

QUALITY CONTROL OF GROUTING FOR POST-TENSIONED TENDONS: IN-
LINE DENSITY MEASUREMENTS

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Dedication

This thesis is dedicated to my supportive and lovely fiancée, Monica Boyer.

Abstract

Cementitious grout has proven to be an effective corrosion protection method in post-tensioning systems. While successful grouting has been used in numerous post-tensioned (PT) bridges, quality control of the material and placement in the field remains a challenge. During the grouting process on-site, ensuring that the grout being placed in the tendon is representative of the intended grout design is critical for the performance of the system. Inconsistencies in the placed grout can be attributed to varying mixing procedures used in the field (such as the addition of water above the design value). In some cases, grout passing the laboratory tests differs significantly from grout placed in the field. To alleviate these discrepancies, it is imperative that the PT industry improves quality control to ensure materials and products meet project requirements throughout production and placement - not just during the grout's initial qualification. Advancements in the quality of in-place grouts can be made by refining specifications and developing a procedure to continuously measure the density of the grout as it is pumped into the tendon.

The objective of this research is to develop a quality control measure that can be used during pumping to ensure suitable and consistent grout quality. Continuous monitoring and recording of the grout density will ensure the grout is of uniform quality throughout the project and meets the water content requirements provided by the grout manufacturer to meet project specifications. Recommendations for procedure and associated specification language is provided.

Table of Contents

1.	Introduction.....	1
2.	Literature Review.....	5
2.1.	PT Grouting History and Failures.....	5
2.1.1.	Collapse of YNS-Y-GWAS Bridge.....	9
2.1.2.	Niles Channel Bridge.....	10
2.1.3.	Midbay Bridge.....	11
2.1.4.	Sunshine Skyway.....	11
2.1.5.	Varina Enon Bridge.....	12
2.2.	Durability.....	13
2.3.	Corrosion.....	14
2.4.	Materials.....	17
2.4.1.	Concrete.....	17
2.4.2.	Strands.....	17
2.4.3.	Ducts.....	19
2.4.4.	Anchorage.....	20
2.4.5.	Unbonded/Flexible Fillers.....	21
2.4.6.	Grout.....	23
2.4.6.1.	Cementitious Materials.....	24
2.4.6.1.1.	ASTM C150.....	25
2.4.6.1.2.	Pozzolans.....	25
2.4.6.2.	Admixtures.....	25
2.4.6.3.	Water to Cement Ratios.....	26
2.4.6.4.	Prepackaged Grout.....	27
2.4.6.5.	Properties and Testing.....	28
2.4.6.5.1.	Fluidity.....	29
2.4.6.5.2.	Volume Change.....	30
2.4.6.5.3.	Bleed and Voids.....	30
2.4.6.5.4.	Large Scale Incline Tube Testing.....	33
2.4.6.5.5.	Wet Density.....	34
2.4.6.5.6.	Set Time.....	35
2.4.6.5.7.	Strength.....	36
2.5.	Specifications.....	36
2.5.1.	PTI Specification for Grouting PT structures.....	36
3.	Experimental Plan.....	38
3.1.	Materials.....	39
3.1.1.	Prepackaged PT Grout.....	39

3.2.	Mixing Equipment	40
3.2.1.	Mixing Procedure.....	41
3.3.	Experiments	42
3.3.1.	Flow Cone.....	42
3.3.2.	Density	43
3.3.2.1.	Mud Balance Test	43
3.3.2.2.	In-line Density Meter.....	43
4.	Results and Analysis.....	45
4.1.	Fresh Property Test Results	45
4.1.1.	Flow Cone Test Results	46
4.1.2.	Density	46
4.1.2.1.	Mud Balance Test Results	47
4.1.2.2.	In-line Density Test Results.....	47
4.1.3.	Temperature	52
5.	Recommended Specifications.....	55
6.	Summary and Conclusions	56
6.1.	Summary	56
6.2.	Conclusion	56
7.	Bibliography	57

List of Tables

Table 3.1 Test Matrix..... 39
Table 3.2 Water Dosage..... 40
Table 4.1 Modified Flow Cone Test Results 46

