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Affordable Lightweight High Performance Concrete (ALWHPC) - Expanding The Envelope of Concrete Mix Design

Kevin J. Simons
University of Nebraska at Omaha, ksimons@jeo.com

AFFORDABLE LIGHTWEIGHT HIGH PERFORMANCE CONCRETE (ALWHPC) EXPANDING THE ENVELOPE OF CONCRETE MIX DESIGN

by

Kevin Jerome Simons

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AFFORDABLE LIGHTWEIGHT HIGH PERFORMANCE CONCRETE (ALWHPC)

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Kevin Jerome Simons, M.S.

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Advisors: E. Terence Foster and Thomas H. Sires

One way to reduce excess material would be to lighten the load on a structure with the use of affordable lightweight high performance concrete (ALWHPC). Most or all lightweight high performance concrete mixes used today include lightweight aggregates as the coarse aggregate and sand for the fine aggregate. ALWHPC mix designs contain all lightweight aggregates and cementitious materials that are readily available throughout the United States. Instead of 115 – 120 pcf, ALWHPC mix designs range from 88 – 100 pcf and strengths from 2,700 – 8,700 psi compressive strength. Lightweight aggregate is the primary difference between normal-weight and lightweight concrete. Lower density aggregates are primarily used for insulating, temporary construction, or moderate-strength concrete applications. Higher density aggregates, such as expanded shales, clays, slates, slags, pumice, and scoria, which yield higher strength concrete, are used for structural lightweight concrete applications (ACI Committee 213, 2003). The first major project to use lightweight concrete was in World War I when the American Emergency Fleet Corporation built lightweight concrete ships from 1917 to 1920 (American Concrete Institute, 2006). This research will explore the use of local lightweight aggregates along with different local cementitious materials (i.e., fly ash and Portland cement) and admixtures to create an affordable lightweight high performance concrete mix design.

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Chapter 1. Introduction

Today there is much concern about the environment and how to efficiently use materials to full potential. One way to reduce excess material would be to lighten the load on a structure with the use of affordable lightweight high performance concrete (ALWHPC). Most or all lightweight high performance concrete mixes used today include lightweight aggregates as the coarse aggregate and sand for the fine aggregate. With this configuration the lightweight unit mix weight is around 115 – 120 pcf compared to 150 pcf for normal weight concrete. ALWHPC mix designs contain all lightweight aggregates and cementitious materials that are readily available throughout the United States. Instead of 115 – 120 pcf, ALWHPC mix designs range from 88 – 100 pcf and strengths from 2,700 – 8,700 psi compressive strength. A reduction of 15 – 20 pcf in dead load throughout an entire structure would lead to substantial reduction in structural member sizes and possibly members within the structure.

Lightweight concrete is not a new material; in fact it has been observed since 7000 B.C. At that time it was made with local materials such as quick lime, water, and stone aggregates. Lightweight high performance concrete of today is still made with approximately the same materials: portland cement, water, lightweight aggregates, and sand.

Chapter 2. Background

Lightweight structural concrete, also known as lightweight high-performance concrete, has several valuable characteristics such as excellent freezing and thawing durability, internal curing, and reduced dead load. The definition of high performance is subjective. It can mean high strength or low unit weight or a combination of the two. In general high performance can be thought of as superlativity of one or more measureable parameters.

Lightweight structural concrete is defined by ACI 213 as concrete with an air-dry density in the range of 85 to 115 pounds per cubic foot (pcf), with some job specifications allowing air-dry densities up to 120 pcf, and a 28-day compressive strength greater than 2500 psi (ACI Committee 213, 2003). When compared to normal-weight concrete with a density of around 150 pcf, lightweight structural concrete has a significantly less dead load. The difference in weight is achieved with the use of lightweight aggregate, usually expanded shale, clay, or slate.

The primary difference between normal-weight and lightweight concrete is the use of lightweight aggregates contained within the mix. There are a number of types of lightweight aggregates available today including expanded shale, expanded clay, expanded slate, expanded slag, vermiculite, perlite, pumice, scoria, and fly ash. Typically, a direct relationship exists between density of the aggregate and compressive strength of the concrete when all other variables are held constant. Lower density aggregates are primarily used for insulating, temporary construction, or moderate-strength concrete applications. Higher density aggregates, such as expanded shales, clays, slates, slags, pumice, and scoria, which yield higher strength concrete, are used for structural lightweight concrete applications (ACI Committee 213, 2003). The process of expanding lightweight aggregate in a kiln was developed by Stephen Hayde in the early 1900s in Kansas City, Missouri (Buildex Inc., 2009). The first major project to use structural lightweight concrete was throughout a three year period during World War I when the American Emergency Fleet Corporation built lightweight concrete ships (American Concrete Institute, 2006). "The entire hull structure of the USS *Selma* and 18 other concrete ships were constructed with 5000 psi, high-performance lightweight concrete in the ship building program in Mobile, Alabama, starting in 1917" (American Concrete Institute, 2006). Since then, structural lightweight concrete has been used for countless purposes and structures including precast structures, high-rise buildings, and bridges. Two well-known lightweight bridges include the San Francisco-Oakland Bay Bridge and the 1950 replacement of the Tacoma Narrows Bridge, which incorporated additional traffic lanes due to reduced dead load (ACI Committee 213, 2003).

2.1. Problem Statement

The problem statement addresses the need for creating a baseline case for the use of lightweight high performance concrete mixes used in the Midwest region today. From this baseline an affordable lightweight high performance concrete (ALHPC) mix design(s) will be created that can be produced at any Ready-Mix plant today.

2.2. Objectives

This research will explore the use of local lightweight aggregates, fine and coarse, along with different local cementitious materials (i.e., fly ash and Portland cement) and admixtures to create an affordable lightweight high performance concrete mix design. With today's focus on the environment and trying to reduce the carbon footprint, this will be a driving force in the research for ALWHPC. An important part of this research will include finding local materials that are readily available and making sure that the resulting mix design is as environmentally friendly (sustainable) as possible.

There are many uses of ALWHPC today, from buildings to bridges to landscaping. With the reduced weight of the concrete, the size and number of load bearing structural members within any structure may be reduced. Using ALWHPC as a decking and/or skin material will also allow a structure to be designed with more stories, therefore creating more rentable/usable space.

2.3. Description of Work and Expected Deliverables

The research performed used lightweight aggregates, both coarse and fine, obtained from Buildex, Inc.'s two production plants, Marquette, Kansas, and New Market, Missouri. The cementitious materials used included, Type III Portland Cement and Class C Fly ash; both materials are readily available in the Midwest. Project admixtures for water-reducing, concrete workability, and air entraining were obtained from Ready Mixed Concrete Company in Omaha, Nebraska. Concrete mix designs were then created from the materials. Mix designs 1-4 were created using a 1:2:2 (cementitious material: fine aggregate:

coarse aggregate) proportion. Coarse aggregate size and water/cement (w/c) ratio were varied for each mix to produce different results. Mix designs 5-7 were created using Somayaji's method, which is discussed later in Section 3.0, Analytical Process. These mixes utilized smaller coarse aggregate sizes which made them ideal for use in a concrete masonry unit (CMU) or modular unit construction.

2.3.1. Buildex: Marquette, Kansas, Aggregate

Marquette, Kansas, is located about 30 miles southwest of Salina, Kansas and about 10 miles west of Interstate 35. The aggregate sampled is expanded shale. All production sizes available and also the ASTM blend size of ½" x No. 4 were sampled. The ASTM gradation was selected due to availability of aggregate. A picture of the Marquette aggregate is shown in Figure 2.1. Buildex manufacturing specifications report that the Marquette ½" x No. 4 aggregate has a bulk specific gravity of 1.09, a loose density of 37 pcf at 6% moisture content, and a saturated density of 52 pcf when the aggregate stockpile is pre-wetted for seven to 14 days (Buildex, Inc., 2009). Particle shape and surface texture of the Marquette aggregate is angular and rough.

