80 were at 95 % and 91.6 % of their initial mass, respectively. None of the saturated or unsaturated samples exhibited any cracking, all the mass loss was due to surface degradation. The Army Corps of Engineers manual 1110-3-137 for soil stabilization for pavements construction requires the maximum mass loss to be 8 % or less at the end of 12 cycles for soils with P1 > 10 to be suitable for pavement construction [64].

Figure 4.59 shows mass change as a percentage of initial mass versus number of cycles for unsaturated samples with 15 % gypsum by weight of fly ash, and W/FA of 0.61 and 0.80. Similar to samples with 20 % gypsum, samples exhibited an initial increase in mass before a decrease in mass due to freeze thaw deterioration could be measured. For samples with W/FA of 0.61, there is very small change in the mass at the end of 12 cycles. Samples with higher W/FA of 0.80 showed greater mass loss compared to samples with W/FA of 0.61, however the mass loss was still less than 8 % which is the limit of acceptability for cement stabilized soils. Similar trends were observed for change in mass with both Sunflower

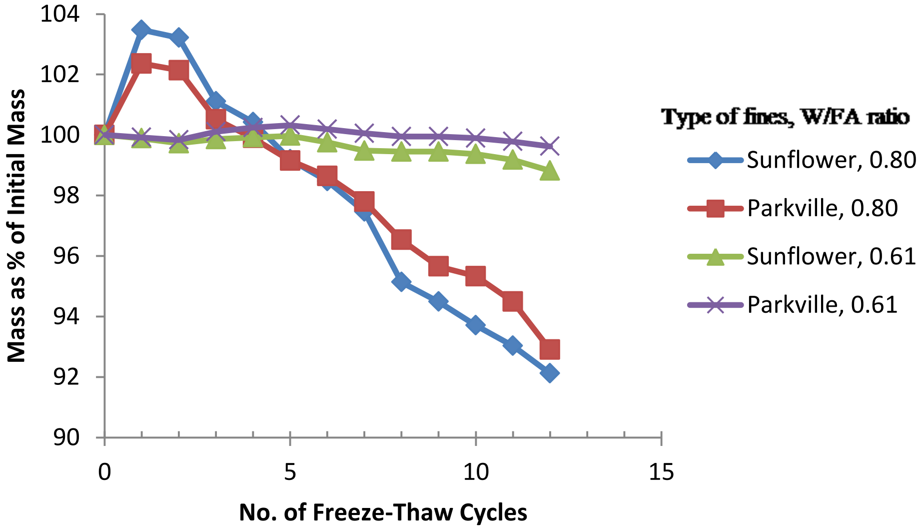


Figure 4-57: Mass of unsaturated samples with 20% gypsum as a percentage of initial mass without air entrainment

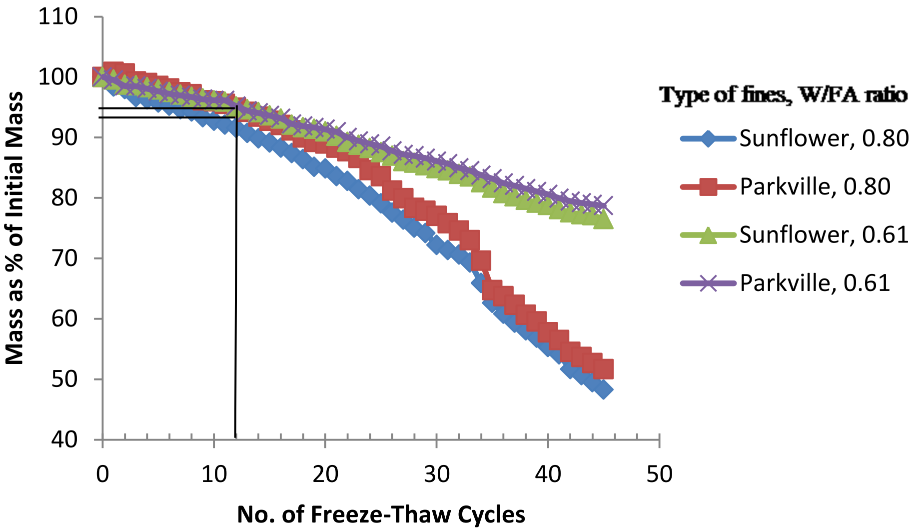


Figure 4-58: Mass of saturated samples with 20% gypsum as a percentage of initial mass without air entrainment

quarry fines and Parkville quarry fines at a given W/FA for unsaturated samples.

Figure 4.60 shows the mass loss results for the saturated sample with 15 % gypsum by weight of fly ash. For W/FA of both 0.61 and 0.80, there is a consistent decrease in the mass until 45 cycles. For a given percentage of gypsum by weight of fly ash, the decrease in mass increased with an increase in W/FA of the mixture. The mass loss of saturated samples with W/FA of 0.80 at the end of 12 cycles was around 8 % similar to samples that were unsaturated. The samples also did not show cracking until 45 cycles. Similar trend was observed for change in mass with both Sunflower quarry fines and Parkville quarry fines at a given W/FA for saturated samples.

Results show that at both gypsum contents, saturated samples did not show the initial increase in mass like the unsaturated samples but at the end of 12 cycles saturated and unsaturated samples showed similar total mass loss values. Although it is not a requirement in ASTM D 560 for cement stabilized soil samples, requiring saturation of CLSM samples prior to testing following this method may give more consistent results.

As discussed earlier, although the ASTM D 560 method measures only mass loss, for this hybrid material, it was decided to test dynamic modulus change over freeze-thaw cycles similar to concrete testing methods. The objective was to determine if dynamic modulus testing would give similar results over 12 cycles of freeze-thaw testing as the mass loss testing. Figure 4.61 shows the dynamic modulus of unsaturated samples as a percentage of initial value versus the number of freeze-thaw cycles for mixture with 20 % gypsum by weight of fly ash, and W/FA of 0.61 and 0.80. The results are shown for unsaturated samples made out of both types of quarry fines. Dynamic modulus testing showed a similar trend as mass loss testing for unsaturated samples. Samples with W/FA of 0.80 showed an increase in dynamic modulus over the first few cycles as they get saturated and then dynamic modulus dropped down over 3 cycles to 40 % of the initial value. After 8 cycles, dynamic modulus stabilized unlike the mass loss measurements that showed continued decrease up to 12

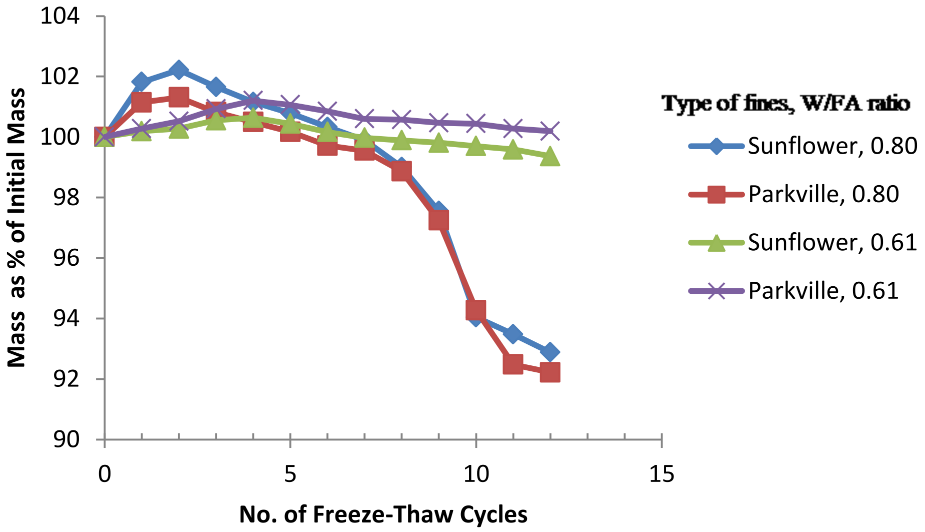


Figure 4-59: Mass of unsaturated samples with 15% gypsum as a percentage of initial mass without air entrainment

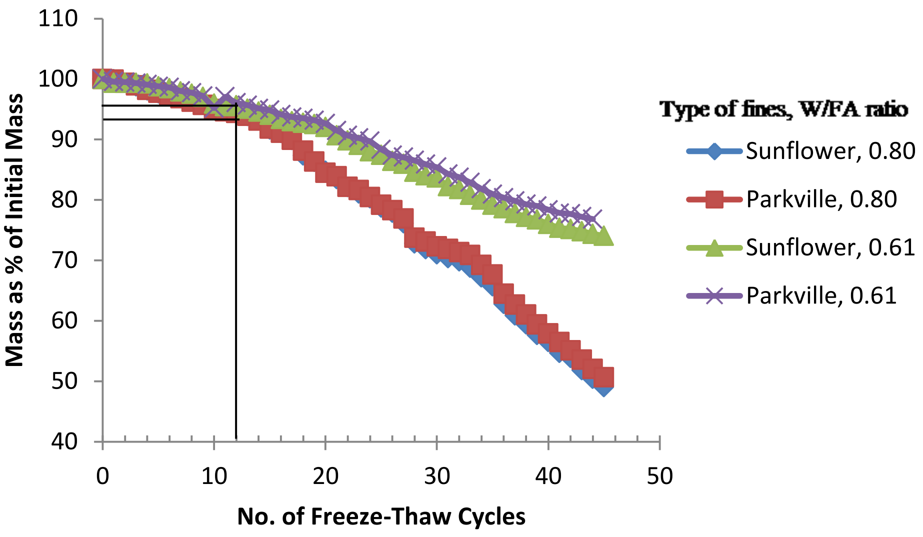


Figure 4-60: Mass of saturated samples with 15% gypsum as a percentage of initial mass without air entrainment

cycles. Dynamic modulus is related to the internal structure of the sample and decreases as it cracks. Results indicate that dynamic modulus testing did not detect more deterioration after a 60 % decrease, while the surface still kept degrading and decreasing the mass of the sample. Samples with 0.61 W/FA most likely did not show mass loss and similarly their dynamic modulus remained stable over 12 freeze-thaw cycles. No substantial difference was observed between samples with different quarry types.

Figure 4.62 shows the dynamic modulus of saturated samples as a percentage of initial value versus number of cycles for mixture with 20 % gypsum by weight of fly ash, and W/FA of 0.61. The results are shown for saturated samples made out of both types of quarry fines. Saturated samples with W/FA of 0.80 were too weak on the surface to be tested for dynamic modulus. The energy of the impact to generate a wave was absorbed by forming an indentation on the surface of the sample and dynamic modulus could not be measured. Figure 4.62 shows that the dynamic modulus of saturated samples with W/FA of 0.61 showed a

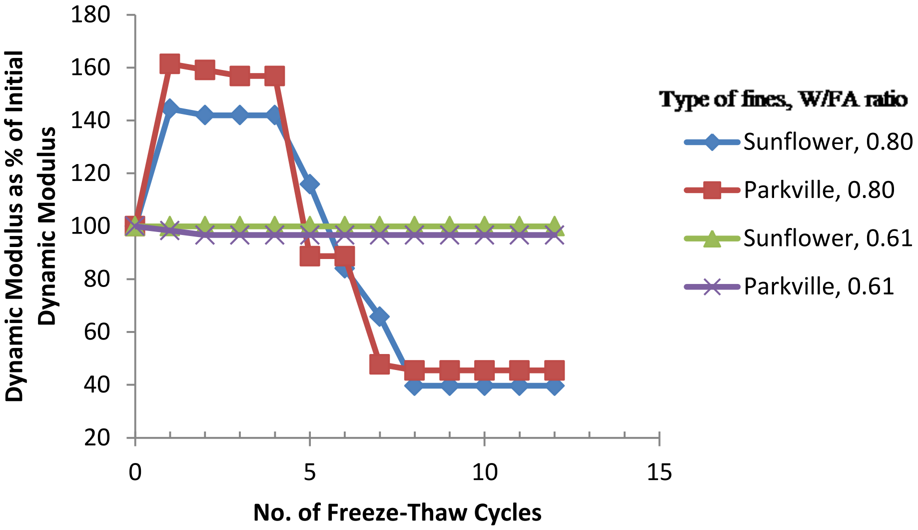


Figure 4-61: Dynamic modulus as a percentage of initial dynamic modulus for unsaturated samples with 20% gypsum without air entrainment

