STRUCTURAL BEHAVIOR OF LIGHTWEIGHT CONCRETE WALL PANELS IN TILT-UP CONSTRUCTION

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
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To Allah for the support I have been blessed with and to my family

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Major: Design, Construction and Planning

In tilt-up wall construction, normal weight concrete is usually poured on top of a floor slab, and then lifted into place by cranes when the wall gains an adequate strength. Prior to lifting a panel, it is required by the ACI 551.2R-10 guide and the inserts manufacturers that compressive and flexural strengths of the concrete testing are performed on samples retained in the field to validate that the wall has attained the required strength.

In this study, the commonly used normal weight concrete in tilt-up constructions was replaced with structural lightweight concrete for its advantageous properties. Furthermore, non-destructive testing methods – maturity and pullout tests- were applied to evaluate the strength of concrete at early age. Although all maturity methods were found to be an effective tool to predict the compressive and flexural strengths of in-place concrete at time of lifting, the equivalent age maturity method was found to be superior to the temperature-time factor maturity method.

The pullout strength method was also used to evaluate the in-place compressive and flexure strengths of the tilt-up wall, and was found effective.

Hence, relationships between the various maturity methods and the pullout strength were derived to provide a better method of estimating the compressive and flexural strength of the lightweight concrete.

In addition, a small scale tilt-up panel (10 feet by 9 feet) was constructed with surface mount strain gages in order to examine the strains and stresses of the panel during lifting. The measured strains and stresses were compared to those obtained from statics calculations and two commercial software programs. They were also compared to strains and stresses of a normal weight concrete.

CHAPTER 1
INTRODUCTION

Definition of Tilt-up Walls

Tilt-up is a method for constructing concrete walls that have been cast horizontally on a building's concrete floor or a temporary concrete casting surface near the building. The walls are lifted by cranes to their final position in the structure, when the concrete reaches or exceeds the specified compressive and flexural strength as interior or exterior load baring walls. Basically, it is a method of site casting precast concrete walls.

The ACI committee 551 defines the Tilt-up as "a construction technique for casting concrete elements in a horizontal position at the jobsite and then tilting them to their final position in a structure" (ACI.551 2010).

Background

Due to the numerous benefits of tilt-up construction, it is one of the fast growing construction methods in the world. In 2007, approximately 790 million square feet of tilt-up buildings were constructed based on a survey conducted by the Tilt-Up Concrete Association. (TCA 2011)

The ACI 551 committee report "Design Guide to Concrete Tilt-Up Panels" indicates that the compressive and tensile strength of the concrete are major factors in designing tilt-up walls. It states that a minimum concrete compressive strength of 3000 psi is required at 28-days. Also the lifting inserts manufacturers call for a compressive strength of 2500 psi at the day of lift; thus a higher 28-day compressive strength is normally desired. In addition, a minimum flexural strength of concrete of 400-500 psi is normally specified to prevent flexural cracking during lifting.(ACI.551 2010)

Another major design factor in tilt-up walls is the self-weight or dead load of the panel. The self-weight represents a significant contribution to internal forces and the P-Δ moments in thin wall sections. The self-weight of the wall upper half is considered an axial loads acting downwards on the wall.

Research Objectives

The Scope of the project is to investigate the strength and behavior of the lightweight concrete tilt-up panels. The objectives of this research are mainly:

1. Study the overall structural effectiveness of the lightweight concrete in tilt-up construction.
2. Estimate the compressive and flexural strengths of lightweight concrete tilt-up panel using Temperature-Time Factor (TTF) maturity method also known as Nurse-Saul maturity method.
3. Estimate the compressive and flexural strengths of lightweight concrete tilt-up panel using Equivalent Age (EA) maturity method based on Arrhenius equation.
4. Estimate the compressive and flexural strengths of lightweight concrete tilt-up panel using pullout strength test.
5. Determine new correlation formulas between the compressive and flexural strengths of lightweight concrete tilt-up panel by performing maturity testing and pullout testing.
6. Determine the actual strains and stresses developed in tilt-up wall panel during lifting, and compare them to stresses obtained from statics calculations and commercial software.
7. Compare the results of the lightweight concrete tilt-up panel to a normal density concrete panel.
8. Provide recommendations for the lightweight concrete tilt-up walls.

Research Approach

Compressive and flexural strengths of concrete are determined using different mechanical test methods that require the breaking of sample concrete cylinders and beams. In this research, semi-destructive and non-destructive tests were utilized to evaluate the strength of concrete used in tilt-up walls construction for a specific lightweight concrete mix design.

In addition, a tilt-up panel was designed and constructed with a lightweight concrete. The wall was instrumented with surface mount strain gages to measure the strains where the maximum negative and positive bending moments are expected due to lifting. The stresses due to lifting were compared with the statically calculated stresses and stresses obtained from two commercial software programs.

The strains and stresses were also compared with those of the normal density concrete to determine the structural efficiency of using lightweight concrete in tilt-up construction.

The following tests were conducted:

- Compressive strength.(ASTM-C39 2011a)
- Flexural strength.(ASTM-C78 2010)
- Temperature-Time Factor Maturity Method.(ASTM-C1074 2011)
- Equivalent Age Maturity Method.(ASTM-C1074 2011)
- Pullout strength.(ASTM-C900 2006)
- Density of concrete.(ASTM-C567 2005a)
- Slump test.(ASTM-C143 2005)
- Air content. (ASTM-C173 2001)

Research Significance

The application of structural lightweight concrete in tilt-up walls seems more logical than the use of normal weight concrete due to its advantageous lightweight properties. Yet there has not been any study on the structural effectiveness of structural lightweight concrete for tilt-up applications.

Furthermore, the use of various nondestructive and semi-destructive methods of estimating concrete compressive and flexural strengths reflects onsite strengths of concrete rather than a lab cured test specimens. This research investigated the use of multiple methods of evaluating the strength of concrete to reach a higher level of confidence.

Dissertation Outline

Chapter 1 covers a general introduction to tilt-up construction, research objectives, approach and significance. Review of literature is summarized in Chapter 2 with an overview of the history of tilt-up walls construction. It also includes structural lightweight concrete mix design specifications and their advantages. In addition, different maturity methods are discussed followed by the pullout strength test and strain gauging concrete structural elements. Chapter 3 demonstrates the testing methodology for fresh and hardened concrete as well as lightweight concrete mix design. It also outlines the different methods used to estimate the strength of the lightweight concrete. Different maturity methods and pullout tests were analyzed in Chapters 4 and 5 respectively. Maturity methods and pullout strength relationships are discussed in Chapter 6. Chapter 7 demonstrates the tilt-up wall design and construction in addition to the behavior of the tilt-up panel during lifting. It also includes calculations of bending moments developed due to lifting. Chapter 8 examines the strain patterns of the lightweight concrete tilt-up wall. It analysis the stresses and compare them to the expected results. Also, a comparative study on the strength and stiffness of lightweight versus normal density concrete is conducted. Chapter 9 draws conclusions and gives recommendations for future studies.

CHAPTER 2
LITERATURE REVIEW

History of Tilt-Up

Tilt-up construction is a very old trade. It was 2000 years ago that Roman builders discovered that tilting-up a wall after casting it horizontally on the ground is a much practical than pouring concrete walls in formwork and then stripping them. (TCA, 2006)

In the US Camp Logan, IL was the first known structure built with the modern tilt-up construction techniques. It was constructed in 1893 by Robert H. Aiken who is known as the father of tilt-up. He poured reinforced concrete walls horizontally on a flat surface and used tipping tables to place them into their final position in the structure. Other projects followed namely, the Memorial United Methodist Church of Zion, IL built 1906 and the Camp Perry Commissary Building, OH built in 1908 by Aiken stand witness of the durability of the tilt-up construction method (Superior 2009). Maura Johnson, an architectural historian, claims that the Camp Perry Mess Hall was the first permanent structure constructed using the tilt-up construction method in 1909. It was constructed using tipping tables with supporting jacks, 3 feet off the ground. The tables were positioned in a way that the walls were tipped into their permanent locations when the tables are raised (Figure 2-1). Aiken utilized a 5 horsepower engine to swing the tipping tables that were removed after the walls are braced. He also built a concrete factory which he considered “the first complete building of this type of construction.” by casting the concrete walls on a smooth sand bed before tipping them on the buildings’ footings by “block-and-pulley derricks and horsepower.” (Johnson 2002)

Irving Gill, a San Diego based architect, took over Aiken’s company and the tilt-up patent when he went bankrupt during the construction of Camp Perry. Gill was influenced by Adler & Sullivan when he worked with them during his early career. He took the tilt-up construction system to a higher level by applying great artistic expression. Gill used the same table tipping technique to build the La Jolla Women's Club in 1914. He designed the porch are using arches to contrast sunlight with shadows and shadings (Figure 2-2). (TCA 2011)

Another early example of innovation of tilt-up is the Schindler House also known as Kings Road House completed in 1922. Rudolf M Schindler became familiar with the technique in his early career in Chicago, when he worked with Gill. Schindler's houses were considered the modern landmarks of the modernist movement. "In his own house, Schindler expressed his philosophy about structure and materials most clearly, but the entire site demonstrates his exploration of the relationship of space, light, and form." (Greatbuildings.com)

The design of the Kings Road House employed a 4ft wide tilt-up panel which was first rejected by the building department due to the official's unfamiliarity with the building system. After many discussions, the building department agreed under the condition of suspending the construction at any point. Schindler agreed on the condition which resulted on an iconic design, one of the first modernist homes in southern California (Figure 2-3). (Greatbuildings.com 2012)

The tilt-up industry deteriorated during the World War I due to the shortage of manpower and steel. Past World War II, major developments to the tilt-up system industry came with the availability of heavy cranes that were able to haul larger sections of walls. Other factors were the huge demand for warehouses and manufacturing plants which were typical and ideal for tilt-up construction during the mid of the 20th century.

The tilt-up industry grew from $2 million in 1946 to $180 million in 1952 (TCA 2011). Nowadays, tilt-up construction is a fast inexpensive method of constructing any low-rise building. In the 2007 survey conducted by the Tilt-Up Concrete Association (TCA), approximately 790 million square feet of tilt-up structure were built in that year and 15% of all low-rise commercial and industrial were constructed with tilt-up system. (TCA 2011)

Structural Lightweight Concrete

The ACI Committee 213 defines the structural lightweight concrete as the concrete with a minimum compressive strength of 2500 psi at 28 days with a density of 70-120 pounds per cubic feet. It may entirely consist of lightweight aggregate or a combination of light and normal weight aggregate.

Background

Lightweight concrete can be dated back to over 2000 years ago. The lightweight concrete structures were used during the early Roman Empire. For example, the Pantheon, and the Coliseum, natural volcanic materials were crushed and used in the making of lightweight concrete. The Pantheon, completed in 27 B.C., used concrete with different densities in different section of the dome. The Coliseum foundations, built in 75 to 80 A.D., were cast with lightweight concrete using crushed volcanic lava. “After the fall of the Roman Empire, the use of lightweight concrete was limited until the 20th century when a new type of manufactured, expanded shale, lightweight aggregate became available for commercial use.”(ACI.213 2003)

The rotary kiln process of expanding slate, shale and clay was patented in 1918 by Stephen J. Hayde, who was a brick manufacturer and ceramic engineer. However, the expanded slag became commercially available in 1928, whereas the sintered-shale lightweight aggregate became available in 1948. During the 1950s, many multistory buildings were entirely designed using lightweight concrete taking advantage of the reduced dead weight. (ACI.213 2003)

Economy of Lightweight Concrete

Generally, the cost of the lightweight concrete per cubic yard is higher than same strength normal weight concrete. However, the extra cost can be offset by the reduction in dead loads which would result in smaller foundations and other structural elements such as beams, girders, slabs, staircases, shear walls and columns. In addition to its fire resistance and acoustic advantages, the use of lightweight concrete is also beneficial for thermally sensitive applications like water tanks, nuclear reactors, petroleum storages or building insulations.

Lightweight Aggregates

Cellular pore system and air voids of the lightweight aggregate keep the relative density of the particles low. The Heating of certain raw materials at high temperatures makes gases escape causing expansion in the raw materials. Structural lightweight aggregates should conform to the Standard Specification for Lightweight Aggregates for Structural Concrete (ASTM-C330 2009). They should also contain a uniformly distributed system of pores ranging from 5 to 300 µm in size.

Surface pores are permeable and can be saturated in the first few hours of the introduction of moisture. On the other hand, internal pores saturate slowly, it could take several months of submerging to reach full saturation. Generally, a small fraction of interior pores are not interconnected and remain dry even after years of submerging. Also, shape and texture of lightweight aggregates may considerably differ due to different sources, or different production methods. This may affect the proportioning of mixtures which affect workability, pumpability, fine-to-coarse aggregate ratio, and water requirement.(ACI.213 2003)

Fire Resistance

Thermal conductivity is directly proportional to thermal diffusivity, specific heat and density. Conductivity and diffusivity variation is relatively small in specific heat with temperature. However the density of the concrete is the overall important variable due to air voids. Thus, lightweight concrete is superior in heat resistance as compare with normal concrete and has significantly lower thermal conductivity and thermal expansion. Figure 2-4, illustrates the fire endurance of different density concrete.

Internal Curing

The ACI committee 308, Guide to Curing Concrete, defines curing as “the process by which hydraulic-cement concrete matures and develops hardened properties over time as a result of the continued hydration of the cement in the presence of sufficient water and heat.”(ACI.308 2001)

Curing process should be made available as soon as the finishing of concrete is completed. In the standard curing for normal weight concrete, moisture is applied to the concrete surface only. In addition to the surface curing, lightweight concrete is characterized by internal curing; where internal curing is defined by ACI 213 as the process by which the hydration of cement continues due to the availability of internal water (ACI.213 2003).

Most expanded lightweight aggregates have the ability to absorb 15% or more water by weight. The absorbed water is readily available to hydrate cement deprived of water especially in low w/c ratio lightweight concrete. As the lightweight concrete sets during the initial hydration and as localized areas become deficient of water, the absorbed water in the large pores of the lightweight aggregates act as replacement of the mixing water and/or it hydrates the dry cement particles. The absorbed water is drawn by gravity or capillary force from its pores, therefore extending the curing period internally (Figure 2-5).

This process promotes the early age strength of the concrete, which is crucial for tilt-up construction. It also eliminates/ minimizes shrinkage cracking and reduces the permeability of the concrete. This process of hydrating the cement internally carries on at later ages as well. (ACI.213 2003)

Modulus of Elasticity

The modulus of each concrete component such as mortar and aggregates, affect the overall modulus of elasticity of the concrete. Normal concrete has a higher modulus of elasticity than the lightweight concrete due to the higher modulus of the natural coarse aggregates (Lamond 2006). The lightweight concrete's modulus of elasticity is ½ to ¾ that of the same strength normal concrete (Figure 2-6 and Figure 2-7) which means that the lightweight concrete is more flexible.

ACI 318-2011, Building Code Requirements for Structural Concrete, permit the use of the formula below to obtain the modulus of elasticity for any concrete with density between 90 and 160 lbs. /ft^3 and compressive strength between 3000 and 5000 psi or to be taken as $57{,}000\sqrt{f'c}$. However, the actual value of the modulus of elasticity may vary by up to 20%. (ACI.213 2003)

$$Ec = Wc^{1.5} 33\sqrt{f'c} \tag{2-1}$$

Nevertheless, in other section of the ACI 318-2011, a reduction factor λ = 0.85 is multiplied by $\sqrt{f'c}$ for the sand-lightweight concrete. This factor accounts for the lower tensile strength of the lightweight concrete. (ACI.318 2011)

Modulus of Rupture

The tensile strength is a function of the tensile strength of the coarse aggregate and mortar, and the bond between them. The tensile strength is traditionally defined as a function of the compressive strength, but this is an approximation and does not reflect the surface condition, the moisture of content, distribution and most importantly the aggregate strength (Lamond 2006). The ACI committee 213 states that tensile strength of the lightweight concrete may not increase in a manner comparable with the compressive strength increase especially in high strength lightweight concrete. Figure 2-8, shows that lighter density concrete have a wider range of modulus of rupture than of the normal density concrete. The equation below describes the modulus of rupture (f_r) as a function of the compressive strength of concrete (f'_c), where λ is the lightweight concrete reduction factor. (ACI.318 2011)

$$f_{\mathrm{r}} = 7.5\, \lambda\sqrt{f'c} \tag{2-2}$$

Tilt-up and Lightweight Structural Concrete

No literature has been found to shed a light on the effects of the lightweight concrete on the tilt-up wall system. One important factor that influences the tilt-up wall system is self-weight. This is due to the significant contribution that self-weight has in the P-Δ moments in walls (Figure 2-9). ACI 551-2010, considers the self-weight of the panel's top half as additional concentrated axial load acting downwards at mid-height (Figure 2-10).

The Tilt-up Construction Product Handbook, by Dayton Superior, suggests a reduction factor of 0.85 for the lightweight concrete when calculating the allowable tensile stress. Another reduction factor of 0.70 is suggested when calculating for the lifting inserts. (Superior 2009)

Maturity

The strength of concrete is a result of exothermic chemical reactions between the cement and the water in the mixture. The (hydration) reaction is a function of temperature, the higher the temperature of the concrete, the higher the reaction rate. In addition, the hydration reaction itself generates heat leading to a faster gaining of strength in the concrete. (ACI.228 2003)

The maturity is a method of tracking the temperature and time of the concrete to estimate the strength of the in-place concrete. The thermal history of the concrete is used through mathematical equations to calculate the maturity index. As mentioned earlier, the rate of hydration depends on the amount of cementitious materials and water. Thus, each concrete design mixture has a unique maturity index. (Carino 2008)

In 1940, the maturity method was developed by McIntosh, Nurse and Saul. The function was developed to account for the temperature history. Nevertheless, in 1977 another function (equivalent age) was developed based on Arrhenius equation that considers the temperature effect of the reaction rate. It measures the maturity index of a certain time and compares it to and equivalent age at a reference temperature, normally 20°C.

Nowadays, Maturity method of estimating the strength of concrete is widely used in concrete pavement construction to decide on the appropriate time to open road pavement to traffic. It is also used for form stripping, removal of Shoring and re-shoring, post-tensioning, loading structures, saw-cutting and harvesting pre-cast members. Hence, maturity method can equally well be applied to estimate the strength of the concrete before lifting a tilt-up panel.

Nurse–Saul Maturity Method

Nurse-Saul maturity method, currently known as Temperature-Time Factor, was based on empirical observations. It was developed under the assumption that for certain mixture of concrete two samples with the same maturity would have the same strength regardless of curing conditions (Figure 2-11).

Calculation of the Temperature-Time Factor requires the calculation of the datum temperature. It is the lowest temperature at which the hydration reaction occurs. In hot weather areas, the datum temperature can be assumed to equal 0° C unless a high accuracy estimate of the concrete strength is required. In such a case, ASTM C 1074-2011 procedure for calculating the datum temperature is preferable.

Figure 2-12 illustrates that the temperature-time factor (maturity index) is calculated by recording the area between the temperature curve and the datum temperature. (ASTM-C1074 2011)

Equivalent Age

The equivalent age is defined as "the number of days or hours at a specified temperature required to produce a maturity equal to the maturity achieved by a curing period different from the specified temperature." (ASTM-C1074 2011)

The equivalent age exponential function follows the rules of the Arrhenius equation that describes the rate of the reaction based on the thermal properties. It converts the actual age of the concrete to an equivalent age at a specified temperature. The calculation of the Equivalent Age requires the value of activation energy or the energy needed for the molecule to generate a reaction. It depends on the cement type, admixture and water/cement ratio. Generally, for type I cement without admixtures, the value of the activation energy is between 40,000-45,000 J/mol. (ASTM-C1074 2011)

It has been investigated that the equivalent age maturity method is more accurate in describing the effect of temperature on concrete strength over a wider range of temperatures than the temperature-time factor method. It overcomes the linear approximation of the Nurse-Saul equation.

Figure 2-13 further illustrates the effect of different activation energy values at different temperatures. It also shows that for a low activation energy concrete, the temperature-time factor is an accurate method of estimating the strength of concrete. However, for higher activation energy and wider spread of temperature range, the equivalent age method is superior. Despite these facts, both functions fail to account for the effects of early-age temperature.(Carino 2008)

COMA Meter

The COMA meter is a disposable glass capillary tube containing a liquid for which the rate of evaporation varies according to the Arrhenius equation. The tube has a scale from 0 to 14 days which reflects the maturity of the concrete according to the equivalent age factor with a reference temperature of 20˚ C and activation energy of 40 KJ/mol. The value of the activation energy of the COMA meter (40 KJ/mol) was determined based on various studies. The studies concluded that the activation energy is proportional to temperature and that for concrete temperature between 5-43˚ C, the average activation energy is 37-39 KJ/mol. (Hansen 1982)

The capillary tube is to be activated by breaking the tube at 0 days and then pressed into the fresh concrete in a container. The maturity is measured by removing the capillary tube from its container and reading the level of the liquid against the scale (Figure 2-14). The tube can be placed back into the container for further monitoring if the required maturity is not achieved.

Pullout

The pullout test originated in the Soviet Union around 1938, but the test mainly measures the tensile strength of the concrete based on the factures mechanism and not the compressive strength. In1962, Danish Lok- meaning punch-out, was developed to estimate the in situ strength of concrete. It measures the power required to pull out a metal disk embedded in the fresh concrete. The measured force can then be used to estimate the compressive and tensile strength of the concrete. It is considered a semi-destructive test due to the damage incurred by pullout testing, however good patching of the tested concrete is achievable.

The test that is most commonly used in industry today is the pullout test as modified by Kaindl in the 1970’s. The metal disk is pulled using a jack reacting with a bearing ring pushing against the concrete (Figure 2-15 and Figure 2-16). The pullout strength is measured by the maximum force require to fracture the concrete by pulling on the metal insert or by loading the disk to the required threshold. The force exerted provides an approximation of the concrete's compressive, tensile and shear strengths. (Stone, Carino et al. 1986)

Commercial metal inserts are available with depths ranging from 1 to 1.2 in. Thus, only the surface of the concrete is tested. Therefore, 7 to 10% variation within the same patch is expected (ACI.228 2003). Consistent empirical correlations can be established between strength properties and pullout test methods. Lightweight concrete utilize different empirical correlations than the normal weight concrete due to the lightweight aggregates used and the fracture patterns. It has been shown that for lightweight concrete aggregates the pullout test yields significantly lower coefficient of variation (6%) than the harder aggregate concrete. In general, pullout test results have been estimated to be within ±8% accuracy for laboratory and field-testing conditions when the test procedure has been performed properly and a proper correlation has been developed.(Stone, Carino et al. 1986)

Literatures tend to disagree on the failure mechanism of the pullout test. Some claim the failure in the concrete is directly related to the compressive strength of the concrete. Others literature concluded that failure is due to the fracture toughness of the matrix or mortar strength. However, all studies indicate the existence of a correlation between the pullout force and the compressive strength of the tested concrete. (ASTM-C900 2006)

Strains and Stresses in Tilt-up Panels

Strain gauges are used to detect and monitor the change in length of an element subjected to loads. Some gauges are static, reading strains in a slow manner such as the ones embedded in the concrete. Contrarily, dynamic gauges can monitor strains in a fraction of a second.

The electrical resistance gauges are among the most common strain measuring devices. They are made of a flat grid of wires and generally mounted using an epoxy bond to the surface of the material being tested. They operate by detecting the changes of the resistance in the electrical field due to the compression or stretching of the gauges. They are ideal for dynamic loading and monitoring of any material, in our case concrete.

The surface of the tested material must be clean and free of dirt to allow a proper adhesion of the gauges. In the case of concrete, long gauges are used to overcome the effect of the local variations of the concrete mixture. The gauge length should be at least four times the size of the coarse aggregates.(IAEA 2002)

In a study conducted by AbiNader, a tilt-up panel was instrumented with surface mount electrical strain gauges at the locations of the maximum calculated bending stresses. The strains were monitored during the tilting of the panel from 0 to 90 degrees. The results were compared with different finite element software. It was concluded that the maximum stresses were exerted at 0 degree angle where a suction force exists between the tilt-up panel and the casting bed. In this research, a similar technique was used to monitor the strain in the lightweight concrete tilt-up panel during lifting.

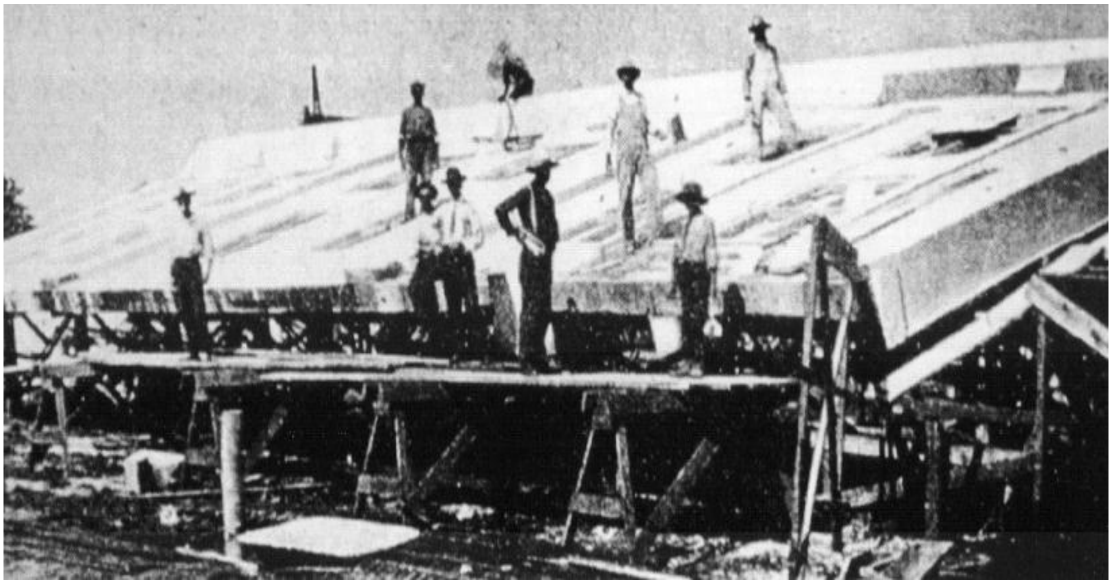


Figure 2-1. Tipping table use in tilt-up construction (TCA 2011)

Figure 2-2. La Jolla Women’s Club, Source: Library of Congress

Figure 2-3. Schindler's House (Greatbuildings.com 2012)

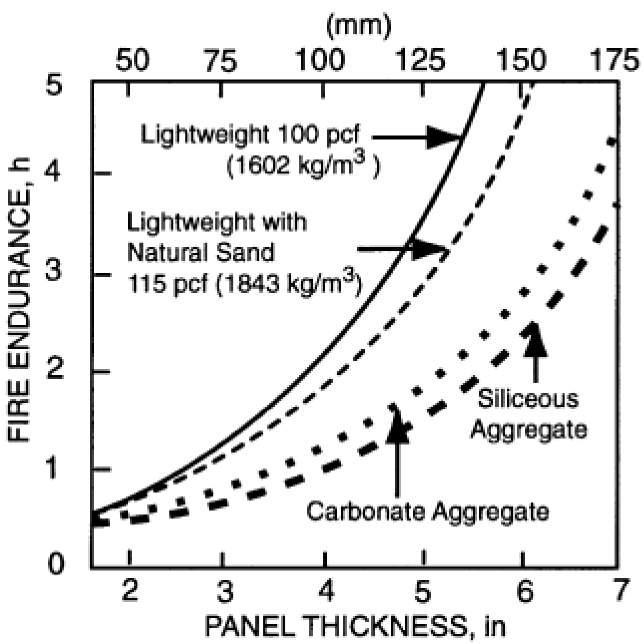


Figure 2-4. Fire rating for various densities of concrete (ACI.213 2003)

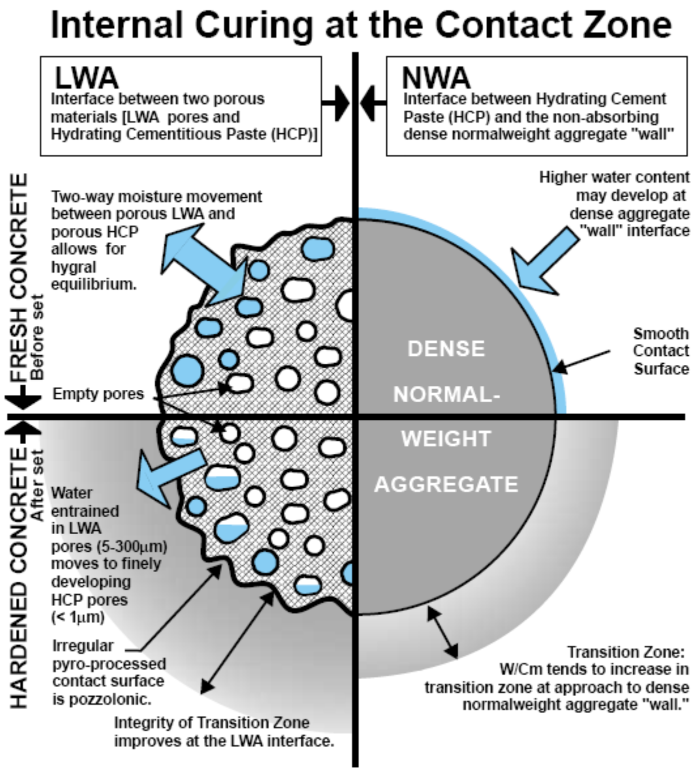


Figure 2-5. Normal vs. lightweight concrete curing characteristics (Norlite 2012)

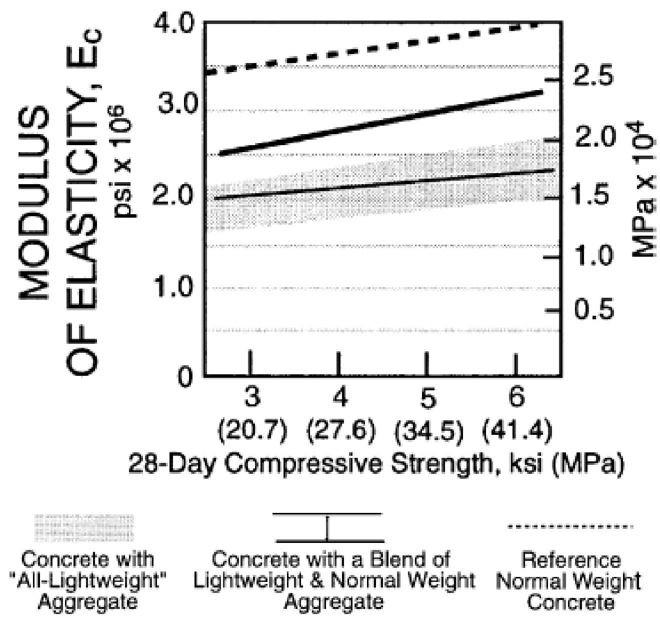


Figure 2-6. Modulus of elasticity of different densities of concrete (ACI.213 2003)

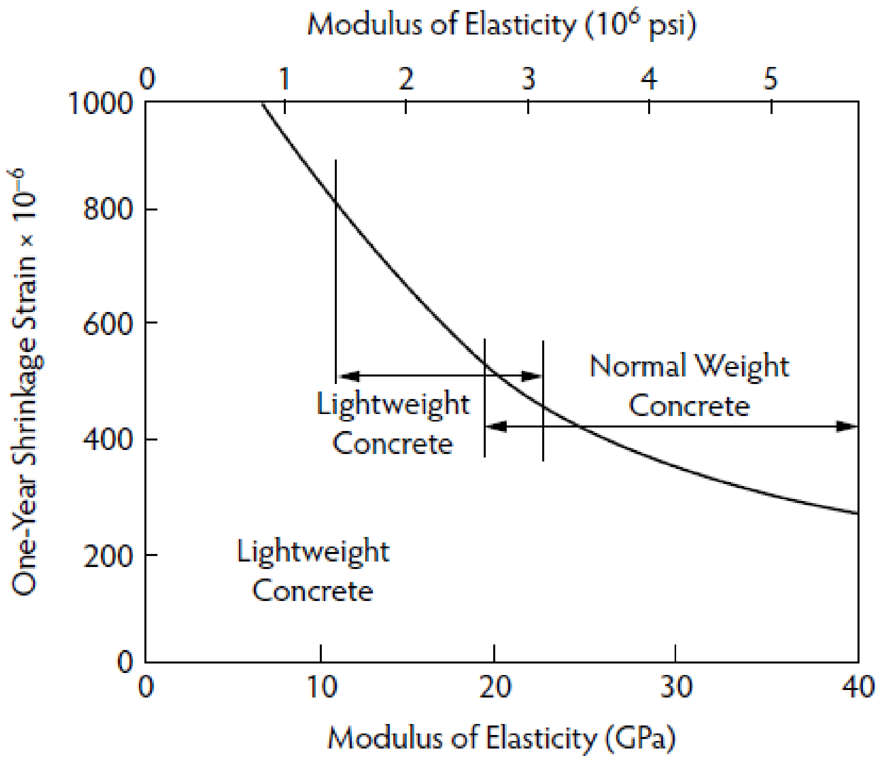


Figure 2-7. Normal vs. lightweight concrete modulus of elasticity (Nawy and Nassif 2008)

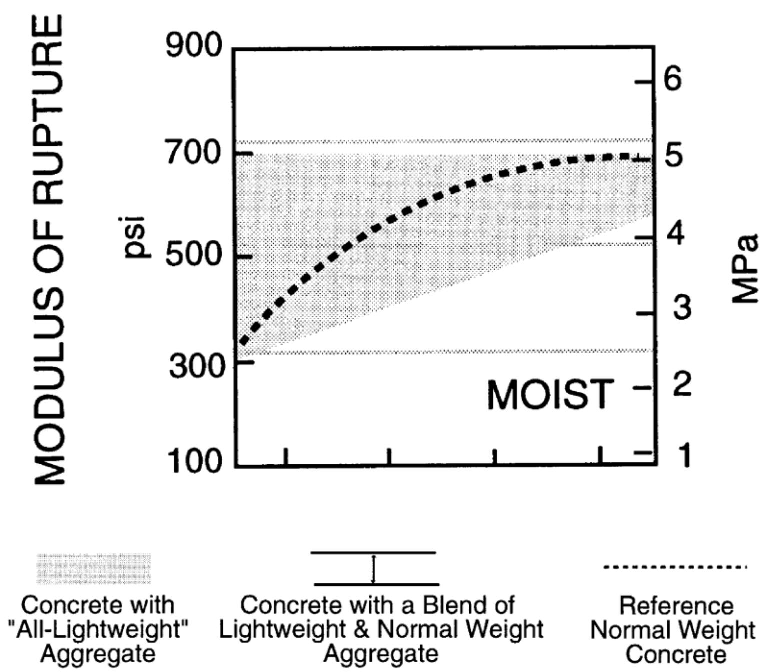


Figure 2-8. Modulus of rupture for different densities of concrete (ACI.213 2003)

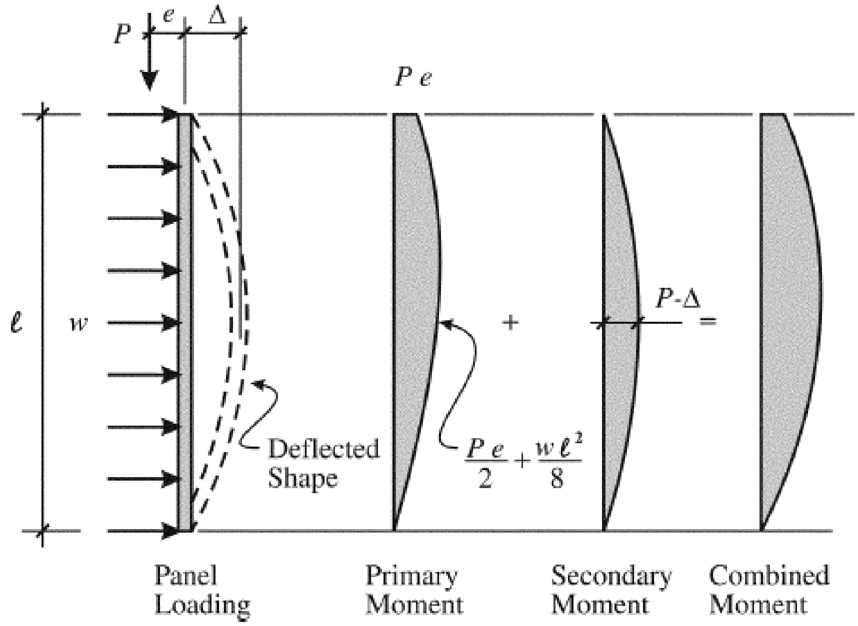


Figure 2-9. Wall design model (Source: ACI 551.2R10)

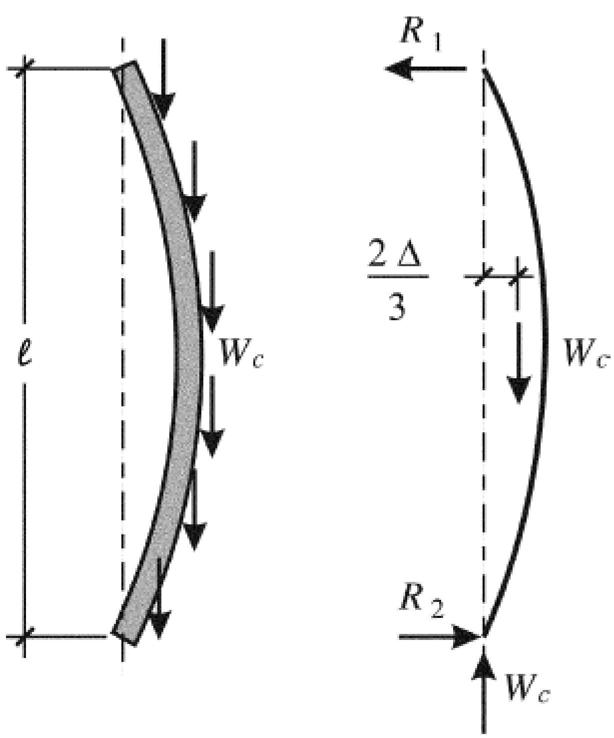


Figure 2-10. Panel self-weigh (Source: ACI 551.2R10)

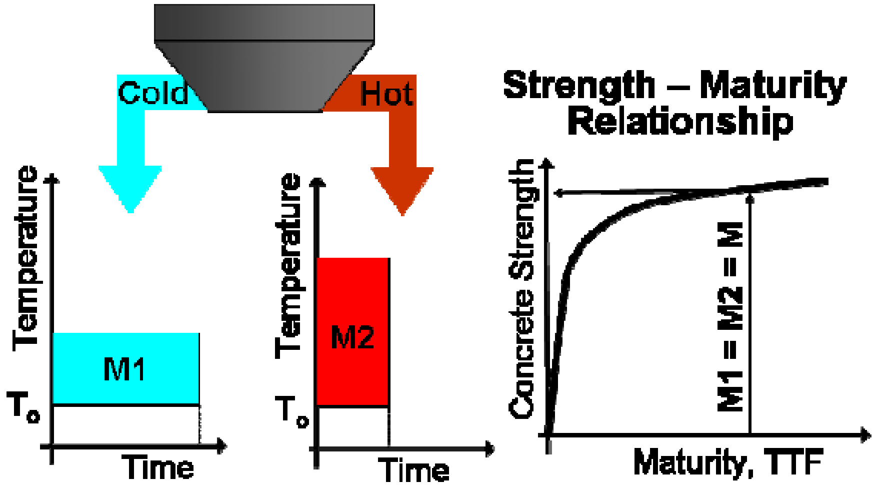


Figure 2-11. Temperature-Time Factor (Nixon, Schindler et al. 2008)

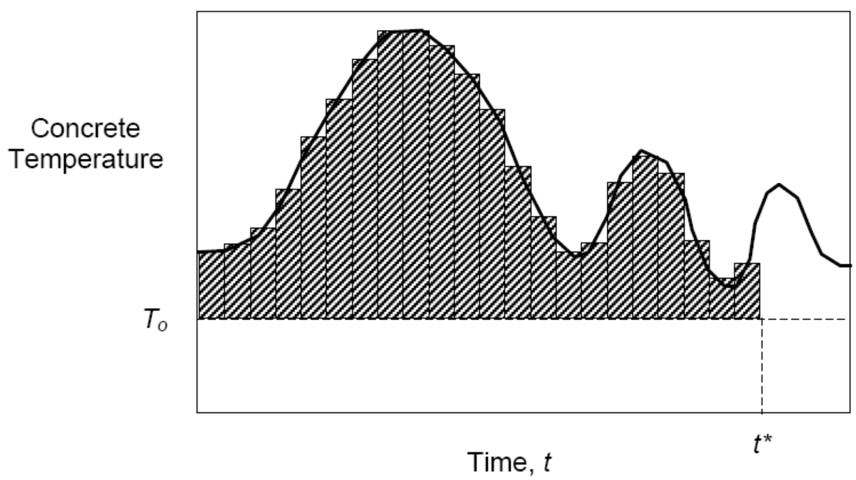


Figure 2-12. Thermal history curve (Carino 2008)