Fig. 2.1 Buildex Marquette, Kansas, Aggregate (Ruler Units: Inches)

2.3.2. Buildex: New Market, Missouri, Aggregate

New Market, Missouri, is located about 20 miles south of St. Joseph and a mile west of United States Highway 71. Again, the aggregate sampled is expanded shale. All production sizes available and also the ASTM blend size of ½" x No. 4 were sampled. The ASTM gradation was selected due to availability of aggregate. A picture of the New Market aggregate is shown in Figure 2.2. Unlike the Marquette aggregate, the New Market aggregate is available pre-saturated by vacuum saturation. Buildex manufacturing specifications report that the New Market rock has a bulk specific gravity of 1.15, a loose density of 43 pcf at 6% moisture content, and a vacuum-saturated density of 54 pcf (Buildex, Inc., 2009). Overall, the New Market aggregate has smaller, more rounded aggregate particles; and the surface texture appears to be smoother than the Marquette aggregate

Fig. 2.2 Buildex New Market, Missouri, Aggregate (Ruler Units: Inches)

Table 2.1 Summary of Aggregate Properties

Aggregate Sample Locations	Bulk Specific Gravity (a)	Loose Density (b)	Saturated Density (d)	Vacuum Saturated Density (e)	Percent Absorbtion (f)
Marquette, Kansas	1.09	37	52	-	22%
New Market, Missouri	1.15	43	-	54	25%

(a) ASTM C 127 / C 128, bulk specific gravity
(b) ASTM C 29, loose unit w eight (density) @ normal 6% shipping moisture content.
(d) Unit Weight (density) w hen stockpile ambient saturated for 7 to 14 days for concrete pump placement
(e) Unit Weight (density) w hen vacuum saturated at Buildex plant for concrete pump placement
(f) ASTM C127 / C 128, 24 hour w ater absorption at ambient pressure. Please note that the 24 hour absorption figure is not appropriate for use in determining moisture content of Buildex used in pumped concrete.
Note: ASTM Blend 1/2" x No.4 used in above table for comparison

2.3.3. Phase I: Development of ALWHPC mix designs

"The design of concrete mixtures involves choosing appropriate proportions of ingredients for particular strengths, long-term qualities, and performance of the concrete produced. Several factors determine these properties. They include the following parameters:

- Quality of cement
- Proportion of cement in relation to water in the mix (water/cement material ratio)

- Strength and cleanliness of aggregate
- Interaction or adhesion between cement paste and aggregate
- Adequate mixing of the ingredients
- Proper placing, finishing, and compaction of the fresh concrete
- Curing at a temperature not below 50°F while the placed concrete gains strength
- Chloride content not to exceed 0.15% in reinforced concrete exposed to chlorides in service and 1% in dry protected concrete

A study of these requirements shows that most control actions have to be taken prior to placing the fresh concrete. Because such control is governed by the proportions of ingredients and the mechanical ease or difficulty in handling and placing the concrete, the development of criteria based on the theory of proportioning for each mix should be studied. Most mixture design methods have become essentially only of historical and academic value. The two universally accepted methods of mixture proportioning for normal weight and lightweight concrete are the American Concrete Institute's methods of proportioning, described in their recommended practices for selecting proportions for normal weight, heavyweight, and mass concrete, and in the recommended practice for selecting proportions for structural lightweight concrete" (Nawy, 2008).

The materials of interest in this research are two types of lightweight aggregates produced from Buildex, Inc. Special attention was given to pre-wetting the aggregate and accounting for the moisture content and absorption values in the mix designs. Two different optimized mix designs were created from this project. The first mix design intended for heavy structural use and the second for light to medium structural use. Each of the mix designs were created using both fine and coarse lightweight aggregates. Specimens from each of these mixes were then subjected to laboratory material tests.

2.3.4. Phase II: Mixing Procedure and Laboratory testing of ALWHPC

Concrete Tests:

To evaluate the preliminary ALWHPC mixtures, slump, unit weight, volumetric air content, and compressive strength of each mixture were determined. Three variables were altered during the preliminary mix design phase.

- Lightweight coarse aggregate production size was the first variable modified for each mix design. Both fine and coarse aggregates used within the mixes were lightweight aggregates.
- Water/cement ratio was the second variable modified, starting with 0.40 as a starting point and ending with 0.30.
- Water reducers and air-entraining admixtures were the third variables used. These admixtures were introduced to the mix designs to ease in the mixing of the fresh concrete and add protection to for freeze and thaw conditions as hardened concrete. The water reducing agent used in all the mixes was Glenium 3030ns (BASF) which is a high range water reducing admixture. Air entrainment admixture which was used on mixes 4 – 6 was Daravair 1400 (Grace Construction Products).

From these fresh and hardened concrete tests the optimum mix design could be selected.

Concrete Slump:

The slump test was conducted on each concrete mixture according to ASTM C172. During the slump test, fresh concrete was placed in the slump cone in three layers of equal volume and each layer was rodded 25 times. Next, the slump cone was lifted, and the plastic concrete was allowed to disperse. The vertical distance between the original height of the cone and the displaced original center of the concrete was then measured as the slump. This test is a measure of workability and mixture consistency between batches. A picture of the slump test being conducted is shown in Figure 2.3.

Fig. 2.3 Fresh Concrete Slump Test

Concrete Unit Weight:

The unit weight or weight density (γ), of the freshly mixed concrete was determined according to ASTM C138. This test consisted of placing concrete in a rigid container with a known volume to obtain a specific volume. The weight density of the fresh concrete is measured by dividing the fresh concrete weight by the volume. The unit weight is especially important in lightweight concrete since a maximum acceptable unit weight is usually specified. For this research project, the unit weight was measured from the bowl of the volumetric air meter (volume = 0.5 cubic feet).

Volumetric Air Content:

The air content of each mix design was measured according to ASTM C173. A picture of the volumetric air gauge is shown in Figure 2.4. Below is a list of the steps followed to perform the test:

- Place fresh concrete in the bowl in three layers of equal volume and each layer was rodded 25 times.
- Tap the Bowl 10 to 15 times with a rubber mallet after each layer is rodded.
- Strike off the top after all the layers are in place with a bar until the surface is flush with the top of bowl and the flange of bowl is wiped clean
- Attach top section, insert funnel, and add water until it appears in the neck.

- Remove funnel and add water with rubber syringe until the bottom of the meniscus is level with zero mark, the cap is attached and tightened
- Invert meter and agitate for a minimum of 45 seconds
- Tilt meter approximately 45 degrees and vigorously roll and rock for approximately 1 minute, with neck elevated at all times
- Set meter upright and allow to stand until liquid level stabilizes by not changing more than 0.1 percent within 1 minute period
- Disassemble meter and examine contents to assure there are no portions of undisturbed, and the concrete is tightly packed in base

Fig. 2.4 Volumetric Air Gauge

Compression Test:

The compressive strength of concrete measured in force per unit area reveals the load that may be applied to a concrete structure. Therefore, for every significant structure, it is important to check the compressive strength from a representative number of concrete cylinders cast from the same batches of concrete used to form the structure. In the design of concrete structures, the design engineer specifies given strengths that the final concrete product must be capable of attaining. When trial batches are prepared during mix design or as a quality control measure to ensure that concrete mixed or delivered in the field satisfies those specified strengths, a compression test is performed. Compression tests (ASTM C39) are conducted to determine the compressive strength of concrete (f'_c). In this test, a standard test load is applied parallel to the longitudinal axis of a pre-molded and properly cured concrete cylinder of a standard size such as 8 in length, 4 in diameter. When the test is properly conducted, a maximum load is obtained at the point at which the cylinder ruptures. With this maximum load, the compressive strength, measured in pounds per square inch (psi), can be easily calculated. A completed compression test can be seen in Figure 2.5.

Fig. 2.5 Completed Compression Test

Chapter 3. Analytical Process

The absolute volume method of proportioning concrete, along with a method found in Somayaji's text was used to create the concrete mix designs for this project. The principle behind the absolute volume method is to design one cubic yard of concrete based on the volume of the mix. This involves setting initial values of weight for cement, water, and coarse aggregate, then using the specific gravity of these materials to convert these weights into volumes. The volume of air assumed to be in the mixture is also calculated. These volumes are summed, and the rest of the volume within the one cubic yard being designed is filled with fine aggregate. Weight of the fine aggregate can then be determined using specific gravity and the calculated volume. This is the common proportioning method used with normal-weight concrete. Problems arise, however, when using this method with lightweight aggregates. The issue in this case evolves from the nature of the specific gravity of the lightweight aggregate. Specific gravity of the lightweight aggregate varies with particle size, where coarse particles are lighter and contain more internal air voids and fine particles are heavier with fewer internal air voids. In addition, specific gravity of lightweight aggregates changes as absorption increases. Tables 3.1 and 3.2 show how, as the aggregate production decreases in particle size the percent absorption also decreases. With the percent absorption decreasing, the specific gravity and density increase noticeably.

Table 3.1 Typical Physical Properties of Marquette, Kansas, Aggregate

Production Size	Specific Gravity (a)	Density, lb/cu ft (b)	Percent Absorption (c)
5/8" x 3/8"	1.05	35	25
3/8" x 1/4"	1.10	40	20
1/4" x 1/8"	1.15	42	16
1/8" x 0	1.50	47	10

(a) ASTM C 127 / C 128, bulk specific gravity.
(b) ASTM C 29, loose unit weight (density).
(c) ASTM C 127 / C 128, 24 hour absorption.