List of Figures

Figure 1.1 Basic PT anchorage system [2]	1
Figure 2.1 Internal and external tendons in segmental bridge section. [17]	6
Figure 2.2 Corroded end-cap from a Niles Channel Bridge tendon [29].....	10
Figure 2.3 Midbay Bridge tendon failure [30].....	11
Figure 2.4 Corroded tendon found in Sunshine Skyway [30]	12
Figure 2.5 Corroded tendon from Verina Enon Bridge [32]	13
Figure 2.6 Tendon injected with wax	22
Figure 2.7 Tendon adequately full of grout	24
Figure 2.8 Grout Voids in Tendon.....	31
Figure 2.9 Schupack Pressure Bleed test apparatus [53]	33
Figure 3.1 Grout Plant [57].....	41
Figure 3.2 Flow Cone Apparatus [58]	42
Figure 3.3 Mud Balance Apparatus [59].....	43
Figure 3.4 Coriolis mass flow meter [60]	44
Figure 4.1 Live Density Reading.....	47
Figure 4.2 Density Results from Test 1 of Grout 1.....	48
Figure 4.3 Density Results from Test 2 of Grout 1.....	49
Figure 4.4 Density Results from Test 1 of Grout 2.....	50
Figure 4.5 Density Results from Test 2 of Grout 2.....	51
Figure 4.6 Temperature Results from Test 1 of Grout 1.....	53
Figure 4.7 Temperature Results from Test 2 of Grout 1.....	53
Figure 4.8 Temperature Results from Test 1 of Grout 2.....	54
Figure 4.9 Temperature Results from Test 2 of Grout 2.....	54

1. Introduction

Post-tensioned (PT) prestressing technology can provide durability and structural benefits to a bridge as well as reduce construction cost and time. PT concrete technology has developed rapidly since the 1960's in the United States [1]. The use of post-tensioned bridges in the U.S. increased because PT bridges are advantageous compared to other bridge structures when long spans, tight curvature, minimal impact on surroundings, or expedited construction is necessary. Properly designed and constructed PT bridges can be extremely durable, reducing maintenance costs.

The system consists of concrete, ducts, grout, and high strength steel strand as shown in Figure 1.1. The steel strand is fed through the duct within the concrete member and stressed in the field to induce compression. To mitigate corrosion and provide dependable load carrying capacity, the steel must be protected. This is typically achieved by pumping cementitious grout inside of the duct that can also create a bond to the surrounding concrete structure. Successful PT has two major benefits of corrosion protection over traditional reinforced concrete: minimal cracking (with active forces to close cracks under loading) and multiple levels of corrosion protection.

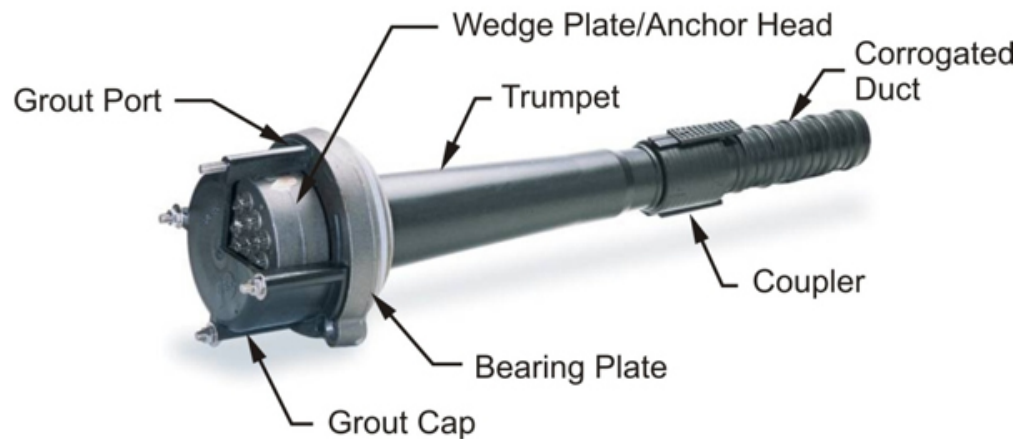


Figure 1.1 Basic PT anchorage system [2]