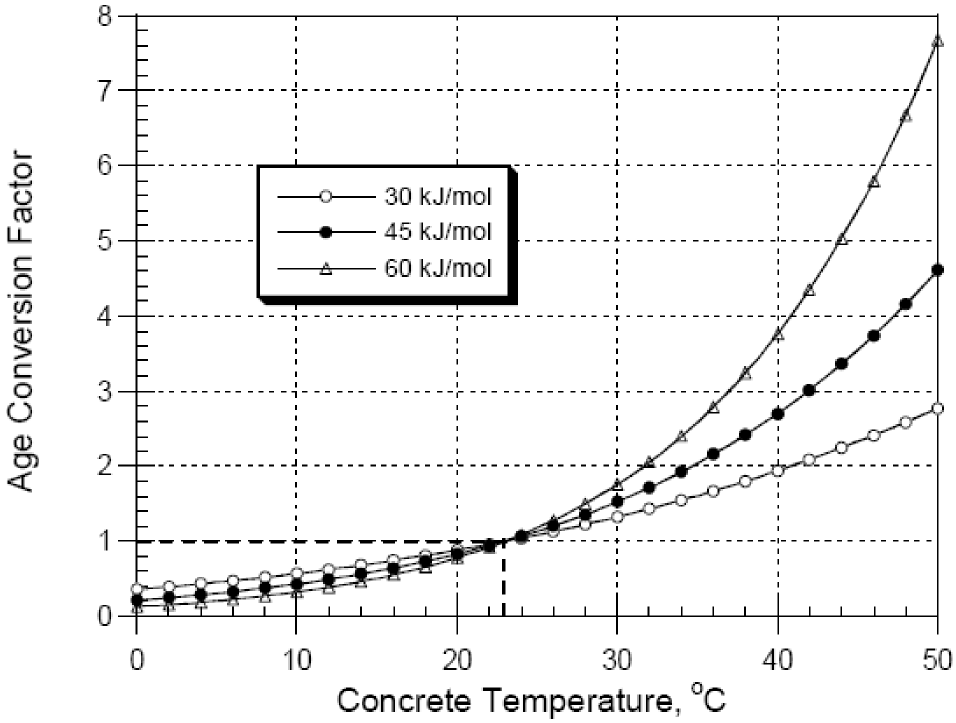


Figure 2-13. Age conversion factor according to activation energy (Carino 2008)

Figure 2-14. COMA maturity meter (photo courtesy of Adel Alsaffar)

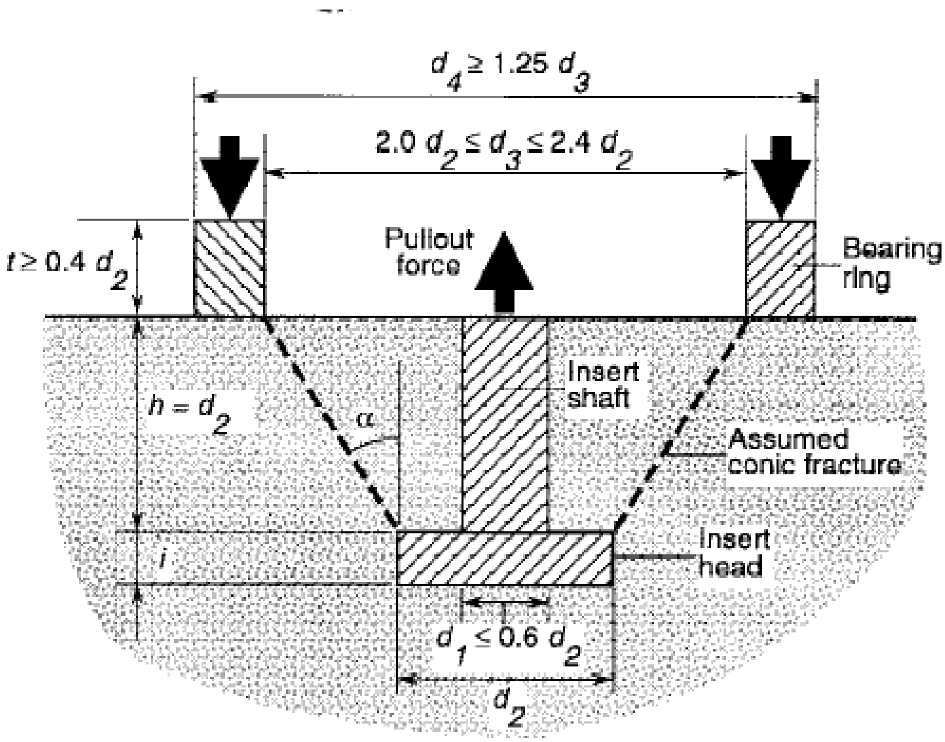


Figure 2-15. Cross section of pullout test (ASTM C 900-06)

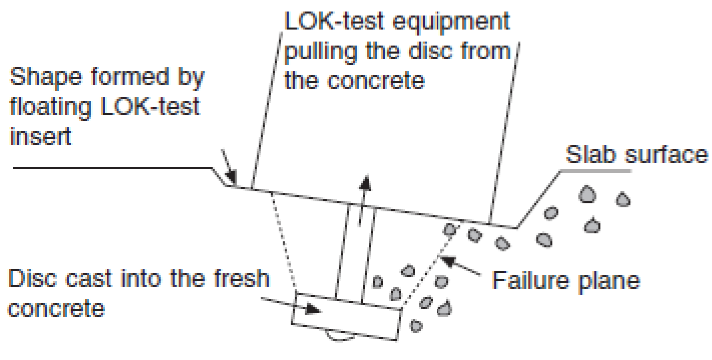


Figure 2-16. Principle of pullout test (Harrison 2003)

CHAPTER 3
RESEARCH METHODOLOGY

General Introduction

This section deals with the lightweight concrete mix design specifications and admixtures. It also discusses the various physical testing performed on fresh and hardened concrete. In addition, it covers the nondestructive testing procedures performed to estimate the strength of the concrete. Three different maturity concepts were tested using temperature-time factor, equivalent age and the COMA meter. The pullout strength test, a semi-destructive test, was also conducted to evaluate the strength of the lightweight concrete. Finally, the panel's surface mount strain gauges instrumentation procedures are highlighted.

The research called for two batches of the same lightweight concrete mixture. The first batch is a control batch, which was utilized to cast concrete specimens that were tested to establish the maturity-strength and pullout- strength relationships. The second batch is an experimental batch, which was used to cast the tilt-up wall and concrete test specimens.

Concrete Mixture Design

Concrete is normally characterized by its 28^{-} day compressive strength such as 4,000 or 5,000 psi concrete. Although the compressive strength is important for any tilt-up construction project, the early age strength of the concrete is vital. The tilt-up wall must gain sufficient strength at early age to facilitate lifting after a few days from casting.

ACI committee 551 requires a 28-day minimum compressive strength of 3,000 psi. Nevertheless, the lifting insert manufacturers call for a compressive strength of 2,500 psi at the day of lift. Therefore, higher 28-day strength is commonly specified to lift the panels as fast as possible. Another factor affecting the lifting of the panels is the flexural strength of the concrete; 28-day modulus of rupture of 550 psi is recommended to avoid flexural cracking. Lifting inserts manufacturers ask for modulus of rupture of 400 to 500 psi if the bending stresses are below 250 psi.

Consequently, a concrete mixture is sometime proportioned for early compressive and flexural strength gain. For example, cementitious materials such as fly ash and slag slow the rate of early strength gain and can disturb panel finishing. Also, air entraining agents reduce the strength of the concrete leading to cracking, particularly during the lifting operation. (ACI.551 2010)

Structural lightweight concrete number H65BC from Florida Rock Industries in Gainesville was found suitable for this research. Table 3-1 describes the mix design of the lightweight concrete used in this project.

The studied structural lightweight concrete, H65BC, is composed of natural sand and lightweight coarse aggregates. Detailed contents of the concrete are stated below.

Cement

T.S. Baker Cement Plant supplied the cement used by Florida Rock Industries to produce the lightweight concrete. Table 3-2 lists the chemical and physical properties of the cement.

Air Entrained Agent

The air entraining agent, AEA-92S, manufactured by Euclid Concrete Admixtures was used in the tested concrete. It meets or exceeded the requirements of ASTM C 260, AASHTO M 154, ANSI/NSF STD 61 and Corps of Engineers CRD C-13.

Water Reducer

The water reducing admixture, EUCON WR, manufactured by Euclid Concrete Admixtures was added to the concrete. It meets the requirements of ASTM C494 (Type A and D), AASHTO M194 and ANSI/NSF STD 61.

Coarse Aggregates

3/8" expanded slate produced by the rotary kiln method conforming to ASTM C 330 was used in the concrete mixture. The lightweight coarse aggregate was manufactured by STALITE. The properties of the aggregate used in the lightweight concrete are stated in Table 3-3.

Fine Aggregate

The physical properties and sieve analysis of fine aggregates used in the lightweight concrete provided by Florida Rock Industries are listed in Table 3-4.

Preparation of Concrete Specimens

Ready mix structural lightweight concrete was used to prepare thirty (6" x 12") cylinders and fifteen (6" x 6" x 21") beams for the control batch. The experimental batch was used to prepare fifteen (6" x 12") cylinders and eight (6" x 6" x 21") beams. Table 3-5 and Table 3-6 list the samples acquired from each batch.

The control batch specimens were prepared according to ASTM C 31, Standard Practice for Making and Curing Concrete Test Specimens in the Field, with a sample concrete acquired according to ASTM C 172-2010, Standard Practice for Sampling Freshly Mixed Concrete. The specimens were prepared in molds and covered with plastic to avoid drying. A day later, these specimens were submerged under water until testing as per ASTM C 511-2010 Standard Specification for Mixing Rooms, Moist

Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes (Figure 3-1).

For the purpose of this research, the specimens of the experimental batch were made according to ASTM C 31, but cured in their molds under the same condition as the tilt-up wall. The concrete sample was acquired according to ASTM C172-2010.

Concrete Cylinders

All specimens were prepared according to ASTM C 192 in 6” x 12” cardboard cylinder molds. The molds were pre-waxed for easier unmolding process and to prevent concrete for sticking to the surface. The concrete was added in a mold using a metal scoop in a circular motion around the perimeter of the mold in 3 equal layers. Each layer was consolidated by rodding the concrete 25 times and hand tapping the side of the mold 10-15 times (Figure 3-2). The access concrete was stroked off the top and finished using a trowel before it was covered with plastic.

Two temperature loggers were embedded midway in two of the concrete cylinders. The loggers were inserted in a hole made by tamping rod before tapping the molds to close the void. The loggers were immediately activated to record temperature and time

For the control batch, some of the cylinder molds had a pullout test insert fixed to the bottom; they were tested to ensure a water seal. Other concrete specimens received the pullout test insert in a floating cup after finishing (Figure 3-3). The inserts in this case were pressed and vibrated into the concrete to guarantee proper concrete encasement.(ASTM-C192 2007)

For the experimental patch, 15 cylinders were prepared using the same method. In two of the cylinder specimens a COMA meter were pressed into the concrete to measure the maturity of the concrete and compare it with the maturity of the tilt-up wall (Figure 3-4).

Concrete Beams

All specimens were prepared according to ASTM C 192 in 6” x 6” x 21” hard plastic beam molds. The molds were sprayed with oil to facilitate for easier unmolding process and prevent concrete for sticking to the walls of the molds. The concrete was added in the molds using a metal scoop in 2 equal layers. Each layer was consolidated by rodding the concrete 63 times and tapping the molds with a rubber mallet 10-15 times. The access concrete was stroked off the top and finished using a trowel before it was covered with plastic.(ASTM-C192 2007)

Two temperature loggers were embedded midway in two of the concrete beams. The loggers were inserted in a hole made by tamping rod before tapping the molds to close the void. The loggers were immediately activated to record temperature and time (Figure 3-5).

Tests on Fresh Concrete

Multiple tests were performed according to ASTM standards to ensure the quality of the delivered concrete. Concrete sample was collected in accordance with ASTM C 172-2010, Standard Practice for Sampling Freshly Mixed Concrete.

Slump of Hydraulic Cement Concrete

The slump test is used as an indicator of concrete’s workability. A clean plastic mold was dampened and placed on a flat non-absorbent base plate, see Figure 3-6. Then a sample of the freshly mixed concrete is collected from the Ready-Mix concrete. The mold was firmly held in position by stepping on the foot pieces of the mold. The first layer of concrete was then placed in the mold (approximately 1/3 by volume) and compacted by striking it 25 times using a 24” metal rod measuring 5/8 in. diameter. A second layer of concrete was added to the 2/3 of the mold by volume, and compacted by a rod strokes just enough to penetrate the first layer. A third layer of concrete was added to the full height of the cone mold and compacted in the same manner as in layer two. The excess concrete was stroked off flush with the top of the mold by the tamping rod. The area around the mold was cleaned before the mold was slowly lifted upward. The vertical difference between the mold and the center of the concrete top surface was immediately measured (Figure 3-7); all in accordance to ASTM C 143-2005. The slump results for the control and experimental batch were measured at 5” and 4” respectively.

Air Content of Freshly Mixed Concrete by Volumetric Method

Air entraining agents are added to the concrete mixture to incorporate air bubbles which improve the concrete against scaling due to freezing and thawing cycles. A common and less complicated method to measure the air content in the concrete is the pressure method procedure explained in ASTM C 231. However, this method is applicable to dense aggregate concrete only. On the other hand, ASTM C 173- 2001, the volumetric method, is the only acceptable air content measure in lightweight aggregate concrete because it measures the air in the mortar and not the voids in the aggregates.

The air meter (Figure 3-8) consists of two sections, a bowl and a top cover. The needed tools are listed below:

- Funnel- to add water without disturbing the concrete.
- Tamping rod- 5/8 in. diameter and at least 12 in. long.
- Strike off bar.
- Calibrated cup.
- Measuring Vessel for Isopropyl Alcohol.
- Isopropyl Alcohol

- Mallet- rubber, weighing 1.25± 0.5 lb.

The bowl was damped and filled with freshly mixed concrete in two layers. Each layer was stroked 25 times for compaction and taped with the mallet 10-15 times to close the voids cause by rodding. Water and alcohol were added using the funnel after fixing the top section of the air meter. Approximately 2 pints of alcohol was used to reduce the amount of foam (Figure 3-9). The meter was inverted and shook for 5 seconds at a time for a minute, and then it was rolled at a 45 degree angle for another minute. The initial reading was recorded to the nearest 0.25% after the cap was removed and the pressure stabilized. The final air content reading was recorded after another minute of rolling and pressure stabilization. The measurement of air from control and experimental batched are recorded in Table 3-7.

Unit Weight

The plastic unit weight of the lightweight concrete was determined by weighing the concrete using a bowl with a known volume and weight. The plastic unit weight of the lightweight concrete was later calculated by dividing the weight of the concrete by the volume of the bowl. The plastic unit weights were calculated to be 115 lb/cf and 117 lb/cf for the control and experimental batch respectively.

Temperature Test

The temperature of the lightweight concrete was recorded in accordance to ASTM C 1064 by pressing an approved thermometer in the fresh concrete until the temperature stabilized (Figure 3-10). The reading was recorded to the nearest 0.5 ˚F. The temperature of the control batch of concrete was recorded at 78 ˚F when the ambient temperature was 70.5 ˚F. The Experimental batch of concrete registered a temperature of 82˚F when the ambient temperature was 79 ˚F.

Tests on Hardened Concrete

Multiple tests were performed according to ASTM standards to ensure the quality of the delivered concrete. The concrete sample was collected in accordance with ASTM C 172-2010.

Compression Test

Compression tests were performed for the control batch cylindrical specimens at 1, 4, 7, 14 and 28 days as per ASTM C 39. The specimens were capped according to ASTM C 617, Standard Practice for Capping Cylindrical Concrete Specimens (Figure 3-11). A FORNEY FX250/300 compression testing machine was used to apply a load rate of 35 psi/sec (1000 lb/sec) until failure. In a similar procedure, the experimental batch cylinders were tested at 1, 3, 7 and 10 days.

The compressive strength of the cylinders was obtained by dividing the maximum applied load by average cross sectional area as follows:

$$S = \frac{P}{\pi r^2} \tag{3-1}$$

Where,

S = Compressive strength (psi),

P = Maximum load (lbs.),

r = Radius (inches), 3” in this case.

Two cylindrical specimens were tested for compressive strength at each testing day. The average compressive strengths were compared with the range of strengths making sure they are within 10% of the average as required by ASTM C 1074.

Third Point Flexure Test

Third Point Flexure tests were conducted for the control batch at 1, 3, 7, 14 and 28 days according to ASTM C 78 (Figure 3-12). The axial loads were applied at an approximate rate of 2700 lb/min. Experimental batch beams were also tested at 1, 3, 7 and 10 days. The following equation was used to calculate the modulus of rupture:

$$R = \frac{PL}{bd^2} \tag{3-2}$$

Where:

R = Modulus of rupture (psi),

P = Maximum applied load (lb),

L = Span length, (in.),

b = Average width of specimen, (in.), at the fracture, and

d = Average depth of specimen, (in.), at the fracture.

Two beam specimens were tested for flexural strength at each testing day. The average flexural strengths were compared to make sure they are within 15% of the average as required by ASTM C 1074.

Maturity Method

Estimation of early age strength of concrete is important in many concrete applications such as stripping forms, re-shoring and opening concrete pavement to traffic. It is particularly critical in the tilt-up construction since the construction process can depend on the concrete reaching sufficient strength prior to lifting the walls.

Therefore, different maturity methods were utilized to estimate the strength of the concrete prior to lifting; since they are reliable, easy to perform and non-destructive.

Maturity Method Process

Fifteen cylinders (6” x 12”) and fifteen (6” x 6” x 21”) beams were prepare from the lightweight concrete (control batch). Temperature loggers were inserted at mid depth of two cylinders and two beams. The loggers were activated as soon as they were inserted to record the temperature of the concrete. Mechanical testing of compressive and flexural strengths were performed on two specimens at day 1, 3, 7, 14 and 28. Depending on the maturity method tested, maturity index is calculated using different methods. A strength-maturity relationship was then plotted showing the average strength of concrete at different maturity stages. A best fit curve was drawn using a log function in Microsoft ® Excel. These relationships were used to estimate the real-time strength of the tilt-up wall. In addition, the relationships were also verified in the experimental batch by testing cylinders and beams for strength.

Evaluating the Strength of Concrete Using Temperature-Time Factor

Temperature-Time Factor (TTF) was one of the methods used in this research to estimate the strength of the lightweight concrete. The control batch temperature history (temperature loggers) and strength (specimens testing) were recorded to compute the temperature-time factor as follows:

$$\mathrm{M(t)} = \sum_{0}^{t} (\mathrm{Ta} - \mathrm{To})\Delta \mathrm{t} \qquad (3\text{-}3)$$

Where:

M(t) = temperature-time factor (maturity index) at age (t), degree-hour,

Ta= average concrete temperature during the time interval Δt,

To = datum temperature (usually taken to be 0°C), and

Δt = time interval (hours).

TTF was used to establish the strength-maturity curve that references the strength of the concrete mix as a function of its maturity.

Evaluating the Strength of Concrete Using the Equivalent Age Method

The equivalent age method was also applied to predict the strength of the lightweight concrete in the tilt-up panel. Temperature loggers were used to record the temperature history, and specimens were tested for strength to produce the equivalent age based relationship by applying the following equation:

$$\mathrm{te} = \sum e^{-\frac{E}{R}\left(\frac{1}{Ta}-\frac{1}{Ts}\right)} \Delta t \tag{3-4}$$

Where:

t_e = equivalent age at a specified temperature T_s, days or hours;

E = Activation energy obtained experimentally, kJ/mol;

R = Molar gas constant = 8.31J/ mol.K;

T_a = average temperature of concrete during interval Δt, K;

T_s = specified temperature, K; and

Δt = time interval, days or hours.

The activation energy was assumed to be equal to 40,000 J/mol based on literature recommendations for type I cement (ASTM-C1074 2011). Calculations were performed; they concluded that different activation energy values had minimal effect on estimating the strength of the tested lightweight concrete under the research curing conditions (Figure 2-13).

Maturity Measurement Device

IntelliRock TPL- temperature loggers manufactured by ENGIUS were used to record the thermal history of the lightweight concrete. The loggers conform to the ASTM

C 107 requirements for digital loggers. Table 3-8, shows the specifications of the temperature loggers. IntelliRock II reader was used to read the loggers and transfer the data to computers via software; Table 3-9 lists the reader's specifications. The temperature data were used to calculate the Maturity Index.

In the control batch, two loggers were embedded in the concrete cylinders and another two were inserted in the beam specimens. Same loggers were embedded in the tilt-up panel and cylinder specimens from the experimental batch.

Pullout Strength Method

The pullout test (LOK test) used in this experiment is manufactured by Germann Instruments. It comprises of 25 mm steel discs at a 25 mm depth (Figure 3-13). A hydraulic, hand operated, pull machine records the maximum force required to cause fracture of the concrete. The fracture caused by the pull force has generally shape of a cone (Figure 3-14).

Fifteen cylinders were prepared using the control batch to establish strength-pullout relationship. Ten cylinders had the inserts fixed to the bottom for the molds, 2 with the inserts placed on top with a floating cup and the rest had inserts at both ends (Figure 3-15). Two inserts were tested at day 1, 3, 7, 14 and 28. The discs (inserts) were pulled using a hydraulic pull machine with a digital gauge. The machine recorded the maximum force required to pull the inserts. The average maximum forces were plotted with the corresponding strengths to establish a reference strength-pull relationship. This relationship was used to estimate the strength of the concrete in the tilt-up panel.

The tilt-up panel was also instrumented with discs fixed on the formwork along the panel sides as shown in Figure 3-16. A disc was also inserted in the surface of the concrete panel at an angle to ensure full encasement.

The complete process of the pullout strength test is shown in Figure 3-17 for a floating cup disc inserted in the surface of the tilt-up panel concrete. The panel inserts were taken as a measure of the concrete strength after they were compared to the pullout-strength relationship curve created with the control batch.

Strain Measurements

N2A-06-40CBY-350/P surface mount strain gauges, manufactured by Micro-Measurements a branch of Vishay Precision Group, were used in this project. The gauges were 4.49" long; this is suitable for concrete application since the gauge length is more than 5 times the size of the large aggregate.

Strain Gauge Installation

The strain gauge installation procedure was done in two major steps using M-Bond AE-10 kit supplied by Micro-Measurements.

Surface preparations

The surface of the concrete was first cleaned with a stiff bristle brush to remove any dust particles (Figure 3-18 A). Then, isopropyl alcohol was applied to the gauge location after it was marked to clean any contaminants (Figure 3-18 B). Although the concrete surface of the panel received a smooth finish, there were some voids and air-pockets that might affect the gauge bonding and reading. Therefore, the M-Bond was used as a sealer to the surface of the concrete (Figure 3-18 D). The adhesive was then applied to the surface of the concrete filling out any voids after it was mixed with the curing agent 10 for five minutes and was let to stand for another five minutes (Figure 3-

18 C). The M-Bond was left to cure overnight before it was abraded using sandpapers starting with 80 grit and ending with 360 grit. The purpose of the abrading was to expose the concrete area with voids being filled with the M-Bond as well as creating a smooth area to bond the gauge.

Gauge bonding

The surface of the concrete was cleaned with isopropyl alcohol. The gauge was placed in its final position and orientation using a piece of tape (Figure 3-19 A). The gauge was then lifted and a light coat of adhesive was applied to the bonding surface of the gauge and the surface of the concrete (Figure 3-19 B, C and D). The gauge was aligned and remounted to the concrete with hand pressure applied to ensure proper distribution of the bond (Figure 3-19 E and F). Silicone rubber was placed on top of the gauge for protection before a 10 psi of dead weight was applied to each strain gauge and left to cure overnight (Figure 3-19 G and H). Due to limited resources, 3 strain gauges were installed at a time.

Data Acquisition System

Two compatible data acquisition conditioners (DA), D4 by Micro-Measurements, were used to monitor the strain gauges as the tilt-up wall was being lifted. Each was connected to 4 quarter-bridge gauges, taking 8 readings per second. The DAs are portable and operate on USB power. The DAs were connected to a computer via software (Figure 3-20). Table 3-10, summarizes the D4 specifications.

Table 3-1. Mix Design for structural lightweight concrete (H65BC)

Material	ASTM	TYPE	Quantity	
Cement	C 150	II	650	Lbs
Water	--		250	Lbs
Fine Aggregate	C 33	Sand	1130	Lbs
Aggregate	C 330	#7LTWT	1075	Lbs
Air Entrained	C 260	AEA-92S	3.0	oz.
Water Reducer	C494	EUCON WR	55	oz.
W/C Ratio			0.39	
Slump (in)			5 ±1"	
Air Content (%)			4.5 ±1.5%	
Plastic Unit Weight (lbs/cf)			115.1 ±1.5	

* Materials per Cubic Yard

Table 3-2. Chemical and physical properties of type I & type II cement

	LIMIT	ASTM C150	FL. DOT 921 & AASHTO M-85	COMPOSITION
Chemical Compounds				
Silicon Dioxide (SiO_2)				19.6
Aluminum Oxide (Al_2O_3)	Maximum	6%	6%	5.2
Iron Oxide (Fe_2O_3)	Maximum	6%	6%	3.6
Calcium Oxide (CaO)		-	-	63.6
Magnesium Oxide (MgO)	Maximum	6%	6%	0.9
Sulfur Trioxide (SO_3)	Maximum	3%	3%	3.1
Loss of Ignition (LOI)	Maximum	3%	3%	2.7
Insoluble Residue (IR)	Maximum	0.75%	0.75%	0.29
Sodium Oxide (Na_2O)				0.09
Potassium Oxide (K_2O)				0.33
Alkalies (Na_2O equivalent)	Maximum	0.60%	0.60%	0.31
Tricalcium Silicate (C_3S)				61.2
Dicalcium Silicate (C_2S)				10.1
Tricalcium Aluminate (C_3A) %	Maximum	8%	8%	7.6
Tetracalcium Aluminoferrite (C_4AF)				11.0
CaCO3 in limestone, %	Minimum	70%	70%	98%
Limestone, %	Maximum	5%	5%	3.7%
Physical Test Results				
(ASTM C204) Blaine Fineness, m2/kg	Minimum	280	280	393
(ASTM C191) Vicat Set, minutes				
Initial Set	Minimum	45	45	112
Final Set	Maximum	375	375	212
(ASTM C185) Air Content %	Maximum	12%	12%	6.3%
(ASTM C 151) Autoclave Expansion	Maximum	0.80%	0.80%	0.0
(ASTM C186) 7 day heat of hydration cal/g	Maximum	N/A	80	78
C_3S = 4.75* (C_3A)	Maximum	100	100	97

Table 3-2. Continued

	LIMIT	ASTM C150	FL. DOT 921 & AASHTO M-85	COMPOSITION
Physical Test Results (Continued)				
Compressive Strength, psi				
1 day				2340
3 days	Minimum	1740	1740	4100
7 days	Minimum	2760	2760	5220
28 days				7200

Table 3-3. Properties of Lightweight Coarse Aggregate

	Content
Absorption:	
Saturated Surface Dry (ASTM C 127)	6%
1 Hour Boil In Water	8%
Under high pumping pressure of 150 psi	9.4%
Soundness (% Loss)	Maximum
Magnesium Sulfate (ASTM C 88))	0-0.01%
Sodium Sulfate (ASTM C 88)	0 - 0.23%
25 Cycles Freezing and Thawing (AASHTO T 103)	0.22 - 0.80%
Toughness:	
Los Angeles Abrasion (AASHTO T 96)	25 - 28%
Stability:	
Angle of Internal Friction (Loose)	40° - 42°
Angle of Internal Friction (Compacted)	43° - 46°
Typical Density (Unit Weight):	
Dry Loose (ASTM C 29)	52 lbs/cf
Dry Rodded (ASTM C 29)	58 lbs/cf
Saturated Surface Dry Loose (ASTM C 29)	53 lbs/cf
Maximum Dry Density (ASTM D 4253)	-
Damp Loose (ASTM C 29)	50-54 lbs/cf
Typical Relative Density (Specific Gravity):	
Dry (ASTM C 127)	1.54
Saturated Surface Dry (ASTM C 127)	1.60
Range in Saturated Surface Dry (ASTM C 127)	1.57-1.64
Sieve Size:	% Passing
1”	100
3/4”	100
1/2”	100
3/8”	90-100
#4	40-80
#8	0-20
#16	0-10

Table 3-4. Properties of the Florida Rock Industries fine aggregate

Physical Properties:	
Fineness Modulus	2.25
Dry Unit Weight	95 lb/cft
Absorption	0.5 %
Sieve Size:	% Passing
#4	99.7
#8	98
#16	86
#30	59.6
#50	25.9
#100	5.6

Table 3-5. Concrete specimens, control batch

Test	Specimen Size	Number of samples	Time of testing (days)	Standard
Compressive	6” by 12” Cylinder	15	1,3,7,14 and 28	ASTM C39
Pullout	6” by 12” Cylinder	15	1,3,7,14 and 28	ASTM C 900
Flexure	6” by 6” by 21 “ Beam	15	1,3,7,14 and 28	ASTM C78

Table 3-6. Concrete specimens, experimental batch

Test	Specimen Size	Number of samples	Time of testing (days)	Standard
Compressive	6” by 12” Cylinder	15	1,3, 7 and 10	ASTM C39
Flexure	6” by 6” by 21 “ Beam	8	1, 3,7 and 10	ASTM C78

Figure 3-1. Concrete curing tank (photo courtesy of Adel Alsaffar)

Figure 3-2. Rodding cylinder specimen (photo courtesy of Adel Alsaffar)

Figure 3-3. Concrete cylinders with pullout inserts (photo courtesy of Adel Alsaffar)

Figure 3-4. COMA meter pressed in concrete cylinders (photo courtesy of Adel Alsaffar)

Figure 3-5. Temperature loggers in cylinders and beams (photo courtesy of Adel Alsaffar)

Figure 3-6. Slump test cone (photo courtesy of Adel Alsaffar)

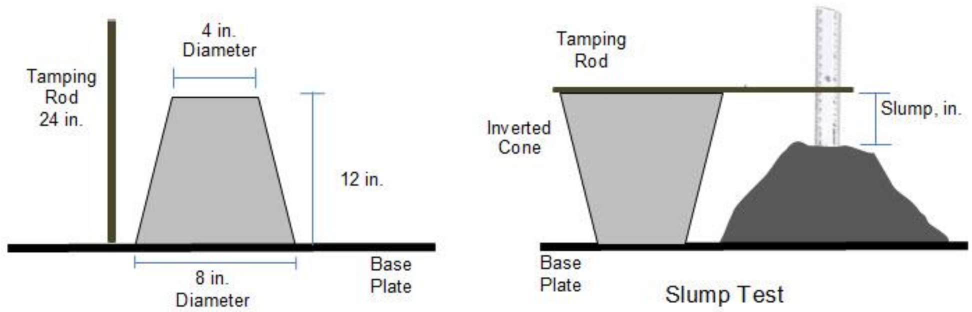


Figure 3-7. Slump test scheme (drawing courtesy of Adel Alsaffar)

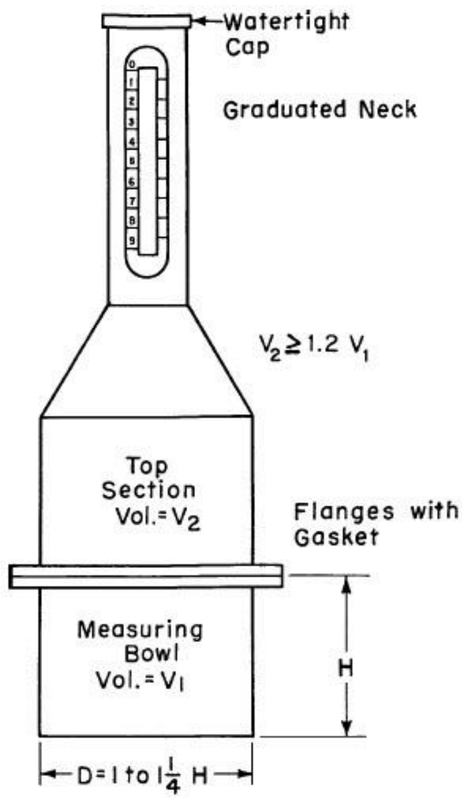


Figure 3-8. Air meter by volumetric method (ASTM C 173)

Figure 3-9. Adding isopropyl alcohol to prevent foaming (photo courtesy of Adel Alsaffar)

Table 3-7. Air content measurement

	Control batch	Experimental batch
First air content reading	5.25%	4.25%
Second air content reading	5.50%	4.25%
Approved air content	5.50%	4.25%

Figure 3-10. Measuring the temperature of concrete (photo courtesy of Adel Alsaffar)

Figure 3-11. FORNEY compressive test machine (photo courtesy of Adel Alsaffar)

Figure 3-12. Flexure testing “modulus of rupture” (photo courtesy of Adel Alsaffar)

Table 3-8. IntelliRock temperature loggers specifications

Operating Temperature	-5 C to 85 °C
Storage Time & Temperature	0 to 35 °C for 2 years.
Max Temperature measurement Range	-18 to 99 °C (unwarranted outside of "operating temperature" range)
Temperature Accuracy	± 1 °C, -5 to 85 °C
Temperature Resolution	1 °C
Time accuracy	1 minute per month
Temperature measurement rate	1 minute (resolution for min/max)
Maturity integration period	1 minute

Table 3-9. IntelliRock II Reader specifications

Operating Temperature	-5 C to 85 °C
Time accuracy	1 minute per month
Logger data storage	999 logger downloads
PC Interface	USB

Figure 3-13. Location of pull insert (disc) in the concrete (photo courtesy of Adel Alsaffar)

Figure 3-14. Pullout fracture in a shape of a cone (photo courtesy of Adel Alsaffar)

Figure 3-15. Cylinder pullout insert with floating cup (photo courtesy of Adel Alsaffar)

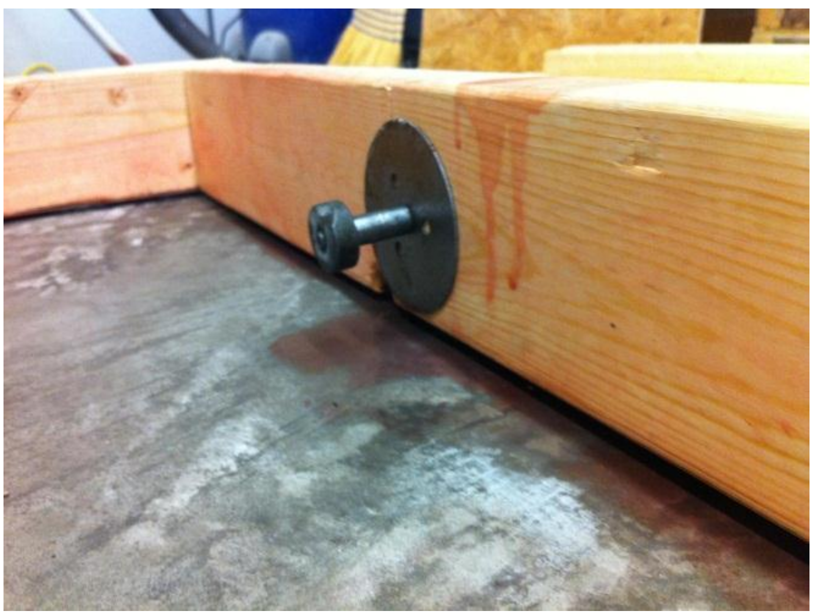


Figure 3-16. Pullout insert attached to panel's formwork (photo courtesy of Adel Alsaffar)

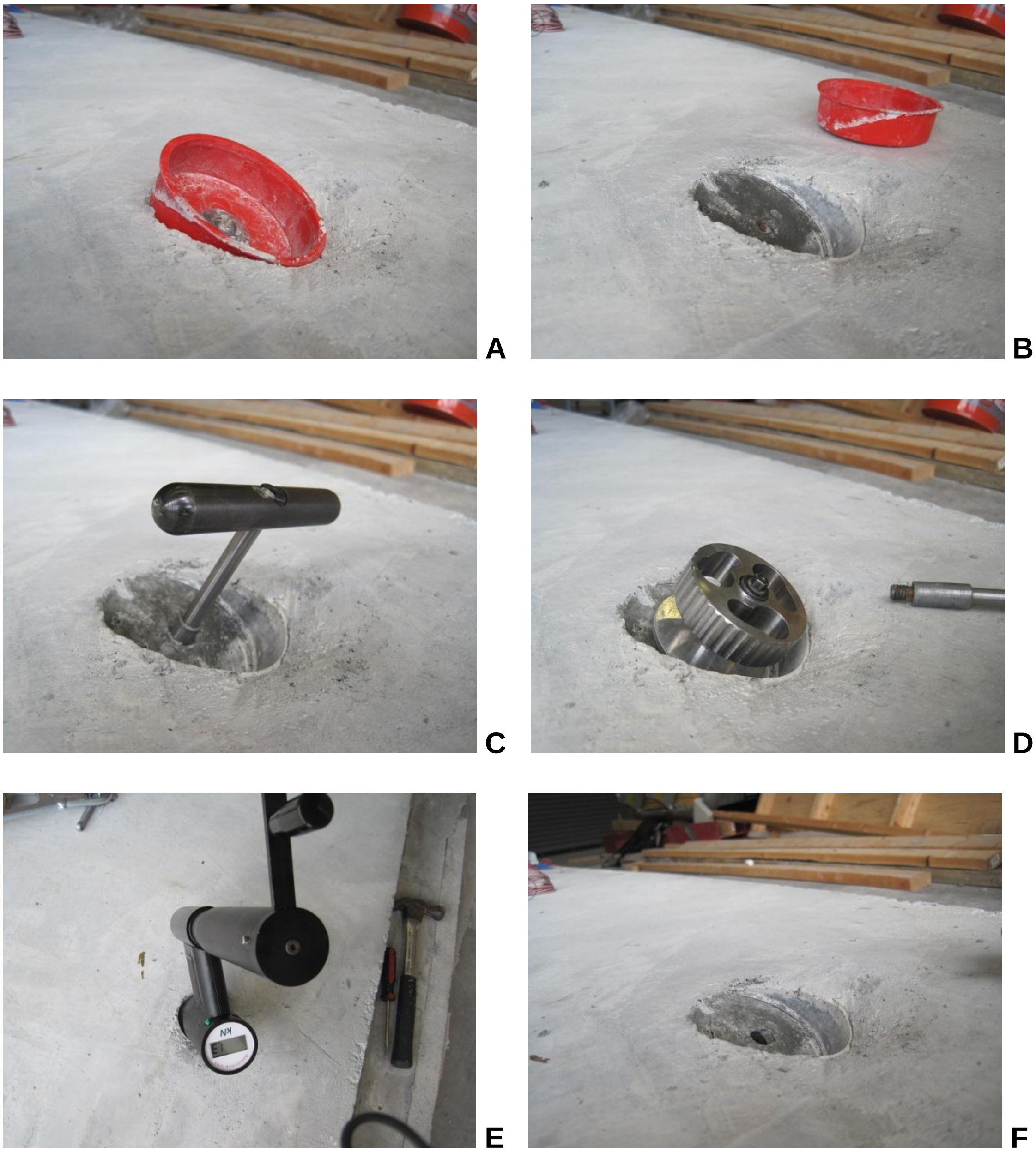


Figure 3-17. Pullout process A) Pullout insert cup. B) Cup removed. C) Stem removal. D) Pull machine attachment. E) Pull machine. F) Surface of concrete after failure. (photo courtesy of Adel Alsaffar)