Table 3.2 Typical Gradation of Marquette, Kansas, Aggregate

Sieve	5/8" x 3/8"	3/8" x 1/4"	1/4" x 1/8"	1/8" x 0
3/4"	0			
1/2"	19	0		
3/8"	79	3	0	
No. 4	99	98	20	0
No. 8	99	99	89	8
No. 16			98	38
No. 30			99	64
No. 50				81
No. 100				88

Table 3.3 Typical Physical Properties of New Market, Missouri, Aggregate

Production Size	Specific Gravity (a)	Density, lb/cu ft (b)	Percent Absorption (c)
5/8" x 3/8"	1.10	38	18
3/8" x 1/4"	1.15	42	15
1/4" x 1/8"	1.20	44	12
1/8" x 0	1.80	58	8

(a) ASTM C 127 / C 128, bulk specific gravity.
(b) ASTM C 29, loose unit weight (density).
(c) ASTM C 127 / C 128, 24 hour absorption.

Table 3.4 Typical Gradation of New Market, Missouri, Aggregate

Sieve	5/8" x 3/8"	3/8" x 1/4"	1/4" x 1/8"	1/8" x 0
3/4"	0			
1/2"	22	0		
3/8"	82	3	0	
No. 4	98	95	22	0
No. 8	99	99	96	12
No. 16			99	43
No. 30				67
No. 50				80
No. 100				86

Furthermore, specific gravity of lightweight concrete cannot be determined accurately using ASTM C127 and C128, which states it is not intended to be used with lightweight aggregates (ASTM International, 2007). For these reasons, specific gravity values used in the mix designs for this project were obtained from Buildex. These specific gravity values were based on aggregate that had been pre-wetted in a stockpile for seven to fourteen days. Although the actual lightweight aggregate specific gravity value likely varied for each concrete batch, using average values from Buildex proved to produce consistent results. Therefore, they were used throughout the project. Specific gravity values used for New Market and Marquette standard production sizes of 1/8"x 0, 1/4" x 1/8", 3/8" x 1/4", and 5/8" x 3/8" were 1.50, 1.15, 1.10, and 1.05, respectively. For this project, an Excel worksheet was created according to Somayaji's method to facilitate mix design calculations. Somayaji's method solves for the weight of each material by setting the total volume of the individual materials equal to the total volume of the concrete mix. Figure 3.1 shows a sample calculation using Somayaji's method for finding material mix weights (Somayaji, 2001).

Fig. 3.1 Example of Somayaji's Method

Find the weights using the following data.

Mix proportion = 1 : 2 : 3.3 : 0.5

Air content = 3%

Specific gravity of cement, fine aggregate, and coarse aggregate = 3.15, 2.65, and 2.7, respectively

Required volume of concrete = 2.2 ft^3

Let weight of cement required = W_c lb.

$$\text{Volume of concrete} = 2.2 = \frac{W_c}{62.4}\left[\frac{1}{3.15} + \frac{2}{2.65} + \frac{3.3}{2.7} + \frac{0.5}{1}\right] + \frac{3(2.2)}{100}$$

$$= \frac{W_c}{62.4}(2.794) + 0.066$$

$$W_c = 48 \text{ lb}$$

$$W_{FA} = 48(2) = 96 \text{ lb}$$

$$W_{CA} = 48(3.3) = 158 \text{ lb}$$

$$W_w = 48(0.5) = 24 \text{ lb}$$

An alternative concrete mix design method is recommended by Buildex, though. This method consists of initially batching the materials required to achieve a certain strength based on the loose bulk density of the pre-wetted aggregate. With this method, material proportions are largely based on past data and experience. Air content and yield of the mixture is then determined, and the proportion of the coarse lightweight aggregate is then adjusted to achieve the desired yield and unit weight (Buildex, Inc, 2009). This method has been used by several batch plants and has been shown to successfully produce consistent concrete mixes. Sample concrete mix design worksheets are shown in Appendix A – Concrete Mix Designs.

Chapter 4. Experimental Results

Over a period of time from May 29, 2009, to August 10, 2009, eight different ALWHPC mix designs were formulated. The main driving forces behind the mix designs were:

1. Affordability – How does cost of ALWHPC compare to normal weight concrete or lightweight pump concrete?
2. Availability – are the lightweight aggregates readily available with production plants within an economical transport radius?
3. Strength (f'_c) – will the mixes meet high performance concrete specifications?
4. Weight – can the weight density be held under 100 pounds per cubic foot?
5. Workability – can the mix be placed and worked with ease?

Today normal weight concrete costs around $85/cu.yd., lightweight pump concrete costs around $108/cu.yd., and ALWHPC will cost around $112/cu.yd. The previous prices have been obtained from Ready Mixed Concrete, Inc. and Buildex, Inc. as of 2009.

The lightweight fine and coarse aggregates used in the mix designs can be shipped via rail or truck from either of Buildex's production sites, thus making it readily available to stockpile for mixing. Buildex has the capability to readily supply lightweight aggregate from Denver, Colorado, to Des Moines, Iowa. Besides Buildex other lightweight aggregate producers are scattered throughout the United States.

ACI 213 states that lightweight structural concrete must meet a unit weight between 85 pcf – 115 pcf and a compressive strength of 2,500 psi (ACI

Committee 213, 2003). All ALWHPC mixes but two meet these specifications with most of them exceeding the specifications by a large margin. The average unit weight of ALWHPC mix designs is 90.5 pcf with an average compressive strength of 4,600 psi.

Unit weight is the most important contribution that ALWHPC will make to the concrete industry. Compared to normal weight concrete, ALWHPC weighs 38.7% less. Compared to lightweight pump mix, ALWHPC weighs 21.4% less. Below is a real world application to help demonstrate the savings of ALWHPC.

Weight savings over a 20' x 20' x 5" slab

- *Volume = 20' x 20' x 0.42' = 168 cu.ft.*
- *Normal weight concrete = 168cu.ft. x 150lb./cu.ft. = 25,200lbs. Or 63lb./sq.ft.*
- *Lightweight concrete pump = 168cu.ft. x 117lb./cu.ft. = 19,656lbs. Or 49lb./sq.ft.*
- *ALWHPC = 168cu.ft. x 92lb./cu.ft. = 15,456lbs. Or 39 lb./sq.ft.*
- *Weight savings of 9,750lbs. over normal weight and 4,200lbs. over lightweight pump mix*

The use of air entrainment and water reducer admixtures greatly aided in the workability of ALWHPC. Mixes 1 – 3 were less workable than mixes 4 – 7 due to the lack of air entrainment. Although all mixes contained water reducing admixtures it seemed that introducing air into the mixes aided the most in regards to the workability of the mix.

Figures 4.1 and 4.2 show comparisons between compressive strength and unit weight versus coarse aggregate size for mixes 1 – 3. Variables held constant for both cases in the three mix designs were W/C ratio and percent of admixture introduced into the mixes. The aggregate sizes that appear in the two figures were converted from the Buildex production sizes of 1/8”x 0, 1/4" x 1/8”, 3/8” x 1/4”, and 5/8” x 3/8” to average aggregate areas. Rectangular and an ellipsoidal areas were used to convert the particle sizes from a nominal length and width to an area. The combined formula used for this process is shown below.

$$\begin{aligned} A_{ave} &= 1/2 \times (A_{rec} + A_{ell}) \\ &= 1/2 \times (2 + \pi/2) \times l \times w \end{aligned}$$

where :
A_{ave} = average area
A_{rec} = area of a rectangle
A_{ell} = area of an ellipse
l = length of aggregate side
w = width of aggregate side

Figure 4.1 shows how larger aggregate sizes give weaker compression strength that the mix design will attain. From the laboratory compression tests performed on mix designs 1 – 3 it was evident that the failure stress was caused due to aggregate failure.

In addition to comparing compressive strength to coarse aggregate size a comparison between unit weight and coarse aggregate size can be made. Figure 4.2 shows how larger coarse aggregate decrease the unit weight of the overall mix. With the exception of mix 2 it should be expected, that internal air voids contained within the larger coarse aggregate to cause a lighter unit weight.

