# Development of a Soft Ground Arrestor System

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# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

Air travel is considered one of the fastest and safest ways of transportation available. However, due to lack of safety area available at the end of runways, approximately 10 overruns (passing beyond the end of the runway) occur every year (Edwards 2007). An overrun generally occurs during landing and some times during take off, however most overruns occur during landing in bad weather. Because of this, the Federal Aviation Administration (FAA) recommends a safety area extending 1000 feet beyond each end of the runway (FAA 2002). Practically, it is difficult to provide this runway extension at many airports. In such cases, installing a Soft Ground Arrestor System (SGAS) can be a solution. The present SGAS available is known as an Engineered Material Arresting System (EMAS).

## 1.2 Background

The primary role of EMAS is to stop an overrun aircraft without causing any injuries to the passengers and causing little or no damage to the aircraft. When an aircraft enters the arrestor bed or EMAS, it crushes the material as it tries to pass through it. This develops a drag force between the tires of the aircraft and the bed material leading to the deceleration of the aircraft.

The typical cross-section suggested by FAA for an EMAS is 1000 feet long and having the same width of the runway (FAA 2002). This is not possible in many of the airports, in such cases the length of the bed is generally determined based on the length of the safety area. The depth is generally varied based on the type of aircraft to be arrested at that particular airport. Figure 1.1 shows the general plan view, section view and elevation of an EMAS.

The arrestor bed can be composed of crushable pre-cast cellular concrete blocks. Blocks are generally four foot in length with varying heights and are shipped to the site for their placement (Zodiac 2007). The front end of the arrestor system is ramped and then the depth of the bed is increased toward the far end as shown in Figure 1.1. This increase in depth is generally provided for maximum deceleration. Side steps are constructed at the sides of the arrestor system which facilitates the access of rescue and firefighting vehicles.

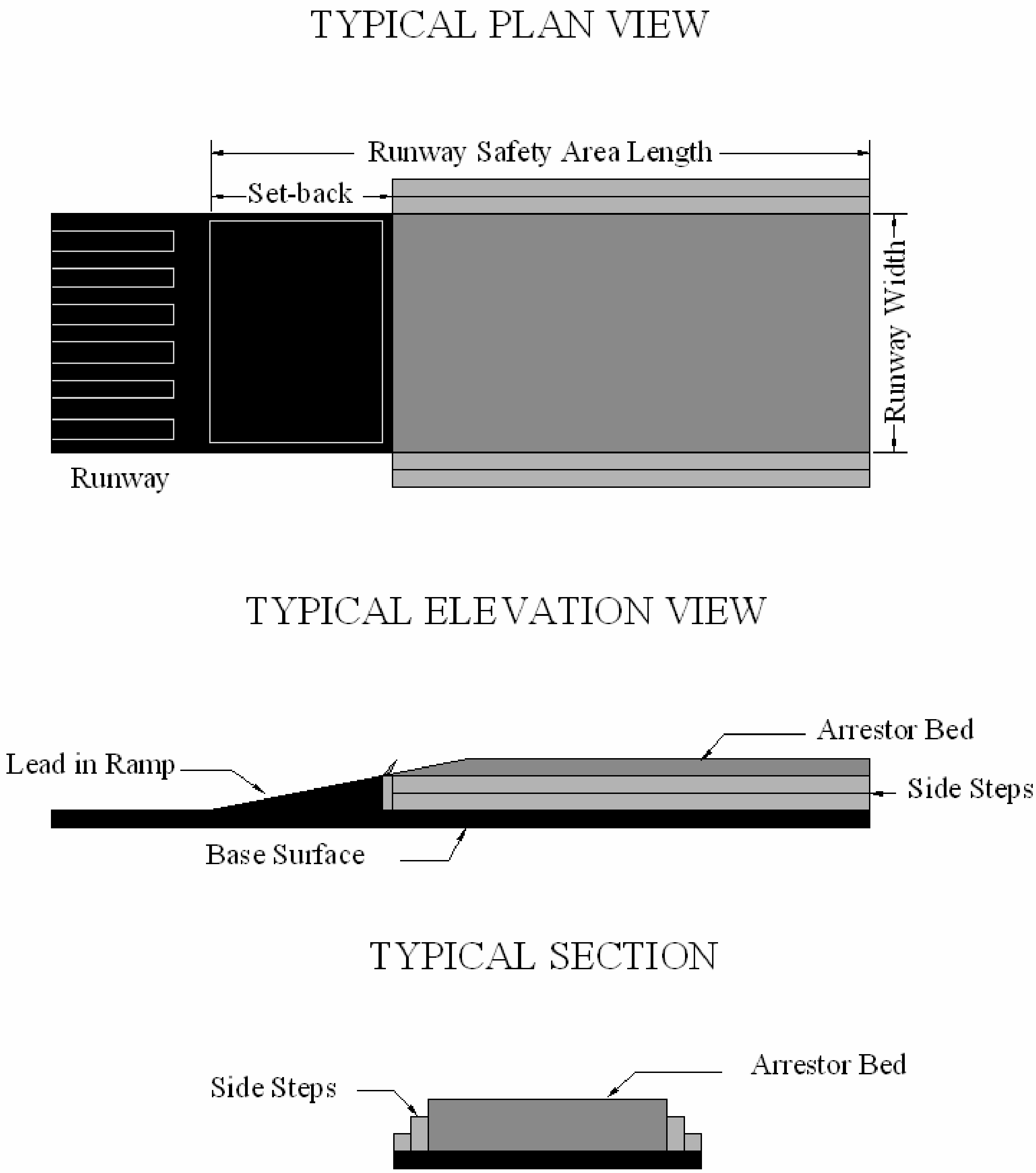


Figure 1.1 Engineered Material Arrestor System

## 1.3 Research Objectives

The objective of this research program is to develop an ultra-lightweight concrete mixture that is reliable and economical and that can be used as a SGAS. The project involves a detailed study of various types of concrete admixtures and their use in ultra-lightweight concrete. Since the behavior of ultra-lightweight concrete is dependent on its density, a relationship between density and concrete properties will also be examined.

## 1.4 Testing Programs

Density, compressive strength, and durability are the concrete properties which are the main concern of this project. These properties can be affected by the mixture proportions, aggregate type, entrained air content, admixtures type and dosage, mixing time, mixing speed, and water to cement ratio (w/c). In the case of arrestor beds, density, yield, and compressive strength play a major role. So, proper research will be conducted on these properties.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction to Ground Arrestor Systems

Since 1982 there have been 23 fatalities, over 300 injuries, and uncounted millions of dollars in aircraft damage at United States airports (United States of America 2005). The National Transportation Safety Board (NTSB) and the International Civil Aviation Organization (ICAO) performed a detailed study on the overruns and it was concluded that overruns can be prevented by providing a 1000 feet long safety area at the end of the runways. After this study, Federal Aviation Administration (FAA) then recommended a 1000 feet long safety area at the end of all runways (FAA 2002).

For many airports, it was impractical to build the 1000 feet long safety area due to man made and natural boundaries such as highways, water ways, natural terrain, residential areas, commercial or industrial uses or sensitive environmental areas. FAA was then asked by NTSB to develop a solution for cases where this safety area cannot be provided.

FAA then partnered with the Port Authority of New York and New Jersey, Academic Community, and ESCO (Engineered Arresting Systems Corporation) to conduct research on arrestor systems (Zodiac 2007). EMAS was then introduced as a solution. The first EMAS was installed in 1996 at John F. Kennedy International Airport (JFK) on runway 04R and was tested in 1999 when a SAAB 320 overran the runway at a speed of more than 70 knots. The aircraft came to a stop with no injuries to the passengers and no damage to the aircraft. Again in 2003, a cargo jet carrying 3 members overran into the same arrestor bed and again there were no injuries to the passengers and no damage to the aircraft (PANYNJ 2004). Currently there are approximately 20 EMAS beds installed in the United States (Edwards 2006). Table 2.1 lists the EMAS installations in the United States.

Table 2.1 EMAS Installations

| #EMAS | Airport | Location | Runways | Installation date |
|---|---|---|---|---|
| 1 | JFK International | Jamaica, NY | 4R | 1996 |
| 1 | Minneapolis/St. Paul | Minneapolis, MN | 12R | 1999 |
| 2 | Little Rock | Little Rock, AR | 4R/22R | 2000/2003 |
| 1 | Rochester International | Rochester, NY | 28 | 2001 |
| 1 | Burbank | Burbank, CA | 8 | 2002 |
| 1 | Baton Rouge Metro | Baton Rouge, LA | 31 | 2002 |
| 2 | Greater Binghamton | Binghamton, NY | 16/34 | 2002 |
| 1 | Greenville Downtown | Greenville, SC | 19 | 2003 |
| 1 | Barnstable Municipal | Hyannis, MA | 6 | 2003 |
| 1 | Roanoke Regional | Roanoke, VA | 15 | 2004 |
| 2 | Fort Lauderdale International | Fort Lauderdale, FL | 27R/9L | 2004 |
| 1 | Dutchess County | Poughkeepsie, NY | 6 | 2004 |
| 2 | LaGuardia | Flushing, NY | 22/13 | 2005 |
| 1 | Boston Logan | Boston, MA | 4L | 2005 |
| 1 | Laredo International | Laredo, TX | 17R | 2006 |
| 1 | Jiuzhai-Huanglong (JZH) | Sichuan, PRC | 20 | 2006 |

Of the 13 overruns that occurred between Oct. 7, 2004 and March 8, 2006, only one occurred on a runway where an EMAS was installed. For this overrun, there were no casualties and also no damage to the aircraft (Edwards 2006). For the other 12 overruns where there was no EMAS, there were 34 deaths, 185 injuries and 10 damaged aircrafts (Edwards 2006). This clearly indicates the importance of the EMAS.

### 2.2 Classifications of Concrete

Concrete can be the material of choice for many EMAS. A concrete mixture can be proportioned to have the density, strength, and durability necessary for an EMAS. The following sections provide a brief overview of various types of concrete and discuss the differences in the concretes.

#### 2.2.1Conventional Concrete

ASTM C 125 - 95a (1996) defines concrete as a composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregate; in hydraulic cement concrete, the binder is formed from a mixture of hydraulic cement and water. Concrete is basically a mixture of two components: aggregates and paste. The quality of concrete depends on the quality of the paste and aggregate, and the bond between the two (Kosmatka et al. 2002).

The paste is comprised of binder, water and air (entrapped and/or entrained). The paste portion makes up about 25-40% of total volume of concrete. Different types of binders are used for specific purposes. The most commonly used binder is portland cement.

Aggregates generally account for 70-80% of the concrete volume. Aggregates can be classified into two groups. These two groups are coarse aggregate (greater than ¼ in.) and fine aggregate (aggregate size smaller than ¼ in.). Generally gravel or crushed stone are used as coarse aggregate and natural sand, crushed natural rock smaller than 0.2 in. or a combination of both, are used as fine aggregate (La Londe and Janes 1961). Some of the aggregate properties that are to be considered while selecting an aggregate for a particular project are shape, size, texture, porosity, water absorption capacity, strength, and impact resistance (Murdock et al. 1991). These properties play a substantial role in the workability, strength, stability, and durability of the concrete. Alternative aggregate material includes granulated plastics, granulated coal ash, blast furnace slag, paper and wood products. The density of conventional concrete normally ranges between 137 to 150 pcf (Kosmatka et al. 2002).

Compressive strength of conventional concrete is approximately 3000 to 6000 psi at 28 days of age and that of high-strength concrete is more than 6000 psi (Kumar 1986). Generally compressive strength is measured at ages of 7, 14, 28, 56, and 90 days. Among which the 28 day strength is considered most important. It is estimated that the compressive strength of concrete at 7 days is 75% of the 28 day strength and there is an increase of about 10 to 15% in compressive strength from 28 days to 56 days and another 10 to 15% increase by 90 days (Kosmatka et al. 2002).

The compressive strength of concrete is dependent upon the water to cement ratio (w/c), constituent materials, mixing procedure, placement and compaction methods, and type of curing. High-strength concrete may have w/c of 0.30 or less (Kumar 1986). A lower w/c significantly helps in reducing permeability, segregation and bleeding.

During the period of 1985 and 1999, studies have been conducted on a variety of mixtures with different compressive strengths and w/c. It was clearly seen that the compressive strength increased with decreases in w/c. Figure 2.1 shows 28 day compressive strength of different portland cement concrete mixtures developed with varying w/c.

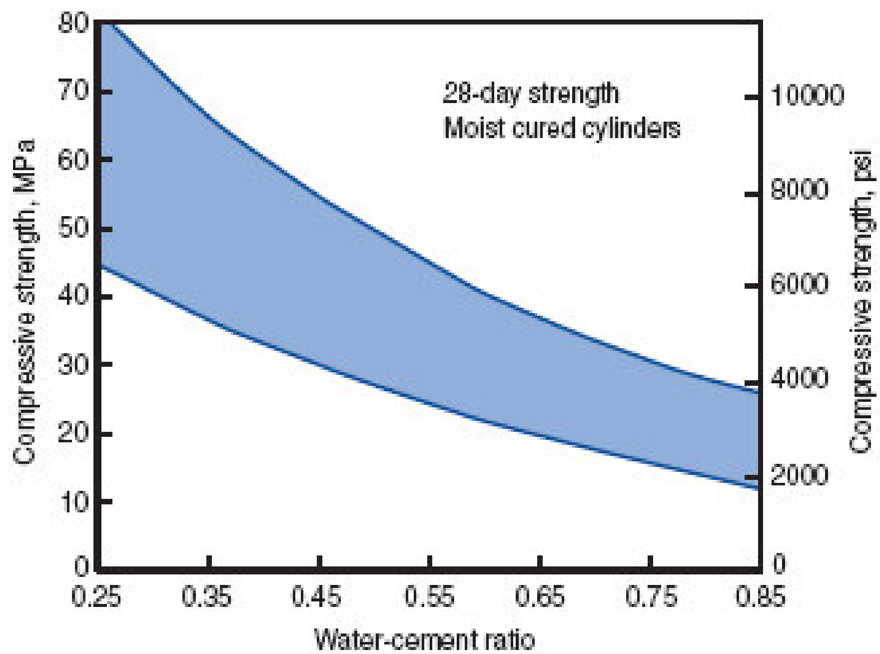


Figure 2.1 Water to Cement Ratio vs. Compressive Strength (Kosmatka et al. 2002)

### 2.2.2 Air-Entrained Concrete

Air-entrained concrete is produced using either air entraining agents (chemical admixture is added) or by using air-entraining cement. Generally, the amount of air in air-entrained concrete ranges between 4 to 8% of the total volume. The entrained air is in the form of minute bubbles (McMillan and Lewis 1987). The amount of entrained air affects the compressive strength of concrete. Generally, with an increase of entrained air of 1% the compressive strength decreases approximately 5% (Murdock et al. 1991). But in spite of this, there are many benefits of using air-entraining concrete, such as; increased workability, resistance to alkali-silica reactivity, sulfate resistance, scaling resistance, and freeze-thaw resistance. Air-entrainment also improves the water tightness. Shown in Table 2.2 is the recommended air content for concrete based on exposure conditions (Kosmatka et al. 2002).

Table 2.2 Recommended Total Target Air Content for Concrete (Kosmatka et al. 2002)

| Nominal maximum size aggregate, mm (in.) | Air content,% | | |
| --- | --- | --- | --- |
| | Severe exposure | Moderate exposure | Mild exposure |
| <9.5 (3/8) | 9 | 7 | 5 |
| 9.5 (3/8) | $7^{1}/2$ | 6 | $4^{1}/2$ |
| 12.5 (1/2) | 7 | $5^{1}/2$ | 4 |
| 19 (3/4) | 6 | 5 | $3^{1}/2$ |
| 25 (1) | 6 | $4^{1}/2$ | 3 |
| 37.5 ($1^{1}/2$) | $5^{1}/2$ | $4^{1}/2$ | $2^{1}/2$ |
| 50 (2) | 5 | 4 | 2 |
| 75 (3) | $4^{1}/2$ | $3^{1}/2$ | $^{11}/2$ |

### 2.2.3 Introduction to Lightweight Concrete

Lightweight concrete is very similar to conventional concrete. Both concretes contain the same basic constituent materials. However the differences lie in the type of coarse aggregate (which are further discussed in section 2.5.1).

Lightweight concrete has been a solution for many construction problems. Lightweight concrete can be designed to have compressive strengths equal to that produced by normal weight concrete but with lower densities (Dolby 1996). The lower densities of lightweight concrete can decrease the dead load of the structure (Anon 1929) and decrease shipping costs. The density of light weight concrete generally ranges between 19-116 pcf (Anon 1989).

There are many benefits of using lightweight concrete, some of which are as follows (Bobrowski 1977):

1. Lightweight concrete can reduce the dead load of the structure. Since the dead load of the structure is a major part in the design, there are economic advantages in using lower-density concrete.
2. Lightweight concrete is widely used as an insulating material as it possesses excellent thermal properties. The thermal insulation property of cellular concrete (detailed description on cellular concrete is discussed in section 2.6.3) depends on its density. Lower densities have better insulation properties (Anon 1963).
3. The segregation resistance of lightweight concrete is greater than that of conventional concrete.
4. Lightweight concrete is much easier to pump when compared to conventional concrete.
5. Large volumes of lightweight concrete are easier to transport and accommodate.

### 2.2.4 Lightweight Aggregate

The behavior of the lightweight aggregate in concrete is difficult to understand as it varies with minimum variations in the mixture design. Environmental conditions may also change the fresh and hardened properties of concrete. Therefore, a proper understanding of the aggregate is required to develop a uniform mixture for meeting the requirements of an arrestor bed.

Lightweight aggregate can be either natural or artificial. Table 2.3 shows various types of aggregate (both normal weight and light weight) and their densities (Spratt et al, 1980). Lightweight aggregate can vary in bulk density based on its absorption capacity.

The absorption capacity of lightweight aggregate is much higher than that of the normal weight aggregate. This is one of the main concerns in the production of lightweight concrete as it might affect the consistency of the concrete mixture (Larrard 1999). The absorption capacity mainly depends on the structure of the aggregate. Lightweight aggregate exhibits a higher porosity when compared to normal weight aggregate resulting in higher absorption capacity (Mindess et al. 2003).

Table 2.3 Different types of aggregate and their density (Spratt et al. 1980)

| Aggregate type | Density (lb/ft$^3$) |
|---|---|
| Normal weight aggregate | 85-100 |
| Sintered PFA | 48-65 |
| Brick rubble | 47-70 |
| Scoria | 45-81 |
| Volcanic slag | 44-75 |
| Furnace clinker and breeze | 45-65 |
| Expanded slag | 44-61 |
| Foamed slag | 30-960 |
| Pumice | 30-55 |
| Expanded slate | 29-50 |
| Sintered diatomite | 28-50 |
| Expanded shale and clay | 20-60 |
| Wood shavings and sawdust | 20-30 |
| Exfoliated vermiculite | 04-10 |
| Expanded perlite | 03-15 |

**2.2.4.1 Perlite** Perlite is the most commonly used lightweight aggregate. It is known as the world's most versatile mineral (Perlite Institute 2005). Perlite is found in acidic volcanic glass rock. Perlite expands almost 20 times its volume when heated, resulting in the production of a very fine powder that is generally white to light gray in color. The expanded perlite has a bulk density ranging between 2 to 15 pcf (Neville 1987). The water absorption capacity of perlite is about 10-50% by weight (Mindess et al. 2003). Lightweight concrete containing perlite has low strength and is mainly used for insulation

Concrete containing perlite has good workability. However perlite decreases concrete strength when compared to concrete made using other light weight aggregates such as pumice, expanded slag, or shale (Perlite Institute 2005). Hence, for concrete where higher strengths are required and perlite is used, the cement content in the mixture is increased. Generally compressive strength of perlite concrete ranges from 100 to 1,500 psi and based on the strength requirements of the project, concrete strengths are varied by changing the amount of cement in the mixture or by introducing an air entraining admixture. High strength concrete made from perlite generally have good resistance to freezing and thawing.

**2.2.4.2 Exfoliated Vermiculite** Exfoliated vermiculite is a very light weight aggregate formed by heating raw vermiculite (micaceous mineral) to 1382-2012ºF (Murdock et al. 1991). It is generally grey to light brown in color, and its density ranges between 4 to 10 pcf. Exfoliated vermiculite has a thermal conductivity that is similar to perlite and is also used in insulating concrete.

The structural strength of concrete containing exfoliated vermiculite is quite low. Exfoliated vermiculite is very soft which makes it very weak in compression. So weak, that during mixing, the material can collapse (Murdock et al. 1991). The water absorption capacity of exfoliated vermiculite ranges between 25-35% by weight (Mindess et al. 2003). Hence it is important to properly understand its resistance to freezing and thawing, as it can cause great damage to the concrete (Murdock et al. 1991).

### 2.2.5 Chemical Admixtures

To achieve the desired fresh and hardened properties needed for concrete used in an EMAS, several types of admixtures may be used. Each of these admixtures is discussed in greater detail in the following sections.

**2.2.5.1 Air–Entraining Agents** According to ASTM C 260 - 94 (1994) an air-entraining agent is defined as a material that is used as an ingredient in concrete, added to the batch immediately before or during mixing, for the purpose of entraining air. The function of air-entraining agents is to stabilize the smaller bubbles and to assure that they remain in the concrete and provide a space where water pressure can be relieved during freezing. Air-entraining agents were first used by early Romans and Greeks to increase the workability of the pozzolanic mixes. Blood or animal fat was used as the air-entraining admixture (Dhir 2005). When used at the proper dosage, these exhibit great benefits, such as: increasing workability, increasing concrete uniformity, increasing frost resistance, and reducing bleeding (Kosmatka et al. 2002). In general, all concrete structures exposed to severe climatic conditions should contain air-entraining agents.

**2.2.5.2 High Range Water Reducers (Superplasticizers)** High Range Water Reducers (HRWR) also known as super plasticizers are admixtures that reduce the amount of water required for the production of concrete. Superplasticizers are well known for their capabilities of improving the workability, long-term durability, and strength of concrete mixtures. Superplasticizers free the water by dispersing the cement particles. They generally reduce the amount of water by 10 to 15% (Ramachandran 1984) which reduces the w/c and therefore improves the concrete's properties. The percentage of water reduction can be increased by increasing the amount of superplasticizer which might lead to some undesirable effects in the concrete such as loss in workability and low compressive strength. The cohesive effect of superplasticizer helps prevent segregation in concrete, but this is dependent upon the HRWR dosage (Ramachandran 1984).

