Exploratory Study of Distortionary Corrective Modification of Concrete Contraction

Joints Through Infused Polymerized Siloxanes-Based Compounds

by

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ABSTRACT

Deformation during hydration of concrete includes curling at joints and terminations. Previous research has explored mix designs, chemical additives, and other material factors to minimize slab distortion due to curling. This research study explores the development and use of externally applied silicone-based compounds after both the placing and cutting of joints. This exploratory study presents the results of controlled testing and a field study results that include distortion of contraction joints as measured with a Spectra LL300N under existing environmental conditions. Specifically, the study presents the results of a side-by-side test of two slabs, a base case, and a silicone-altered case, as well as field measures of two large commercial buildings using the developed methods. The results of the study show reduced distortion due to curling as compared to standard comparative slabs and warrant the continued exploration and testing of the concept.

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CHAPTER 1

INTRODUCTION

Concrete over the years has morphed into a product that has allowed concrete contractors to place concrete at or above their designed strength by using chemical admixtures. Chemicals (plasticizers) allow for a homogeneous material with increased slumps creating a more workable concrete material. This allows a concrete contractor to use less manpower and still achieve higher than normal test cylinder breaks. The concrete material used in the two-slab side-by-side case study of this study has a design strength of 4000 pounds per square inch (psi), but resulted in a much higher strength averaging about 4900 psi (See Appendix A).

This higher strength concrete has solved the problem of ensuring that construction projects receive a concrete material at the proper strength designed by the structural engineer. The introduction of chemicals has helped produce a concrete material with an increased strength that can carry loads much greater than anticipated.

Saw cutting contraction joints has allowed the concrete contractor to place more concrete in one placement instead of making multiple placements using construction joints. This would cause the placement contractor to spend more on labor and time to produce the same amount of concrete surface.

In current processes of concrete placement, the use of chemically altered concrete and saw cutting joints allow concrete contractors to place larger concrete slabs and facilitate the ability to meet the demands of larger construction projects under time constraints demanded by the general contractors and project owners. Unfortunately, saw cutting contraction joints coupled with the use of higher strength concrete has created another problem. This problem is the curling of the concrete at the sawcut contraction joint and happens over a period of time after the final finishing of the concrete.

1.1 Statement of the Problem

Concrete is a perishable material and must be placed with 90 minutes of the raw materials being introduced in the delivery concrete truck (ACI, 2014). Concrete flatwork is typically leveled by means of a hand screed for small concrete projects or for larger concrete projects a laser screed may be used. Both methods are effective given the size of project, but the laser screed will produce a flatter floor given the technology built into this type of machinery.

Once the concrete is placed and initially leveled it is necessary to allow excess bleed water to rise to the top of the slab and evaporate. When the bleed water has evaporated the finishing process begins until a final finish is achieved.

After the final finishing process is completed, a method of reducing moisture loss in the concrete slab or curing must occur. The curing process can be done in several different ways which typically involve either supplying additional water to the surface or preventing water in concrete from escaping. One way to provide additional water would be to place burlap over the concrete, keeping the burlap moist for whatever period of time required by the contract. The most common curing method used today is to chemically cure the concrete by spraying the surface with a compound designed to create a barrier over the finished concrete and protect it from moisture loss.

This is the problem statement, because after the chemical curing compound has been placed and given time to solidify, the concrete contractor is sawing the contraction joints with an early-entry saw. This sawcut joint, one quarter the thickness of the slab and usually being one inch in depth, results in the creation of an avenue for moisture loss. The purpose of the curing compound is to lock the moisture into the slab, which is needed for the proper design strength of the concrete to be achieved. The result of not addressing this moisture loss in the sawcut contraction joint is resulting in a phenomenon called curling. Curling can be the result of rapid evaporation in the sawcut joint area and cause tension in the surface of the concrete slab, ultimately causing a curling effect at the edges of the concrete sawcut joint.

The statement of the problem aims to address this area of the slab. Does saw cutting through the moisture barrier provided by the curing compound lead to more curling? What is being done to the sawcut joint to prevent moisture loss? To date, there is no evidence of any preventive measures taking place to avoid moisture loss in the sawcut contraction joint, which as stated earlier, is necessary to control curling in a concrete floor slab.

1.2 Research Questions

In the literature review, there will be a discussion about the effects the material strength has on the curling of sawcut contraction joints. The research question of this study is investigating is as follows:

1) If a silicone-based compound is placed in the sawcut joint immediately after saw cutting the joints, will it minimize the amount of curling?
2) How much silicone-based compound will be needed to reduce or eliminate moisture loss in the sawcut joint to reduce curling?

The first question will be explored by examining the research projects completed and measured by laser instruments and 3D scanning of the side-by-side project. The second question will be explored by a comparison of a completed project through an understanding of the use of silicone-based products and their related elastic/tensile relationships and properties between the silicone-based compound and the concrete.

1.3 Research Hypotheses

The main hypotheses of this paper are to research if silicone-based compound will reduce moisture loss from concrete slabs when placed in contraction joints immediately after early entry saw cut contraction joints are cut.

One of the projects was placed in July 2018, the hottest time of the year in the Phoenix metropolitan area, and the other project was placed in May 2018 in a milder climate in the Sedona area. Both projects are based in Arizona, where the relative humidity is very low, and temperatures regularly reach well over 100 degrees.

Hypotheses 1*: Two buildings in the Cottonwood, AZ area were placed in two-day intervals. Both slabs were placed, finished, cured with a chemical compound, and then the control joints were saw cut. For the first slab, the contraction joints were filled with a foam back rod one-quarter inch deep and then filled with a silicone-base product to the top of the slab. The second slab had the same system placed as the first slab, but the process was completed 30 days after the slab was placed due to weather issues.*

Hypotheses 2: *Two test slabs were placed with saw cut contraction joints at no more than 100 square feet apart. Each slab was to be locked in by a foundation system not allowing the slab to move in a lateral direction. One slab will have a silicon-based product introduced into the contraction saw cut joint immediately after saw cutting, while the other slab will not have a silicone-based product introduced to the control joints (See Appendix C).*

1.4 Thesis Outline

Chapter One or the introductory chapter explains the basis for this paper and the questions related to the research hypotheses. Chapter Two will detail a literature review on what research has been done regarding concrete materials to reduce the curling effects on concrete slabs. Chapter Three will describe the methodology of the exploratory work including the construction of the members to be studied and the methodology along with the instruments used for data collection. Chapter Four presents the results from the data collected and an analysis of the data. This is followed by Chapter Five, which draws conclusions from the analysis. Finally, Chapter Six explores the possibilities for future research needed and possible recommendations on this topic.

1.5 Research Scope

Due to the nature of this research topic very few clients are willing to pay for a project where the concrete will be curling, and expensive repairs could be a possibility. Therefore, the two test slabs were placed in a strategic location where they will be used for parking equipment once the research is completed. Data were collected on the two test slabs using a laser level. 3D scanning was also administered to verify the measuring process and for future research possibilities. The two tests slabs were placed in July of 2018.

For the warehouse slabs in the Cottonwood, Arizona, one slab received a silica-based compound 30 days later than the first slab; this situation occurred due to unforeseen weather conditions and scheduling issues. These two slabs were placed in May of 2018. The data was retrieved in October of 2018 and analyzed in this report.

This process is unique in nature and can be a great contribution to the concrete placement industry, as many warehouse specifications are requiring higher floor flatness/floor levelness (FF/FL) numbers. These numbers are difficult to achieve due to the nature of concrete and the environment whether it be cold or hot weather concreting. Further research will need to be conducted to determines that this process contributes to minimizing the curling of concrete slabs.

CHAPTER 2

LITERATURE REVIEW

To help summarize the reasoning behind this research, this report will discuss a restaurant retrofit project in old town Cottonwood, Arizona that required a slab on grade concrete pad without the saw cut contraction joints curling. In this project, the slab needed to be stained and polished. However, the curling may pose a problem, as one remediation process to curling of concrete at the contraction joints is grinding the floor to level. This procedure exposes the course aggregate below the surface matrix of the concrete slab and creates an atheistic problem (Mailvaganam et al., 2001). This slab was not available for measurement and is not a project referred to in this paper; however, is described to allow the reader to understand why there is a need to research this topic.

Therefore, after researching for a solution, all literature searches lead us to look at concrete materials. After much discussion and no literature to validate our hypothesis, a decision was made to fill the saw cut joint immediately after saw cutting with a silica-based compound. This allows containment of the needed moisture in the concrete slab to achieve the necessary compressive strength required by the contract and possibly reduce curling to an acceptable tolerance. On this project, the process worked perfectly and achieved the desired look for the owner of the project. These results lead to a more in-depth literature review on this topic.

The short and concise article provided by the National Ready Mixed Concrete Association (NRMCA) *"Concrete in Practice (CIP) number 19)"* (2004) will be used as the basis for the literature review.

2.1 What is Curling?

The article Concrete in Practice 19 (CIP-19) describes "Curling is the distortion of a slab into a curved shape by upward or downward bending of the edges. The occurrence is primarily due to differences in moisture and/or temperature between the top and bottom surfaces of a concrete slab. The distortion can lift the edges or the middle of the slab from the base, leaving an unsupported portion. In most cases, curling is evident at an early age. Slabs may, however, curl over an extended period" (NRMCA, 2004).

In the journal, Concrete International, Dobson describes that concrete curling is due to several factors, but attributes the degree of curling on the top and/or bottom of the slab as drying at a faster rate (Dobson, 1995).

The Portland Cement Association's (PCA), manual Design and Control of Concrete Mixtures, discusses "enclosed slabs, such as floors on the ground, only curl upward. When the edges of an industrial floor slab curl upward, they lose support from the subbase. Lift-truck traffic passing over joints causes a repetitive vertical deflection that creates a great potential for fatigue cracking in the slab" (Kosmatka and Wilson, 2016, pg. 301).

Concrete curling is most likely more prevalent in regions that are hot and dry. Curling persists, and contractors continue to fix the problem by grinding the concrete edge smooth to match the concrete slab that is adjacent. This concept is mentioned in the Concrete in Practice (CIP-19) (NRMCA, 2004).

2.2 Why Does Concrete Curl?

CIP-19 explains this in a concise manner by stating "The most common occurrence of curling is when the top surface of the slab dries and shrinks with respect to the bottom. This causes upward curling of the edges of a slab (See Figure 2.1)" (NRMCA, 2004). In retrospect, if the temperature of the slab at the top is higher than underneath the slab, then a downward curling effect can take place (See Figure 2.1).

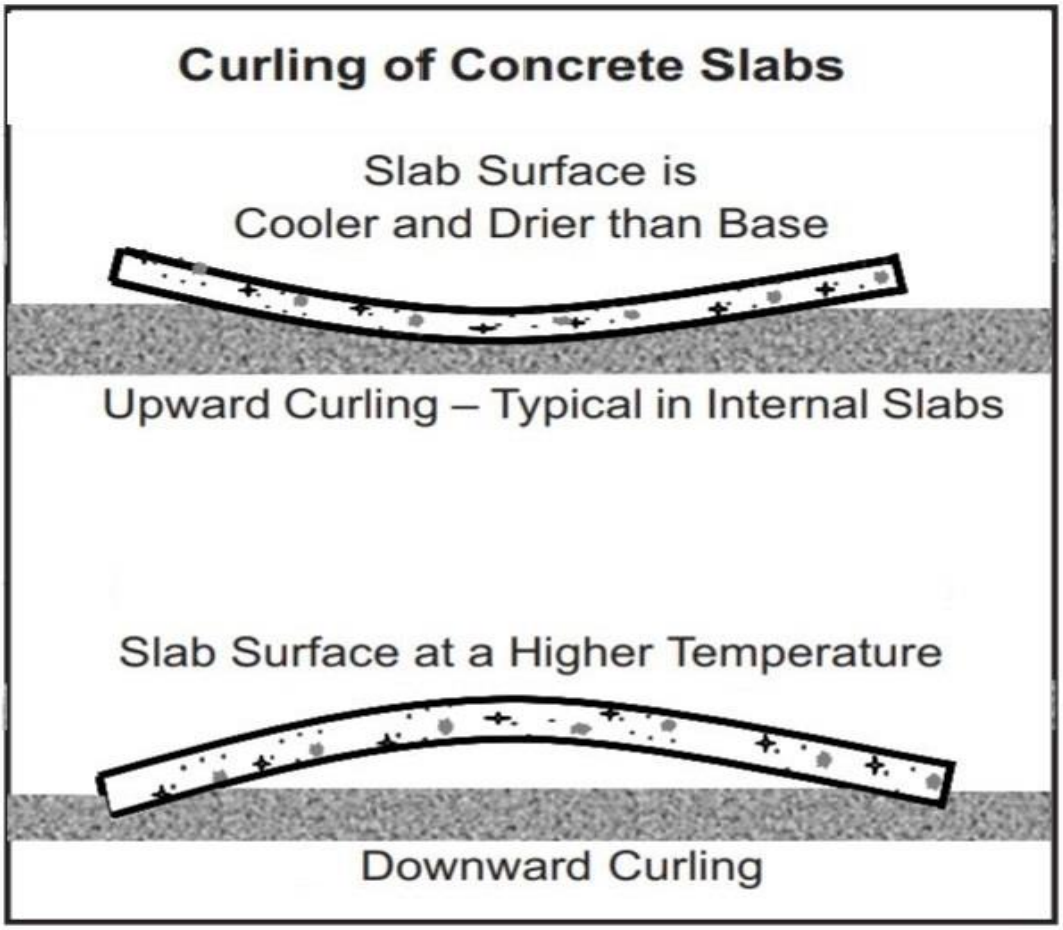


Figure 2.1: Graphical Representation of the Concrete Curling (Adapted from NRMCA, 2004)

In a journal article Walker and Holland (1999) describe the effect of ambient temperatures and curling of concrete. The authors state that the ambient temperature needs to be as low as feasible during the placement process to minimize the curling effects of concrete.

Curling issues with concrete slabs have been attributed to poor curing practices after the final finishing process of a concrete slab. The American Concrete Institute (ACI)

302.1R-04, Chapter 9 describes proper methods of curing concrete and its essential part of the strength gain of concrete (ACI, 2014).

2.3 Minimizing Curling of Concrete Slabs

CIP-19 lists 11 ways or techniques to reduce the effects of concrete curling. These 11 techniques are very important when considering the placement of a concrete slab (NMRCA, 2014). There are many variables that need to be considered when placing a slab. Many of the questions are 1) The location of the project, 2) The location of the concrete batch plant and how far or close in proximity to the construction site, 3) What are the concrete mix design requirements, and 4) What admixtures are allowed, such as water reducing agents and others to help reduce curling effects of the concrete? Based on the NMRCA (2014), the following subsections will explore and provide further details on these variables.