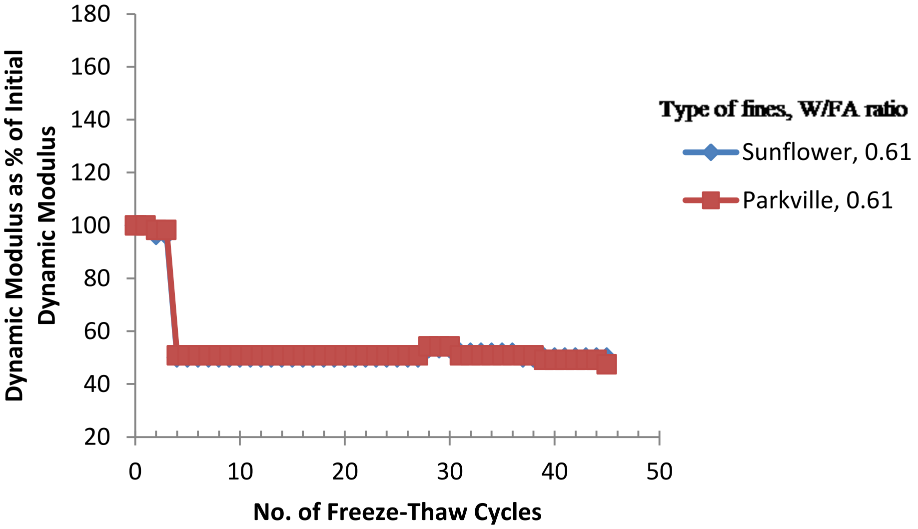


Figure 4-62: Dynamic modulus as a percentage of initial dynamic modulus for saturated samples with 20% gypsum without air entrainment

decrease of 50 % after only 1 cycle although these samples most likely did not show a decrease in mass over 12 cycles.

Figure 4.63 shows the dynamic modulus as a percentage of the initial value versus number of cycles for unsaturated samples with 15 % gypsum by weight of fly ash, and W/FA of 0.61 and 0.80. The results are shown for unsaturated samples made using both types of quarry fines. For samples with a W/FA of 0.80, there is an increase in the dynamic modulus from 1st to 3rd cycle due to water absorption. After 3rd cycle, dynamic modulus stabilized around its initial value and after 9 cycles it rapidly decreased below 60 % of the initial value. Evaluation of mass loss data of samples with 15 % gypsum by weight of fly ash and W/FA of 0.80 shows that the mass loss was minimal up to the 8th cycle, which fits to the dynamic modulus data. For W/FA of 0.61, there is very small change in the dynamic modulus at the end of 12 cycles which reflects the findings of the mass loss data. Similar trend was observed for change in dynamic modulus with both Sunflower quarry fines and Parkville quarry fines at a given W/FA for unsaturated samples.

Figure 4.64 shows the dynamic modulus as a percentage of the initial value versus number of freeze-thaw cycles for saturated samples with 20 % gypsum by weight of fly ash, and W/FA of 0.61. The results are shown for saturated samples made out of both types of quarry fines. Similar to the samples with W/FA of 0.80 and 20 % gypsum, samples with 15 % gypsum and 0.80 W/FA were too weak to be tested for dynamic modulus. For samples with a W/FA of 0.61, most likely there is a decrease in the dynamic modulus after 1 freeze-thaw cycle. After 1 cycle, dynamic modulus stabilized at 50 % of its initial value. Similar trends were observed for change in dynamic modulus with both Sunflower quarry fines and Parkville quarry fines at a given W/FA ratio for saturated samples.

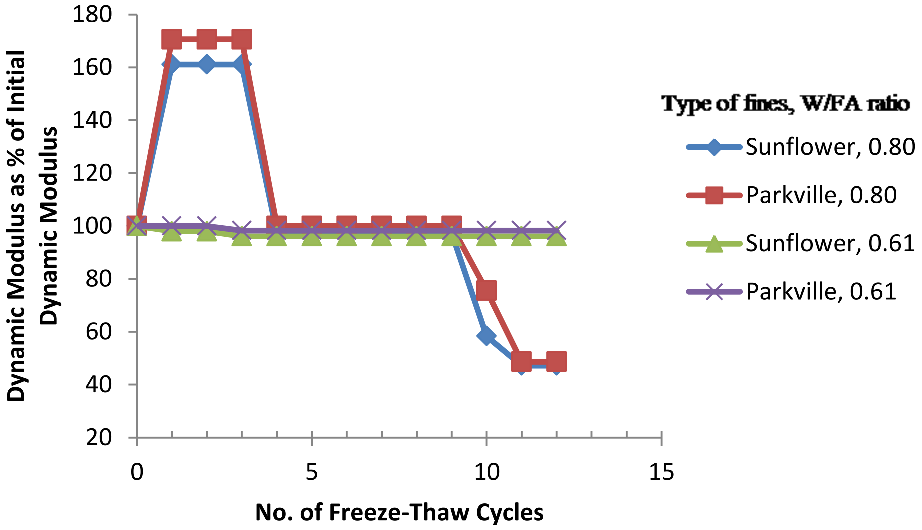


Figure 4-63: Dynamic modulus as a percentage of initial dynamic modulus for unsaturated samples with 15% gypsum without air entrainment

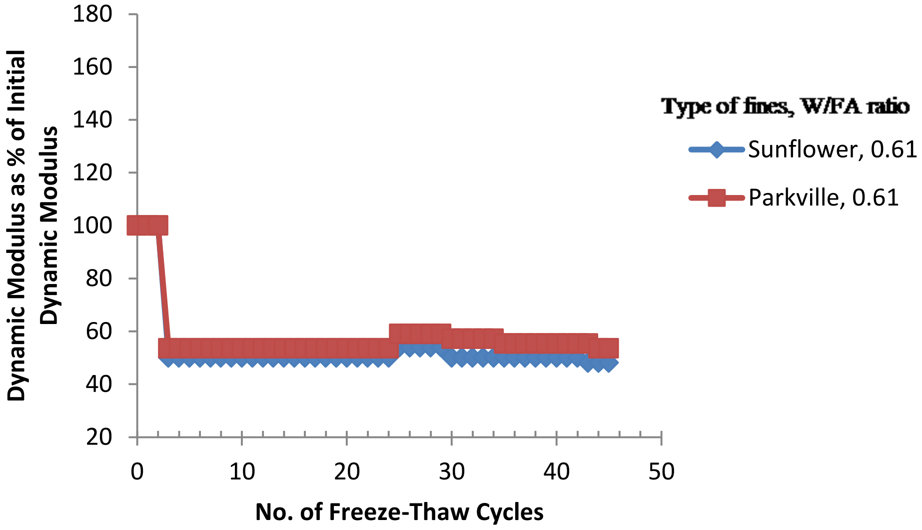


Figure 4-64: Dynamic modulus as a percentage of initial dynamic modulus for saturated samples with 15% gypsum without air entrainment

Evaluation of overall results indicates that for unsaturated samples at both gypsum contents the mass loss results were showing a similar trend as the dynamic modulus results. Samples with 0.61 W/FA showed very small changes in mass which was reflected in stable dynamic modulus values over 12 freeze-thaw cycles. For unsaturated samples with W/FA of 0.80 both mass loss and dynamic modulus showed an initial increase due to water absorption with followed deterioration. The mass loss values for all samples showed that these were acceptable mixtures for pavement construction following the mass loss criteria of corps of engineers for cement stabilized soils [64]. Dynamic modulus results stabilized around 40 to 50 % of the initial value at the end of 12 cycles. A limit of 40 % instead of 60 % used for concrete and the use of unsaturated samples may be recommended for testing CLSM.

Figures 4.65 and 4.66 show the mass of samples with W/FA of 0.80 as a percentage of their initial mass for unsaturated and saturated samples, respectively. As mentioned earlier at the end of 12 cycles, samples exhibit a maximum mass loss of 8 %, which is the case for samples at both gypsum levels.

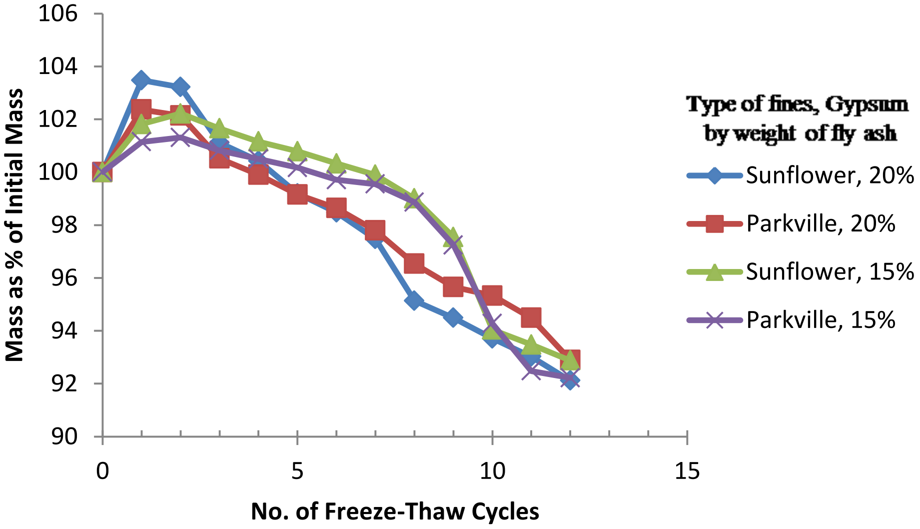


Figure 4-65: Mass of unsaturated samples with W/FA of 0.80 as a percentage of initial mass without air entrainment

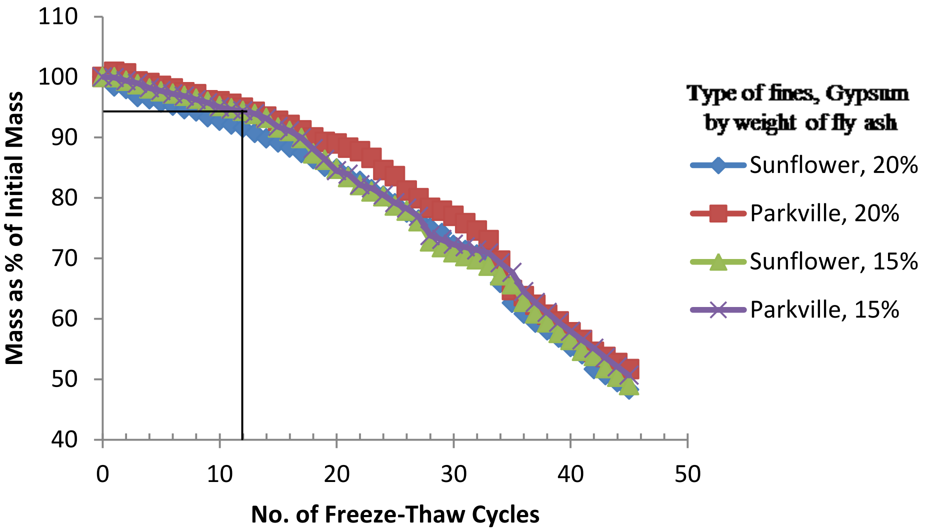


Figure 4-66: Mass of saturated samples with W/FA of 0.80 as a percentage of initial mass without air entrainment

Figures 4.67 and 4.68 show the mass loss of samples with W/FA of 0.61 as a percentage of their initial mass for unsaturated and saturated samples, respectively. Comparison of samples again shows that the gypsum content most likely did not have an effect on the freeze-thaw resistance of CLSM samples and the main factor was the W/FA. Samples with W/FA of 0.80 exhibited an average mass loss of 8 % compared to only 1 % for samples with W/FA ratio of 0.61 at the end of 12 cycles. Comparison of mass loss results at the end of 45 freeze-thaw cycles showed that the maximum mass loss of samples with W/FA of 0.80 and 0.61 were 50 and 25 percent, respectively. For the samples considered in this study the gypsum content and the type of quarry fines did not affect the freeze-thaw resistance.