The quality of the concrete, ducts, and anchor materials in PT bridges has improved in the last 20 years. This multiple layered system provides a redundant and highly durable structure if properly installed. Even when the majority of the system is properly designed and installed, challenges related to grouting can still occur. Grout

issues in some major PT bridges have caused state transportation departments to reconsider the use of cementitious grout in some PT structures due to difficulty with effective and consistent grout injection [3]. Grouting concerns such as bleeding, voids, and recharge (such as moisture and chlorides breaching the tendon) came to light at the turn of the 21st century with the failure of multiple tendons in bridges across the US including the Niles Channel Bridge, Midbay Bridge, Sunshine Skyway, and Varina Enon Bridge [4]–[8]. The most common cause for corroded PT tendons is poorly grouted, even partially grouted, tendons. A Denmark survey of PT bridges conducted in 1998 found that although most of the bridges were in acceptable condition, the majority of the ducts evaluated in the survey were not fully grouted with consistent material [9]. These voids in the grout can leave the bridges vulnerable to corrosion of the steel strands which, if gone unnoticed, can lead to catastrophic consequences. The grouting operation is among the most important aspects of PT construction. When successfully executed, the PT ducts will be sufficiently grouted, and corrosion will be prevented throughout the service life of the bridge. Over the last 20 years, the PT industry has made multiple improvements to ensure the durability of bridges [9].

Research conducted at the turn of the century provided high-performance grouts with anti-bleed and thixotropic characteristics that revolutionized the grouting industry [10]. As a result, successful grouting operations have been achieved in hundreds of PT bridges across the country. These new-found solutions led to the publication of the Post-Tensioning Institute (PTI) Specification for Grouting of Post-Tensioned Structures and grouting certification courses by PTI and the American Segmental Bridge Institute (ASBI). ASBI and PTI collaborated to develop the M50.3 Guide Specification for Post-Tensioning and M55.1 Specification of Grouting of Post-Tensioned Structures to provide guidelines for designing and constructing durable PT bridges. These specifications provide procedures for proper mixture design, storage, tracking of expiration dates, water to cementitious material ratios, batching parameters, and testing of the grout in order to achieve fully grouted tendons [1].

Unfortunately, during the grouting process in the field, ensuring the properly designed grout is consistently placed in the tendon continues to be difficult to monitor. The primary reason being that the procedures used in the field may differ from best

practice used to qualify grout in the laboratory and field testing for quality control is limited to snapshots in time [11]. Additionally, inspection of the tendons is very difficult due to the enclosed nature of the system [12]. Inspectors may be unable to see the ducts and are unable to visually inspect grout inside the ducts without destructive testing that often exposes the system to oxygen and moisture. Since the grout is usually out of sight after construction, it is necessary to ensure the materials are properly installed throughout the construction process.

The addition of excess water to ease the pumping process is the most common on-site issue leading to voids in tendons. In some cases, the overwatering of the grout appears to be extensive [7]. The grout can also become overwatered due to water that has accumulated in the tendons prior to grouting. To ensure a durable PT bridge is constructed the quality control of the final grouted tendon is of utmost importance. To achieve high reliability of the end product, good plans, specifications, project details, quality control, education, and training are all required to minimize the chance of corrosion.

Industry leaders believe the best way to ensure PT durability is to have diligent grouting operations with good quality control [7]. It is important that manufacturers have an ongoing quality control program to verify that their materials and products meet project requirements throughout production and not just during the initial qualification [14]. Likewise, contractors must ensure quality control of the on-site grouting operation, including verification of the material as it is pumped into the tendons.

Quality control measures specified by PTI M55.1-12(13) require production tests during grout pumping including the minimum of one pressure bleed test at the mixer, two mud balance (density) tests per day, or when there is apparent change in the grout, one strength test per day, and two fluidity tests (at inlet and outlet) every 2 hours (these tests are described in depth in Chapter 2). It should be noted these tests are required throughout the grouting procedure as quality control measures for prepackaged grouts that have already passed qualification tests for PT grouting.

The objective of this project was to develop a performance testing method to ensure quality grout is being pumped into the tendons. This is achieved by performance-based testing of various grout mixtures and the development of an in-line quality

assurance solution. The new performance-based specification and procedures for use of an in-line density meter provide constant monitoring and recording of the grout properties throughout the pumping process.