2.3.1 Use the Lowest Practical Water Content in the Concrete

Questions posed in the previous paragraph included: What admixtures are allowed in the design of the concrete mix? Will the engineer of record allow the addition of water reducing admixtures or shrinkage-compensating admixtures? The premise behind this paper is to reduce curling by keeping the necessary curing moisture within the concrete slab. The reason for a lower water-cement ratio is to reduce the amount of water, and in return, the slab will have less shrinkage and the added benefit would be less curling.

Robert F. Ytterberg (1993) discusses this principle in his three-part paper titled “Control of Shrinkage and Curling in Slabs on Grade.” Ytterberg suggests using reinforcement in the slab in addition to shrinkage-compensating concrete will help in the reduction of curling (Yetterber, 1993). Yetterber summarizes his findings as to the importance of using concrete mix designs which are not based on slump test alone but also using a concrete mix design with the lowest practical shrinkage. Moreover, the author states that shrinkage testing should be done prior to and during the placement process (Yetterber, 1993).

Ready-mix producers have historical data on mix designs, and most mix designs are often overdesigned from a strength standpoint because of the possibility of litigation. Appendix A of this paper shows the average strength cylinder samples of a 4000 psi mix design by a ready-mix producer, tested at 4900 psi. This is 800 to 1000 psi over the design strength for the two test slabs. It may be important for the engineer, ready-mix producer, general contractor, and concrete contractor to evaluate the mix design by looking at historical data. This could prove to be a very valuable tool in cutting back on the amount of cement and likewise the needed water for the mix. Less water will produce a concrete slab with less shrinkage and curling (See Appendix A).

2.3.2 Use the Largest Size Aggregates Possible

Slab thickness will dictate the maximum size aggregates a concrete contractor may use. PCAthe discusses maximum size versus nominal maximum size aggregate. The maximum size of aggregate will depend on the thickness of the slab. The PCA manual recommends the maximum size aggregate be limited to one-third the thickness of the slab, unless an engineer determines that the concrete can be placed without honeycomb or voids (Kosmatka and Wilson, 2016, pg. 191-192).

Why are larger aggregate important in reducing the curling effects of concrete? First, in the transition zone, cement particles need to coat all surfaces of all aggregates to produce a high-quality product. If larger than normal aggregates are used, these aggregates will have a smaller surface area thus requiring less cement to coat all aggregates. Reducing the amount of cement required in a mix is a recommendation for the reduction of curling and will be discussed further in this paper.

Aggregates make up 60 and up to 75 percent of a concrete's volume (Kosmatka and Wilson, 2016, pg. 181). There is a problem with using larger than normal aggregates and as increased aggregate size decreases the workability of the concrete. The concrete contractor will not favor this mix because of the difficulty in placing the concrete during its plastic state. Thus, concrete contractors will be reluctant to use a mix design with larger than normal aggregates and therefore, typically opt for the use of three quarter to one-inch aggregates in the mix design, instead of using one inch and a half aggregate. This choice will most likely produce a larger curling effect.

2.3.3 Precautionary Measures to Avoid Excessive Bleeding

CIP-19 also discusses taking precautionary measures to avoid excessive bleeding. The following suggestion is for an environment with dry conditions and recommends to "place concrete on a damp, but absorptive, subgrade so that all the bleed water is not forced to the top of the slab" (NRMCA, 2004).

The PCA Design and Control manual lists eight suggestions on pg. 263 to reduce bleeding. To answer the question of why do we want to reduce bleeding? First, free water is a necessary component of a concrete mix design to allow workability at the time of placement. If the free water is only allowed to escape through evaporation from the top of the slab, then the strength of the top matrix will be weaker due to a higher water content near the surface. This will produce a concrete slab with a surface that will not be durable and is susceptible to crazing and dry shrinkage cracking (Kosmatka and Wilson, 2016, pg. 261-263).

One of the eight suggestions to reduce bleed water is to increase the amount of cement; reducing the water-cement ratio (Kosmatka and Wilson, 2016, pg. 263). Increasing the cement is exactly what is discouraged in Section 2.3.2 of this paper. An increase of cement will reduce the water/cement ratio, but also will increase the amount of paste in the matrix and with the increase of cement paste will then lead to increased shrinkage, which will create a greater possibility of curling.

In the article by Suprenant and Malisch (1998), the authors discuss how much free water is required in a mix design. The study mentions, "If the 250 pounds of mix water is used in concrete with a water/cement ratio of 0.50, about 100 pounds of the water will be free water that must evaporate as the floor dries" (Suprenant and Malisch, 1998). This means 40 percent of the mixing water must either be absorbed in the subgrade under the slab or evaporate into the atmosphere through the top surface of the concrete slab. Gravity forces free water to the surface (bleed water), and if the bleed water is mixed with the surface matrix of the concrete, then the surface will be weak due to a high water/cement ratio at the surface of the concrete slab. This will lead to many complications other than just curling.

The PCA Design and Control manual also suggests using air-entrainment. This will work fine in a humid climate. However, in hot weather concreting this is not an option, as there is a need for some bleed water to work the surface of the slab for a uniform desired floor. The manual also suggests using chemical admixtures to reduce the amount of water needed for workability. This would be the best solution, as the use of water reducing admixture also will typically retard the concrete's set time, which in a dry or hot climate is a desired feature that may result in a higher strength gain (Kosmatka and Wilson, 2016, pg. 219).

2.3.4 Avoidance of Vapor Barriers

CIP-19 also discusses "Not to use polyethylene vapor retarders unless covered with at least four inches of a trimable, compactible granular fill" (NRMCA,2004). Again, this aims to reduce the amount of bleed water going to the surface of the concrete slab. It is necessary to have a certain amount of the bleed water being absorbed by the subgrade or compactible granular fill. If all the bleed water rises to the surface of the slab, then the top surface matrix will be weak and susceptible to a weakened surface and more curling.

In an article titled "Curling of Slab over Vapor Barrier," the authors discuss that when concrete is placed directly over vapor barrier, then there is a greater difference in moisture content and a greater difference in shrinkage, which will produce more curling in a slab. This article also discusses a five-inch slab which contained wire welded fabric embedded two inches from the surface and placed over a four-inch layer of crushed stone and vapor barrier. This slab ended up with a curling deflection of 3/8 of an inch (Concrete Construction Staff, 1987).

The literature review suggests to not place concrete directly over a vapor barrier/retarder. This will not only give the surface of the concrete a high water/cement ratio but also due to the drying issues will have a much greater effect on the amount of curl in a slab.

2.3.5 Avoidance of High Cement Content

The use of a low cement content concrete mix design has been discussed in detail in Section 2.3.2 of this paper. It was mentioned to use a larger than normal aggregate to reduce the surface area around the aggregate to be coated with cement.

In the CIP-19 article, it also discusses the use of supplementary cementitious materials or SCM's in the mix design (NRMCA,2004). The use of flyash is commonly utilized, as increasing the amount of flyash as a replacement of cement greatly enhances the performance of a concrete mix design. "A common amount of flyash in a mix design may be 15 percent and up to 25 percent of the cement content. A high dosage flyash mix may contain up to 40 percent flyash replacement. Flyash will retard the strength gain of a concrete slab and may require a 56-day cylinder break to determine the compressive strength of concrete" (Kosmatka and Wilson, 2016, pg. 148). This slow cure could reduce the amount of heat of hydration, which would have a beneficial effect on the curling of a concrete slab.

The reason a high flyash mix design has a slow strength gain is because of the free lime. Calcium Silicate Hydrate (CSH) is produced when water is introduced to cement and the byproduct of CSH is free lime. Flyash reacts to the free lime and produces more CSH, thus creating a stronger, densified concrete mix. This denser concrete helps produce a concrete slab with less curling due to its slow strength gain.

Reducing the amount of cement in a mixture reduces the amount of curling on a concrete slab. Lower cement content leads to less paste in the mix which leads to lower heat of hydration, which correlates to less dry shrinkage of the surface of the concrete. Using admixtures such as flyash or water-reducing agents will have a positive effect on reducing curling of a concrete slab. The positive effect of having a high flyash content mix design is to slow the curing process plus strength gain is achieved over a longer time period. This time period may take up to 56 days to achieve the strength designed by Structural Engineers.

2.3.6 Cure Concrete Thoroughly

To minimize the effects of curling of a slab on grade, it is recommended to cure the concrete as thoroughly as possible. In the article "Curling of Concrete Floor Slabs on Grade – Causes and Repairs," Malivaganam el al. (2001) discuss the importance of curing concrete slabs immediately after the final finish. The article also discusses the importance of minimizing alternate wetting and drying cycles caused by inefficient curing (Mailvaganam et al., 2001).

The ACI manual (2014) identifies six different ways of curing concrete. One is water curing where the slab is located. "This method of curing uses water that is within 20 degrees of the concrete surface, completely ponds the entire slab of concrete with water, another is wet covering, which is done by means of a material or organic material such as straw, earth, or sand which is moistened to maintain the moisture in the concrete slab. Another method is the use of moisture coverings (i.e., burlap), which is used to constantly moisten the slab and never allowed it to dry. Two other methods are achieved with the use of polyethylene (plastic) film or the use of waterproof paper." There are certain precautions with all these methods and require a thorough evaluation per given project (ACI, 2014). This form of curing is not usually utilized in the concrete industry, due to the lack of monitoring after the curing process takes place.

The most used curing method, because of convenience, is a liquid membrane-forming curing compound. The advantages and disadvantages to this method of curing are outlined in ACI 302.1R-04 Chapter 9.2.4. The section states "advantages are relatively low in-place cost, early access to the floor, elimination of the need to monitor the curing process, and the opportunity for longer uninterrupted cure. The membrane must be protected from damage due to construction traffic. Disadvantages included the potential for insufficient and uneven coverage, conflict with regulations on the release of volatile organic compounds (VOC), interference with the bond of surfacing materials, and variability of quality and solids content" (ACI, 2014).

A chemical curing membrane is applied to the surface of the concrete. This can be done with a spray apparatus or manually with rollers. Spraying is preferred due to the ease of application but can be problematic as uniformity of the spray is always a concern due to mechanical breakdowns or uneven spray patterns.

Because this is a popular method of curing concrete, this is the exact reason for researching the issue of curling concrete. Curing a concrete slab begins immediately after the final finishing process by applying a chemical curing compound. Sawcutting contraction joints begins as soon as the concrete surface can support the weight of the concrete saw, without any spalling or damaging the surface from the movement of the concrete saw. After the sawcutting process is completed the contraction joint then becomes an area where there is a possibility for moisture loss.

2.3.7 Joint Spacing Not to be Exceeded

Walker and Hollan (1999) stated, "Minimizing slab-joint spacing can greatly decrease curl and the resultant cracking as well as other problems. For unreinforced or lightly reinforced slabs, the commonly used joint spacing criteria of 36 times the slab thickness can be nonconservative for many of today's concretes, especially as slab thickness increases……..we believe that, unless a people really know what they are doing, a spacing of about 15 feet should not be exceeded for unreinforced or lightly-reinforced slabs" (Walker and Holland, 1999).

The slabs measured in Cottonwood, Arizona had a contraction joint spacing of 15 feet in one direction and in the other direction the joint spacing was 25 feet. This is more than the recommended contraction joint spacing by Walker and Holland (1999). As per Walker and Holland, the recommended spacing for a four-inch concrete slab is 144 square feet. Therefore, the maximum spacing for the contraction joints should be 12 feet in each direction. Most concrete contractors use the rule of thumb of 25 times the thickness of the slab to calculate this number. However, using this formula would cause the contraction joints to be 10 feet in each direction for a 4-inch concrete slab. Concrete contractors want the spacing to be as large as possible due to curling. If the concrete slab does curl, the larger spacing of contraction joints would result in fewer areas to grind and patch. The problem with larger spacing is that the concrete slab will be more susceptible to cracking, which will not provide the desired appearance. Joint spacing should be planned prior to any concrete placement, making sure the look is desired by the project owner, and that it will facilitate the best results for the use of the concrete slab project.

2.3.8 Use Thicker Slabs

In the CIP-19 the ninth recommendation is to increase the entire concrete slab's thickness or increase the slab's thickness around the perimeter of the slab (NRMCA, 2004). Another benefit of thicker slabs is that the contraction joint spacing is increased, reducing the amount of sawcutting of contraction joints; resulting in less linear footage of joint repair needed if curling occurs. It would be recommended to increase the size of the concrete slab rather than increasing the edges only. If only the perimeter of the concrete slab is increased, then this can cause the concrete slab to crack as the free water evaporates and the slab will contract pulling the edges of the concrete slab inward, thus causing cracking in areas when there are no contraction joints (even when there are contraction joints placed in the concrete). When edges are thickened, the necessity for sawcutting joints must be timed correctly to avoid unnecessary cracking.

2.3.9 Use of Slab Reinforcement

In the article "Shrinkage and Curling of Slabs on Grade," Ytterberg (1987) discusses how steel reinforcement can help prevent shrinkage and curling in slabs. The author mentions "Since it is the upper half of a slab on grade that has the greatest shrinkage, the reinforcement should be as close as possible to the top of slab [but not closer than 1 ½ in. (38 mm)] in order to restrain the shrinkage and reduce curling" (Ytterberg, 1987).

Reinforcement can be problematic when it comes to contraction joints. Contraction joints are there to control cracking and force a crack to form at a preset location according to the joint layout plan. If reinforcement is placed in the upper half of the slab and is continuous throughout the slab, this may result in random cracking. Great care must be taken with the use of steel reinforcement and an evaluation of the rebar going through the contraction joints. Best practice may be to separate the rebar into preplanned areas where contraction joints will not be placed; then utilizing a smooth dowel within the contraction joint area, allowing the slab to shrink and move in a horizontal manner; yet the smooth bar will not allow the contraction joint to move vertically which will reduce any curling effect.

This method of controlling shrinkage and curling is very labor intensive and preplanning of steel reinforcement is critical. This may not be the most economical way of placing a slab on grade, unless budgets allow for this type of concrete slab.

2.3.10 Remediation of Curling

In the article by Suprenant (2003), the author discusses the fact that concrete contraction joints will curl and that the flooring contractor will need to include 20,000 dollars into the bid to remedy any necessary need for the grinding and patching of floors.

For most projects where there is light traffic, mainly vehicular traffic, grinding may be the solution to the problem. Curling will also lift the base of the concrete slab and thus cause a void under the slab. If there is heavy traffic such as forklift usage, then grinding the slab will cause the thickness of the slab to be thinner and may cause cracking a short distance away from the contraction joint or worsen contraction joint deterioration.

If a void is present underneath a slab that has curled, it may be necessary to fill that void (See Figure 2.2).