The results from Table 4.29 and Table 4.30 show the compressive strength of samples at W/FA ratios of 0.80 and 0.61 at 56 days after freeze-thaw testing. It can be seen that there is a decrease in the unconfined compressive strength of samples at 56 day (from casting date)

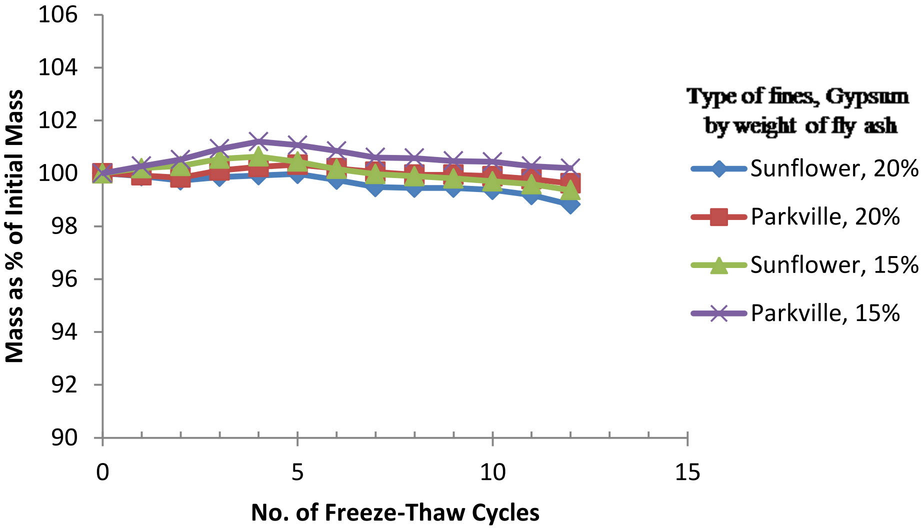


Figure 4-67: Mass of unsaturated samples with W/FA of 0.61 as a percentage of initial mass without air entrainment

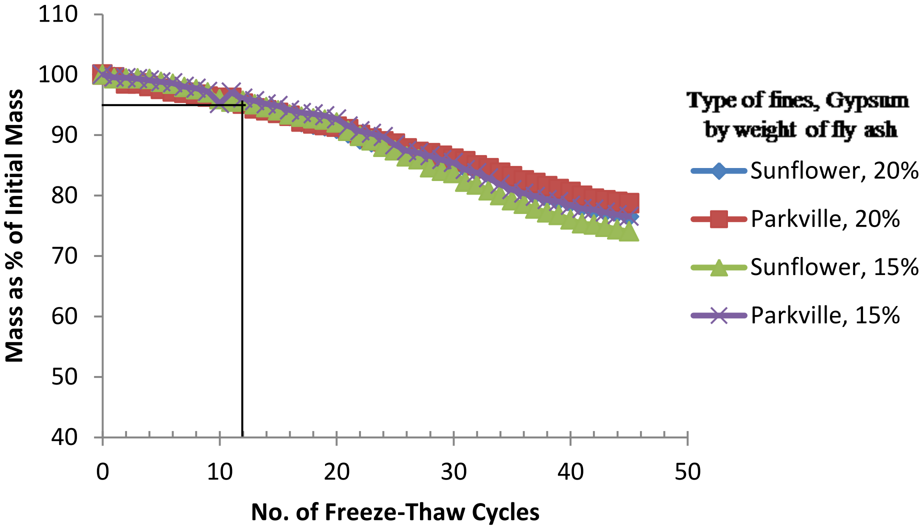


Figure 4-68: Mass of saturated samples with W/FA of 0.61 as a percentage of initial mass without air entrainment

when they are subjected to 12 cycles of freeze-thaw. Figures 4.69 and 4.70 show the compressive strength of samples with and without exposure to freeze-thaw cycles at 56 days for Sunflower and Parkville quarry fines, respectively. Results indicate that the compressive strength of samples decreased due to exposure to freeze-thaw cycles. The average decrease with 15 % gypsum by weight of fly ash was 33 % and 10 % for W/FA of 0.61 and 0.80, respectively with both quarry fines. The average decrease with 20 % gypsum by weight of fly ash was 30 % and 15 % for W/FA of 0.61 and 0.80, respectively with both quarry fines.

Table 4-29 Result of Compressive Strength at 56 day after subjection to 12 Freeze-Thaw Cycles for 20% Gypsum without Air Entrainment

| **Type of Quarry Fines** | **Compressive Strength at 56 day (kPa) [psi]** | **W/FA** |
|---|---|---|
| Sunflower | 327.3 [47.5] | 0.80 |
| Sunflower | 964.8 [139.9] | 0.61 |
| Parkville | 378.3 [54.9] | 0.8 |
| Parkville | 1065.0 [154.5] | 0.61 |

Table 4-30 Result of Compressive Strength at 56 day after subjection to 12 Freeze-Thaw Cycles for 15% Gypsum without Air Entrainment

| **Type of Quarry Fines** | **Compressive Strength at 56 day (kPa) [psi]** | **W/FA** |
|---|---|---|
| Sunflower | 353.0 [51.2] | 0.80 |
| Sunflower | 851.8 [123.5] | 0.61 |
| Parkville | 397.0 [57.6] | 0.80 |
| Parkville | 1009.0 [146.3] | 0.61 |

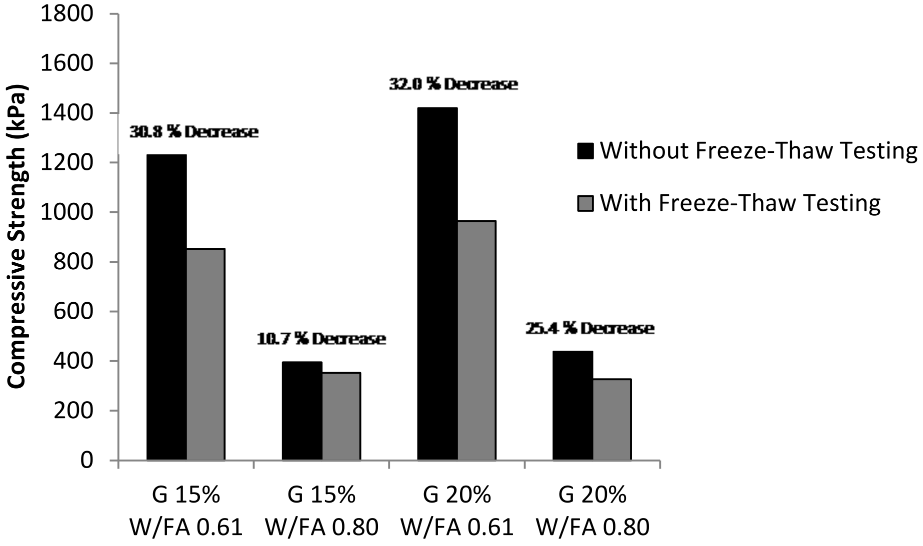


Figure 4-69: Compressive strength of samples with and without exposure to freeze-thaw cycles at 56 days without air entrainment for Sunflower quarry fines

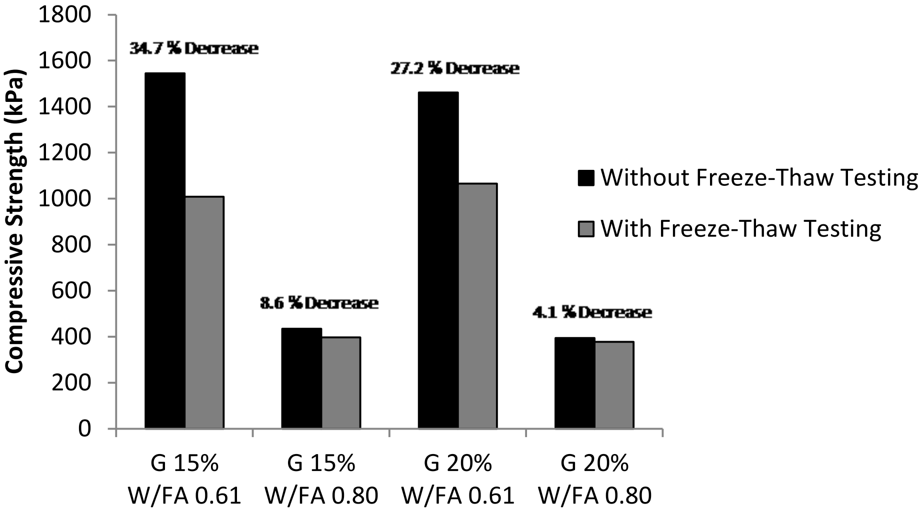


Figure 4-70: Compressive strength of samples with and without exposure to freeze-thaw cycles at 56 days without air entrainment for Parkville quarry fines

### 4.7.2. Freeze-Thaw Testing with Air Entrainment

Figures 4.71 and 4.72 show the mass of air entrained samples as a percentage of their initial mass over 12 freeze-thaw cycles. Figure 4.71 shows the results of unsaturated samples with different quarry fines and W/FA values. Figure 4.72 shows the results of air entrained samples that were saturated at the beginning of testing and were kept at a high humidity environment as explained in chapter 3. Figure 4.71 shows the results with air entrained samples with 20 % gypsum by weight of fly ash. Results are similar to samples with 20 % gypsum without air. Samples gained initially some mass due to water absorption. Samples with W/FA of 0.61 most likely did not show a mass loss similar to samples without air over 12 cycles. Mass loss of samples with W/FA of 0.80 was about 3 % which is less than 8 % observed for the samples without air entrainment. Figure 4.72 shows the mass of saturated samples as a percentage of the initial mass over 45 cycles. Since the samples were saturated, no increase in mass was observed and the mass loss values after 12 cycles were similar to the values observed for unsaturated samples. Comparison of mass values of saturated samples after 45 cycles between air entrained and without air samples shows that there was a large difference. Saturated samples without air and with W/FA of 0.61 and 0.80 were at 78 and 50 % of their initial mass, respectively. Air entrained samples with W/FA of 0.61 and 0.80 were at 90 and 78 % of their initial mass on average.

Figures 4.73 and 4.74 show the mass values of air entrained samples with 15 % gypsum. Results are shown for both types of quarry fines and for both W/FA values used in freeze thaw testing. Similar to samples without air entrainment and with 15 % gypsum, unsaturated air entrained samples with W/FA of 0.61 showed very little mass loss. Unsaturated samples with both W/FA values showed an initial increase in mass due to absorption. Samples with W/FA of 0.80 started to decrease in mass after about 8 cycles and exhibited an average mass loss of 2.5 % after 12 cycles, which is smaller than the 8 % mass loss observed for corresponding samples without air entrainment. Figure 4.74 show the change in mass of saturated samples over 45 cycles. Evaluation of results show again that although there was no increase in mass of saturated samples, their mass at the end of 12 cycles was similar to the mass of unsaturated samples. This is a common observation between unsaturated and saturated samples of corresponding mixtures. Final mass of saturated samples with 15 % gypsum and W/FA of 0.61 at the end of 45 cycles was at an average of 88 % of their initial mass. This value was 75 % for corresponding samples without air entrainment. On Figure 4.74 the average mass after 45 cycles was at 77.5 % for samples with W/FA of 0.61. Corresponding saturated samples without air entrainment had an average mass of 50 % after 45 cycles.