Fig. 4.1 Compressive Strength vs. Coarse Aggregate Size

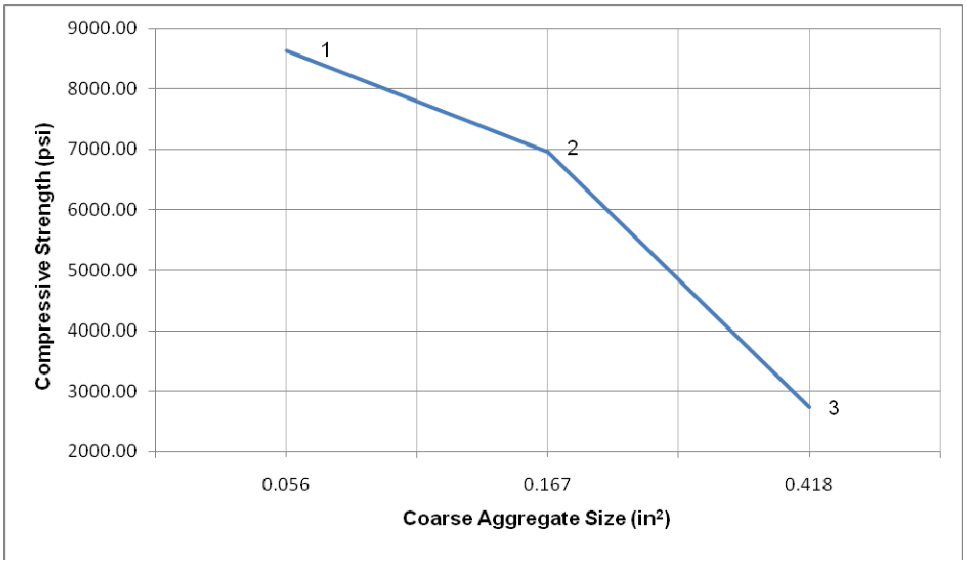
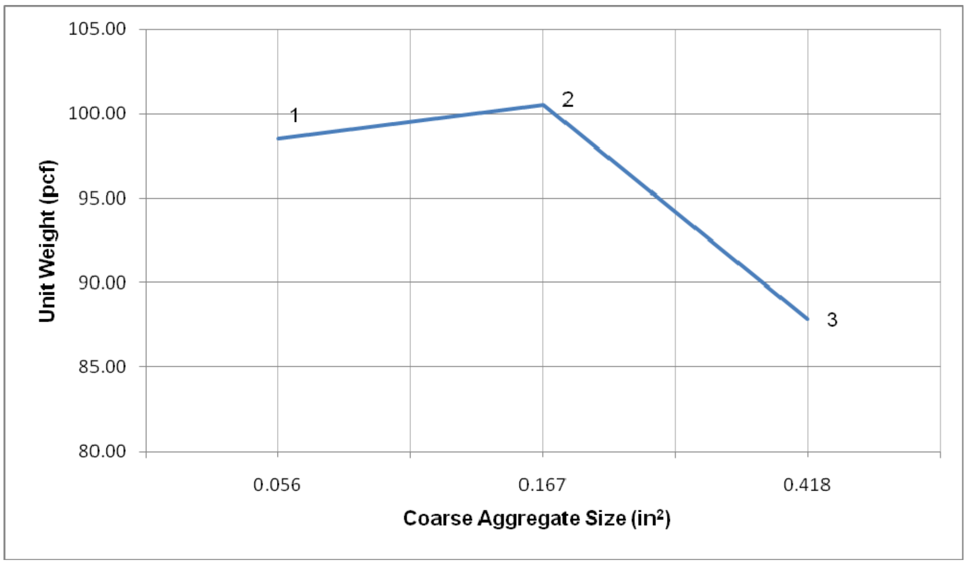


Fig. 4.2 Unit Weight vs. Coarse Aggregate Size



Concrete exposed to elemental (freeze/thaw) conditions can be damaged without the addition of air entrainment. Figures 4.3 and 4.4 compare the compressive strength and unit weight versus the percentage of air entrainment added for mixes 4A, 5, and 7. Variables held constant for both cases in the four mix designs were W/C ratio and aggregate size. Figure 4.3 shows as air entrainment is increased the compressive strength is decreased dramaitcally over a 3% range. Laboratory compressive tests indicated that increasing air entrainment led to lower compressive strength. Samples containing larger percentages of air entrainment crumbled not sheared when loaded to failure.

Air entrainment in concrete also aids in the workability of the mix. Air entrainment works by reducing the surface tension of the mixing water. Tiny bubbles are also created within the mix binding cement particles with aggregate particles. The tiny bubbles created by the air entrainment also aid in reducing the unit weight of the overall concrete mix. Figure 4.4 shows the effect of air entrainment over unit weight.

Fig. 4.3 Compressive Strength vs. % Air Entrainment

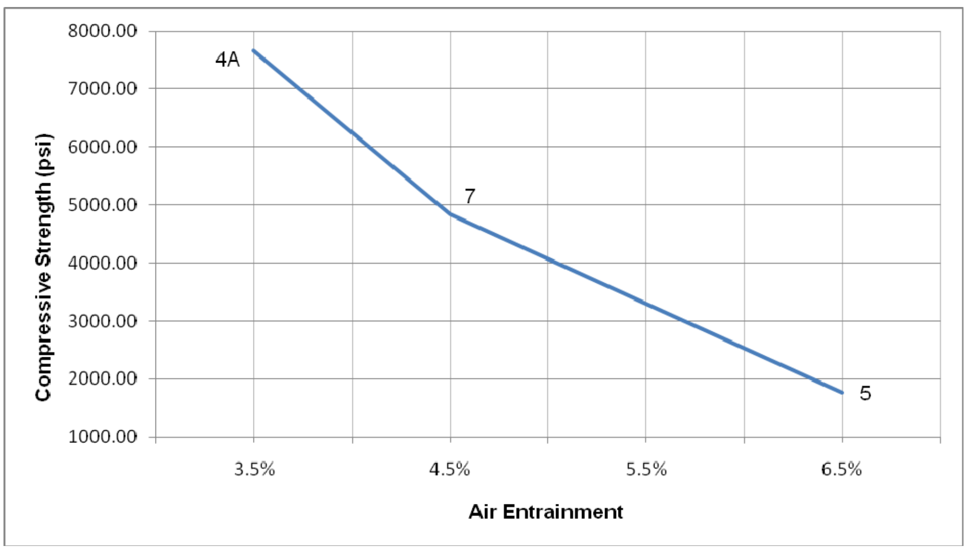
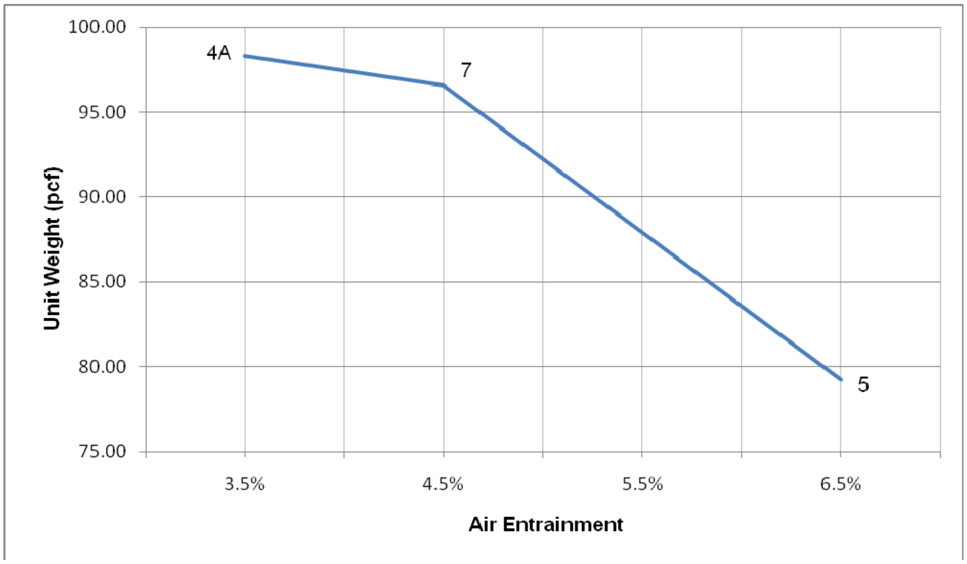


Fig. 4.4 Unit Weight vs. % Air Entrainment



Water to cement ratio is an important part of concrete mix design, as the mixing water is decreased compressive strength increases. Figures 4.5 and 4.5 show compressive strength and unit weight versus W/C ratio for mixes 4A, 6, and 7. Variables held constant for both cases in the three mix designs were aggregate size and percent of admixture introduced into the mixes. Figure 4.5 shows as the W/C ratio is increased the compressive strength of the mix is decreased. Varying W/C ratio on compressive strength is one of the most important relationships in concrete, using excess water in a mix design can greatly reduce the strength of that mix.