**2.2.5.3 Air-Stabilizing Agents** Shrinkage is the most common problem found in the lightweight air-entrained concrete (Regan 1990). The stability of the foam (the entrained air in cellular concrete is generally in the form of foam) or the air bubbles can be increased by adding an air-stabilizing agent. Resinate foams may be stabilized by adding aluminum sulfate to the mixing water (Taylor 1974). Sometimes foaming agents with moderate foaming properties work better than the other agents.

## 2.3 Classifications of Lightweight Concrete

Of the different types of concrete previously mentioned, light weight concrete is most promising for use in an EMAS. According to Anon (1989), lightweight concrete can be classified into three types; lightweight aggregate concrete, lightweight concrete with no-fines, cellular concrete. Each of these three types of lightweight concrete are discussed in greater detail in the following sections.

### 2.3.1 Lightweight Aggregate Concrete

Lightweight aggregate concrete is similar to conventional concrete except the normal weight aggregate is replaced by lightweight aggregate. The density of lightweight aggregate concrete ranges between 75-125 pcf. BS 3797 (British Standard) gives a detailed specification for lightweight aggregates for concrete. BS 3797 sets limits of 24-75 pcf (400-1200 kg/m$^3$) for fine lightweight aggregate and 16-62 pcf for coarse aggregate.

Factors that affect the density of lightweight concrete are: mixture proportions, aggregate size, entrained air, admixtures, and water content (ISE and CS 1987). Typical ranges of nominal air-dry densities for the aggregates are shown in the Figure 2.2. While using light weight aggregate such as perlite and exfoliated vermiculite water absorption is one of the main concerns as it may affect the workability and density of concrete (ISE and CS 1987).

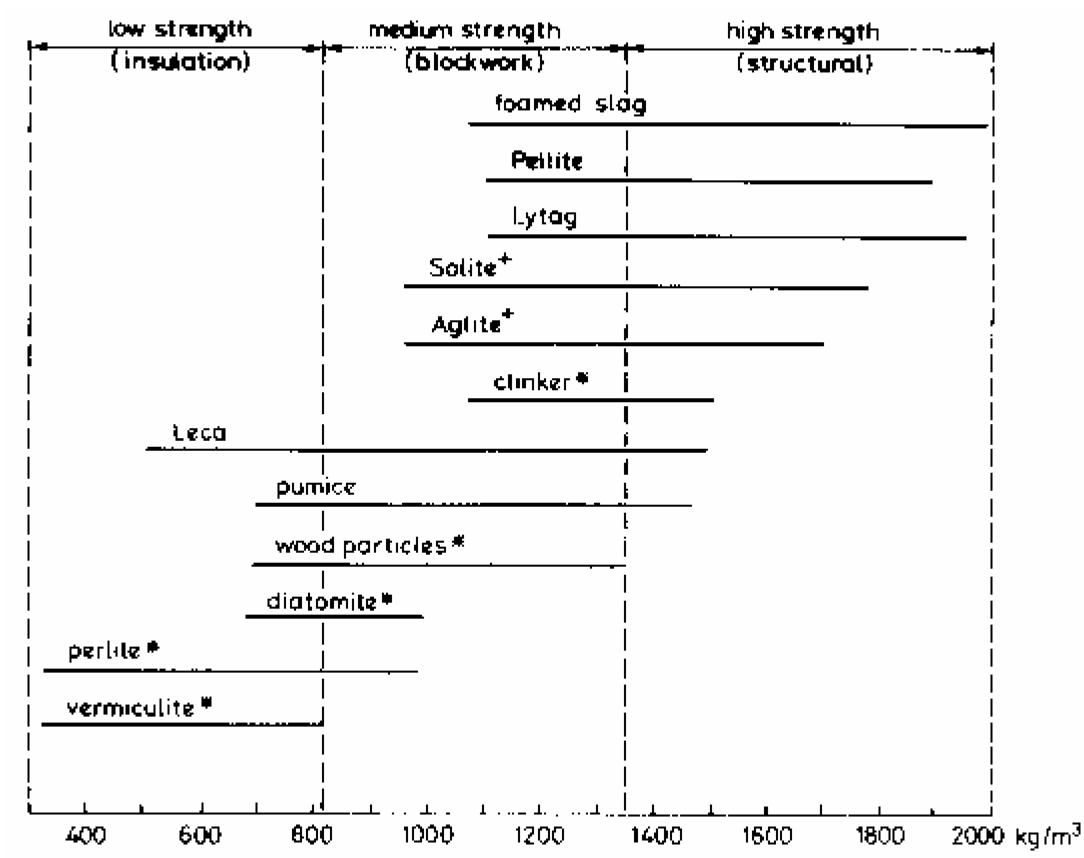


Figure 2.2 Nominal Range of Air-Dry Densities for Various Light Weight Aggregate Concrete (ISE and CS 1987)

Lightweight aggregate concrete can then be divided into three classes based on their function: Class I (for structural use), Class II (for both structural and insulation purpose), Class III (for insulation use). Table 2.4 shows different types of lightweight aggregate concrete and their corresponding densities, compressive strength, and coefficient of thermal conductivity values.

Table 2.4 Classification of Lightweight Aggregate Concrete (ISE and CS 1987).

| | Class | | |
|---|---|---|---|
| | I | II | III |
| Type of light weight concrete | Structural | Structural and Insulating | Insulating |
| Oven-dry density ($kg/m^3$) | <2000 | Not specified | Not specified |
| Compressive strength ($N/mm^2$) | >15.0 | >3.5 | >0.5 |
| Coefficient of thermal conductivity (W m.k) | - | <0.75 | <0.30 |

Recognizing the importance of lightweight aggregate, the Bureau of Reclamation, the United States Department of the Interior, and the National Bureau of Standard Investigation (NBSI) examined the properties of lightweight aggregate concrete in 1950 (HHFA 1949). Their research showed that concrete made of perlite also showed good resistance to freezing and thawing but had higher shrinkage which is of interest for an EMAS.

The mixture design of lightweight aggregate concrete mainly depends on the dry density of the aggregate that is used. At the same time it is important to maintain proper wet density during the project which can only be done by maintaining mixing time, proper mixing speed, and proper proportioning of mixture (Clarke 1993).

### 2.3.2 No-Fines Concrete

No-fines concrete is produced by eliminating fine aggregate from the concrete mix. In this type of concrete, the cement paste bonds the coarse aggregate together (Neville 1987). Coarse aggregate of ordinary weight are generally used in no-fines concrete, and they have a size of less 20 mm (Shetty 2004). Due to the absence of fines, the requirement of cement paste reduces as the surface area to be coated is decreased. This in turn makes no-fines concrete economical (Neville 1987).

No-fines concrete has low density, low strength and exhibits good resistance to frost action which is due to high volume of voids. No-fines concrete has a density of 100 to 120 pcf when conventional aggregates are used and about 22.5 pcf when lightweight aggregates are used (Shetty 2004). The strength of no-fines concrete is dependent on w/c, aggregate to cement ratio (a/c), and unit weight of concrete (Shetty 2004). It can be clearly seen from Figure 2.3 that high strength no-fines concrete can be attained by maintaining lower w/c and lower a/c.

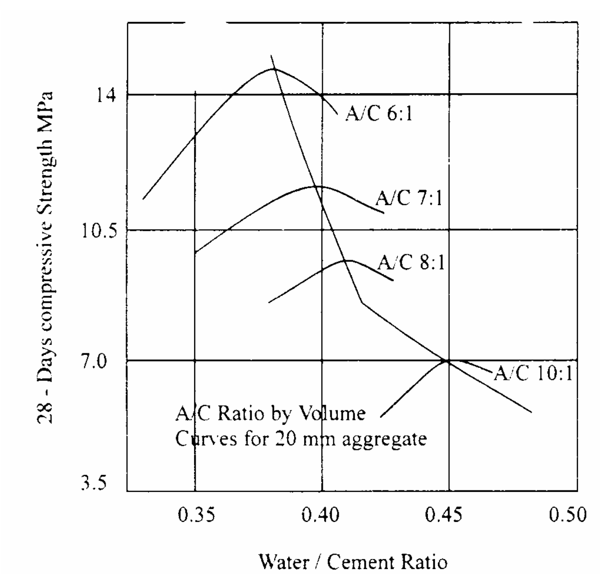


Figure 2.3 28-Days Compressive Strength vs. Water/Cement Ratio (Shetty 2004)

The drying shrinkage of no-fines concrete is relatively low and has no segregation (The Concrete Center 2007). No-fines concrete is used in various types of construction, some of which are: exterior and interior building walls (Paul 2005), free drainage pavements, playing surfaces such as tennis courts, drainage layers, and leveling courses (CCAA 1999).

### 2.3.3 Cellular Concrete

Cellular concrete is a type of lightweight concrete formed by entraining air into the cement slurry. A cellular concrete mixture is composed of binder and slurry (Legatski 1987). While batching, air is entrained into the concrete in the form of stable bubbles (foam) which disintegrate upon hardening of the concrete. This results in the formation of numerous air voids. There are a number of physical properties that affect the behavior of cellular concrete among which unit weight is the most important property to be considered.

For cellular concrete, the w/c and aggregate are chosen based on the required density (Kearsley and Mostert 2005). The density of cellular concrete generally ranges between 20-120 pcf and is generally controlled by changing the amount of entrained air (Legatski 1987). In some cases light weight aggregates are introduced into the cellular concrete in order to attain certain properties such as strength, durability, and economy. Figure 2.4 provides the relationship between density and 28 day compressive strength of different cellular concrete mixtures (Fouad 2006).

Cellular concrete is commonly batched by two methods. The first method involves mixing foam or mixing foaming agents in the cement and water slurry (Fouad

2006). The second method involves the mixing of lime, sand, cement, water, and an expansion agent such as aluminum powder or hydrogen peroxide. During mixing, a chemical reaction occurs which produces gases such as hydrogen and oxygen which form a gas bubble structure in the concrete. This process of gas production results in a significant expansion of the concrete. The concrete is then cured under high-pressured-steam ranging from 356°-410°F to form the final structure (Fouad 2006).

It is important to maintain a proper w/c in cellular concrete. If the water added is less than the amount of water required, then the cement absorbs the water from the foam resulting in deterioration of the foam. If the amount water added is more than that required, then segregation will occur (Kearsley and Mostert 2005).

There are many benefits of cellular concrete. Some of which are: reduced dead load, increased durability, ease of production, workability, pumpability, economy, good freeze-thaw resistance, good insulating properties, reduced permeability, seismic resistance, fire resistance, and shock absorption (Fouad 2006).

Cellular concrete is used in many types of concrete construction. Cellular concrete is best known for its thermal property which makes it one of the best insulating material. The thermal conductivity of cellular concrete is directly proportional to density (Anon 1963). One of the most common uses of cellular concrete as insulating material is in roof decks (Legatski 1987). Cellular concrete is also used as backfill.

Figure 2.4 shows the relationship between the oven dry density and compressive strength of cellular concrete made of different aggregates. The figure clearly shows that the compressive strength increases with increase in density. Cellular concrete made with perlite as aggregate has the lowest density and therefore the lowest compressive strengths when compared to other aggregates.

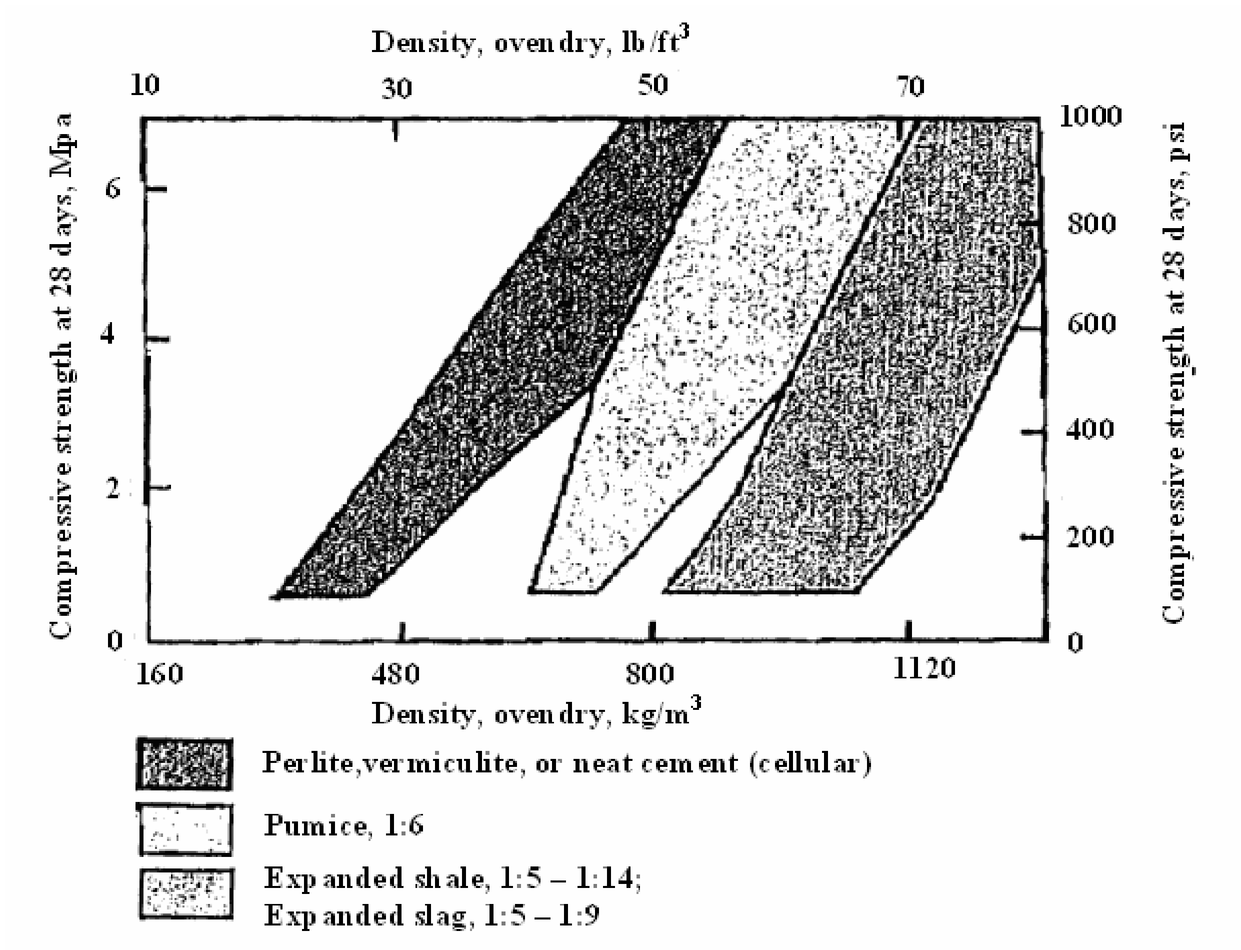


Figure 2.4 Density vs. Compressive Strength of Cellular Concrete (Kosmatka et al. 2002)

Anon (1963) examined the relationship of compressive strength to density for cellular neat cement (containing only foam, cement, and water) and a cement/sand mix (a mix ratio of 1 part cement to 4 parts sand). The results of his research are shown in Figure 2.5. Figure 2.5 clearly shows that the cellular concrete was able to attain compressive strength equal to that attained by cement/sand mix at much lower densities.

The general relationship of compressive strength to density for cellular neat cements and 1 : 4 cement/sand mixtures.

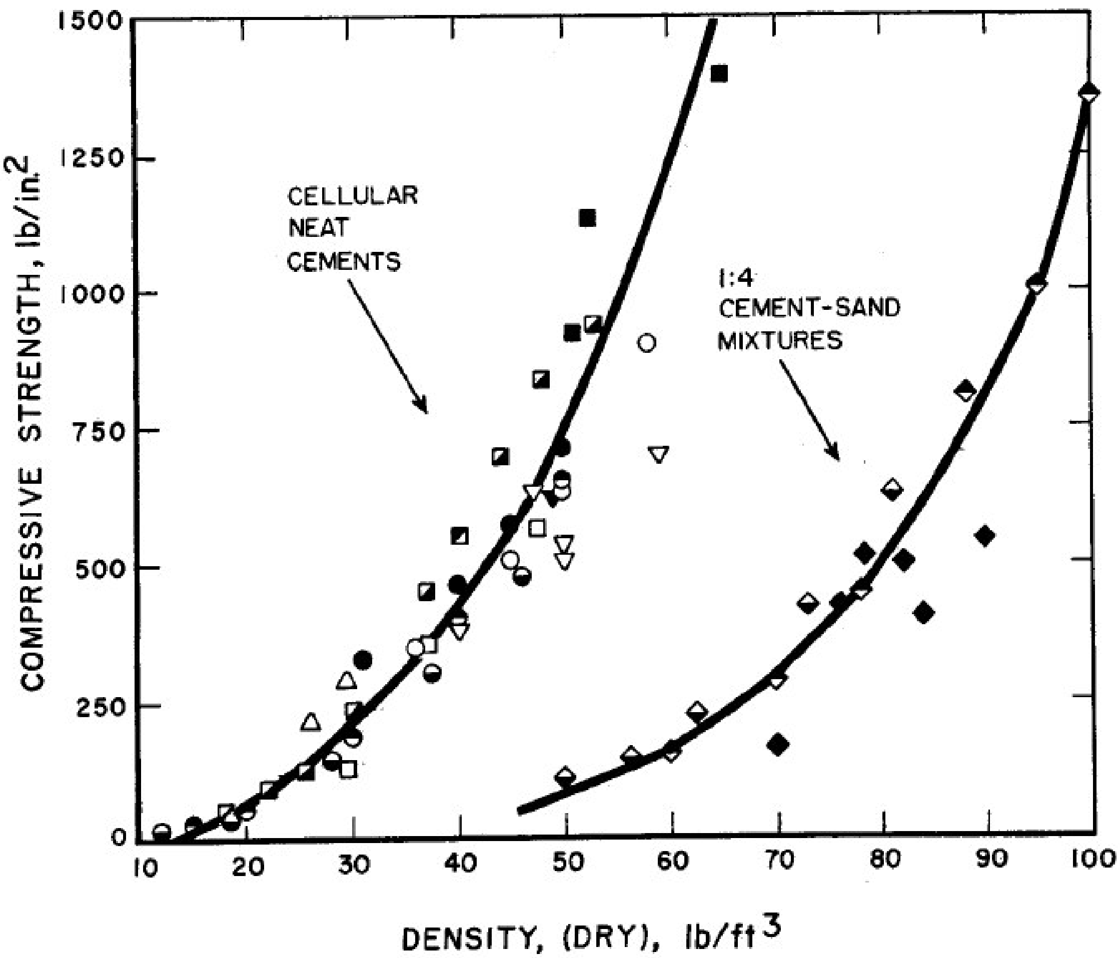


Figure 2.5 Density vs. Compressive Strength for Cellular Neat Cements and Cement-Sand Mixture (Anon 1963)

### 2.3.4 Mechanical Properties of Lightweight Aggregate Cellular Concrete

Regan and Arasteh (1990) conducted research on the material and structural properties of lightweight aggregate cellular concrete. A foaming agent (DeeCell) was used to produce foam with a density of 5 pcf. Rapid hardening portland cement was also used as the binder. The density and compressive strength were measured for all mixtures.

Shown below in Figure 2.6 is the cube strength versus concrete density. The plot clearly indicates that there is a steep increase in cube strength with small variations in cured density which shows a clear indication of the influence of cured densities on the strength of concrete. According to Regan and Arasteh, there was approximately a 25% increase in strength of concrete from 14 day to 90 day and there was approximately a 10% increase in strength from 7 day to 14 day. Some of the samples were oven dried which had lower strengths than samples that were normally cured concrete (cured at 70ºF).

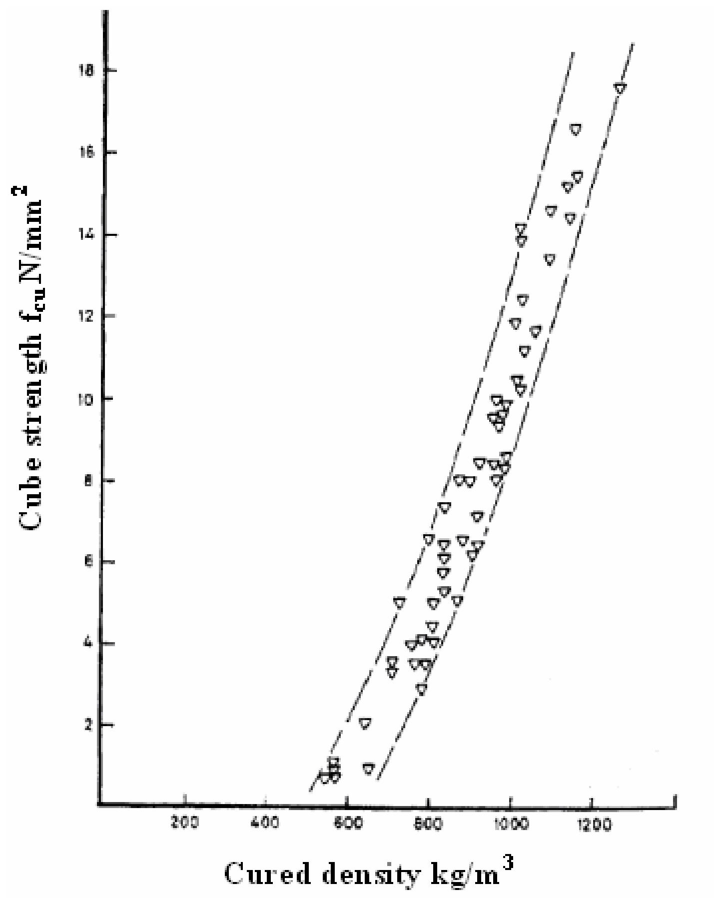


Figure 2.6 Cube Density vs. Cube Strength (Regan and Arasteh 1988)

The second graph (Figure 2.7) shows the relationship between the cellular concrete and the cube strength. Regan and Arasteh varied the amount of foam in the concrete and measured compressive strength at the various foam contents. The plot clearly shows that there was a gradual decrease in the strength with increase in foam content.