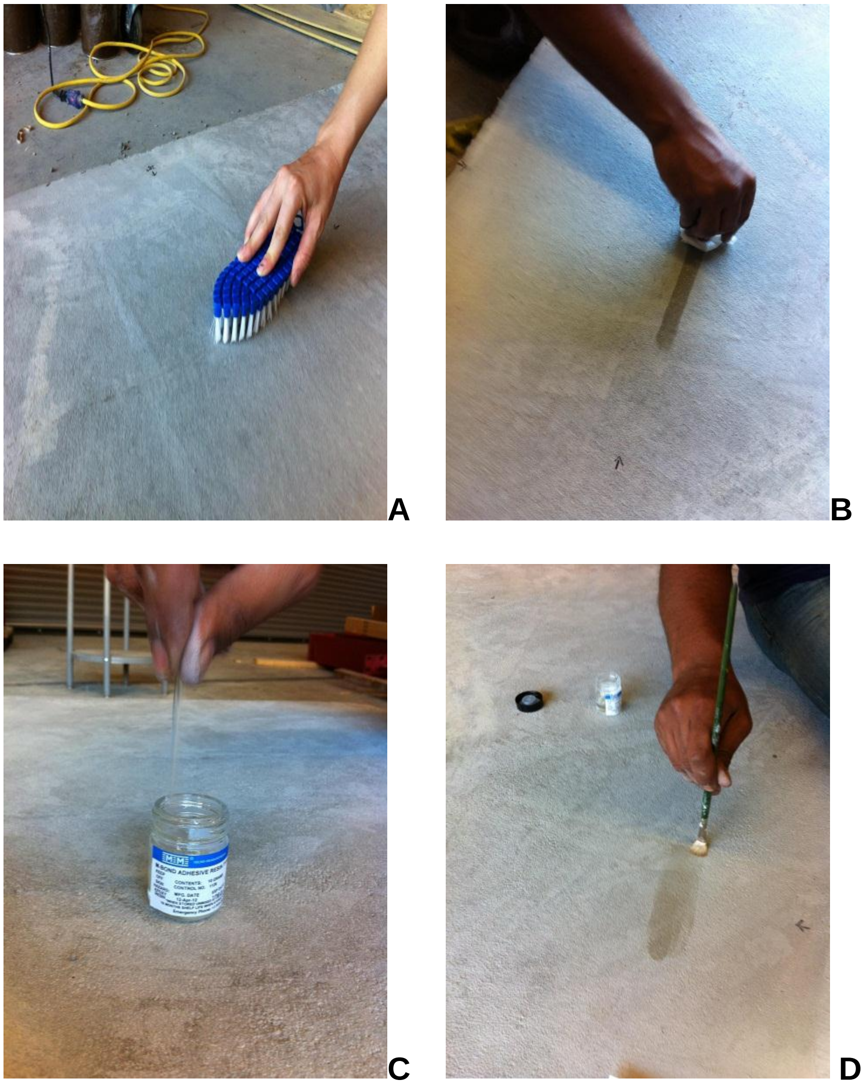


Figure 3-18. Surface preparation A) Clean with bristle brush. B) Wipe with isopropyl alcohol. C) Mixing M-Bond adhesive. D) Apply adhesive. (photo courtesy of Adel Alsaffar)

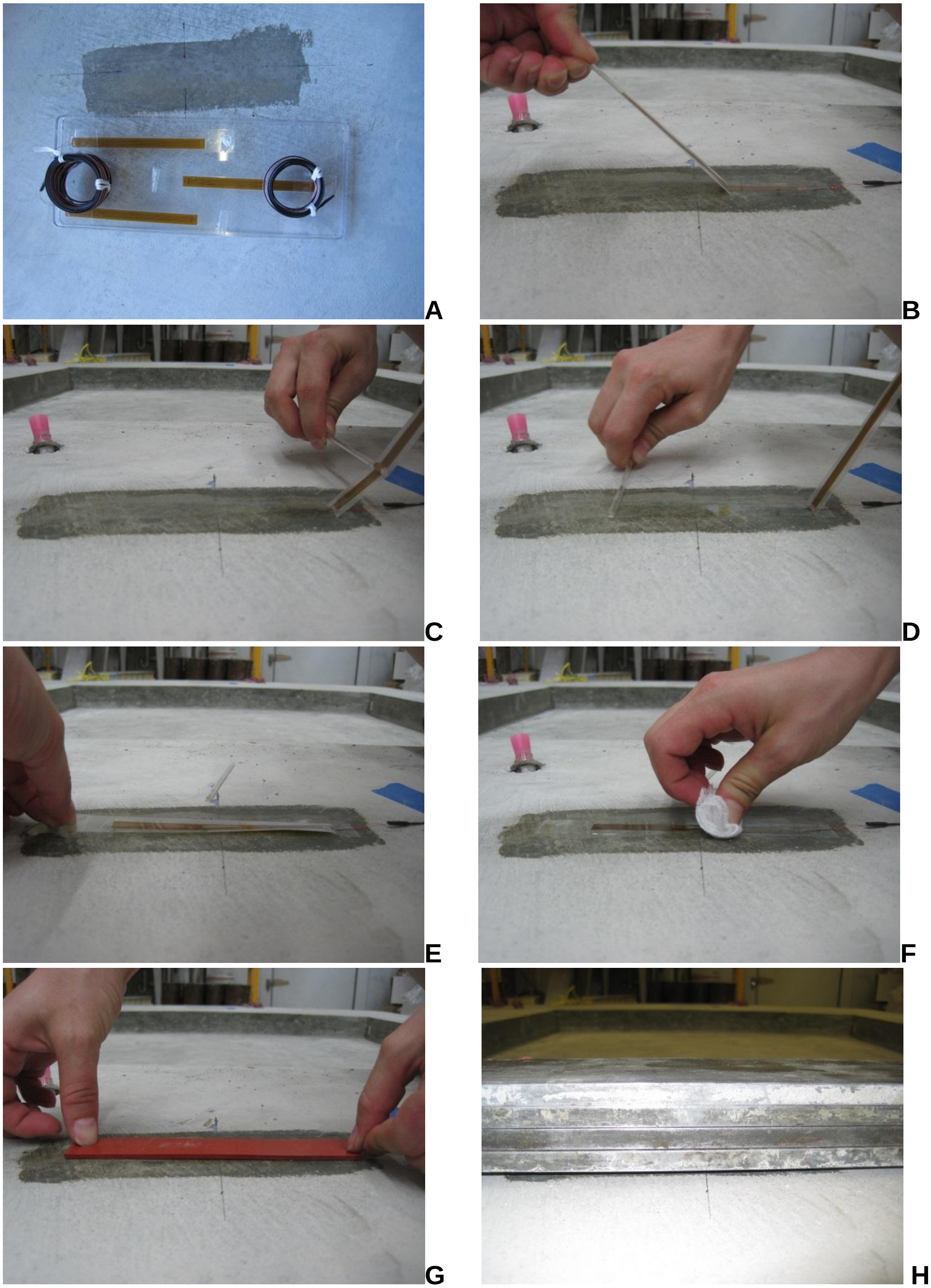


Figure 3-19. Gauge bonding procedure A) Gauges and receiving surface. B) Gauge removal. C) Adhesive application to gauge. D) Adhesive application to surface. E) Installation and alignment. F) Adhesive distribution. G) Gauge protection. H) Applying pressure. (photo courtesy of Adel Alsaffar)

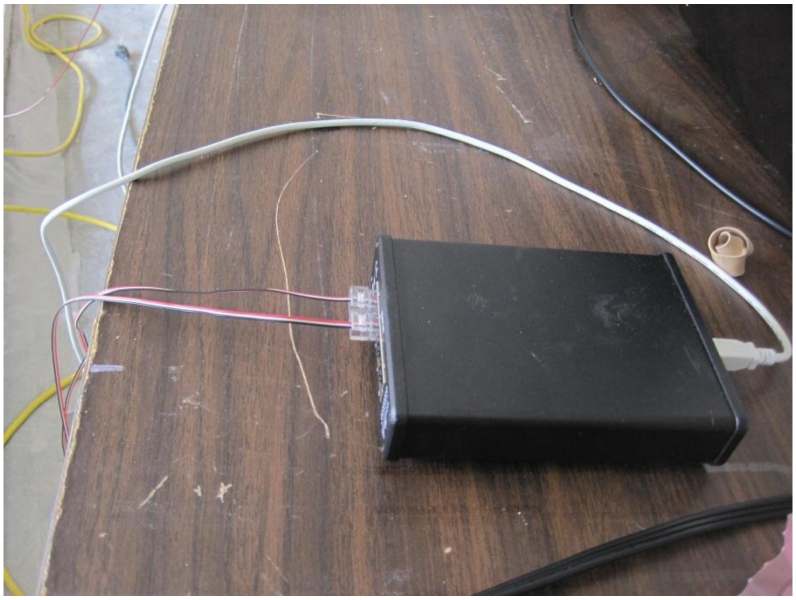


Figure 3-20. D4 data acquisition conditioner (photo courtesy of Adel Alsaffar)

Table 3-10. D4 data acquisition conditioner specifications

Strain Range	±31,000 με
Resolution	±1 με
Temperature	0-50 ˚C
Humidity	90% Relative Humidity

CHAPTER 4
MATURITY METHODS

Strength-Maturity Relationship

Three maturity techniques were used to estimate the strength of the lightweight concrete tilt-up wall. Strength-maturity relationships were established using the maturity equations. The strength-maturity relationship defines the compressive strength as a function of the maturity index. In this research, strength-maturity relationships were also created to reflect the relationship between flexural strength and maturity index.

Temperature-Time Factor (TTF)

As described in ASTM C 1074, the thermal history of the control patch of concrete was obtained using digital temperature loggers- refer to Appendix A for temperature logger data. Consequently, the temperature-time factor (maturity index or TTF) was calculated according to Equation 3-3. The datum temperature was assumed to be equal to 0˚C, based on ASTM C 1074-2011.

Compressive strength-TTF relationship

Table 4-1 lists the averages of temperature-time factor and average compressive strength of the cylinders prepare using the control batch.

Pursuant to the obtained TTF and compressive strengths, the data was plotted in Figure 4-1. The x-axis indicates the maturity index or TTF in degree Celsius- hours. The y-axis is the compressive strength of the lightweight concrete. The data points were connected using the Trendline feature in Microsoft ® Excel. The best fit curve with the higher coefficient of determination (R^2) was the logarithmic curve. The function of the relationship is shown in same figure.

This curve/ function is unique to this particular lightweight design mixture. The function was used to estimate the compressive strength of the experimental batch at various maturity values.

Flexural strength-TTF relationship

The TTF method was also applied using the control batch to establish a relationship between the maturity index and the flexural strength of lightweight concrete mixture under study. Table 4-2, shows the average of the modulus of rupture values at different maturity indices. The data were calculated using the third point flexural strength (psi) and the temperature history (˚ C-hrs).

Figure 4-2 was plotted using the data point from Table 4-2. The Trendline feature in Microsoft ® Excel was used to sketch a best fit curve that follow a logarithmic function.

The graph was later used to evaluate the flexural strength of the concrete during the experimental batch. It was also used to estimate the flexural strength on the tilt-up panel before hoisting.

Equivalent Age (EA)

The equivalent age method was also used to estimate the compressive strength of the lightweight concrete. Although, it requires the calculation of the activation energy, ASTM C 1074-2011 indicates that 40-45 KJ/mol is a good approximation. In this research, the activation energy was assumed to be 40 KJ/mol and reference temperature was taken at 20˚C. These assumptions coincided with the COMA meter specifications. Equation 3-4 was used to calculate the EA the concrete as per ASTM C 1074.

Compressive strength- Equivalent Age relationship

Table 4-3, lists the averages of EA and compressive strength of control batch for each testing day. It can be noted that for the first 14 days the calculated Equivalent Age is higher than the actual age of the concrete. This is due to the fact that the temperature of the concrete was higher than the reference temperature of 20˚C. For example, the actual age of the concrete for the first 24 hours is equivalent to 28 hours of concrete maturing at 20˚C. Beyond 14 days the temperature of the concrete dropped below the reference temperature leading to a less equivalent age compared with actual age.

The values of the EA of the control batch were plotted against the corresponding compressive strength of the concrete, yielding an equivalent age-compressive strength relationship (Figure 4-3). This relationship was used to estimate the compressive strength of the lightweight concrete tilt-up wall without performing a compressive strength test.

Flexural strength- Equivalent Age relationship

The equivalent age method was also applied to establish a flexural strength relationship. Table 4-4 displays the average flexural strength at different Equivalent ages. One can notice that the same equivalent age versus actual age pattern was repeated for the beam specimens. The equivalent age started higher than the actual age until day 14.

Figure 4-4 shows the relationship between the equivalent age in the x-axis and the flexural strength in the y-axis. The curve was used to predict the flexural strength of the lightweight concrete tilt-up panel.

Evaluation of Strength-Maturity Relationship

Establishing the strength-maturity relationship was the first step to estimating the strength of the concrete given any maturity index. However and as an extra precautionary step, the relationships were re-verified by testing specimens taken from the experimental batch.

Evaluating Temperature-Time Factor Method

In the experimental batch, two temperature loggers were inserted into the cylindrical concrete specimens to measure maturity in addition to two loggers in the panel. Concrete cylinders and beams were tested to verify the strength-TTF relationship created in the control batch.

Evaluating compressive strength-TTF relationship

Table4-5 lists the experimental batch compressive strength test for cylinders cured next to the tilt-up panel. It also lists the temperature-time factor of the panel.

Figure 4-5 shows the experimental relationship between compressive strength and the temperature-time factor. It also shows an acceptable range of 10% according to ASTM C 1074-2011. The figure concludes that the relationship developed in the control batch yielded a good evaluation of the experimental batch compressive strength.

Evaluating flexural strength-TTF relationship

Table 4-6 shows the flexural strength of the experimental batch beams and the temperature-time factor. These values were used to verify the effectiveness of the developed control batch relationship.

Figure 4-6 show the flexural strength-TTF curve of the control batch. It also plots the verification flexural strength with the corresponding TTF for the experimental batch. It also shows an acceptable range of 10% according to ASTM C 1074-2011.The figure indicates that the control batch relationship provided a very good prediction of the flexural strength of the panel.

Evaluating Equivalent Age Method

Using the equivalent age maturity method, the lightweight concrete strength of the panel was estimated using the developed control batch relationship. The relationship was also verified by testing cylinder and beam specimens at different age.

Evaluating compressive strength-EA relationship

Table 4-7 shows the compressive strengths and their equivalent age for the experimental batch. This data was used to verify the compressive strength-EA relationship developed with the control batch.

Figure 4-7 shows the verification data of the experimental batch with the control batch relationship developed earlier. It also shows an acceptable range of 10% according to ASTM C 1074-2011.It is evident that the control batch compressive strength-EA relationship yields an accurate approximation of the compressive strength of the experimental batch.

Evaluating flexural strength-EA relationship

Table 4-8 shows the flexural strengths and their equivalent age for the experimental batch. This data was used to verify the flexural strength-EA relationship developed with the control batch.

Figure 4-8 shows the verification data of the experimental batch with the control batch relationship developed earlier. It also shows an acceptable range of 10% according to ASTM C 1074-2011.It is evident that the control batch flexural strength-EA relationship yields an excellent approximation of the flexural strength of the experimental batch.

Evaluating COMA-Meter

The COMA meter is a mini maturity meter that reflects the age of the concrete based on the equivalent age method. Four COMA meters were used to test the maturity of concrete in the experimental batch. Two meters were placed in cylinder specimens, the others were inserted in the tilt-up panel.

Table 4-9 shows the average of COMA meter readings and compares them to the equivalent age calculations. It was noticed that the COMA meter readings were similar to the calculated equivalent age which means that COMA meter ultimately provided a good early age strength of concrete (within the first three days) . However, as the concrete further matured the COMA meter underestimated the strength of the concrete.

Table 4-1. Control batch TTF and compressive strength

		Cylinder Specimens	
Time (Days)	Time (hrs)	Average (TTF) Temperature-Time Factor (C-hour)	Average Compressive Strength (psi)
1	24	844	844
4	94	2,526	2,526
7	164	2,930	2,930
14	333	3,645	3,645
28	669	4,234	4,234

* Numbers are rounded to the nearest integer

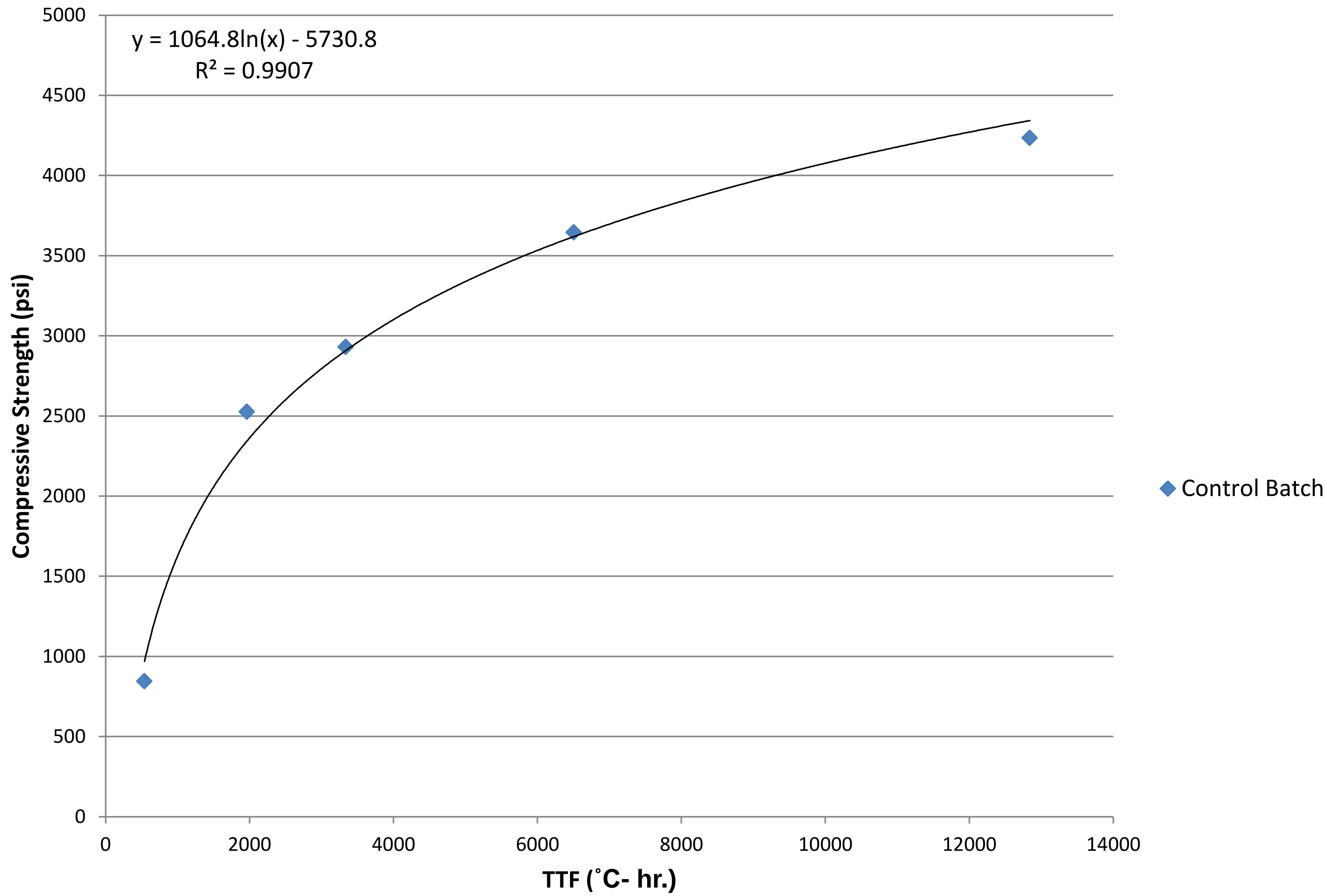


Figure 4-1. Compressive Strength-TTF Relationship

Table 4-2. Control batch TTF and flexural strength

		Beam Specimens	
Time (Days)	Time (hrs)	Average (TTF) Temperature-Time Factor (C-hour)	Average Flexural Strength (psi)
1	25	598	220
3	71	1,518	406
7	165	3,293	542
14	333	6,376	646
28	669	12,493	713

* Numbers are rounded to the nearest integer

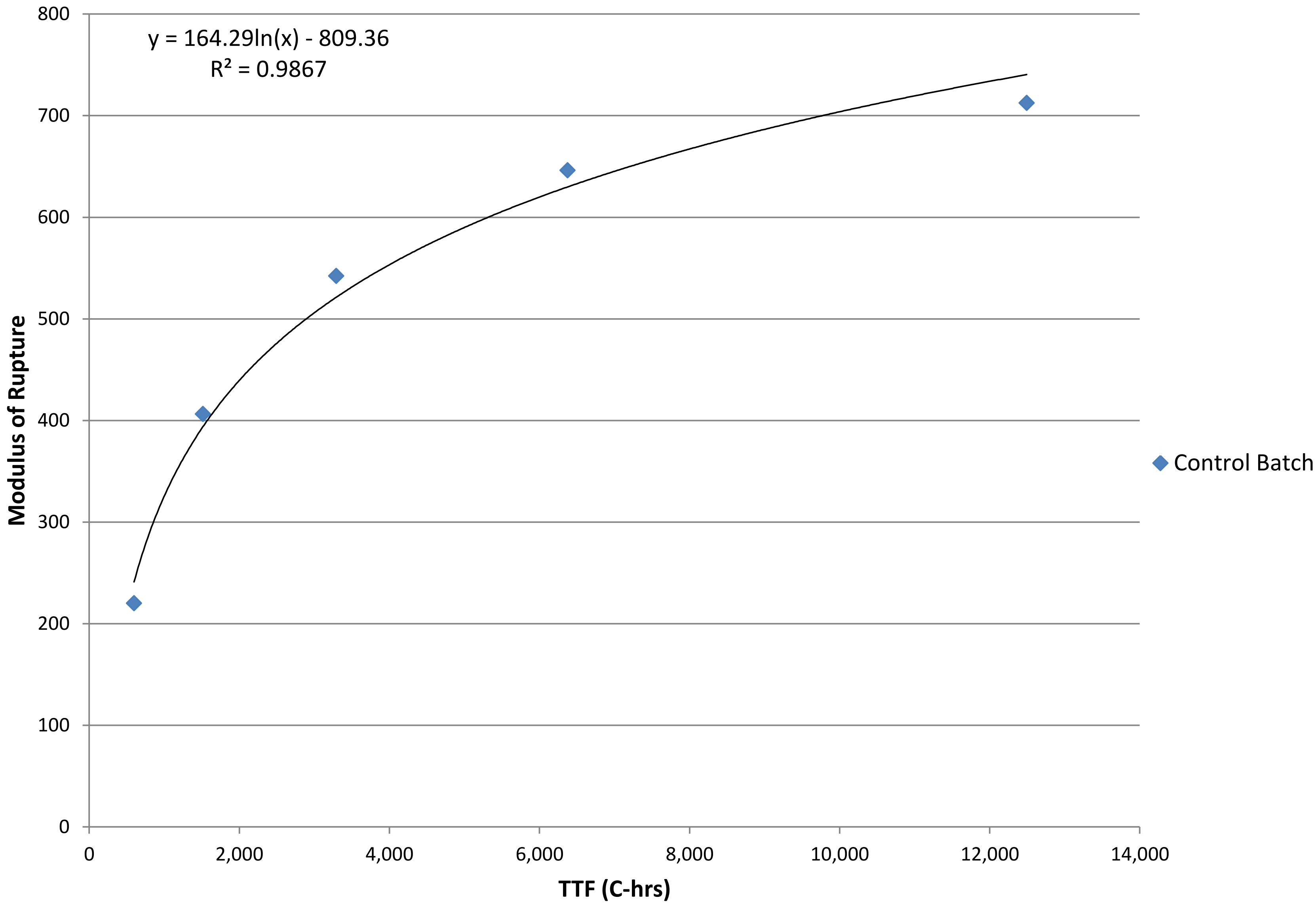


Figure 4-2. Flexural Strength-TTF Relationship

Table 4-3. Equivalent age and compressive strength

Approx. Time (Days)	Actual Time (hrs)	Cylinder Specimens Equivalent Age (hrs)	Average Compressive Strength (psi)
1	24	28	844
4	94	101	2,526
7	164	173	2,930
14	333	337	3,645
28	669	658	4,234

Numbers are rounded to the nearest integer

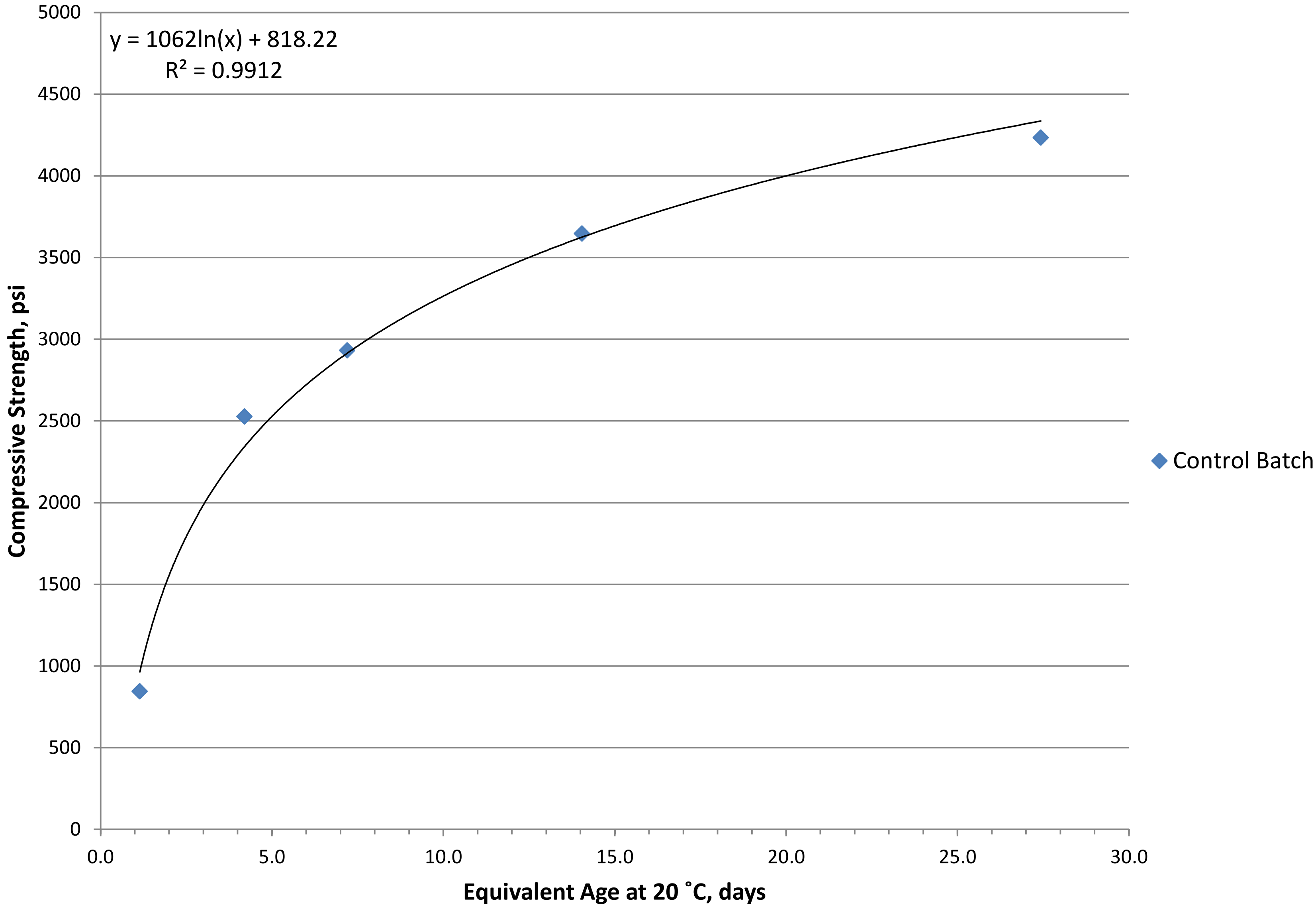


Figure 4-3. Compressive Strength - Equivalent Age Relationship

Table 4-4. Equivalent age and flexural strength

Time (Days)	Time (hrs)	Beam Specimens Equivalent Age (hrs)	Beam Specimens Average Flexural Strength (psi)
1	25	29	844
3	71	78	2,526
7	165	173	2,930
14	333	332	3,645
28	669	645	4,234

Numbers are rounded to the nearest integer

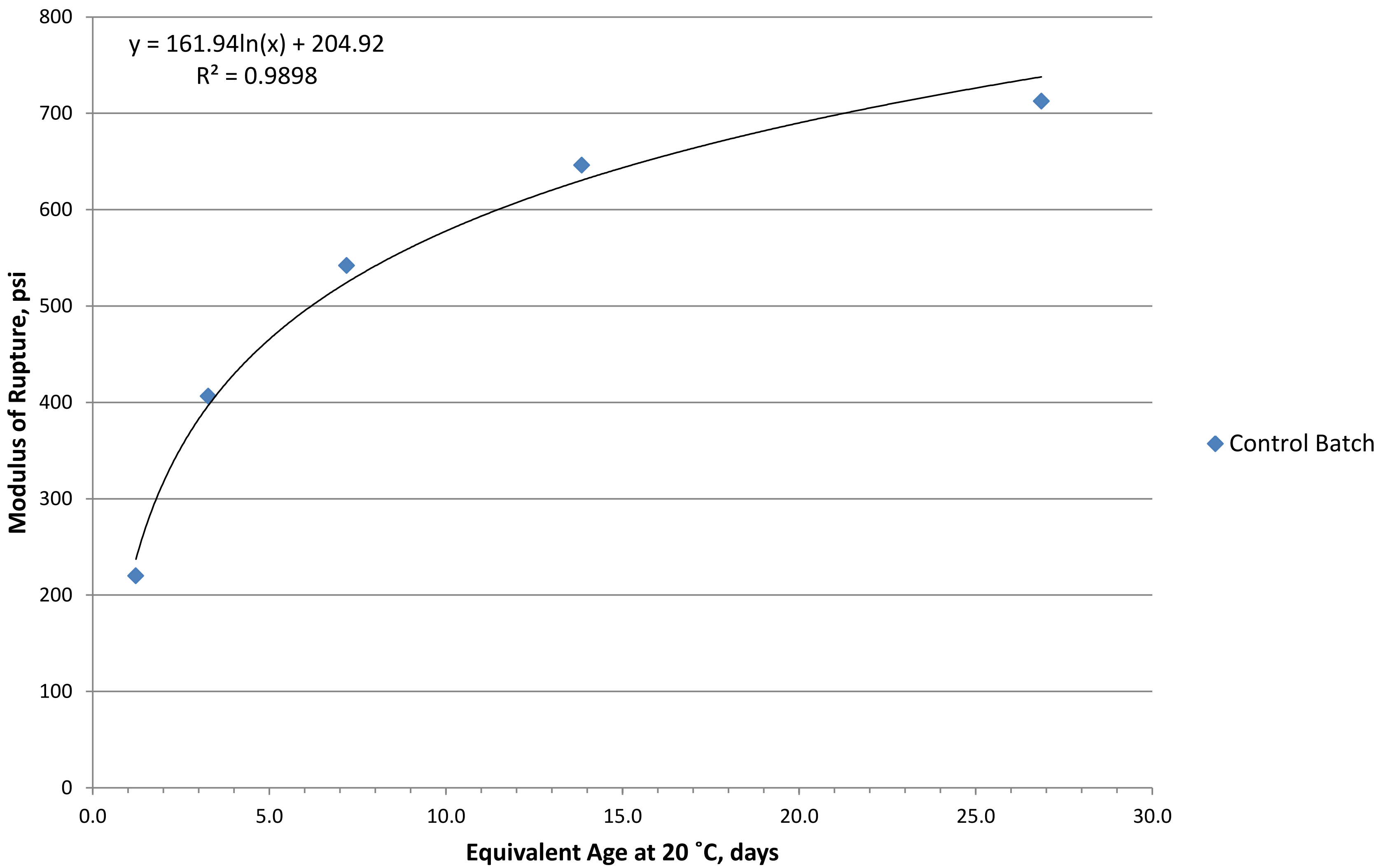


Figure 4-4. Flexural Strength- Equivalent Age Relationship

Table 4-5. Compressive strength-TTF verification, experimental batch.

		Cylinder Specimens	
Time (Days)	Time (hrs)	Average (TTF) Temperature-Time Factor (C-hour)	Average Compressive Strength (psi)
1	25	787	1,670
3	76	2,178	2,620
7	168	4,350	3,389
10	249	6,430	3,989

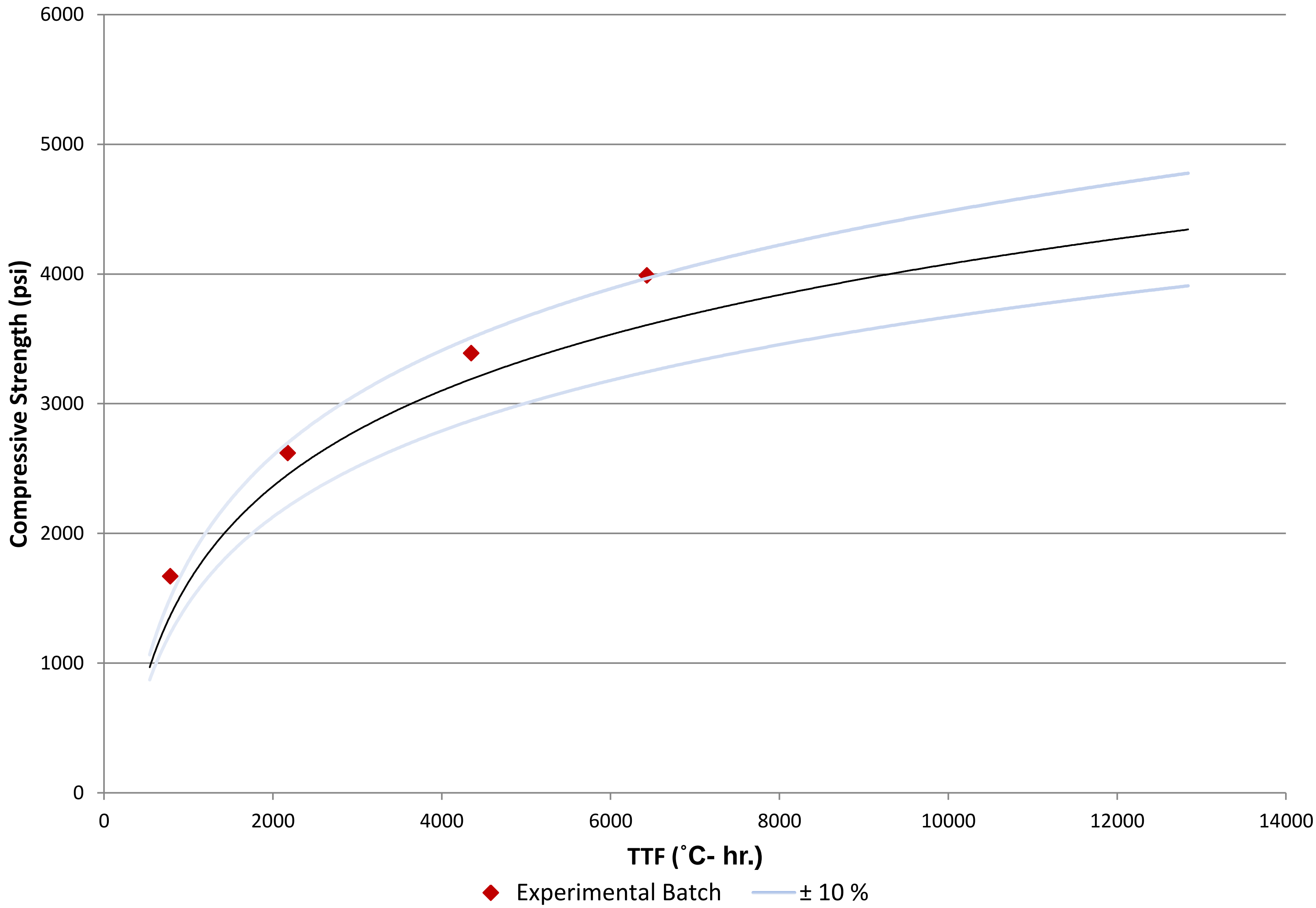


Figure 4-5. Verification of Compressive strength- TTF relationship, experimental batch

Table 4-6. Flexural strength-TTF verification, experimental batch

		Beam Specimens	
Time (Days)	Time (hrs)	Average (TTF) Temperature-Time Factor (C-hour)	Average Flexural Strength (psi)
1	25	787	1,670
3	76	2,178	2,620
7	168	4,350	3,389
10	249	6,430	3,989

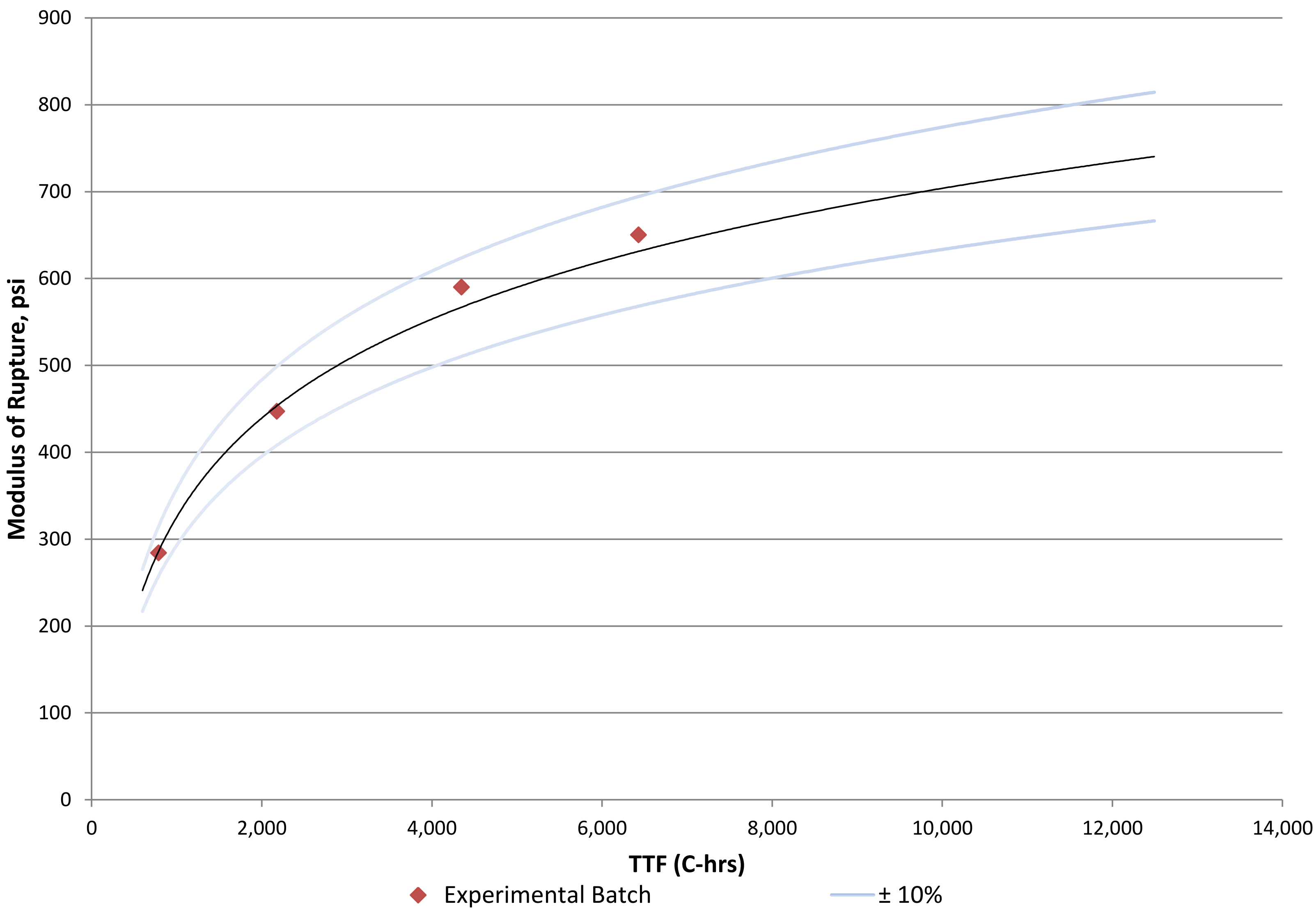


Figure 4-6. Verification of flexural strength- TTF relationship, experimental batch

Table 4-7. Compressive strength-EA verification, experimental batch

Time (Days)	Time (hrs)	Cylinder Specimens Equivalent Age (hrs)	Average Compressive Strength (psi)
1	25	46	844
3	76	128	2,526
7	168	255	2,930
10	249	367	3,645

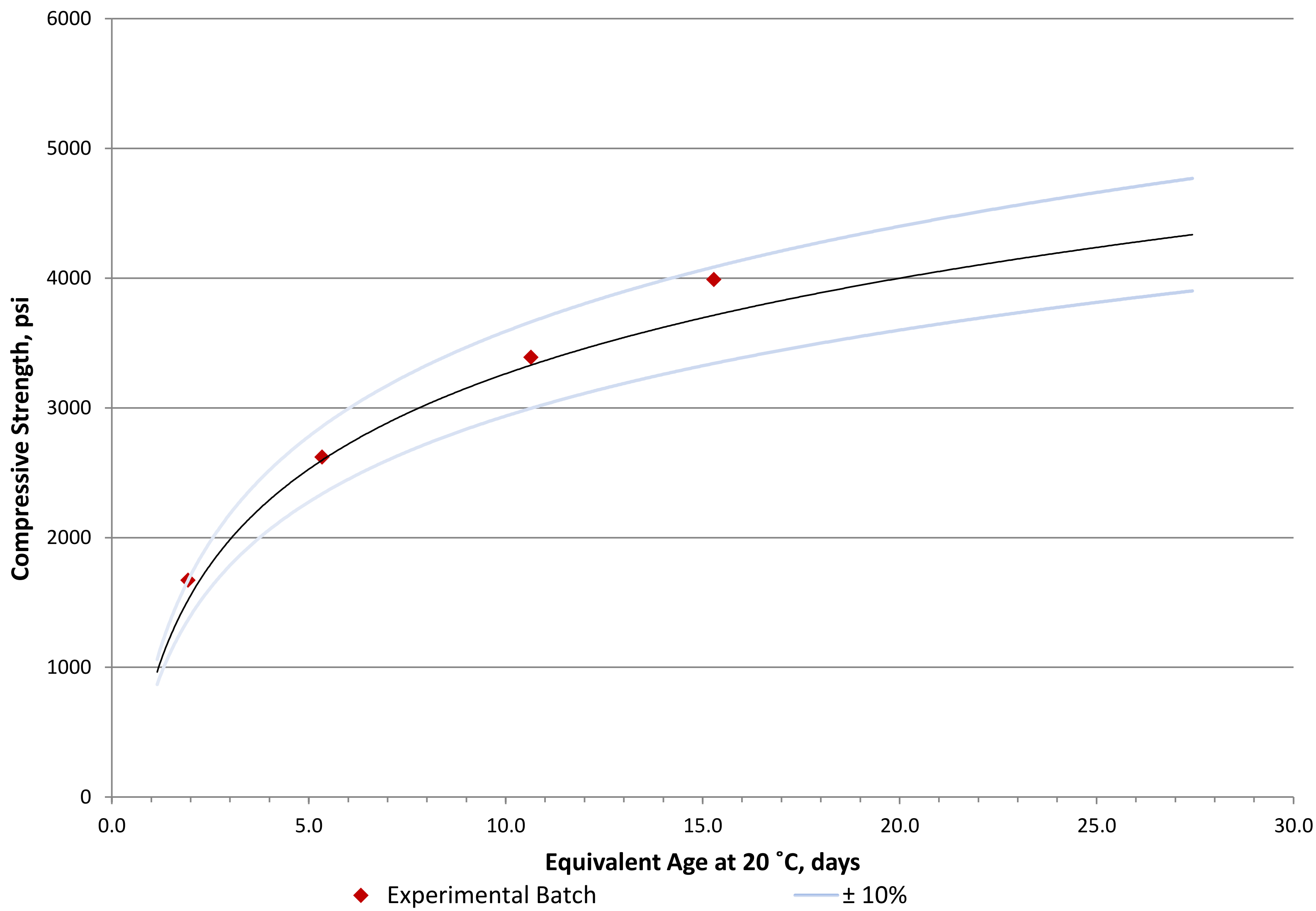


Figure 4-7. Verification of compressive strength-EA relationship, experimental batch

Table 4-8. Flexural strength – EA verification, experimental batch.