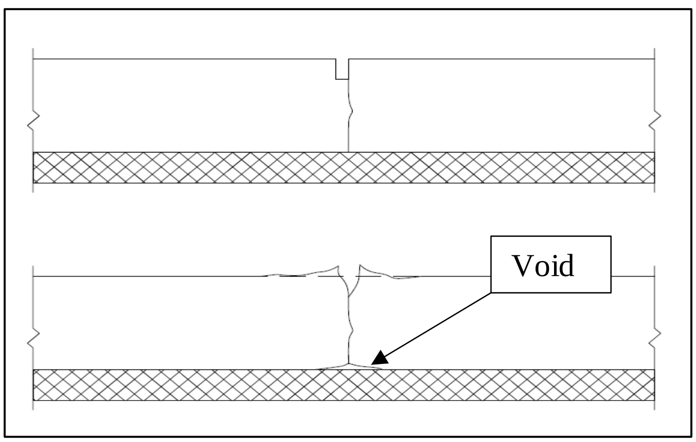


Figure 2.2: Example of Concrete Curing

In the article by Tarr and McCall (2007), the authors examine what process is needed if a concrete slab on grade needs the void underneath filled. The article mentions drilling a series of staggered holes along each side of the contraction joint that has lifted and to inject them with a rapid-setting polymer. However, this process needs to be done prior to grinding, as the grinding process will level any spoils from excess polymer (Tarr and McCall, 2007).

Grinding and patching seem to be the most common remediation for concrete slabs that have some type of curling. This process is expensive, and construction stakeholders have found no formula for how much contingency funding needed to be placed in a construction budget to remedy curling. One reason for this is the belief that no one can predict how much curling will take place on any one given project. As discussed previously, there are several factors, which can cause a curling effect, and therefore the funding required to estimate the remediate potential curling effects is difficult to estimate.

2.4 Summary of Literature Review

In the literature review, there have been ten items discussed. Of those ten items, four items examine concrete materials and mix designs. These mix designs should follow a certain criterion to minimize any type of curling. The other six deal with means and methods, or items out of the control of concrete materials such as curing methods, contraction joint spacing, and reinforcement of concrete slabs.

In the literature review, the section on the curing of concrete is where this research initially begins. There are different methods of curing, one of which was the best but most likely the most impractical. This method is ponding the entire slab with water. Moreover, this method is usually not a viable option when it comes to curing concrete.

The other method is the use of burlap and having a constant moisture supply during the first seven days of curing. This will keep the necessary moisture in the slab to allow the proper strength gain of the concrete. Again, this may not be the most practical or economical method of curing, but again for the curling effect of concrete, this will keep the necessary moisture in the entire slab including after performing sawcut contraction joints.

The most prevalent way of curing concrete in the concrete industry is the use of chemical compound cures. As mentioned in the literature review, this method is simple, economical, and does not require any monitoring of the concrete slab once the finishing process has taken place (ACI, 2014).

One of the most common mistakes made with the application of a chemical curing compound is the distribution of the material itself onto the slab. Mechanical failures and getting the correct amount of coverage to properly cure the concrete are disadvantages. However, these disadvantages can be over-come with good equipment and knowledgeable concrete personnel who can effectively apply these products.

For the hypothesis for this paper, the final finish has taken place and the concrete slab has already been cured. Once the slab surface is cured enough to allow for a sawcutting procedure to take place, the sawcutting process starts and is completed.

What has happened to the area of the sawcut and has the curing compound barrier been compromised? It is the opinion of this paper, that this sawcut area has been compromised and that the curing compound barrier has now been breached and the concrete surface exposed to the environment for increased moisture loss.

There has been no literature found on this area of concern, and it is believed that there is a need to investigate the effects of contraction joints produced by an early entry sawcutting machine, which have penetrated and compromised the curing compound barrier creating an area for moisture loss.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This portion of the dissertation will deal with the systematic method of reducing moisture loss during the concrete curing process with the use of a chemical curing compound. Figure 3.1 shows the sawcut contraction joint and the area of concern for moisture loss. This area will have a potential for excessive moisture loss needed for the curing process to ensure adequate resistance to curling.

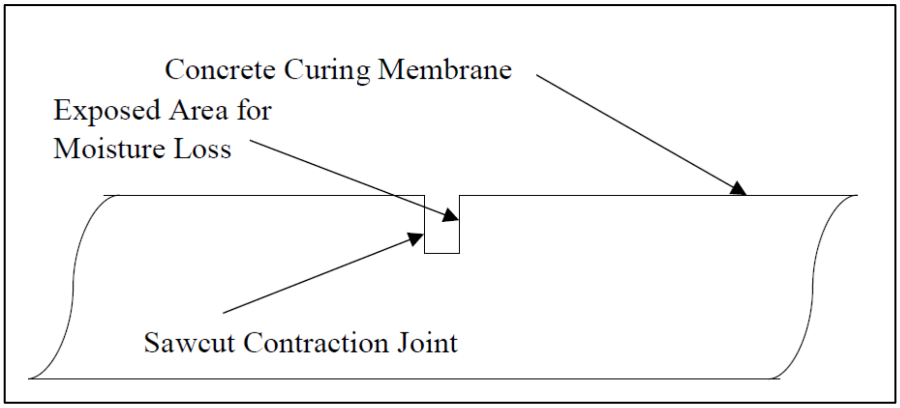


Figure 3.1: Chemically cured and the Sawcut Contraction Joint

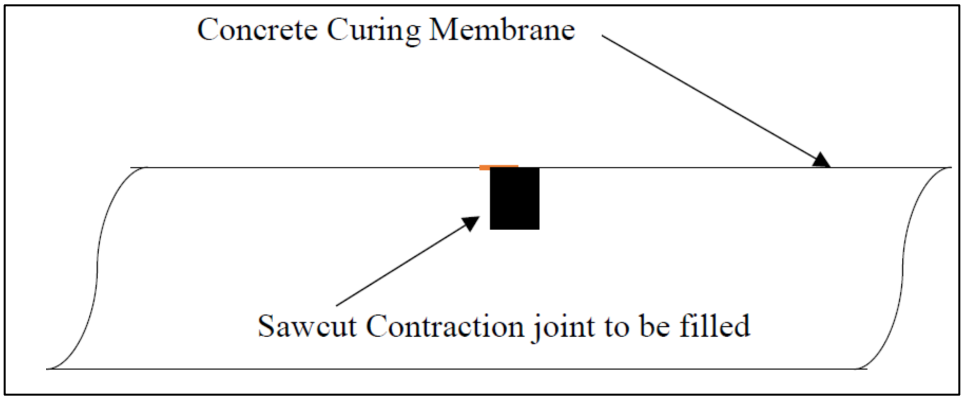


Figure 3.2: Traditional Method of Curing Concrete with Silicone in Contraction Joint

As discussed in the earlier, this research project proposes to solve the moisture loss created by the sawcutting during critical times of the curing process and the curling this moisture loss can create by filling the contraction sawcut joint with a compound as soon as possible after the sawcutting process has taken place, as shown in Figure 3.2. Filling the sawcut contraction joint will reduce the moisture loss, and the joint will retain the necessary moisture for the curing process.

What does this have to do with curling of concrete? If the moisture loss is great enough, the edges of the sawcut joint will dry at a faster rate than that of the concrete slab. Moreover, the evaporation will increase and cause tension in the surface of the concrete slab. As noted earlier, this area is the top matrix of the concrete slab and usually has a higher water/cement ratio because of the free water needing to bleed. The combination of both the evaporation and higher water/cement ratio near the surface and in the contraction joints will cause tension in the surface of the slab inducing a curling effect.

The Southwest region of the United States has higher temperatures and lower humidity levels than most areas in the country. The higher temperature and lower humidity will increase the effects of curling in concrete slab-on-grade by the evaporation process and therefore there is a need to address this area of concern, especially in this region of the United States.

The methodology for this study required a control slab where the processes of placing, finishing, curing with a chemical compound, and sawcutting were completed according to ACI 302 Manual of Concrete Practice (See Appendix B). The means and methods of the control slab followed industry practices with no intervention of the sawcut contraction joint.

The experimental slabs followed similar means and methods except for one variable. This variable was to fill the sawcut contraction joint immediately after the sawcutting process has taken place. Additionally, the silicone-based compound that was used to fill the sawcut joints was different between the two sites (Cottonwood, AZ site and Phoenix, AZ site). This was done in order to see which silicone compounds performed better given the intensity of the temperatures and low humidity in the Phoenix metropolitan area (See Figure 3.3).

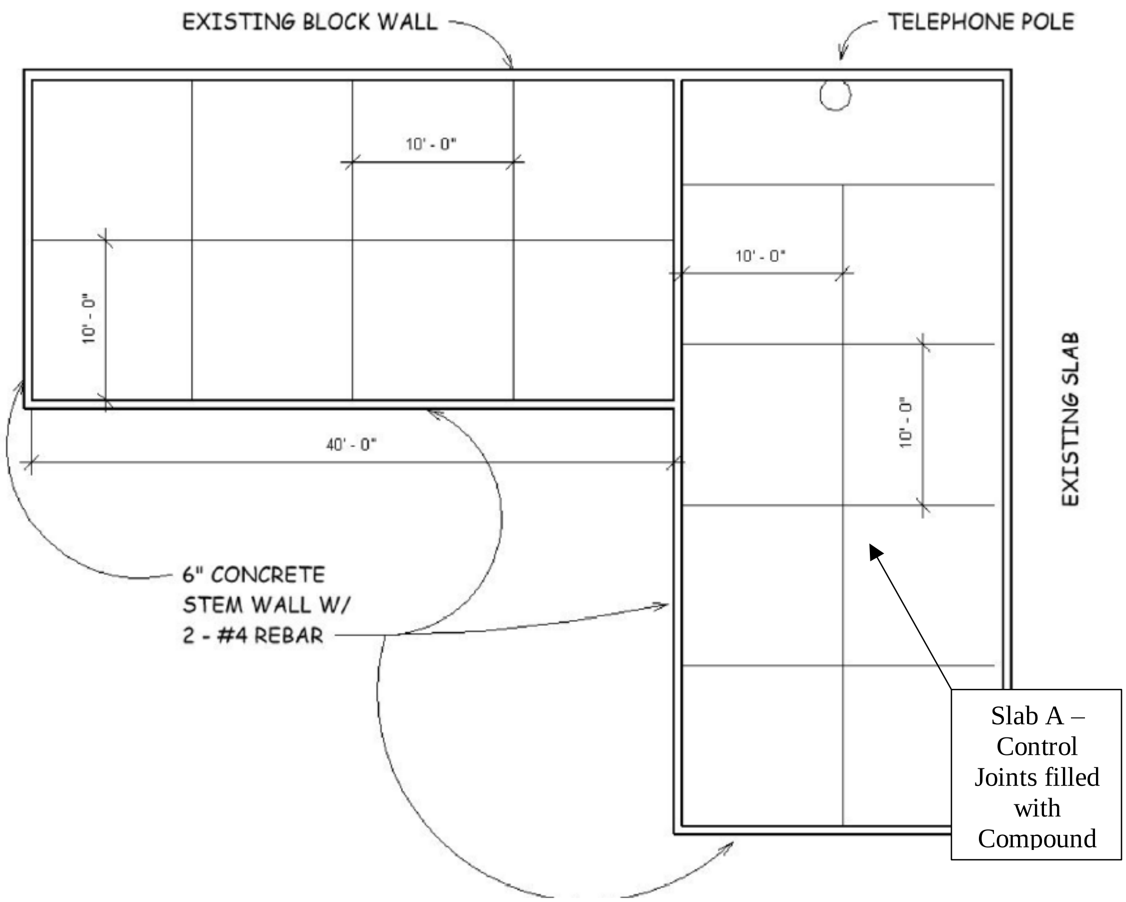


Figure 3.3: Contraction Joint Layout for Test Slabs in Phoenix, AZ

3.2 Industrial Slabs in Cottonwood, Arizona

The two identical slabs placed in Cottonwood, Arizona are two industrial buildings both 8,320 square feet each. The concrete was placed in May of 2018, with a four-inch slab using 3000-psi concrete. There was no vapor barrier placed underneath the concrete, and the contraction joint spacing was 15 feet by 20 feet leaving a square footage of 300 square feet within each space of the contraction joints. This is well over the recommended 36 times the thickness of the concrete slab or 144 square feet (Walker and Holland, 1999, pg. 50) (See Picture 3.1 and 3.4). These pictures were taken at the beginning of August; thus, the concrete slabs were exposed to outside environmental conditions for nearly three months prior to measuring.

Picture 3.1: Inside Building - Cottonwood, AZ

Picture 3.2: Outside Building - Cottonwood, AZ

Both industrial floors were placed with the use of a concrete pump and a laser screed. This process produces a very flat concrete floor. The concrete was cured with a chemical curing compound. The first floor placed received a silicone-based compound the day after the placement of the concrete and immediately after the sawcut contraction joints were placed.

The second floor was cast one day after utilizing the same concrete and equipment. The only difference was the contractor was not able to put a silicone-based compound in the sawcut joints until 30 days after the placement of the concrete slab. This helped to observe if it was important to introduce the silica-based compound as soon as the sawcutting process has been completed.

3.2.1 Measurement Process

The measurement process was done nearly five months after the placement of the concrete floors in September of 2018. The process was done by placing a tape measure perpendicular to the sawcut contraction joint placing the 5-foot mark of the tape measure at the center of the contraction joint, measuring for a total of 10 feet across the contraction joint perpendicular to the joint line.

Measurements were taken every foot starting with the one-foot mark. The measurement distances changed when coming closer to the contraction joint. Between the four-foot mark and 6-foot mark measurements were taken every six inches on either side of the contraction joint. After the 6-foot mark the measurement pattern continued to be measured every foot. At each point on the tape measure as described above, elevation measurements were taken with a laser level (Spectra LL300N), which has the capability to measure within 1/100th of a foot. There were approximately 150 measurements were taken within each building (See Figure 3.4).