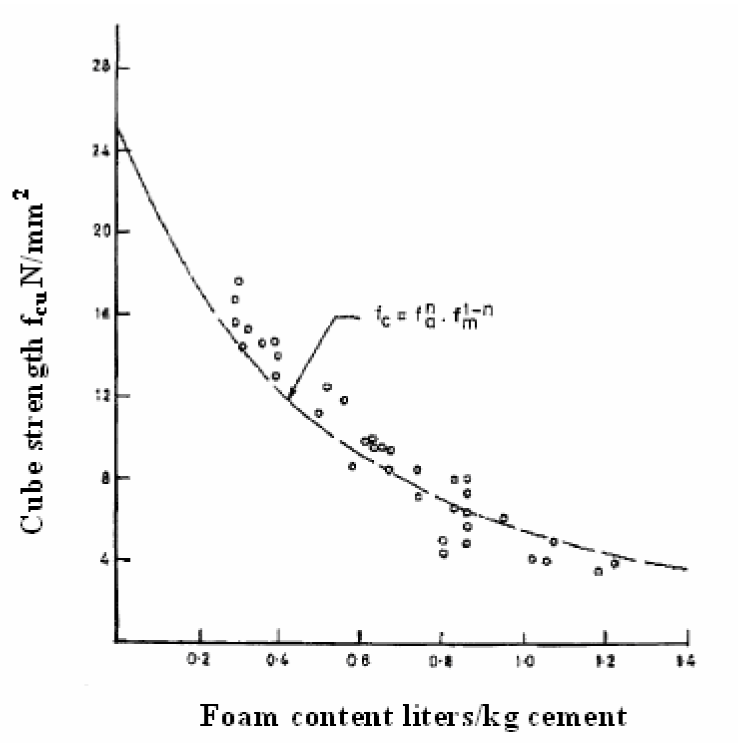


Figure 2.7 Foam Content vs. Cube Strength (Regan and Arasteh 1988)

Density is one of the most important factors affecting the behavior of lightweight concrete, Regan and Arasteh examined the relationship between foam content and density of concrete. The values obtained from the experiments were then compared with the theoretical calculations. Figure 2.8 shows this relationship. This clearly shows that there is a gradual decrease in density with increase in foam content which is expected.

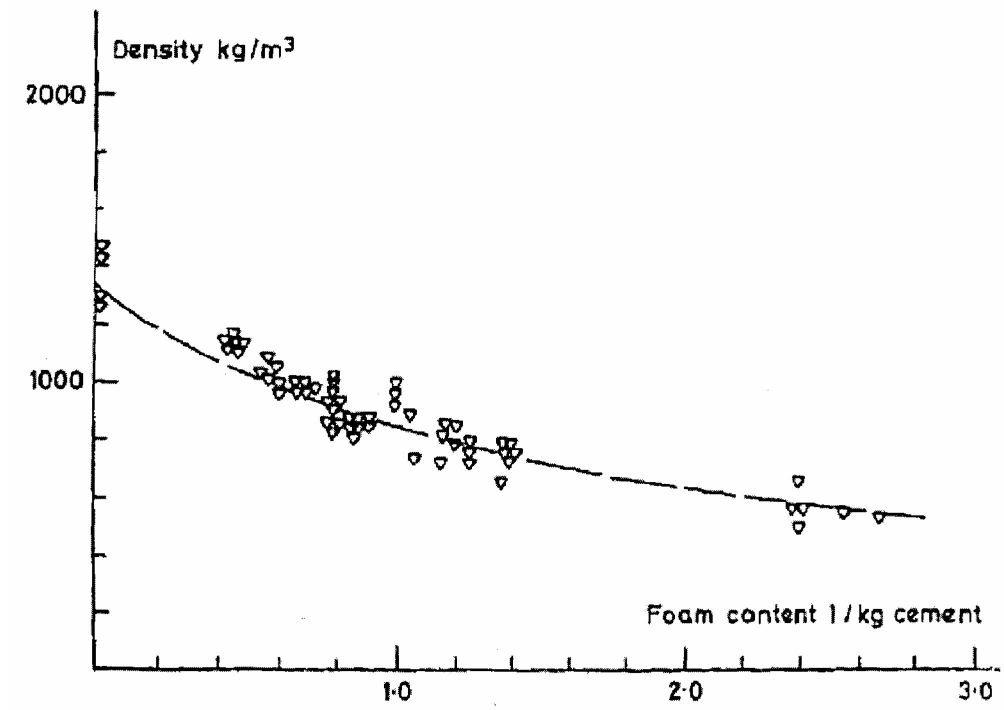


Figure 2.8 Foam Content vs. Density (Regan and Arasteh 1988)

Figure 2.9 displays the variation in cube strength with respect to w/c, which showed that with increases in w/c there was a decrease in the strength. Initially when the w/c ratio was varied from 0.5 to 1.5 there was a reduction of nearly 6400 psi and with further increases in w/c there was little change in the strength.

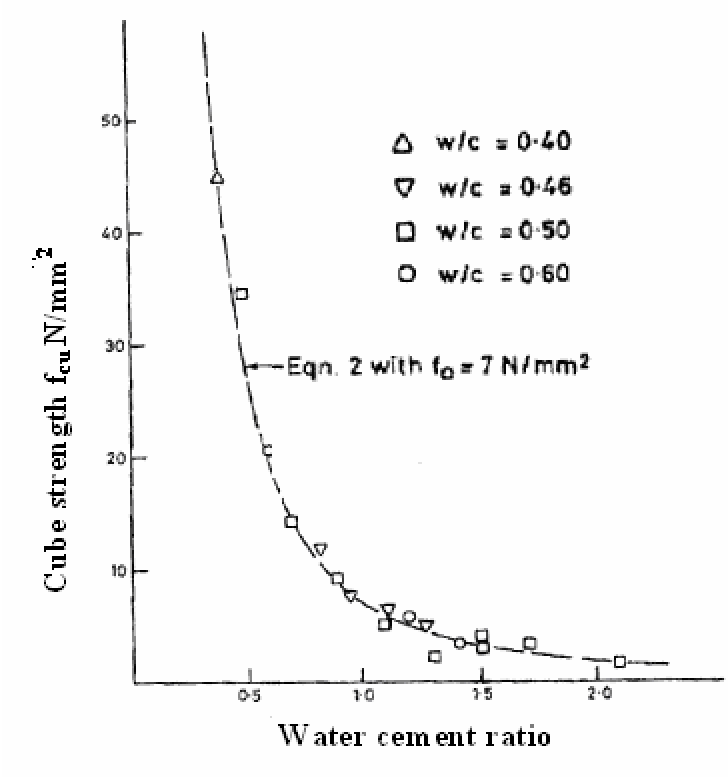


Figure 2.9 w/c vs. Cube Strength (Regan and Arasteh 1988)

**2.4 Summary**

A great deal of research has been conducted on different types of lightweight concrete and its importance compared to conventional concrete. In this research ultra-lightweight concrete (lightweight aggregate concrete with a high amount of air content and a density less than 70 pcf) is of main concern.

Little research has been conducted on ultra-lightweight concrete. It is difficult to understand the behavior of ultra-lightweight concrete. Water absorption is a great concern for an ultra-lightweight concrete with density under 30 pcf, because of the large percentage of entrained air. This in turn leads to a loss in compressive strength after saturation. This might also lead to significant deterioration when subjected to freezing and thawing cycles.

Another concern is the density of ultra-lightweight concrete. Efforts to establish a relationship between the density and compressive strength of concrete using under various admixtures and mixing temperatures should be determined. This research program will examine a complete range of ultra-lightweight concrete mixtures to develop a mix suitable for construction of a soft ground arrestor system.

# CHAPTER 3

# RESEARCH PROGRAM AND EXPERIMENTAL PROCEDURE

## 3.1 Introduction

The project involves development of ultra-lightweight concrete mixtures that will meet the requirements of an arrestor system (EMAS). According to FAA advisory circular AC 150/5220-22A the material used for EMAS should possess following characteristics:

1. Water resistant.
2. Not attract wildlife.
2. Non-sparking.
3. Non-flammable.
4. Non-combustible.
5. Not emit toxic or malodorous fumes during a fire.
6. Not support plant growth.
7. Have constant strength and density characteristics throughout life.
8. Be resistant to deterioration that might result from contact with soil, aircraft fluids, water, paint, sunlight, etc.

This project focuses on the strength and density characteristics of the EMAS and the role that chemical admixtures play in attaining the fresh and hardened concrete properties. Any improper use of chemical admixtures can reduce performance. Therefore this study will focus on developing ultra-lightweight concrete using a variety of chemical admixtures.

## 3.2 Materials

The following sections list and describe the materials used in the experimental research program. The materials used in the study include the binders, aggregates, and chemical admixtures. Each material is discussed in greater detail below.

### 3.2.1 Binders

Strong Company Inc, being one of the official project sponsors, supplied the two binders used in this project. Type I portland cement (PC-I) manufactured by Ash Grove Cement Company and calcium aluminate cement (CAC) manufactured by Heidelberger Calcium Aluminates Inc were the binders used in the project. The specific gravity of PC-I and CAC was 3.15.

### 3.2.2 Lightweight Aggregate

Two types of lightweight aggregates were used in the project, perlite and exfoliated vermiculite. Grefco Minerals Inc of Torrance, California manufactured the perlite and American Vermiculite Corporation of Kennesaw, Georgia manufactured the exfoliated vermiculite used in the project.

ASTM C 332-87 classifies lightweight aggregate into two groups. Perlite and exfoliated vermiculite are placed in Group I (aggregate prepared by expanding products). These aggregates are generally used in manufacturing lightweight insulating concrete. These two aggregates are non flammable and meet the EMAS requirements listed in Section 3.1. Proper protective gear such as goggles, gloves, and dust masks were used when handling these aggregate because they are considered hazardous. These aggregates were stored dry in closed containers at all times. The physical properties of the lightweight aggregates are shown in Table 3.1.

Table 3.1 Physical Properties of Lightweight Aggregate

| | Perlite | Exfoliated Vermiculite |
|---|---|---|
| Melting Point | NA | 2426º F |
| Specific Gravity | 2.35 | 0.66-0.96 |
| Water Absorption | 10-50% | 25-35% |

### 3.2.3 Chemical Admixture

Chemical admixtures are the ingredients in concrete other than binder, aggregate, fibers, and water. There are various types of admixtures and these admixtures are added before or during mixing to modify specific fresh and hardened concrete properties. The chemical admixtures used in the project are discussed in greater detail below.

**3.2.3.1 Stepanol Medry** Stepanol medry, commonly known as medry is an air-entraining agent manufactured by Stepan Company in Northfield, Illinois. It is white in color and is manufactured in a dry powdered form. It is also known as Sodium Lauryl Sulfate. It has excellent foaming properties and is generally used in preparation of detergents. Medry tends to agglomerate and is biodegradable. Hence, medry should be sealed properly and should be kept in a cool place. Medry is considered to be toxic and it has a pH of 8.5-11. Hence proper precautions such as using a dust mask, safety glasses and gloves should be taken while handling it.

**3.2.3.2 Rheocell 30** Rheocell 30 is the second type of air entraining agent used in the project. It is manufactured by BASF Corporation. It is a dark brown colored liquid with a pH ranging from 7-9 and specific gravity 1.015. It is water soluble, and it is very suitable for developing ultra-lightweight concrete. It tends to flocculate at a temperate lower than 34ºF and hence should be stored in a safe place.

**3.2.3.3 Melflux 2651F** Melflux 2651F, also known as melflux is a pastel colored powder used as a high range water reducer (HRWR). HRWR's increase the workability of concrete without adding additional water. Therefore, HRWR'S allow for a reduction in mixing water which will increase strength without sacrificing workability. Melflux can also be used as viscosity modifying agent to increase the workability of concrete. The melflux used in this project is manufactured by the Degussa Corporation. It has a pH of 6.5-8.5. Melflux can be mixed directly either to the dry mixture (dosage rate of 0.05% to 1.5% by weight of cementitious material) or added to the water. Melflux is a stable compound unless exposed to temperature more than 105ºF (stable until 105ºF, but flocculation's occurs above this temperature). Proper dosage of melflux improves the hardened concrete properties such as early age compressive strength. However, if used in excess, it can cause bleeding and segregation. Melflux is considered a hazardous material and proper protective measures should be taken while handling it.

**3.2.3.4 Methocel K 100 LV Hydroxypropyl Methylcellulose (Methocel)** The methocel used in this project is a water soluble cellulose ether manufactured by The Dow Chemical Company. It was used as a viscosity modifying agent (VMA) to reduce bleeding.

Methocel increases the workability and also increases the working time of the mix. It is easily dissolved in the mixing water. Methocel is also a hazardous material and care should be taken when handling the material. The product is flammable and should be stored in safe environment where the temperature is less than 90ºF.

**3.2.3.5 Aluminum Sulfate** The aluminum sulfate used in this project was manufactured by Alfa Aesar, A Johnson Matthey Company. The white colored powder was used to stabilize entrained air bubbles in the fresh concrete. It has a density 100 pcf, and is considered as toxic. Hence, care should be taken while handling. It is soluble in water and can be added directly to the dry mixture or to the mixing water.

## 3.3 Experimental Procedures

The experimental procedures section contains a discussion of the mixing techniques, batching, and curing method. Also, discussed in detail is the preparation of the pre-blend mixture (section 3.3.1.1) for batching. Finally, the fresh and hardened concrete property tests are listed along with the ages at which the mixtures were tested.

### 3.3.1 Mixtures and Batching

The following sections provide detailed discussions on material blending, mixing, and curing.

**3.3.1.1 Aggregate Blending** Prior to batching, the dry ingredients for the concrete mixtures required blending. For some mixtures, the Strong Company provided the blended mixtures to the University of Arkansas. For others, the mixtures were blended by the research team. The lists of pre-blends used in this project are listed in Table 3.2.

The pre-blend mixture contained lightweight aggregate (perlite and exfoliated vermiculite), binder (PC-I, CAC, or both), and chemical admixtures (medry and methocel). The quantity of lightweight aggregate was measured in terms of volume not weight. This is because the absorption capacity of lightweight aggregate is much higher when compared to normal weight aggregate. Hence it is better to check the bulk density of lightweight concrete and adjust the weights accordingly. A cubic foot box made of wood shown in Figure 3.1 was used in the project to measure the light weight aggregate.

Aggregate blending was accomplished using a revolving drum mixer with a 6 $ft^3$ capacity. The aggregate blend was dry mixed until uniform. Since perlite is light weight, precautions were taken to ensure that perlite did not accumulate at the top of the mix. To ensure homogeneity, a particular order of mixing was maintained in the blending process (perlite followed by vermiculite and then binder and finally chemical admixtures). Careful attention to mixing time is necessary, because excessive mixing can cause the mixture to lose homogeneity. This is due to the variation in density of the different ingredients (binder being the heaviest tends to settle to the bottom). A mixing time of 4-5 minutes was maintained for all the pre-blend mixture batches. While blending aggregate, the mixer was covered to prevent the loss of material.

Table 3.2 Blended Mixes

| | Pre-Blend 1 | Master Blend 1 | Master Blend 2 | Pre-Blend 2 |
|---|---|---|---|---|
| Pre-blend | (PB 1) | (MB 1) | (MB 2) | (PB 2) |
| PC-I (lb/ft³ aggregate) | 10.4 | 5.2 | 7.8 | 10.4 |
| CAC (lb/ft³ aggregate) | 0 | 5.2 | 2.6 | 0 |
| Vermiculite (ft³) | 0.5 | 0.5 | 0.5 | 0.5 |
| Perlite (ft³) | 0.5 | 0.5 | 0.5 | 0.5 |
| Medry (g/ft³ aggregate) | 6 | 6 | 6 | 0 |
| Methocel (g/ft³ aggregate) | 12 | 12 | 12 | 12 |


Figure 3.1 Cubic Foot Box

### 3.3.1.2 Concrete Mixing Techniques

In this project three types of concrete mixers were used to batch the ultra-lightweight concrete. For smaller batches of approximately 0.2 $ft^3$ or less, a kitchen aid mixer (Figure 3.3) or a hobart mixer (Figure 3.2) was used. For larger batches of approximately 2.5 $ft^3$, a double drum shear mixer as shown in Figure 3.4 was used.

For mixing in the double drum shear mixer, the following procedure was followed throughout the project. First, one third of the water was poured in the mixer, followed by the dry ingredients being certain to evenly distribute the dry ingredients equally throughout the mixer. Once these ingredients were added, the mixer was turned on and the remaining mixing water was added and mixing continued for 15 seconds. Once all the ingredients were added, the dry mixture accumulated at the opening gate of the mixer. The dry mixture was collected in a bowl and reintroduced back into the mixer. This is repeated every 10 seconds for 2 to 3 times. The wet unit weight of concrete was measured (section 3.4.1.1) at one minute and then at intervals of 30 seconds until the targeted unit weight was attained.

For batching trial batches, a kitchen aid mixer (Figure 3.3), and hobart mixer (Figure 3.2) were used. The kitchen aid mixer has five control speeds. For this project "Speed 2" which mixed the concrete at 54 revolutions per minute, was used throughout the project. The hobart mixer has two control speeds. For this project, "Speed 1" was used throughout the project. At this speed, the mixer turned at a speed of 47 revolutions per minute. The maximum amount of sample that could be batched using the kitchen aid mixer was approximately 1100 g and that by the hobart mixer was approximately 2000 g.


Figure 3.2 Hobart Mixer

Figure 3.3 Kitchen Aid Mixer


(A) Front View

(B) Rare View

Figure 3.4 Double Drum Shear Mixer

**3.3.2 Curing** All the concrete specimens were cured at 70°F and 50 percent relative humidity. Ultra-lightweight concrete cubes (2 in.) and cylinders (3 in.×6 in.) were stored in air tight plastic bags measuring 12 in.×15 in. Also, larger specimen which measured 12 in. in height and diameter were cast to examine the stability of the mixture. These specimens were periodically checked to determine if the concrete collapsed during curing. A "stability" test specimen is shown in Figure 3.5a. These specimens were also covered with plastic and cured at 70°F. The samples were then removed from their molds after they had gained sufficient strength and returned to the air tight plastic bags and cured at 70°F until testing.

(a) (b)

Figure 3.5 Curing of Ultra-Lightweight Concrete in Environmental Chamber.

### 3.3.3 Concrete Properties

The concrete mixtures were subjected to fresh and hardened concrete tests. The only fresh concrete property that was tested in the project was wet unit weight. The compressive strength of the mixtures were tested on 2 in. cubes as well as 3 in.×6 in. cylinders at 1, 7, 28, 56, and 90 days.

It is also important to determine the accurate dry unit weight of the per blend mixture (because the varying absorption capacities of the lightweight aggregate can affect the unit weight of the concrete). The dry unit weight was measured using a 6×12 in. single-use cylinder mold made of plastic. While measuring the dry unit weight of per-blend mixture, the cylinder was not compacted or vibrated, because the material can settle and result in an inaccurate prediction of density. The weights were then adjusted based on the dry density of the mixture.

#### 3.3.3.1 Fresh Concrete Tests

In general terms unit weight is also known as specific weight or relative density and is defined as weight per unit volume of material. In the case of ultra-lightweight concrete, wet unit weight test (also known as fresh concrete density) acts as a control test and can be used in predicting later age concrete behavior. For this project, the unit weight was determined using a brass 3 in. in diameter (internal) and 3.5 in. tall (Shown in Figure 3.6). To accurately measure the wet unit weight of the concrete, it is vital that the proper test procedures be followed. The following steps were used to measure the wet unit weight of the ultra-lightweight concrete:

- Weigh unit weight cup.

- Fill the cup in three equal layers. Instead of tamping or rodding after each layer, the unit weight cup was tamped three times against the table.
- The third layer was filled in excess and then a trowel was applied to the top surface.
- Excess concrete was then removed from the exterior of the cup.

The unit weight can also be used to determine the yield of concrete batch. Yield is the measure of volume of concrete batched. Yield of concrete batch can be determined using the following equation (Mindess et al. 2003):

$$Y = [C+W/(WUW)]/[C/(DUW)] * 100$$

Where, C = weight of cement content in the concrete mixture

W = weight of water in the concrete mixture

WUW = wet unit weight

DUW = dry unit weight

Figure 3.6 Unit Weight Cup

#### 3.3.3.2 Hardened Concrete Tests

The compressive strength was tested at 1, 7, 28, 56, and 90 days of age. Three 2 in. cubes and three 3 in. × 6 in. cylinders were tested at each of these days. The samples were tested using a MTS testing machine (Figure 3.7). Prior to testing, the dimensions of the samples were measured using calipers. Early testing showed that the cylinders were not able to be demolded due to lack of concrete strength, and therefore limited test results were obtained from the cylinders.

**3.3.3.2.1 Test Specimen** Three different types of specimens were cast to measure the compressive strength and crushing strength of ultra-lightweight concrete. Two inch cubes and 3 in. × 6 in. cylinders were cast to measure the compressive strength.

Prior to casting, a particular procedure was followed to cast the cube specimens. WD-40 was applied to the faces of the mold for ease of stripping and preventing damage to the concrete specimen. Concrete was placed in 1 in. layers in the mold. Instead of tamping or rodding, the concrete was consolidated by lifting the ends of the molds off the table approximately 1 in. and then allowing them to drop. This procedure was repeated for 3 to four times. This was repeated for the second and final layer of concrete. The excess concrete was then struck off using a scraper and finished. The samples were then cured in the environment chamber at 70ºF. A similar procedure was followed for the cylinders, except the cylinders were cast in two equal layers of 3 inches.

Concrete stability was tested by casting concrete specimens 12 in. diameter and 12 in. height using sona tubes. In casting the samples, the concrete was placed in the molds in two layers of equal height and for each layer the outer surface of the sona tube was slightly tapped. The excess concrete was struck off using a trowel. The samples were then cured according to the test.