		Beam Specimens	
Time (Days)	Time (hrs)	Equivalent Age (hrs)	Average Flexural Strength (psi)
1	25	46	284
3	76	128	447
7	168	255	590
10	249	367	650

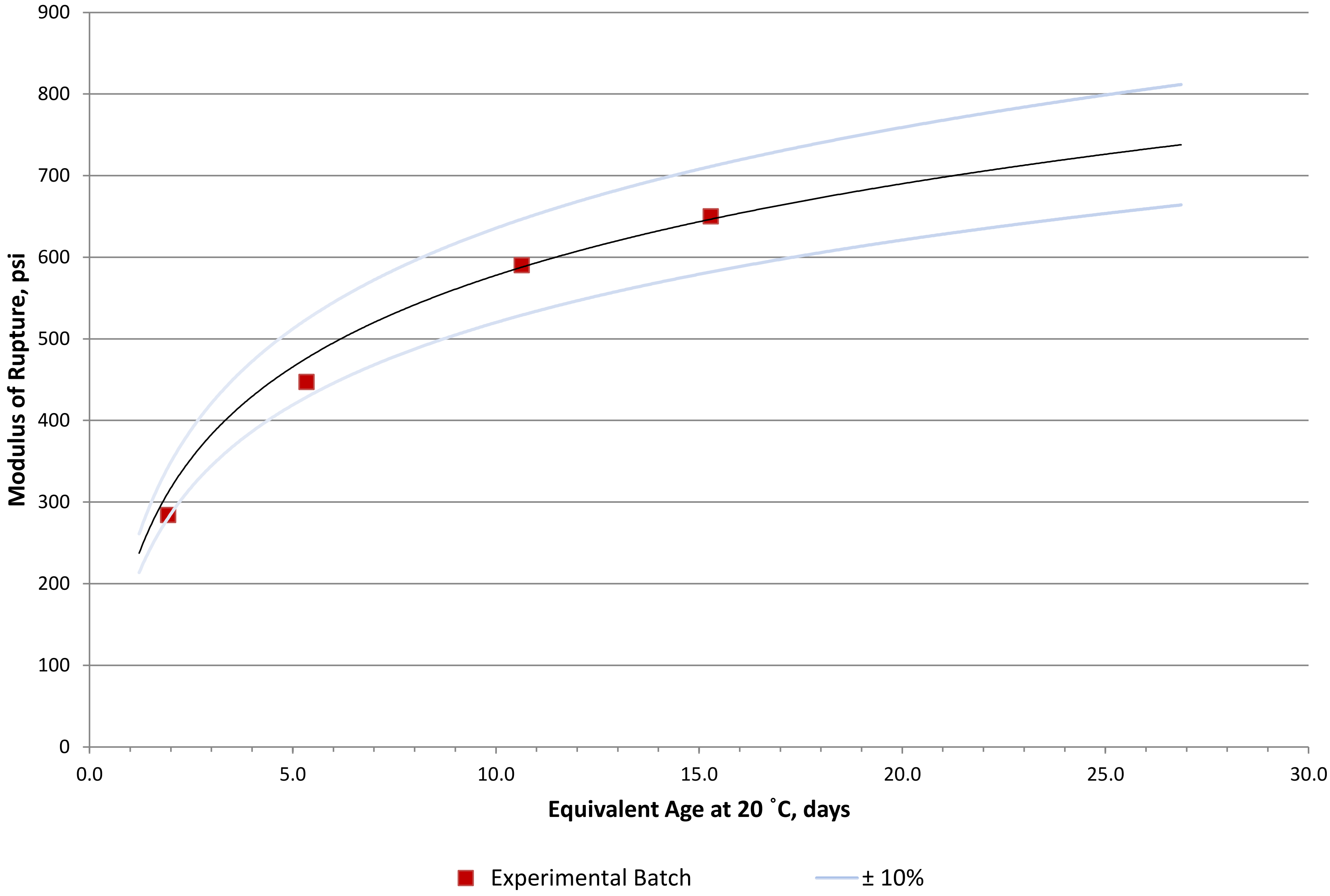


Figure 4-8. Verification of flexural strength–EA relationship, experimental batch

Table 4-9. COMA Meter and Equivalent Age

Time of reading (hrs)	COMA reading (days)	COMA reading (hrs)	Calculated EA Reading (hrs)
0	0	0	0
60	4.5	108	101
145	7.5	180	204
254	13	312	350

CHAPTER 5
PULLOUT METHOD

Strength-Pullout Relationship

The pullout strength test, as described by ASTM C 900, is a semi-destructive test for estimating the compressive strength of the concrete. This test was performed on the control batch of the lightweight concrete to create a relationship between the pull force and the strength of the concrete. This relationship was then applied to estimate the strength of the tilt-up panel before lifting. The pull force relationship with compressive strength and flexural strength were compared, results are stated below. It was observed at day 7 of the control batch that the pullout test has developed radial cracks in the cylinder specimen outside of the testing area (Figure 5-1 A). The cracks further developed as the insert was being extracted out of the concrete (Figure 5-1 B).This may have been the reason for the off coarse reading in that day. This problem was resolved by encasing the cylinder specimen in a thick plastic pipe (Figure 5-2).

Compressive Strength- Pullout Relationship

Table 5-1 shows the pullout force obtained by applying the LOK-test with the corresponding compressive strength.

The data was plotted with the pull force in the x-axis and the compressive strength in the y-axis. The points were connected via Microsoft ® Excel Trendline feature (Figure 5-3). The best fit curve was applied as a linear function. The relationship was used to estimate the strength of the tilt-up wall.

Flexural Strength- Pullout Relationship

The data for the pull force was used to develop a relationship with flexural strength of the lightweight concrete, control batch. Table 5-2 lists the values of the pull force and the flexural strength of the lightweight concrete side by side.

Figure 5-4 draws the relationship between the flexural strength and the pull force. This relationship was used to estimate the flexural strength of the tilt-up panel.

Evaluation of Strength- Pullout Relationship

The strength of the tilt-up panel was estimated using the pullout test. Pullout inserts were embedded on the sides of the tilt-up panel in addition to a surface insert. It was noticed that the pullout test performed on the side pullout underestimated the actual strength of the concrete; this was verified by testing the concrete specimens for strength. The estimating errors of the panel side inserts were related to the slenderness of the panel, 3.5 inches (Figure 5-5). Nevertheless, the surface insert yielded a good approximation of the strength of the panel with no visible cracks (Figure 5-6).

Evaluating Compressive Strength- Pullout Relationship

Table 5-3 lists the pullout force of the experimental batch. It also lists two values for pullout strength, one for the panels’ side inserts and the other is for the panel’s surface.

Figure 5-7 shows the compressive strength- pullout curve for the control batch and the experimental batch data verifications. It also shows a 10% range of acceptable results. The acceptable range was derived from the acceptable variations of the pullout test which may be as high as 36% of the average according to ASTM C 900-06. The acceptable range for this research was limited to 10% due to the critical nature of the tilt-up operation.

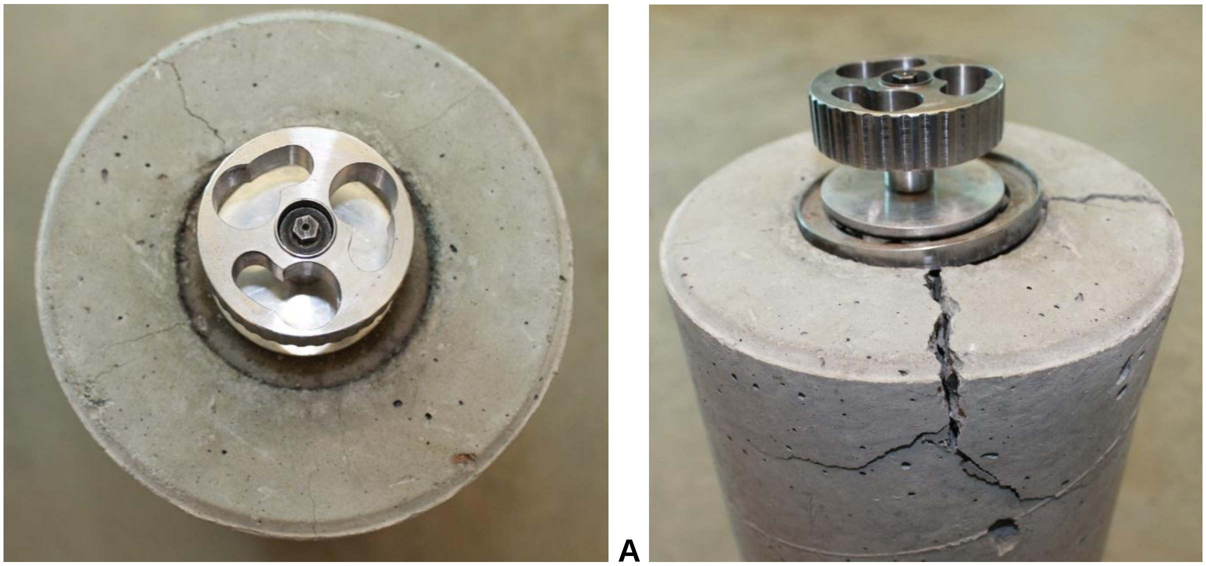
As previously discussed, most of the errors in the verification data can be attributed to the slenderness of the panel. Generally, the inserts located in the tilt-up panel sides underestimated the compressive strength of the lightweight concrete. In other words, the measured pullout force was less than the anticipated result according to the developed relationship in the control batch. However, the surface of the panel pullout insert resulted in a compressive strength estimate that was in line with the control batch relationship.

Evaluating Flexural Strength- Pullout Relationship

Table 5-4 indicates the values of the flexural strength of the lightweight concrete in the experimental batch and the corresponding pullout force.

Figure 5-8 depicts the flexural strength- pullout curve for the control batch and the experimental batch data. It also shows a 10% range of acceptable results. The acceptable range was derived from the acceptable variations of the pullout test which may be as high as 36% of the average according to ASTM C 900-06. The acceptable range for this research was limited to 10% due to the critical nature of the tilt-up operation.

As previously stated, the pull force results of the inserts of the panels’ sides deviated more from the actual flexural strength of the experimental batch than their counterpart surface insert.



A B

Figure 5-1. Radial cracking on cylinder due to pull force. A) Cracks at failure. B) Cracks at insert extraction. (photo courtesy of Adel Alsaffar)

Figure 5-2. Encased cylinder during pullout testing (photo courtesy of Adel Alsaffar)

Table 5-1. Pull force and compressive strength

Time (Days)	Time (hrs)	Pullout Force (KN)	Cylinder Specimens Compressive Strength (psi)
1	24	6.3	1024
3	70	12.1	2059
7	161	17.65	2918
14	331	19.1	3627
28	667	21.6	4335

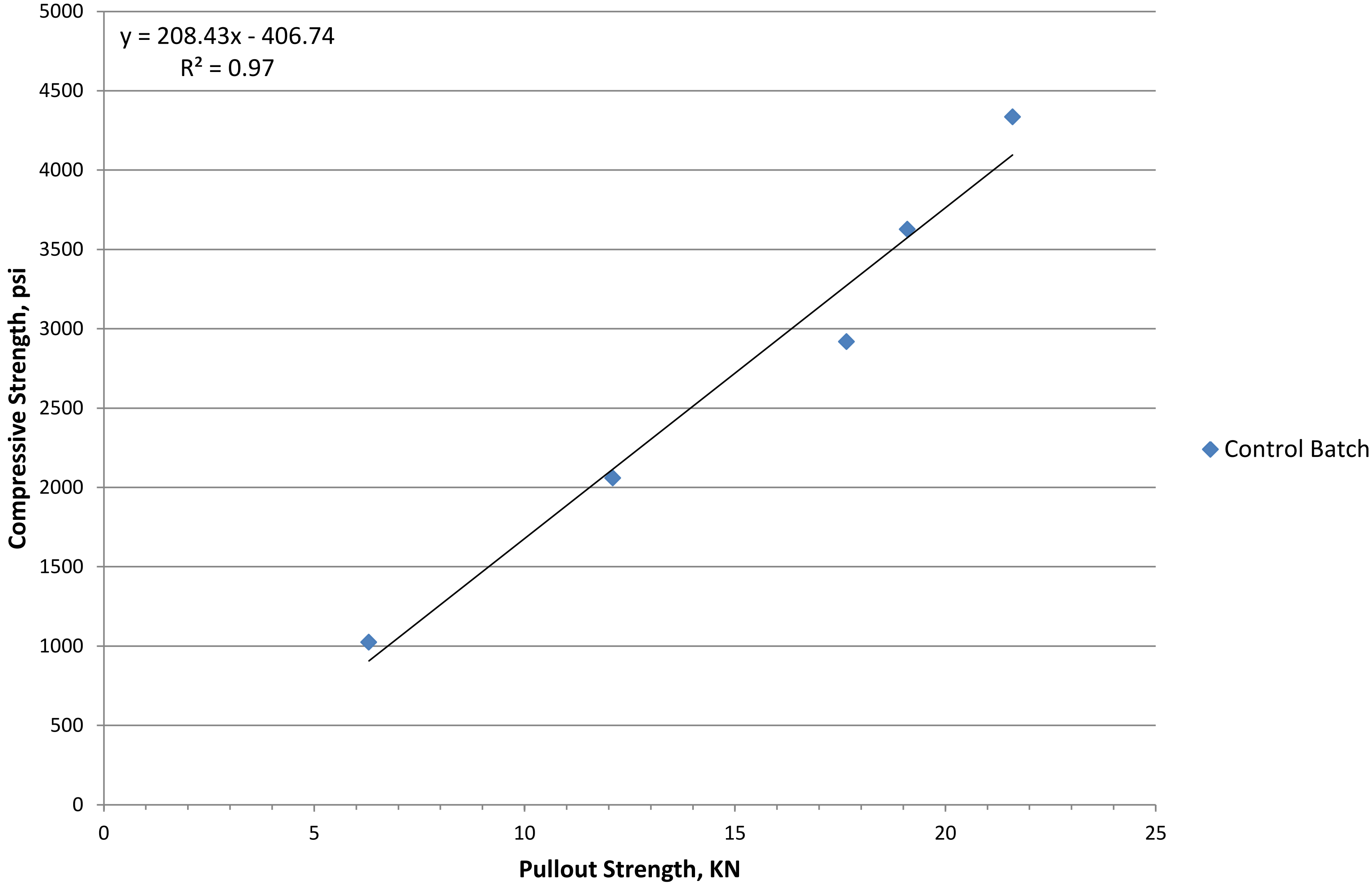


Figure 5-3. Compressive strength- pullout relationship

Table 5-2. Pull force and flexural strength

Time (Days)	Time (hrs)	Cylinder Specimens Pullout strength (KN)	Flexural Strength (psi)
1	24	6.3	246
3	70	12.1	399
7	161	17.65	527
14	331	19.1	632
28	667	21.6	737

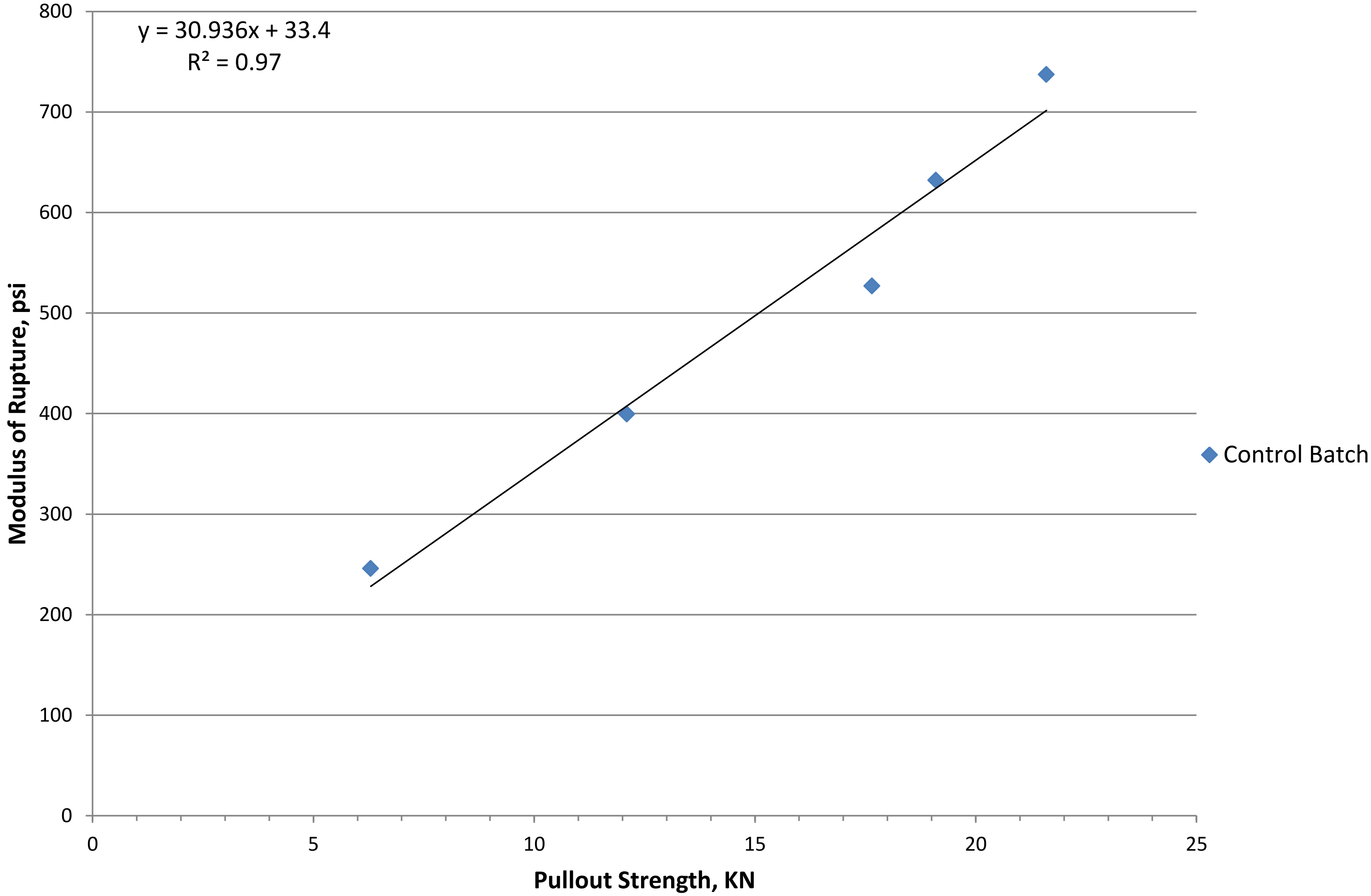


Figure 5-4. Flexural strength- pullout relationship

Figure 5-5. Cracking outside the testing area- tilt-up panel side (photo courtesy of Adel Alsaffar)

Figure 5-6. Pullout insert, tilt-up panel surface (photo courtesy of Adel Alsaffar)

Table 5-3. Compressive strength and pullout, experimental batch

		Panels' sides		Panel's surface	
Time (Days)	Time (hrs)	Pull Force (KN)	Compressive Strength (psi)	Pull Force (KN)	Compressive Strength (psi)
1	25	10.1	1670		
3	76	12	2620		
7	168	15	3389		
10	249	17.2	3989	20.6	3989

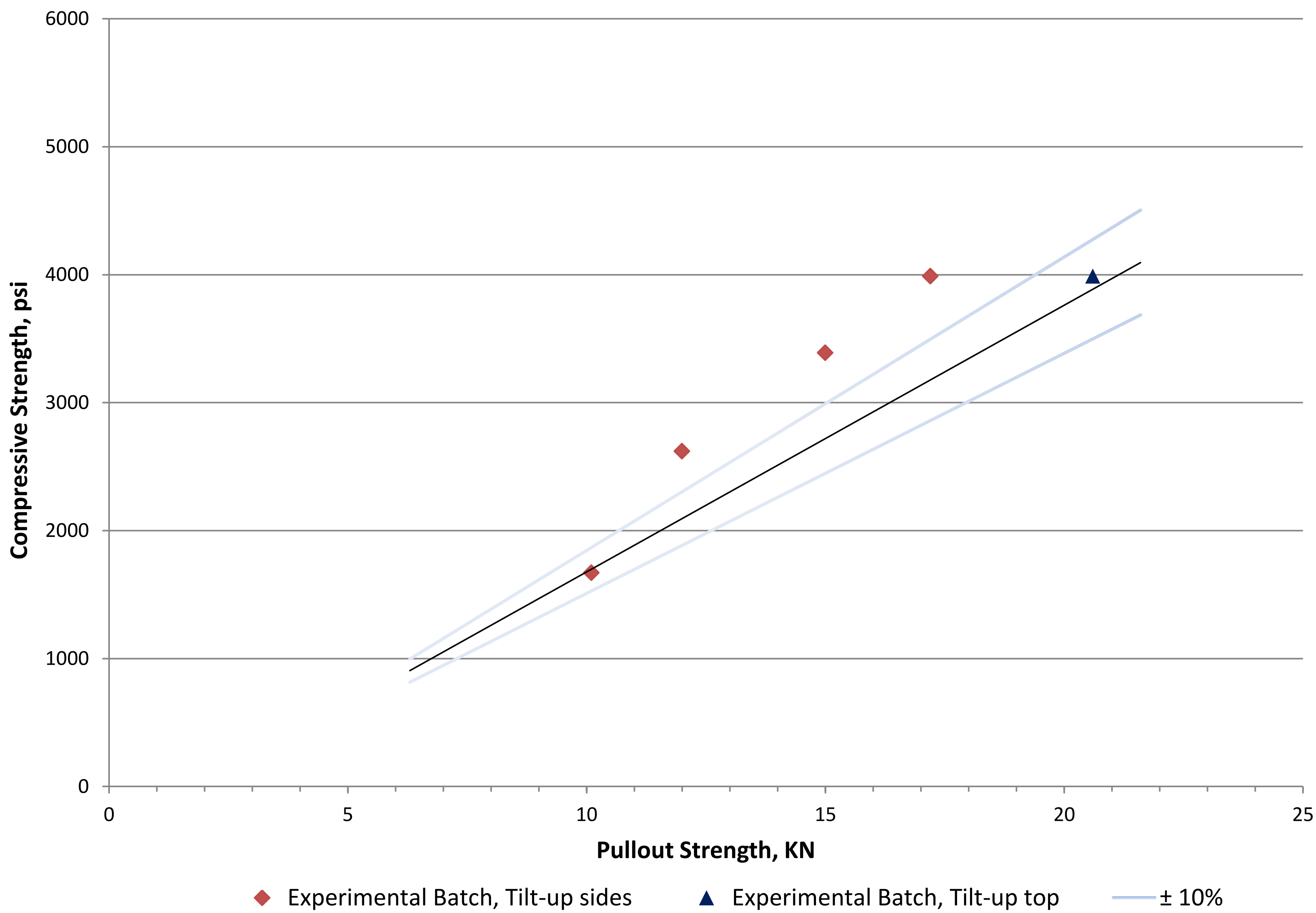


Figure 5-7. Verification of compressive strength- pullout relationship

Table 5-4. Flexural strength and pullout, experimental batch

Time (Days)	Time (hrs)	Panels' sides Pull Force (KN)	Panels' sides Flexural Strength (psi)	Panel's surface Pull Force (KN)	Panel's surface Flexural Strength (psi)
1	25	10.1	284		
3	76	12	447		
7	168	15	590		
10	249	17.2	650	20.6	650

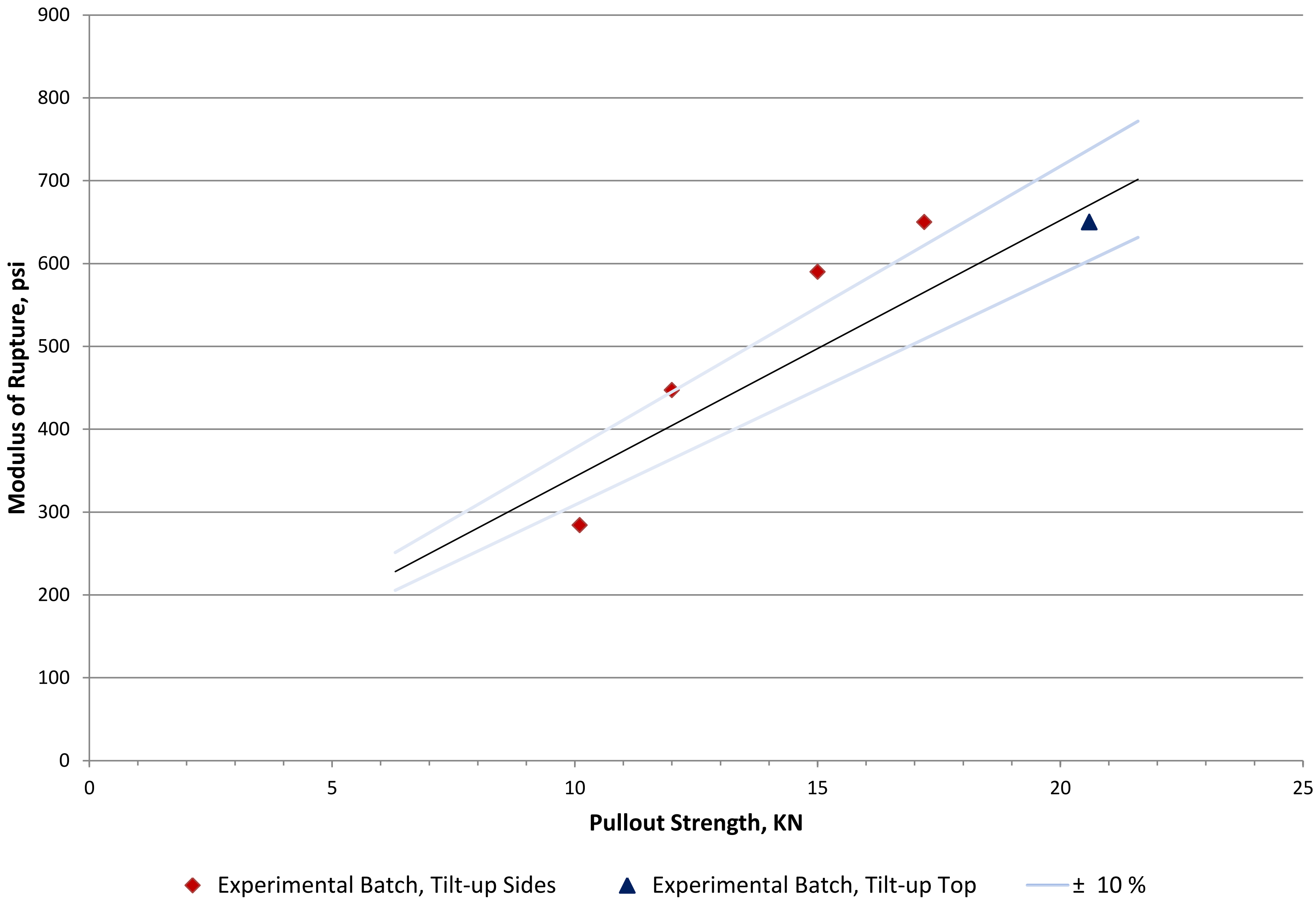


Figure 5-8. Verification of flexural strength- pullout relationship

CHAPTER 6
MATURITY AND PULLOUT STRENGTH

Pullout Strength-Maturity Relationship

ASTM C 1074-2011 states that for critical operations such as post-tensioning or form removal, strength tests other than maturity should be performed for verification. The standard suggests tests such as penetration resistant (ASTM C 803), cast in place mold (ASTM C 873) or pullout test (ASTM C 900). In this research, the pullout test was performed along with the maturity method to estimate the strength of the lightweight concrete before lifting the tilt-up panel.

As demonstrated in Chapter 5, the pullout strength is linearly proportionate to the compressive and flexural strength of concrete. Furthermore, it has been shown that compressive and flexural strength- maturity relationships exist. Therefore, the relationship between pullout strength and maturity was investigated to provide more confidence in the concrete strength estimation.

Pullout Strength-TTF

The pullout strength test results were linked to the temperature time factor maturity method results. The links were used to estimate the compressive and flexural strength of the lightweight concrete.

Table 6-1 lists the pullout force at different TTF values for the control batch. This data was used to establish a pullout strength- TTF relationship.

Pullout strength-TTF-compressive strength

Figure 6-1 shows the relationship of the pullout strength and the temperature-time factor maturity method. The relationship was developed using Microsoft ® Excel with the best fit curve being a logarithmic function. The secondary y-axis shows the compressive strength of the concrete for easy reference. It was used as verification of the compressive strength of the tilt-up panel.

Pullout strength-TTF-flexural strength

Figure 6-2 illustrates the relationship of the pullout strength and the temperature-time factor maturity method. The relationship was developed using Microsoft ® Excel with the best fit curve being a logarithmic function. The secondary y-axis shows the flexural strength of the concrete for easy reference. It was used as verification of the flexural strength of the tilt-up panel.

Pullout Strength-Equivalent Age (EA)

The pullout strength test results were linked to the equivalent age maturity method results. The links were used to estimate the compressive and flexural strength of the lightweight concrete.

Table 6-2 lists the pullout strength at different equivalent ages for the control batch. This data was used to establish a pullout strength-EA relationship.

Pullout strength-EA-compressive strength

Figure 6-3 shows the relationship of the pullout strength and Equivalent age maturity method. The relationship was developed using Microsoft ® Excel with the best fit curve being a logarithmic function. The secondary y-axis shows the compressive strength of the concrete for easy reference. It was used as verification of the compressive strength of the tilt-up panel.

Pullout strength-EA-flexural strength

Figure 6-4 illustrates the relationship of the pullout strength and the equivalent age maturity method. The relationship was developed using Microsoft ® Excel with the best fit curve being a logarithmic function. The secondary y-axis shows the flexural strength of the concrete for easy reference. It was used as verification of the flexural strength of the tilt-up panel.

Evaluation of Pullout Strength-Maturity

The pullout strength- maturity relationships were used to estimate the strength of the lightweight concrete in the experimental batch. The relationships were verified to test their validities.

Pullout Strength-TTF Verification

The pullout strength-TTF relationships created in the control batch were used to estimate the compressive and flexural strength of the experimental batch concrete.

Pullout strength-TTF –compressive strength verification

Figure 6-5 demonstrates the verification data of the pullout strength in the experimental batch as a function of TTF. The figure also shows a 10% range of acceptable results.

The pullout strength taken at the side of the tilt-up panel underestimated the compressive strength of the concrete due to radial cracks developed during testing. However the pullout strength determined at the surface of the tilt-up slightly overestimated the compressive strength of the concrete, but within the 10% acceptable range.

Pullout strength-TTF–flexural strength verification

Figure 6-6 illustrates the verification data of the pullout strength in the experimental batch as a function of TTF. The figure also shows a 10% range of acceptable results.

The pullout strength taken at the side of the tilt-up panel underestimated the flexural strength of the concrete due to radial cracks developed during testing (Figure 5-

5). However the pullout strength taken at the surface of the tilt-up panel slightly overestimated the flexural strength of the concrete, but within the 10% acceptable range.

Pullout Strength-EA Verification

The pullout strength-EA relationships created in the control batch were used to predict the compressive and flexural strength of the experimental batch concrete.

Pullout strength-EA–compressive strength verification

Figure 6-7 demonstrates the verification data of the pullout strength in the experimental batch as a function of EA. The figure also shows a 10% range of acceptable results.

The pullout strength taken from the side of the tilt-up panel underestimated the compressive strength of the concrete due to radial cracks developed during testing (Figure 5-5). However the pullout strength taken at the surface of the tilt-up panel slightly overestimated the compressive strength of the concrete, but within the 10% acceptable range.

Pullout strength-EA–flexural strength verification

Figure 6-8 illustrates the verification data of the pullout strength in the experimental batch as a function of EA. The figure also shows a 10% range of acceptable results.

The pullout strength taken at the side of the tilt-up panel underestimated the flexural strength of the concrete due to radial cracks developed during testing. However the pullout strength taken at the surface of the tilt-up panel slightly overestimated the flexural strength of the concrete, but within the 10% acceptable range.

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Table 6-1. Pullout strength- TTF , control batch

Time (Days)	Time (hrs)	Pullout strength (KN)	Average TTF (C-hrs)
1	24	6.3	540
3	70	12.1	1470
7	161	17.65	3242
14	331	19.1	6468
28	667	21.6	12803

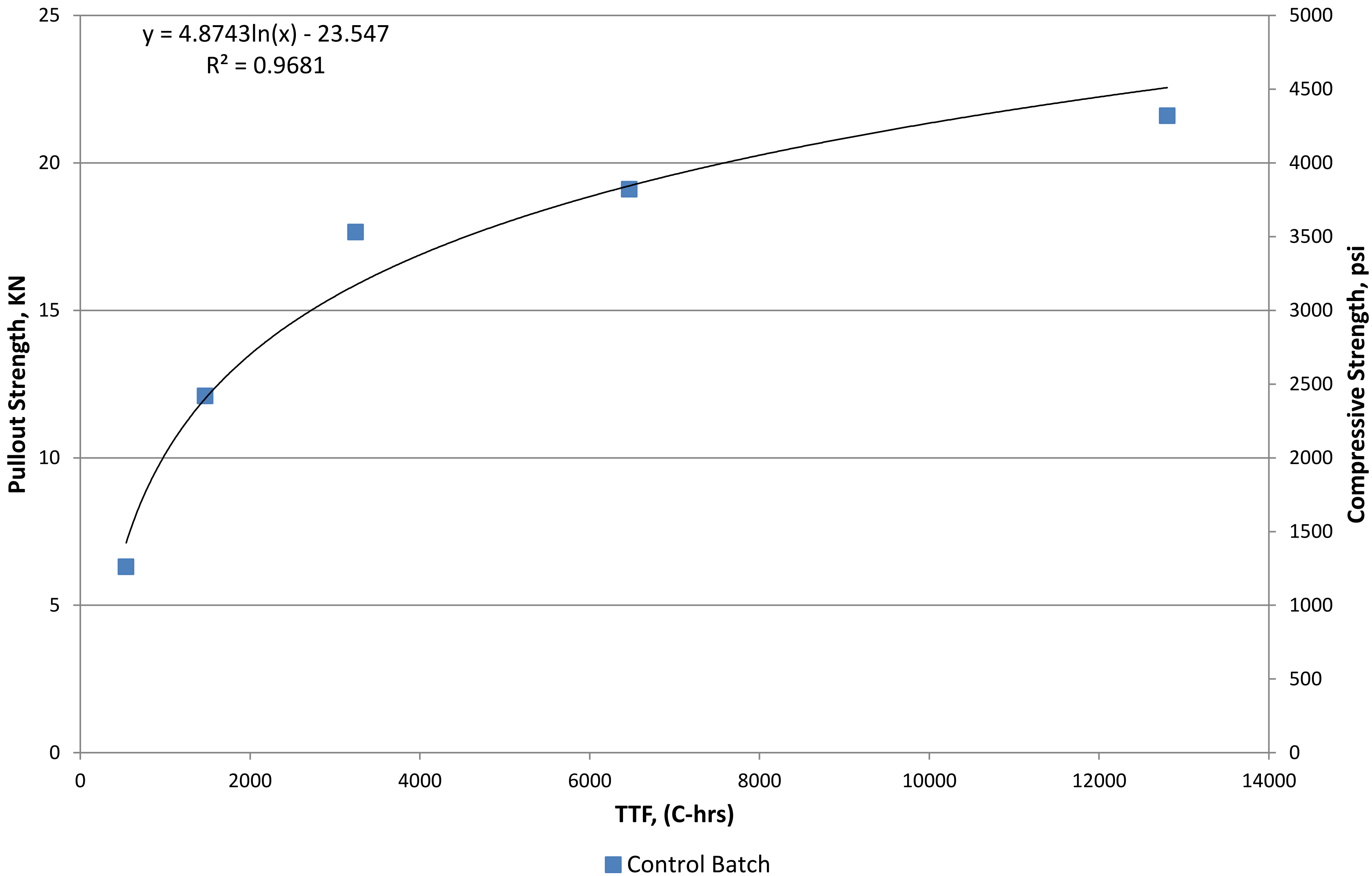
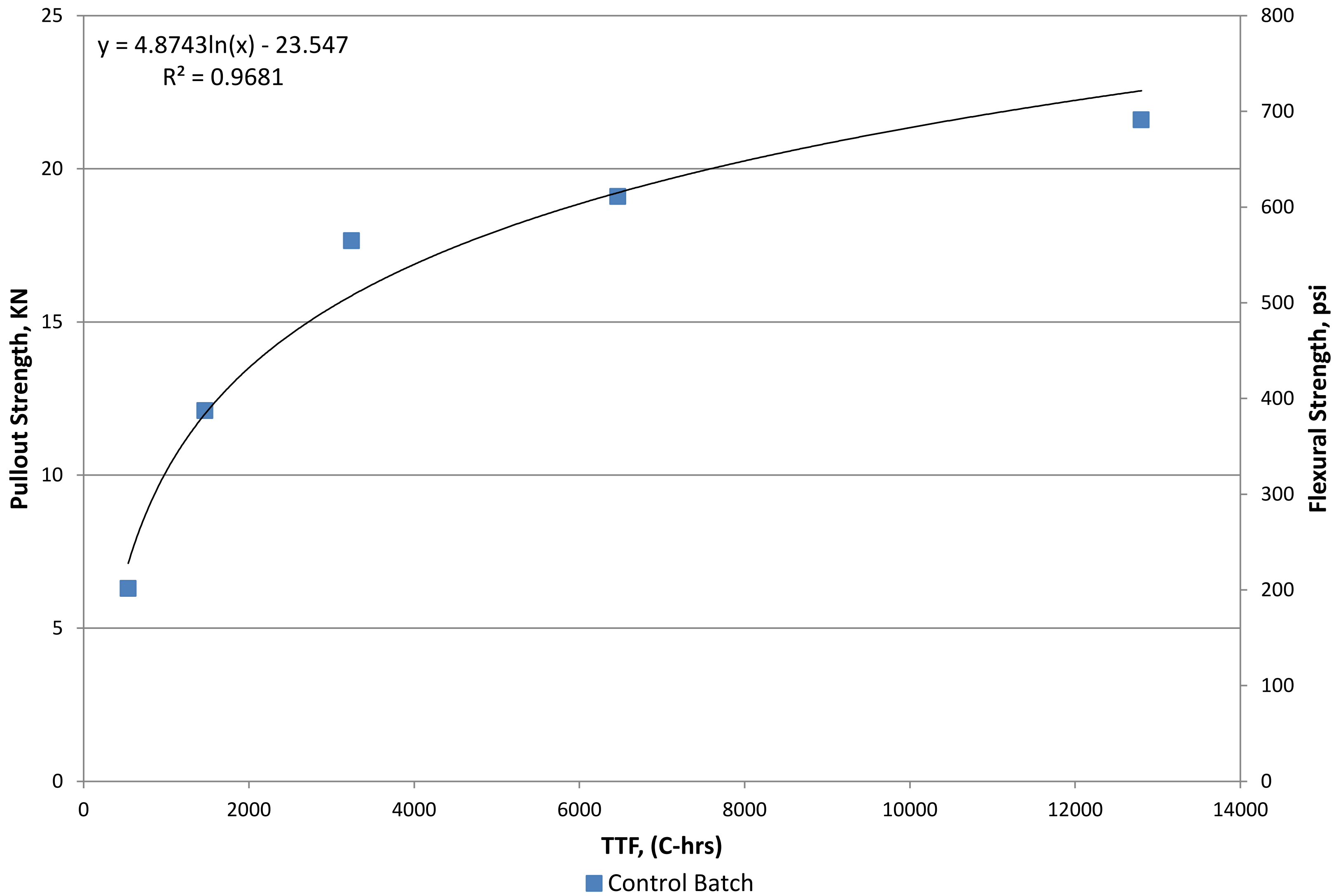