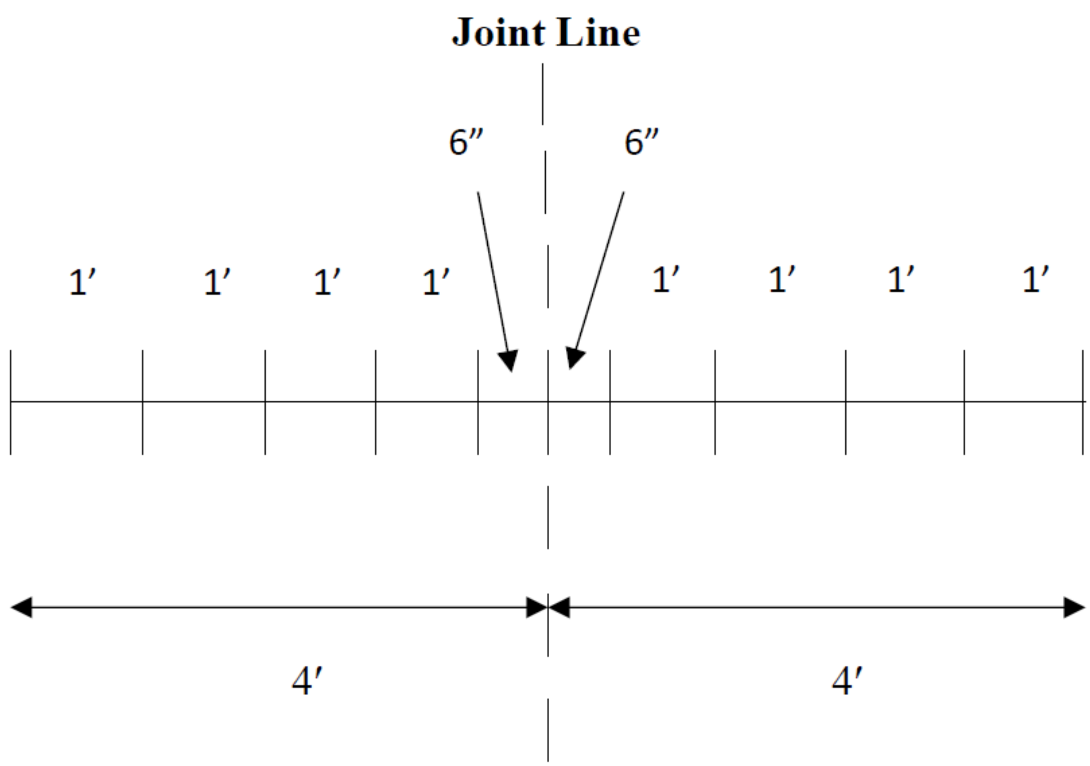


Figure 3.4 : Typical Measurement Regimen

The measurements were set up into thirteen locations. Both buildings are the same size, and the drawing in Figure 3.4 is representative of both buildings and how both buildings were measured. In Figure 3.4, number 8 or station 8 on the **contraction joint** is the point which establishes the elevation point of 0.00. This is consistent with both buildings, A and B (See Figure 3.5).

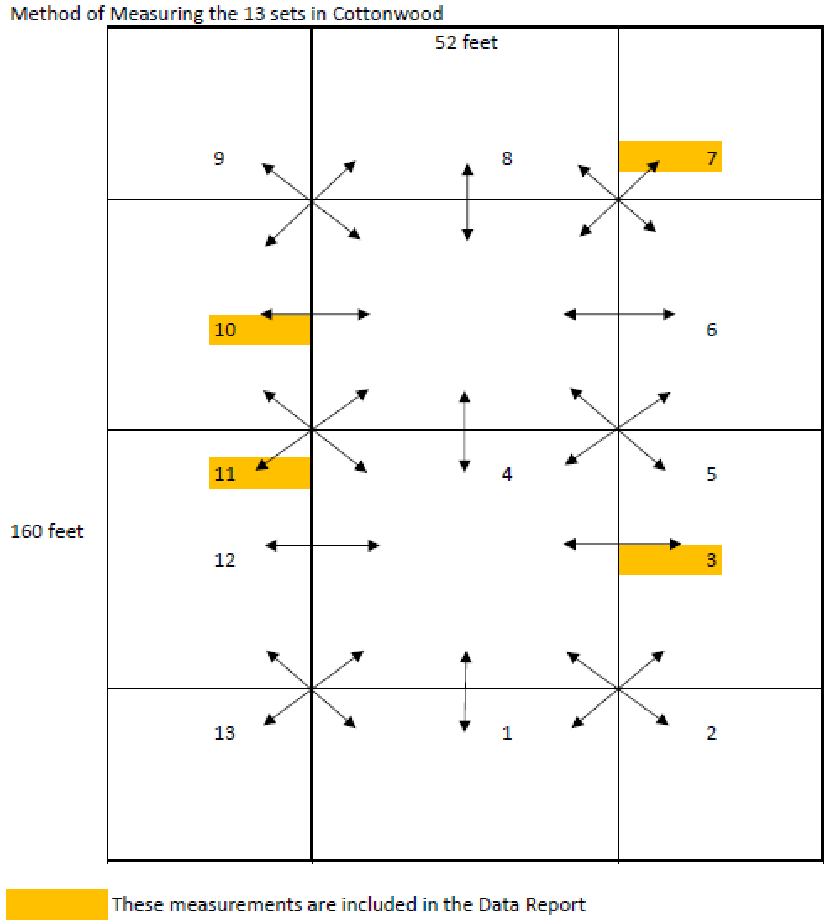


Figure 3.5: Measurement Configuration for Cottonwood Slabs

3.3 Test Slabs in Phoenix, Arizona Metropolitan Area

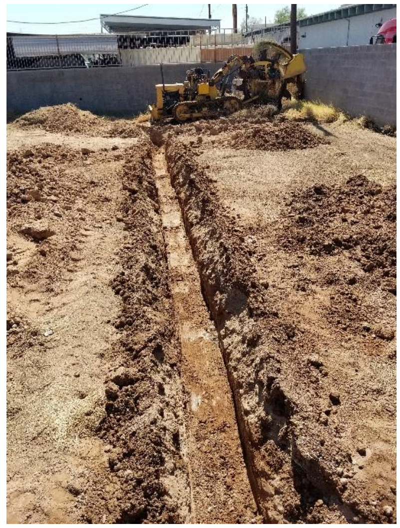
As mentioned in the introduction, two test slabs were placed, and a measurement system was conducted in the Phoenix metropolitan area. The following pages will detail the means and methods used to produce these test slabs, which were cast on July 2018.

In Chapter 2, nine techniques were identified in the literature review that should be employed to help reduce the curling effect of saw cut contraction joints. In this section, along with the following subsections, there will be a discussion on what type of means and methods were taken to force a curling effect within both slabs.

As mentioned in the introduction of Chapter 3, the only variable changed between the two slabs was the filling with silicone of the saw cut contraction joints. The silicone was placed in the sawcut joint in Slab A and not in the saw cut joints in Slab B. Each slab is 800 square feet in size or 20 feet by 40 feet.

3.3.1 Foundation System

As noted in Figure 3.3, there is an existing block wall along the south side of both slabs and an existing slab to the west. This constrained the slab where it cannot move in a horizontal direction to the south and westerly directions. There was a desire to constrain the slab from all other directions to encourage curling to occur in order to more easily differentiate the effect of filling the joint. This was accomplished by placing a foundation wall around opposite walls with a foundation 18 inches in depth into the existing soil and 6 inches in width. Picture 3.3 and 3.4, shows the excavated foundation around the north and east sides of the two slabs. The foundation system will separate and lock both slabs from any horizontal movement and hopefully encourage curling.



Picture 3.3: Footer System for Phoenix Test Slabs

Picture 3.4: Stem Wall Forms for Phoenix Test Slabs

3.3.2 Soil Preparation

The soil conditions prior to the commencement of these slabs were very hard and compacted. A soil analysis was not performed on the current conditions of the soil, but with a foundation system around the slab, this would provide protection against any moisture intrusion, and is a typical foundation system one would find in a building in this area.

The existing soil was removed eight inches below the finish floor elevation, and four inches of A.B.C. (Aggregate Base Coarse) was introduced to give the necessary compaction needed for the subgrade of the slab. The subbase was then moistened with water and compacted with a plate compactor. This provided a smooth base for the concrete to be placed as shown in Picture 3.5.

Picture 3.5: Foundation Completed and Backfilled for Phoenix Test Slabs

3.3.3. Vapor Barrier

As mention in the literature review, there is a recommendation for the removal of a vapor barrier, as this has proven to be a cause for concrete curling. If a vapor barrier is to be used, then there is a recommendation to place a layer of sand or some type of base to absorb excess water or water of convenience in the concrete. This reduces the amount of bleed water to the surface, which also reduces the water/cement ratio of the top matrix.

Since the purpose of this test slab was to study the effect of sealing the sawcut joints on the curling, it was decided to increase the probability of its occurrence, and therefore a six-millimeter plastic vapor barrier was placed between the subbase and the concrete. This will force all bleed water to the surface, and the slab with silicone introduced to the saw cut contraction joints would hypothetically minimize the amount of curl in the contraction joint system, as desired. The vapor barrier can be seen in Picture 3.6.

Picture 3.6: Vapor Barrier Installed on Phoenix Test Slabs

3.3.4 Concrete Strength

In the two test slabs, a normal strength concrete was used, which one would find in most warehouse buildings. The design compressive strength of the concrete used in the two test slabs was 4000 psi (pounds per square inch). No water was added at the jobsite and was placed at an eight-inch slump with the use of a mid-range water reducing agent provided by the ready-mix concrete producer

Concrete test specimens were taken according to ASTM Standard C31 "Standard Practice for Making and Curing Concrete Test Specimens in the Field" (ACI CP-1, 2017) compressive strength test results can be seen in Appendix A. The average between the two test cylinders at 28 days was 4900 psi., nearly 900 psi higher than the design strength of the mix ordered which is also typical over design amount seen in industry. Shown in Appendix B, a letter from a registered professional engineer attests that all means and methods of these two test slabs were in accordance with ACI (American Concrete Institute) 302, which is the guide for the placement of slabs on grade.

3.3.5 Steel Reinforcement

Since steel reinforcement is considered to reduce curling in slabs. There was no reinforcement placed in the test slabs in order to "purposely" allow them to curl. The foundation system had two # 4 rebar introduced which was done to mirror standard industry practice and support future use of the slab.

3.3.6 Placement of Materials and Temperatures

As mentioned in Section 3.3.4, the concrete used on these two test slabs was a 4000-psi concrete. There was no water added at the jobsite, as shown by the batch tickets seen in Appendix D, which also show the batch weights. Slump tests were performed according to ASTM Standard 143 "Standard test method for Slump of Hydraulic Cement Concrete" (ACI CP-1 36th, 2017) on all trucks and all tests consistently measure an eight-inch slump.

At the time of placement, the temperature of the concrete was taken per ASTM Standard C 1064 "Standard test method of Freshly Mixed Hydraulic-Cement Concrete" (ACI CP-1 36th, 2017) which was recorded at 89 degrees Fahrenheit. At the beginning of the placement, the ambient temperature was 90 °F (Fahrenheit), and at the completion of the placement of concrete, the ambient temperature had risen to 99 °F. The humidity level was 19 percent with calm winds. The high temperature was 116 °F, and the slab surface reached 141 degrees °F at 5 PM which was measured by a Non-Contact Infrared Laser Thermometer.

3.3.7 Finish Process

The finishing process was done by hand, without the use of a laser screed. Grade stakes were measured, and the concrete was placed with the use of shovels and a screed. Since the concrete was placed at an eight-inch slump, it was not necessary for the use of a tamp. A magnesium bull float was used for the initial leveling of the concrete surface. The bleed water was then allowed to rise to the surface and evaporate.

The bleed water eventually evaporated and then the finishing process began with the introduction of a small double ride on power trowel. The first blades on the power trowel included floater pans, allowing excess moisture to continue to bleed. Then the floater pans were removed, and the finishing process was completed with finish blades. The finish on the slab was burnish-type finish, very smooth and flat.

A video of this process can be seen on:

https://www.youtube.com/watch?v=To6IYrXlb90

3.3.8 The Curing Process

After the completed finishing process, it was necessary to cure the concrete. This curing process needs to continue for a critical time period of seven days. The method of curing chosen by the study was the use of a chemical cure due to its prevalent use in industry. The test slabs were cured with a chemical cure “Cure Hard Clear” produced by SpecChem.

The application of this product is important and was done according to the manufacturer's specification. A new hand spray pump was purchased and applied in one direction. After the cure set up, another application was applied in the perpendicular direction, making sure of ample coverage. The cure then needed to dry prior to the saw cutting of the contraction joints. The type of cure used can be seen in Picture 3.7.

Picture 3.7: Concrete Cure Used for Test Slabs in Phoenix Slabs

3.3.9 Saw Cutting Contraction Joints/Spacing

The two test slabs were 20 feet by 40 feet or 800 square feet each. This made it very easy for the layout of the saw cut contraction joints. In previous sections of this paper, the authors Walker and Holland suggested that 36 times the thickness of the slab should be used. These authors in the article "Thou Shalt Not Curl Nor Crack…….(hopefully)" mention that if a contractor is going to use the 36 times the slab thickness rule, they (The Contractor) needs to understand the nature of concrete and to be very cautious.

In the industry, most concrete contractors use 25 times the thickness of the slab. Therefore, the two test slabs are four inches thick, which calculates to an area of 100 square feet maximum. This is a perfect situation for the two test slabs with 20 feet wide by 40 feet long slab-on-grade. The saw cut contraction joints were cut 10 feet on center. This allowed for each section between the saw cut contraction joints to be exactly 100 square feet. Once the concrete had hardened enough to support a soft-cut early entry saw, the cutting began and continued until complete. Refer to Figure 3.3 for a drawing of the joint layout.

3.3.10 Application of Silicone in Saw Cut Joints of Test Slab A

Immediately following the saw cutting of the contraction joints, the workers began to fill the saw cut contraction joints in test Slab A with silicone. The product used was a pure silicone produced by General Electric, as shown in Picture 3.8.

The saw cut contraction joint is 1/8-inch-wide and one inch deep, with the complete contraction joint filled with silicone. This proved to be problematic, as the ambient temperature during this day was 116 degrees °F. The heat, combined with the requirement to fill the joint completely full, caused the silicone to dry quickly and separate from the edges of the contraction joints. During this experiment, silicone had to be applied two more times at later dates to make sure there was no moisture loss during the curing period of the concrete.

A video of the completed project can be seen at the following link:

https://www.youtube.com/watch?v=ehtHmttG8iQ

3.3.11 Measurement Collection Data

The data collection for the two test slabs were taken in the same manner as the building slabs in Cottonwood, Arizona. There were approximately 150 measurements taken from 13 different locations on each slab. Temperature readings were also taken, both highs and lows of the ambient temperature, and the temperature at the slab surface was also

Picture 3.8: Silicone Product Used to Fill Contraction Joints in the Phoenix Slabs

recorded. The humidity of each day was also recorded. All readings were taken for a period of 56 days.

3.3.11.1 Temperature and Humidity

These slabs were cast during the hottest period in this region to help produce the most curling effect possible. The high temperature during this period was 116 degrees °F and the lowest evening temperature was 90°F. The high evening temperature recorded was 95 °F and with a lowest was 75°F. The average daytime temperature was 104°F and the average evening temperature was 82°F.

The highest humidity level was 48 percent while the lowest was 16 percent, with an average humidity level of 24 percent. The highest surface temperature of the slabs was 162°F, with the lowest being 132°F and an average slab surface temperature at 149 °F.

3.3.11.2 Test Slab Data Collection

A 3D laser scanner along with an industry survey instrument was used as dual methods for the measurement of the test slabs in the Phoenix metropolitan area. Local industry also volunteered to assist to complement the scanning measurements with traditional instrument surface measurements; however, after starting the initial measurements they were unable to complete the measurement process due to an increase workload at their respective company. This unfortunate loss of data placed some of the initial exploratory goals of the research at risk.