Comparing unit weight to W/C ratio is a relationship that is not represented often. Table 4.6 compares how W/C ratio and unit weight are related. The graph shows as water is increased within the mix unit weight deceases. Water is introduced and combined with the air entrainment, this in turn creates air bubbles within the mix. The more water introduced into the mix the more air bubbles, thus creating a less dense unit mix weight.

Fig. 4.5 Compressive Strength vs. W/C Ratio

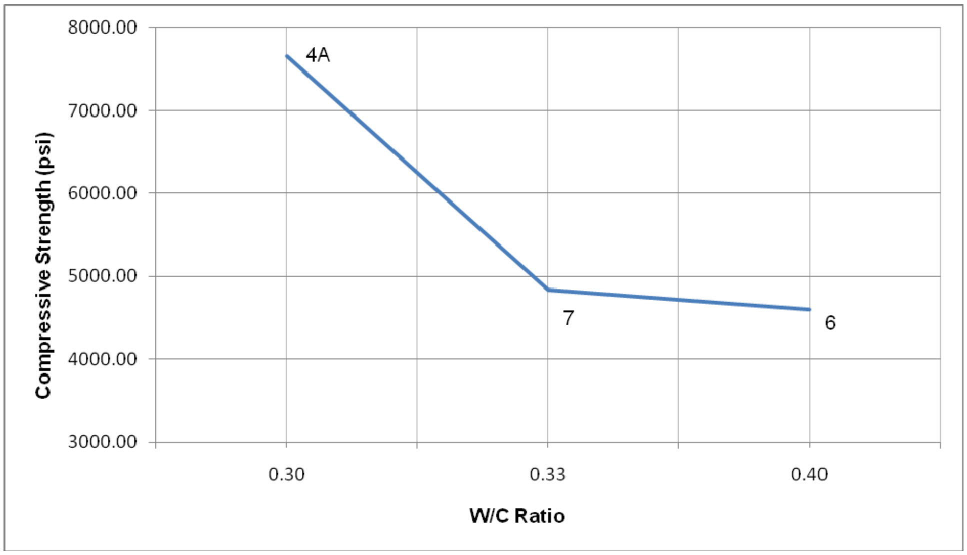
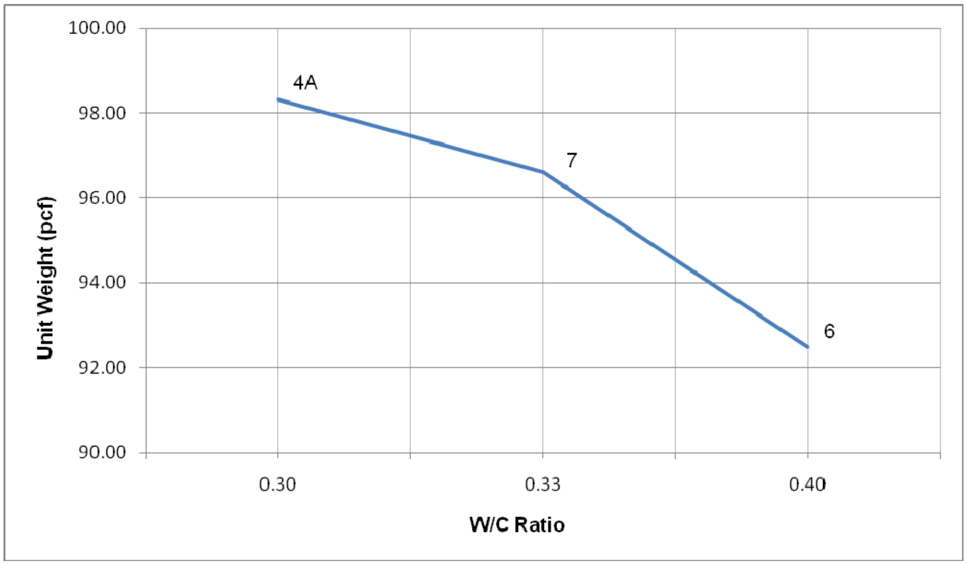


Fig. 4.6 Unit Weight vs. W/C Ratio



One of the goals for the ALWHPC mix design project was to find a lightweight mix design that also posessed high strength. Figure 4.7 compares compressive strength versus unit weight for all ALWHPC mix designs tested.

From the scatted data a tool was created within the graph called a solution space. Using the solution space tool an origin can be specified and lines drawn perpendicular through that origin to create a space containing accpetable mix designs. To further aid in selecting the best mix design a vector could be drawn at a solved distance from the origin to encompass a second solution space. The equation used to solve for the vector distance is shown below.

$$d = (((\gamma - \gamma_o) \div \gamma_o)^2 + ((f'_c - f'_{co}) \div f'_{co})^2)^{1/2}$$

where :
d = vector distance
γ = mix unit weight
γ_o = unit weight limit
f'_c = mix compressive strength
f'_{co} = compressive strength limit

From Figure 4.7 a total of five mix designs out of eight fall within the solution space. The solution space origin is set at 100 pcf and 2,500 psi and all mix designs that fall upward and to the left of the origin are acceptable. Solution space graph can aid in selection of mix designs even if the origin shifts due to different specifications. The origin of 100 pcf and 2,500 psi for Figure 4.7 was chosen based on lightweight structural concrete as defined by ACI 213.

Fig. 4.7 Compressive Strength vs. Unit Weight (Solution Space Graph)

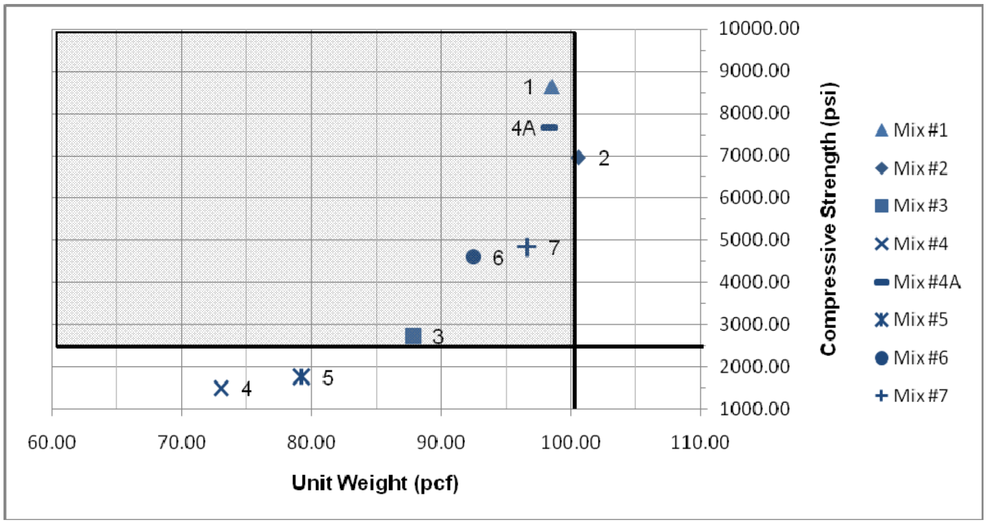
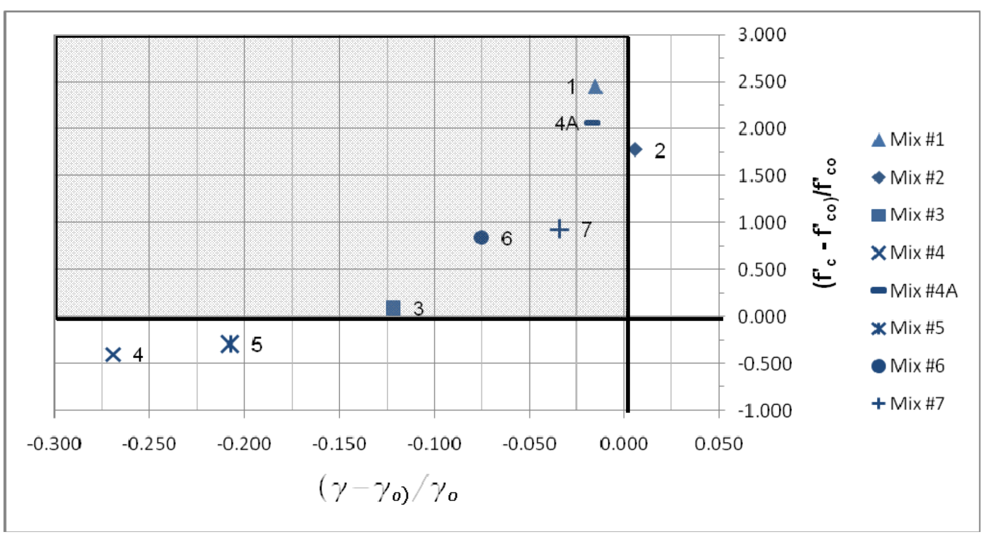


Figure 4.8 shows a solution space graph with dimensionless units. From this graph one can choose a desirable mix design within the shaded area. As the mix designs move upward and toward the origin they become more desirable. This graph, like Fig. 4.7 can be adapted to be used with many different types of mix designs. The use of the solution space graph could also be used as a decision tool for many different types of materials.