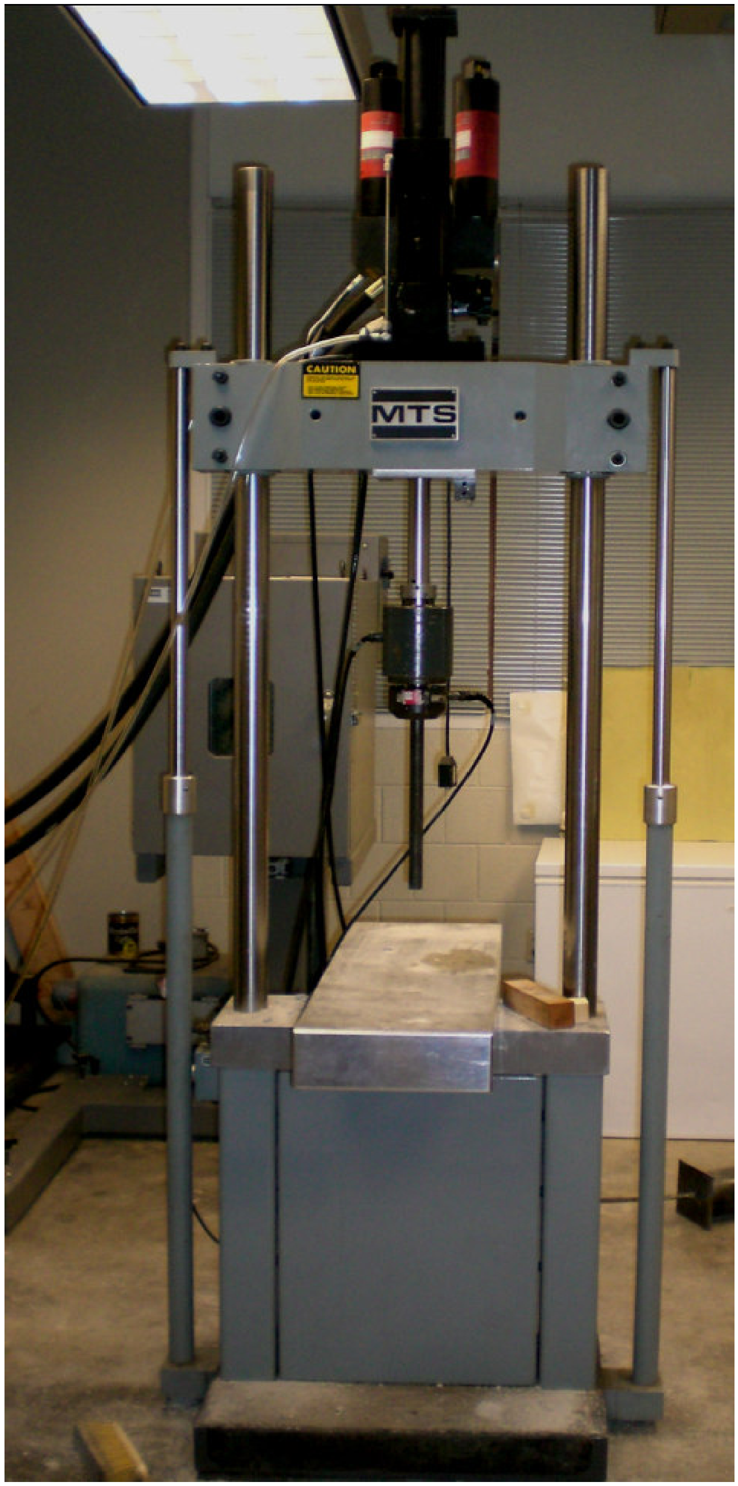


Figure 3.7 MTS Testing Machine

# CHAPTER 4

# TEST DATA AND DISCUSSIONS

## 4.1 Introduction

This chapter presents the results of the trial batches made to develop ultra-lightweight concrete for use in a Soft Ground Arrestor System (SGAS). In addition, this chapter shows problems that were faced and the efforts made to address them.

Mixture proportions were first chosen based on some reference mixtures developed by the Strong Company. These trial mixtures were cast to determine a mixture that is durable with a compressive strength close to 20 psi, with little to no increase in compressive strength with age. Preliminary tests conducted by the Strong Company on ultra-lightweight concrete showed that the unit weights and compressive strengths corresponding to a yield of 130% produced the best results. Therefore, in addition to 20 psi, and 26 to 28 pcf goals, a yield of 130% was also targeted.

Mixture designs provided by Strong Company were the reference mixtures from which the research began and new mixtures developed at the University of Arkansas were based on the reference mixtures and designed to meet the requirements of SGAS. In the present chapter there are recommendations for different chemical admixtures and dosage rates which were selected considering the desired properties, such as unit weight and compressive strength. W/cm of 0.99 was initially chosen to attain low compressive strength.

The present project examines the effects of various chemical admixtures and their dosage rates on ultra-lightweight concrete with the goal of developing a concrete mixture that can be used in a SGAS.

### 4.2 Reference Mixtures

The proportions of the first mixture, M 1, were developed by the Strong Company. In mixture M 1, the general pre-blend 1 (shown in Table 3.2) was used. The pre-blend 1 mixture contained PC-I, perlite, vermiculite, medry, and methocel. All pre-blend mixtures used in the project were batched in accordance to Section 3.3.2.1. Mixture proportions of M 1 and M 2 are listed below in Table 4.1. The unit weight results obtained were plotted with respect to time (Figure 4.1).

Table 4.1 Mixture Proportions for Mixtures M 1 and M 2

| Material | Mixture Number | |
|---|---|---|
| | M 1 | M 2 |
| Pre-Blend Mixture | PB 1 | PB 1 |
| Sample Weight (g) | 1006 | 1100 |
| Dry unit weight (lb/ft$^3$) | 18.0 | 18.0 |
| Water (g) | 996 | 996 |
| w/cm | 0.99 | 0.99 |
| Melflux 2651 (% Cement) | 0 | 0 |

With reference to mixture M 1, M 2 was batched to get acquainted with ultra-lightweight concrete. The dry unit weight of M 2 was 18.0 pcf. The concrete mixture was mixed for four minutes and the wet unit weight was measured at one, one and a half, two, three, and four minutes. After one minute of mixing the wet unit weight was 30 pcf and was increased to 31.2 pcf after four minutes of mixing. The yield of the mixture was 115% which was less than the desired yield of 130%. Eighteen cubes and one cylinder were cast for testing purposes. At seven days of age, the cylinder could not be demolded because of low strengths. Three cubes also broke during demolding at day one. Also, the cubes that did not break during demolding contained many surface defects. The cubes attained an average compressive strength of 21.3 psi at 28 days. The fresh and hardened properties of mixture M 2 are listed in Table 4.2. Unit weight was plotted with respect to time and is shown in Figure 4.1. From the results, it was observed that the increase in compressive strength from 7 days to 28 days was 6 psi. The early age strength was too low and the increase in the compressive strength was high from 7 days to 28 days (15.6 psi to 21.6 psi respectively). Hence in order to increase the early age strength and also maintain minimal increase in compressive strength with time, calcium aluminate cement (CAC) was introduced as a partial replacement for type-I portland cement (PC-I).

Table 4.2 Fresh and Hardened Properties of Mixture M 2

| | Mixture Designation |
|---|---|
| | M 2 |
| Mixing Time (minutes) | Unit Weight (pcf) |
| 1 | 30.0 |
| 1.5 | 31.6 |
| 2 | 31.2 |
| 3 | 31.4 |
| 4 | 31.2 |
| Yield (%) | 115% |
| Age (day) | Compressive Strength (psi) |
| 7 | 15.6 |
| 28 | 21.6 |

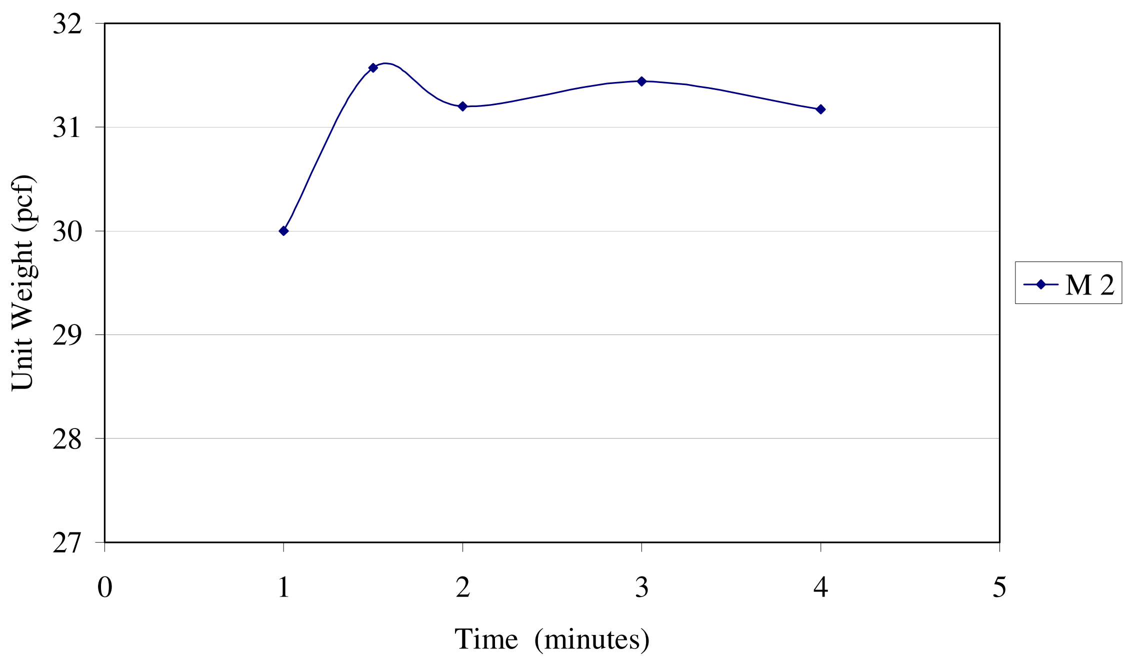


Figure 4.1 Variation in Unit Weight with Time for Mixture M 2

### 4.3 Mixture Proportions with a Combination of CAC and PC-I

In order to minimize the later age strength gain but increase in early age strength, several mixtures were cast that contained a combination of CAC and PC-I. Previous research has shown that concrete mixtures cast with CAC gain strength rapidly, but the strength gain after 7 days of age is minimal (Shetty 2004). M 3 through M 8 were the first set of mixtures batched with 50% of the PC-I replaced with CAC. For these mixtures master-blend (MB) 1 was used. MB 1 was contained different proportions of binders (PC-I and CAC). The contents of MB 1 are listed in Table 3.2. M 4, M 6, and M 7 mixture proportions were similar to that of mixture M 3 except the percentage of melflux was varied to examine its effects on the behavior of ultra-lightweight concrete. The mixture proportions for M 3 through M 8 are shown below in Table 4.3.

Table 4.3 Mixture Proportions for Mixtures M 3 through M 10

| Material | Mixture Number | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | M 3 | M 4 | M 5 | M 6 | M 7 | M 8 | M 9 | M 10 |
| Pre-Blend Mixture | MB 1 | MB 1 | MB 1 | MB1 | MB 1 | MB 1 | MB 2 | MB 2 |
| Sample Weight (g) | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 |
| Dry unit weight (lb/ft$^3$) | 19.2 | 19.2 | 19.2 | 19.2 | 19.2 | 19.2 | 18.8 | 18.8 |
| Water (g) | 1310 | 1310 | 1050 | 1310 | 1310 | 1050 | 1310 | 1310 |
| w/cm | 1.19 | 1.19 | 0.95 | 1.19 | 1.19 | 0.95 | 1.19 | 1.19 |
| Melflux (% cement) | 0.5% | 1.0% | 1.5% | 0 | 0.1% | 1.0% | 0.5% | 1.0% |

Mixture M 3 contained 0.5% melflux (% of weight of cement). The unit weight of M 3 after one minute of mixing was 34.9 pcf and was further reduced to 34.2 pcf after an additional three minutes of mixing. Additional mixing had little effect on the unit weight. The yield for M 3 was 123% (close to the yield required of 130%), which was slightly higher than that of the reference mixture (115%). At 28 days of age, the cylinders were very weak and both cylinders cracked during demolding. The cubes attained an average compressive strength of 17.0 psi at 7 day which is an improvement when compared to M 2 (15.6 psi), and only an increase of 3.6 psi was observed between 7 and 28 days.

To increase the yield and reduce compressive strength increase with time, M 4 was then batched with an increase in melflux content to 1%. M 4 had a unit weight of 34.1 pcf at one minute and after four minutes of mixing, the unit weight decreased to 32.5 pcf. The unit weight for M 4 (32.5 pcf) was less than that of M 3 (34.2 pcf). An increase of melflux also increased the yield (130%) which was expected. During the process of casting the test samples for compressive strength tests, bleeding was observed. While demolding the cylinders at 28 days, both the samples cracked at the middle. The compressive strength of M 4 was significantly lower than that of M 3 mixture which was due to unstable air bubbles (Table 4.4). Excessive bleeding was also observed in M 4 specimens. Mixture M 4 had a 7 day compressive strength of 11.8 psi and 13.9 psi at 28 days which was lower than the desired compressive strength of 20 psi, however the increase in compressive strength from 7 day to 28 day was reduced to 2 psi. To reduce bleeding and increase early age strength, the amount of melflux was increased to 1.5%, and at the same time the amount of water was reduced to 1050 g and was batched as M 5.

After one minute of mixing, the unit weight of M 5 was 31.7 pcf which was 2.4 pcf less than that of M 4. On further mixing for 3 minutes, the unit weight decreased to 29.3 pcf and no bleeding was observed. The yield of M 5 was 128% which was close to the targeted yield of 130%. The increase in yield and decrease in unit weight was the result of the reduction in water content and increase in melflux dosage. The compressive strength was 18.7 psi at 28 days which was slightly less that the targeted strength of 20 psi, but the increase in compressive strength from 7 days to 28 days was 8.6 psi.

Increase in melflux improved unit weight and yield, and because of this mixtures were batched to properly understand the behavior of melflux in ultra-lightweight concrete. Mixture M 6 was then batched with no melflux to understand the behavior of ultra-lightweight concrete with no melflux. The unit weight was 1 pcf higher after one minute of mixing when compared to that attained by mixture M 3 which contained 0.5% of melflux. The mixture was mixed for two additional minutes but the decrease in the unit weight was only 0.1 pcf. The yield of M 6 was 118%, which showed that there was an increase in yield with the presence of melflux. The average compressive strength was 10.2 psi at seven days and 18.3 psi at 28 days. The compressive strength values were close in comparison with M 5. Since the melflux was omitted from mixture M 6, the amount of water available for bubble formation was reduced which resulted in higher unit weights compared to M 3 (shown in Figure 4.2). The demolding problem was also observed in case of M 6, and 6 out of 18 cubes broke during the process of demolding at 7 days of age.

Melflux was then introduced and batched as M 7 (0.1% of melflux). This was done to see if there would be any variation in fresh and hardened properties of ultra-lightweight concrete with a small amount of melflux. The mixture was initially mixed for 10 seconds before the melflux was added. The mixture reached its peak (lowest) unit weight of 31.5 pcf after one and a half minutes of mixing. The mixture was mixed for a total of three minutes and an increase in unit weight (4.1 pcf) was observed. With the addition of 0.1% of melflux, there was no difference in the yield between M 6 and M 7 (in both the cases yield was 118%). The increase in compressive strength from 7 days to 28 days was also high (4.3 psi). For this particular mixture, a melflux dosage rate of 0.1% was not effective in increasing yield and reducing unit weight.

For mixture M 8, the w/cm was reduced to 0.95 and the melflux content was increased to 1%. Mixture M 8 was similar to mixture M 4 but with a reduction of water content. Melflux was added after mixing for ten seconds. M 8 had a 31.5 pcf unit weight after one minute of mixing, which was 3.4 pcf less than the unit weight of M 4 (34.1 pcf). Since water was the second heaviest ingredient in the mixture and M8 contained less water than M 7, the lower unit weight was expected. The unit weight was 29.8 pcf after 3 additional minutes of mixing. The yield increased to 126% as expected due to the increase in melflux. This mixture had good 7 day and 28 day compressive strengths of 17.3 psi and 23.4 psi which was higher than that of mixture M 4 (11.8 psi and 13.9 psi). So, the increase in melflux clearly increased the yield and decreased unit weight. But in mixtures M 3 through M 8 an increase in compressive strength from 7 day to 28 day was observed.

For mixtures M 9 and M 10, 25% of PC-I was replaced with CAC. This was done to increase compressive strength at early ages (7 days or earlier). For these mixtures, MB 2 was used. MB 2 contained PC-I, CAC, perlite, vermiculite, medry, and methocel (see Table 3.2 for the proportions). The melflux dosage rate was 0.5% for M 9 and 1% for M 10. The unit weight of M 10 was 1.4 pcf less than that of M 9 at one minute but both unit weights were greater than the targeted value of 26-28 pcf. For both mixtures, little change in unit weight was observed after mixing for three minutes. A yield of 120% for M 9 and 125% for M 10 was measured. The one day compressive strengths of both mixtures were much less when compared to that of mixtures developed with a 50% replacement of PC-I with CAC, which was expected because of the reduction of percentage of CAC. The increase in compressive strengths after 28 days was much higher in the case of M 9 and M 10 when compared to mixtures with 50% replacement of PC-I with CAC, which was due to greater percentages of PC-I in M 9 and M 10.

The unit weights and compressive strengths for the mixtures containing both percentage replacement of PC-I with CAC are shown in Table 4.4 and the unit weight plotted against mixing time is shown as Figure 4.2. From the above test results it was clearly shown that the replacement of PC-I with CAC for these ultra-lightweight concrete mixtures was ineffective for reducing the strength gain from 7 days to 28 days. Hence future mixture proportions were designed containing only portland cement.

Table 4.4 Fresh and Hardened Properties of Mixtures M 3 through M 10

| | Mixture Designation | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | M 3 | M 4 | M 5 | M 6 | M 7 | M 8 | M 9 | M 10 |
| Mixing Time (minutes) | Unit Weight (pcf) | | | | | | | |
| 1 | 34.9 | 34.1 | 31.7 | 35.9 | 32.4 | 31.5 | 34.5 | 33.1 |
| 1.5 | 33.3 | 32.8 | 30.2 | - | 31.6 | 30.7 | 34.2 | 32.5 |
| 2 | 34.1 | 32.2 | 29.9 | 33.5 | 32.3 | 29.7 | 34.1 | 32.9 |
| 3 | 33.3 | 32.2 | 29.4 | 35.7 | 35.7 | 29.8 | 34.1 | 32.9 |
| 4 | 34.2 | 32.5 | 29.3 | - | - | - | - | - |
| Yield (%) | 123% | 130% | 128% | 118% | 118% | 126% | 120% | 125% |
| Age (day) | Compressive Strength (psi) | | | | | | | |
| 7 | 17.0 | 11.8 | 10.1 | 10.2 | 16.2 | 17.3 | 17.0 | 15.2 |
| 28 | 20.6 | 13.9 | 18.7 | 18.3 | 20.5 | 23.4 | 51.1 | 51.7 |

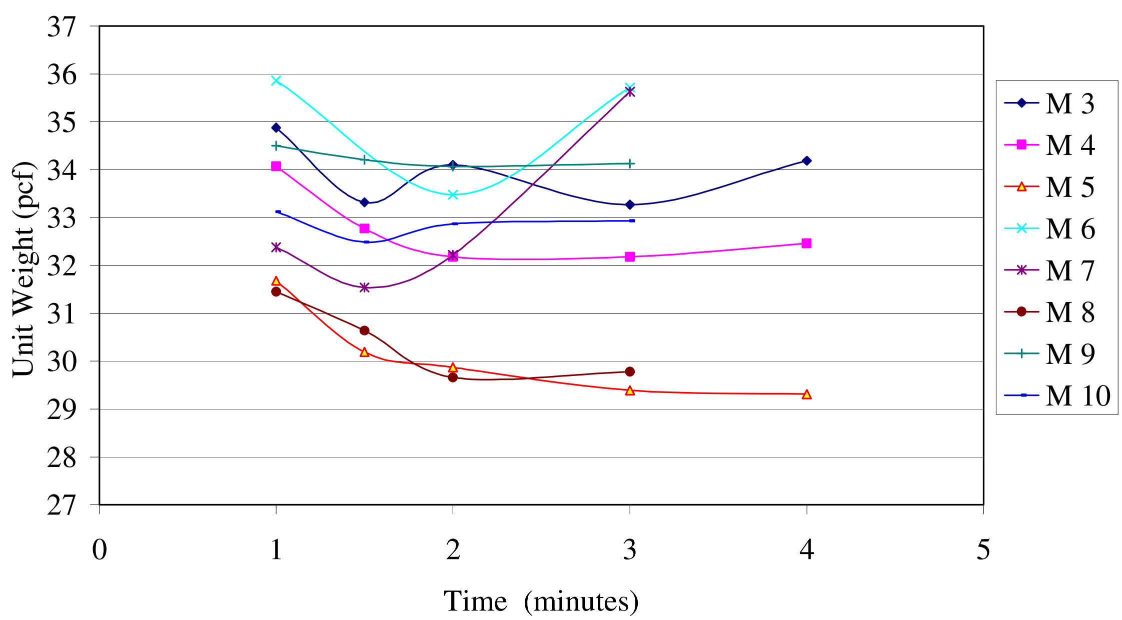


Figure 4.2 Variation in Unit Weight with Time for Mixtures M 3 through M 10

### 4.4 Increased Batch Quantities

Previously mixtures M 1 though M 10 were batched using the kitchen aid mixer described in Chapter 3. For most of these mixtures, the total quantity of concrete batched was approximately less then 0.2 $ft^3$. The behavior and performance of the concrete mixtures can change as batch size increases. To examine these potential changes, the double drum shear mixer, which was described in Chapter 3, was used to batch mixtures M 12 through M 14.

Mixture M 11 was developed by the Strong Company, which served as the reference mixture M 12 was developed and tested to check the behavior of ultra-lightweight concrete when batched using double drum shear mixer. M 13 and M 14 were then batched with the same mixture proportions as that of M 12 to examine the repeatability of the mixture. PB 1 was used in these four mixtures. The mixture proportions for M 11 through M 14 are shown in Table 4.5. In all these mixtures, a sample weight of approximately 36 pounds was maintained. Mixture M 11, which was developed by the Strong Company, contained no melflux and had a w/cm of 0.99. As from the previous results, it was observed that the addition of melflux resulted in a decrease in unit weight, in mixtures M 12 through M 14, 0.1% melflux and w/cm of 1.008 was maintained.