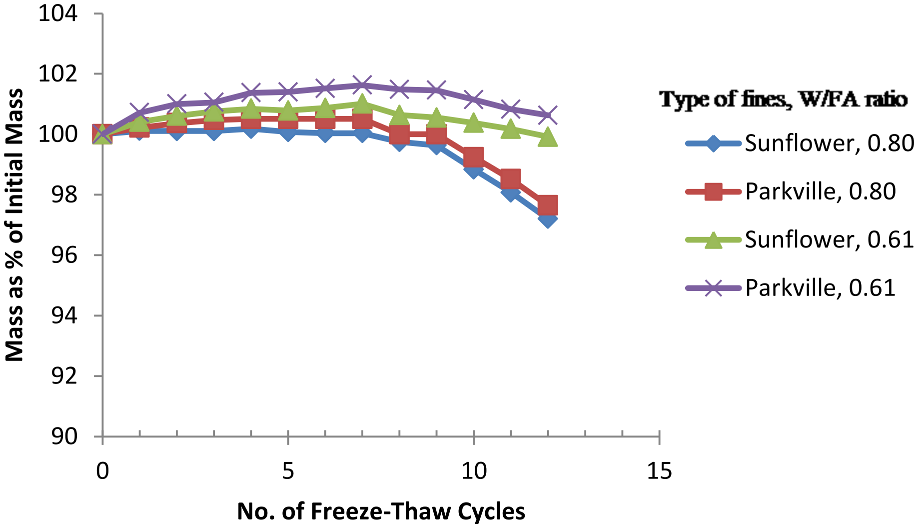


Figure 4-71: Mass of unsaturated samples with 20% gypsum as a percentage of initial mass with air entrainment

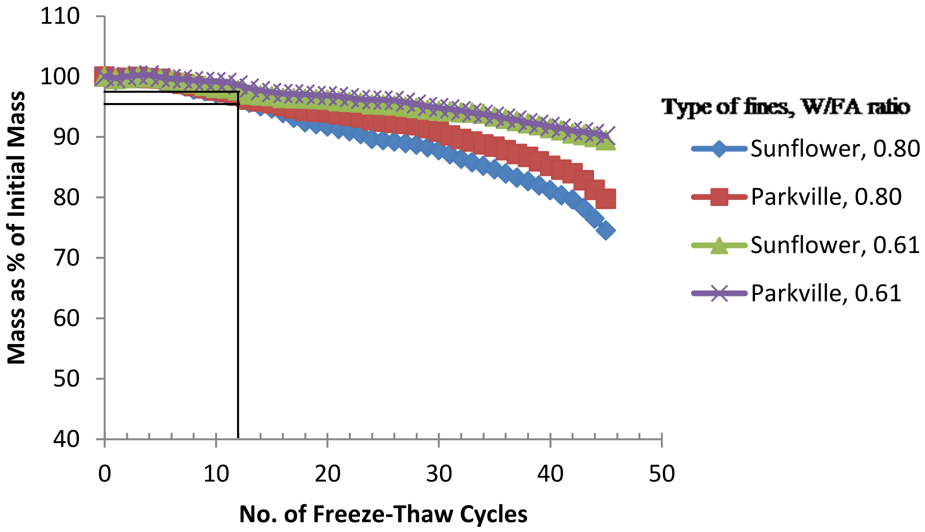


Figure 4-72: Mass of saturated samples with 20% gypsum as a percentage of initial mass with air entrainment

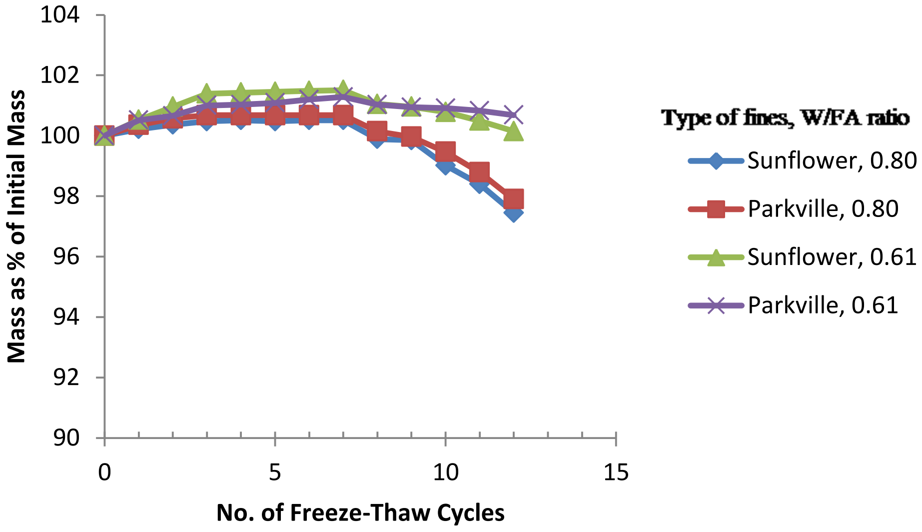


Figure 4-73: Mass of unsaturated samples with 15% gypsum as a percentage of initial mass with air entrainment

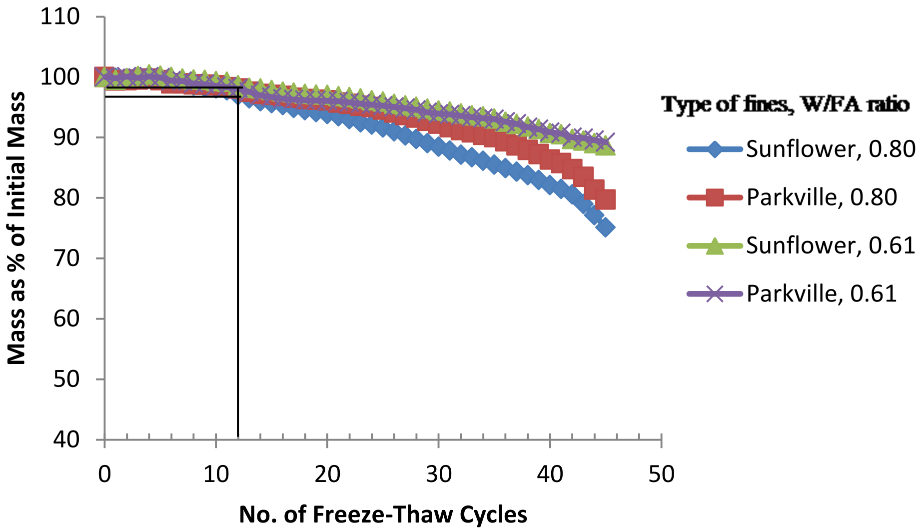


Figure 4-74: Mass of saturated samples with 15% gypsum as a percentage of initial mass with air entrainment

Evaluation of results for both gypsum contents and for samples with and without air entrainment indicate that;

- there was no difference between quarry types
- air entrainment decreases the mass loss of unsaturated and saturated samples over 12 and 45 cycles. All samples with and without air showed a mass loss at 12 freeze thaw cycles that was less than the maximum acceptable limit set by the corps of engineers for cement stabilized soils used in pavement construction [64]

Similar to the study performed for the samples without air, the applicability of dynamic modulus measurement was also evaluated for the air entrained samples. One issue with dynamic modulus testing of CLSM samples is that they may be too weak to generate a response to a mechanical impact on the surface. This was observed earlier for non-air entrained saturated samples with W/FA of 0.80. They were too weak to be tested.

Figures 4.75 and 4.76 show the dynamic modulus results of unsaturated air entrained samples over 12 cycles for samples with 20 and 15 % gypsum by weight of fly ash and W/FA of 0.61. Air entrained samples with W/FA of 0.80 were too weak to be tested even in unsaturated condition. As described in chapter 3, freeze thaw testing of samples was started after 28 days of curing. Unconfined compressive strength results showed that air entrained samples were weaker than non-air entrained samples. Since saturated samples were weaker compared to unsaturated samples, saturated samples could not be tested for dynamic modulus.

Mass loss testing of unsaturated samples with 20 % gypsum by weight of fly ash and W/FA of 0.61 showed negligible amount of mass loss over 12 freeze thaw cycles as shown in Figure 4.71. Figure 4.75 shows the dynamic modulus of these samples decreased to 90 % of their original value at the end of 12 freeze thaw cycles. Figure 4.76 shows the dynamic modulus of unsaturated samples with 15 % gypsum by weight of fly ash. These samples also

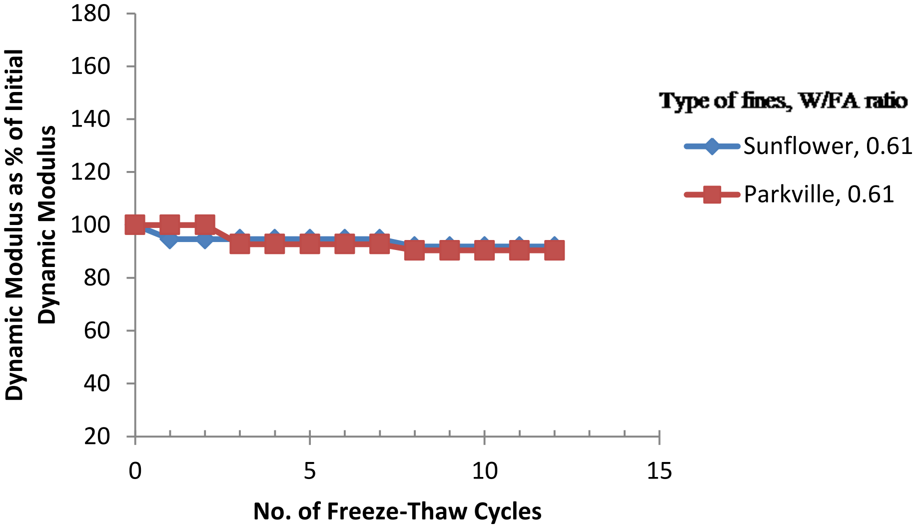


Figure 4-75: Dynamic modulus as a percentage of initial dynamic modulus for unsaturated samples with 20% gypsum with air entrainment

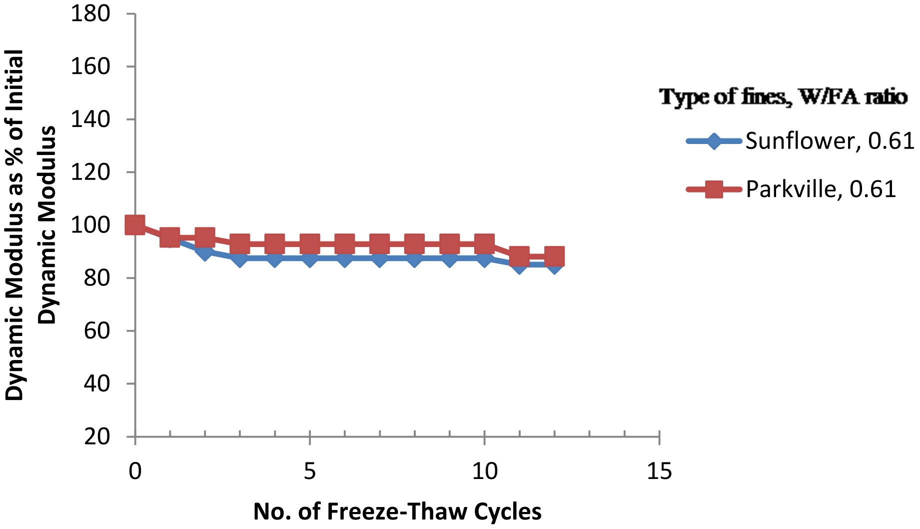


Figure 4-76: Dynamic modulus as a percentage of initial dynamic modulus for unsaturated samples with 15% gypsum with air entrainment

showed negligible mass loss value and their average dynamic modulus was about 87 % of their initial value. Evaluation of results for air entrained samples show that, similar to the results of non-air entrained samples, dynamic modulus testing and mass loss testing were showing similar trends. However, the weakness of air entrained samples with W/FA of 0.80 at the 28 day testing age required by ASTM D 560 made it impossible for these samples to be tested. The researchers believe that dynamic modulus testing can be used to evaluate freeze-thaw resistance of CLSM samples, however a modification of testing age to 56 days may resolve strength related issues.