2. Literature Review

2.1. PT Grouting History and Failures

Concrete has been used as a building material for a millennia and towards the middle of the 19th century reinforced concrete was discovered to be an efficient building material [15]. Reinforcing concrete with steel allowed the concrete to be used more effectively, however, it could still be improved upon for applications needing high flexural resistance such as bridges or other long span purposes. Inducing compression into the systems, via prestressing, allows concrete to be used more efficiently.

Prestressing (post-tensioning and pre-tensioning) precompresses the concrete taking advantage of the benefits of concrete's greater strength in compression than in tension. The main benefit of prestressed concrete is that the members are in compression during the service life, therefore avoiding the formation of flexural cracking during loading [16].

Prestressed concrete includes both post-tensioned and pre-tensioned members, depending on the sequence of stressing the steel and casting the concrete. Post-tensioning involves casting the concrete with voids (ducts) integrated within the structure. Multiple high strength steel strands make up a tendon and are inserted into the ducts through the member and anchored at one end. On the opposite end of the member, the tendon is pulled on by a hydraulic jack, creating tension in the tendon. The tendons are then anchored with an active tensile force applied, leaving the concrete member in compression. Pre-tensioning, on the other hand, places the strand in the desired locations in the form. The strand is tensioned and held in place while the concrete is cast around the strand. After the concrete cures, the strands are cut, and the member is subjected to the prestressing force. This research focuses on multi-strand post-tensioned applications.

Post-tensioning uses two types of tendons, external and internal. External tendons are located outside the concrete. Examples of external tendons are shown as T1, T2 and T3 in Figure 2.1. The advantages of external tendons are simplified construction and inspection processes due to easier access. However, external tendons are also costlier, can only be used with a few tendon profiles, and the strands are not bonded throughout the structure [16]. Internal tendons (T4, T5, T6, and T7 in Figure 2.1) differ from external tendons by being placed within the concrete member. After grouting, these tendons are

bonded along the length allowing for redevelopment of the strand in case of failure at the anchors. Internal tendons do not allow for easy access for inspecting or replacing the tendons.

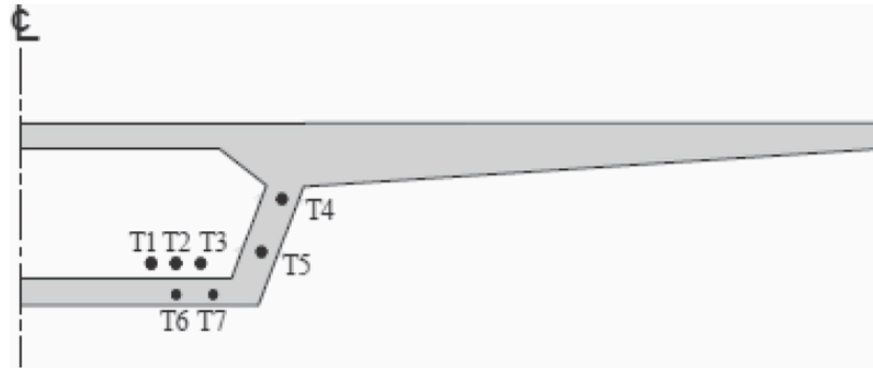


Figure 2.1 Internal and external tendons in segmental bridge section. [17]

In the 1920's, Freyssinet designed the first post-tensioned bridge [18]. He used PT technology effectively when constructing an arch bridge thereby eliminating formwork. Freyssinet quickly learned that creep caused significant issues for retaining pre-compression so high strength steel working in tandem with the concrete was required to produce an effective structure. He went on to develop and patent the anchorage systems made out of high strength mortar [19]. Advantages of the PT system were obvious and use of the technology spread quickly.

Prestressing was used often during WWII to provide for the fast erection of bridges. The sizable amount of prestressed construction applications was also spurred on by the large number of bridges that needed to be built following the war. Between 1965 and 1975, prestressed concrete bridges accounted for roughly 75 percent of all bridges built. During the second half of the 20th century, post-tensioned segmental bridges became more prominent as wealthier countries looked toward labor-saving methods due to rising labor costs; the standardized construction style allowed for a reduction in man-hours during construction [20]. Post-tensioned concrete became more economical than other methods for long spans, leading to further research and development of the technology.