Table 4.5 Mixture Proportions for Mixtures M 11 through M 14

| Material | Mixture Number | | | |
|---|---|---|---|---|
| | M 11 | M 12 | M 13 | M 14 |
| Pre-Blend Mixture | PB 1 | PB 1 | PB 1 | PB 1 |
| Sample Weight (lb) | 36.0 | 36.0 | 36.6 | 36.0 |
| Dry unit weight ($lb/ft^3$) | 18.4 | 18.4 | 18.4 | 18.4 |
| Water (lb) | 36.4 | 36.3 | 36.9 | 36.3 |
| w/cm | 0.99 | 1.008 | 1.008 | 1.008 |
| Melflux (% cement) | 0 | 0.1% | 0.1% | 0.1% |

M 11 and M 12 had unit weights of 37.3 pcf and 36.5 pcf after one minute of mixing, whereas mixtures M 13 and M 14 were too dry and therefore the unit weight was not able to be measured after one minute of mixing. After mixing for two additional minutes, the unit weights were 40.5 pcf and 41.6 pcf for M 13 and M 14 respectively. After five minutes of mixing, M 11 attained a unit weight of 29.2 pcf and M 12 had a unit weight of 25.9 pcf. A decrease of 10 pcf was observed in cases M 13 and M 14, after five minutes of mixing (Figure 4.3).

For further study on the variation in unit weight of M 13 and M 14, the mixing was continued for four additional minutes (a total mixing time of 9 minutes). The unit weight was measured after every minute. The unit weight was approximately 29 pcf after eight minutes of mixing. M 13 and M 14 required double the mixing time to attain a unit weight equal to that of M 11. For mixtures M 11 through M 14, the cubes cast for compressive strength testing were too weak to be demolded at one day. M 11 and M 13 showed similar compressive strengths of 8.6 psi at 7 day. M 14 had a 7 day strength of

12.6 psi. Not enough samples were left for testing compressive strength at 28 days. From the test results it was clearly seen that M 13 and M 14 (batched with same mixture proportion) showed similar results. From the results shown in Table 4.6, it was clear that concrete batched in larger quantities had better unit weights, yield and compressive strength.

Table 4.6 Fresh and Hardened Properties for mixtures M 11 through M 14

| | Mixture Designation | | | |
|---|---|---|---|---|
| | M 11 | M 12 | M 13 | M 14 |
| Mixing Time (minutes) | Unit Weight (pcf) | | | |
| 1 | 37.3 | 36.5 | Dry | Dry |
| 1.5 | - | - | - | - |
| 2 | 35.3 | 32.7 | 40.5 | 41.6 |
| 3 | 32.5 | 29.9 | 36.9 | 36.2 |
| 4 | 30.3 | 27.9 | 34.2 | 33.4 |
| Yield (%) | | | 149% | 145% |
| Age (day) | Compressive Strength (psi) | | | |
| 7 | 8.8 | - | 8.6 | 12.6 |
| 28 | 12.2 | - | 15.4 | 21.4 |

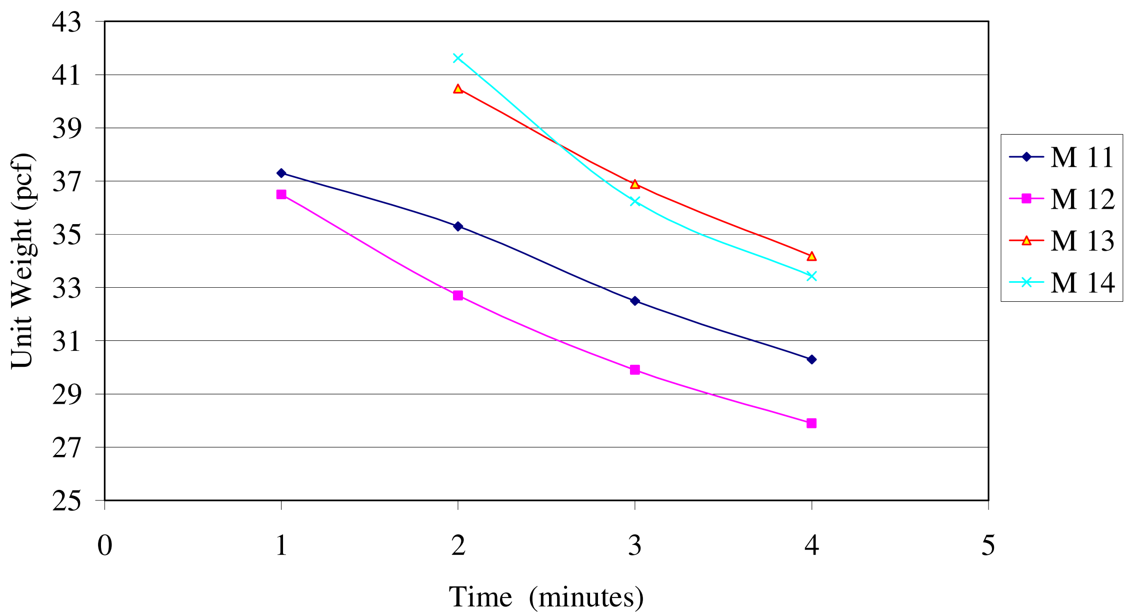


Figure 4.3 Variation in Unit Weight with Time for Mixtures M 11 through M 14

### 4.5 Variation in Medry and Melflux

As the unit weights observed in the previous tests were higher than the desired unit weight of 26-28 pcf at 3 minutes of mixing, mixtures were developed to reduce the unit weight within 3 minutes of mixing. In the case of mixtures M 15, M 16, M 17, and M 18, the amount of medry was increased by 0.3% in order to increase air content earlier during the mixing. These four mixtures were mixed using the kitchen aid mixer. These mixtures had a targeted unit weight of 28 pcf after 3 minutes of mixing.

M 15 was developed using PB 1. Melflux content was very much effective in reducing the unit weight and increasing the yield of concrete, 0.5% melflux was used. An additional amount of 0.3% of medry was added to the dry mixture to increase the amount of air bubble. The mixture proportions for M 15 and all other mixtures developed in this section of the research program are shown in Table 4.7. After one minute of mixing the unit weight was 32.0 pcf. The mixture was then mixed for an additional 3 minutes and the unit weight was 30.8 pcf. The decrease in the unit weight was minimal after two minutes of mixing. The mixture had a yield of 106%, which was very low. Melflux reduced the mixing water which in turn increased strength (1 day strength and 28 day strengths were 44.7 psi and 59.4 psi).

Table 4.7 Mixture Proportions for Mixtures M 15 through M 18

| Material | Mixture Designation | | | |
|---|---|---|---|---|
| | M 15 | M 16 | M 17 | M 18 |
| Pre-Blend Mixture | PB 1 | PB 1 | PB 1 | PB 1 |
| Sample Weight (g) | 1100 | 1100 | 1100 | 1100 |
| Dry unit weight ($lb/ft^3$) | 18.0 | 18.0 | 18.0 | 18.0 |
| Water (g) | 900 | 875 | 875 | 875 |
| w/cm | 0.82 | 0.80 | 0.80 | 0.80 |
| Medry (% cement) | 0.3% | 0.3% | 0.3% | 0.3% |
| Melflux (% cement) | 0.5% | 0.5% | 1.0% | 1.25% |

M 16 was very similar to M 15, except the w/cm was reduced to 0.80 from 0.82. This was done to reduce the unit weight because water is the second heaviest ingredient in ultra-lightweight concrete. After one minute of mixing, the unit weight was 38.1 pcf which was due to the lack of air bubble formation. The mixture was dry after one minute of mixing. After additional 30 seconds of mixing, the unit weight dropped to 30.1 pcf. The mixture was further mixed for two and a half minutes, but the drop in the unit weight was not as significant as the first. After a total of four minutes of mixing, the unit weight was 29.6 pcf. This showed that the concrete produced lower unit weights when the w/cm was reduced from 0.82 to 0.80. M 16 had a yield of 109% which was better than that of M 15 (106%) but was still much less than the targeted yield (130%). The samples for mixture M 16 were cast at 29.6 pcf and that of M 15 were cast at 30.8 pcf. This small variation in unit weight resulted in lower compressive strengths of M 16 when compared to that of M 15. The average compressive strength at 28 days was 43.1 psi. The compressive strength results also showed that there was an increase of 10.7 psi compressive strength from 28 days to 90 days (the 90 day compressive strength was 69.1 psi). As it was clearly seen that a w/cm of 0.80 was effective in reducing the unit weight and hence was maintained the same for the remaining batches.

To further reduce unit weight and increase yield, the melflux dosage was increased to 1% and batched as M 17. A w/cm of 0.80 was used. It was observed that after one minute of mixing the mixture had a unit weight of 29.3 pcf which was less than that of M 15 and M 16 (32.0 pcf and 38.1 pcf). It was then further mixed for 30 seconds and the unit weight decreased to 28.4 pcf. Further mixing resulted in little difference in unit weight and, after three minutes of mixing, the unit weight was 28.0 pcf. The additional melflux resulted in a yield of 115% which was higher than that of M 15 (106%) and M 16 (109%) but still less than the targeted. Even though the test samples were cast with unit weight 27.9 pcf (after 3 minutes of mixing), the compressive strength was measured high after 28 days (50.1 psi), which was not expected.

For M 18 the amount of melflux was further increased to 1.25% while maintaining the same medry dosage rate as M 17, this was done to increase the yield and decrease the unit weight. The w/cm was 0.80. After one minute of mixing, the unit weight was 35.0 pcf and the mixture appeared dry. At one and a half minutes, the unit weight of the mixture decreased 5 pcf (Figure 4.4). On further mixing, the unit weight at 2, 3, and 4 minutes was 29.1, 28.9, and 28.7 pcf respectively (Table 4.8). The unit weight with respect to time is shown in Figure 4.4. M 18 produced a yield of 112% (lower than the desired yield of 130%). M 18 had an average compressive strength of 71.9 psi after 28 days this was due to the high amount of melflux. The high amount of melflux reduced the amount of mixing water which in turn increased the compressive strength. This showed that the increase in melflux to 1.25% was not helpful in reducing the unit weight and maintaining proper compressive strength. Among the four mixtures, those containing 0.3% medry and 0.5% melflux had better unit weights as well as compressive strengths.

Table 4.8 Fresh and Hardened Properties of Mixtures M 15 through M 18

| | Mixture Number | | | |
|---|---|---|---|---|
| | M 15 | M 16 | M 17 | M 18 |
| Mixing Time (minutes) | Unit Weight (pcf) | | | |
| 1 | 32.0 | 38.1 | 29.3 | 35.0 |
| 1.5 | 31.1 | 30.7 | 28.4 | 29.9 |
| 2 | 30.9 | 29.7 | 28.2 | 29.1 |
| 3 | 30.9 | 29.6 | 28.0 | 28.9 |
| 4 | 30.8 | 29.6 | - | 28.7 |
| Yield (%) | 106% | 109% | 115% | 112% |
| Age (day) | Compressive Strength (psi) | | | |
| 7 | 44.7 | 35.1 | 38.1 | 45.7 |
| 28 | 59.4 | 43.1 | 50.1 | 71.9 |

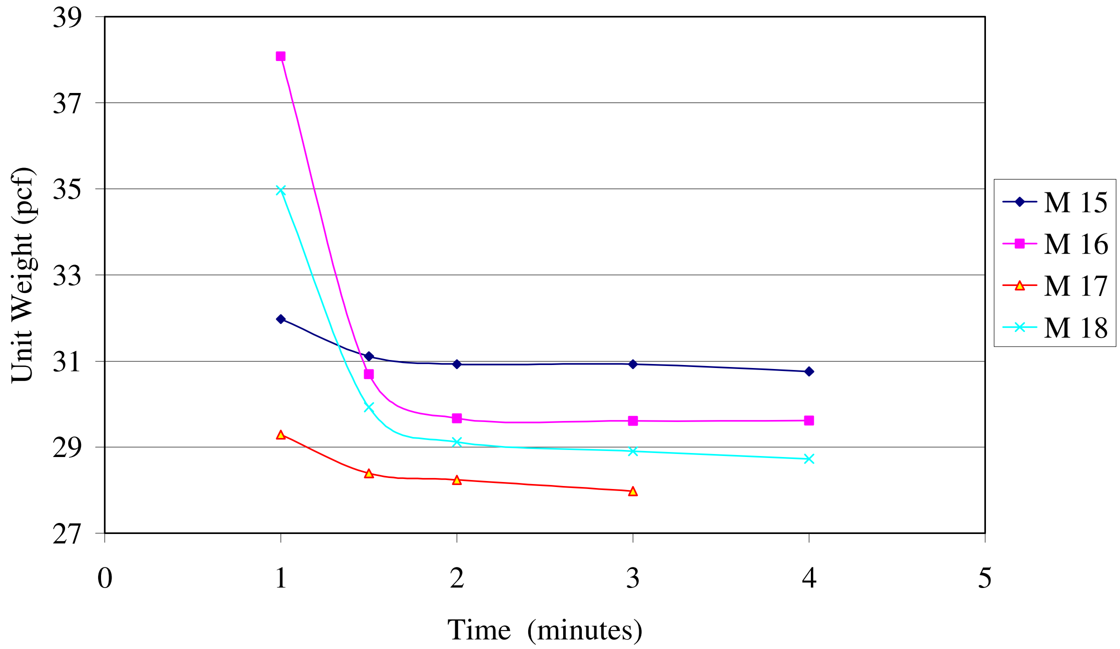


Figure 4.4 Variations in Unit Weight with Time for Mixtures M 15 through M 18

The medry and melflux content of 0.3% and 0.5% was contained for M 19 and M 20, and these mixtures were batched using a double drum shear mixer to examine the concrete behavior when mixed in larger quantities. A sample weight of 36.5 pounds with a 0.8 w/cm was used to batch M 19 and at the same time, M 20 was batched with a sample weight of 38.6 pounds and a w/cm of 0.79. Both mixtures had the same dry unit weight of 18.0 pcf. The mixture proportions for both these batches are listed in Table 4.9.

Table 4.9 Mixture Proportions for Mixtures M 19 and M 20.

| Material | Mixture Number | |
|---|---|---|
| | M 19 | M 20 |
| Pre-Blend Mixture | PB 1 | PB 1 |
| Sample Weight (lb) | 36.5 | 38.6 |
| Dry unit weight (lb/ft³) | 18.0 | 18.0 |
| Water (lb) | 29.1 | 30.7 |
| w/cm | 0.80 | 0.80 |
| Medry (g/ft³ aggregate) | 0.3% | 0.3% |
| Melflux (% cement) | 0.5% | 0.5% |

It was observed that the mixtures were dry after one minute of mixing and hence the unit weight was not measured. M 19 had a high unit weight of 38.4 pcf after one and a half minutes, and M 20 had a unit weight of 34.9 pcf after one and a half minutes, which was expected, since the water content was reduced. Both mixtures were mixed for five minutes and a unit weight of approximately 27 pcf was measured in both the cases. These low unit weights showed the combination of 0.3% medry and 1% melflux was effective in decreasing unit weight. M 19 had 7 day and 28 day compressive strengths of 18.5 psi and 24.6 psi, respectively. Whereas M 20 had similar average compressive strengths of 32.2 psi at 7 days and 32.2 psi at 28 days. Mixture M 20 had a higher yield than M 19 and both are listed in Table 4.10. In spite of casting both batches at the same unit weight (27.5 pcf), a difference in the compressive strength was observed. The unit weights are plotted against time and are shown in Figure 4.5.

Since the research team observed inconsistencies in compressive strength, the next set of mixtures were batched using the kitchen aid mixer to examine the consistency of the mixtures.

Table 4.10 Fresh and Hardened Properties of Mixtures M 19 & M 20

| | Mixture Designation | |
|---|---|---|
| | M 19 | M 20 |
| Mixing Time (minutes) | Unit Weight (pcf) | |
| 1 | Dry | Dry |
| 1.5 | 38.4 | 34.9 |
| 2 | 38.5 | 33.0 |
| 3 | 34.6 | 30.7 |
| 4 | 29.5 | 28.8 |
| Yield (%) | 139% | 150% |
| Age (day) | Compressive Strength (psi) | |
| 7 | 18.5 | 32.2 |
| 28 | 24.6 | 32.2 |

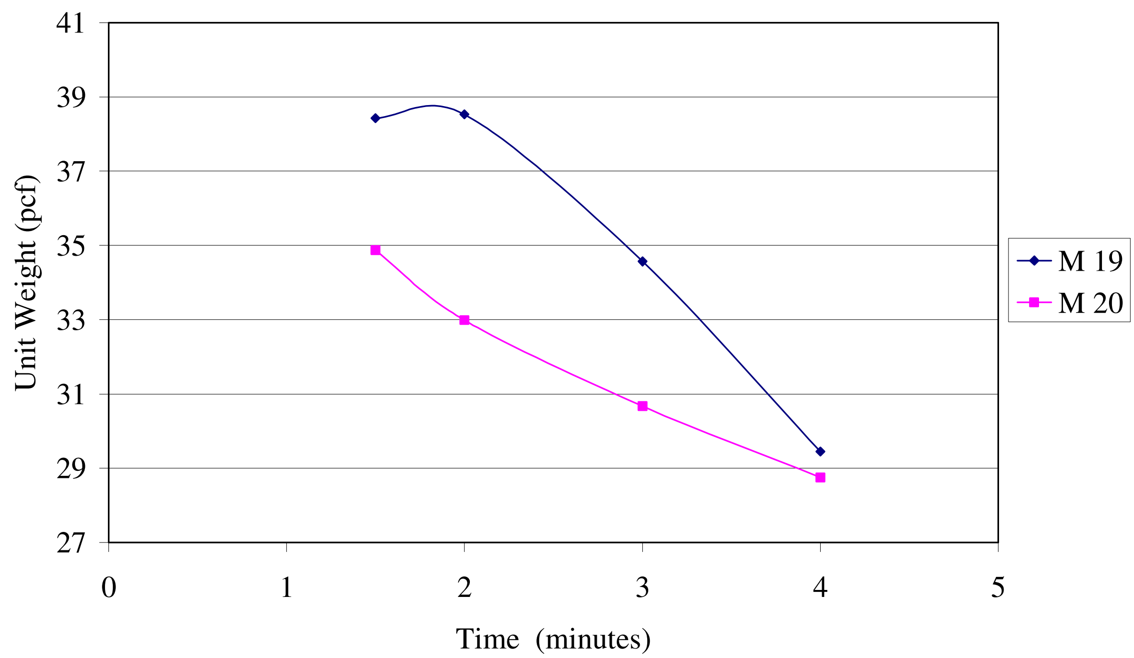


Figure 4.5 Variation in Unit Weight with Time for Mixture M 19 through M 20

### 4.6 Consistency Check Using M 16 as Reference Mixture

From the previous mixtures M 15 and M 16, it was clearly seen that there was no consistency in the results of unit weight and compressive strengths. Hence four mixtures, M 21 through M 24, were batched with mixture proportion M 16 to check the repeatability of the mixture. The mixture proportions are shown in Table 4.13. For these mixtures PB 1 was used. The mixtures were batched on the same day and the water temperature, mixing technique, and mixing speeds were kept constant. As shown in Table 4.11 the w/cm for all four mixtures was maintained at 0.8, and the targeted unit weight was 28 pcf. The dry unit weight of the mixture was 18.0 pcf. Unit weights obtained from the following tests were plotted with respect to time and are shown as Figure 4.6.

Table 4.11 Mixture Proportions for Mixtures M 21 through M 24.

| Material | Mixture Number | | | |
|---|---|---|---|---|
| | M 21 | M 22 | M 23 | M 24 |
| Pre-Blend Mixture | PB 1 | | | |
| Sample Weight (g) | 1100 | | | |
| Dry unit weight (lb/ft³) | 18.0 | | | |
| Water (g) | 875 | | | |
| w/cm | 0.80 | | | |
| Medry (% cement) | 0.3% | | | |
| Melflux (% cement) | 0.5% | | | |

After one minute of mixing, the unit weight of M 21 was 33.4 pcf and an additional two minutes of mixing was required to attain a unit weight of 28.0 pcf. The mixture was too dry at one minute. The yield was very low (115%) when compared to the required yield of 130%. The 28 day compressive strength was 42.8 psi, which was higher than required compressive strength (20 psi).

M 22 had an initial unit weight of 31.5 pcf after one minute of mixing and the unit weight decreased to 28.5 pcf after an additional two minutes of mixing. This mixture had the lowest yield of 113% among the four batches. The average 28 day compressive strength was 49.4 psi (an approximately 15% increase in strength when compared to M 21).

M 23 weighed 32.0 pcf after one minute of mixing and decreased to 28.1 pcf after two additional minutes of mixing. M 23 showed results similar to M 21 and are listed in Table 4.14. The yields were also similar for mixtures M 21 and M 23. The average 28-day compressive strength was 44 psi. This showed that a consistency in the results was observed between M 21 and M 23.

M 24 had a unit weight of 28.7 pcf after one minute of mixing and reached 27.8 pcf after an additional one and a half minutes of mixing. The samples were difficult to demold at one day and this difficulty resulted in uneven surfaces at the bottom of the specimens. This mixture had a yield of 116% and the lowest 28 day average compressive strength among the four batches (36.7 psi). The reduction in the compressive strength was most likely due to the lower unit weight (27.8 pcf) at which the cubes were cast.

Hence, the consistency of the mixtures was checked and found sufficient. So, the M 25 batch was batched with same proportions, except the mixture was batched in the hobart mixer to examine the behavior of the mixture when batched in greater quantities.