Figure 6-1. Pullout strength-TTF- compressive strength relationship, control batch



.
Figure 6-2. Pullout strength-TTF- flexural strength relationship, control batch

Table 6-2. Pullout stregth-EA , control batch

Time (Days)	Time (hrs)	Pullout strength (KN)	Calculated Equivalent Age (days)
1	24	6.3	540
3	70	12.1	1470
7	161	17.65	3242
14	331	19.1	6468
28	667	21.6	12803

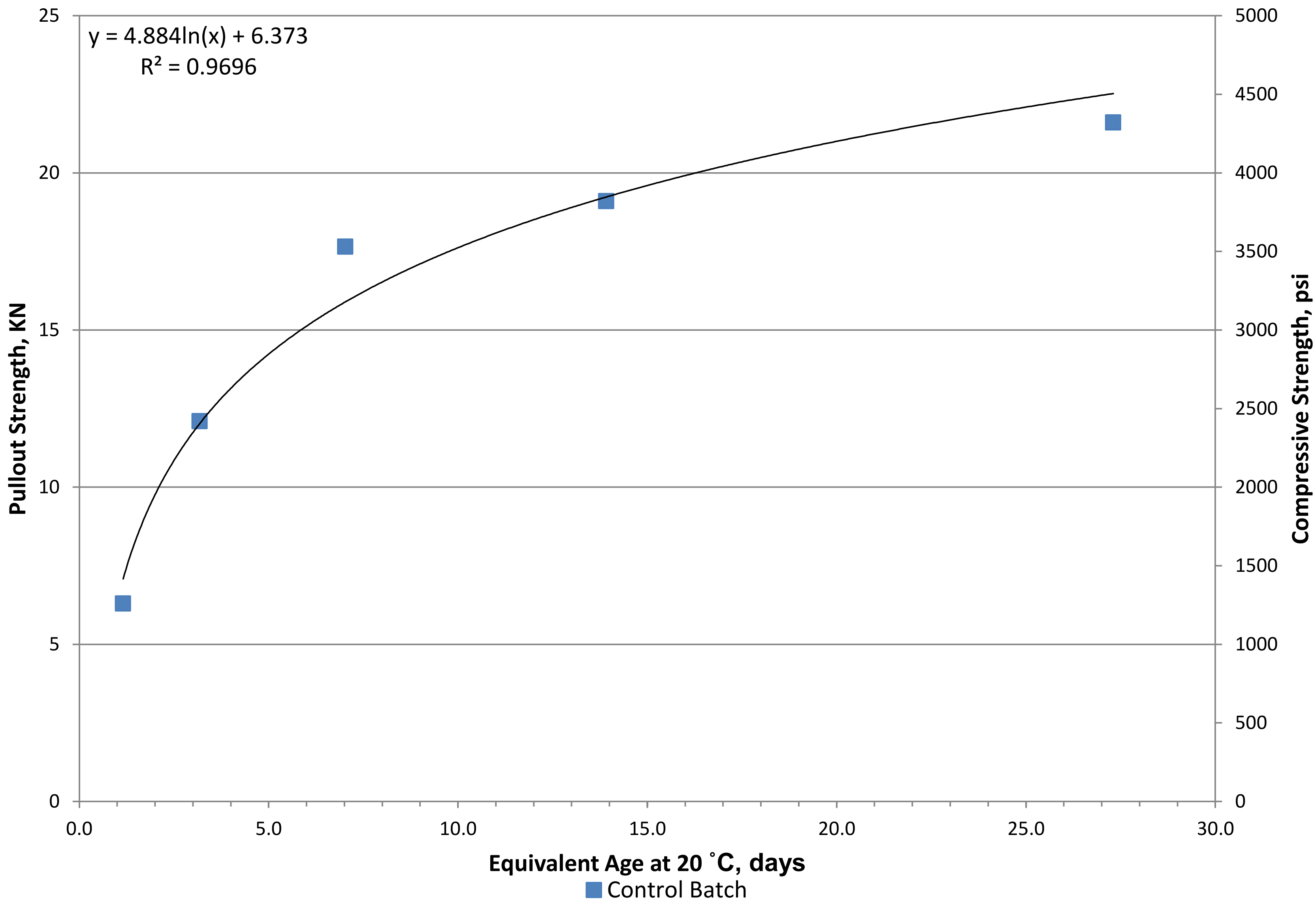


Figure 6-3. Pullout stregth-EA-compressive strength relationship, control batch

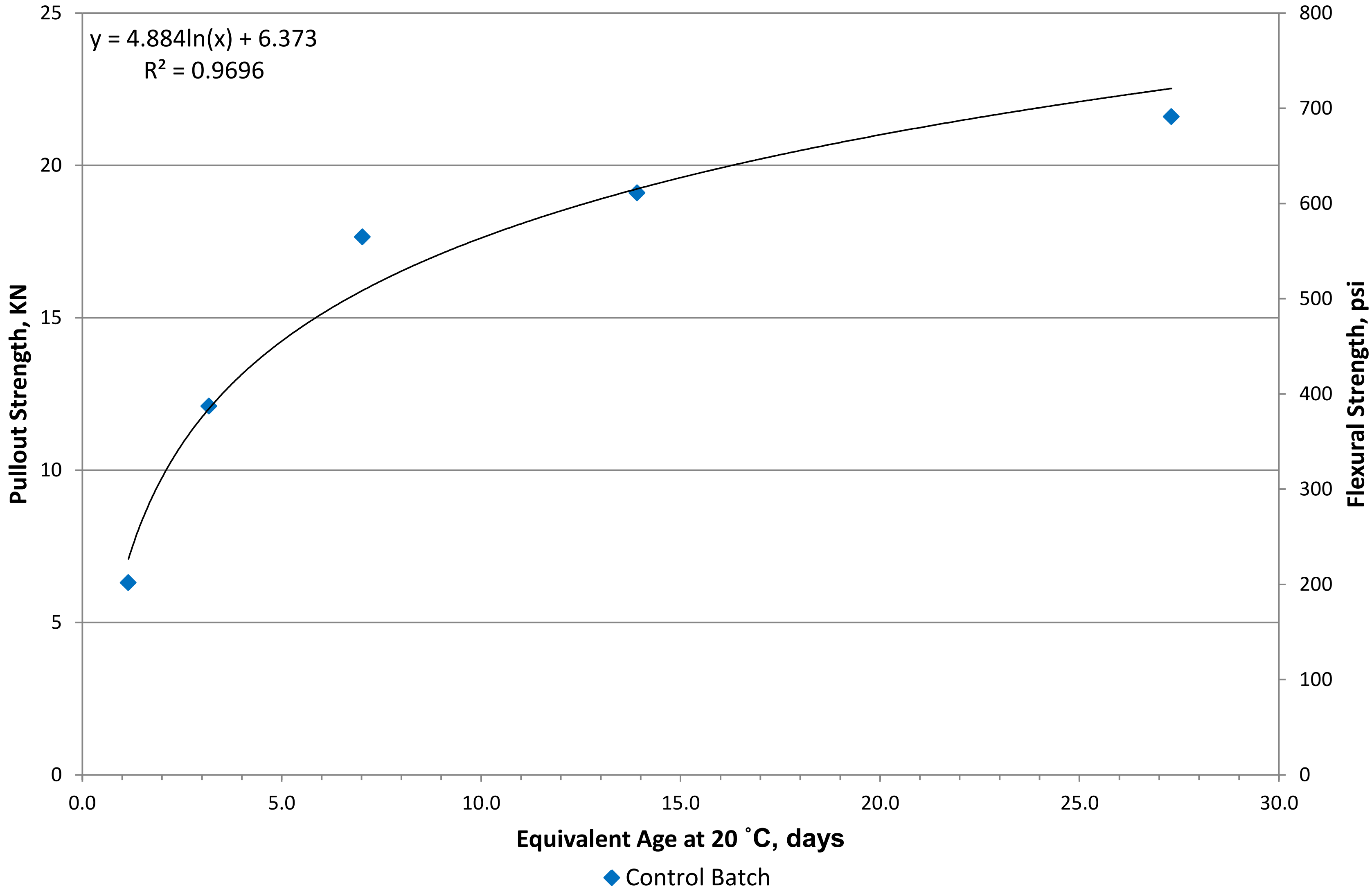


Figure 6-4. Pullout stregth-EA-flexural strength relationship, control batch

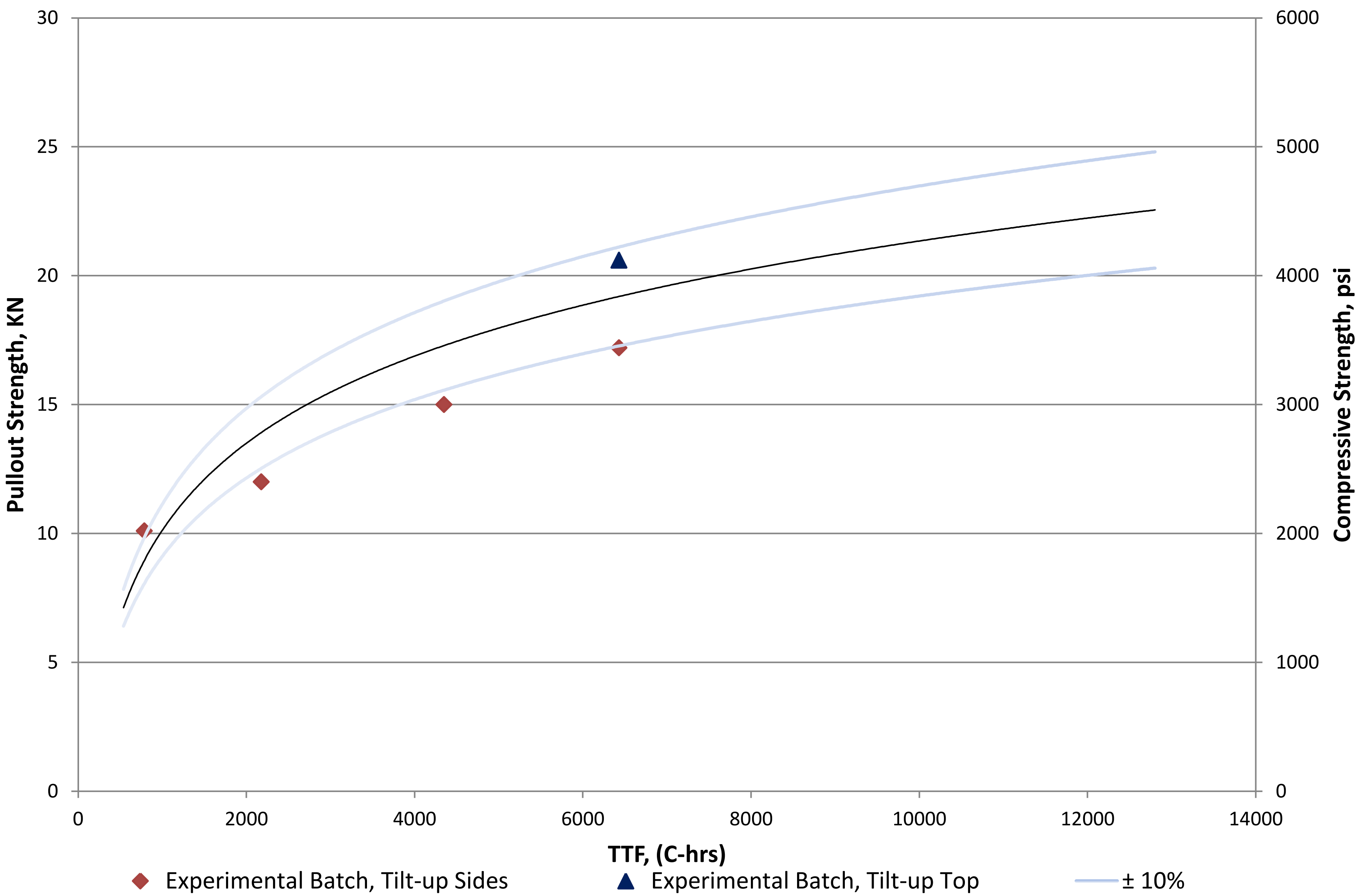


Figure 6-5. Verification of pullout strength-TTF-compressive strength relationship, experimental batch

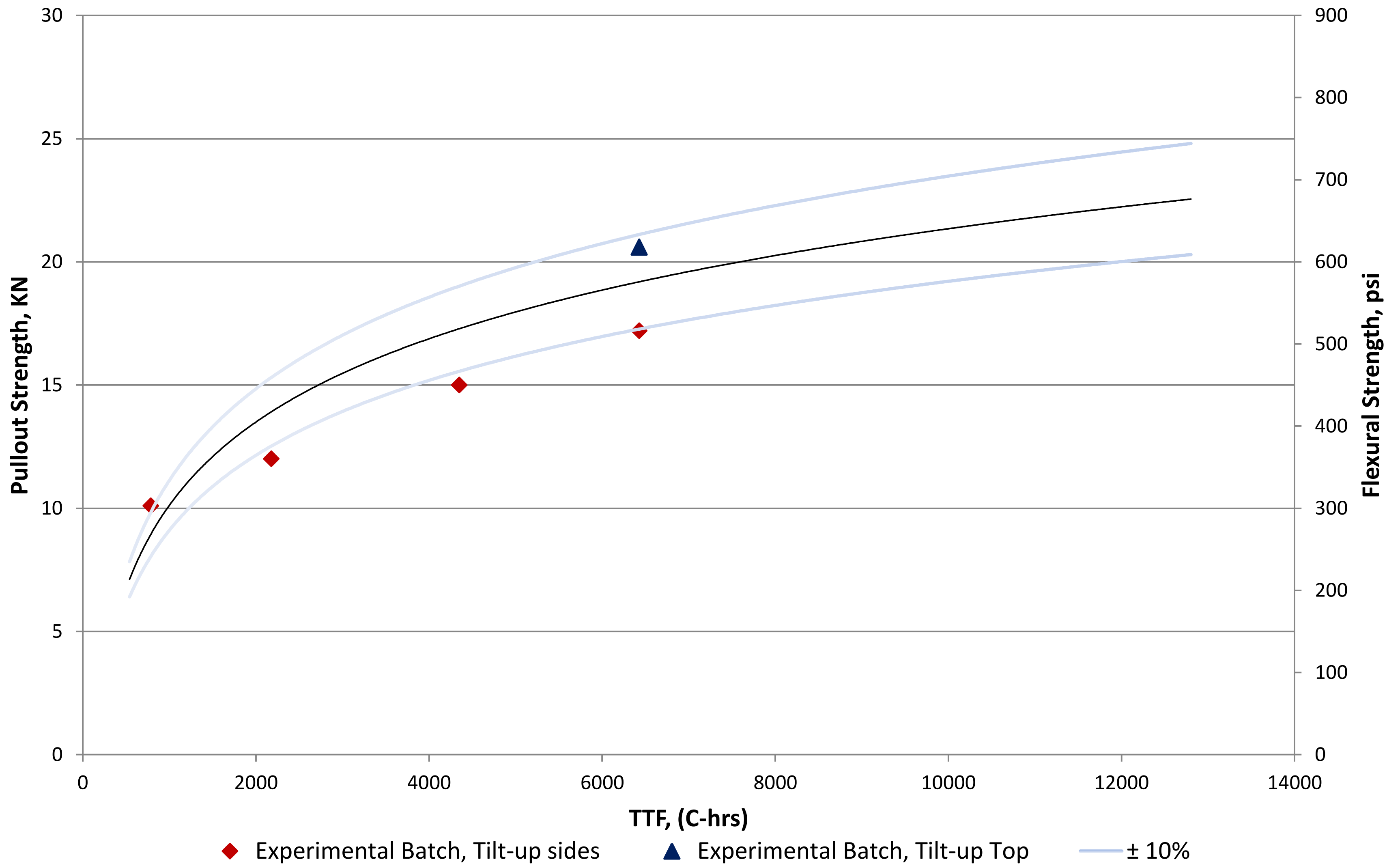


Figure 6-6. Verification of pullout strength-TTF-flexural strength relationship, experimental batch

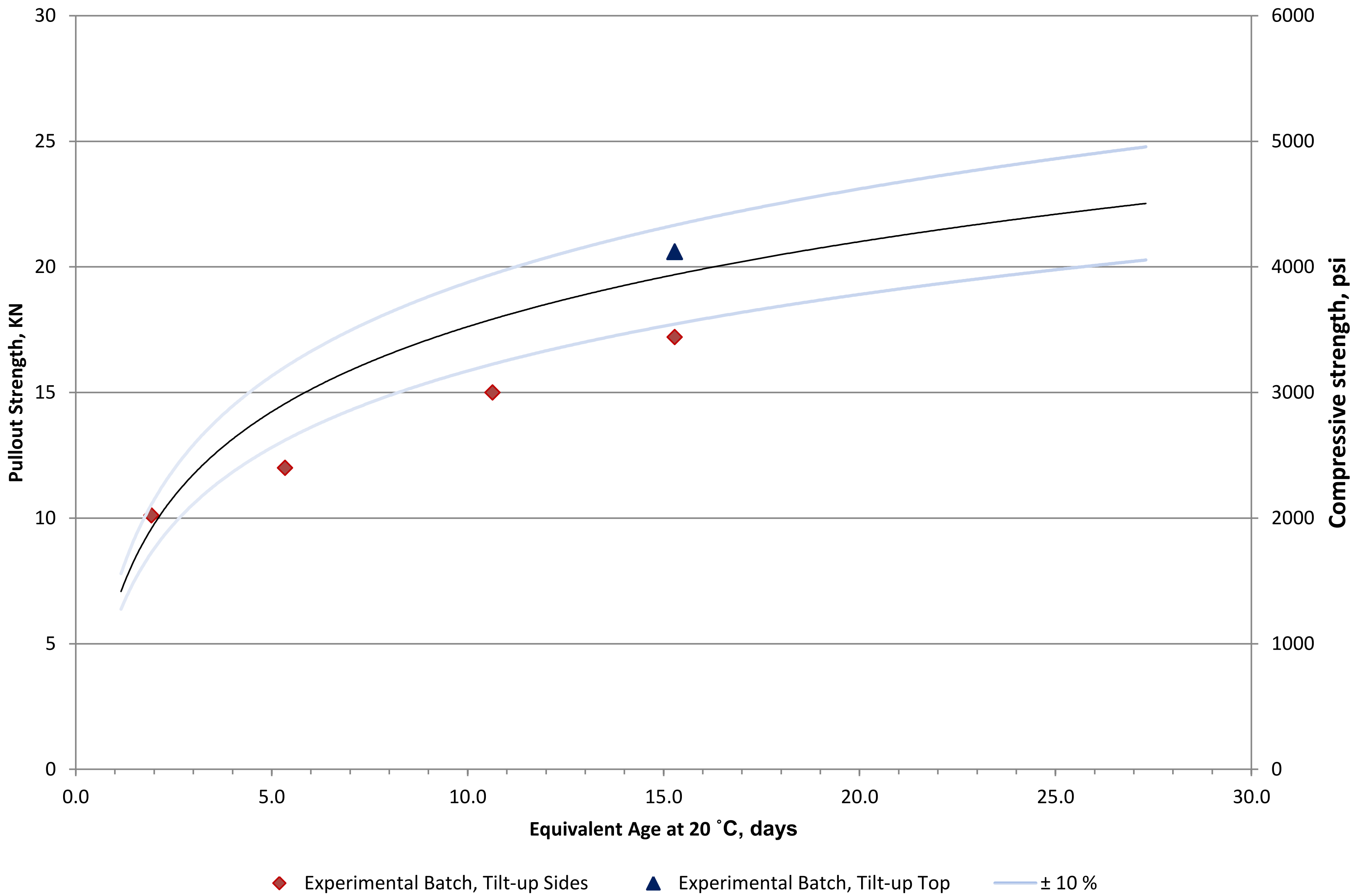


Figure 6-7. Verification of pullout strength-EA-compressive strength relationship, experimental batch

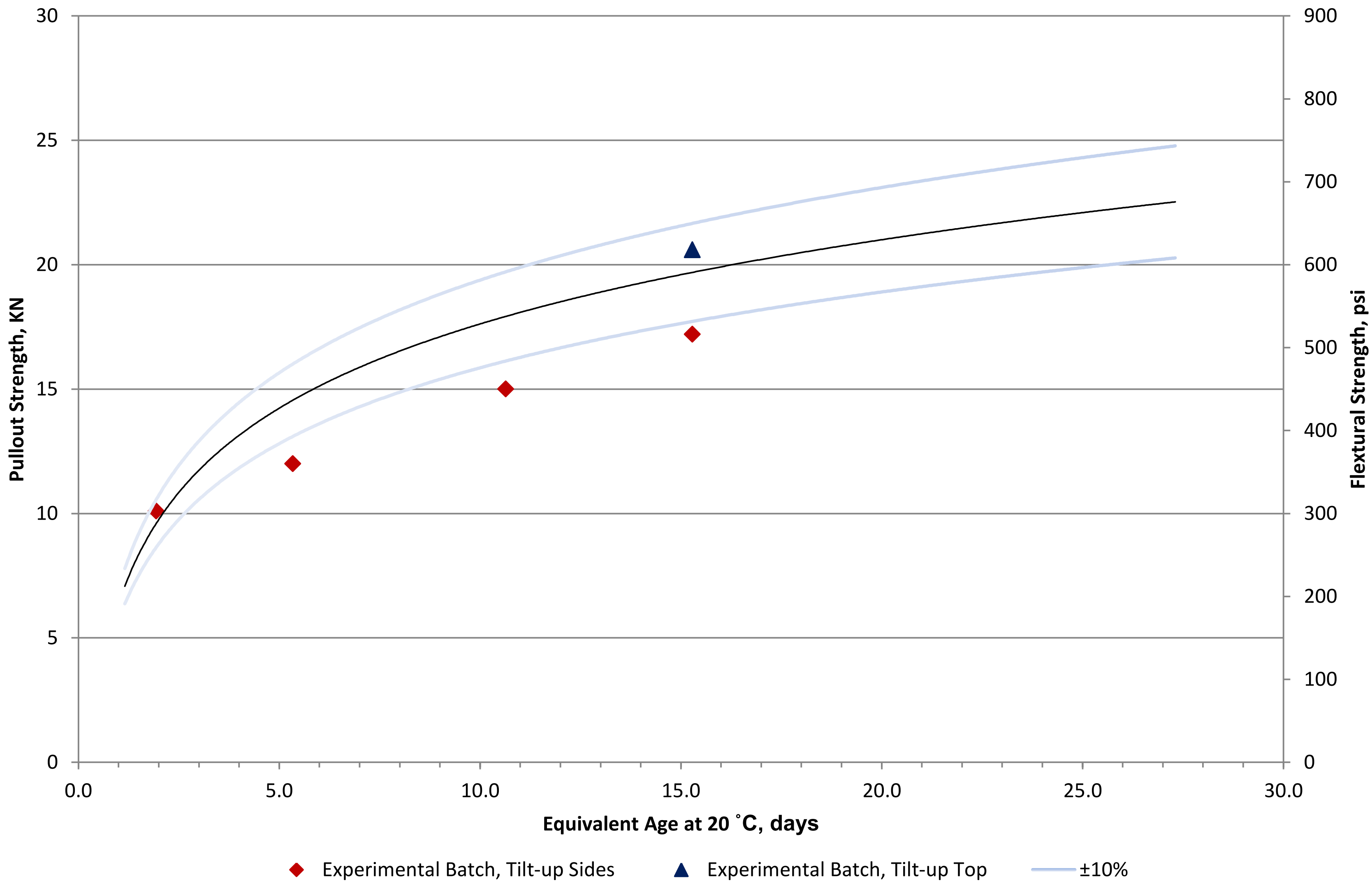


Figure 6-8. Verification of pullout strength-EA-flexural strength relationship, experimental batch

CHAPTER 7
TILT-UP PANEL DESIGN AND CONSTRUCTION

Overview

The design of the tilt-up panel undergoes two engineering design considerations. The first is to design the tilt-up panel for service and ultimate loads. The second is to design the tilt-up panel for the lifting stresses.

Although there are few references on designing the tilt-up panel for lifting stresses, there is no reference found for lightweight concrete tilt-up panel design for lifting stresses. Therefore, this research focused on investigating lightweight tilt-up panel stresses during lifting.

Panel Design

The original design of the tilt-up panel was analyzed in Abi-Nader's dissertation using normal density concrete (150 lb/ft^3). This research adopted the same design, approach but using structural lightweight concrete (117 lb/ft^3), for the sake of comparing the stresses developed in both panels during lifting (Figure 7-1) (Abi-Nader 2010).

The design consists of the following:

- Tilt-up panel thickness= 3.5 Inches.
- 28-day compressive strength = 4000psi.
- Compressive strength at day of lifting > 2500psi.
- Reinforcement #4 bars
- Two (2) Lifting inserts
- A 16 square feet opening

Statics Computations

Statics calculations were performed to determine the maximum positive and negative moment due to lifting. Based on these maximum values of moments, strain gauges were mounted to monitor the change in lengths.

Angle of Inclination

The tilt-up panel was considered as a simply supported beam with the maximum moment in the mid span

$$M(\max) = \frac{WL^2}{8} \tag{7-1}$$

Where:

W = Self-weight of the panel

L = Length of the panel

For Tilt-up panel, “θ” is the angle of inclination between the tilt-up panel and the casting surface as the panel being lifted (Figure 7-2).

The maximum moment was calculated with the angle of inclination “θ” as follows:

$$M = \frac{\frac{W}{\cos\theta}\ x(L\cos\theta)^2}{8} \tag{7-2}$$

The maximum moment occurs when cos θ equals to 1, that is when θ equals to 0. This indicates that the maximum moment occurs when the tilt-up panel is flat on the ground.

Moment Computations in the Y-Y Direction

The tilt-up panel was divided into three sections (Figure 7-3) to calculate the weight of each section of the panel. The weight the sections were used to calculate the Maximum moments of the panel at zero degree.

The Unit Weight of concrete used in these calculations is 117 lbs/ft^3 which was the wet unit weight of the lightweight concrete in the experimental batch.

W1 = Weight of section 1
W2= Weight of section 2
W3= Weight of section 3

$$W1 = 10ft \times 3.5in \times \frac{1\ ft/in}{12} \times 117\ pcf = 341.25\ lb/ft$$

$$W2 = 6ft \times 3.5in \times \frac{1\ ft/in}{12} \times 117\ pcf = 204.75\ lb/ft$$

$$W3 = 10ft \times 3.5in \times \frac{1\ ft/in}{12} \times 117\ pcf = 341.25\ lb/ft$$

The shear and moment diagrams for the tilt-up panel in the Y-Y direction are illustrated in (Figure 7-4).

Reaction at zero feet (A) is the reaction of the casting floor. It was calculated to be 784.9 lbs. acting upward. The reaction at 7 feet (B) is the reaction due to lifting. It was calculated to be 1,740.4 lbs. acting upward. Reaction B represents the vertical tension on the on the lifting inserts. Thus, each lifting insert underwent 870.2 lbs. of tension (Figure 7-5).

The moment diagram (Figure 7-4 and Figure 7-5) shows a maximum positive moment of 1,094.8 ft-lb. at 3.17 feet. A negative moment at 7 feet amounts to 682.5 ft-lb. at the inserts locations.

Stresses Computations in the Y-Y Direction

The stresses in the Y-Y direction were calculated for the maximum moment at 3.17 feet from the panel's bottom according to the following equation:

$$S_b = \frac{M}{Sx} \tag{7-3}$$

Where:

S_b = Bending Stress (psi)

M= Bending Moment (in-lb)

S_x= Section Modulus (in^3)

The section modulus is determined using the following equation

$$Sx = \frac{bd^2}{6} \tag{7-4}$$

Where:

Sx= Section Modulus (in^3)

b= width of the section studied (in)

d= Thickness of the panel (in)

$$Sx = \frac{(10ft - 4\ ft) \times 12\ (in/ft) \times (3.5in)^2}{6} = 147\ in^3$$

$$S_b = M/\ Sx = \frac{1{,}094.8\ lb\text{-}ft \times 12(in/ft)}{147\ in^3} = 89.7\ psi\ \ @\ 3.17$$

On the other hand, the stresses at 7 ft were calculated as follows:

$$S_x = \frac{bd^2}{6} = \frac{(10ft\ ) \times 12\ (in/ft) \times (3.5in)^2}{6} = 245\ in^3$$

$$S_b = M/\ S_x = \frac{682.5\ lb\text{-}ft \times 12(in/ft)}{245\ in^3} = 33.4\ psi\ @\ 7\ ft.$$

Moment Computations in the X-X Direction

The tilt-up panel was divided into three sections as shown in Figure to calculate the weight of each section of the panel. The weight the sections were used to compute the maximum bending moments of the panel at zero degree. The weight of the panel was divided into two sections along the zero shear point (3.17 ft from the bottom).

The Unit Weight of the lightweight concrete is 117 lb/ft³.

- W1 = Weight of section 1
- W2= Weight of section 2
- W3= Weight of section 3

$$W1 = (9ft-3.17) \times 3.5in \times \frac{1\ ft/in}{12} \times 117\ pcf = 199\ lb/ft$$

$$W2 = 4ft \times 3.5in \times \frac{1\ ft/in}{12} \times 117\ pcf = 136.5\ lb/ft$$

$$W3 = (9ft-3.17ft) \times 3.5in \times \frac{1\ ft/in}{12} \times 117pcf = 199\ lb/ft$$

Figure 7-7, shows the shear and moment diagrams for the tilt-up panel in the X-X direction. The P1 and P2 are the vertical tension values of the lifting inserts of 870.2 lb. as calculated earlier. Figure 7-8, shows a maximum negative moment of 488.9 ft-lb. at the right insert. It also shows a maximum positive value of 300.1 lb-ft. at 4.38 feet from the left edge of the panel. The left insert has a negative moment value of 315.3 ft-lb.

Stresses Calculations in the X-X Direction

Stresses at the lift and right inserts were the highest due to the maximum negative bending moments. On the other hand, stresses occurred along the inserts axis, 4.38 ft form the left edge of the panel due to the maximum positive bending moment. The stresses were calculated as follows:

The stress at the right insert:

$$S_b = M/\ S_x = \frac{488.9\ lb\text{-}ft \times 12(in/ft)}{4\ ft \times 12(in/ft) \times 3.5^2/\ 6} = 59.9\ psi$$

The stress at the left insert:

$$S_b = M/\ S_x = \frac{315.3\ lb\text{-}ft \times 12(in/ft)}{(9\text{-}3.17)\ ft \times 12(in/ft) \times 3.5^2/\ 6} = 56.3\ psi$$

The stress at 4.38 ft from the left edge:

$$S_b = M/\ S_x = \frac{300.1\ lb\text{-}ft \times 12(in/ft)}{4\ ft \times 12(in/ft) \times 3.5^2/\ 6} = 36.8\ psi$$

Statics Computations Using 1.5 Suction Factor

Same concepts of the statics calculations were applied using a 1.5 suction factor to the weight of the panel.

Moment Computations in the Y-Y Direction with Suction

The panel was divided into three sections (Figure 7-3) and the weight of each section is shown below.

$$W1 = (10ft \times 3.5in \times \frac{1\ ft/in}{12} \times 117\ pcf) \times 1.5 = 512\ lb/ft$$

$$W2 = (6ft \times 3.5in \times \frac{1\ ft/in}{12} \times 117\ pcf) \times 1.5 = 312\ lb/ft$$

$$W3 = (10ft \times 3.5in \times \frac{1\ ft/in}{12} \times 117\ pcf) \times 1.5 = 512\ lb/ft$$

The maximum positive moment of 1,666 lb-ft occurred at 3.17 feet from the bottom of the panel. The maximum negative moment of 1,024 occurred at 7 feet where the inserts are located (Figure 7-9).

Stresses Computations in the Y-Y Direction with Suction

According to the maximum moments in the Y-Y direction, the following stresses can be calculated:

$$S_{b.} = M/\ S_{x} = \frac{1{,}666\ lb\text{-}ft \times 12(in/ft)}{147\ in^3} = 136\ psi\ @\ 3.17\ ft.$$

$$S_b = M/\ S_x = \frac{1{,}024\ lb\text{-}ft \times 12(in/ft)}{245\ in^3} = 50.1\ psi\ @\ 7\ ft.$$

Moment Computations in the X-X Direction with Suction

The panel was divided into three regions. The weight of each region is calculated with a 1.5 suction factor below.

$$W1 = ((9ft-3.17) \times 3.5in \times \frac{1\ ft/in}{12} \times 117\ pcf) \times 1.5 = 298.5\ lb/ft$$

$$W2 = (4ft \times 3.5in \times \frac{1\ ft/in}{12} \times 117\ pcf) \times 1.5 = 205\ lb/ft$$

$$W3 = ((9ft-3.17ft) \times 3.5in \times \frac{1\ ft/in}{12} \times 117pcf) \times 1.5 = 298.5\ lb/ft$$

In addition to the weight of the panel, 1,310 lbs. of upward force was applied to the panel during lifting at each insert.

The moment at the right insert was found to be negative 733.3 lb-ft. The maximum positive moment occurred at 4.38 ft from the left with a value of 450.9 lb-ft. The left insert had a negative moment of 472.9 lb-ft (Figure 7-10).

Stresses Calculations in the X-X Direction with Suction

The maximum positive/ negative moments were applied to calculate the stresses as shown below:

The stress at the right insert:

$$S_b = M/ S_x = \frac{733.3 \text{ lb-ft} \times 12(\text{in/ft})}{4\text{ft} \times 12(\text{in/ft}) \times 3.5^2/ 6} = 89.8 \text{ psi}$$

The stress at the left insert:

$$S_b = M/ S_x = \frac{472.9 \text{ lb-ft} \times 12(\text{in/ft})}{(9-3.17) \text{ ft} \times 12(\text{in/ft}) \times 3.5^2/ 6} = 84.4 \text{ psi}$$

The stress at 4.38 ft from the left edge:

$$S_b = M/ S_x = \frac{450.9 \text{ lb-ft} \times 12(\text{in/ft})}{4\text{ft} \times 12(\text{in/ft}) \times 3.5^2/ 6} = 55.2 \text{ psi}$$

Panel’s Construction

Casting Mud Slab

An 11’ by 11’ casting bed was prepared at the Perry Building at the University of Florida. A 3.5” thick concrete slab was poured on top of the existing floor slab to achieve an acceptable leveled slab. The casting bed provided a smooth steel troweled finish to accommodate the tilt-up panel requirements (Figure 7-11).

Formwork and Steel Reinforcement

After the casting slab has fully cured and gained sufficient strength, the tilt-up panel formwork was prepared using 2 x 4 wood studs. It provided the required thickness of 3.5 “. The formwork was drilled to allow for the temperature loggers wires to extend out. It was also used to fix the pullout inserts (Figure 7-12).

Grade 60 steel reinforcements were used. The size and location of the rebar in the tilt-up panel were in accordance to Abi-Nader’s research (Figure 7-13, Figure 7-14 and Figure 7-15). The steel reinforcements were provided by “Gerdau AmeriSteel” of Jacksonville, Florida.

The steel reinforcements were placed and tied using rebar tie wires. The reinforcing steel mesh was removed by the overhead crane to allow for the bond breaker to be sprayed before it was placed back into position.

One inch bolsters were used to support steel reinforcement at level 2 every 2 feet. The following is a list of the steel bars used:

- 3 #4 rebar 0 ft- 8in long,
- 3 #4 rebar 1 ft- 8in long,
- 6 #4 rebar 3 ft -8in long,
- 4 #4 rebar 4 ft- 0in long,
- 8 #4 rebar 8 ft- 8in long,
- 8 #4 rebar 9 ft- 8in long, and
- 8 #4 rebar 1ft- 6in long.

Lifting Inserts

The lifting inserts were used at 7 feet from the bottom of the panel. The RL- 24, two-tone plate anchors were used; they were provided by Meadow Burke.

Each lifting insert was surrounded four 18 “long #4 rebar according to the manufacturer application manual (Figure 7-16).

Bond Breaker

A day before pouring the tilt-up panel, J6WB Sure Lift by Dayton Superior was sprayed. The bond breaker was sprayed using a portable low pressure pump-up sprayer (Figure 7-17). It was applied by spraying the casting bed in rows, each with a 50% spray overlap. Each layer was applied perpendicular to the previous layer after allowing it to dry for more than 2 hours. The casting bed prepared showed a sign of high porosity when the bond breaker turned to white color. Therefore, as per the manufacturer recommendations third and fourth layers were applied to ensure a proper bondage break.

Table 7-1 lists the chemical and physical properties of the J6WB Sure Lift bond breaker used in this research. The bond breaker was supplied by BNG Construction Company.

Tilt-up Panel Casting

H65BC lightweight concrete design mix was supplied by Florida Rock Industries. The concrete was delivered in a truck as a wet mix ready to be poured (Figure 7-18). Three temperature loggers were impeded in the concrete. Two loggers were located at 3.17 feet from the bottom, where the maximum moment in the Y-Y direction was expected (Figure 7-19). The third logger was placed between the lifting inserts at 7 feet from the bottom, where the positive moment in the X-X direction was determined. In addition, a pullout insert was placed at each side of the tilt-up panel. Two were placed at 3.17 feet from the bottom and the others in mid span (Figure 7-19). Another insert was inserted into the concrete surface at a location where it has minor effect on the panel as it was being lifted. Furthermore, two COMA meters were inserted into the panel while the concrete was fresh. One was placed at 3.17 feet from the panel's bottom edge, while the other was inserted in the one foot wide strip below the opening of the panel (Figure 7-20).

Strain Gauges Location

Surface mount strain gauges were strategically fixed where the maximum positive/negative moments are expected based on the design calculations. A total of eight gauges were installed to monitor the strains that the concrete undergoes as the tilt-up panel was being lifted. Five of them were vertically fixed in the direction of the Y-axis and three horizontally in the X-axis direction. Figure 7-21, shows the location of the strain gauges.

Lifting of Tilt-up Panel

At the day of lift, the lightweight concrete was tested for compressive and flexural strength as discussed earlier. A digital level was glued to the surface of the tilt-up panel to indicate the angle of inclination while lifting. The process was video recorded for later referencing. The stain gauges were connected to the data acquisition devices and synchronized to a computer via a USB cable. Software showing the real-time strains and logs them in a file was employed (Figure 7-22). The process of lifting the tilt-up panel is shown in Figure 7-23.