The Spectra LL300N laser scanner provided approximately 150 data points for each slab A and slab B. This information provided a highly accurate representation of the curling of the two test slabs measuring elevation change to an accuracy of 0.02 mm. Though having had the industry survey data would have been valuable as a cross reference, the 3D laser scan (See Picture 3.9) complemented the use of the Spectra LL300N laser level which provided more than adequate information to understand the validity of the hypothesis. The same instrument used to measure the slabs in Cottonwood, Arizona was used to measure the two test slabs in the Phoenix metropolitan area.

Picture 3.9: 3D Laser Scanning of Test Slabs in the Phoenix Area

The research team from Arizona State University was able to use the data points provided and replicated the information from the initial data points to the end at 60 days. This provided an understanding of how the two slabs are curled during that time.

A benchmark was placed one foot above the concrete slab on an existing telephone pole (See Figure 3.3). This provided a reference point to start from and was established at the very beginning of the measurement process and is displayed as 0.0 in elevation on the figures. Similar to the Cottonwood, Arizona buildings, the same measurement pattern was followed (See Figures 3.6 and 3.7).

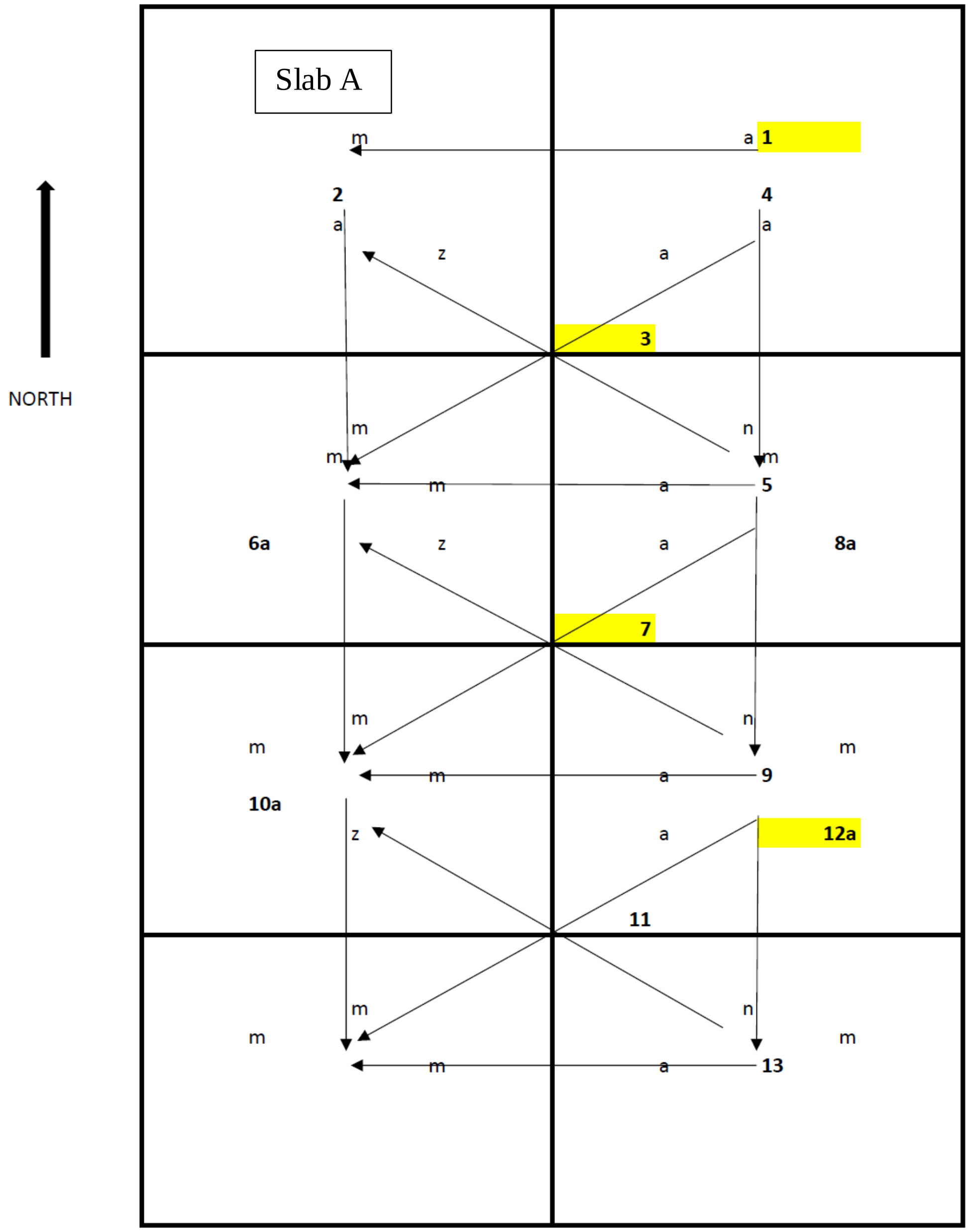


Figure 3.6: Measurement Configuration in Phoenix Test Slab A

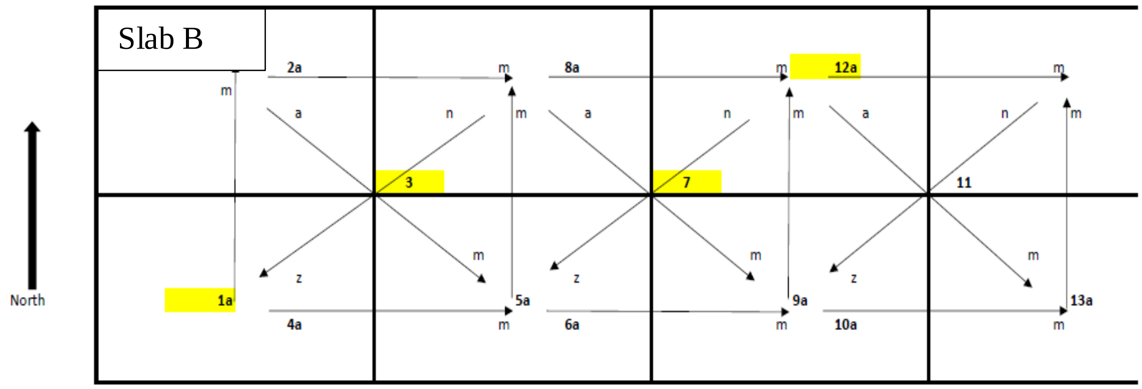


Figure 3.7: Measurement Configuration in Phoenix Test Slab B

As shown, Figure 3.6 is Slab A, and Figure 3.7 is Slab B. Slab A had silicone placed in the contraction joints, whereas Slab B did not. Similar in natural of the Cottonwood slabs, the measurements were taken the same. The process was done by placing a tape measure perpendicular to the sawcut contraction joint placing the 5-foot mark of the tape measure at the center of the contraction joint, measuring for a total of 10 feet across the contraction joint

Measurements were taken every foot starting with the one-foot mark. The measurement distances changed when coming closer to the contraction joint. Between the four-foot mark and 6-foot mark, measurements were taken every six inches on either side of the contraction joint. After the 6-foot mark, the measurement pattern continued to be measured every foot. At each point on the tape measure as described above, elevation measurements were taken with a laser level. There were approximately 150 measurements taken on each slab and were set up into thirteen locations on the slab. See Figure 3.4 for a diagram of the measurement regimen

CHAPTER 4

ANALYSIS OF DATA

4.1 Analysis of Data for Slabs in Cottonwood, Arizona

As mentioned in the methodology, the Cottonwood Industrial concrete slabs were placed in May of 2018. Approximately 150 measurements were taken at 13 different locations. Four samples were taken from the 13 locations which are in the same location in each building (See Figure 3.5).

Line A represents slab elevation data from the intervention concrete slab that received the silicone-based compound the day after casting. Line B displays identical data from the concrete slab that received the silicone-based compound 30 days after the initial casting of the slab. Station 6 on the graph is the location of the sawcut joint. This will be the same for all four examples of this section. In Figure 4.1, the observation at station 6 is a peak which would suggest a curling effect in slab B and slab A showed no similar curling behavior. From this profile, it is easy to see the concrete slab that was caulked immediately had a reduced curling effect. This would indicate there is a larger effect on Slab B where the silicone was introduced 30 days later.

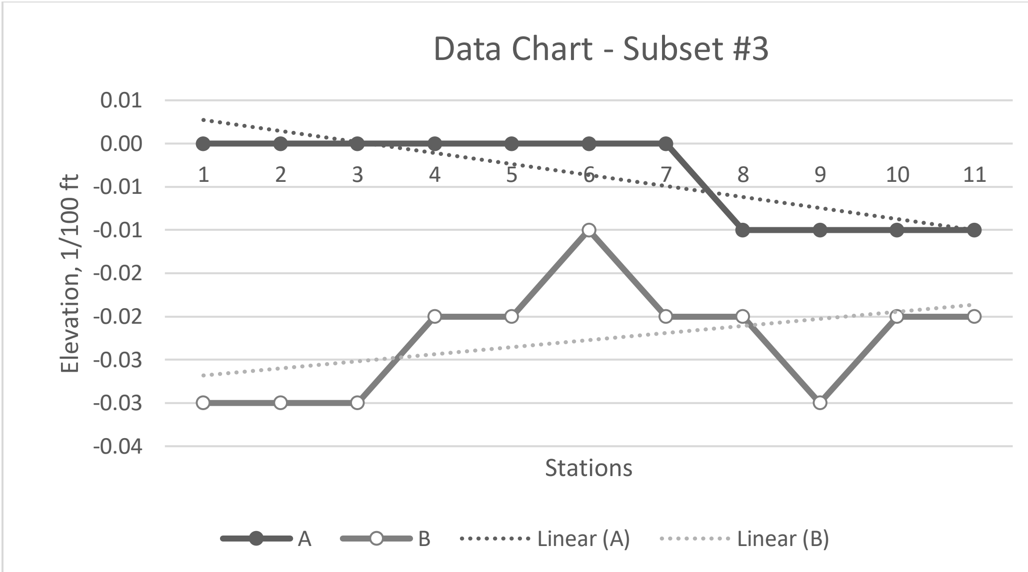


Figure 4.1: Location #3 – Cottonwood Slab Elevation Measurements

Figure 4.2 shows the elevation data measured at location 7 on the Cottonwood slabs. Location 7 represents the intersection point of two sawcut joints, and the measurement line runs diagonally through the intersection as shown in Figure 3.5.

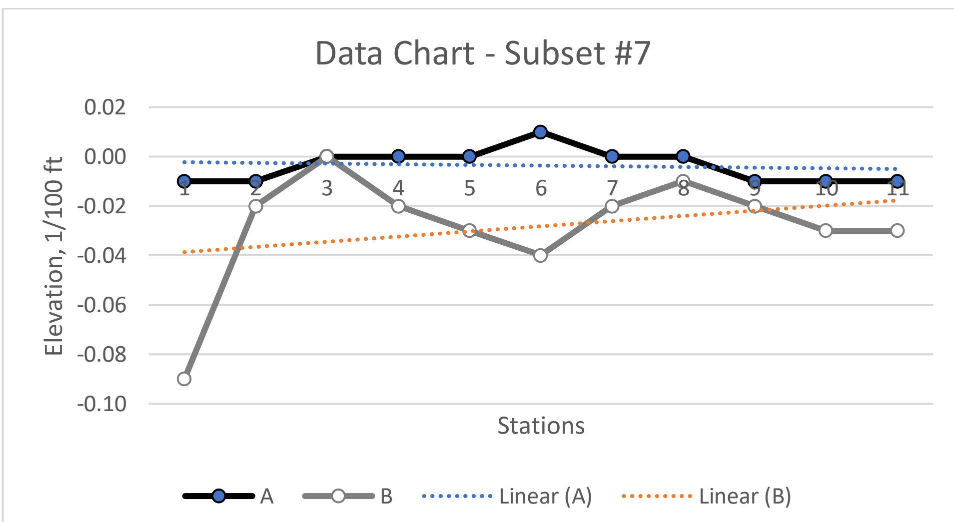


Figure 4.2: Location #7 – Cottonwood Slab Elevation Measurements

In Figure 4.2, across the sawcut joint there is a noticeable difference between the Slab A and Slab B. Slab A has a more uniformity to the slab where Slab B shows peaks and valleys which may have a been contributed by the later application of silicone or this data may show there were finishing problems during the placement of the concrete slab.

Figure 4.3 shows the elevation data measured at location 10 on the Cottonwood slabs. Location 10 represents a single sawcut joint where the measurement line runs perpendicular to the direction of the joint as depicted in Figure 3.5.

In Figure 4.3, again Slab A has a more uniform flatness at station 6 where Slab B shows a drop-in finish floor height (F.F.E.). Slab B is showing varying floor flatness in the slab at station 6 the concrete slab drops which could show a loss of moisture in the contraction joint.

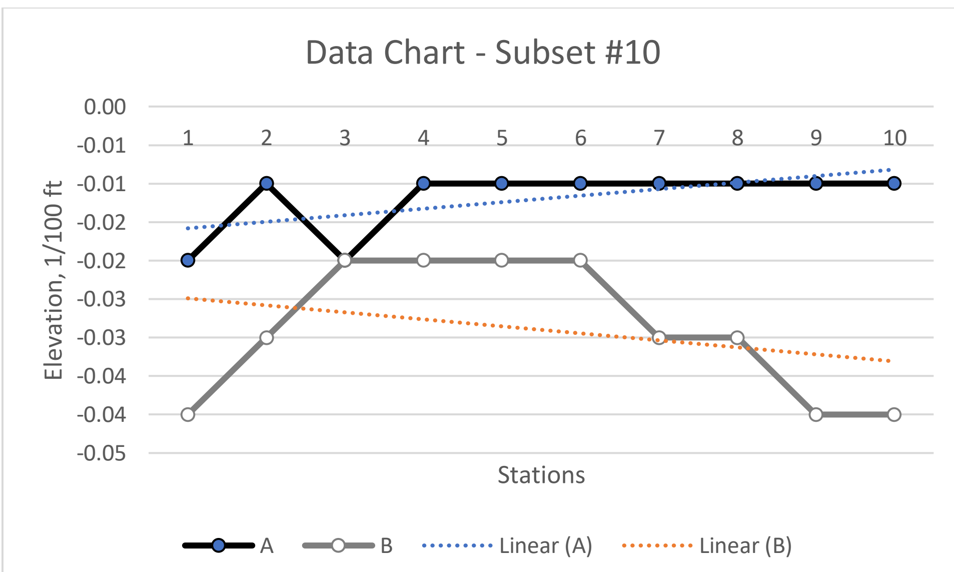


Figure 4.3: Location #10 – Cottonwood Elevation Measurements

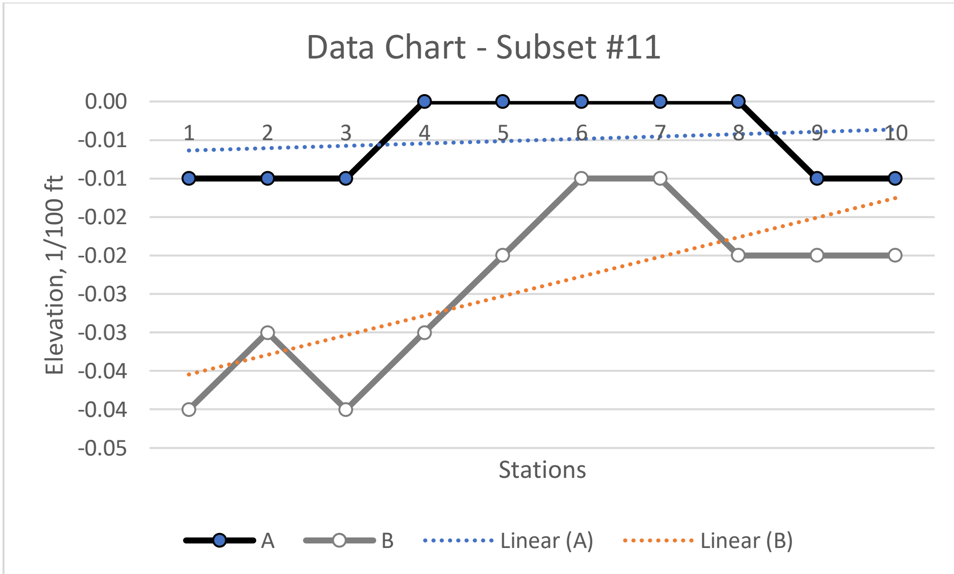


Figure 4.4: Subset #11- Cottonwood

Figure 4.4, across the sawcut joint there is a noticeable difference between the Slab A and Slab B. Slab A has a more uniformity to the slab where Slab B shows peaks and valleys which may have a been contributed by the later application of silicone or this data may show there were finishing problems during the placement of the concrete slab.