Table 4.12 Fresh and Hardened Properties of Mixtures M 21 through M 24

| | Mixture Designation | | | |
|---|---|---|---|---|
| | M 21 | M 22 | M 23 | M 24 |
| Mixing Time (minutes) | Unit Weight | | | |
| 1 | 33.4 | 31.5 | 32.0 | 28.7 |
| 1.5 | 29.5 | 29.3 | 28.7 | 27.8 |
| 2 | 28.0 | 28.5 | 28.1 | - |
| 3 | - | - | - | - |
| 4 | - | - | - | - |
| Yield (%) | 115% | 113% | 115% | 116% |
| Age (day) | Compressive Strength (psi) | | | |
| 7 | 33.3 | 44.2 | 31.4 | 28.7 |
| 28 | 42.8 | 49.4 | 44.0 | 36.7 |

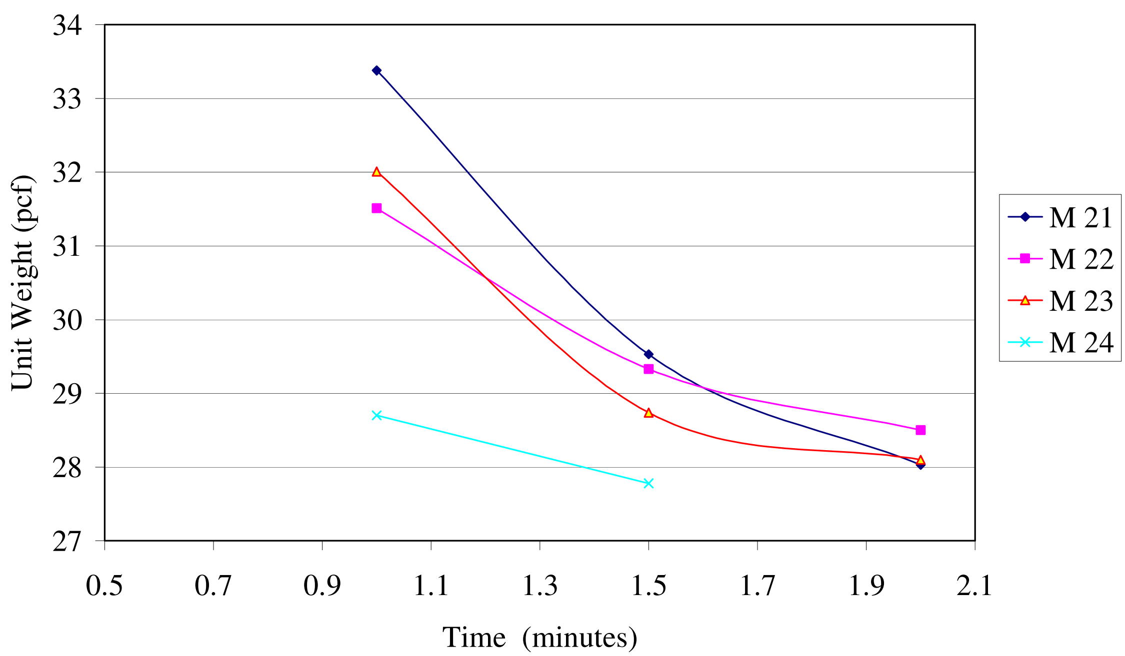


Figure 4.6 Variation in Unit Weight with Time for Mixtures M 21 through M 24

### 4.7 Effect of Batch Size on Mixture Performance

To determine the effect of batch size on mixture proportion M 16, mixture M 25 was mixed in a larger quantity using a hobart mixer. Water temperature, mixture temperature, and air temperature were all monitored for these mixtures. The mixture proportions for M 25 are shown below in Table 4.13. The dry unit weight of M 25 was 20.8 pcf, which was much higher than the normal dry unit weight (18.0 pcf). The increase in the dry unit weight was most likely due to an increase in moisture content due to improper storage of the dry material.

Table 4.13 Mixture Proportion for Mixture M 25

| Material | Mixture Number |
|---|---|
| | M 25 |
| Pre-Blend Mixture | PB 1 |
| Sample Weight (g) | 1888.9 |
| Dry unit weight (lb/ft$^3$) | 20.8 |
| Water (g) | 1501.7 |
| w/cm | 0.80 |
| Medry (% cement) | 0.3% |
| Melflux (% cement) | 0.5% |

M 25 was initially mixed for one minute and unit weight was 33.9 pcf. After mixing for another 30 seconds, the unit weight dropped down by 4.8 pcf and on further mixing for 1.5 minutes, unit weight dropped to 26.2 pcf in two minutes. M 25 had a yield of 143% which exceeded the targeted value of 130%. The samples in case of M 25 were cast at lower unit weight compared to M 21 through M 24, which in turn resulted in lower compressive strength. The mixture had a 28 day compressive strength of 27 psi, which is less than mixtures M 21 through M 24. At 3 days of age, the specimens were so weak that it was difficult to demold the cubes. The fresh and hardened properties of M 25 are listed in Table 4.14, and unit weights were plotted against time and are shown in Figure 4.7.

It was noted that the mixture properties also vary with the amount of mixture batched. From the results, it appears that the hobart mixer more effectively mixed the concrete, meaning more air and therefore lower unit weights. From the above test results it was also clear that lower unit weights result in lower compressive strengths. Hence unit weight optimization tests were conducted to obtain the desired unit weight of 26-28 pcf.

Table 4.14 Fresh and Hardened Properties of Mixture M 25

| | Mixture Number |
|---|---|
| | M 25 |
| Mixing Time (minutes) | Unit Weight (pcf) |
| 1 | 33.9 |
| 1.5 | 29.1 |
| 2 | 26.2 |
| 3 | - |
| 4 | - |
| Yield (%) | 143% |
| Age (day) | Compressive Strength (psi) |
| 7 | 23.5 |
| 28 | 27.7 |

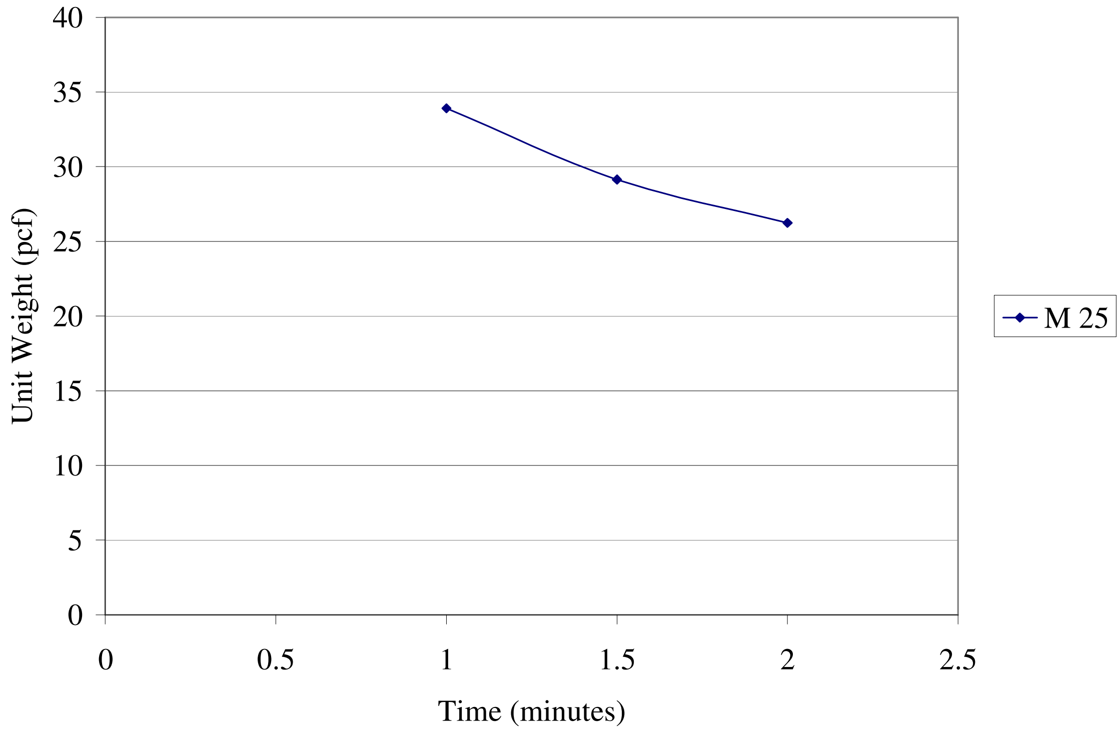


Figure 4.7 Variation in Unit Weight with Time for Mixture M 25

### 4.8 Unit Weight Optimization

One of the main objectives of this research was to develop a mixture with unit weights between 26 to 28 pcf within a mixing time of three minutes. Hence, 22 mixture proportions were developed during the process of optimizing the unit weight. The pre-blend material PB 1 (Table 3.2) was used in all these mixtures. All the mixtures in this section of the study were batched using the kitchen aid mixer. Since the goal for this series is obtaining a unit weight of 26 to 28 pcf in less than 3 minutes of mixing, the compressive strength of the mixtures was not measured. The mixture proportions of different batches developed in this series are listed in Table 4.15 through Table 4.18. All mixtures were batched for four minutes using the kitchen aid mixer maintained at speed 4 (unless noted elsewhere). The unit weight was measured after 1, 1.5, 2, 3, and 4 minutes of mixing. The unit weight results for all mixtures are listed in Table 4.19 through Table 4.21.

Table 4.15 Mixture Proportions for Mixtures UW 1 through UW 7

| Material | Mixture Number | | | | | | |
|---|---|---|---|---|---|---|---|
| | UW 1 | UW 2 | UW 3 | UW 4 | UW 5 | UW 6 | UW 7 |
| Pre-Blend Mixture | PB 1 | PB 1 | PB 1 | PB 1 | PB 1 | PB 1 | PB 1 |
| Sample Weight (g) | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 |
| Water (g) | 1089 | 1089 | 1089 | 1310 | 1210 | 950 | 1050 |
| w/cm | 0.99 | 0.99 | 0.99 | 1.19 | 1.10 | 0.86 | 0.95 |
| Medry (g) | 0.6 | 0.6 | 1.8 | 0.6 | 1.8 | 1.8 | 1.8 |
| Melflux (g) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 4.16 Mixture Proportions for Mixtures UW 8 through UW 14

| Material | Mixture Number | | | | | | |
|---|---|---|---|---|---|---|---|
| | UW 8 | UW 9 | UW 10 | UW 11 | UW 12 | UW 13 | UW 14 |
| Pre-Blend Mixture | PB 1 | PB 1 | PB 1 | PB 1 | PB 1 | PB 1 | PB 1 |
| Sample Weight (g) | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 |
| Water (g) | 1050 | 1089 | 1089 | 1089 | 1050 | 1050 | 1050 |
| w/cm | 0.95 | 0.99 | 0.99 | 0.99 | 0.95 | 0.95 | 0.95 |
| Medry (g) | 3.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 1.8 |
| Melflux (g) | 0 | 0 | 0.6 | 3.0 | 0.6 | 3.0 | 3.0 |

Table 4.17 Mixture Proportions for Mixtures UW 15 through UW 18

| Material | Mixture Number | | | |
|---|---|---|---|---|
| | UW 15 | UW 16 | UW 17 | UW 18 |
| Pre-Blend Mixture | PB 1 | PB 1 | PB 1 | PB 1 |
| Sample Weight (g) | 1100 | 1100 | 1100 | 1100 |
| Water (g) | 950 | 950 | 900 | 900 |
| w/cm | 0.86 | 0.86 | 0.81 | 0.81 |
| Medry (g) | 1.8 | 1.8 | 3.0 | 1.8 |
| Melflux (g) | 0.6 | 3.0 | 1.8 | 3.0 |

Table 4.18 Mixture Proportions for Mixtures UW 19 through UW 22

| Material | Mixture Number | | | |
|---|---|---|---|---|
| | UW 19 | UW 20 | UW 21 | UW 22 |
| Pre-Blend Mixture | PB 1 | PB 1 | PB 1 | PB 1 |
| Sample Weight (g) | 1100 | 1100 | 1100 | 1100 |
| Water (g) | 875 | 875 | 900 | 875 |
| w/cm | 0.79 | 0.79 | 0.81 | 0.79 |
| Medry (g) | 1.8 | 1.8 | 1.8 | 1.8 |
| Melflux (g) | 3.0 | 6.0 | 0.5 | 7.5 |

The first set of mixtures was batched with varying medry and water content. UW 1 was batched using 1100 g of PB 1 mixture and 0.6 g of medry and 1089 g of water (w/cm of 0.99). After one minute of mixing, the unit weight was 34.3 pcf and there was little decrease in unit weight after two minutes of mixing, which can be clearly seen in Figure 4.8. The mixing speed was then increased to 4 and the unit weight decreased to 29.4 pcf and 29.2 pcf after three and four minutes of mixing, respectively. The unit weight was greater than the targeted value of 26 to 28 pcf. To determine if the increase in unit weight was due to excessive moisture content in the pre-blend, a second mixture UW 2 was batched with the same mixture proportion as that of UW 1 except an unopened bag of PB 1 was used. UW 2 had a similar unit weight (34.7 pcf) as UW 1 (34.3 pcf) at one minute and upon further mixing, the unit weight of UW 2 decreased (Figure 4.8) to 31.3 pcf after four minutes. The speed of the mixer was increased to 4 from 2 in case of mixture UW 1 at 3 and 4 minutes, where as the speed of the mixer was maintained at 2 for the complete 4 minute mixing in case of UW 2. Hence the unit weight results obtained at 3 and 4 minutes for these mixtures were not compared. Figure 4.8 clearly showed that UW 2 had lower unit weights within 3 minutes of mixing when compared to that of UW 1. Based on the results of UW 2 when compared to UW 1, a new bag of PB 1 was used for remaining mixtures and care was taken to properly seal the bag once it was opened.

Since the unit weights of UW 1 and UW 2 were too high, the amount of medry was increased by 0.6 g for UW 3. The unit weight at one minute was 36.6 pcf which was higher than that of UW 1 (34.3 pcf) and UW 2 (34.7 pcf). Upon further mixing for one minute, the unit weight was reduced by 4.5 pcf. The mixing continued for four minutes, but there was little decrease in unit weight. This drop in the unit weight can be clearly seen in Figure 4.8. With a unit weight of 32.5 pcf after four minutes of mixing, the mixing speed was increased from 2 to 4, and the concrete was mixed for an additional two minutes. The unit weight was 30.5 pcf and 29.9 pcf after 5 minutes and 6 minutes of mixing which is still greater than the targeted values. The increase in medry had no effect on unit weight, and therefore the amount of medry was reduced to 0.6 g and the water content was increased to 1.19. These changes were done to determine if there was sufficient water available in the concrete mixture for air bubbles to form, which would in turn reduce the unit weight.

Based on the results of UW 3, the amount of water in UW 4 was increased to 1310 g. Since water is the second heaviest ingredient in the mixture (next to cement), the unit weights were higher than those of UW 1 and UW 2 (Table 4.19) which was expected. A unit weight of 37.2 pcf was measured after one minute of mixing and it decreased 0.2 pcf after an additional two minutes of mixing. The mixer speed was increased to speed 4 for the next two minutes to determine if increasing mixer speed would reduce unit weight. After one minute of mixing at speed 4, the unit weight decreased by 5.3 pcf and on further mixing for one minute, the unit weight decreased by 1.7 pcf. This showed that the higher mixing speed reduced unit weight at a faster rate.

To decrease unit weight, UW 5 contained more medry (1.8 g) and less water to 1210 g (w/cm of 1.10). In this batch the unit weight was initially 35.2 pcf after one minute of mixing and after two minutes, the unit weight was 34.3 pcf. On further mixing the unit weight remained at 34.5 pcf. For this mixture, the increase in medry was ineffective.

Since water is the second heaviest ingredient in the concrete, the water content was further reduced to 950 g (UW 6). The resulting mixture, UW 6 was very dry, and the unit weight could not be measured after 1.5 minutes of mixing. However, after two minutes, the unit weight was 31.6 pcf. UW 6 was then mixed for an additional 2 minutes (a total of 4 minutes), but there was little reduction in unit weight. The speed of the mixer was increased from 2 to 4 and mixed for one minute which resulted in a unit weight of 29.8 pcf. Reducing the water content was not an effective means of reducing unit weight, and the mixture was too dry after 1.5 minutes of minutes of mixing.

Therefore the amount of water was increased to 1050 g for mixture UW 7. This change in water content resulted in a unit weight of 31.3 pcf after one minute of mixing. UW 7 was further mixed for three additional minutes, but the unit weight remained constant at approximately 30.2 pcf which was 2.7 pcf greater than the targeted unit weight of 26-28 pcf. Since the increase in water appeared to have decreased the unit weight for the mixture UW 7 when compared to UW 6, mixture UW 8 was batched with the same water content (as UW 7) but twice the dosage of medry (3.6 g). It was hoped that the observed increase in workability for UW 7 along with the increase in medry would decrease the unit weight. However, little difference in unit weight was observed between UW 8 and UW 7.

Since the unit weight of UW 2 was the lowest measured in this series, UW 2 was batched again as mixture UW 9. UW 9 had higher unit weight of 35.5 pcf when mixed for one minute when compared to that of UW 2 (34.7 pcf). After 4 minutes, UW 9 had a unit weight 2.4 pcf higher than UW 2. In both the batches the unit weight was much higher than the targeted unit weight of 26-28 pcf, hence to reduce the unit weight melflux was introduced.

UW 10 through UW 22 was then batched using melflux (high range water reducer) with the hopes of reducing water content but maintaining workability. Since 0.6 g medry was effective for mixtures UW 1, UW 2, & UW 3 with mixtures unit weights of 29.2 pcf, 31.3 pcf, & 30.0 pcf respectively, the same dosage of medry was used in UW 10. The melflux content was 0.6 g for the mixture. With the additional melflux, a decrease in unit weight was expected. Whereas, UW 10 had a high unit weight of 37.2 pcf after one minute of mixing, and the unit weight decreased to 35.0 pcf after mixing for 4 minutes. For UW 11, the melflux dosage was increased to 3 g with the intent that the workability would increase, which would then allow the air-entraining agent to work better and therefore reduce the unit weight.

UW 11 had a unit weight of 35.8 pcf after one minute of mixing, which was similar to UW 9 (35.5 pcf). UW 11 was then mixed for 4 minutes, but the resulting decrease in unit weight was only 1 pcf. Hence, the increase in melflux showed a small variation in unit weight, the amount of melflux was reduced to 0.6 g and at the same time, the w/cm was reduced to 0.95 (1050 g) and batched as UW 12.

UW 12 was then batched with 0.6 g melflux, 0.6 g medry, and 1050 g of water (Table 4.16). UW 12 had unit weights similar to those of UW 9, which were too high (33.7 pcf). To reduce the unit weight, the amount of melflux was then increased to 3 g for UW 13. The unit weight after one minute of mixing was 33.9 pcf (nearly 2 pcf less than that of UW 12). However, upon further mixing the unit weight remained at approximately 33.3 pcf.

Since the unit weights for UW 13 were too high, the medry content was increased for mixture UW 14 to 1.8 g the and melflux content remained same (3 g). The increase in medry, the air-entraining agent, resulted in an increase in air bubbles which in turn, decreased the unit weight by 0.5 pcf when compared to that of UW 13.

Both mixtures, UW 13 and UW 14, had higher unit weights (33.65 pcf and 32.64 pcf) than the desired unit weight of 26-28 pcf. For both batches, 3.0 g of melflux was used. Since the high amount of melflux had no effect on unit weight, the amount of melflux was decreased to 0.6 g. At the same time the amount of water was decreased to 950 g and batched as UW 15. This was done to examine the effect of water reduction on unit weight. The reduction of water and melflux at the same time poorly affected the unit weight after one and a half minutes of mixing. The unit weight dropped 4.8 pcf from one minute of mixing to two minutes mixing and after four minutes, the unit weight was 31.9 pcf which was higher than the targeted value. Since the unit weight decreased for UW 15, for UW 16, the amount of water was maintained the same as UW 15 and the amount of melflux was increased to 3 g to further reduce the unit weight. The increase in melflux resulted in a low initial unit weight of 31.4 pcf after one minute of mixing, but there was little change in the unit weight with additional mixing. The increase in melflux did lower the unit weight at one minute, but little change in unit weight was observed after one minute (this can be clearly seen in Figure 4.9). Hence the amount of melflux was reduced, and the medry was increased with the intent of increasing the amount of entrained air.

UW 17 was batched with 3 g medry, 900 g of water, and 1.8 g of melflux with 1100 g of PB 1 dry mixture. The initial unit weight was 30.9 pcf after one minute of mixing. After additional mixing, the unit weight decreased by 1 pcf to approximately 29.8 pcf.

The changes in medry content did not significantly decrease the unit weight. Therefore, UW 18 was batched with a similar mixture proportion as UW 16 but the water content was reduced by 50 g. This change decreased the unit weight by 0.5 pcf, when compared to that of UW 16 after one minute mixing. Further mixing reduced the unit weight only by 1.3 pcf. Since the changes in the mixture proportions were positive, the water content was further reduced by 25 g, while maintaining the other ingredients at the same amount. This mixture was UW 9. After one minute of mixing, the mixture was dry, and the unit weight was 38.1 pcf. The mixture was then mixed for another 30 seconds, and the unit weight dropped 8 pcf, upon further mixing, the unit weight remained constant at 29.6 pcf.

UW 20 was the next mixture batched, and it contained twice the melflux (6 g) content than UW 19. The amount of medry was increased to improve the air content which would reduce the unit weight. This mixture had lower unit weights than all previous mixtures. The unit weight after one minute of mixing was 29.3 pcf, and upon further mixing, for two and a half minutes, the unit weight decreased to 28.0 pcf. The change in UW 20 appeared to indicate that the increase in melflux was decreasing the unit weight. To understand better the effect of melflux, UW 21 was batched with 0.5 g of melflux which was $^{1}/_{12}{}^{th}$ the dosage of UW 20. UW 21 had a unit weight of 32.0 pcf after one minute of mixing and after mixing for 3 additional minutes, it decreased by 1.2 pcf.

The results of UW 20 and UW 21 showed that the melflux content did affect the unit weight. Since UW 20 achieved the target unit weight with 6 g of melflux, mixture UW 22 was batched with 7.5 g of melflux with the hope of further reducing the unit weight. However, the increase in melflux was not effective. The mixture was dry after one minute of mixing and the unit weight was 35.0 pcf. On further mixing, the unit weight decreased nearly 5 pcf after one and a half minutes of mixing. The mixture was then mixed for another two and a half minutes, but the change in unit weight was minimal.

The results from mixtures UW 1 through UW 22 showed that medry was not very effective at entraining air for these mixtures, since the unit weights of the mixtures were higher than the targeted unit weight of 26-28 pcf. Hence, rheocell, a liquid air-entraining agent was introduced and used in the remaining mixtures.