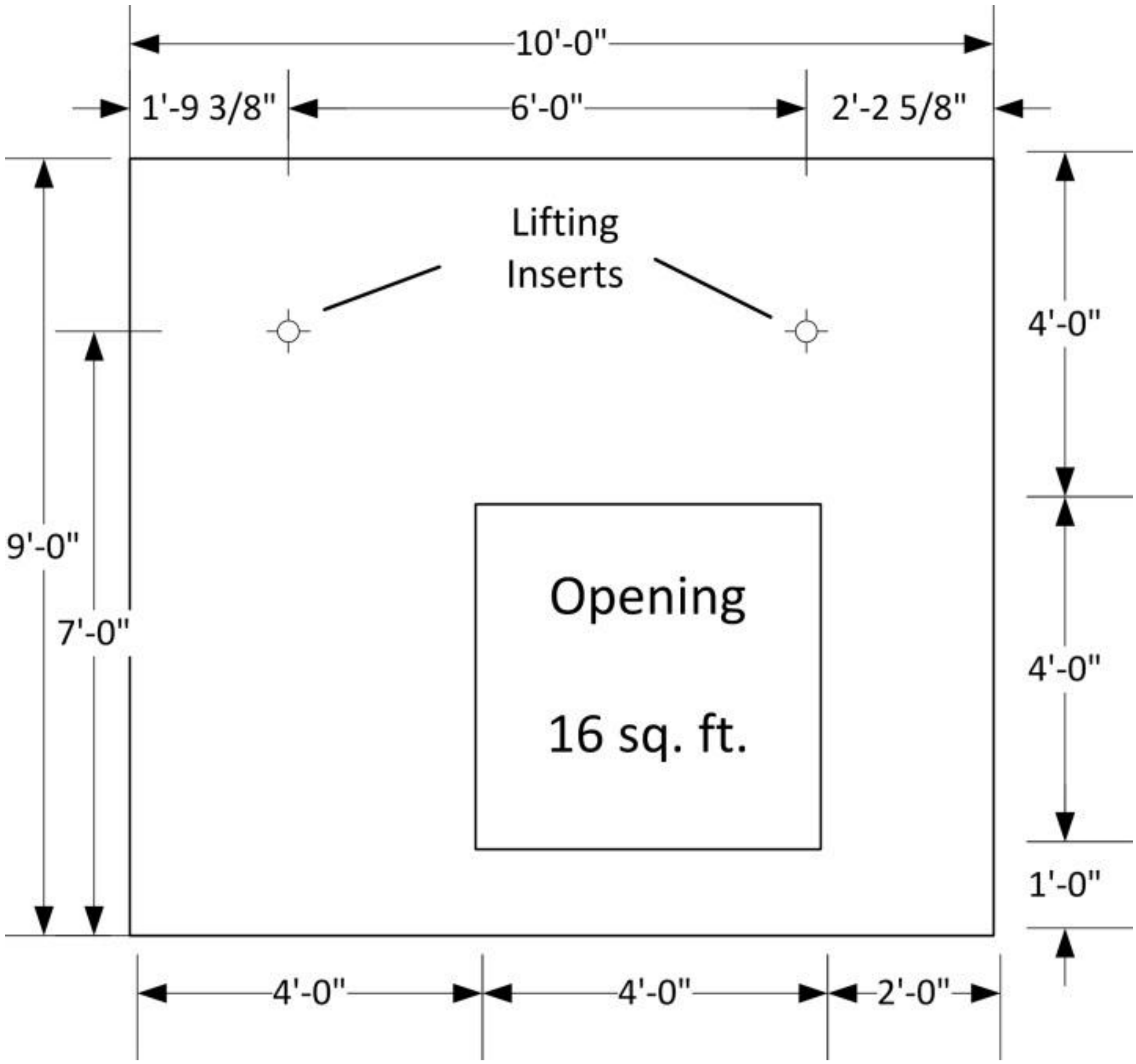


Figure 7-1. Tilt-up panel dimensions (drawing courtesy of Adel Alsaffar)

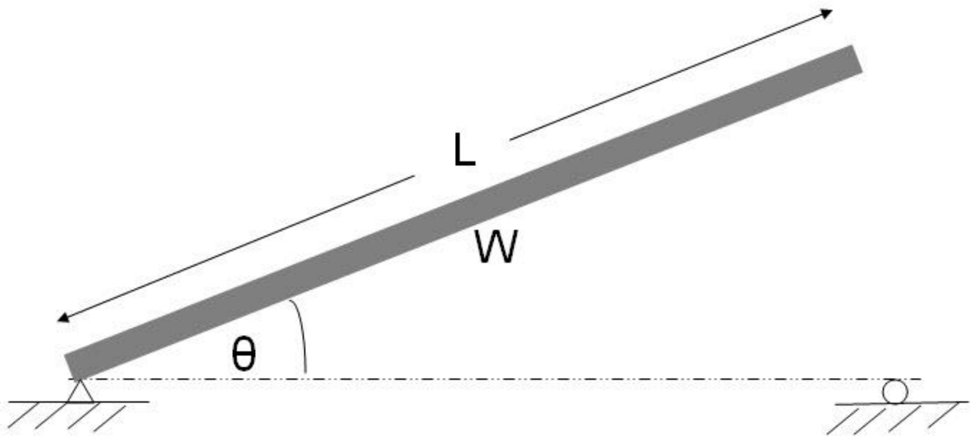


Figure 7-2. Angle of inclination (drawing courtesy of Adel Alsaffar)

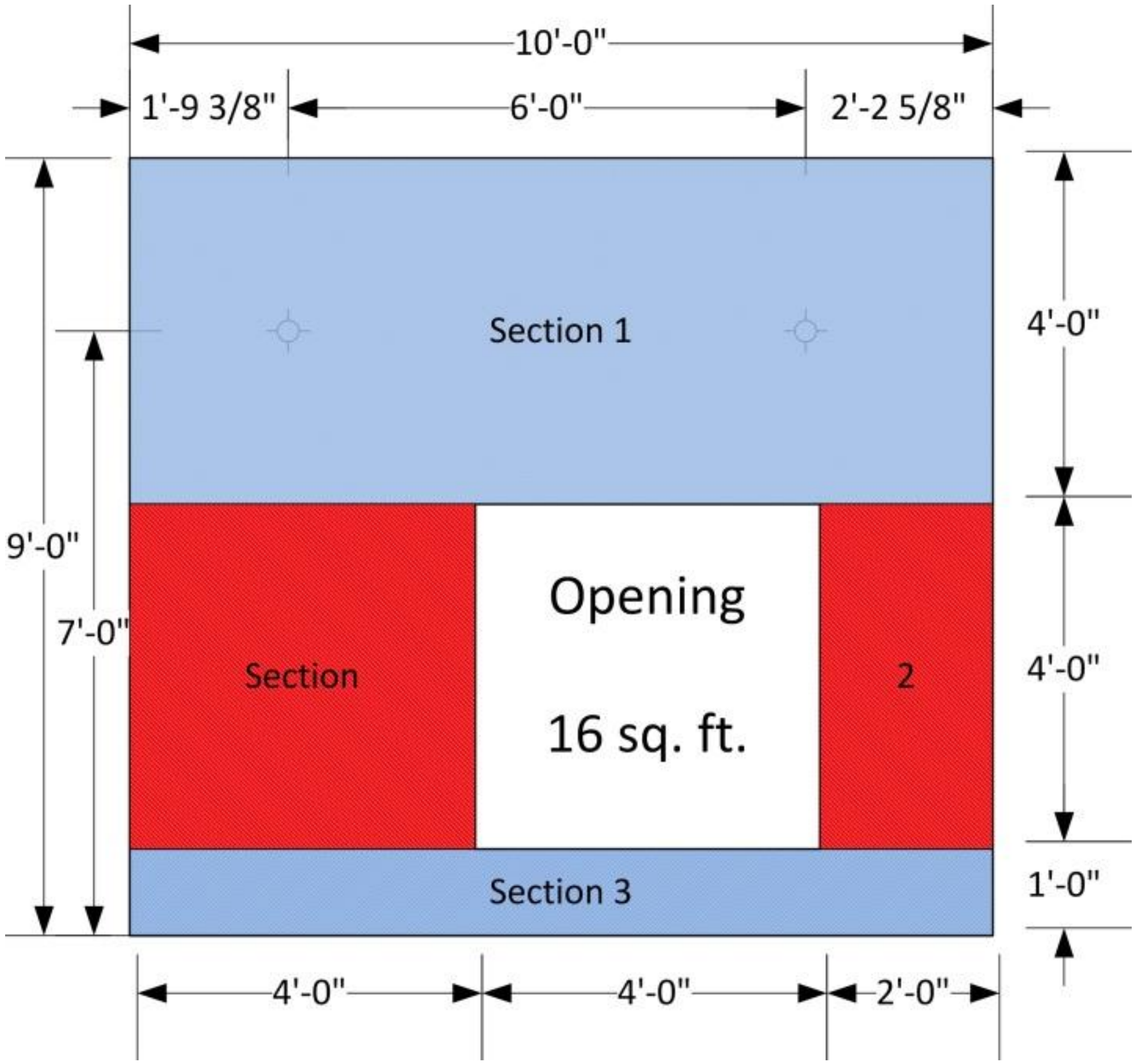


Figure 7-3. Tilt-up panel sections to calculate moments in Y-Y direction (drawing courtesy of Adel Alsaffar)

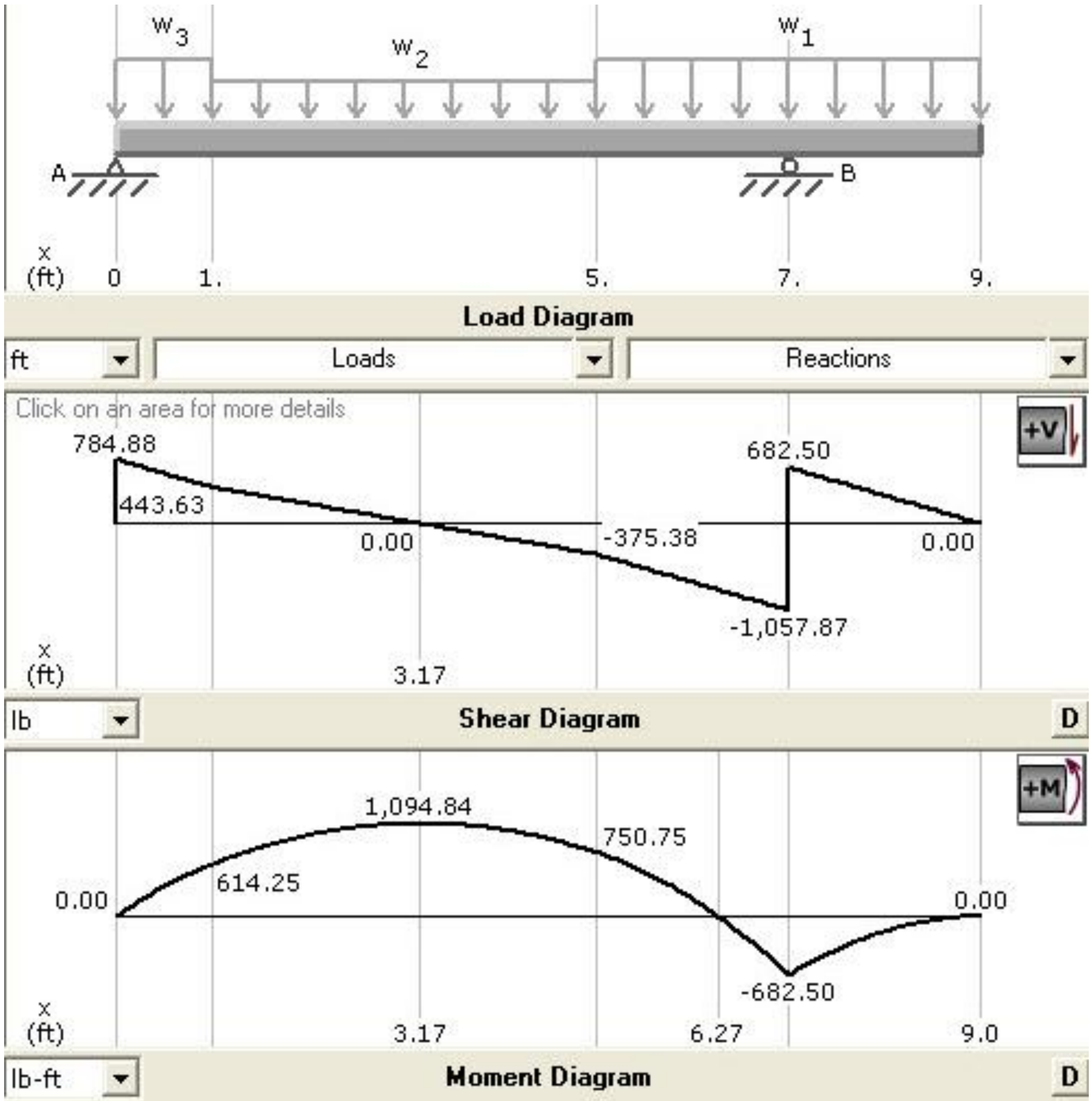


Figure 7-4. Shear and moment diagram of tilt-up panel at zero degree in Y-Y direction (drawing courtesy of Adel Alsaffar)

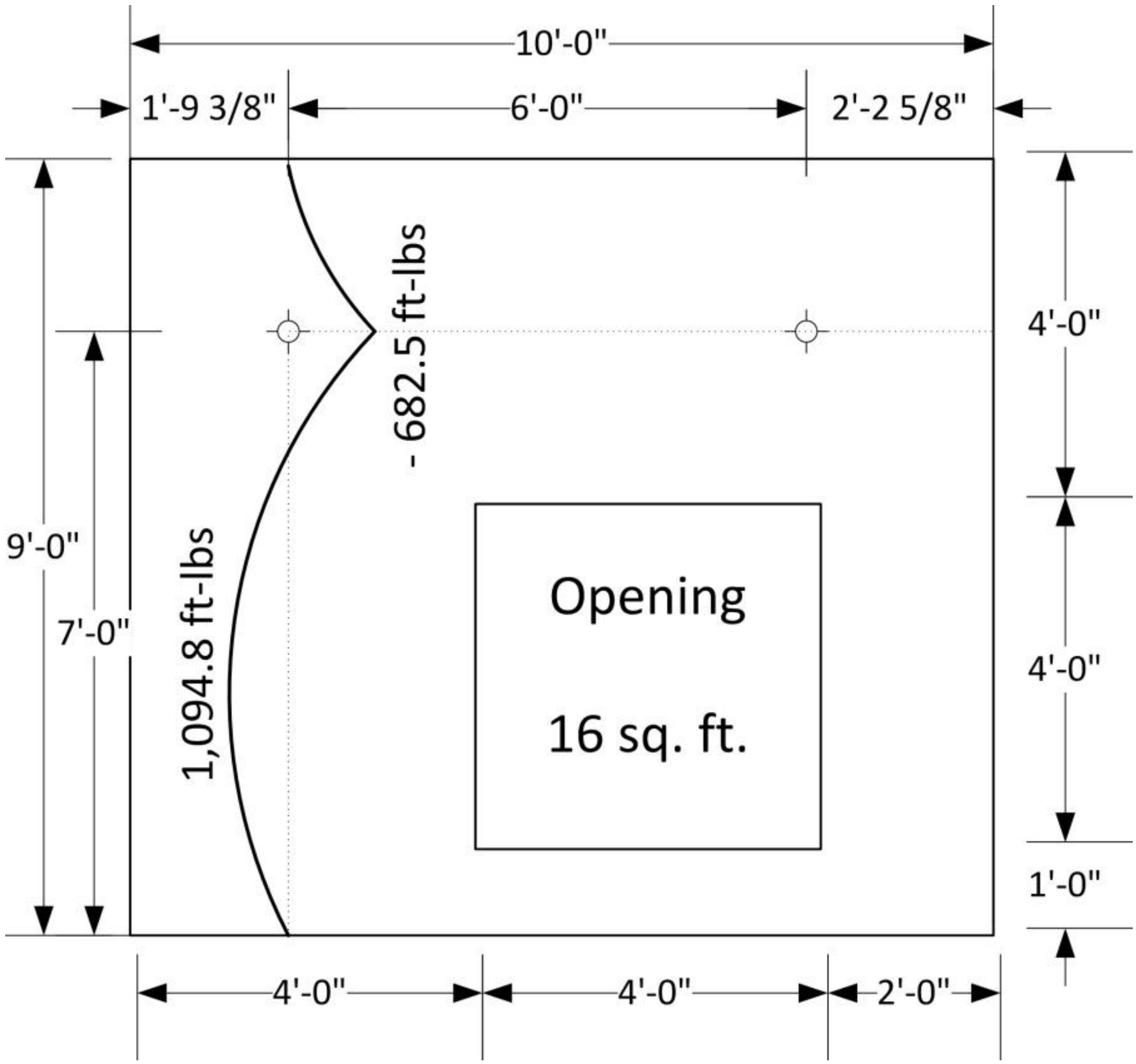


Figure 7-5. Maximum moments Y-Y direction, at zero degree due to lifting (drawing courtesy of Adel Alsaffar)

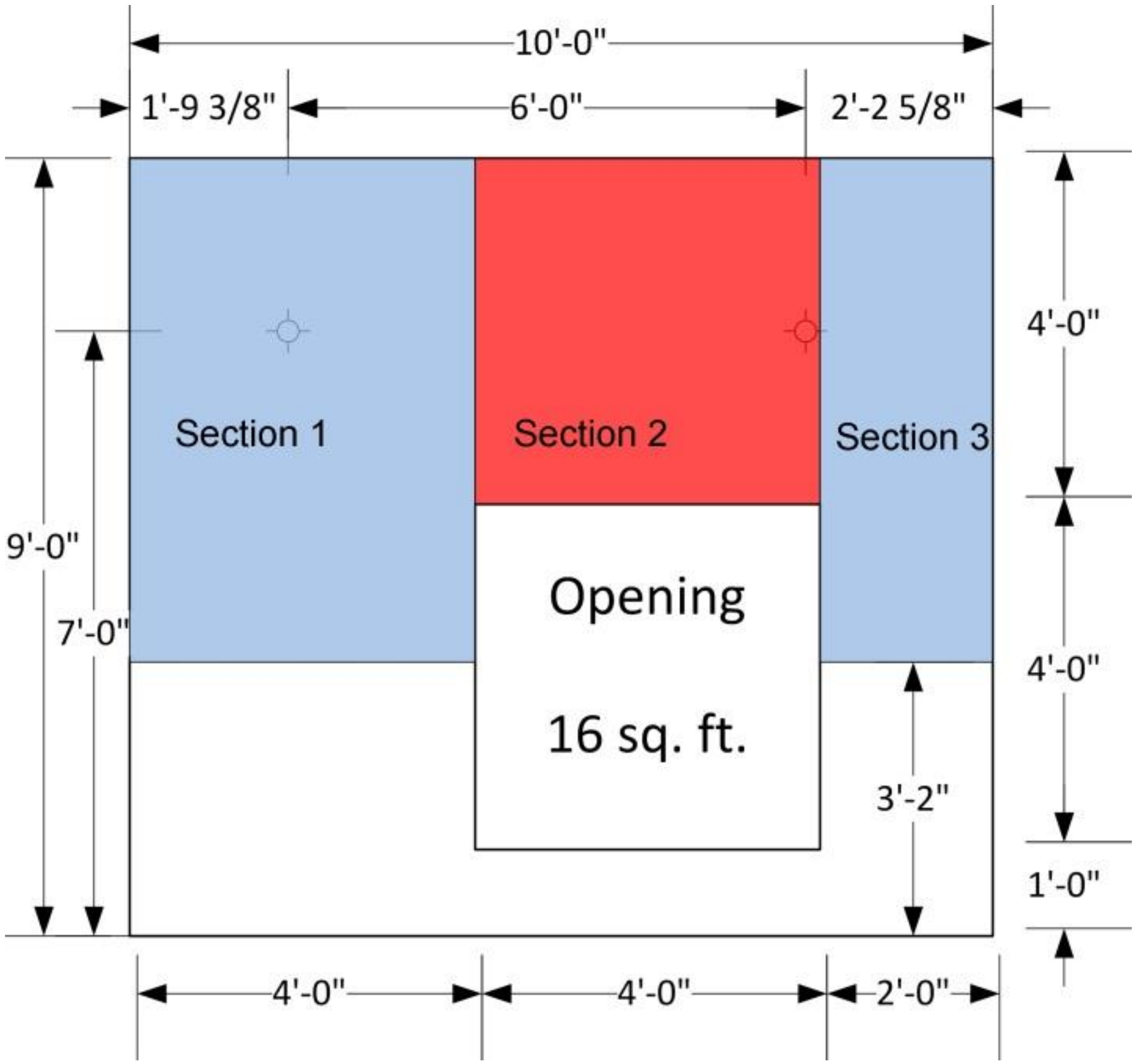


Figure 7-6. Tilt-up panel sections to calculate moments in X-X direction (drawing courtesy of Adel Alsaffar)

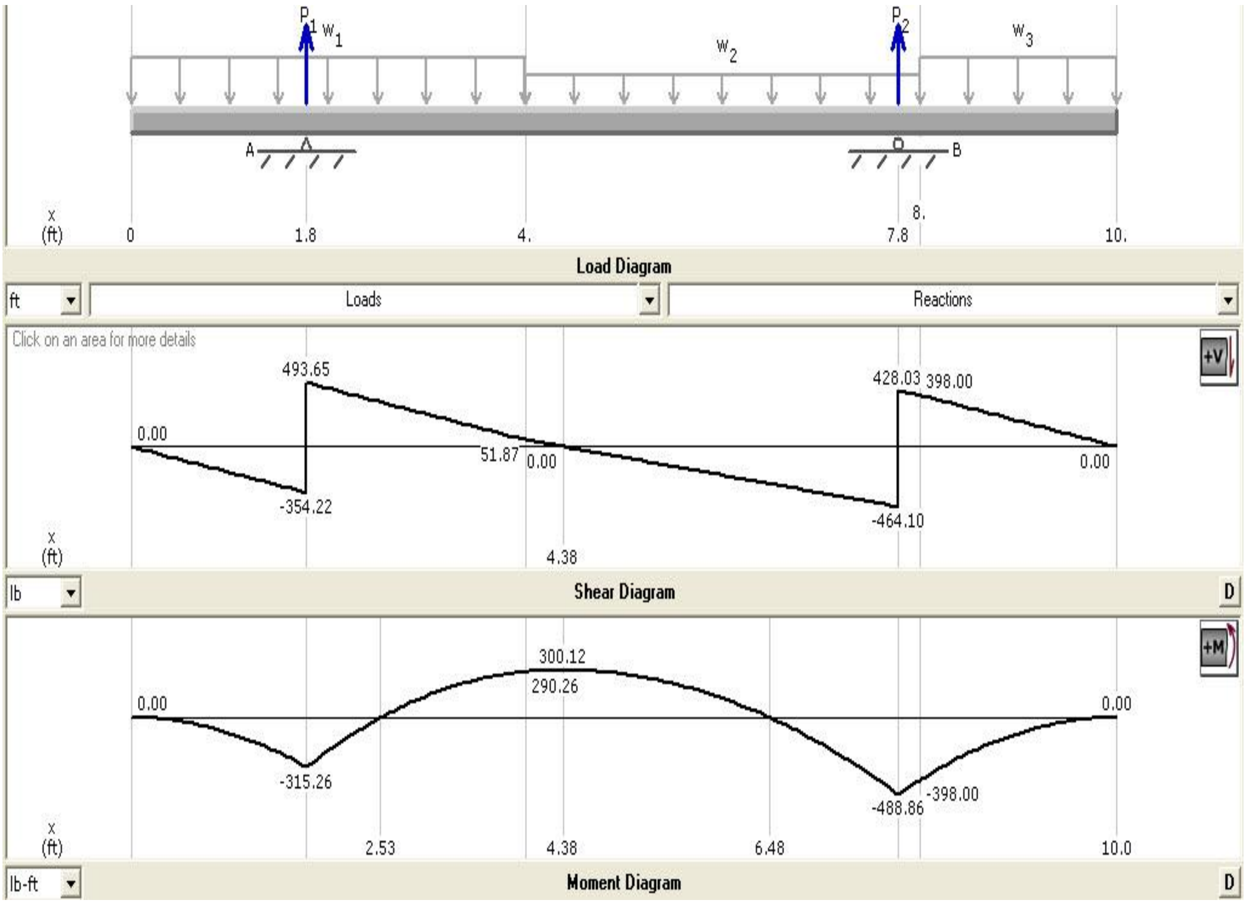


Figure 7-7. Shear and moment diagram of tilt-up panel at zero degree in Y-Y direction (drawing courtesy of Adel Alsaffar)

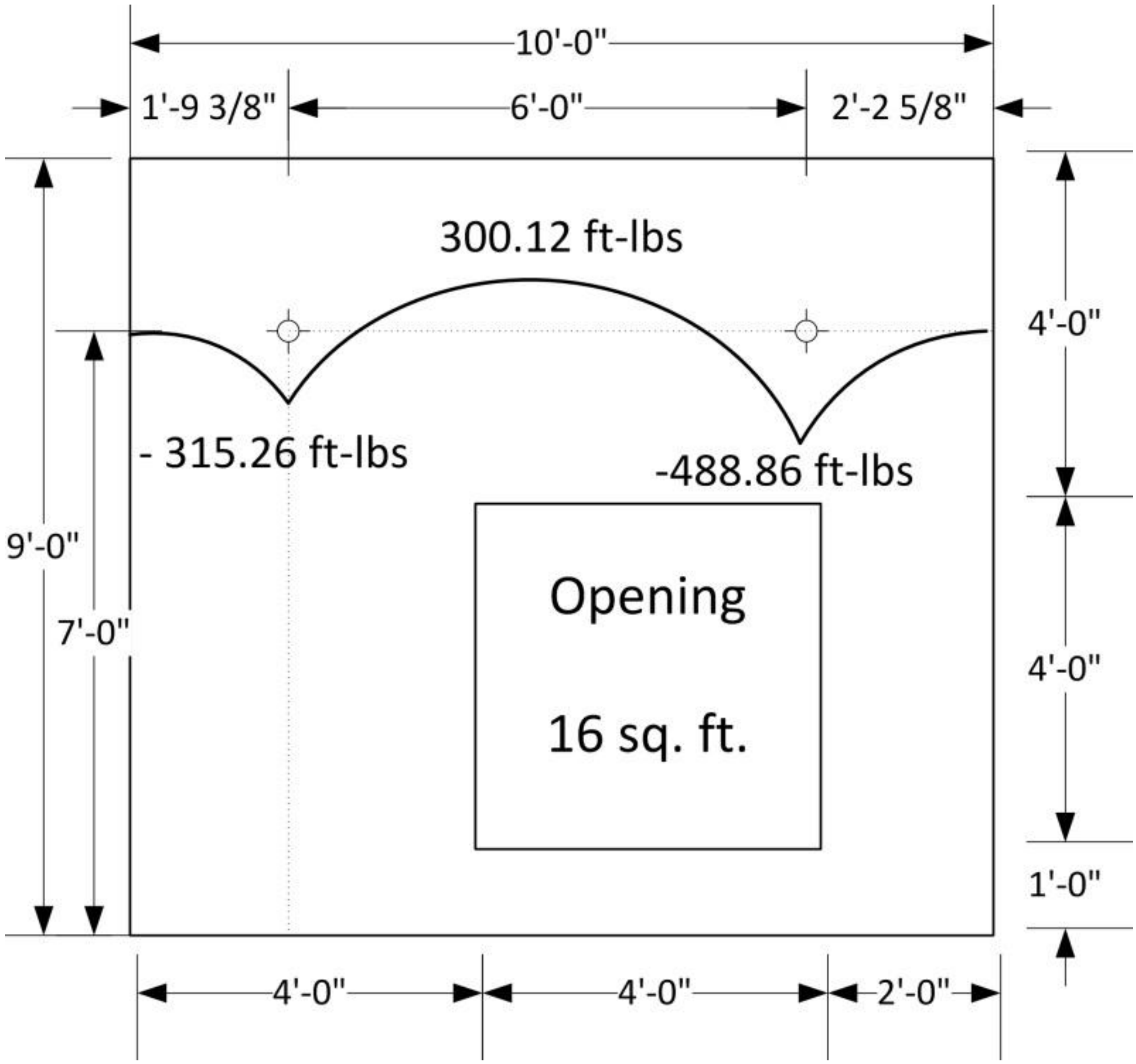


Figure 7-8. Maximum moments X-X direction, at zero degree due to lifting (drawing courtesy of Adel Alsaffar)

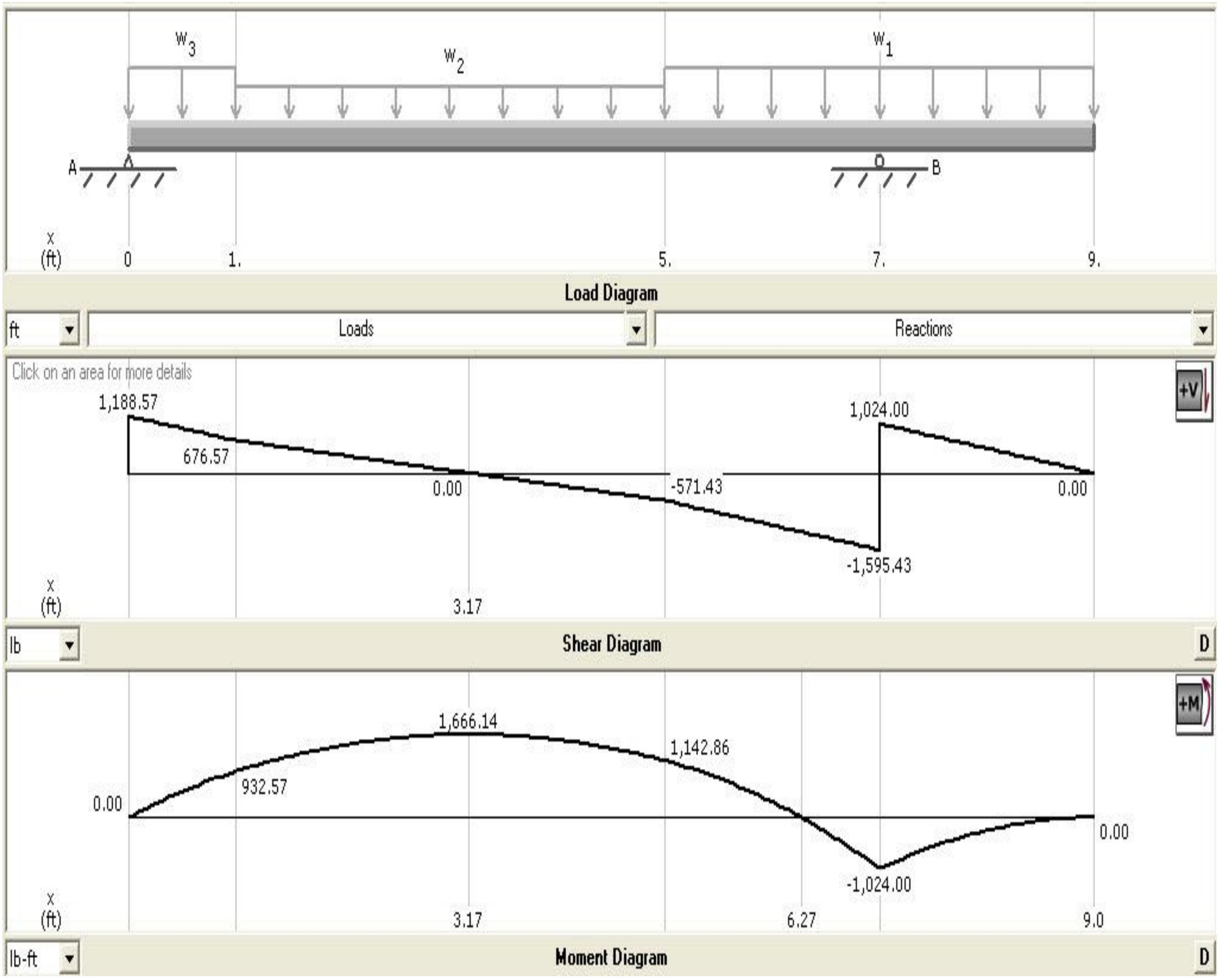


Figure 7-9. Shear and moment diagram, Y-Y direction with suction (drawing courtesy of Adel Alsaffar)

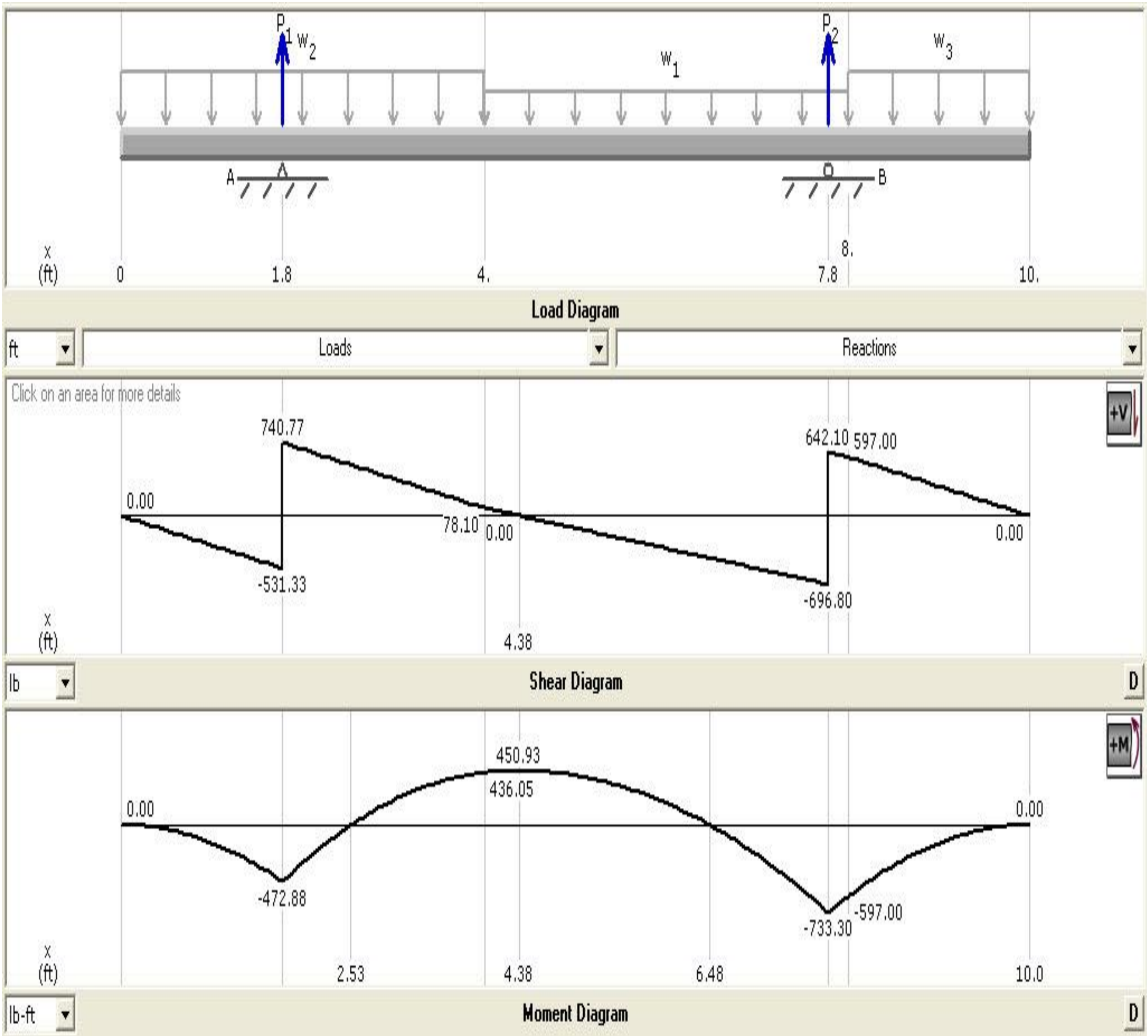


Figure 7-10. Shear and moment diagrams, X-X direction with suction (drawing courtesy of Adel Alsaffar)


A 
B

Figure 7-11. Casting-bed preparations A) formwork and plastic. B) leveling and finishing. (photo courtesy of Adel Alsaffar)

Figure 7-12. Tilt-up panel formwork (photo courtesy of Adel Alsaffar)

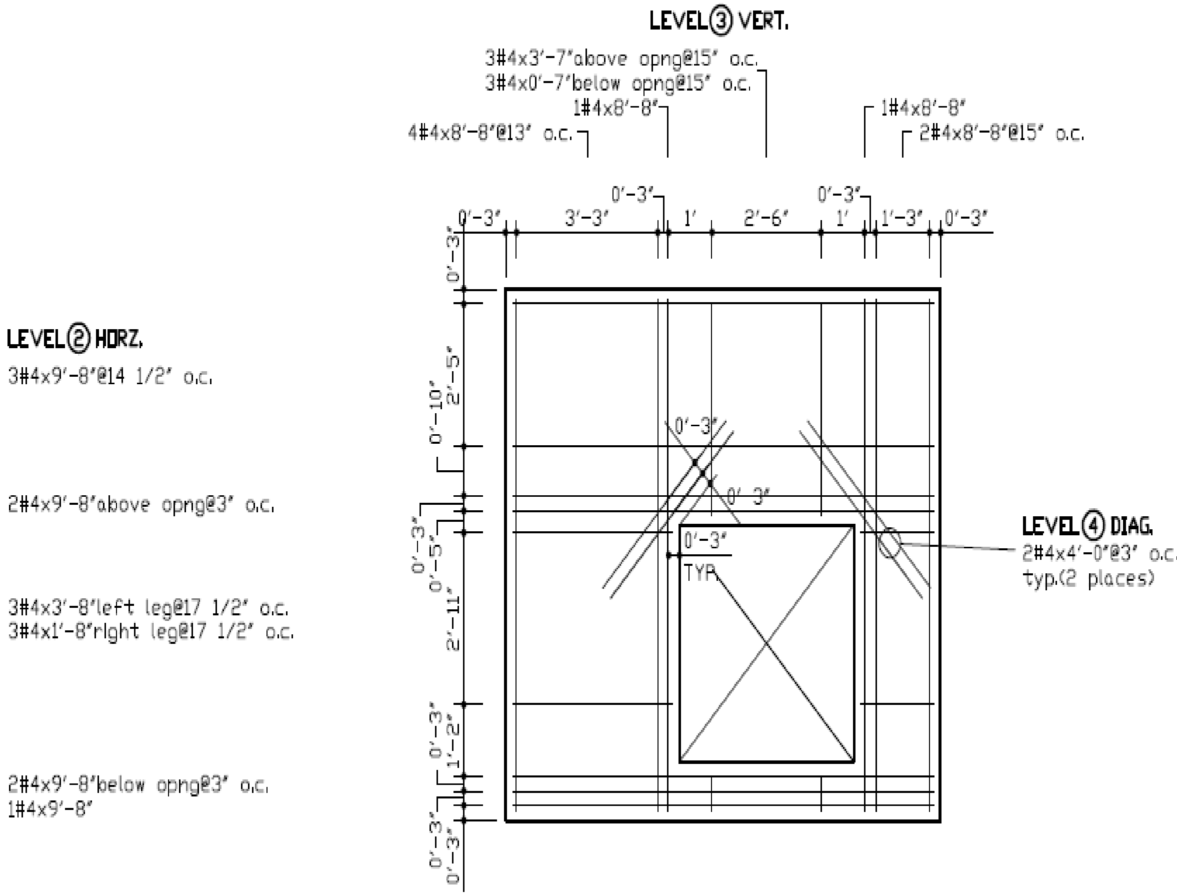


Figure 7-13. Steel reinforcement design (Abi-Nader 2010)

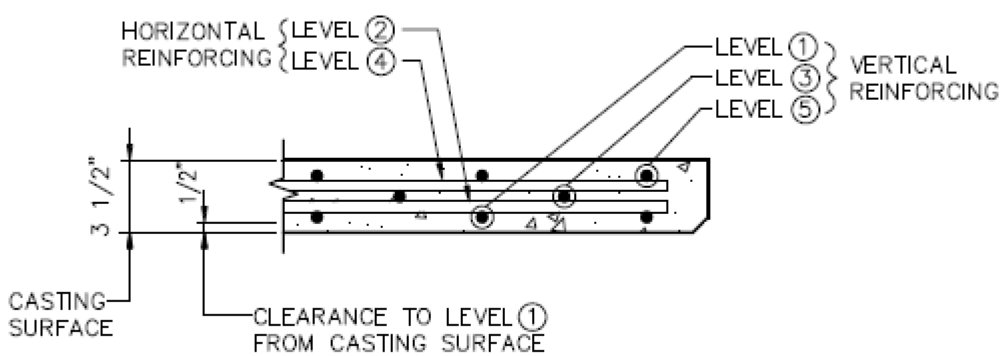


Figure 7-14. Steel reinforcement levels (Abi-Nader 2010)

Figure 7-15. Tilt-up panel steel reinforcement (photo courtesy of Adel Alsaffar)

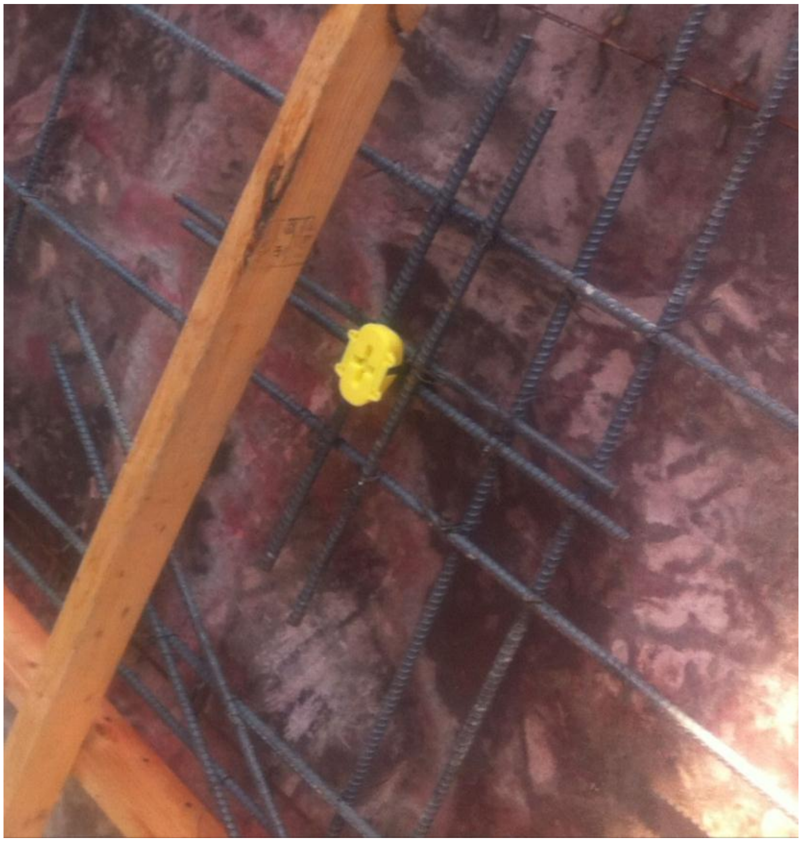


Figure 7-16. Lifting inserts and reinforcement (photo courtesy of Adel Alsaffar)

Figure 7-17. Bond breaker being sprayed (photo courtesy of Adel Alsaffar)

Table 7-1. Physical and Chemical Properties of J6WB Sure Lift by Dayton Superior.