Fig. 4.8 $(\gamma - \gamma_o)/\gamma_o$ vs. $(f'_c - f'_{co})/f'_{co}$ (Dimensionless Solution Space Graph)



Chapter 5. Conclusions

ALWHPC is a viable and economical solution to reduce traditional dead loads on a structure. The reduction in dead load will ultimately reduce the size and configuration of structural systems. ALWHPC can be used in many different applications, from buildings to pavements.

- Building floor and roof slabs
- Building structural systems (girders, beams, columns)
- Road and bridge pavements
- Modular building shapes (blocks, wall panels)

The ALWHPC project produced many unique mix designs that could be used in a variety of different applications. Two mix designs were chosen from the many. Mix #1 was chosen for having the characteristics of a heavy structural concrete with the following attributes:

- γ= 98 lb/cu ft
- W/C ratio = 0.4
- Aggregate size = 1/8”x0 & 1/4”x1/8”
- f’c = 8,600 lb /sq in
- HRWR = Glenium 3030ns (BASF)
- No air entrainment

The above attributes make Mix #1 a choice for structural concrete in buildings, roads and bridges, and modular precast structural panels. One item pertaining to

Mix #1 that would have to be investigated further would be the addition of air entrainment if the concrete is exposed to the elements.

Mix #6 was the second mix that was chosen for light to medium structural concrete uses.

- γ= 92 lb/cu ft
- W/C ratio = 0.4
- Aggregate size = 1/8"x0 & 1/4"x1/8"
- f'c = 4,600 lb/sq in
- HRWR = Glenium 3030ns (BASF)
- Air entrainment = Daravair 1400 (Grace Construction Products)

The above attributes also make Mix #6 a choice for light to medium structural concrete in buildings, roads, and bridges. Unlike Mix #1, Mix #6 does incorporate air entrainment making it a viable solution to be exposed to the freeze / thaw cycle of the elements.

The development of the 'Solution Space Graph' also became an important part of the research. This tool aided in the selection of a mix design(s) within a given set of parameters. The use of this graph can also be expanded and used in other facets of construction and engineering to efficiently aid in the selection of materials or systems.

The ALWHPC research only scratched the surface of lightweight concrete mix design. With today's push to become a 'greener' community many more sustainable materials could be researched and included into mix designs. Some materials that could be researched further are: Styrofoam, glass, and rubber. All of the listed materials are recyclable and are very different in material make-up.

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Appendix A – ALWHPC Mix Designs

Note: shaded areas indicate user input

Kevin Simons	Graduate Research	Advisors: Dr. Foster and Professor Sires

Date: **5/29/2009** **Mix Design #1**

Proportioning Concrete

Volume of a cylinder				
$Volume\ (cyl) = (\pi \times h \times D^2)/4$			1728	in^3/ft^3
Volume=	**1621.06**	**in^3**	**0.94**	**ft^3**
π=	3.141592654			
h=	8	in	12	
D=	4	in	6	
no. of cyl=	4	cylinders	2	
factor=	1.5			

Total number of Test Cylinders =4-4"x8" and 2-6"x12"

From Civil Engineering Materials by Shan Somayaji 2nd ed. p.172			
Mix Proportions:			**Material Specific Gravities**
Cem't.	1		3.15
FA	0.82		1.5
CA	0.71		1.15
Wat	0.4		1
Air	0.00%		
Vol Conc	0.83	ft^3	
γ_{wat}=	62.42796	lb/ft^3	
1.885388 proportions + air			
W_{cem}=	27.5	lb	
W_{FA}=	22.6	lb	
W_{CA}=	19.7	lb	
W_{wat}=	11.0	lb	

Material Specific Gravities		**Material Unit Weights (lb/ft^3)**	**Volume (ft^3)**
Portland Cem't. (Type III) =	3.15	196.65	0.14
Regular FA =	2.64	164.81	
Regular CA =	2.68	167.31	
Buildex 1/8"x0 (FA) =	1.50	93.64	0.24
Buildex 1/4"x1/8" (CA) =	1.15	71.79	0.27
Water=	1.00	62.43	0.17
		Total=	***0.83***

Actual Amts Used		
W_{conc}=	80.67	lb
W_{cem}=	27.53	lb
W_{FA}=	22.56	lb
W_{CA}=	19.68	lb
w/c ratio=	0.40	
W_{wat}=	10.9	lb
Slump=	3.25	in

Admixtures		
Glenium 3030NS	2.0	fl oz

HRWR (4-12 fl oz/cwt of cementitious materials)

Kevin Simons	Graduate Research	Advisors: Dr. Foster and Professor Sires

Date: **6/5/2009** **Mix Design #2**

Proportioning Concrete

Volume of a cylinder				
$Volume\ (cyl) = (\pi \times h \times D^2)/4$			1728	in^3/ft^3
Volume=	**1621.06**	**in^3**	**0.94**	**ft^3**
π=	3.141592654			
h=	8	in	12	
D=	4	in	6	
no. of cyl=	4	cylinders	2	
factor=	1.5			

Total number of Test Cylinders =4-4"x8" and 2-6"x12"

From Civil Engineering Materials by Shan Somayaji 2nd ed. p.172			
	Mix Proportions:		**Material Specific Gravities**
Cem't.	1		3.15
FA	1.20		1.5
CA	0.87		1.1
Wat	0.4		1
Air	0.00%		
Vol Conc	0.96	ft^3	
γ_{wat}=	62.42796	lb/ft^3	
2.310234	*proportions + air*		
W_{cem}=	26.0	lb	
W_{FA}=	31.3	lb	
W_{CA}=	22.6	lb	
W_{wat}=	10.4	lb	

Material Specific Gravities		**Material Unit Weights (lb/ft^3)**	**Volume (ft^3)**
Portland Cem't. (Type III) =	3.15	196.65	0.13
Regular FA =	2.64	164.81	
Regular CA =	2.68	167.31	
Buildex 1/8"x0 (FA) =	1.50	93.64	0.33
Buildex 3/8"x1/4" (CA) =	1.10	68.67	0.33
Water=	1.00	62.43	0.16
		Total=	***0.96***

Actual Amts Used		
W_{conc}=	89.9	lb
W_{cem}=	26	lb
W_{FA}=	31.3	lb
W_{CA}=	22.6	lb
w/c ratio=	0.38	
W_{wat}=	10	lb
Slump=	3.75	in

Admixtures		
Glenium 3030NS	2.0	fl oz

HRWR (4-12 fl oz/cwt of cementitious materials)

Kevin Simons	Graduate Research	Advisors: Dr. Foster and Professor Sires

Date: **6/12/2009** **Mix Design #3**

Proportioning Concrete

Volume of a cylinder				
$Volume\ (cyl) = (\pi \times h \times D^2)/4$			1728	in^3/ft^3
Volume=	**1621.06**	**in^3**	**0.94**	**ft^3**
π=	3.141592654			
h=	8	in	12	
D=	4	in	6	
no. of cyl=	4	cylinders	2	
factor=	1.5			

Total number of Test Cylinders =4-4"x8" and 2-6"x12"

From Civil Engineering Materials by Shan Somayaji 2nd ed. p.172			
	Mix Proportions:		**Material Specific Gravities**
Cem't.	1		3.15
FA	1.14		1.33
CA	0.82		1.05
Wat	0.4		1
Air	0.00%		
Vol Conc	1.04	ft^3	
γ_{wat}=	62.42796	lb/ft^3	
2.359149 proportions + air			
W_{cem}=	27.5	lb	
W_{FA}=	31.3	lb	
W_{CA}=	22.6	lb	
W_{wat}=	11.0	lb	

Material Specific Gravities		**Material Unit Weights (lb/ft^3)**	**Volume (ft^3)**
Portland Cem't. (Type III) =	3.15	196.65	0.14
Regular FA =	2.64	164.81	
Regular CA =	2.68	167.31	
Buildex 1/8"x0 (FA) =	1.50	93.64	0.17
Buildex 1/8"x1/4" (FA) =	1.15	71.79	0.22
Buildex 5/8"x3/8" (CA) =	1.05	65.55	0.34
Water=	1.00	62.43	0.18
		Total=	***1.05***

W_{conc}=	92.4	lb
W_{cem}=	27.5	lb
W_{FA}=	31.3	lb
W_{CA}=	22.6	lb
w/c ratio=	0.40	
W_{wat}=	11	lb
Slump=	2.5	in