Figures 4.77 and 4.78 show the combined results of air entrained samples with W/FA of 0.80 at both gypsum contents for unsaturated and saturated samples, respectively. Similar to samples without air entrainment, results indicate that neither the quarry fines type nor the gypsum content had a substantial effect on freeze-thaw resistance of CLSM.

Figures 4.79 and 4.80 show the combined mass loss results of air entrained samples with W/FA of 0.61 at both gypsum contents for unsaturated and saturated samples, respectively. Results show that the samples with a W/FA of 0.61 had a negligible mass loss

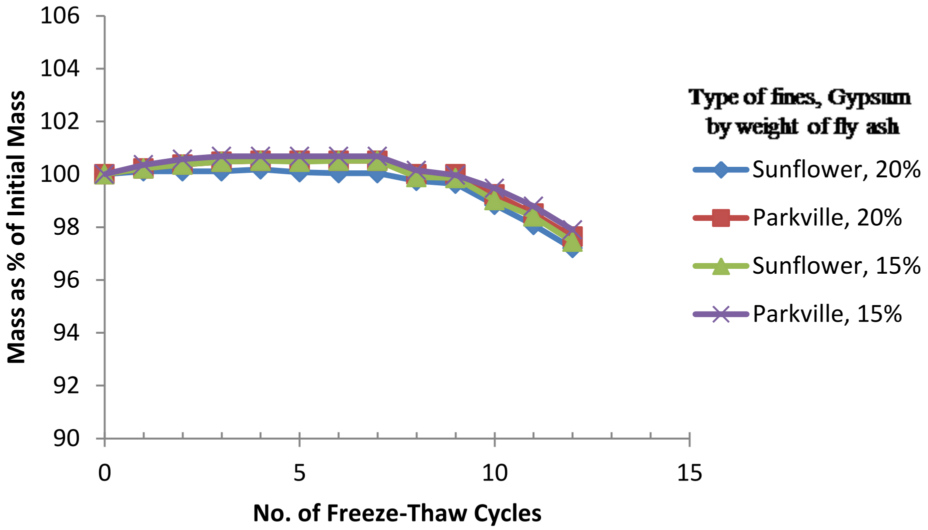


Figure 4-77: Mass of unsaturated samples with W/FA of 0.80 as a percentage of initial mass loss with air entrainment

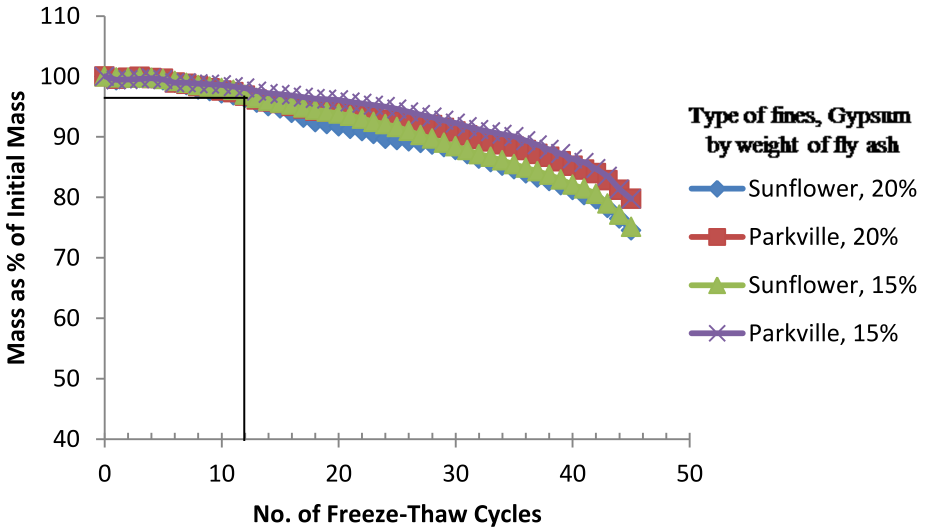


Figure 4-78: Mass of saturated samples with W/FA of 0.80 as a percentage of initial mass loss with air entrainment

at 12 freeze-thaw cycles and changing gypsum content from 15 to 20 % by weight of fly ash did not make a big difference in freeze-thaw resistance.

Evaluation of samples without air entrainment at both gypsum contents and air entrained samples at both gypsum contents showed that air entrainment most likely did not have an improvement for samples with a W/FA of 0.61. It is clearly visible that for both air entrained and non-air entrained samples W/FA was the most important factor affecting the freeze thaw resistance.

The result from Table 4.31 and Table 4.32 show the compressive strength of air entrained samples at W/FA ratios of 0.80 and 0.61 at 56 days after freeze-thaw testing. Figures 4.81 and 4.82 show the compressive strength of air entrained samples with and without exposure to freeze-thaw cycles at 56 days for Sunflower and Parkville quarry fines, respectively. It can be seen that there is a decrease in the unconfined compressive strength of samples at 56 day (from casting date) when they are subjected to 12 cycles of freeze-thaw.

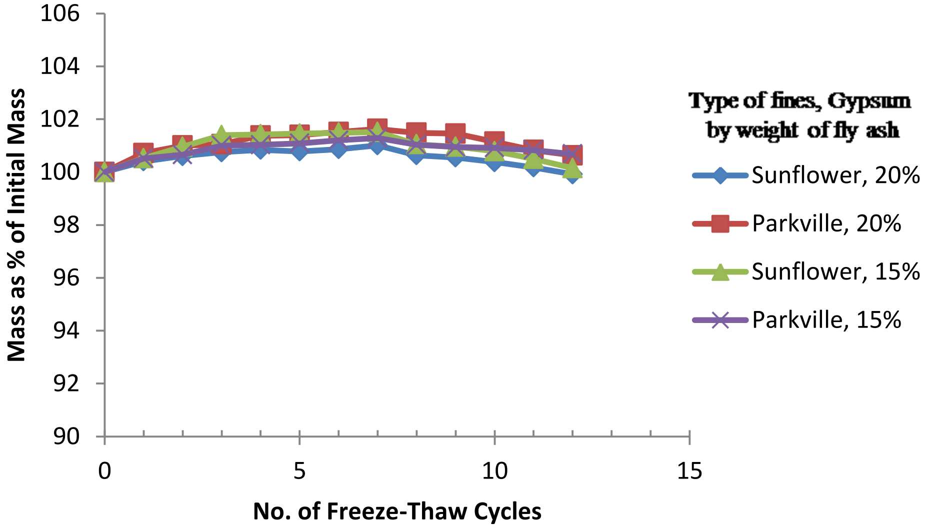


Figure 4-79: Mass of unsaturated samples with W/FA of 0.61as a percentage of initial mass with air entrainment

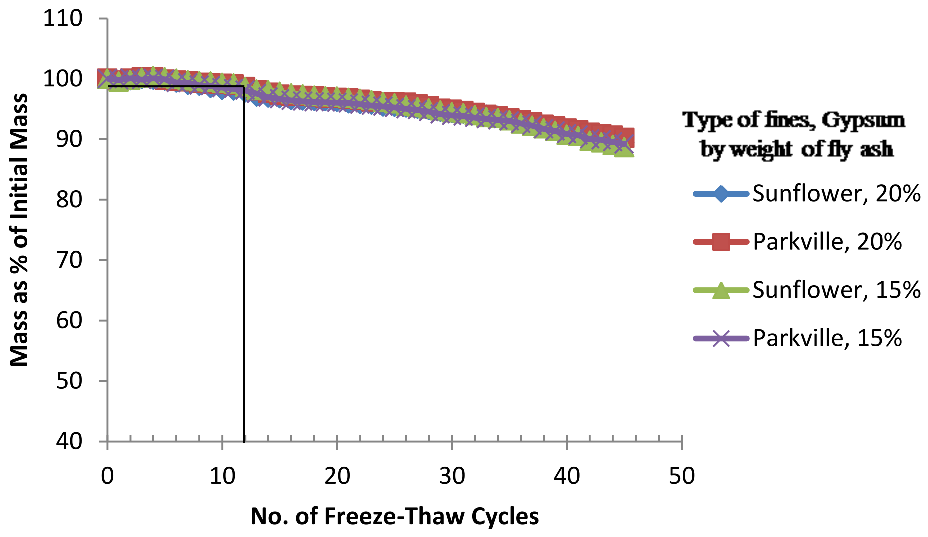


Figure 4-80: Mass of saturated samples with W/FA of 0.61as a percentage of initial mass with air entrainment

Table 4-31 Result of Compressive Strength at 56 day after subjection to 12 Freeze-Thaw Cycles for 20% Gypsum with Air Entrainment

| Type of Quarry Fines | Compressive Strength at 56 day (kPa) [psi] | W/FA |
|---|---|---|
| Sunflower | 306.5 [44.5] | 0.80 |
| Sunflower | 849.3 [123.2] | 0.61 |
| Parkville | 261.2 [37.9] | 0.80 |
| Parkville | 909.7 [131.9] | 0.61 |

Table 4-32 Result of Compressive Strength at 56 day after subjection to 12 Freeze-Thaw Cycles for 15% Gypsum with Air Entrainment

| Type of Quarry Fines | Compressive Strength at 56 day (kPa) [psi] | W/FA |
|---|---|---|
| Sunflower | 328.2 [47.6] | 0.80 |
| Sunflower | 857.0 [124.3] | 0.61 |
| Parkville | 358.3 [52.0] | 0.80 |
| Parkville | 928.2 [134.6] | 0.61 |

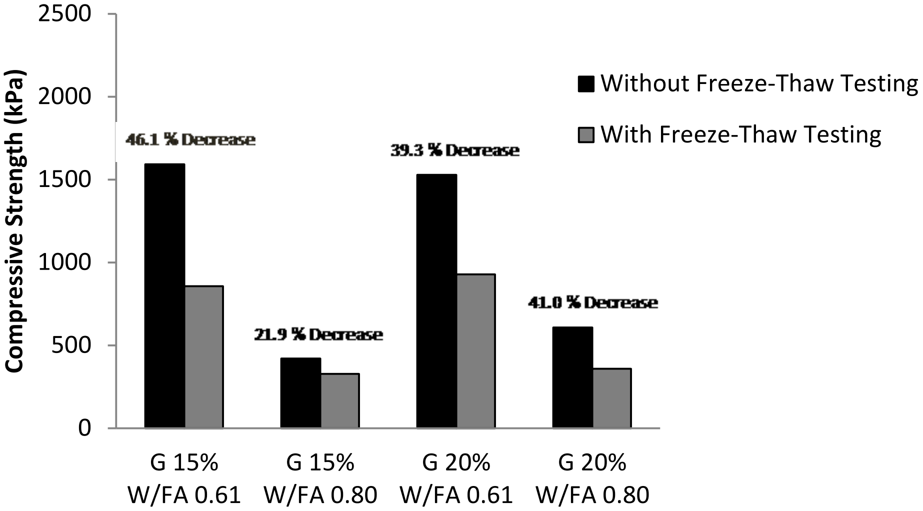


Figure 4-81: Compressive strength of samples with and without exposure to freeze-thaw cycles at 56 days with air entrainment for Sunflower quarry fines

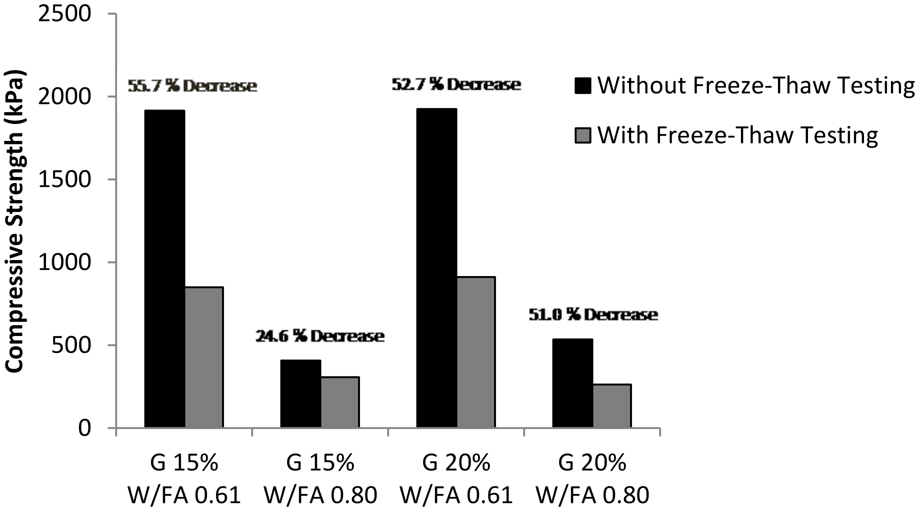


Figure 4-82: Compressive strength of samples with and without exposure to freeze-thaw cycles at 56 days with air entrainment for Parkville quarry fines

# CHAPTER 5

# SUMMARY, CONCLUSIONS AND SUGGESTED FUTURE RESEARCH

## 5.1. Introduction

The main objective of this proposed project was to research the use of a low strength flowable cementitious fill material, produced mainly from a by-product of the limestone aggregate industry, for different applications as an alternative to compacted embankment soils. This study aimed to develop cheap cementitious flowable fill mixtures out of quarry fines, fly ash, synthetic gypsum, and water for different applications without using any cement or good quality aggregates. The fly ash used in the study was obtained from a local power plant. Also, the synthetic gypsum used in the study was an industrial waste product.