The data in Figure 4.4 shows that Slab A is much flatter with less curling than Slab B. The center of the contraction joint at Station 6 on slab B there is a noticeable floor flatness height difference. There is a noticeable difference of variation between slab A and slab B which indicate that Slab B curled significantly more than Slab A which could be attributed to the delay sealing of the sawcut joints.

4.2 Analysis of Data for Test Slabs in Phoenix, Arizona

Since the industry did not finish the measurements of the two slabs in the Phoenix metropolitan area. The experimental use of the 3D laser proved to be very useful in the completion of this research project. The data produced from both the 3D laser, coupled with the data collected using the Spectra LL330N gave the necessary data for the curling amount of the two test slabs.

Over 150 data points were collected in each test slab. These points were taken at 13 different locations as described in Chapter 3. Of the 13 locations measured, four are graphically analyzed and displayed. The data points were taken on day 0 and again on day 60.

Since these two test slabs will be used for parking equipment once the testing portion is complete, the slabs were designed with a slope for the runoff of rainwater. Therefore, the elevation data for the two test slabs will graphically show slope. The slope is not the concern as it is the curling effect of the concrete at the contraction joints that is of interest; however, the design slope does tend to skew the appearance of the elevation data. This analysis will focus on the contraction joint. Silicone was only installed in Slab A sawcut joints to minimize moisture loss while the sawcut joints in slab B were unfilled throughout the test period.

In the graphs that follow, there could be a difference in height from the first day to day 60. The graph of day 60 may show the slab being lower in elevation and this is normal as a result of loss in moisture in the concrete slab and resulting shrinkage.

The concrete mix used had a 0.49 water/cement ratio, which is very conservative and did not provide a lot of excess water to be used for convenience. A water-reducing admixture was also used to allow for a more workable concrete mix. Any shrinkage indicated by the elevation measurements could be a result of the extreme hot environment as this type of shrinkage has been observed before in the literature and is referred to as thermal contraction (Nmai et al. 2018).

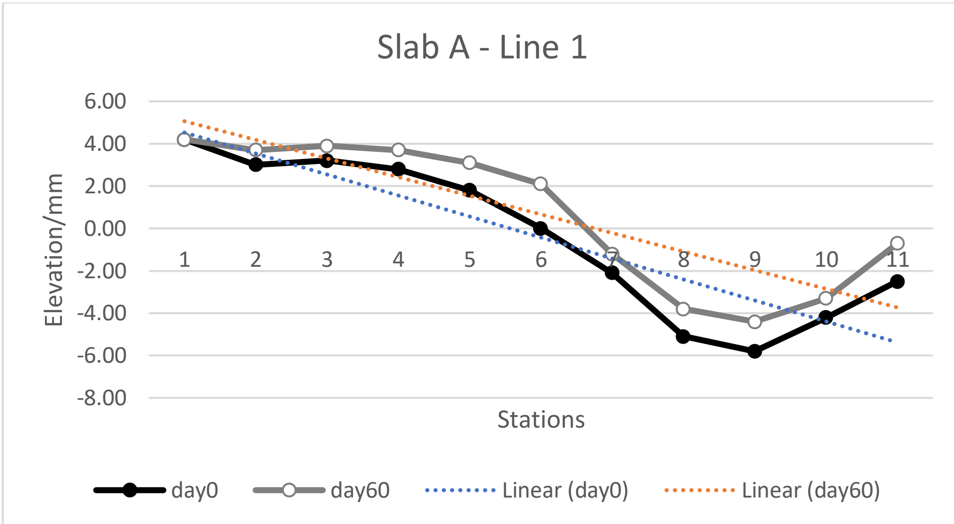


Figure 4.5: Location #1 – Phoenix Test Elevation Measurements Slab A

Figure 4.5 shows the elevation measurements taken at location 1 on Slab A on day 0 and day 60. Location 1 measurements were made along a line perpendicular to a sawcut joint which was caulked immediately after placement. If one considers the effect of the design slope on the shape of the graph indicates a small amount of curling took place.

By referring to the graph in Figure 4.5, the 60-day measurement shows an increase at Station 6 over that measured at day 0, even when trying to mitigate moisture loss in the contraction joint by sealing the joint.

Slab B (with no silicone) in Figure 4.6 shows the whole slab shrinking in elevation. Notice the difference between the first day and ay 60 graph lines, which decreased in height between Day 0 and Day 60. This could be an example of thermal contraction. Looking at the graph, the consistency is there and on station 5 is the high point. Point 5 is six inches away from station 6, which could have risen just before the center of the contraction joint as showing on this graph (See Figure 4.6).

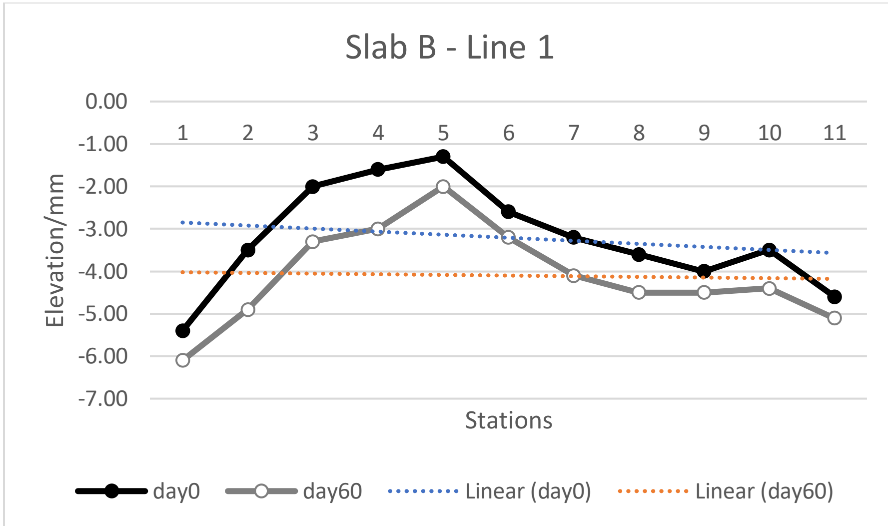


Figure 4.6: Location #1 – Phoenix Test Elevation Measurements Slab B w/o Caulking

Figure 4.7 shows elevation measurements taken at location 3 on Phoenix Test Slab A on Day 0 and Day 60. Location 3 measurements were made along a line that runs diagonally through the intersection of 2 sawcut joints.

Figure 4.7 indicates the elevations changes were gradual and unnormal between station 1 and 4. Between stations 5 and 9 the volume change reverses with an increase of up to 0.5 mm at station 7, and this is the region where contraction joints divide the slab. This data is difficult to explain as the later age measures indicate curling at some points along the measurement line and then shrinking at other points along the same line.

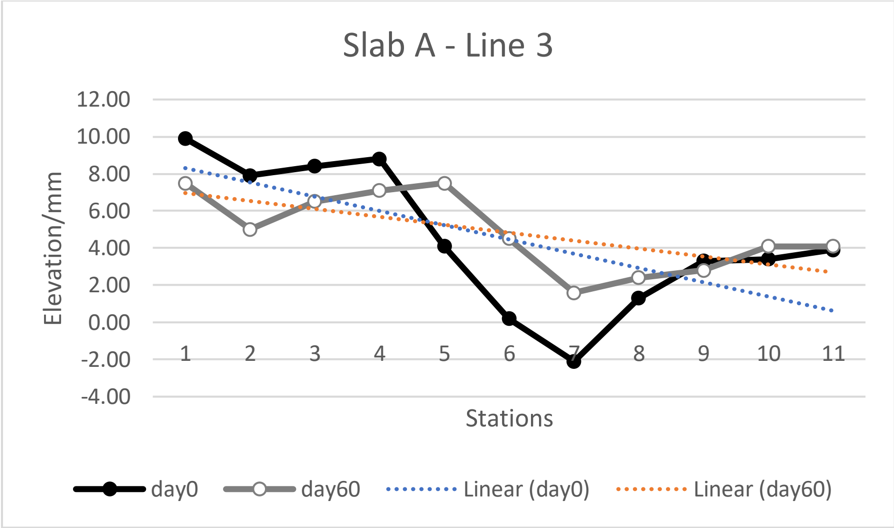


Figure 4.7: Location #3 – Phoenix Test Elevation Measurements Slab A

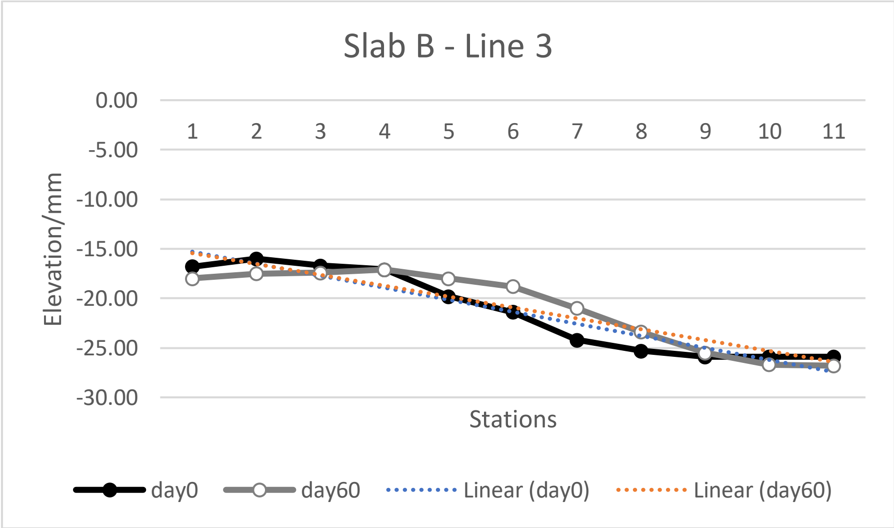


Figure 4.8: Location #3 – Phoenix Test Elevation Measurements Slab B w/o Caulking

Figure 4.8 represents the elevation profile of the control Slab B. Station 6 measures the location of the contraction joints. The profile of these 2-measurement lines reflects what one would expect to see and the higher values at the sawcut joint which would indicate higher curling there. The change in elevation on day 60 indicates the warping effect in the slab due to moisture loss at a higher rate as compared to the slab with the intervention (Slab A). Given that this slab was not caulked it is surprising to see the relatively low level of curling indicated by the measurements.

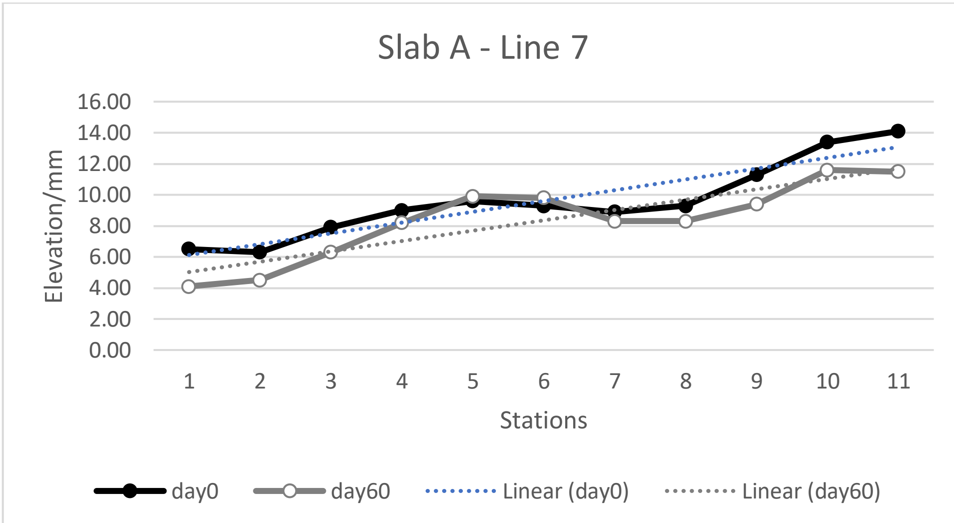


Figure 4.9: Location #7 – Phoenix Test Elevation Measurements Slab A

The profile of Slab A in Figure 4.9 indicates the changes in elevation of the slab from day 0 to day 60. The changes in elevation are almost negligible between station 5 and 7, as this is the region of contraction joints, which were sealed using silicone to prevent moisture loss. (See Figure 4.9)

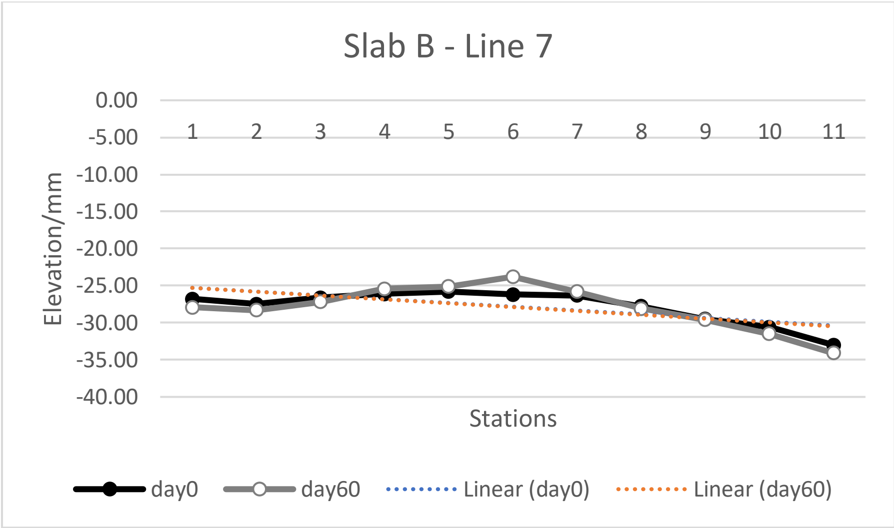


Figure 4.10: Location #7 – Phoenix Test Elevation Measurements Slab B w/o Caulking

In Figure 4.10, both profiles at day 0 and day 60 do not vary, but at the contraction joint; Station 6 an increase of the slab of 2.4 mm can be noticed, probably due to excess moisture loss. One does see an increase in elevation change overtime which would indicate increased curling.