Mixed Buildex 1/8"x0 and 1/4"x1/8" half and half (used as FA)

Admixtures		
Glenium 3030NS	3.0	fl oz

HRWR (3-7 fl oz/cwt of cementitious materials)

Kevin Simons	Graduate Research	Advisors: Dr. Foster and Professor Sires

Date: **6/19/2009** **Mix Design #4**

Proportioning Concrete *for CMU Applications*

Volume of a cylinder				
$Volume\ (cyl) = (\pi \times h \times D^2)/4$			1728	in^3/ft^3
Volume=	**1621.06**	**in^3**	**0.94**	**ft^3**
π=	3.141592654			
h=	8	in	12	
D=	4	in	6	
no. of cyl=	4	cylinders	2	
factor=	1.5			

Total number of Test Cylinders =4-4"x8" and 2-6"x12"

From Civil Engineering Materials by Shan Somayaji 2nd ed. p.172			
	Mix Proportions:		**Material Specific Gravities**
Cem't.	1		3.15
FA	1.09		1.5
CA	0.86		1.15
Wat	0.3		1
Air	6.00%		
Vol Conc	0.87	ft^3	
γ_{wat}=	62.42796	lb/ft^3	
2.147779 proportions + air			
W_{cem}=	25.3	lb	
W_{FA}=	27.6	lb	
W_{CA}=	21.9	lb	
W_{wat}=	7.6	lb	

Material Specific Gravities		**Material Unit Weights (lb/ft^3)**	**Volume (ft^3)**
Portland Cem't. (Type III) =	3.15	196.65	0.13
Regular FA =	2.64	164.81	
Regular CA =	2.68	167.31	
Buildex 1/8"x0 (FA) =	1.50	93.64	0.30
Buildex 1/4"x1/8" (CA) =	1.15	71.79	0.30
Water=	1.00	62.43	0.12
		Total=	***0.85***

Actual Amts Used		
W_{conc}=	82.46	lb
W_{cem}=	25.34	lb
W_{FA}=	27.64	lb
W_{CA}=	21.88	lb
w/c ratio=	0.30	
W_{wat}=	7.6	lb
Slump=	6.5	in

Admixtures			
Glenium 3030NS	2.0	fl oz	*HRWR (4-12 fl oz/cwt of cementitious materials)*
Daravair 1400	0.25	fl oz	*Air Entrainer*

Kevin Simons	Graduate Research	Advisors: Dr. Foster and Professor Sires

Date: **6/19/2009**

Mix Design #4A

for CMU Applications

(Trial Mix w/ Professor Sires)

Proportioning Concrete

Volume of a cylinder				
$Volume\ (cyl) = (\pi \times h \times D^2)/4$			1728	in^3/ft^3
Volume=	**604.80**	**in^3**	**0.35**	**ft^3**
π=	3.141592654			
h=	8	in	12	
D=	4	in	6	
no. of cyl=	4	cylinders	0	
factor=	1.50			

Total number of Test Cylinders =4-4"x8" and 2-6"x12"

From Civil Engineering Materials by Shan Somayaji 2nd ed. p.172			
	Mix Proportions:		**Material Specific Gravities**
Cem't.	1		3.15
FA	0.48		1.5
CA	0.86		1.15
Wat	0.3		1
Air	4.00%		
Vol Conc	0.35	ft^3	
γ_{wat}=	62.42796	lb/ft^3	
1.700515	*proportions + air*		
W_{cem}=	12.8	lb	
W_{FA}=	6.2	lb	
W_{CA}=	11.1	lb	
W_{wat}=	3.9	lb	

Material Specific Gravities		**Material Unit Weights (lb/ft^3)**	**Volume (ft^3)**
Portland Cem't. (Type III) =	3.15	196.65	0.06
Regular FA =	2.64	164.81	
Regular CA =	2.68	167.31	
Buildex 1/8"x0 (FA) =	1.50	93.64	0.07
Buildex 1/4"x1/8" (CA) =	1.15	71.79	0.15
Water=	1.00	62.43	0.06
		Total=	***0.34***

Actual Amts Used		
W_{conc}=	33.47	lb
W_{cem}=	12.67	lb
W_{FA}=	6.1	lb
W_{CA}=	10.9	lb
w/c ratio=	0.30	
W_{wat}=	3.8	lb
Slump=	4	in

Admixtures			
Glenium 3030NS	2.0	fl oz	*HRWR (4-12 fl oz/cwt of cementitious materials)*
Daravair 1400	0.25	fl oz	*Air Entrainer*

Kevin Simons	Graduate Research	Advisors: Dr. Foster and Professor Sires

Date: **6/26/2009** **Mix Design #5**

Proportioning Concrete *for CMU Applications*

Volume of a cylinder				
$Volume\ (cyl) = (\pi \times h \times D^2)/4$			1728	in^3/ft^3
Volume=	**1729.13**	**in^3**	**1.00**	**ft^3**
π=	3.141592654			
h=	8	in	12	
D=	4	in	6	
no. of cyl=	4	cylinders	2	
factor=	1.6			

Total number of Test Cylinders =4-4"x8" and 2-6"x12"

From Civil Engineering Materials by Shan Somayaji 2nd ed. p.172

	Mix Proportions:		**Material Specific Gravities**
Cem't.	1		3.15
FA	1.2		1.5
CA	1.1		1.15
Wat	0.3		1
Air	5.00%		
Vol Conc	1	ft^3	
γ_{wat}=	62.42796	lb/ft^3	
2.423982 proportions + air			
W_{cem}=	25.8	lb	
W_{FA}=	30.9	lb	
W_{CA}=	28.3	lb	
W_{wat}=	7.7	lb	

Material Specific Gravities		**Material Unit Weights (lb/ft^3)**	**Volume (ft^3)**
Portland Cem't. (Type III) =	3.15	196.65	0.13
Regular FA =	2.64	164.81	
Regular CA =	2.68	167.31	
Buildex 1/8"x0 (FA) =	1.50	93.64	0.33
Buildex 1/4"x1/8" (CA) =	1.15	71.79	0.39
Water=	1.00	62.43	0.14
		Total=	***0.99***

Actual Amts Used		
W_{conc}=	93.2	lb
W_{cem}=	25.6	lb
W_{FA}=	30.7	lb
W_{CA}=	28.2	lb
w/c ratio=	0.34	
W_{wat}=	8.7	lb
Slump=	5.5	in

Admixtures		
Glenium 3030NS	2.0 fl oz	*HRWR (4-12 fl oz/cwt of cementitious materials)*
Daravair 1400	0.25 fl oz	*Air Entrainer*

Kevin Simons	Graduate Research	Advisors: Dr. Foster and Professor Sires

Date: **7/3/2009** **Mix Design #6**

Proportioning Concrete *for CMU Applications*

Volume of a cylinder				
$Volume\ (cyl) = (\pi \times h \times D^2)/4$			1728	in^3/ft^3
Volume=	**1729.13**	**in^3**	**1.00**	**ft^3**
π=	3.141592654			
h=	8	in	12	
D=	4	in	6	
no. of cyl=	4	cylinders	2	
factor=	1.6			

Total number of Test Cylinders =4-4"x8" and 2-6"x12"

From Civil Engineering Materials by Shan Somayaji 2nd ed. p.172

	Mix Proportions:		**Material Specific Gravities**
Cem't.	1		3.15
FA	1.2		1.5
CA	1.1		1.15
Wat	0.4		1
Air	5.00%		
Vol Conc	1	ft^3	
γ_{wat}=	62.42796	lb/ft^3	
2.523982	*proportions + air*		
W_{cem}=	24.7	lb	
W_{FA}=	29.7	lb	
W_{CA}=	27.2	lb	
W_{wat}=	9.9	lb	

Material Specific Gravities		**Material Unit Weights (lb/ft^3)**	**Volume (ft^3)**
Portland Cem't. (Type III) =	3.15	196.65	0.13
Regular FA =	2.64	164.81	
Regular CA =	2.68	167.31	
Buildex 1/8"x0 (FA) =	1.50	93.64	0.33
Buildex 1/4"x1/8" (CA) =	1.15	71.79	0.39
Water=	1.00	62.43	0.16
		Total=	***1.01***

Actual Amts Used		
W_{conc}=	94.74	lb
W_{cem}=	25.6	lb
W_{FA}=	30.7	lb
W_{CA}=	28.2	lb
w/c ratio=	0.40	
W_{wat}=	10.24	lb
Slump=	5.5	in

Admixtures			
Glenium 3030NS	2.0	fl oz	*HRWR (4-12 fl oz/cwt of cementitious materials)*
Daravair 1400	0.25	fl oz	*Air Entrainer*