The study evaluated new mixture proportions, a new mixing and testing procedures, and characterized materials. The mixtures were evaluated for fresh and hardened properties, and durability characteristics. Various parameters like flow diameter, setting time, compressive strength, elastic modulus, Poisson's ratio, and freeze-thaw resistance (in terms of mass loss and dynamic modulus) were tested and evaluated in the laboratory to study the behavior of flowable fill mixtures. The effects of an air-entrainment agent, Darafill, on flow diameter, setting time, compressive strength and freeze-thaw resistance of mixtures were also evaluated.

Successful use of quarry fines in flowable fill mixtures for different applications can reduce costs related to storage and disposal of fines, save dwindling landfill space, and generate additional revenue for quarries. This constant density fill material can provide a homogenous and continuous support layer with very low settlement compared to soils which can eliminate high percentage of the maintenance problems resulting in significant cost savings. The cheap flowable fill material produced mainly from by-products should benefit environmental protection agencies apart from federal and state highway agencies, when practically used for the desired purpose.

## 5.2. Summary

Flowable fill mixtures only from by-products were evaluated in this research to assess their applicability to backfill different applications. Based on the comprehensive study, the following conclusions can be drawn:

1. Workability is an important property of CLSM. It was desired that CLSM should have enough flowability after half an hour of mixing so that it could easily be used on site as a backfill material. On average, the flow values after 15 and 30 minutes of mixing decreased by 62.4 and 66.4 %, respectively, compared to the flow values after 90 seconds of mixing. However, increase of mixing time from 15 to 30 minutes decreased the flow values on average by 6.1 % only. The flowability increased with an increase in W/FA from 0.61 to 1 for all flowable fill mixtures with different amounts of gypsum. However, at the same W/FA increasing the gypsum content most likely did not have an effect between 10, 15 and 20 %. On an average air entrainment has an increasing effect on the flowability. The mixtures with both Sunflower and Parkville quarry fines showed similar results.
2. The initial setting time increased with an increase in W/FA from 0.61 to 1 for all flowable fill mixtures with different amounts of gypsum. However, at the same W/FA, increasing the gypsum content most likely did not have an effect between 10, 15, and 20 %. Air entrainment generally increased the setting time, especially for mixtures with higher W/FA. The initial setting time of air entrained mixture with 15 % gypsum

increased by 111 and 54.5 % for W/FA of 0.61 and 0.80, respectively. The initial setting time of air entrained mixture with 20 % gypsum increased by 25 and 13.8 % for W/FA of 0.61 and 0.8, respectively. The mixtures with both Sunflower and Parkville quarry fines showed similar results.

3. The weight decreased substantially at 56 day compared to weights at 1 day and 7 day. For a given percentage of gypsum, the weight also decreased with an increase in W/FA from 0.61, 0.80 and 1 of the mixture. For mixtures with same W/FA, weight decreases with an increase in gypsum content. The average weight of samples with air entrainment is lower compared to the average weight of samples without air entrainment. At 7 day, the weight of air entrained mixture with 15 % gypsum decreased by 6.2 and 12.2 % for W/FA of 0.61 and 0.80, respectively, compared to the weight of same mixture at 7 day without air entrainment. At 7 day, the weight of air entrained mixture with 20 % gypsum decreased by 5.2 and 10.4 % for W/FA of 0.61 and 0.80, respectively, compared to the weight of same mixture at 7 day without air entrainment. At 56 day, the weight of air entrained mixture with 15 % gypsum decreased by 4 and 15.4 % for W/FA of 0.61 and 0.80, respectively, compared to the weight of same mixture at 56 day without air entrainment. At 56 day, the weight of air entrained mixture with 20 % gypsum decreased by 3.1 and 4.7 % for W/FA of 0.61 and 0.80, respectively, compared to the weight of same mixture at 56 day without air entrainment. The mixtures with both Sunflower and Parkville quarry fines showed similar results.
4. ACI committee 229 (1994) stated that the maximum long term compressive strength should generally not exceed 2068.4 kPa (300 psi) if future excavation is desired. In general, CLSM mixtures with compressive strength of 350 kPa (50 psi) or less can be

manually excavated and CLSM mixtures with compressive strength between 690 to 1400 kPa (100 to 200 psi) require mechanical equipment for excavation [5]. The 56 day unconfined compressive strengths of all air entrained and non-air entrained CLSM mixtures were less than 2068.4 KPa (300 psi). The 56 day unconfined compressive strengths of non-air entrained mixtures with 0 % gypsum at all W/FA were less than 350 kPa (50 psi) and can be termed as manually excavatable. The 56 day unconfined compressive strengths of non-air entrained mixtures with 10, 15, and 20 % gypsum at W/FA of 1 were less than 350 kPa (50 psi) and can be termed as manually excavatable. The 56 day unconfined compressive strengths of non-air entrained mixtures with 10, 15, and 20 % gypsum at W/FA of 0.61 and 0.80 exceeded 350 kPa (psi) and cannot be excavated manually. Also, the 56 day unconfined compressive strength of all air entrained mixtures exceeded 350 kPa (psi) and cannot be excavated manually. All mixtures can be termed as excavatable, if need for maintenance arises in the future. The presence of synthetic gypsum in the mix influenced the later age compressive strength gain of the mixture. However, the increase in compressive strength due to increasing gypsum from 10 to 20 % by weight of fly ash at all W/FA was not substantial. For a given gypsum percentage, the compressive strength decreased with an increase in W/FA of the mix from 0.61 to 1. Comparison of air entrained samples with non-air entrained samples showed that although at earlier ages the strength of air entrained samples was lower, at 56 days they surpassed the strength of non-air entrained samples. The compressive strength did not differ with the type of quarry fines. The unconfined compressive strength of the proposed material is near or higher compared to the unconfined compressive strength of CLSM mixtures with cement mentioned in the literature. As mentioned in the literature, the removability modulus (RE) of mixtures with 0 % gypsum at all W/FA was less than 1 and can be considered removable. The RE of all mixtures with 10, 15, and 20 % gypsum at W/FA of 0.80 and 1 was less than 1 and can be considered removable. The RE of all mixtures with 10, 15, and 20 % gypsum at W/FA of 0.61 exceeded 1 and cannot be considered removable [7, 8]. The mixtures with both Sunflower and Parkville fines showed similar results for RE.

5. According to Elson, typical value of elastic modulus of subgrade soil as homogeneous elastic material is considered within the range of 5 to 20 MPa (0.5 to 3 ksi). Also, according to Elson, the Poisson's ratio of subgrade soil as homogeneous elastic material is considered within the range of 0.30 to 0.40 [62]. The value of elastic modulus of concrete is generally considered to be 27579.20 MPa (4,000 ksi) and the Poisson's ratio of concrete is considered within the range of 0.15 to 0.20 [63]. The elastic modulus of the proposed CLSM material is higher compared to the elastic modulus of soils but less than the elastic modulus of concrete. The Poisson's ratio of the proposed CLSM material is lower compared to soils. This shows that the proposed material will undergo lesser deformation in lateral direction on application of vertical load. The proposed material will provide a homogenous and continuous layer with lower differential settlement as compared to soils. Thus, the CLSM mixture can prove to be a better backfill material for different applications as compared to soils. The elastic modulus and Poisson's ratio of CLSM material increased with a decrease in the W/FA from 0.80 to 0.61. However, at the same W/FA, increasing the gypsum content did not have a significant effect between 10, 15, and 20 %, for results of elastic modulus and Poisson's ratio. Results with 15 and 20 % gypsum show that air entrainment generally has a decreasing effect on the elastic

modulus of samples with W/FA 0.61, and an increasing effect on the elastic modulus of samples with W/FA 0.80. Results show that air entrainment has a decreasing effect on the Poisson's ratio of samples. The mixtures with both Sunflower and Parkville quarry fines showed similar results.

6. The material proved to be freeze-thaw resistant (in terms of mass loss and dynamic modulus) following the corps of engineers criteria. The CLSM samples showed deterioration on the surface but did not show any visible surface cracking. Evaluation of samples without air entrainment at both gypsum contents and air entrained samples at both gypsum contents showed that air entrainment improved the freeze-thaw resistance for samples with a W/FA of 0.80. Comparatively less improvement in the freeze-thaw resistance was seen for samples with W/FA of 0.61. For W/FA 0.80 and both gypsum contents of 15 and 20 %, the change in mass as percentage of initial mass after subjecting the unsaturated samples to 12 freeze-thaw cycles was decreased by 5.0 % and the change in mass as percentage of initial mass after subjecting the saturated samples to 45 freeze-thaw cycles was decreased by 27.4 %. For W/FA 0.61 and both gypsum contents of 15 and 20 %, the change in mass as percentage of initial mass after subjecting the unsaturated samples to 12 freeze-thaw cycles was decreased by 0.9 % and the change in mass as percentage of initial mass after subjecting the saturated samples to 45 freeze-thaw cycles was decreased by 12.9 %. The mixtures with both Sunflower and Parkville quarry fines showed similar results. The mass loss values at 12 cycles for all samples were 8 % or less which categorize them as acceptable mixtures for pavement construction following the mass loss criteria of corps of engineers for cement stabilized soils [64]. For unsaturated samples at both gypsum contents of 15 and 20 %, the mass loss results were

showing a similar trend as the dynamic modulus results. Results indicate that the compressive strength of air entrained and non-air entrained samples at 56 day decreased due to exposure to freeze-thaw cycles. For W/FA of 0.61 and both gypsum contents of 15 and 20 %, the 56 day compressive strength of non-air entrained samples subjected to freeze-thaw cycles decreased by 31.4 % and 31.0 % for Sunflower and Parkville quarry fines, respectively, compared to the 56 day compressive strength of same mixture without being subjected to freeze-thaw cycles. For W/FA of 0.8 and both gypsum contents of 15 and 20 %, the 56 day compressive strength of non-air entrained samples subjected to freeze-thaw cycles decreased by 18.1 % and 6.4 % for Sunflower and Parkville quarry fines, respectively, compared to the 56 day compressive strength of same mixture without being subjected to freeze-thaw cycles.

## 5.3. Conclusions

In general, the type of quarry fines did not affect the fresh properties, hardened properties and freeze-thaw resistance. The results with both Sunflower and Parkville quarry fines followed the same trend and were similar.