General information	Properties
Form	Liquid
Color	Red
Odor	Slight
Change in condition:	
Melting point	-
Boiling Point	212^{o}F
Flash point	484^{o}F
Auto Igniting	not self-igniting
Danger of explosion	Does not present an explosion hazard
Vapor pressure at 68ºF	17 mm Hg
Density at 68ºF	0.992g/cm^3
Miscibility with water	Not miscible or difficult to mix
Solvent content:	
Organic solvents	0.50%
Water	90.40%
Volatile Organic Compounds	88g/l

Figure 7-18. Casting tilt-up panel (photo courtesy of Adel Alsaffar)

Figure 7-19. Maturity logger and pullout insert at 3.17 feet (photo courtesy of Adel Alsaffar)

Figure 7-20. COMA meter being inserted into the fresh concrete (photo courtesy of Adel Alsaffar)

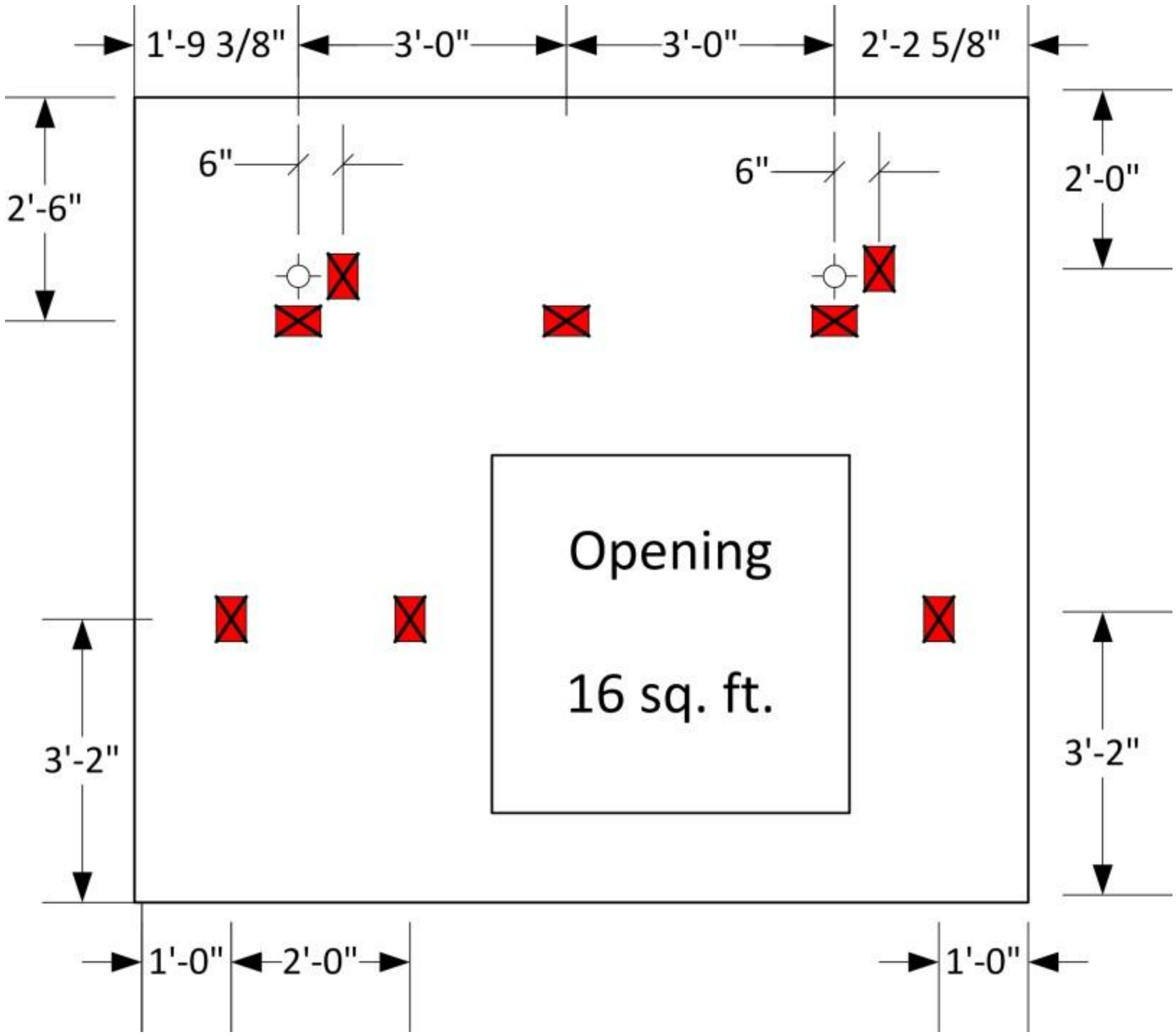


Figure 7-21. Strain gauges locations (drawing courtesy of Adel Alsaffar)

Figure 7-22. Stain gauge data acquisition devices links to a computer (photo courtesy of Adel Alsaffar)

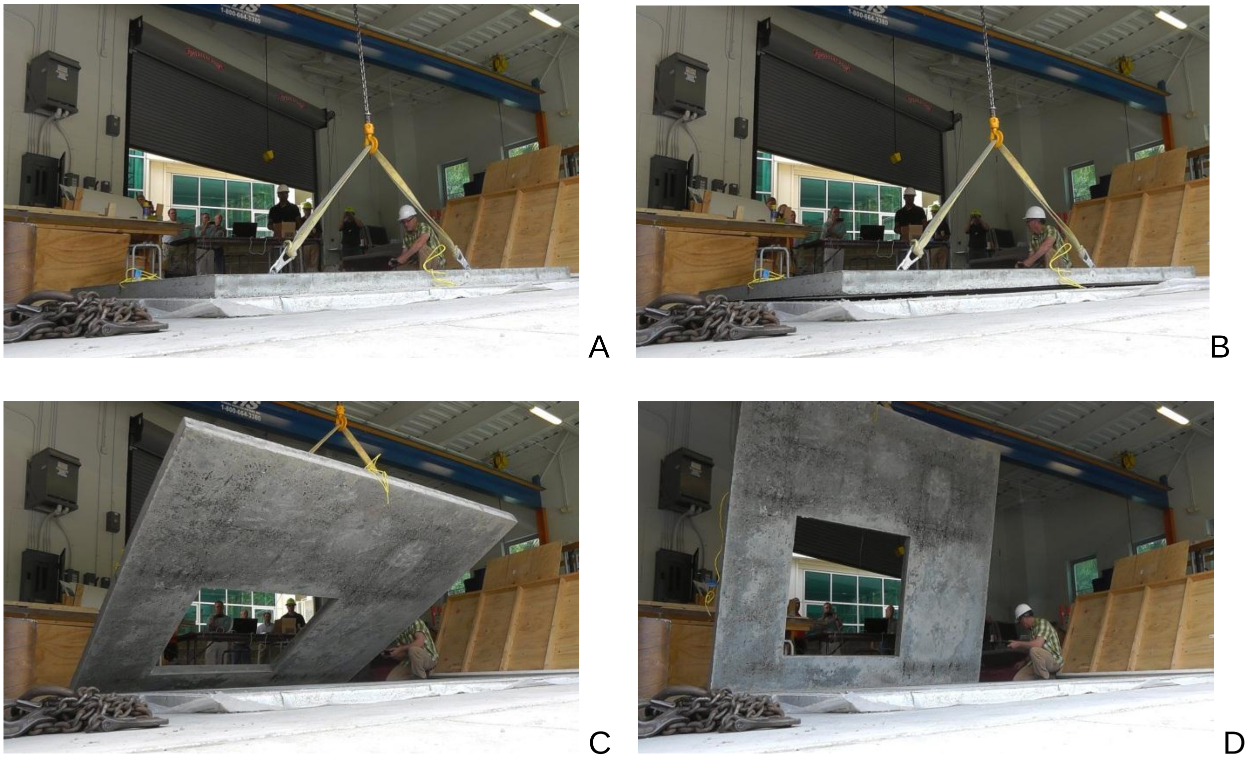


Figure 7-23. Tilt-up lifting process A) Just before lifting B) Bond breaking C) 45˚ of inclination D) Upright (photo courtesy of Adel Alsaffar)

CHAPTER 8
STRESS AND STRAIN ANALYSIS OF TILT-UP PANEL DURING LIFTING

Overview

Surface mount strain gauges were instrumented on the panel to measure the actual elongation and contraction of the concrete due to bending moments during lifting. The obtained strains at different locations were converted to stress to compare results with statics calculations and software ones. The strains extracted from the field were also compared to those of a normal weight concrete panel performed in Abi-Nader's research. (Abi-Nader 2010)

Figure 8-1 shows the locations and labels of the strain gauges on the tilt-up panel. The locations of the gauges were selected based on critical bending moment locations in each direction.

Critical Angle of Inclination

Results from manual statics computations and commercial software output as well as the work performed by Abi-Nader indicate that the maximum bending moments occur at zero degree angle of inclination. This means that maximum stresses/ strains occur just as the tilt-up panel breaks off the casting slab (Abi-Nader 2010).

Field Strains Collection

Figure 8-2 shows the overall strain measurements obtained during lifting the tilt-up panel. It depicts the cycle of lifting the panel from 0-90 degrees. The time of lifting is marked on the figure as the time of the panel being straight upward and back down. It can be observed that the maximum positive or negative strains happen at zero degree angle.

Table 8-1 shows the maximum value of strains recorded at zero degree of inclination. Positive strains indicate that the concrete was in tension at that location. In the contrary, negative strains reflect compression of the concrete surface at the gauge location.

Modulus of Elasticity

The modulus of elasticity was determined by measuring the compressive strength of the lightweight concrete cylinder and the corresponding strain in accordance to ASTM Standard (ASTM-C469 2010).

Two strain gauges were glued to the sides of the concrete cylinder with a similar procedure as in the tilt-up panel. They were connected to a computer via a data acquisition device (Figure 8-3). The following equation was used to determine the modulus of elastic:

$$E = (S_2 - S_1) / (\varepsilon_2 - \varepsilon_1) \tag{8-1}$$

Where:

E= chord modulus of elasticity, psi

S_2 = stress corresponding to 40% of ultimate load (psi)

S_1 = stress corresponding to a longitudinal strain ε_1 (psi)

ε_2 = longitudinal strain produced by stress S_2 (psi)

ε_1 = longitudinal strain of 50 micro-strain (in/in)

The compressive strength at the day of tilt was determined according to ASTM C 39 to be 3,989 psi. The value of S_2 was determined as 40% of the compressive strength at 1596 psi with a corresponding stain of 630 millionths. The stress of 160 psi was determined for a strain of 50 millionths. Thus, the modulus of elasticity was calculated as follows:

$E = (1596 – 160)\ \text{psi} / (6.3 \times 10^{-4} – 5.0 \times 10^{-5})\ (\text{in/in}) = 2.475 \times 10^{6}\ \text{psi}$

Converting Strains to Stresses

The following equation was used to calculate the stresses at certain locations of the tilt-up panel using the modulus of elasticity of the lightweight concrete and the strains obtained from the strain gauges.

$$E = S_b / \mathcal{E} \tag{8-2}$$

Where:

S_b= Bending Stress (psi)

$\mathcal{E}$= Strain (in/in)

E= Modulus of Elasticity (psi)

The equation was rearranged to the following format:

$$S_b = E \times \mathcal{E} \tag{8-3}$$

Table 8-2 shows the measured strains of the tilt-up panel at zero degree inclination and the corresponding stresses.

Stresses Comparison

Table 8-3 lists the stresses of the lightweight concrete tilt-up panel calculated from the surface mount strain gauges, calculated stresses with and without suction, and stress determined by commercial software 1 and commercial software 2.

Stresses with negative values reflect the compressive stresses of the top surface of the panel. This is due to the positive moment exerted on the concrete. Positive moments should have been reflected as tension stresses acting on the lower surface of the panel. However, due to the inaccessibility of the bottom side of the panel and the neutral axes of the panel being through mid-thickness, the tension stresses were measured as compressive stresses at the top surface of the panel.

It can be concluded that the calculated stresses without the suction effect underestimated the actual stresses. On the other hand, the calculated stresses with an increase factor of 50 percent due to suction, yielded a good estimation of the actual stresses at zero inclination degree.

Table 8-3 also shows some discrepancies between the measured and calculated stresses at gauge number 4, 5 and 7. These discrepancies can be attributed to the lifting mechanism. The tilt-up panel under study was lifted using strap cables instead of a spread beam due to limited resources (Figure 8-4). This has affected the stress distribution by increasing the compressive stresses at gauge number 5, which is located between the two lifters. It also affected the stresses in the region around the lifting lugs. However, the tilt-up panel was designed for the overall maximum stresses (at gauge number 1, 2 and 8). Figure 8-5, illustrates the stresses of the lightweight concrete panel.

Stresses Lightweight versus Normal Concrete

The lightweight concrete tilt-up panel was designed exactly as the normal weight concrete panel investigated previously by Abi-Nader. The aim was to compare the stresses due to lifting for both panels.

Table 8-4 compares the lightweight tilt-up panel stresses and stresses from the normal weight concrete tilt-up panel. The stress results are listed side by side for studying the comparison purposes. By comparing both types of concrete, it can be concluded that the lightweight concrete panel experienced lower stresses. This is due to its lower density, despite the fact that it has a lower modulus of elasticity. Figure 8-6, depicts stresses in tilt-up wall for both types of concrete tilt-up wall panels.

The stresses and strains of lightweight versus normal concrete tilt-up wall panels were also calculated using basic statics to show their relationships. Equation 8-3 was rearranged by dividing the stresses of the lightweight concrete (LWC) by the stresses of the normal concrete (NC) as follows:

$$\frac{Stress(\mathrm{LWC})}{Stress(\mathrm{NC})} = \frac{\mathrm{M(LWC)}}{\mathrm{M(NC)}} = \frac{W(\mathrm{LWC})}{W(\mathrm{NC})} = \frac{E(\mathrm{LWC})}{E(\mathrm{NC})}\ x\ \frac{Strain(\mathrm{LWC})}{Strain(\mathrm{NC})}$$

Where:

E(LWC) = 2.48 x 10^6 psi (measured)

E(NC) = 3.84 x 10^6 psi (measured in Abi-Nader research)

Hence,

$$\frac{E(\mathrm{LWC})}{E(\mathrm{NC})} = \frac{2.48}{3.84} = 0.65$$

$$\frac{Stress(\mathrm{LWC})}{Stress(\mathrm{NC})} = \frac{W(\mathrm{LWC})}{W(\mathrm{NC})} = \frac{115\ lb/ft^3}{150\ lb/ft^3} = 0.77$$

$$Stress(\mathrm{LWC}) = 0.77\ Stress(\mathrm{NC})$$

$$Strain(\mathrm{LWC}) = 1.18\ Strain(\mathrm{NC})$$

This shows that for same strength of concrete, the lightweight concrete tilt-up wall panel experienced 18% more strain during lifting, but the stresses were 23% less than stresses in the normal weight concrete tilt-up wall panel.

Since lightweight concrete has lower stiffness than normal weight concrete, concerns were also raised as to the structural effectiveness of the lightweight tilt-up panel as an element of a structure or a building. Therefore, Appendix B shows an example of a 31 ft x 15 ft tilt-up panel. The panel design example was illustrated in ACI 551.2R-10 for normal weight concrete. With simple substitutions of lightweight concrete properties, $\Delta_{\mathrm{ultimate}}$ was calculated and compared to normal concrete.

It was concluded that for all three load cases the lightweight concrete panel exerted less Δ than the normal concrete wall. Therefore, the lightweight concrete outperformed the normal concrete during and after tilting.

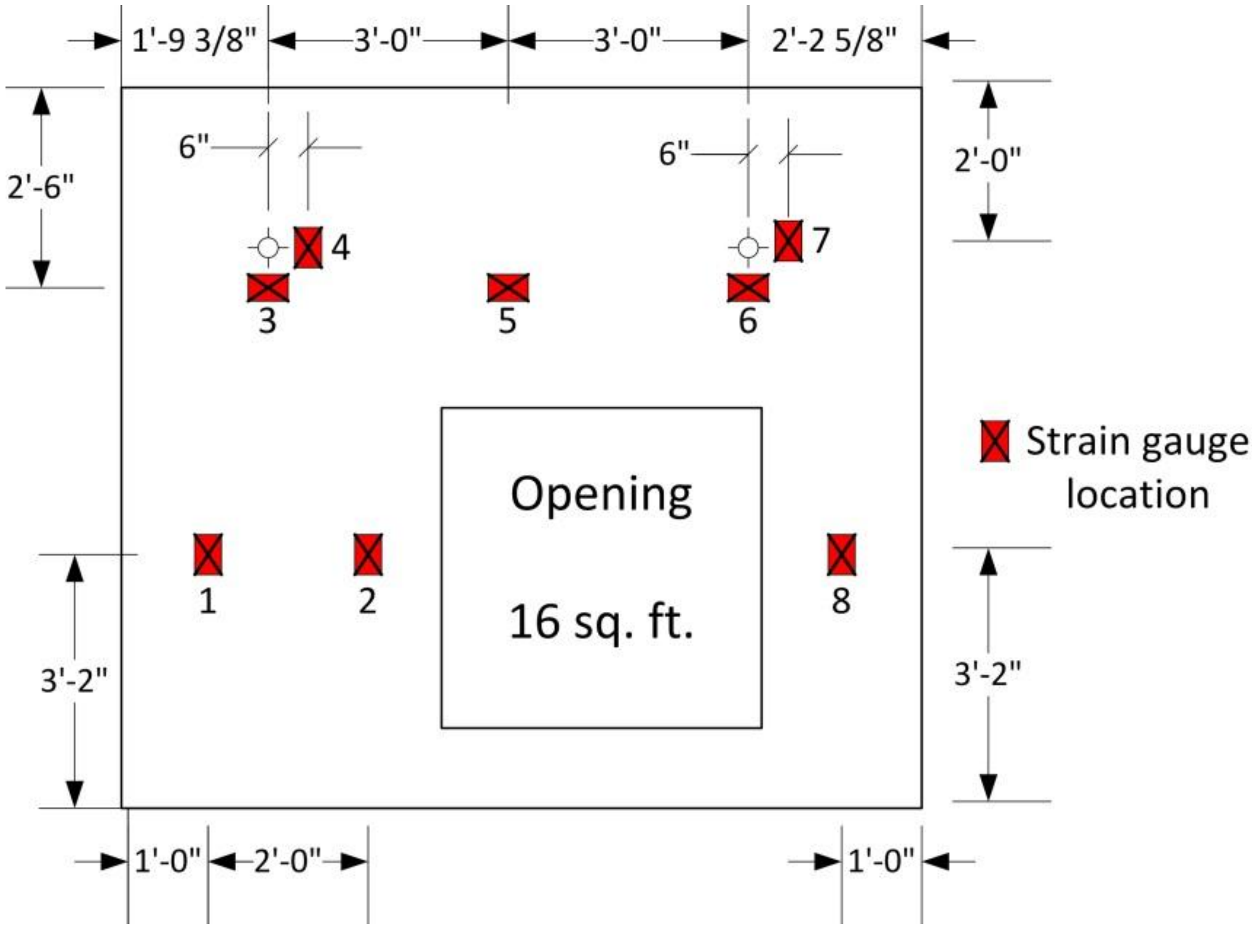


Figure 8-1. Surface-mount strain gauge locations (drawing courtesy of Adel Alsaffar)

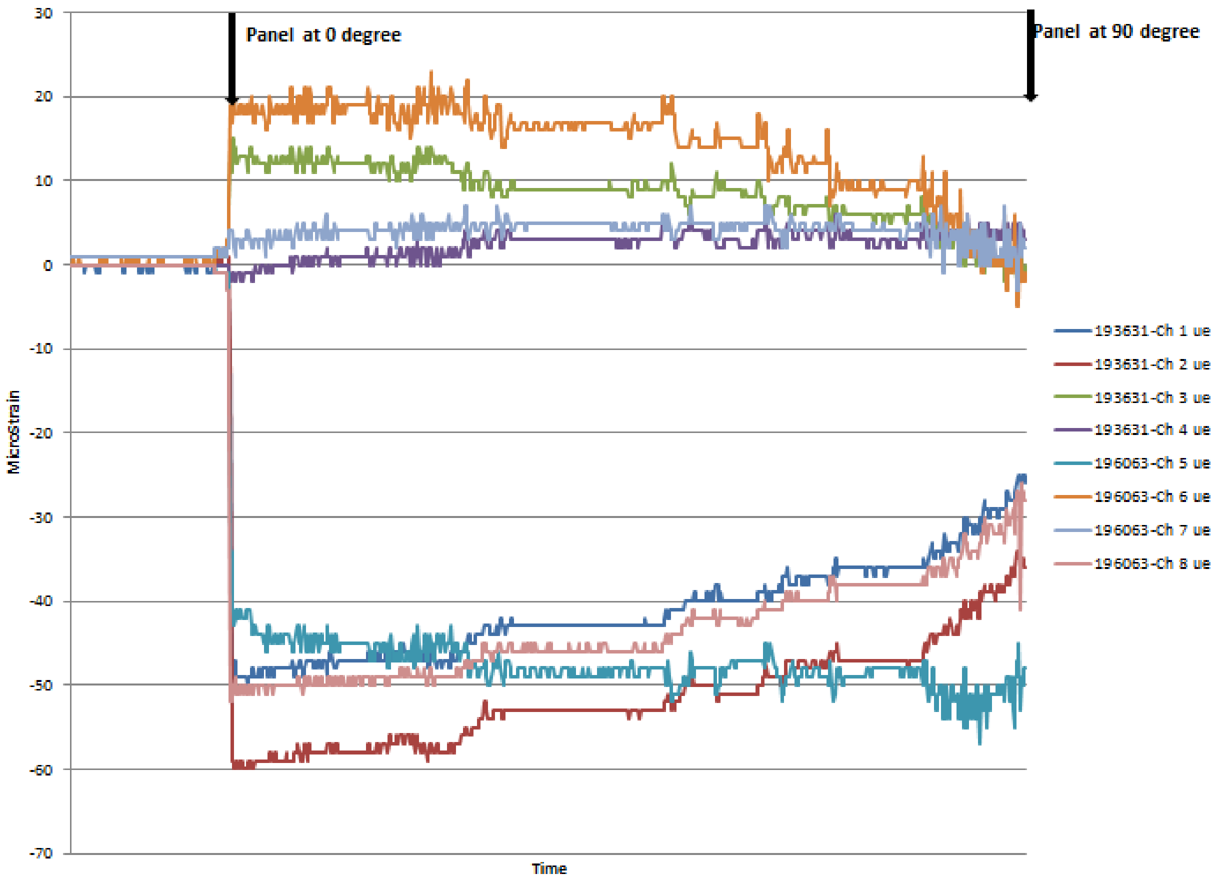


Figure 8-2. Strain measurements during tilt-up panel lifting

Table 8-1. Maximum strain at zero degree of inclination

Strain Gauge No.	Maximum Strain (in/in)
1	-5.4 x 10-5
2	-5.8 x 10-5
3	1.4 x 10-5
4	-2.0 x 10-6
5	-4.3 x 10-5
6	1.9 x 10-5
7	4.0 x 10-6
8	-5.2 x 10-5

Figure 8-3. Modulus of elasticity test (photo courtesy of Adel Alsaffar)

Table 8-2. Stresses calculations

Strain Gauge No.	Maximum Strain (in/in)	Stresses (psi)
1	-5.4 x 10-5	-133.66
2	-5.8 x 10-5	-143.56
3	1.4 x 10-5	34.65
4	7.0 x 10-6	17.33
5	-4.3 x 10-5	-106.43
6	1.9 x 10-5	47.03
7	1.0 x 10-5	24.75
8	-5.2 x 10-5	-128.71

Table 8-3. Stress comparison of lightweight concrete tilt-up panel

Strain Gauge No.	Measured stresses (psi)	Calculated stresses – no suction (psi)	Calculated stresses – suction (psi)	Commercial Software 1 (psi)	Commercial Software 2 (psi)
1	133.7	89.7	136.0	112.0	88.2
2	143.6	89.7	136.0	112.0	88.2
3	34.7	38.6	57.9	24.0	26.9
4	17.3	56.3	84.4	45.0	32.8
5	106.4	36.8	55.2	44.0	25.2
6	47.0	59.9	89.8	50.0	56.3
7	24.8	33.4	50.1	45.0	32.8
8	128.7	89.7	136.0	112.0	88.2

Figure 8-4. Strap cables lifting at 45 degree angle (photo courtesy of Adel Alsaffar)

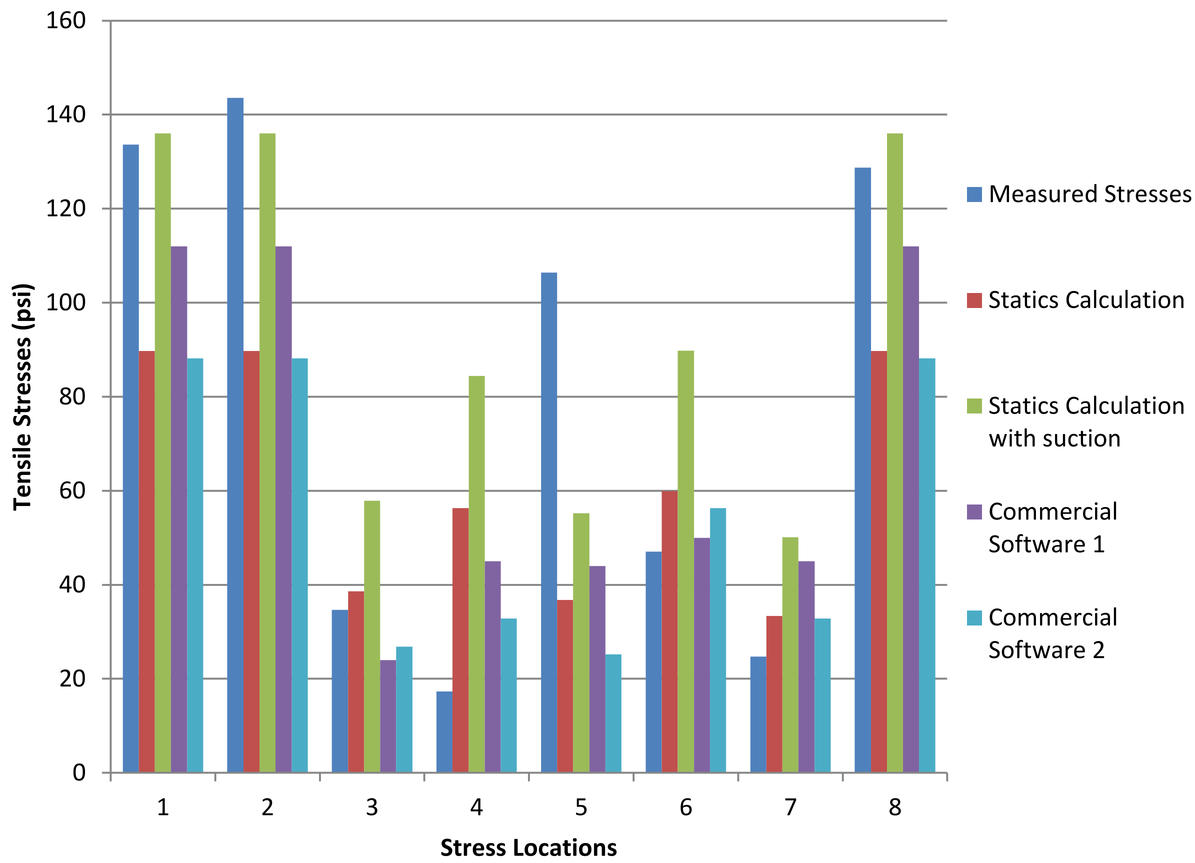


Figure 8-5. Tilt-up panel stress comparison

Table 8-4. Stress comparison of lightweight versus normal concrete

Strain Gauge No.	Measured Stresses (lightweight concrete) (psi)	Measured Stresses (normal concrete) (psi)
1	133.7	154
2	143.6	157
3	34.7	77
4	17.3	54
5	106.4	61
6	47.0	92
7	24.8	46
8	128.7	165

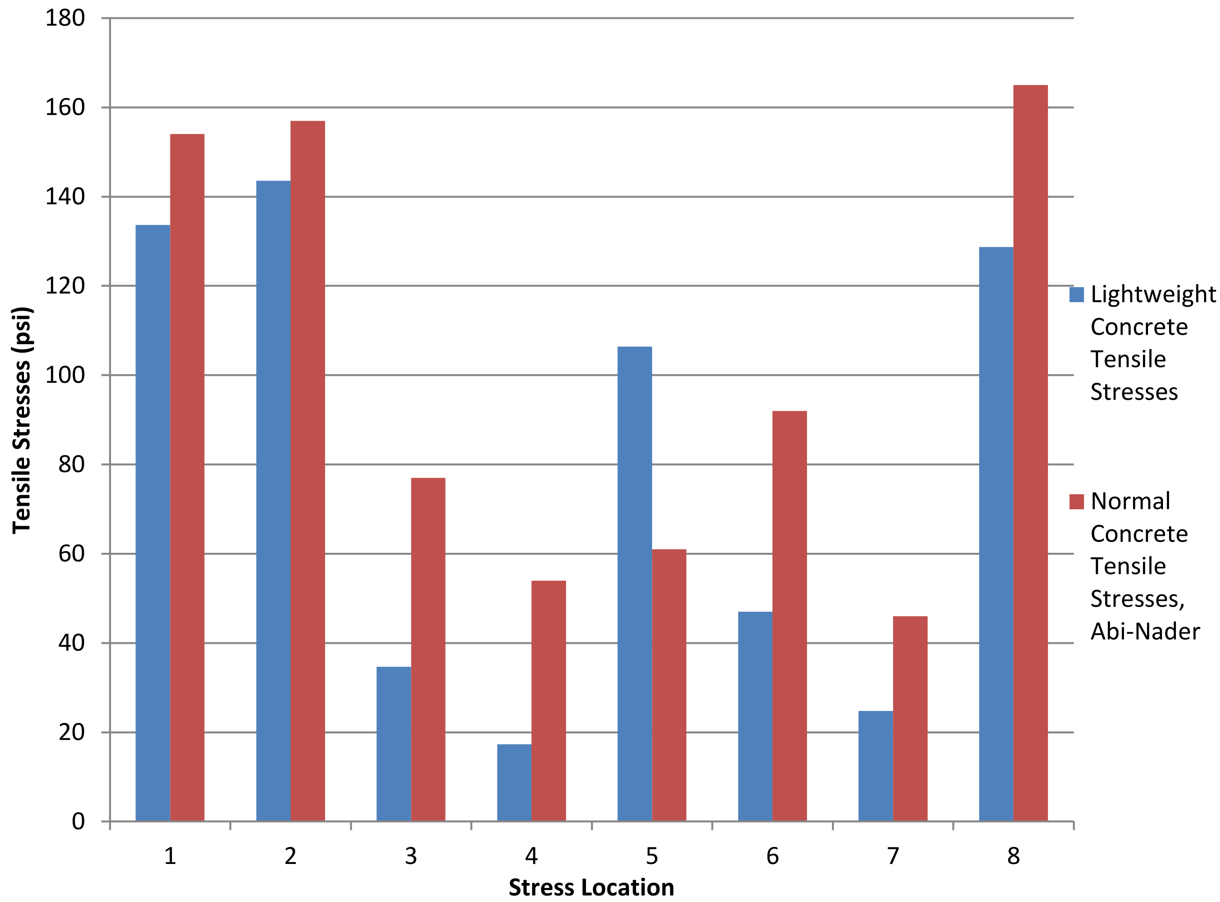


Figure 8-6. Stress comparison of lightweight versus normal concrete

CHAPTER 9
CONCLUSIONS AND RECOMMENDATIONS

Conclusions

All maturity methods were found effective in estimating the compressive and flexural strength of the lightweight concrete tilt-up panel. However, the equivalent age factor method was the most accurate one followed by the temperature-time factor. The COMA meter method was also effective but it underestimated the strength of the concrete. Nevertheless, for the purpose of tilt-up construction it was found within an acceptable range.

Despite the effectiveness of the maturity methods, ASTM C 1074 requires different concrete strength estimation tests to be executed before performing a critical operation, in our case lifting a tilt-up panel. The pullout strength test method was used and found effective in estimating the compressive and flexural strength of the lightweight concrete tilt-up panel. However, the pullout inserts must be place on the surface of the panel for an accurate estimation. Side pullout inserts used in our experiment have failed to yield a good estimation of the strength due to the slenderness of the panel.

The maturity methods and pullout strength test relationships were investigated and found to be very effective in predicting the strength of the lightweight concrete and can be utilized in different applications such as tilt-up panels.

Furthermore, the tilt-up panel surface mount strain gauges have shown that maximum stresses occur at zero degree of inclination, when the tilt-up just breaks free off the casting bed. A suction factor of 50% must be considered in the computations of the maximum negative or positive bending moments in order to obtain an accurate panel design. The lightweight concrete was found structurally effective in the construction of the tilt-up panel despite the lower modulus of elasticity.

Recommendations

- The application of lightweight concrete in tilt-up constructions.
- Evaluate the compressive and flexural strength of concrete using the Equivalent Age method.
- Applying pullout inserts to the surface of the tilt-up panel.
- The used of Maturity Methods with Pullout strength test to evaluate the strength of lightweight concrete prior to lifting.
- Re-evaluate the lifting software using data obtained in this research.
- Using 50% suction factor at zero inclination degree
- Study the suction effect on tilt-up panel for a better understanding.
- Study of pullout inserts on panel sides for walls 6” thick or more
- Study the stresses in tilt-up panel with two layers of reinforcement
- Study the application of more non-destructive testing to evaluate the strength of lightweight concrete.
- Study the application of lightweight coarse and fine aggregates in tilt-up panel.