Table 4.19 Fresh Properties of Mixtures UW 1 through UW 9

| | Mixture Designation | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | UW 1 | UW 2 | UW 3 | UW 4 | UW 5 | UW 6 | UW 7 | UW 8 | UW 9 |
| Time (minutes) | Unit weight (pcf) | | | | | | | | |
| 1 | 34.3 | 34.7 | 36.6 | 37.2 | 35.2 | 36.3 | 32.2 | 32.4 | 35.5 |
| 1.5 | 33.3 | 32.6 | 33.2 | 36.3 | 34.3 | - | 31.3 | 31.7 | 34.0 |
| 2 | 33.2 | 31.9 | 33.2 | 37.0 | 34.7 | 31.6 | 30.7 | 31.3 | 33.9 |
| 3 | 29.4* | 31.7 | 32.7 | 31.6* | 34.6 | 31.4 | 30.9 | 31.0 | 33.6 |
| 4 | 29.2* | 31.3 | 32.5 | 30.0* | - | 31.2 | 30.6 | 30.8 | 33.6 |
| 5 | - | - | 30.5* | - | - | 29.8* | - | 30.3 | - |
| 6 | - | - | 29.9* | - | - | - | - | - | - |

- Represents the unit weight of the mixture noted after the speed of the mixer is increased from 2 to 4

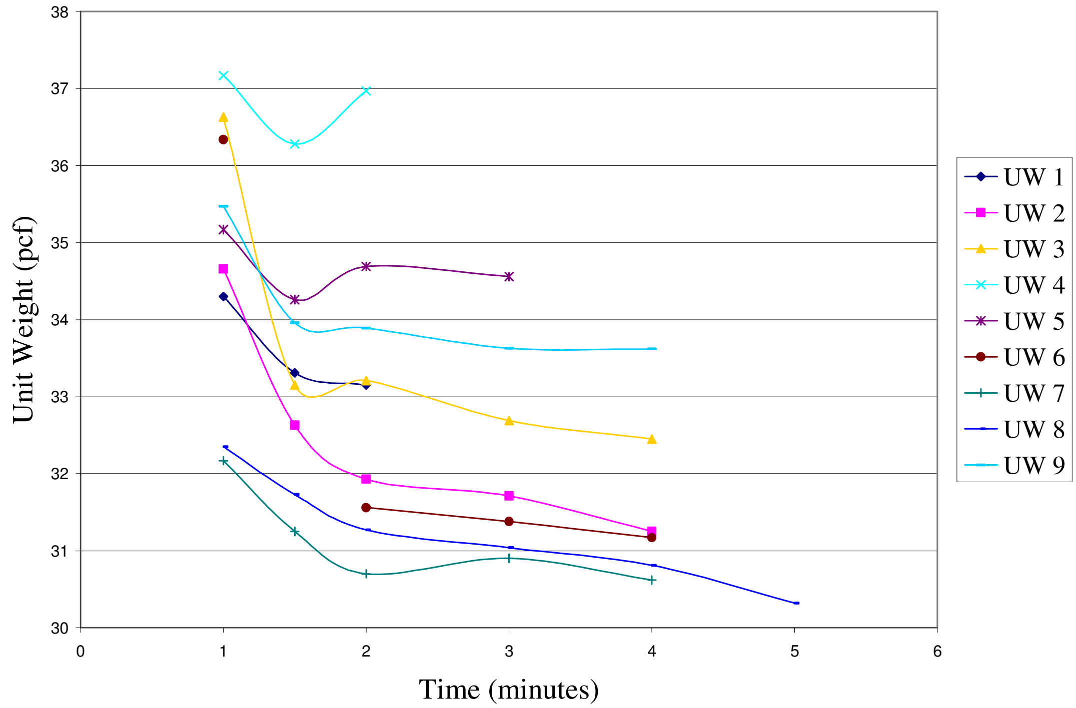


Figure 4.8 Variation in Unit Weight with Time for Mixtures UW 1 through UW 9

Table 4.20 Fresh Properties of Mixtures UW 10 through UW 16

| | Mixture Designation | | | | | | |
|---|---|---|---|---|---|---|---|
| | UW 10 | UW 11 | UW 12 | UW 13 | UW 14 | UW 15 | UW 16 |
| Time (minutes) | Unit weight (pcf) | | | | | | |
| 1 | 37.2 | 35.8 | 36.0 | 33.9 | 33.6 | 37.7 | 31.4 |
| 1.5 | 35.3 | 34.8 | 34.1 | 33.1 | 32.6 | 35.1 | 30.9 |
| 2 | 35.3 | 34.8 | 34.0 | 33.0 | 32.7 | 33.0 | 31.1 |
| 3 | 35.1 | 34.6 | 33.9 | 33.2 | 32.6 | 32.0 | 31.0 |
| 4 | 35.0 | 34.8 | 33.7 | 33.2 | 32.6 | 31.9 | 31.1 |

Table 4.21 Fresh Properties of Mixtures UW 17 through UW 22

| | Mixture Designation | | | | | |
|---|---|---|---|---|---|---|
| | UW 17 | UW 18 | UW 19 | UW 20 | UW 21 | UW 22 |
| Time (minutes) | Unit weight (pcf) | | | | | |
| 1 | 30.9 | 30.9 | 38.1 | 29.3 | 32.0 | 35.0 |
| 1.5 | 30.6 | 30.0 | 30.7 | 28.4 | 31.1 | 29.9 |
| 2 | 30.3 | 30.0 | 29.7 | 28.2 | 30.9 | 29.1 |
| 3 | 29.8 | 29.9 | 29.6 | 28.0 | 30.9 | 28.9 |
| 4 | 29.8 | 29.6 | 29.6 | - | 30.8 | 28.7 |

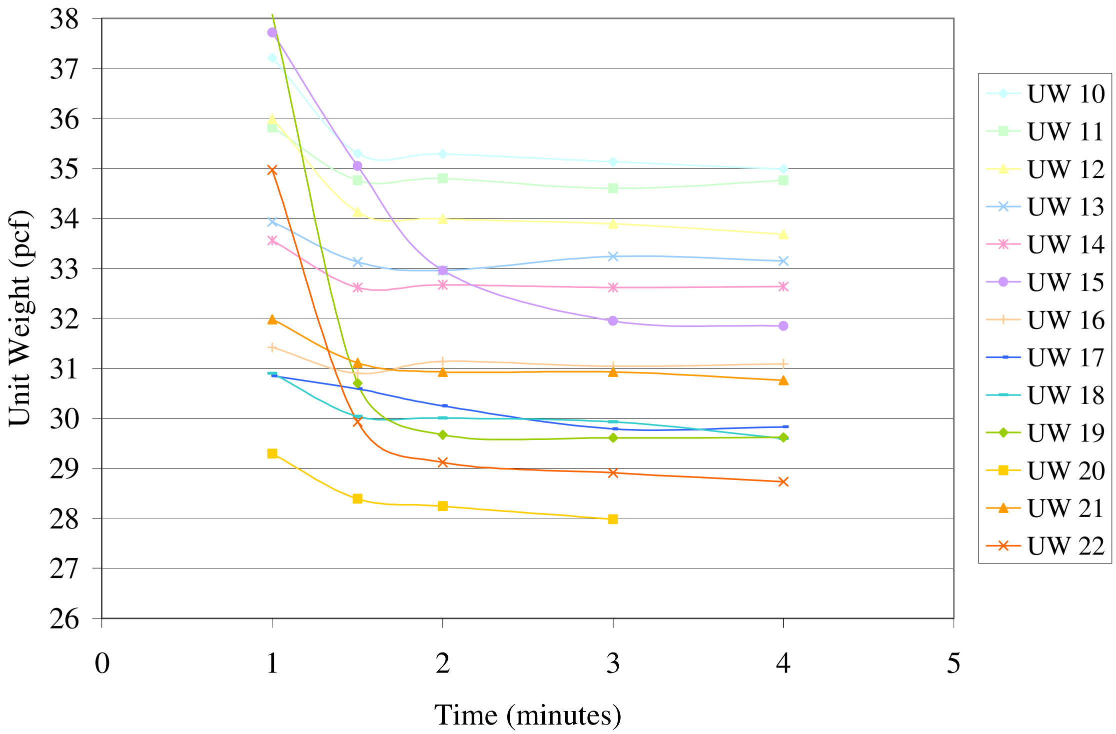


Figure 4.9 Variation in Unit Weight with Time for Mixtures UW 10 through UW 22

### 4.9 Introduction of Rheocell

A different type of air-entraining agent, rheocell, was introduced in this series of mixtures. As described in chapter 3, rheocell is a liquid admixture that is added to the mixing water. M 26 was the first mixture batched with rheocell. The mixture proportion was provided by the Strong Company and shown below in Table 4.22. The rheocell dosage was dependent on the amount of water in the mixture. The rheocell dosage shown in Table 4.22 is represented as the ratio of rheocell to the amount of water. Medry from PB 1 was removed and the new pre-blend material was named as PB 2 (Table 3.2), which was used in all the mixtures developed using rheocell as air-entraining agent. For these mixtures, the temperature of the ingredients and the mixture were recorded to determine the effects of temperature on unit weight.

Table 4.22 Mixture Proportions for Mixtures M 26 through M 28

| Material | Mixture Number | | |
|---|---|---|---|
| | M 26 | M 27 | M 28 |
| Pre-Blend Mixture | PB 2 | PB 2 | PB 2 |
| Sample Weight (g) | 2013.7 | 2067.5 | 1997.6 |
| Dry unit weight (lb/ft$^3$) | 22.2 | 22.8 | 22.0 |
| Water (g) | 2028.2 | 2015.8 | 1897.7 |
| w/cm | 1.008 | 0.97 | 0.95 |
| Rheocell (Rheocell/Water) | 1:136 | 1:102 | 1:102 |

Mixture M 26 contained a ratio of rheocell to water of 1:136. After one minute of mixing, the unit weight was 35.1 pcf, and the mixture was too dry. However, after an additional minute of mixing, the unit weight dropped to 27.4 pcf, and compressive strength samples were cast. The remaining concrete was left in the mixer for fifteen minutes. The mixer remained off, and after the 15 minutes, the unit weight was 32.6 pcf. This was done to examine the stability of the air bubbles. The yield of the concrete was 163% which was higher than the desired yield of 130%. The average 28 day compressive strength was 42.1 psi which was also too high.

M 27 and M 28 were then batched with a r/w (ratio of rheocell to water) of 1:102. Both mixtures had a unit weight as high as 35 pcf after one minute of mixing. After two minutes of mixing, the unit weight of the mixtures was approximately 27 pcf. This increase in the amount of rheocell increased the yield of the concrete to approximately 165%. For M 27, 18 cubes were cast for compressive strength testing, and out of which, 6 samples broke during demolding at 7 days. The 28 day compressive strength of the cubes was 18.3 psi. For M 28, the 28 day compressive strength was 15.1 psi. The compressive strengths for all these mixtures are shown in Table 4.23.

The results from this series of mixtures clearly showed that rheocell was more effective in entraining air than medry. When used at a dosage rate of 1:102, rheocell was very effective, and further batches were conducted to refine the mixtures. Unit weights were plotted against time and are shown in Figure 4.10. All these mixtures attained the targeted unit weight (26-28 pcf) within two minutes. Hence, no further unit weight readings were recorded.

Table 4.23 Fresh and Hardened Properties of Mixtures M 26, M 27, & M 28

| | Mixture Designation | | |
|---|---|---|---|
| | M 26 | M 27 | M 28 |
| Mixing Time (minutes) | Unit Weight (pcf) | | |
| 1 | 35.1 | 35.0 | 35.8 |
| 1.5 | 29.8 | 29.7 | 29.7 |
| 2 | 27.4 | 27.1 | 26.5 |
| 3 | - | - | - |
| 4 | - | - | - |
| Yield (%) | 163% | 167% | 163% |
| Age (day) | Compressive Strength (psi) | | |
| 7 | 24.9 | 12.5 | 8.5 |
| 28 | 31.4 | 18.3 | 15.1 |

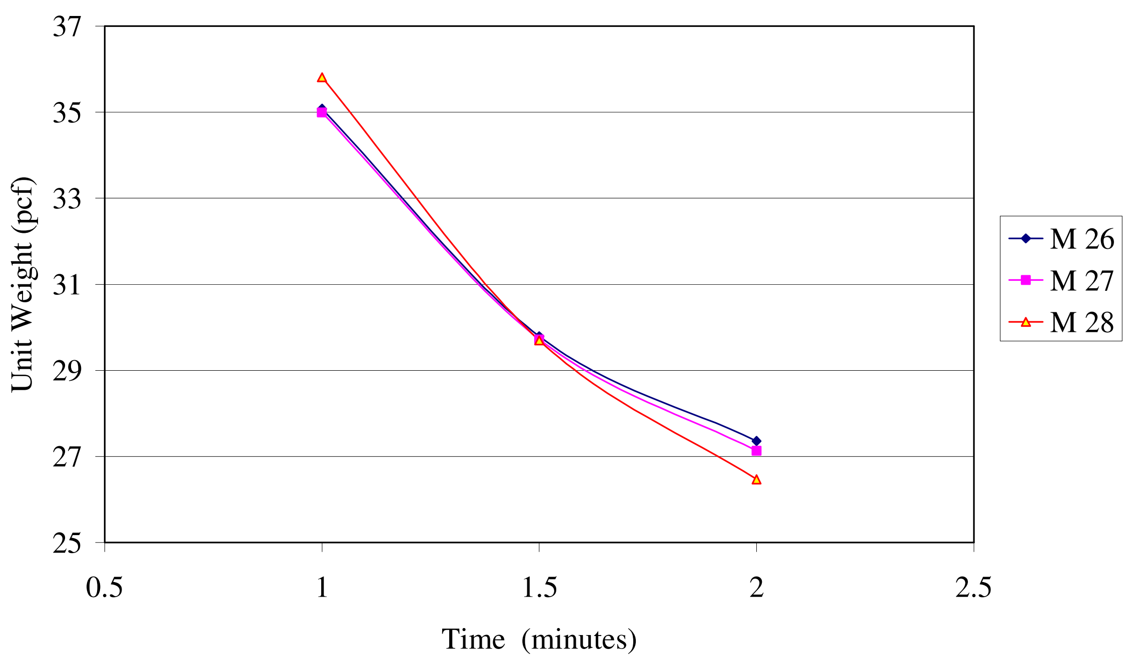


Figure 4.10 Variation in Unit Weight with Time for Mixtures M 26 through M 28

### 4.10 Effect of Batch Size on Mixture Performance using Rheocell

The preliminary unit weights measured in the previous section using rheocell at a dosage of 1:102 were successful. The next mixtures were cast to determine if rheocell was as effective in larger batch sizes. The mixtures (M 26-M 28) in section 4.9 had a batch size of approximately 4.4 lb. Whereas these mixtures had a batch size of approximately 42 pounds. Due to the larger batch size, these mixtures, M 29 through M 31, were batched in the double drum shear mixer. The mixture proportions and concrete properties for M 29 through M 31 are shown in Table 4.24.

Table 4.24 Mixture Proportions for Mixtures M 29 through M 31

| Material | Mixture Number | | |
|---|---|---|---|
| | M 29 | M 30 | M 31 |
| Pre-Blend Mixture | PB 2 | PB 2 | PB 2 |
| Sample Weight (lb) | 44.3 | 39.9 | 41.6 |
| Dry unit weight (lb/ft³) | 22.2 | 20.0 | 20.8 |
| Water (lb) | 44.7 | 40.2 | 41.9 |
| w/cm | 1.008 | 1.008 | 1.008 |
| Rheocell (Rheocell/Water) | 1:102 | 1:102 | 1:102 |

M 29 was batched with same mixture proportions as M 26 but at a lower dosage rheocell (1:102). M 29 was mixed for one minute and the unit weight was 33.5 pcf. The mixture was further mixed for two minutes, and the unit weight dropped to 29.1 pcf. Since the targeted unit weight was 26 to 28 pcf, the mixture was mixed for one additional minute, and the resulting unit weight was 25.4 pcf. The unit weight was slightly lower than the desired unit weight which in turn produced a yield of 175%. At 28 days, a concave shape was observed on the specimens cast from the concrete with a unit weight of 25.4 pcf concrete.

The concave shape was not present on the specimens cast from the concrete with unit weights more than 27 pcf. This shape possibly showed that the air voids became unstable and collapsed. Additionally, the remaining concrete was left in the mixer for twenty five minutes and the unit weight increased to 38.7 pcf. The gain in the unit weight was attributed to the instability of the air bubbles. The average 28 day compressive strength was 47.2 psi, which was higher than the desired compressive strength of 20 psi (Table 4.25).

To check the repeatability of mixture M 29, M 30 and M 31 were cast with the identical mixture proportions. These mixtures contained PB 2, and the dry unit weight was 20.0 pcf (M 30) and 20.8 pcf (M 31). Both mixtures had unit weights that were similar to that of M 29 (Figure 4.11), which was approximately 27.5 pcf. M 30 was mixed for a total of three minutes, and the resulting yield was 155%. M 31 was mixed for two minutes, and the resulting yield was 151%. For M 30 and M 31, 18 cubes, 3 cylinders (3 in. × 6 in.), and 3 blocks (12 in. × 12 in.) were cast. Among the three blocks, one was cast and stored in the environmental chamber. The second was cast outside in ambient conditions and then cured in the environmental chamber. The third was cast and cured in ambient conditions. The goal of using the three different curing environments was to examine the stability of the air bubbles in different environmental conditions. The results showed that the different curing environments had little to no effect on specimen shrinkage. All the blocks had a smooth surface (non-concave), but the surface of the cubes was concave. Since the cubes experienced some shrinkage (concave shape), further research on bubble stability with respect to temperature was conducted.

Table 4.25 Fresh and Hardened Properties of Mixtures M 29 through M 31

| | Mixture Designation | | |
|---|---|---|---|
| | M 29 | M 30 | M 31 |
| Mixing Time (minutes) | Unit Weight (pcf) | | |
| 1 | 33.5 | 32.0 | 33.5 |
| 1.5 | 30.7 | 29.8 | 30.0 |
| 2 | 29.1 | 27.5 | 27.7 |
| 3 | 25.4 | 26.1 | - |
| 4 | - | - | - |
| Yield (%) | 176% | 155% | 151% |
| Age (day) | Compressive Strength (psi) | | |
| 7 | - | 19.7 | 15.9 |
| 28 | 47.2 | 29.9 | 15.0 |

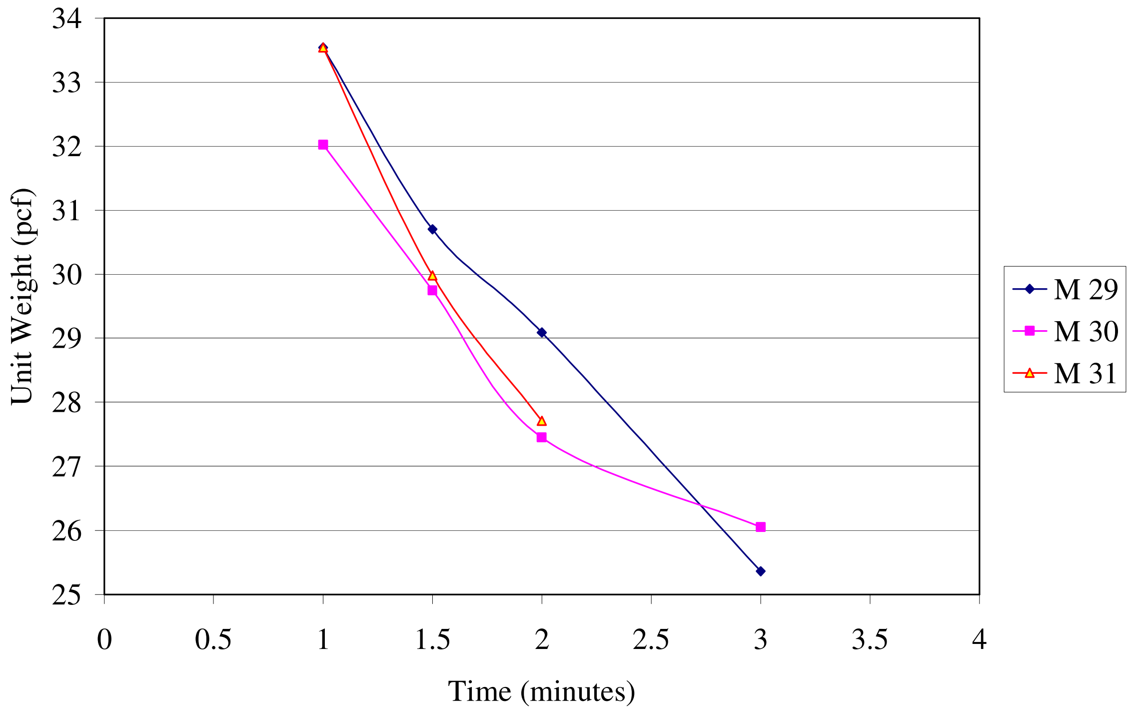


Figure 4.11 Variation in Unit Weight with Time for Mixtures M 29 through M 31

Since M 29 had a high yield and low unit weight, the same mixture proportion was used to batch two mixtures, M 32 and M 33, to examine the effects of temperature on the unit weight and volume change of the mixtures. M 32 was batched with a fresh concrete temperature of 65ºF, and M 33 had a fresh concrete temperature of 80ºF. To obtain these fresh concrete temperatures, M 32 was batched in the morning and M 33 was batched in the afternoon of the same day. Additionally the mixing water temperature was 62ºF and 71ºF for M 32 and M 33, respectively. The mixture proportions for both mixtures are shown in Table 4.26.

Table 4.26 Mixture Proportions for Mixtures M 32 through M 33

| Material | Mixture Number | |
|---|---|---|
| | M 32 | M 33 |
| Pre-Blend Mixture | PB 2 | PB 2 |
| Sample Weight (lb) | 42.4 | 45.2 |
| Dry unit weight (lb/ft³) | 21.2 | 22.6 |
| Water (lb) | 42.4 | 45.2 |
| w/cm | 1.008 | 1.008 |
| Rheocell (Rheocell/Water) | 1:102 | 1:102 |

After 2.5 minutes of mixing, M 32 had attained a unit weight of 27.6 pcf. As with M 31, three blocks (12 in. diameter and 12 in. height) were cast for M 32. The first block was cast and cured in the environmental chamber, the second block was cast outside the environmental chamber and was immediately moved to the environmental chamber, and the third block was cast and cured outside the environmental chamber and was left outside in the lab. For all blocks, there was no shrinkage or volume change observed.