### 5.3.1. Fresh Properties

#### 5.3.1.1. Workability

- The flowability increased with an increase in W/FA from 0.61 to 1 for all flowable fill mixtures with different amounts of gypsum
- At the same W/FA increasing the gypsum content most likely did not have an effect between 10, 15 and 20 %
- On an average air entrainment has an increasing effect on the flowability

#### 5.3.1.2. Setting Time

- The initial setting time increased with an increase in W/FA from 0.61 to 1 for all flowable fill mixtures with different amounts of gypsum
- At the same W/FA, increasing the gypsum content most likely did not have an effect between 10, 15, and 20 %
- Air entrainment generally increased the setting time

### 5.3.2. Hardened Properties

#### 5.3.2.1. Weight

- The weight decreased substantially at 56 day compared to weights at 1 day and 7 day
- For a given percentage of gypsum, the weight also decreased with an increase in W/FA from 0.61 to 1 of the mixture
- The average weight of samples at 7 and 56 day with air entrainment is lower compared to the average weight of samples at 7 day and 56 day without air entrainment

#### 5.3.2.2. Unconfined Compressive Strength

- The compressive strength increased with an increase in gypsum from 0 to 10 %. However, the compressive strength did not increase most likely due to increasing gypsum from 10 to 20 % at all W/FA
- For a given gypsum percentage, the compressive strength decreased with an increase in W/FA of the mix from 0.61 to 1
- Comparison of air entrained samples with non-air entrained samples showed that although at earlier ages the strength of air entrained samples was lower, at 56 days they surpassed the strength of non-air entrained samples

- In general, CLSM mixtures with compressive strength of 350 kPa (50 psi) or less can be manually excavated and CLSM mixtures with compressive strength between 690 to 1400 kPa (100 to 200 psi) require mechanical equipment for excavation
- Results show that CLSM mixtures can be designed as manually excavatable or mechanically excavatable

#### 5.3.2.3. Elastic Modulus and Poisson's Ratio

- Typical value of elastic modulus of subgrade soil as homogeneous elastic material is considered within the range of 5 to 20 MPa (0.5 to 3 ksi) and the Poisson's ratio of subgrade soil as homogeneous elastic material is considered within the range of 0.30 to 0.40
- The value of elastic modulus of concrete is generally considered to be 27579.20 MPa (4,000 ksi) and the Poisson's ratio of concrete is considered within the range of 0.15 to 0.20
- The elastic modulus of the CLSM material is higher compared to the elastic modulus of soils but less than the elastic modulus of concrete. The Poisson's ratio of the CLSM material is lower compared to soils
- This shows that the material will undergo lesser deformation in lateral direction on application of vertical load. The proposed material will provide a homogenous and continuous layer with lower differential settlement as compared to soils
- The CLSM mixture can prove to be a better backfill material as compared to soils

### 5.3.3. Durability: Freeze-Thaw Resistance

- The mass loss values at 12 cycles for all samples were 8 % or less which categorize them as acceptable mixtures for pavement construction following the mass loss criteria of corps of engineers for cement stabilized soils
- Evaluation of samples with and without air entrainment at both gypsum contents showed that air entrainment improved the freeze-thaw resistance for samples with a W/FA of 0.80

## 5.4. Future Research

Although this research focused on many important issues, additional research is needed to further advance the state-of-the-art regarding flowable fills made out of quarry fines, fly ash, and synthetic gypsum. Some issues that deserve further exploration include:

1. Additional field work is required to evaluate the fresh properties and hardened properties along with excavatability of flowable fill and examine the effects of surrounding environments and local climate conditions on these properties compared to laboratory results.
2. The internal mechanism or reactions taking place in the flowable fill mixture due to the synthetic gypsum, air-entrainment or both should be properly studied. The materials like quarry fines and fly ash should not be neglected in the study.
3. The use of other types of air entraining agents widely available in the market should be considered.
4. A structural model should be created using advanced software for different applications with flowable fills (backfill) to computationally understand the behavior of material and structure as a whole component.