APPENDIX A
TEMPERATURE AND TIME DATA RECORDED BY MATURITY LOGGERS

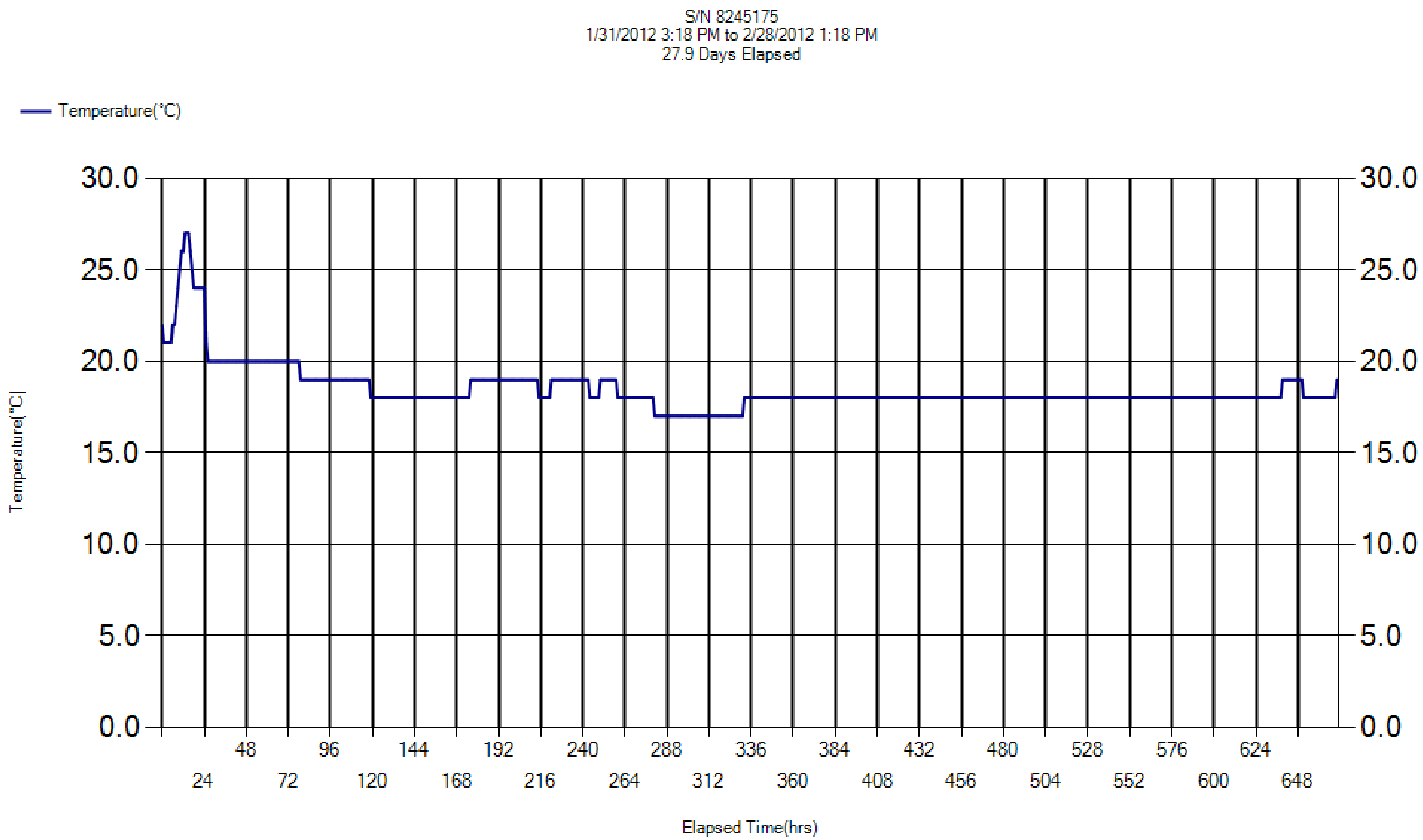


Figure A-1. Temperature vs. Time of logger embedded in beam 1, control batch

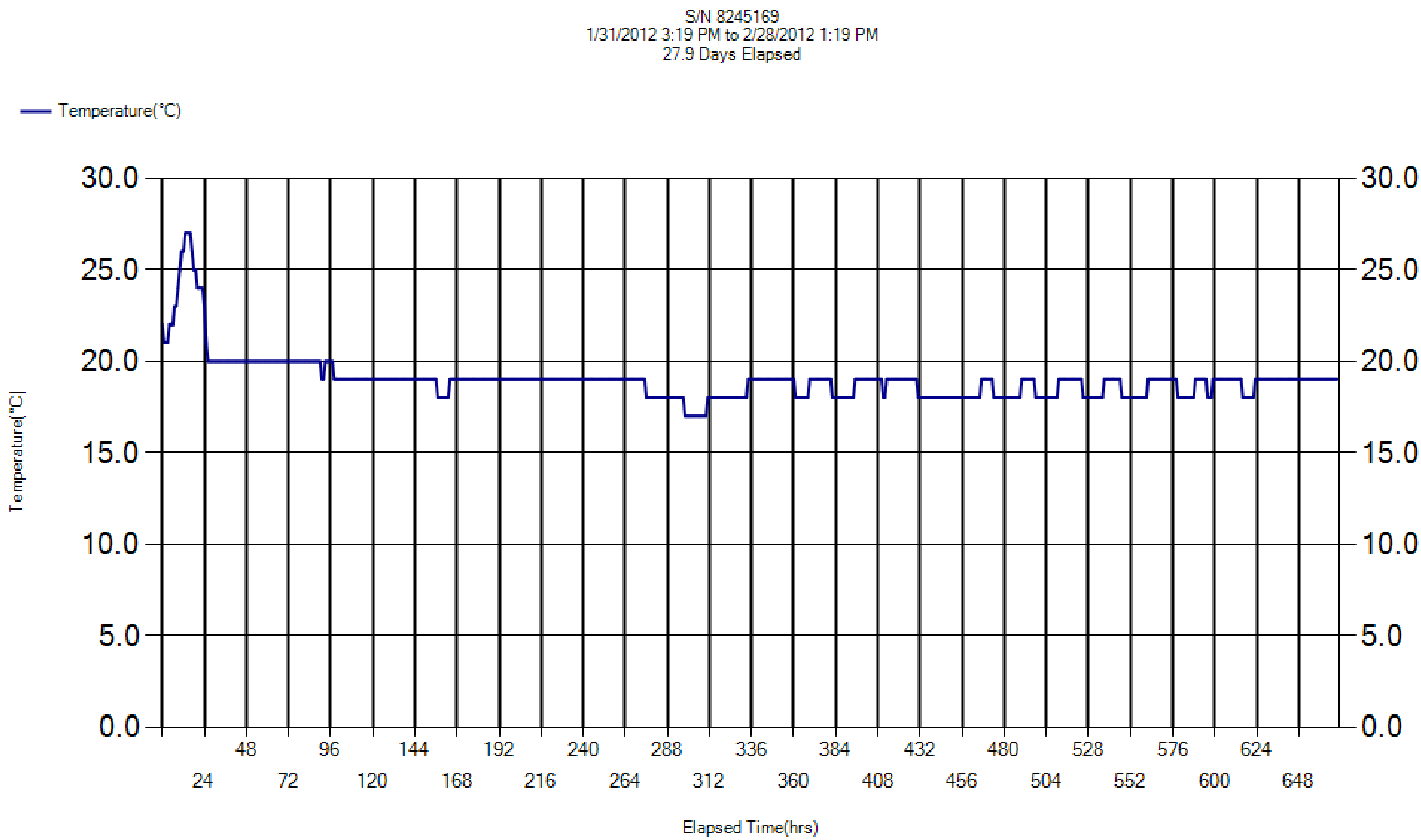


Figure A-2. Temperature vs. Time of logger embedded in beam 2, control batch

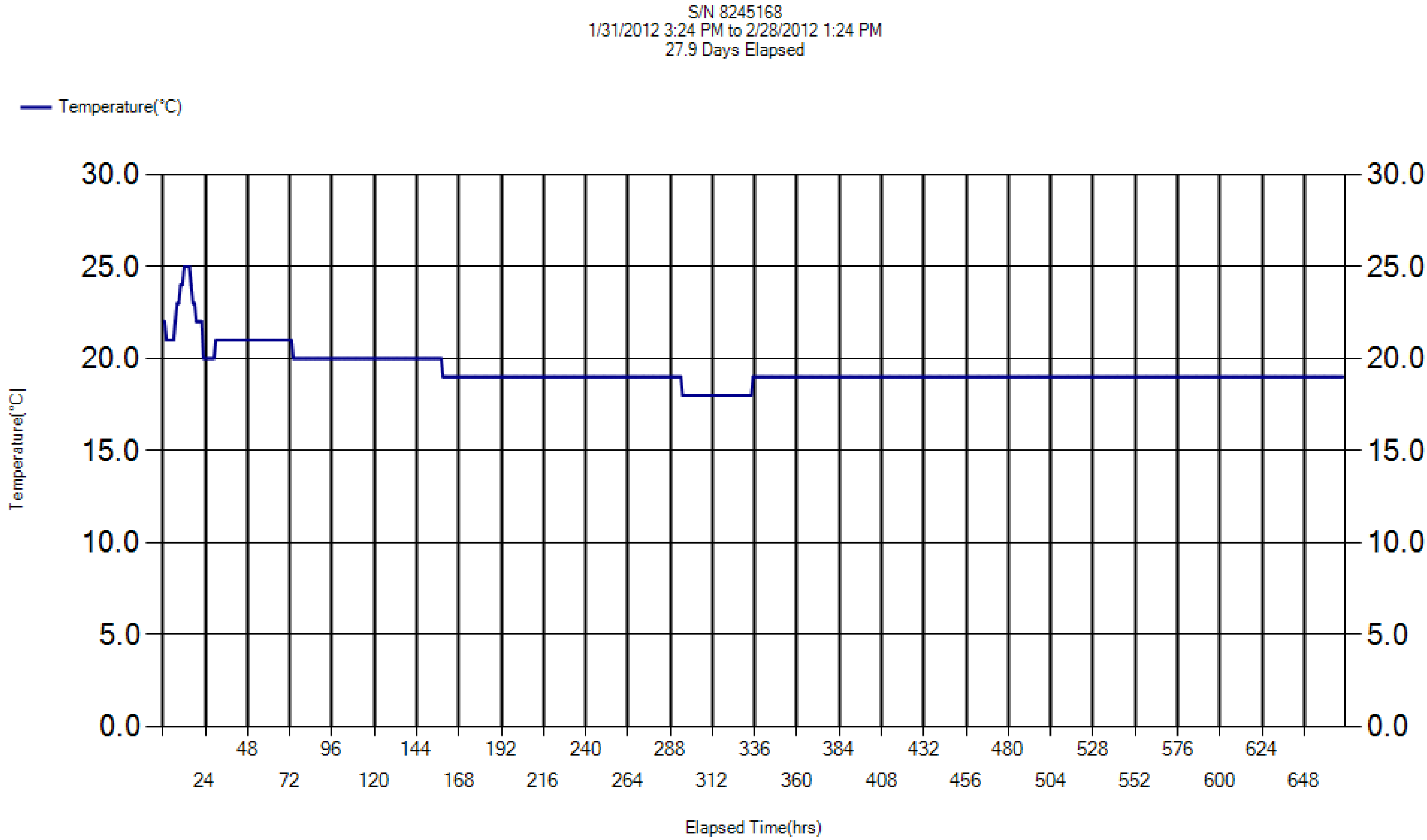


Figure A-3. Temperature vs. Time of logger embedded in cylinder 1, control batch

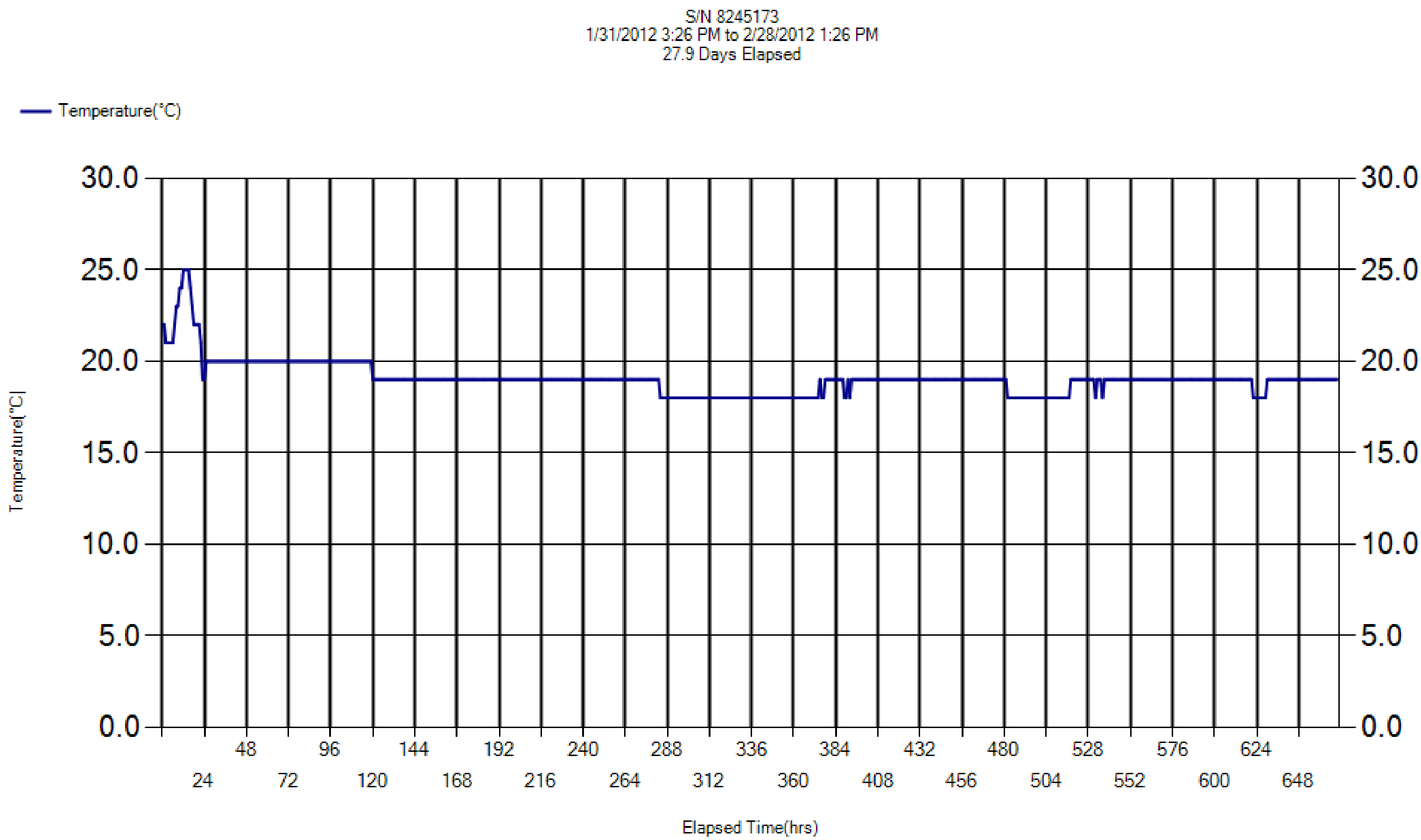


Figure A-4. Temperature vs. Time embedded in cylinder 2, control batch

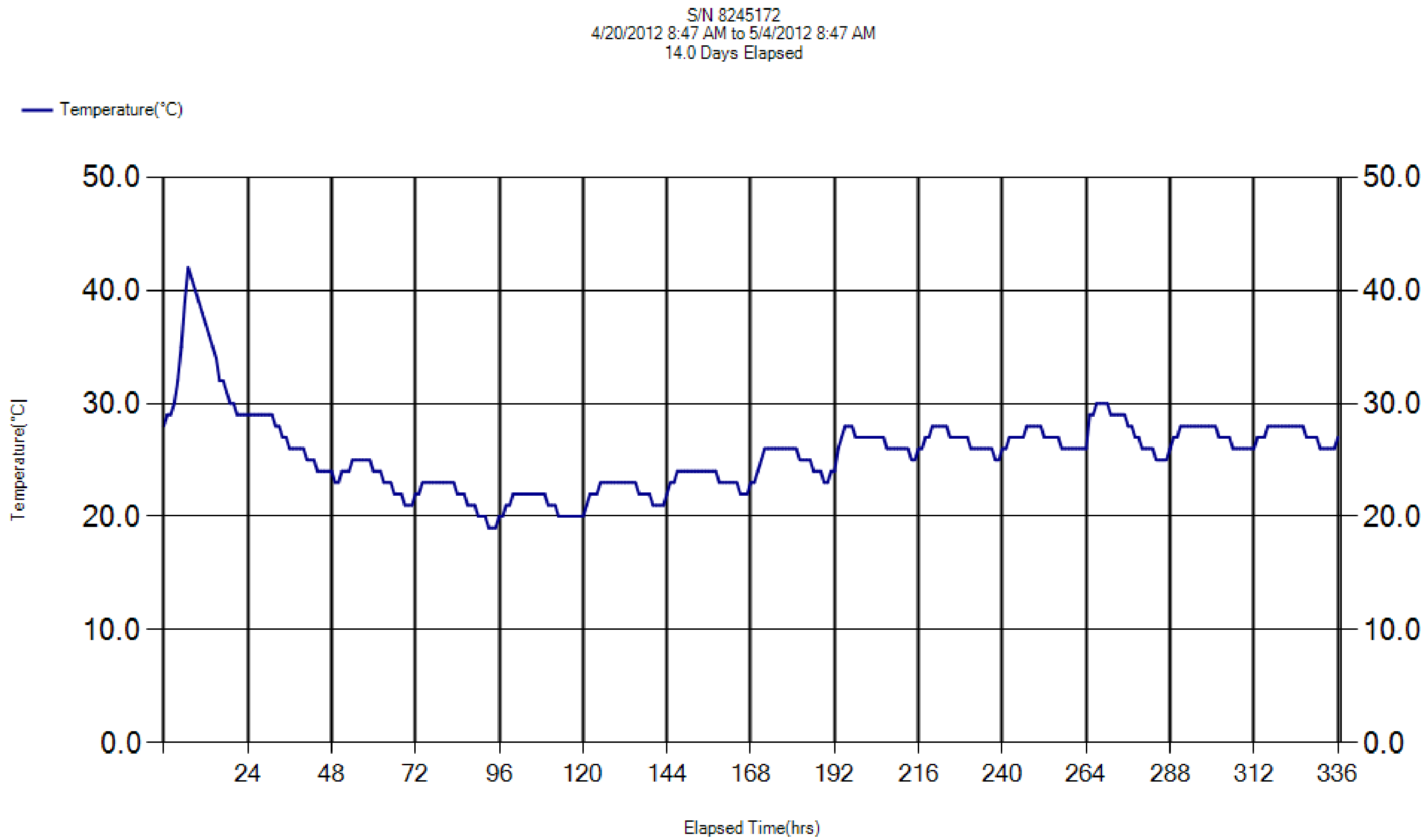


Figure A-5. Temperature vs. Time of logger embedded in cylinder 1, experimental batch

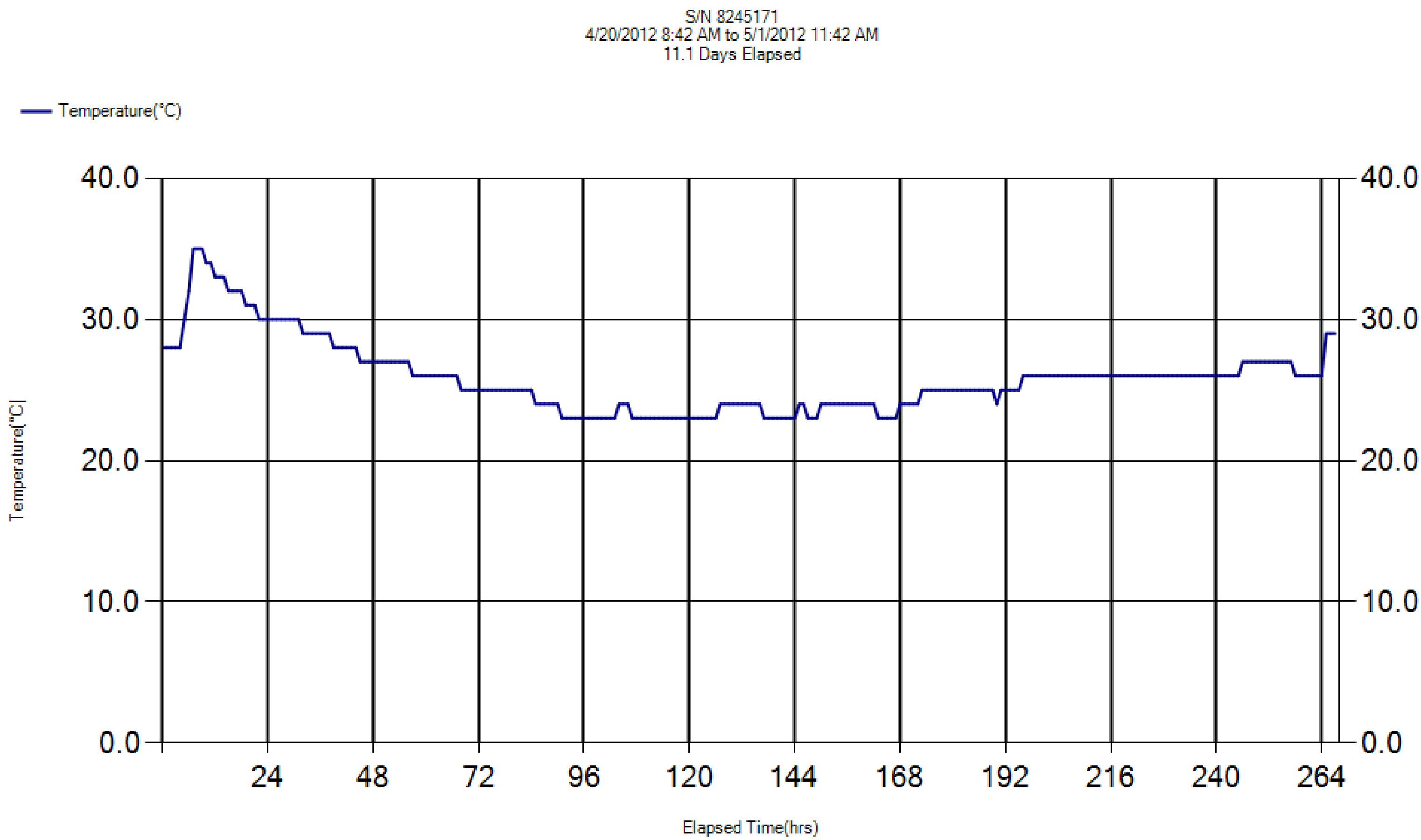


Figure A-6. Temperature vs. Time of logger 1 embedded in tilt-up wall panel, experimental batch

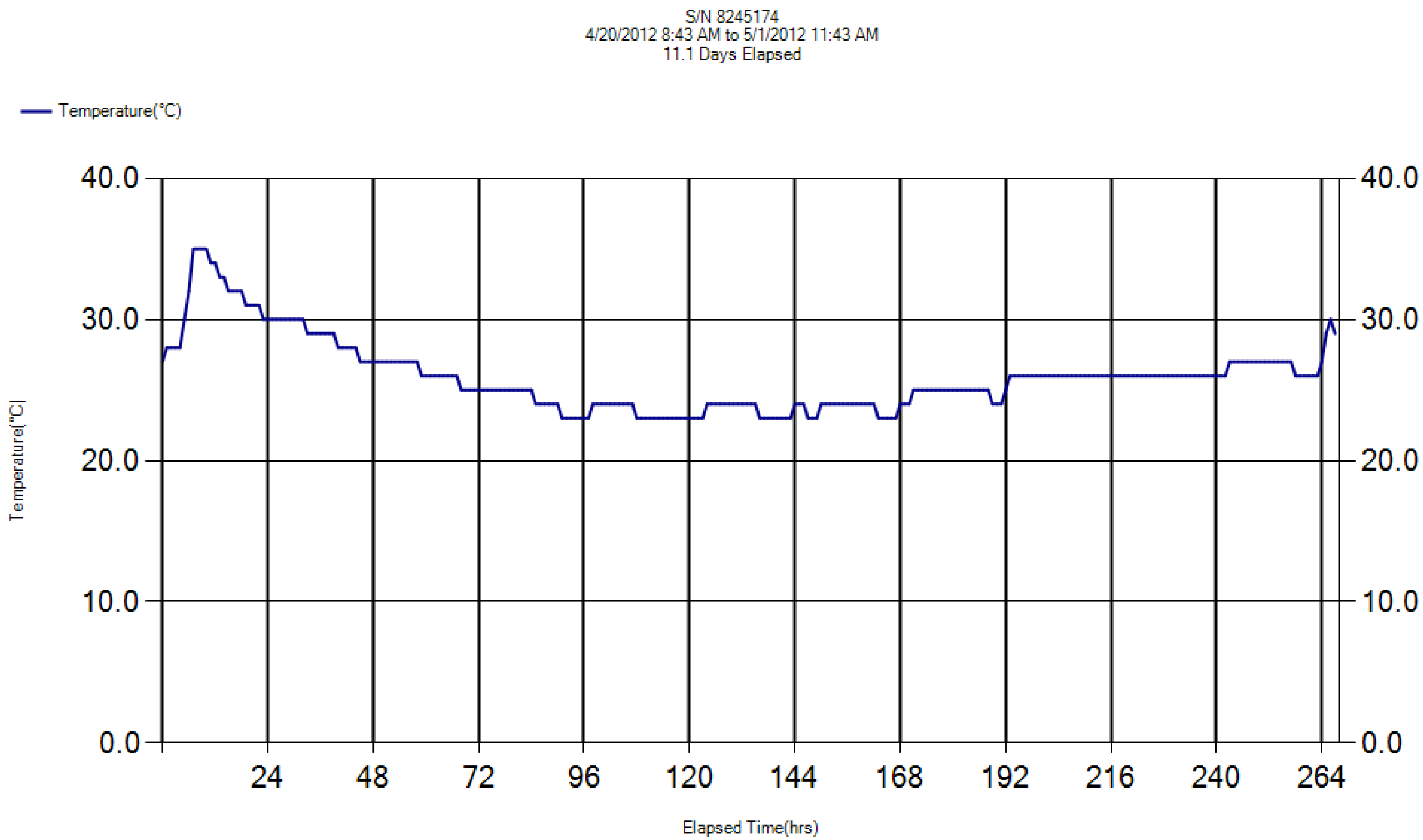
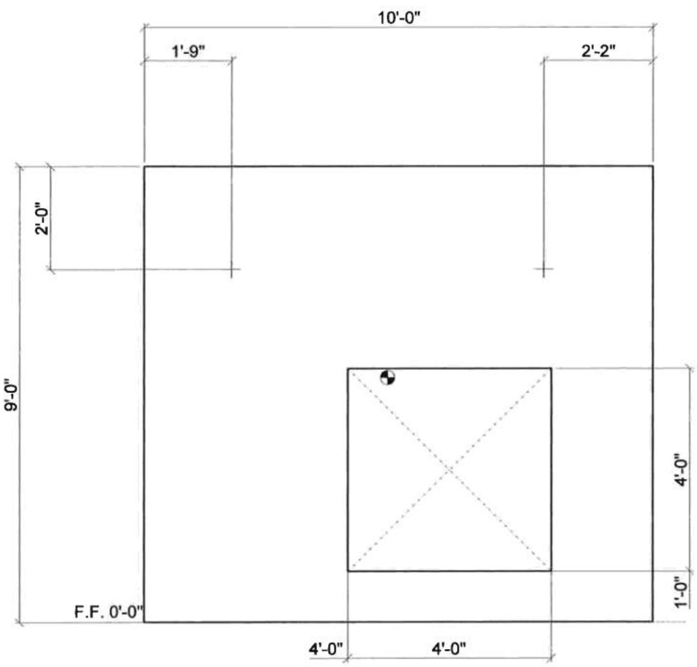


Figure A-7. Temperature vs. Time of logger 2 embedded in tilt-up wall panel, experimental batch

APPENDIX B
COMMERCIAL SOFTWARE RESULTS

Commercial Software 1

NON STR. THK.	STRUCT. THK.	WEIGHT	WIDTH	HEIGHT	NO. REQ'D.	PANEL NUMBER OR TYPE
	3 1/2"	3.2 kips	10'-0"	9'-0"	1	1



W B F

VERIFY ALL DIMENSIONS PRIOR TO POURING PANEL

MINIMUM COMPRESSIVE STRENGTH REQ'D.= 2,500 PSI

Construction Period Design Wind Speed	TOTAL BRACE LOAD =	B=	W=	F=	BRACE REQ'D.:
72 mph					

GROUND RELEASE II TILT-UP SYSTEM This drawing is furnished solely for the purpose of clarifying the proper use, installation and application of products supplied by Dayton Superior. Dayton Superior does not assume any responsibility for the correctness of structural designs or dimensions furnished by others. These drawings are intended merely to supplement the architectural and structural drawings and are to be used only in conjunction with them. In no way are these drawings to be interpreted as shop drawings for panel fabrication.	$\bar{X}$ 4'-9 3/8"	$\triangle X$ -.22 <	CY= 1.	SCALE:	RIGGING DETAILS
	$\bar{Y}$ 4'-9 7/8"	$2\triangle X$ -.43	GROSS AREA 90.0	3/8"	R12
	PANEL VIEWED FROM:	CHECKED BY	NET AREA 74.0	JOB NO.	SHEET
	INSIDE	LAYOUT BY KLC	DATE 3/19/12	12128	16F1

NOTE: INSERT AND BRACING DESIGN SHOWN IS BASED ON THE USE OF DAYTON SUPERIOR PRODUCTS ONLY!

********************** GROUND RELEASE II Tilt-up Analysis ***********************

Operator : KLC
Job no.: 12128
Panel no.: 1
Date : 3/19/2012

VERTICAL ANALYSIS

Uniform loads

Segment Number	Length (Feet)	Load (PPF)
01	001.00	00335.42
02	004.00	00201.25
03	001.96	00335.42
04	002.04	00335.42

Section Properties

N	D(N) (Ft.)	Area (In.^2)	Mom. of In. (In^4)	Neut. Axis (In.)	+Sec. Mod. (In.^3)	-Sec. Mod. (In.^3)	Eff. Thk. (In.)
01	001.00	00420.00	000000429	001.75	00000245	00000245	003.50
02	004.00	00252.00	000000257	001.75	00000147	00000147	003.50
03	001.96	00420.00	000000429	001.75	00000245	00000245	003.50
04	002.04	00420.00	000000429	001.75	00000245	00000245	003.50

Additional reinforcing

							Strongbacks	
Angle Deg.	Loc. Feet	Flexure Stress PSI	Bending Moment Ft-Lbs	Allow. Moment Ft-Lbs	Tens. Steel Sq. In.	Comp. Steel Sq. In.	Sec. Mod. Wood In^3	Sec. Mod. Steel In^3
00	00.20	B 0010	00000190	00000102	00.03	00.00	00001.22	00000.11
00	01.00	B 0039	00000777	00000102	00.11	00.00	00004.97	00000.47
00	01.00	B 0064	00000777	00000061	00.11	00.00	00004.97	00000.47
00	03.10	B 0112	00001370	00000061	00.19	00.00	00008.77	00000.82
00	06.18	B 0002	00000026	00000102	00.00	00.00	00000.17	00000.02
00	06.38	T 0009	-0000180	-0000102	00.02	00.00	00001.15	00000.11
00	06.96	T 0045	-0000900	-0000102	00.13	00.00	00005.76	00000.54
00	08.39	T 0004	-0000073	-0000102	00.01	00.00	00000.47	00000.04

Insert loads

Maximum tension load = 1121.34 lbs per insert.
Maximum shear load = 1618.75 lbs per insert.
Maximum ground reaction = 994.82 lbs
Maximum positive stress (Bottom)= 112 psi @ 3.1 ft. and 0°
Minimum bottom steel required = .19 sq. in.
Maximum negative stress (Top)= 45 psi @ 6.96 ft. and 0°
Minimum top steel required = .13 sq. in.

Strongback req'ments (Applicable only if printout shows add'l steel req'd.)

Wood: 1 single 2X12's or equivalent.
1 single 4X12's or equivalent.
Steel: 1 double C6X8.2 or equivalent.
1 double C8x11.5 or equivalent.

********************** GROUND RELEASE II Tilt-up Analysis ***********************

Operator : KLC
Job no.: 12128
Panel no.: 1
Date : 3/19/2012

HORIZONTAL ANALYSIS

Uniform loads

Segment Number	Length (Feet)	Load (PPF)
01	01.72	00196.85
02	02.28	00196.85
03	03.85	00134.17
04	00.15	00134.17
05	02.00	00196.85

Section Properties

N	D(N) (Ft.)	Area (In.^2)	Mom. of In. (In^4)	Neut. Axis (In.)	+Sec. Mod. (In.^3)	-Sec. Mod. (In.^3)	Eff. Thk. (In.)
01	001.72	00246.49	000000252	001.75	00000144	00000144	003.50
02	002.28	00246.49	000000252	001.75	00000144	00000144	003.50
03	003.85	00168.00	000000171	001.75	00000098	00000098	003.50
04	000.15	00168.00	000000171	001.75	00000098	00000098	003.50
05	002.00	00246.49	000000252	001.75	00000144	00000144	003.50

First point of zero shear = 03.13 ft.

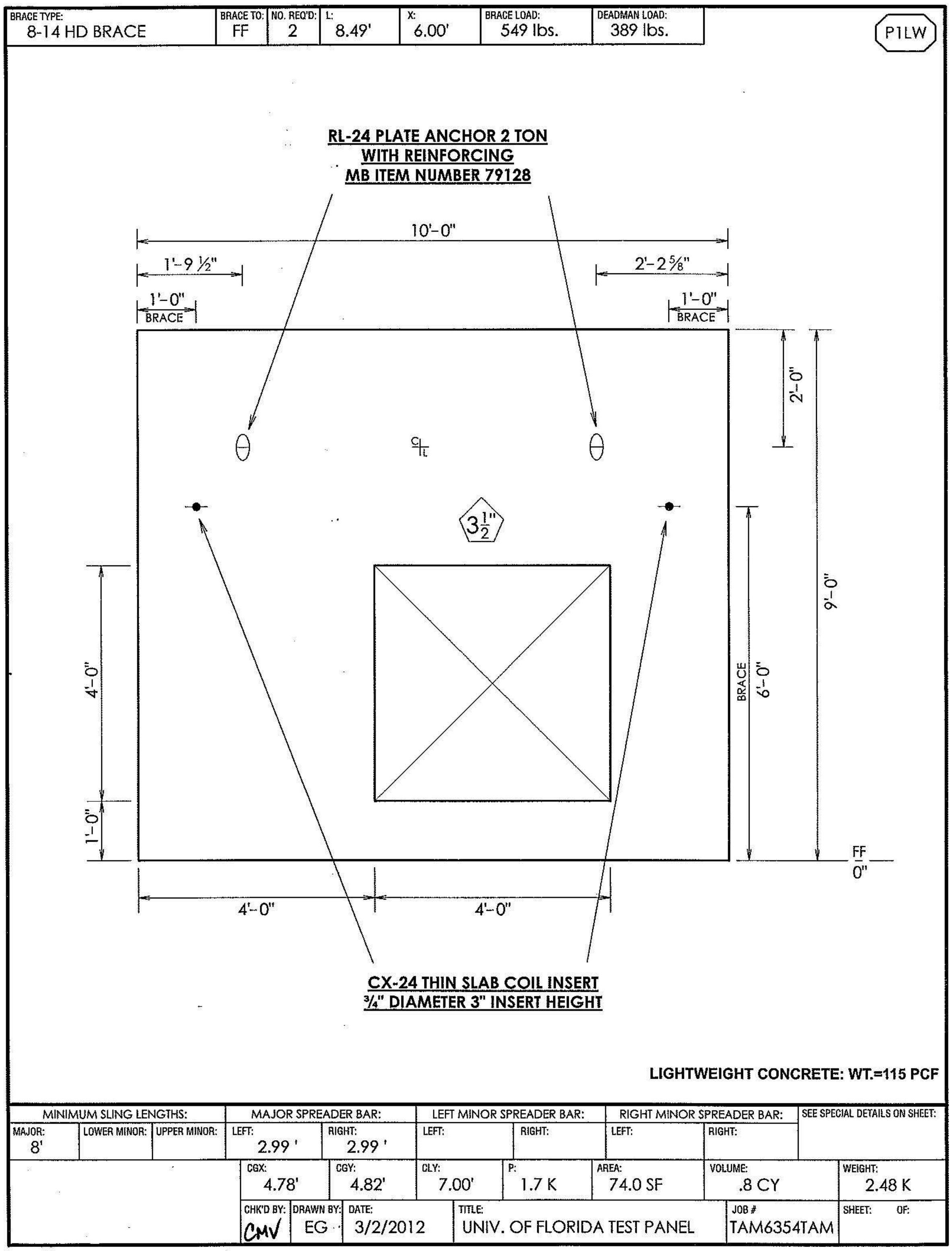
Additional reinforcing

Angle Deg.	Loc. Feet	Flexure Stress PSI	Bending Moment Ft-Lbs	Allow. Moment Ft-Lbs	Tens. Steel Sq. In.	Comp. Steel Sq. In.	Strongbacks Sec. Mod. Wood In^3	Strongbacks Sec. Mod. Steel In^3
00	00.69	T 0006	-0000064	-0000060	00.01	00.00	00000.41	00000.04
00	01.72	T 0024	-0000283	-0000060	00.04	00.00	00001.81	00000.17
00	02.29	T 0002	-0000022	-0000060	00.00	00.00	00000.14	00000.01
00	02.52	B 0006	00000063	00000060	00.01	00.00	00000.40	00000.04
00	04.00	B 0030	00000352	00000060	00.05	00.00	00002.25	00000.21
00	04.00	B 0044	00000352	00000041	00.05	00.00	00002.25	00000.21
00	06.57	B 0005	00000033	00000041	00.00	00.00	00000.21	00000.02
00	06.82	T 0006	-0000048	-0000041	00.01	00.00	00000.31	00000.03
00	07.85	T 0050	-0000406	-0000041	00.06	00.00	00002.60	00000.24
00	09.20	T 0004	-0000046	-0000060	00.01	00.00	00000.30	00000.03

Maximum positive stress (Bottom)= 44 psi @ 4.0 ft. and 0°
Minimum bottom steel required = .05 sq. in.
Maximum negative stress (Top)= 50 psi @ 7.85 ft. and 0°
Minimum top steel required = .06 sq. in.

Balancing moment = -25.23 ft.-lbs./ft. over 4.78 ft.W-Shift 0.07
Strongback req'ments (Applicable only if printout shows add'l steel req'd.)
Wood: 1 single 2X12's or equivalent.
1 single 4X12's or equivalent.
Steel: 1 double C6X8.2 or equivalent.
1 double C8x11.5 or equivalent.

Commercial Software 2



```
H,W,T: 9.000 10.000 3.500    F.F. =0.00

HOLE  1: RT      1.000  4.000  4.000  4.000

CONCRETE STRENGTH = 2500 psi   MODULUS OF RUPTURE = 500 psi
CONCRETE DENSITY = 115 pcf

---------- VERTICAL ANALYSIS ----------

WT. =  2.482        SURFACE AREA =  74.00
CGX =  4.784        GROUND REACTION= 0.77
CGY =  4.824        CLy =  7.000
Min. CLy = 6.824 (Cgy + 2 ft.)

VERTICAL SPACING: 7.000 (2.000)

   LOCN   MOMENT   K'/ft
   1.00     0.60    0.10
-  3.17     1.08    0.18
   5.00     0.74    0.12
@  7.00    -0.67   -0.07
  TOP

HEIGHT FOR LEG SECTIONS = 3.17
LEG WIDTHS > 4 ft. WERE DIVIDED

        HORIZ. LOCN          R       Ht.
LEG 1 ( 0.00 TO  4.00) =  0.41    3.03
LEG 2 ( 8.00 TO 10.00) =  0.23    3.43
                          -----
BEAM WT. = 0.13           0.64

LEG   LOCN   MOMENT  K'/ft
1     1.00    0.37    0.09
1     3.04    0.65    0.16
1 R   5.00    0.39    0.10
1     7.00   -0.54   -0.09

2     1.00    0.23    0.12
2     3.43    0.43    0.21
2 L   5.00    0.35    0.17
2     7.00   -0.13   -0.03

--------- M.R. HORIZONTAL ---------

WT.'=  1.711       DISCREPANCY MOMENT = 0.00
CGX'=  4.784       CLx =  4.784

HORIZONTAL SPACING:  1.790  7.778 (2.222)

   LOCN   MOMENT   K'/ft
@  1.79    -0.32   -0.05
   4.00     0.29    0.07
-  4.41     0.30    0.08
@  7.78    -0.46   -0.12
   8.00    -0.37   -0.09

VERT. DIMS
       2.000
       7.000
HORIZ. DIMS.  1.790   5.988   2.222
```

Insert Loads: TENSION/SHEAR

$P = \frac{1.2}{1.84} = 0.652$

(4000 SNL)(.652) = 2,608

COLUMN:	1	2
ROW		
1:	0.86/ 1.24	0.86/ 1.24

MAX. INSERT TENSION= 0.86
MAX. INSERT SHEAR = 1.24
WARNING! THE FOLLOWING INSERTS MAY BE OVERLOADED:
H=7.0 W=1.79
H=7.0 W=7.78

---------- BRACING ---------- (FF)

Wind Speed = 72 mph
Outside Grade = 0.000'
Inside Slab/Grade = 0.000'
Brace Insert Type: NORMAL
CGY + 5% = 5.27 (from panel bottom)

Safety Factor = 1.50
Brace to: INSIDE
Footing Condition = NORMAL
Floor Slab: NORMAL
Area CGY+5% = 5.27 (from panel bottom)

Vertical Bracing Moments

	LOCN	MOMENT	K'/ft	ALLOW.
	1.00	0.20	0.03	0.61
-	2.25	0.29	0.05	0.61
	5.00	-0.14	-0.02	0.61
@	6.00	-0.52	-0.05	0.61
	TOP			

----BRACE CHARACTERISTICS (ft.)----

	LOCN	TYPE	V	Vb	%TOT. HT.	ABOVE CGy	X	L	SHOE ELEV.	BRACE ANGLE
1	1.00	HD Brace	6.00	6.00	66%	1.18	6.00	8.49	0.00	45.0
2	9.00	HD Brace	6.00	6.00	66%	1.18	6.00	8.49	0.00	45.0

----ACTUAL BRACE LOADS (plf.)----

HORIZ.	VERT.	CONCENT.
77.6	77.6	109.8

----BRACE DESIGN CAPACITIES (lbs.)----

REDUCTION FACTOR	ULTIMATE BRACE	ULTIMATE SHOE	WORKING	MAX. SPACING
0.000	23294.4	13500.0	9000.0	20.00'

----CONTRIBUTORY WIDTHS (ft.)----

	RANGE	WIDTH
1	0.00 - 5.00	5.00
2	5.00 - 10.00	5.00

----TOTAL ACTUAL BRACE LOADS (lbs.)----

CONCENT.	VERT.	HORIZ.
549	389	389
549	389	389

Total Load to Panel Base = 258.8 lbs.

APPENDIX C

DESIGN COMPARISON OF LIGHTWEIGHT AND NORMAL WEIGHT CONCRETE TILT-UP WALL PANELS

Load Case 1: 1.2 D + 1.6 Lr + 0.8 W

Table C-1. Tilt-up panel design comparison for load case 1

Calculation	Normal Concrete	Lightweight Concrete
Pua	20.6 k	20.6k
Pum	43.4 k	38.2 k
wu	0.204 klf	0.204 klf
Pum/Ag	38.6 psi	33.9 psi
Ase	7.72 in2	7.63 in2
a	0.757 in	0.749 in
c	0.891 in	0.881 in
c/d	0.285	0.281
Icr	353 in4	494 in4
Mcr	46.3 ft-k	39.4 ft-k
ΦMn	95.5 ft-k	94.7 ft-k
Kb	97.4 k	93.8 k
Mua	24.8 ft-k	24.8 ft-k
Mu	61.2 < ΦMn	54.2 < ΦMn
Δu	10.0 in	9.2 in

Load Case 2: 1.2D + 0.5 Lr + 1.6W

Table C-2. Tilt-up panel design comparison for load case 2

Calculation	Normal Concrete	Lightweight Concrete
Pua	12.4 k	20.6k
Pum	35.2 k	29.91 k
wu	0.408 klf	0.408 klf
Pum/Ag	31.3 psi	26.6 psi
Ase	7.59 in2	7.50 in2
a	0.744 in	0.735 in
c	0.875 in	0.865 in
c/d	0.280	0.276
Icr	349 in4	489 in4
Mcr	46.3 ft-k	39.4 ft-k
ΦMn	94.0 ft-k	93.2ft-k
Kb	96.4 k	93.0 k
Mua	54.9 ft-k	45.9 ft-k
Mu	89.5 < ΦMn	80.4 < ΦMn
Δu	14.8 in	13.83 in

Load Case 3: 0.9D + 1.6W

Table C-3. Tilt-up panel design comparison for load case 3

Calculation	Normal Concrete	Lightweight Concrete
Pua	6.48 k	6.48 k
Pum	23.6 k	19.6 k
wu	0.408 klf	0.408 klf
Pum/Ag	21.0 psi	17.4 psi
Ase	7.39 in2	7.33 in2
a	0.725 in	0.72 in
c	0.853 in	0.845 in
c/d	0.273	0.270
Icr	344 in4	484 in4
Mcr	46.3 ft-k	39.4 ft-k
ΦMn	91.9 ft-k	91.4 ft-k
Kb	95.1 k	92.0 k
Mua	45.2 ft-k	45.2 ft-k
Mu	67.5 < ΦMn	63.1 < ΦMn
Δu	11.4 in	11 in

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BIOGRAPHICAL SKETCH

Adel Alsaffar was born in Kuwait City, Kuwait. He received his education in Kuwait until graduated from high school. He joined the University of Miami, FL for his bachelor's degree. He graduated with double majors in Civil and Architectural Engineering in 1999. He returned to his homeland and worked for Kuwait Oil Company for more than five years, during which he received his master's degree in Civil Engineering from Kuwait University. After showing interest in higher education and research, he got awarded a scholarship from Kuwait University to continue his higher education. In 2005, he joined the School of Building Construction and graduated with a master's degree early 2007. He then joined the Ph.D program at the College of Design Construction and Planning at the University of Florida. Prior to completing his PhD requirements, Adel obtained another master's degree in Real Estate Program at the University of Florida in 2008.