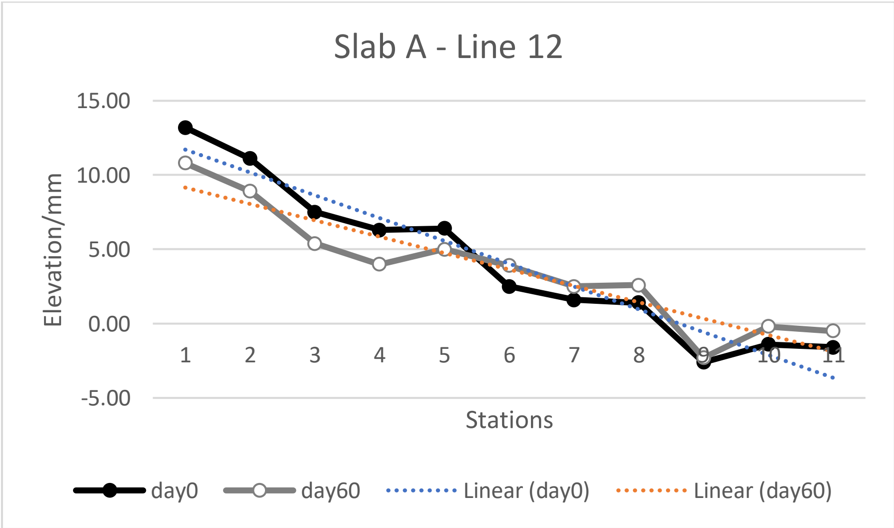


Figure 4.11: Location #12 – Phoenix Test Elevation Measurements Slab A

The two profiles shown in Figure 4.11 and 4.12, indicate almost a uniform change in elevation from station 1 to 5. In Figure 4.11, the elevation moves upward from stations 6 to 11. In Figure 4.12, there is little to no change throughout the entire graph. This may be due to the situation where the slabs in both areas are close to the edge and the foundation kept the slabs from making any noticeable changes in elevation.

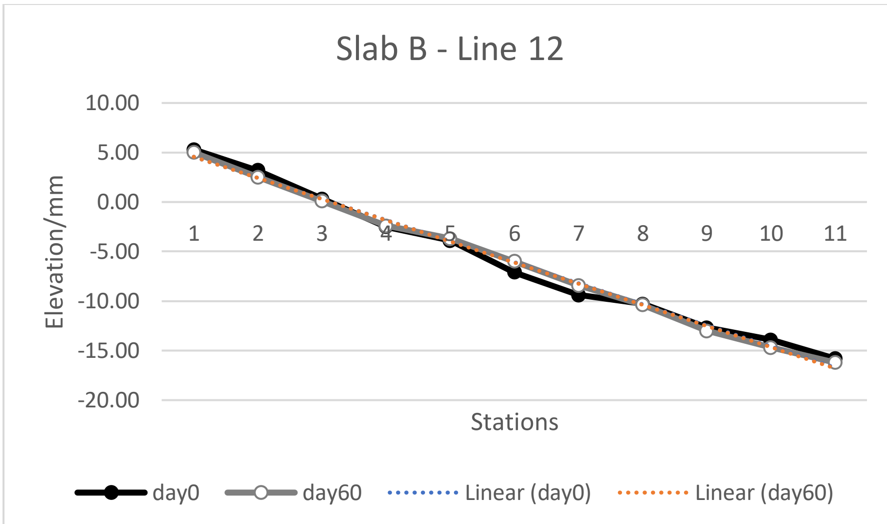


Figure 4.12: Location #12 – Phoenix Test Elevation Measurements Slab B w/o Caulking

CHAPTER 5

CONCLUSION OF ANALYSIS

5.1 Cottonwood Project Conclusion

Looking at the data from the Cottonwood project, it is clear to see that the use of a silicone-based compound has minimized the effect of curling on the concrete slab. The intervention slab, which received the silica-based compound the day after placement of concrete, had very little to no curling effect.

The control slab or the slab which did not receive a silicone-based compound until 30 days after placement, showed significant signs of concrete curl, based on the measurements shown in Figures 4.1 to 4.4.

5.2 Test Slabs in Phoenix, Arizona Metropolitan Area

The results from the test slabs constructed and measured in Phoenix were small in nature, and for future research the slabs need to be larger for a more accurate test. Measurements taken for numbers 3 and 7 are where the contraction joints have an intersection. This type of contraction joint will usually cause the most problems with FF/FL numbers. In ASTM E1155, it is recommended not to measure these areas for floor flatness due to the increased risk of the floor curling in these areas of contraction joints.

By referring to Figure 4.7 for Slab A (silicone introduced), the measurement for number 3 on the 60-day measurement increased in curl. This was not expected, but occurred; however, looking at the slab as a whole; the entire slab increased in size. This would be a situation where the slab is being locked in and could be the result of the raising of the entire slab, which is not uncommon.

By observing Figure 4.8, Slab B (no silicone), there was not a significant amount of curl in the slab where the contraction joints intersected. The amount of slab movement between Slab A (with silicone) to Slab B was significant, and it was very hard to conclude if the introduction of silicone in the contraction joints of Slab A affected or not. However, as stated, this may have been a factor where the slabs were too small in size to force curling in the two test slabs.

When comparing Figure 4.9 to Figure 4.10, it shows that there is an increase in elevation at the intersection of the contraction joint. Slab B (without silicone) shows a slightly higher increase in elevation verses Slab A (with silicone). This shows that there may be validity to the fact that controlling the moisture loss in a contraction joint is important, but to say this is an answer to the curling problem cannot be proven at this point. There is still testing needed on this topic to help understand what and how much moisture loss is taking place at the contraction joints which are sawcut after a chemical cure has been placed.

CHAPTER 6

RECOMMENDATIONS FOR FUTURE RESEARCH

This paper was an exploratory discussion on moisture loss in a contraction joint and studied if there is an effect on curling of concrete. Measurements produced on the Cottonwood projects would certainly validate that necessity for future exploration of this topic. There were definite miscalculated items made on the test slabs in the Phoenix metropolitan area that caused a negative reaction. This section aims to discuss areas to avoid, which may produce better results from testing the hypothesis.

6.1 Vapor Barrier

A suggestion would be to not have vapor barriers present. In the literature review, the use of a vapor barrier is suggested as a causal factor for concrete to curl. If a vapor barrier were to be used, as suggested in the literature review, it would be best to place two to four inches of base over the vapor barrier to allow water of convenience to be drawn into the base above the vapor barrier.

6.2 Size of Test Slabs

Given the fact the research team did everything to the slabs to cause a factor of curling, hoping for a result of some difference between the two slabs. There was an observable difference, but not significant enough to prove validity to the hypothesis.

The measured results from the slabs in Cottonwood, Arizona gave a better understanding to the effect of the placement of a silicone-based compound in the joints immediately after saw cutting of contraction joints has occurred. The climate in Cottonwood, Arizona is not as extreme as the Phoenix metropolitan area but proved to the validity of this process.

Going forward, it would be advisable to have larger projects examined that are willing to allow a research team to conduct side-by-side testings of this hypothesis. The reason for this is that in a larger slab-on-grade there is room for expansion and contraction, allowing the concrete to move horizontally in a normal environmental situation.

6.3 Process of Joint filling

In Cottonwood, Arizona the contraction joints were filled with a product that had a portion of the compound with silicone. It was a filler used by painters and was not of the highest grade; nevertheless, the filler used in the contraction joints was successful and as a result, worked well both in appearance and in controlling the amount of measured curling.

The silicone used in the Phoenix metropolitan area was pure silicone. It was difficult to use, and because the full depth of the contraction joint was filled, the caulk tended to separate from the concrete slab joint. This required the research team to return and fill the joint two additional times after the initial filling of the joint. This may have been part of the problem as to why the curling results were different in certain areas of the test slabs. Further research should be done placing caulking in the sawcut to a depth no greater than its width. This will allow the caulking material to expand and contract with the concrete slab. This can be done by the placement of a foam backer rod in the contraction joint prior to the filling of the contraction joint with caulking material.

6.4. Measurement of Slabs

Although resources were not plentiful for this project and this was an exploratory paper, the measurement process of test slabs is crucial. Initially, industry support was willing to help with the measurement portion of this experimental process, but very important data was lost due to industry being incapable of finishing the project. This is very understandable, but this test could have been more conclusive had all the data been available.

In the future, it would be best to hire a testing laboratory to obtain the data points. Having a testing lab perform the measurements of test slabs would have led to more accurate data. They would also have also obtained the measurements according to ASTM E1155, which is a recognized method of measurement in industry and would have carried more validity in the research findings.

6.5 Level versus Sloped Slab-on-Grade Concrete Slabs

The slabs in Cottonwood, Arizona were level concrete pads, which made the measurement and analysis of the data more simplified. The research team concluded that it would make a difference if the concrete slabs were level or had no slope.

The concrete test slabs in the Phoenix metropolitan area were sloped, and that fact, coupled with the loss of Industry measurement data made it very difficult to ensure the validity of the data. The data was difficult to understand, and this made the analysis of the data very difficult as well. In future projects, it may be recommended to have slab level, which may result in better conclusions of the analyzed data.

6.6 Measurement of Moisture Loss at Contraction Joints

During this testing process, it would have been helpful to understand how much moisture loss is occurring at the contraction joint. There are several methods of obtaining this information, and this would be another point of interest in determining an intervention process in the event. There are large amounts of moisture loss in the contraction joint particularly if nothing is introduced to lessen or stop moisture loss. In the concrete industry, there is a certain amount of moisture needed for the curing process, and if that needed moisture is escaping via the contraction joint, then an intervention to stop moisture loss is needed. This would definitely prove to be useful in understanding moisture loss in contraction joints and may help researchers understand the importance of addressing this issue.

CHAPTER 7

FINAL DISCUSSION

As an overall research project, there was a certain sense of satisfaction at the completion of this research effort. There is a growing problem in the industry dealing with curling concrete. Engineers typically fix curled concrete by grinding and there is a budget line item needed in a bid for grinding floors. Concrete contractors solely follow the ASTM E1155, measuring Floor Flatness/Floor Levelness within 72 hours of finishing; thus, meeting that standard, the burden is then placed on the owner of the building. There is an understanding that concrete will curl and much has been researched on reducing the curling effect of concrete, but these efforts have been on the material side instead of investigating different means and methods.

This paper has taken the approach from the side of means and methods and aims to help reduce or minimize the curling effects of concrete. According to the performed literature review, water curing slab-on-grade concrete does reduce the amount of curling. This method of curing is difficult, and the feasibility of water curing may not be available. This is a reason why chemical curing is so popular in the concrete placement industry.

It is a known fact that chemical curing compounds are applied at the final finishing stage and then a saw cutting process forms contraction joints. This area of the slab is exposed to possible moisture loss and it is the hypothesis of this paper that there is a need for intervention to the contraction joint and to reduce moisture loss for the proper curing of concrete in a saw cut contraction joint in slab-on-grade concrete pads.

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APPENDIX A

TEST SAMPLE RESULTS

Project Data

Project Name R. Standage Research Curling Project
Job Location 1059 S. Lewis
Customer Alamo Concrete
Lab No. 2089
Plant No.

Field/Mix Data

Specimen Type x Concrete ____ Grout ____ Beams ____ Other

Design Strength 4000 PSI
Mix ID A4000P
Ticket No.
Truck No.
Batch Time
Sample Time
Slump 8 in
Temp 89 degrees
Ambient 99 degrees
Load Size

Tested By RS
Cast Date 7/24/2018
Submitted By RS
Date Submitted 7/25/2018
Set No. 1
Specimen Size 4x8
Unit Wt. na pcf
% Air na
Water Added gal

Lab No.	Age (Days)	Test Date	Max Load (lbs)	Compressive Strength (psi)	Fracture Type	Tested By
2089	1	7/25/2018	33214	2640	shr	TV
	1		29896	2380	shr	TV
	3	7/27/2018	40206	3200	shr	BD
	3		41078	3270	shr	BD
	7	7/31/2018	47490	3780	shr	BD
	7		44098	3510	shr	BD
	28	8/21/2018	57450	4570	cone	BD
	28		65864	5240	cone	BD
	56	9/18/2018				
	56					

APPENDIX B

VERIFICATION LETTER

James M. Willson, P.E., Ltd
Consulting Engineer
3449 North 47th Way
Phoenix, Arizona 85018-6013
602-840-7517
602-290-9585 cell
cementaz@cox.net

To Whom It May Concern August 1, 2018

Subject: Concrete Slab Placement
Research on Curling
Arizona State University (ASU)
Mesa, Arizona

On July 24, 2018 I witnessed the placement of 24 cubic yards of conventional concrete in two adjacent flat slabs in Mesa, Arizona. The work was completed under the direction of Richard Standage, Doctoral Candidate at ASU, as part of a research project.

The construction of the concrete slab was conducted with the intention of following the requirements of American Concrete Institute document *Guide for Concrete Floor and Slab Construction, ACI 302.* I witnessed the placement and finishing using that document as my general specification.

It is my opinion that the construction of the slabs followed the intention of ACI 302 for concrete slabs on ground.

Please contact me at the letterhead address if you have questions or desire discussion regarding this project.