# APPENDIX

## A. Freeze-Thaw Testing without Air-Entrainment

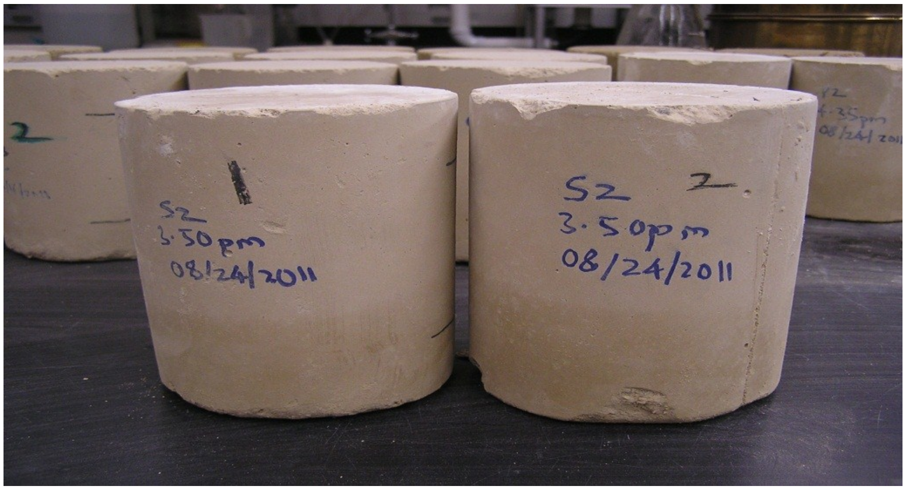


Figure A1. Samples S2 after 28 days of curing

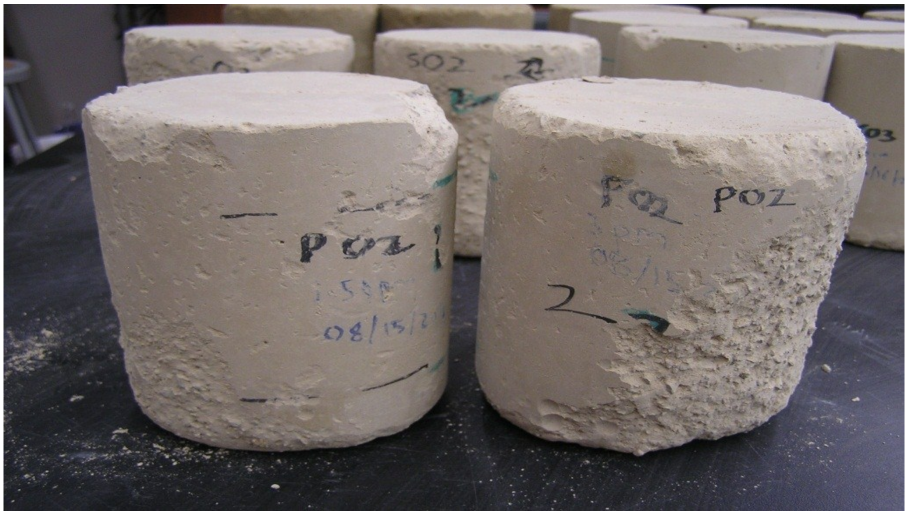


Figure A2. Unsaturated samples P02 after 09 freeze-thaw cycles

Figure A3. Saturated samples S02 and P02 after 36 freeze-thaw cycles

Figure A4. Saturated samples S3 and P3 after 36 freeze-thaw cycles

Figure A5. Saturated samples S3 and P3 after 44 freeze-thaw cycles

## B. Freeze-Thaw Testing with Air-Entrainment

Figure B1. Samples S02 and P02 after 28-days of curing

Figure B2. Samples S03 and P03 after 28-days of curing

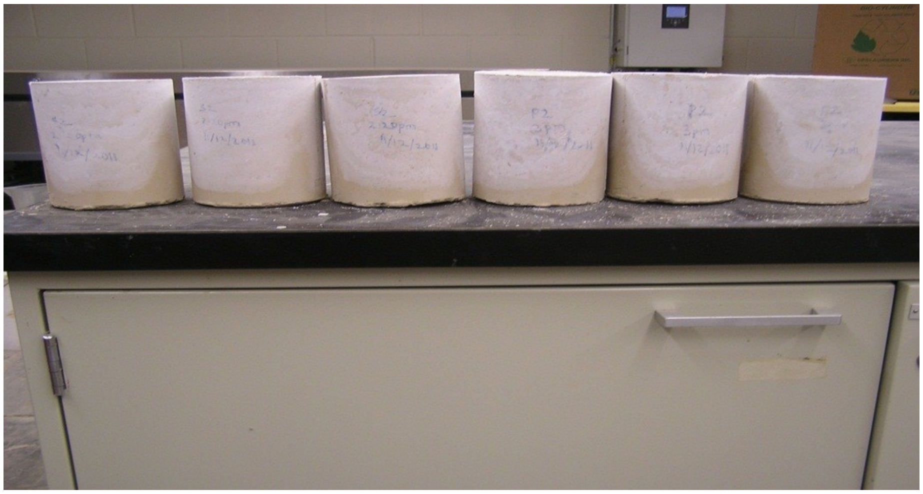


Figure B3. Samples S2 and P2 after 28 days of curing

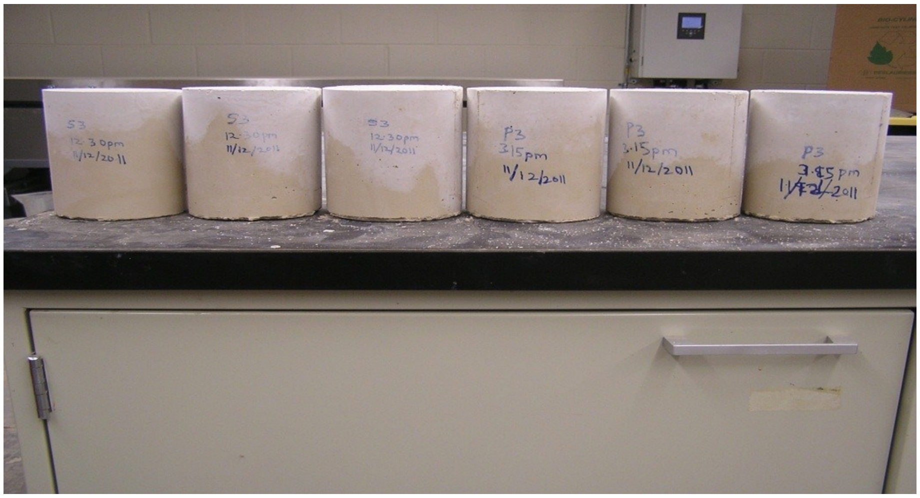


Figure B4. Samples S3 and P3 after 28-days of curing

Figure B5. Unsaturated samples S02 after 11 freeze-thaw cycles

Figure B6. Unsaturated samples P03 after 11 freeze-thaw cycles

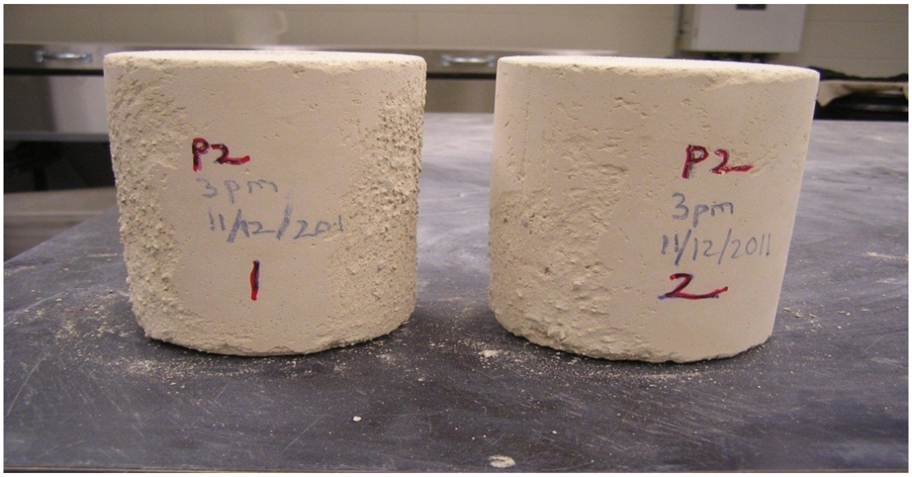


Figure B7. Unsaturated Samples P2 after 11 freeze-thaw cycles

Figure B8. Unsaturated samples S3 after 11 freeze-thaw cycles

Figure B9. Saturated samples S02, P02, S03, and P03 after 11 freeze-thaw cycles

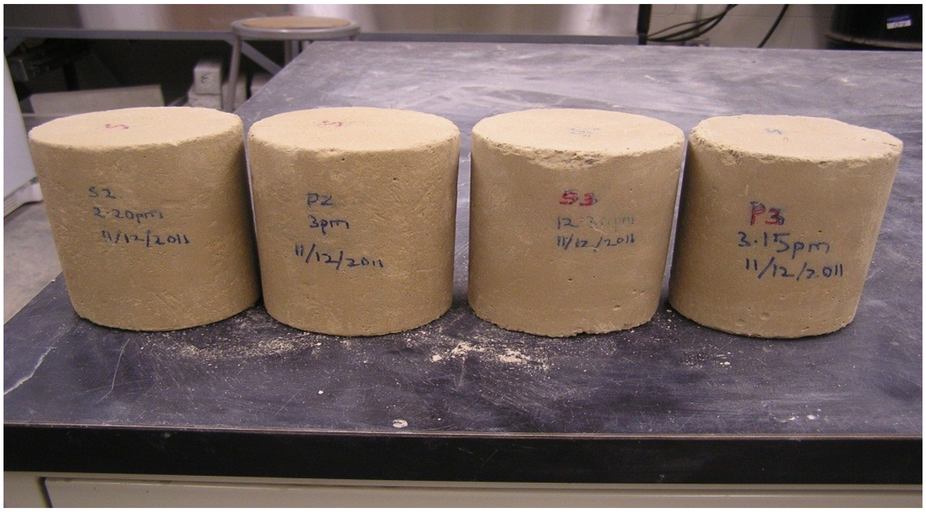


Figure B10. Saturated samples S2, P2, S3, and P3 after 11 freeze-thaw cycles

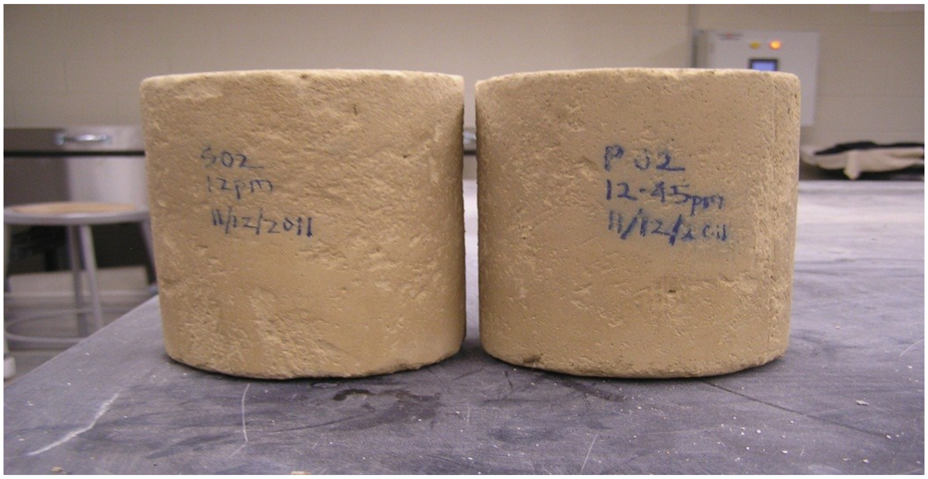


Figure B11. Saturated samples S02 and P02 after 27 freeze-thaw cycles

Figure B12. Saturated samples S03 and P03 after 27 freeze-thaw cycles

Figure B13. Saturated samples S2 and P2 after 27 freeze-thaw cycles

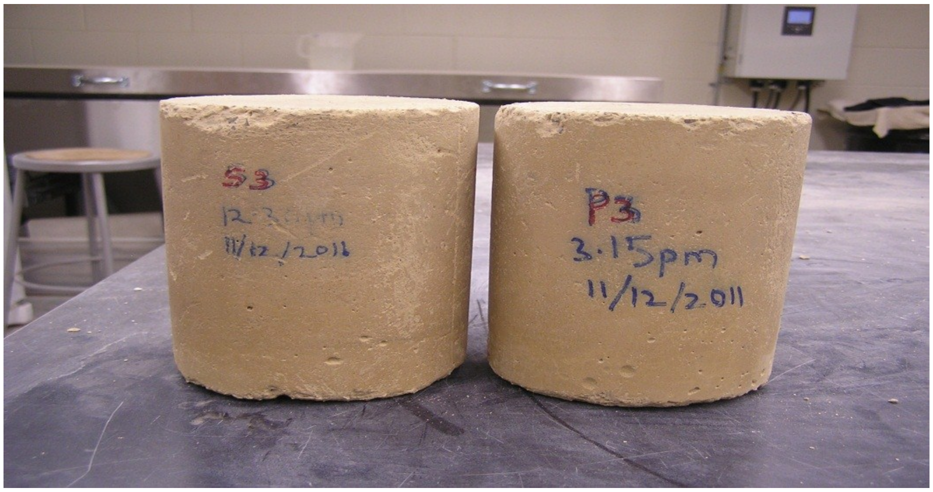


Figure B14. Saturated Samples S3 and P3 after 27 freeze-thaw cycles

Figure B15. Saturated samples S02 and P02 after 44 freeze-thaw cycles

Figure B16. Saturated samples S03 and P03 after 44 freeze-thaw cycles

Figure B17. Saturated samples S2 and P2 after 44 freeze-thaw cycles

Figure B18. Saturated samples S3 and P3 after 44 freeze-thaw cycles

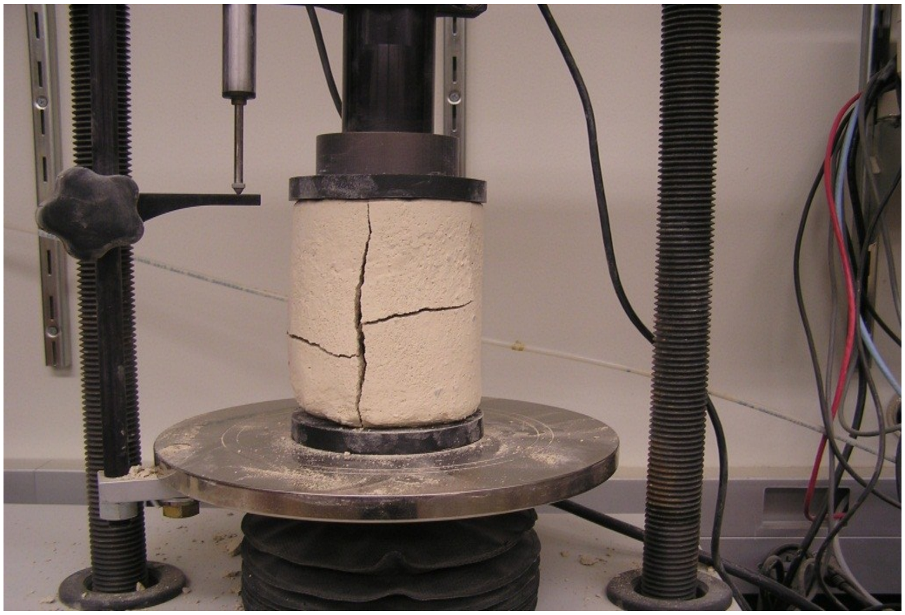


Figure B19. Testing for 56-day unconfined compressive stress after subjecting the samples to 12 freeze-thaw cycles

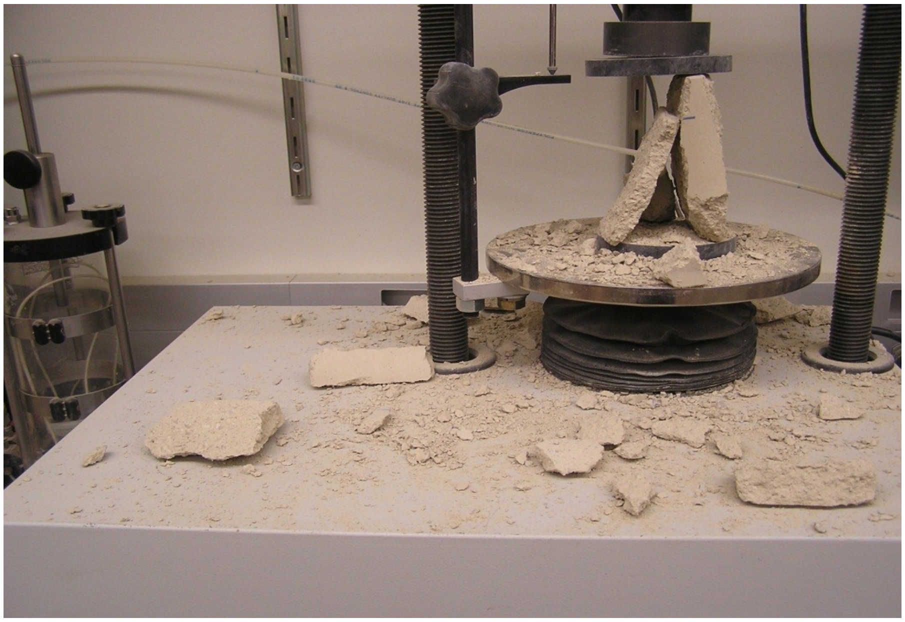


Figure B20. Testing for 56-day unconfined compressive stress after subjecting the samples to 12 freeze-thaw cycles

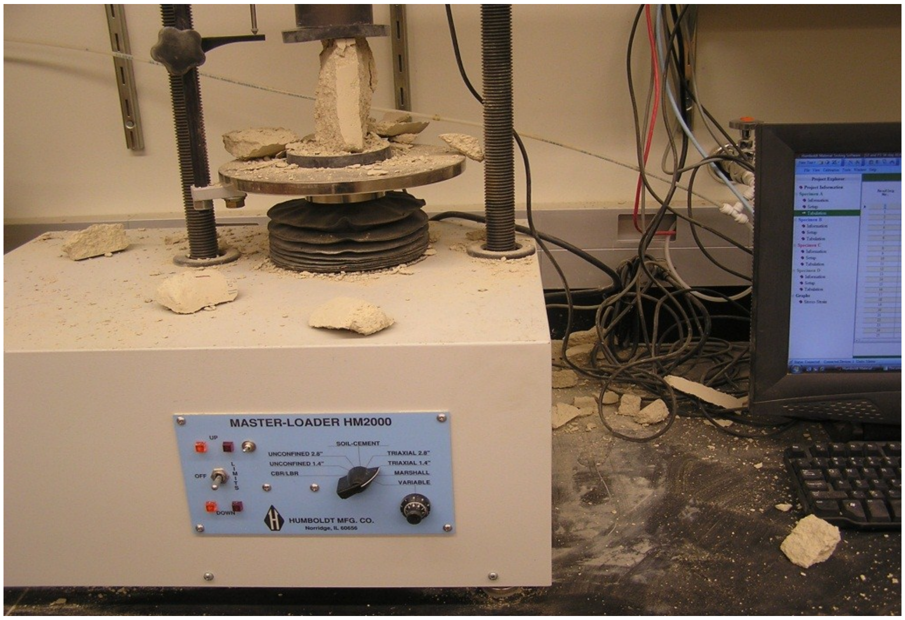


Figure B21. Testing for unconfined compressive stress
after subjecting the samples to 12 freeze-thaw cycles

Figure B22. Testing for unconfined compressive stress
after subjecting the samples to 12 freeze-thaw cycles

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# VITA

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