For M 33, the mixture was initially dry after one minute of mixing and had a unit weight of 32.4 pcf. Upon further mixing, the unit weight dropped to 27.7 pcf after two minutes. The concrete was very fluid with a yield of 165%. Once again, blocks were cast from M 33. The blocks were subjected to the same curing regimens as M 31 and M 32. Among the three blocks, the block that was cast and stored in the environmental chamber was the only block that did not experience any volume changes. However, the concrete collapsed and had a concave surface on the top for the other two blocks. This collapse was due to the failure of the air void system (Figure 4.12). The concave surface was also noted on cubes and cylinders. The fresh and hardened properties of M 32 and M 33 are shown in Table 4.27. The unit weights vs. time for the mixtures are shown in Figure 4.13.

From the results, it was observed that the air void system produced by rheocell was more unstable at high temperatures. Maintaining an appropriate batching temperature is not only difficult but also expensive, for future mixtures, aluminum sulfate was added to stabilize the air bubbles.

Table 4.27 Fresh and Hardened Properties of Mixtures M 32 & M 33

| | Mixture Designation | |
|---|---|---|
| | M 32 | M 33 |
| Mixing Time (minutes) | Unit Weight (pcf) | |
| 1 | 34.4 | 32.4 |
| 1.5 | 31.7 | 29.6 |
| 2 | 28.9 | 27.7 |
| 2.5 | 27.6 | - |
| Yield (%) | 155% | 165% |
| Age (day) | Compressive Strength (psi) | |
| 1 | 6.5 | 14.1 |
| 28 | 14.1 | 23.0 |

Figure 4.12 Failure of Air Bubble

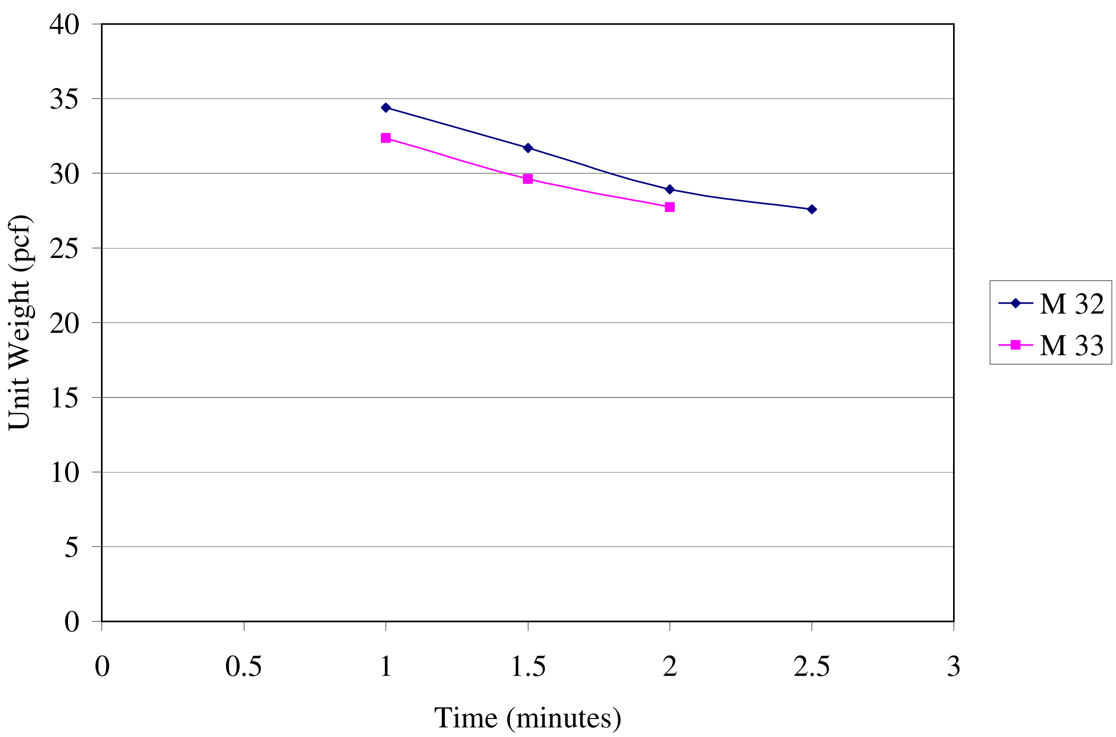


Figure 4.13 Variation in Unit Weight with Time for Mixtures M 32 & M 33

### 4.11 Bubble Stabilization Using Aluminum Sulfate

To increase the stability of the air voids, aluminum sulfate was introduced. Aluminum sulfate acts as an air-stabilizing agent when added to fresh concrete (Taylor 1974). For this series of mixtures, a kitchen aid mixer was used to mix the concrete. M 34 was the control mixture for this series and did not contain aluminum sulfate. The mixture proportions for M 34 through M 38 are shown in Table 4.28. For all mixtures, the unit weight was measured at 1, 1.5, 6.5, 11.5, and out to 16.5 minutes to check the bubble stability. The unit weight results are listed in Table 4.29.

Table 4.28 Mixture Proportions for Mixtures M 34 through M 38

| Material | Mixture Number | | | | |
|---|---|---|---|---|---|
| | M 34 | M 35 | M 36 | M 37 | M 38 |
| Pre-Blend Mixture | PB 2 | PB 2 | PB 2 | PB 2 | PB 2 |
| Sample weight (g) | 811 | 811 | 811 | 811 | 811 |
| Dry unit weight ($lb/ft^3$) | 21.3 | 21.3 | 22.3 | 22.3 | 22.3 |
| Water (g) | 817.5 | 817.5 | 817.5 | 817.5 | 817.5 |
| w/cm | 1.008 | 1.008 | 1.008 | 1.008 | 1.008 |
| Aluminum Sulfate (% of cement) | 0 | 0.25% | 0.50% | 0 | 0 |
| Rheocell | 1:102 | 1:102 | 1:102 | 1:102 | 1:102 |

M 34 was batched with the same mixture proportions as M 33 and was considered as control mixture. It attained a unit weight of 30.01 pcf after one minute of mixing. Upon further mixing for 30 seconds, the unit weight dropped to 27.59 pcf. M 34 was further mixed for six minutes, but there was little change in unit weight. However, after 11.5 minutes of mixing, the unit weight increased 0.7 pcf, and after 16.5 minutes, the final unit weight was 28.4 pcf.

M 35 was the first mixture containing aluminum sulfate, and it contained 0.25% aluminum sulfate per weight of cement. This mixture performed similar to the reference mixture. There was little change in unit weight with the addition of aluminum sulfate. For M 36, the aluminum sulfate dosage was increased to 0.5%. The dry unit weight was 22.3 pcf which was slightly higher than the normal range of 18 to 20 pcf. This resulted in a higher unit weight compared to that of the reference mixture. As shown in Figure 4.14, the unit weights of these two mixtures (M 35 & M 36) showed the addition of aluminum sulfate was not able to stabilize bubbles. M 37 and M 38 were then batched to determine mixing water temperatures, which would in turn help in increasing the stability of the bubbles.

The dry unit weight of the material used in both these mixtures (M 37 and M 38) was 22.3 pcf. Mixture proportions are shown in Table 4.28. Both mixtures were batched on the same day at an air temperature of 84ºF. M 37 was batched with hot water (85ºF), and M 38 was batched with cold water (57ºF). The unit weights obtained from the tests is shown in Table 4.29. For M 37, the initial unit weight was 2 pcf greater than M38. Figure 4.14 shows clearly that after seven minutes of mixing the rate of increase in unit weight was higher in the case of the hot water mixture (M 37). Based on the results from M 37 and M 38, it appears that concrete at lower temperatures has a more stable air void system than at higher temperatures.

Table 4.29 Fresh Properties of Mixtures M 34 through M 38

| | Mixture Designation | | | | |
|---|---|---|---|---|---|
| | M 34 | M 35 | M 36 | M 37 | M 38 |
| Mixing Time (minutes) | Unit Weight (pcf) | | | | |
| 1 | 30.0 | 30.0 | 30.8 | 32.0 | 30.7 |
| 1.5 | 27.4 | 27.6 | 27.4 | 29.1 | 27.5 |
| 6.5 | 27.6 | 28.0 | 27.7 | 28.5 | 27.4 |
| 11.5 | 28.2 | 28.3 | 28.3 | 29.7 | 27.9 |
| 16.5 | 28.4 | 28.2 | 28.6 | 30.5 | 28.0 |

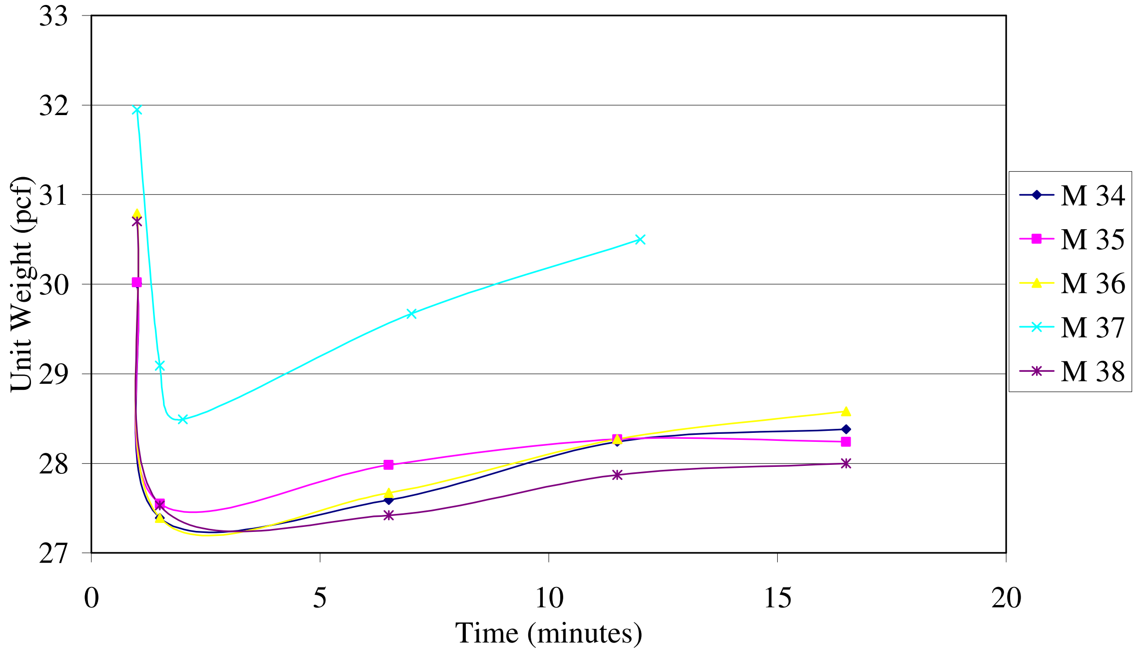


Figure 4.14 Variation in Unit Weight with Time for Mixtures M 34 through M 38.

### 4.12 Check for Repeatability of Drum Mixtures M 30 through M 33

From the previous batches conducted in the research, M 30 through M 33 had the properties that were suitable for use in SGAS. Hence a test with three batches was conducted to check the repeatability of these mixtures. In reference to mixtures M 30 through M 33, three batches, M 39, M 40, and M 41 were batched to examine the repeatability of the mixture when batched in larger quantities. These mixtures were batched with the same mixture proportions. A w/cm of 1.008 was maintained for the three mixtures. The mixture proportions are listed in Table 4.30. Also, fresh concrete and ambient temperatures were measured for these mixtures.

Table 4.30 Mixture Proportions for Mixtures M 39 through M 41

| Material | Mixture Number | | |
|---|---|---|---|
| | M 39 | M 40 | M 41 |
| Pre-Blend Mixture | PB 2 | PB 2 | PB 2 |
| Sample Weight (lb) | 43.3 | 40.3 | 35.1 |
| Dry unit weight (lb/ft$^3$) | 21.7 | 20.2 | 17.5 |
| Water (lb) | 43.7 | 40.7 | 35.3 |
| w/cm | 1.008 | 1.008 | 1.008 |
| Rheocell (Rheocell/Water) | 1:102 | 1:102 | 1:102 |

For these mixtures, the portland cement used for the pre-blends contained small pebbles of cement which in turn affected the dry unit weight. The dry unit weight of the three mixtures ranged from a low of 17.5 pcf for mixture M 41 to a high of 21.7 pcf for M 64. Due to time constraints, the batches were conducted with the same mixtures. For the mixtures, the mixing water temperature was maintained between 56 to 60ºF. The unit weight for M 39 and M 40 was measured at 1, 1.5, 2, 3 and 4 minutes. The unit weights of M 39 and M 40 were initially at 33.4 pcf and 31.4 pcf after one minute of mixing, and after 3 minutes of mixing their unit weights reached a low of 27.0 pcf and 26.1 pcf.

Since the targeted unit weights were attained, further mixing was not continued. Both mixtures had an average 7 day compressive strength of 4.8 psi (M 39) and 3.4 psi (M 40), which was due to low unit weights at which the concrete was cast (less than 28 pcf). Most of the specimens failed during demolding, and there were not enough specimens left for testing the compressive strength at 28 days. Both these mixtures had high yields of 162% (M 39) and 156% (M 40).

For M 41, the mixing continued until four minutes, because M 41 required a longer mixing to attain a unit weight of approximately 29 pcf. As the mixture was mixed for a longer time, no cubes were cast to test the compressive strength. The test results are listed in Table 4.31, and the relationship between unit weight and time are shown in Figure 4.15. As shown in Figure 4.15, the unit weights for M 39 and M 40 were very similar as was the final mixture temperature (59ºF). For all mixtures, three blocks were cast to assess the stability of the mixtures. All blocks were cast and cured in the environmental chamber, and shrinkage was not observed in any of the blocks.

Table 4.31 Fresh and Hardened Properties of Mixtures M 39 through M 41

| | Mixture Designation | | |
|---|---|---|---|
| | M 39 | M 40 | M 41 |
| Mixing Time (minutes) | Unit Weight (pcf) | | |
| 1 | 33.4 | 31.4 | 33.8 |
| 1.5 | 30.1 | 29.2 | 32.8 |
| 2 | 27.8 | 27.7 | 31.4 |
| 3 | 27.0 | 26.1 | - |
| 4 | - | - | 28.8 |
| Yield (%) | 162% | 156% | 130% |
| Age (day) | Compressive Strength (psi) | | |
| 7 | 4.8 | 3.4 | - |
| 28 | - | - | - |

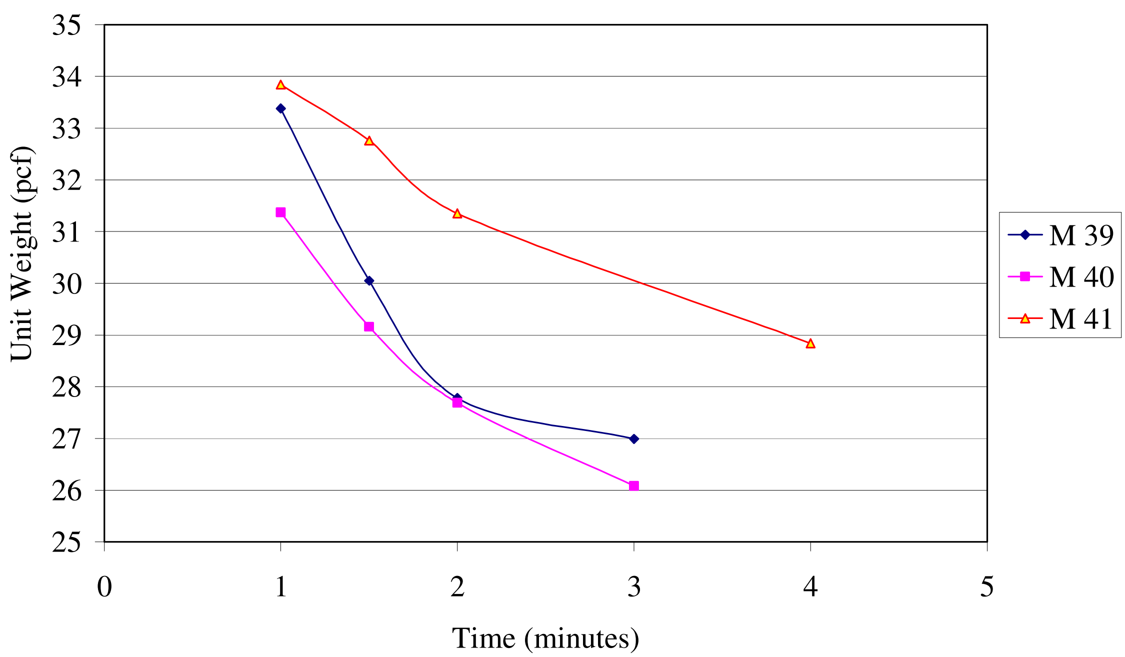


Figure 4.15 Variation in Unit Weight with Time for Mixtures M 39 through M 41

# CHAPTER 5

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Introduction

This project examined different types of admixtures that can be used to develop ultra-lightweight concrete for use in a Soft Ground Arrestor System (SGAS). The fresh and hardened properties of the concrete were analyzed while varying the type and dosage of chemical admixtures. For these mixtures the wet unit weight of the concrete and the compressive strength were the only concrete properties measured. The targeted unit weight was 26 pcf to 28 pcf after 3 minutes of mixing. The targeted 28 day compressive strength was 20 psi with minimal to no increase in compressive strength beyond 28 days of age.

## 5.2 Conclusions

The research project showed that the appropriate use of chemical admixtures can result in the targeted fresh and hardened properties. The following is a summary of the conclusions and observations from the research project. The following section is divided into conclusions regarding the mixing procedures, chemical admixtures, and materials.

### 5.2.1 Mixing Procedures

- The speed of the mixer is an important factor that must be considered when batching ultra-lightweight concrete. For the double drum shear mixer used in the study, a mixer speed of 58 revolutions per minute produced the best results. Any decrease in speed requires more time to attain the targeted unit weights. For speeds greater than 58 revolutions/minute, the targeted unit weights can be attained within 3 minutes, but the stability of air bubble is reduced which may result in the collapse of the concrete.

- For the mixtures examined in this study, the ideal concrete temperature during mixing was 60ºF.
- The concrete properties are dependent on the quantity batched. The higher the quantity, the better the homogeneity of the concrete.
- Proper curing is considerably important. Proper curing consisted of maintaining a ambient temperature of 70ºF and curing the specimens in a sealed container.

**5.2.2 Chemical Admixtures**

- An increase in melflux dosage increased the concrete's yield, but overdosing can cause bleeding and segregation.
- Combinations of medry and melflux were more effective than concrete mixtures containing only medry in reducing unit weight. Medry when used at a dosage rate of 1.8 g for every 1100 g of PB-1 produced the best results and any further increase in medry was ineffective. It was also observed that mixtures without melflux had higher unit weights.
- For the mixtures developed in this program, the suggested dosage rate for melflux is 0.5% (percent of cement by weight) to 1%. Any further decrease in melflux increases unit weights and compressive strengths. Also, increasing the melflux above 1% has no effect on unit weight and compressive strength.

- Rheocell produced concrete with lower unit weights, higher yields, and lower compressive strengths than mixtures containing medry. For the mixtures tested, a rheocell dosage of 1:102 (rheocell to water ratio) was effective in producing ultra-lightweight concrete.
- For mixtures containing rheocell, the optimum mixing time is 5 minutes. Mixing longer than 7 minutes can diminish bubble stability and cause settlement.
- For mixtures containing rheocell, concrete with unit weights less than 27 pcf were prone to collapse.
- Aluminum sulfate was ineffective in increasing the stability of bubbles.

### 5.2.3 Material

- Improper storage of the dry material can cause variations in the unit weight. This is due to high absorption capacity of the lightweight aggregate. Therefore, the pre-blend mixtures and materials should be stored in a dry place at all times.
- To limit the strength gain of the concrete, several mixtures were cast using calcium aluminate cement (CAC). Since the amount of cement used in ultra-lightweight concrete is very small, CAC was not helpful in reducing the compressive strength gain.
- For mixtures containing medry, a w/cm of 0.80 was effective in producing concrete with the targeted unit weights and compressive strengths. For mixtures containing rheocell, the most effective w/cm was 1.008. Any further reduction in water content results in a mixture that was too dry with higher unit weights and

compressive strengths. Increasing the water content caused segregation and bleeding.

### 5.3 Research Team Difficulties

- The research team experienced difficulty in maintaining the water temperature and mixture temperature, which was required for bubble stability.
- Problems in demolding the concrete specimens at one day were observed. This was due to slow setting times and low early age strengths of ultra-lightweight concrete. Hence the ultra-lightweight concrete was demolded at 3 days and cured in the environmental chamber at 70ºF.

### 5.4 Batching Recommendations

- While preparing and weighing the materials prior to testing, it is important not to subject the material to any type of compaction. This is mainly to avoid settlement of particles which would increase the unit weight and compressive strength.
- While casting ultra-lightweight concrete specimens, make sure that they are not subjected to excessive compaction. Excessive compaction can lead to the failure of the air void system in the concrete.
- Dry admixtures worked well when added to the dry ingredients rather than when added to the mixing water. For admixtures such as medry, melflux, and methocel, better results were achieved when the admixture was added to the dry mixture prior to batching. For mixtures containing rheocell, adding directly to the mixing water prior to batching produced better results.

- For the mixtures developed and tested in this study, a uniform batching and mixing procedure was employed. For the mixtures, one third of mixing water was added along with all the dry ingredients including the admixtures to the mixer. The mixer was then started, and the remaining water was slowly added.
- Multiple trial batches should be conducted on the same mixture in order to properly understand the behavior of the concrete with respect to batch quantity, mixer, concrete temperature, and ambient temperature.

**5.5 Research Recommendations**

Recommendations for future research work are listed below.

- Because of the difficulties in maintaining a constant mixing temperature and its effect on air void stability, further research is needed in the area of air bubble stabilization (specifically admixtures to improve bubble stability).
- Another area of potential research is to examine the effects of pumping ultra-lightweight concrete. Pumping the concrete will reduce labor costs and reduce the time required for casting SGAS.

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