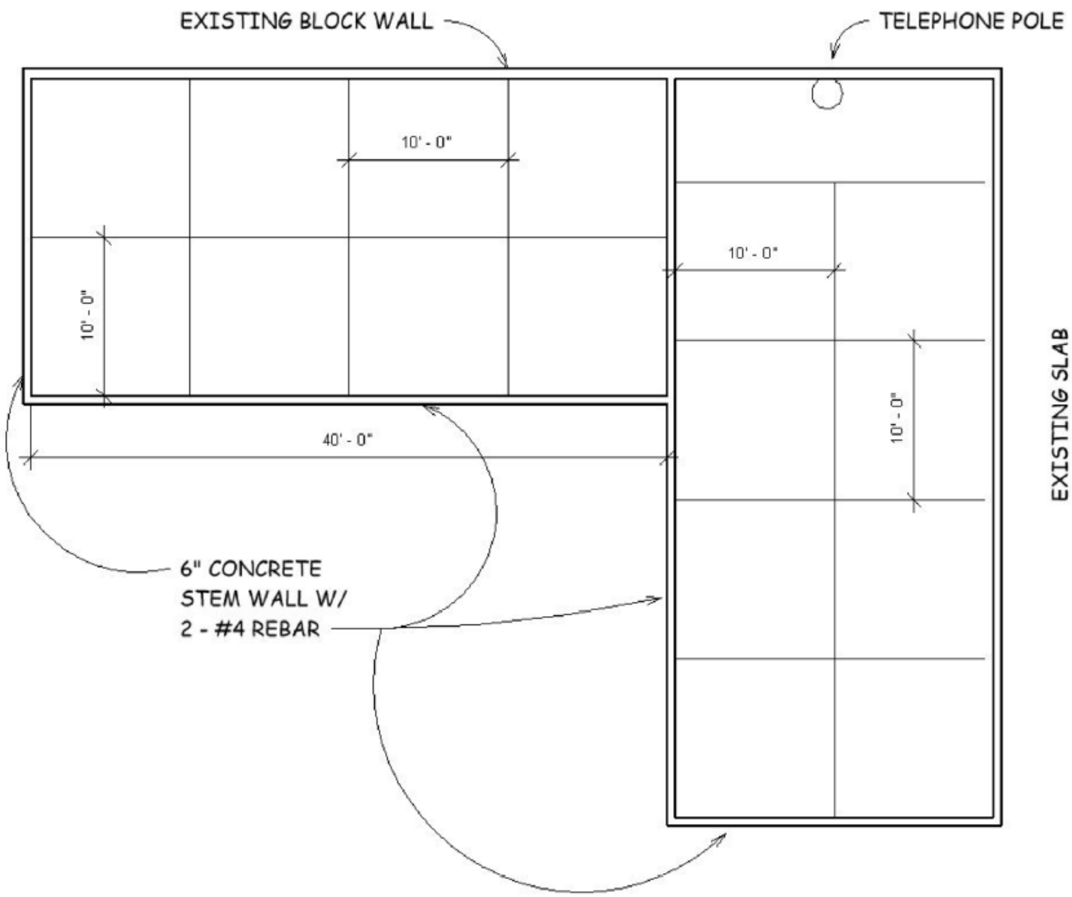
Respectfully submitted,

James M. Willson, P.E.

Registered Professional Engineer (Civil)
CERTIFICATE NO.
13928
JAMES MITCHELL
WILLSON
DATE SIGNED 08-01-18
ARIZONA U.S.A.
Expires: 12-31-2019

APPENDIX C

SLAB DRAWING


EXISTING BLOCK WALL
TELEPHONE POLE
10' - 0"
10' - 0"
10' - 0"
10' - 0"
40' - 0"
EXISTING SLAB
6" CONCRETE
STEM WALL W/
2 - #4 REBAR

APPENDIX D

DELIVERY RECEIPTS

ROCK SOLID

AMERICAN MADE ★ FAMILY OWNED

6741 W. ROCK SOLID WAY, BOX 5062 • CHANDLER, AZ 85226
PHONE: 480-496-9633 FAX: 480-496-7212

148722

TERMS AND CONDITIONS

Drivers are prohibited from delivering concrete except under the truck's own power, and where site conditions permit the safe and proper operation of the equipment. Drivers are not permitted to go beyond the curb line, except upon the authorization of the customer and his acceptance of risk for any loss or damage to the property or our equipment. This includes any wrecker or towing charges for getting out of the location.

We allow 6 minutes per cubic yard unloading time free; any additional time will be billed at our normal rate. All deliveries are subject to sellers normal terms and conditions for delivery and credit at time of delivery. Drivers are not permitted to add water to the mix to exceed the maximum slump. Additional water added to this concrete will reduce its strength. Any water added is at customer's risk.

Delivery/Terms Accepted By
X Richard Owens
Customer's Representative

Water added on Job ______ gals.
Water requested by ______

CUSTOMER ID	P.O. NUMBER	ZONE	ORDER NUMBER	BATCH TIME	DATE	TICKET NO.
ALAMO	RICH		10	06:02:05	07/24/18	504830

SOLD TO	DELIVER TO	
ALAMO CONCRETE	H'S DISSERTATION 1059 S LEWIS MESA	Lot# 150-27 Block# Sect

QUANTITY THIS LOAD	QUANTITY ORDERED	QUANTITY DELIVERED	PRODUCT NUMBER	PRODUCT DESCRIPTION	UNIT OF MEASURE	UNIT PRICE	EXTENDED PRICE
08.00	24.00	8.00	A4000P	4000 PSI FLOWABLE	CU Y		
1.00			P1E	TEMPERED WATER	PER		

TRUCK	PLANT	SLUMP	DUE AT JOB	USE OF CONCRETE	
314	5	7.1	06:30	FOUNDATION	SUB TOTAL TAX TOTAL
ACCELERATOR	AIR ENTRAIN	SUPER PLAS.			

LOADING TIME	ARRIVE JOB	START UNLOADING	FINISH UNLOADING	LEAVE JOB	ARRIVE PLANT
6:12	6				

DELIVERY INSTRUCTIONS N. SOUTHERN -WATCH SLUMP

SPECIAL INSTRUCTIONS

TEAR HERE

Batch 1 of 1 8.00 CuYds Wtr Adjust 0.00 Gal/CuYd Admix % 100 100
Scale Zeros: Control # 00504830
% Moist:

DESCRIPTION	MTRL	BIN	AMOUNT	TARGET	DESCRIPTION	MTRL	BIN	AMOUNT	TARGET	DESCRIPTION	MTRL	BIN	AMOUNT	TARGET
57 ROCK	3	AGA4	12334 Lb	12360	3/8	1	AGA2	2945 Lb	2960	CONCRETE SAN	2	AGA3	9798 Lb	9776
CEMENT	11	CMA1H	3826 Lb	3760	FLY ASH	12	CMA2	955 Lb	960	TEMP WATER	16	WTA2	232 Gal	232
X15	27	ADA3	441 Oz	440	WR91	22	ADA2L	159 Oz	160					

Richard Owens

WTR/CMT RATIO 0.488

ROCK SOLID

AMERICAN MADE ★ FAMILY OWNED

6741 W. ROCK SOLID WAY, BOX 5062 • CHANDLER, AZ 85226
PHONE: 480-496-9633 FAX: 480-496-7212

148727

TERMS AND CONDITIONS

Drivers are prohibited from delivering concrete except under the truck's own power, and where site conditions permit the safe and proper operation of the equipment. Drivers are not permitted to go beyond the curb line, except upon the authorization of the customer and his acceptance of risk for any loss or damage to the property or our equipment. This includes any wrecker or towing charges for getting out of the location.

We allow 6 minutes per cubic yard unloading time free; any additional time will be billed at our normal rate. All deliveries are subject to sellers normal terms and conditions for delivery and credit at time of delivery. Drivers are not permitted to add water to the mix to exceed the maximum slump. Additional water added to this concrete will reduce its strength. Any water added is at customer's risk.

Delivery/Terms Accepted By
X Alamo
Customer's Representative

Water added on Job 0 **gals.**
Water requested by ______

CUSTOMER ID	P.O. NUMBER	ZONE	ORDER NUMBER	BATCH TIME	DATE	TICKET NO.
ALAMO	RICH		10	06:32:05	07/24/18	504835

SOLD TO	DELIVER TO		
ALAMO CONCRETE	H'S DISSERTATION 1059 S LEWIS MESA	Lot# Block#	150-27 Sect

QUANTITY THIS LOAD	QUANTITY ORDERED	QUANTITY DELIVERED	PRODUCT NUMBER	PRODUCT DESCRIPTION	UNIT OF MEASURE	UNIT PRICE	EXTENDED PRICE
08.00	24.00	16.00	A4000P	4000 PSI FLOWABLE	CU Y		
1.00			P16	TEMPERED WATER	PER		

TRUCK	PLANT	SLUMP	DUE AT JOB	USE OF CONCRETE		
423	5	7.1	07:01	FOUNDATION	SUB TOTAL	
ACCELERATOR	AIR ENTRAIN	SUPER PLAS.	Brad		TAX TOTAL	

LOADING TIME	ARRIVE JOB	START UNLOADING	FINISH UNLOADING	LEAVE JOB	ARRIVE PLANT
640	701				

DELIVERY INSTRUCTIONS N. SOUTHERN -WATCH SLUMP

SPECIAL INSTRUCTIONS

TEAR HERE

Batch 1 of 1 8.00 CuYds Wtr Adjust 0.00 Gal/CuYd

Admix %: 100 100

Control # 00504835

Scale Zeros:
% Moist:

DESCRIPTION	MTRL	BIN	AMOUNT	TARGET	DESCRIPTION	MTRL	BIN	AMOUNT	TARGET	DESCRIPTION	MTRL	BIN	AMOUNT	TARGET
57 ROCK	3	AGA4	12288 Lb	12360	3/8	1	AGA2	2933 Lb	2960	CONCRETE SAN	2	AGA3	9760 Lb	9776
CEMENT	11	CMA1	3759 Lb	3760	FLY ASH	12	CMA2	960 Lb	960	TEMP WATER	16	WTA2	232 Gal	232
X15	27	ADA3	441 Oz	440	WR91	22	ADA2L	159 Oz	160					

WTR/CMT RATIO 0.494

ROCK SOLID

AMERICAN MADE ★ FAMILY OWNED

6741 W. ROCK SOLID WAY, BOX 5062 • CHANDLER, AZ 85226
PHONE: 480-496-9633 FAX: 480-496-7212

148730

TERMS AND CONDITIONS

Drivers are prohibited from delivering concrete except under the truck's own power, and where site conditions permit the safe and proper operation of the equipment. Drivers are not permitted to go beyond the curb line, except upon the authorization of the customer and his acceptance of risk for any loss or damage to the property or our equipment. This includes any wrecker or towing charges for getting out of the location.

Delivery/Terms Accepted By
X
Customer's Representative

We allow 6 minutes per cubic yard unloading time free; any additional time will be billed at our normal rate. All deliveries are subject to sellers normal terms and conditions for delivery and credit at time of delivery. Drivers are not permitted to add water to the mix to exceed the maximum slump. Additional water added to this concrete will reduce its strength. Any water added is at customer's risk.

Water added on Job ______ gals.
Water requested by ______

CUSTOMER ID	P.O. NUMBER	ZONE	ORDER NUMBER	BATCH TIME	DATE	TICKET NO.
ALAMO	RICH		10	06:55:55	07/24/18	504838

SOLD TO: ALAMO CONCRETE

DELIVER TO: H'S DISSERTATION, 1059 S LEWIS, MESA

Lot# 150-27
Block# Sect

QUANTITY THIS LOAD	QUANTITY ORDERED	QUANTITY DELIVERED	PRODUCT NUMBER	PRODUCT DESCRIPTION	UNIT OF MEASURE	UNIT PRICE	EXTENDED PRICE
08.00	24.00	24.00	A4000P	4000 PSI FLOWABLE	CU Y		
1.00			P16	TEMPERED WATER	PER		

TRUCK	PLANT	SLUMP	DUE AT JOB	USE OF CONCRETE	SUB TOTAL
812	5	7.1	07:22	FOUNDATION	

ACCELERATOR	AIR ENTRAIN	SUPER PLAS.		TAX / TOTAL
			Tom	

LOADING TIME	ARRIVE JOB	START UNLOADING	FINISH UNLOADING	LEAVE JOB	ARRIVE PLANT
700	720				

DELIVERY INSTRUCTIONS N. SOUTHERN -WATCH SLUMP

SPECIAL INSTRUCTIONS

TEAR HERE

Batch 1 of 1 8.00 CuYds Wtr Adjust 0.00 Gal/CuYd Admix %: 100 100
Scale Zeros: Control # 00504838
% Moist:

DESCRIPTION	MTRL	BIN	AMOUNT	TARGET	DESCRIPTION	MTRL	BIN	AMOUNT	TARGET	DESCRIPTION	MTRL	BIN	AMOUNT	TARGET
57 ROCK	3	AGA4	12297 Lb	12360	3/8	1	AGA2	2933 Lb	2960	CONCRETE SAN	2	AGA3	9810 Lb	9776
CEMENT	11	CMA1	3743 Lb	3760	FLY ASH	12	CMA2	H 999 Lb	960	TEMP WATER	16	WTA2	232 Gal	232
X15	27	ADA3	441 Oz	440	WR91	22	ADA2	L 159 Oz	160					

WTR/CMT RATIO 0.492

APPENDIX E

TEMPERATURES AND HUMIDITY

Temperatures

	Ambient Temp. Highs	Ambient Temp. Lows	Relative Humidity %	Slab Surface Temp.
7/24/2018	116	90	21	141
7/25/2018	115	90	17	153
7/26/2018	110	88	21	152
7/27/2018	109	86	23	162
7/28/2018	107	85	27	
7/29/2018	104	85	37	
7/30/2018	108	86	27	152
7/31/2018	106	86	23	159
8/1/2018	110	87	23	152
8/2/2018	110	87	23	154
8/3/2018	109	88	23	156
8/4/2018	111	88	18	
8/5/2018	113	87	16	162
8/6/2018	109	87	12	156
8/7/2018	101	86	20	153
8/9/2018	102	79	31	152
8/10/2018	97	81	30	143
8/11/2018	102	81	31	
8/12/2018	102	82	26	
8/13/2018	100	82	48	137
8/14/2018	103	83	28	134
8/15/2018	97	80	27	132
8/16/2018	98	81	31	
8/17/2018	101	81	36	144
8/18/2018	105	84	36	
8/19/2018	107	85	23	
8/20/2018	106	86	23	
8/21/2018	99	83	25	
8/22/2018	101	84	25	
8/23/2018	100	81	45	
8/24/2018	100	78	40	
8/25/2018	100	75	38	
8/26/2018	99	81	0	
8/27/2018	105	78	0	
8/28/2018	100	79	0	
8/29/2018	104	80	19	
8/30/2018	103	80	20	

Temperatures				
	Ambient Temp. Highs	Ambient Temp. Lows	Relative Humidity %	Slab Surface Temp.
8/31/2018	100	82	21	
9/1/2019	100	79	29	
9/2/2018	99	81	29	
9/3/2018	95	77	27	
9/4/2018	97	82	30	
9/5/2018	103	75	34	
9/6/2018	104	79	30	
9/7/2018	105	81	28	
9/8/2018	104	81	19	
9/9/2018	104	77	21	
9/10/2018	102	80	21	
9/11/2018	106	79	19	
9/12/2018	105	79	20	
9/13/2018	104	75	17	
9/14/2018	108	77	10	
9/15/2018	106	80	12	
9/16/2018	104	79	16	
9/17/2018	104	81	22	
9/18/2018	103	80	32	
Average	103.96	82.04	24.11	149.67