Kevin Simons	Graduate Research	Advisors: Dr. Foster and Professor Sires

Date: **8/10/2009** **Mix Design #7**

Proportioning Concrete *for CMU Applications*

Volume of a cylinder

$Volume\ (cyl) = (\pi \times h \times D^2)/4$			1728	in^3/ft^3
Volume=	**1729.13**	**in^3**	**1.00**	**ft^3**
π=	3.141592654			
h=	8	in	12	
D=	4	in	6	
no. of cyl=	4	cylinders	2	
factor=	1.6			

Total number of Test Cylinders =4-4"x8" and 2-6"x12"

From Civil Engineering Materials by Shan Somayaji 2nd ed. p.172

	Mix Proportions:		**Material Specific Gravities**
Cem't.	1		3.15
FA	1.2		1.5
CA	1.1		1.15
Wat	0.3		1
Air	5.00%		
Vol Conc	1	ft^3	
γ_{wat}=	62.42796	lb/ft^3	
2.423982	*proportions + air*		
W_{cem}=	25.8	lb	
W_{FA}=	30.9	lb	
W_{CA}=	28.3	lb	
W_{wat}=	7.7	lb	

Material Specific Gravities		**Material Unit Weights (lb/ft^3)**	**Volume (ft^3)**
Portland Cem't. (Type III) =	3.15	196.65	0.09
FlyAsh (Type C)=	2.60	162.31	0.04
Regular FA =	2.64	164.81	
Regular CA =	2.68	167.31	
Buildex 1/8"x0 (FA) =	1.50	93.64	0.33
Buildex 1/4"x1/8" (CA) =	1.15	71.79	0.39
Water=	1.00	62.43	0.13
		Total=	***0.98***

Actual Amts Used		
W_{conc}=	91	lb
W_{cem}=	17.5	lb
W_{flyash}=	7	lb
W_{FA}=	30.5	lb
W_{CA}=	28	lb
w/c ratio=	0.33	
W_{wat}=	8	lb
Slump=	6.5	in

Admixtures			
Glenium 3030NS	3.0	fl oz	*HRWR (4-12 fl oz/cwt of cementitious materials)*
Daravair 1400	0.25	fl oz	*Air Entrainer*

Appendix B – Concrete Strength Results

Concrete Strength
Cylinder compression tests without strain measurements
University of Nebraska - Summer 2009

Loading Rate = 35 psi/second

$Area\ (circle\ ) = (\pi \times D^2)/4$ Cylinders = 4"x8" and 6"x12"

$Volume\ (cyl\ ) = (\pi \times h \times D^2)/4$ Vol (6x12) cyl = 0.196 Vol (4x8) cyl = 0.058 π= 3.141592654

Cylinder Number	Age (days)	Diameter (inches)	Area (in^2)	Failure Load (lb)	Failure Stress (lb/in^2)	Weight (lb)	Density (lb/ft^3)	Mix Date	Test Date
Mix 1 - #1	7	4	12.57	100740	8016.63	5.87	100.90	5/29/2009	6/5/2009
Mix 1 - #2	14	4	12.57	94960	7556.68	5.70	97.98		6/12/2009
Mix 1 - #3	28	4	12.57	108510	8634.95	5.73	98.49		6/26/2009
Mix 1 - #4		4	12.57						
Mix 1 - #5	14	6	28.27			18.25	92.95		6/12/2009
Mix 1 - #6	28	6	28.27			18.21	92.74		6/26/2009
Mix 2 - #1	7	4	12.57	98650	7850.32	6.01	103.30	6/5/2009	6/12/2009
Mix 2 - #2	14	4	12.57	89740	7141.28	5.79	99.52		6/19/2009
Mix 2 - #3	28	4	12.57	87320	6948.70	5.85	100.55		7/3/2009
Mix 2 - #4		4	12.57	92390	7352.16	5.94	102.10		
Mix 2 - #5	14	6	28.27			20.02	101.96		6/19/2009
Mix 2 - #6	28	6	28.27			20.11	102.42		7/3/2009
Mix 3 - #1	7	4	12.57	33360	2654.70	5.30	91.10	6/12/2009	6/19/2009
Mix 3 - #2	14	4	12.57	20880	1661.58	5.16	88.69		6/26/2009
Mix 3 - #3	28	4	12.57	34330	2731.89	5.11	87.83		7/10/2009
Mix 3 - #4		4	12.57			5.08	87.32		
Mix 3 - #5	14	6	28.27			17.29	88.06		6/26/2009
Mix 3 - #6	28	6	28.27			17.14	87.29		7/10/2009
Mix 4 - #1	7	4	12.57	18340	1459.45	4.41	75.80	6/19/2009	6/26/2009
Mix 4 - #2	14	4	12.57	21800	1734.79	4.46	76.66		7/3/2009
Mix 4 - #3	28	4	12.57	18740	1491.28	4.25	73.05		7/17/2009
Mix 4 - #4		4	12.57	23790	1893.15	4.56	78.38		
Mix 4 - #5		4	12.57			4.40	75.63		
Mix 4 - #6		4	12.57			4.34	74.60		
Mix 4 - #7		4	12.57	21330	1697.39	4.25	73.05		
Mix 4 - #8		4	12.57			4.35	74.77		
Mix 4 - #9	14	6	28.27			14.62	74.46		7/3/2009
Mix 4 - #10	28	6	28.27			14.01	71.35		7/17/2009
Mix 4A - #1	7	4	12.57	92390	7352.16	5.86	100.73	6/19/2009	6/26/2009
Mix 4A - #2	14	4	12.57	93460	7437.31	5.70	97.98		7/3/2009
Mix 4A - #3	28	4	12.57	96240	7658.54	5.72	98.32		7/17/2009
Mix 5 - #1	7	4	12.57	19260	1532.66	4.70	80.79	6/26/2009	7/3/2009
Mix 5 - #2	14	4	12.57	22940	1825.51	4.69	80.62		7/10/2009
Mix 5 - #3	28	4	12.57	22190	1765.82	4.61	79.24		7/24/2009
Mix 5 - #4		4	12.57	25090	1996.60	4.72	81.13		
Mix 5 - #5	14	6	28.27			15.68	79.86		7/10/2009
Mix 5 - #6	28	6	28.27			15.82	80.57		7/24/2009
Mix 5 - #7		4	12.57						
Mix 6 - #1	7	4	12.57	58240	4634.59	5.40	92.82	7/3/2009	7/10/2009
Mix 6 - #2	14	4	12.57	50910	4051.29	5.47	94.02		7/17/2009
Mix 6 - #3	28	4	12.57	57870	4605.15	5.38	92.48		7/31/2009
Mix 6 - #4		4	12.57	44800	3565.07	5.25	90.24		
Mix 6 - #5		4	12.57			5.20	89.38		
Mix 6 - #6	14	6	28.27			18.67	95.09		7/17/2009
Mix 6 - #7	28	6	28.27			18.45	93.97		7/31/2009
Mix 7 - #1	7	4	12.57	44260	3522.10	5.54	95.23	8/10/2009	8/17/2009
Mix 7 - #2	14	4	12.57	51360	4087.10	5.60	96.26		8/24/2009
Mix 7 - #3	28	4	12.57	60750	4834.33	5.62	96.60		9/7/2009
Mix 7 - #4		4	12.57	54370	4326.63	5.58	95.91		
Mix 7 - #5	14	6	28.27			18.72	95.34		8/24/2009
Mix 7 - #6	28	6	28.27			18.83	95.90		9/7/2009

Mix #1 = portland cement (Type III), water, Buildex aggregates (1/8"x0 & 1/4"x1/8")
Mix #2 = portland cement (Type III), water, Buildex aggregates (1/8"x0 & 3/8"x1/4")
Mix #3 = portland cement (Type III), water, Buildex aggregates (1/8"x0 , 1/4"x1/8" ,& 5/8"x3/8")
Mix #4 = portland cement (Type III), water, Buildex aggregates (1/8"x0 , 1/4"x1/8"), Air Entrainer, HRWR
Mix #4A = portland cement (Type III), water, Buildex aggregates (1/8"x0 , 1/4"x1/8"), Air Entrainer, HRWR
Mix #5 = portland cement (Type III), water, Buildex aggregates (1/8"x0 & 1/4"x1/8"), Air Entrainer, HRWR
Mix #6 = portland cement (Type III), water, Buildex aggregates (1/8"x0 & 1/4"x1/8"), Air Entrainer, HRWR
Mix #7 = portland cement (Type III), Flyash (Type C), water, Buildex aggregates (1/8"x0 & 1/4"x1/8"), Air Entrainer, HRWR