Post-tensioning was introduced to the United States in the mid 20th century. Gustave Magnel, a Belgian engineer, and Charles Zollman, Magnel's student, designed

the first major post-tensioned concrete bridge, The Walnut Lane Bridge, in Philadelphia, PA [19]. The proposed design utilized 160 ft spans. The City of Philadelphia was hesitant about such a substantial span, so they required a full-scale test of the post-tensioned beam. The test was conducted in October of 1949 and was attended by over 300 engineers from five different countries. To the amazement of the engineers, Mangel correctly predicted the behavior of the girder during each loading phase and foretold the favorable outcome of the load test [21].

Despite early success, some issues arose during the implementation of PT bridges throughout the world. In 1977, the UK banned the use of exterior post-tensioning due to corrosion issues [22]. After the UK banned the use of post-tensioned concrete bridges, multiple countries including the UK, France, Switzerland, and Austria performed detailed investigations on the PT bridge inventory [23]. Although the majority of bridges were in serviceable condition, all countries found instances of tendon corrosion in some bridges. At the Segmental Concrete Bridge Conference in Kansas City, Missouri in 1982, it was recognized that the grouting of post-tensioned tendons was becoming a major issue in Europe. It was well known in the group that special attention was necessary regarding the grouting materials and techniques to provide durable structures to the public [20].

Proper grouting procedures are necessary to construct a robust structure. Improper grouting is the most common problem leading to the corrosion of bonded post-tensioned tendons in bridges [9]. Grouting is a critical component of the construction and is essential to achieving a corrosion resistant structure. Competent grouting operators and inspectors are necessary to provide an adequate product. ASBI and PTI offer training classes to provide opportunities to learn best grouting practices. Requiring foremen, grout operators, and even owners and managers to enroll in training classes can greatly reduce improper grouting.

Both the design and installation of the grout must meet requirements to have a successful structure. Prepackaged grout mixtures provide a mixture design required to meet the PTI M55.1-12(13) specifications. Still, if the procedures are not completed properly, improper grouting can occur. One common issue is the over addition of water during construction [24]. Too much water in the mixture may allow the grout to flow and pump easier, however, the increase in water leads to an increase in bleed water resulting

in voids throughout the ducts. Proper design and construction are necessary to produce long-lasting structures. The optimal grout mixture is insufficient if it is not placed following proper grouting procedures. Improvements to PT grouted tendons cannot be achieved by any single action but by a combination of consistent high performing materials, grouting techniques, grouting equipment, and QA/QC systems [13].

A review of reported cases of corrosion in prestressed concrete bridges indicates that sources of corrosion issues are typically traceable to two problems: poor design or poor construction. Most problems in prestressed concrete structures result from avoidable issues and inherent durability related deficiencies of these structures are extremely rare [25]. The most common grout related issues are attributed to incomplete grouting. The problem could be small voids or a complete lack of grout. Many problems can contribute to the lack of grout in the duct including: improper construction practices, improper placement or usage of vents, or unforeseen construction difficulties. Fresh properties of the grout affect the grouting process, especially fluidity. Insufficient fluidity leads to difficulty pumping the grout which may result in grout operators resorting to adding additional water beyond the approved range for the material or blockages during pumping. Over watering the grout causes bleed water, leading to the formation of voids. The presence of voids increases the likelihood of corrosion, especially in the presence of moisture, oxygen, and chlorides. The effectiveness of the grout for corrosion protection is dependent on the properties and the placement of the grout; poor grouting will reduce the ability of the grout to resist corrosion. Isecke and Schupack have found the most severe corrosion occurs when the tendon is sporadically exposed then surrounded by grout [26].

Isecke examined a bonded post-tensioned bridge in Germany after it was demolished due to corrosion related deterioration. In the bridge, he found multiple levels of grouting. Tendons were found fully grouted, partially grouted, and not grouted at all. The fully grouted tendons were still in good condition. The tendons with no grout were rusted along the outside of the strand (uniform surface corrosion), however they seemed to be performing well. Tendons with partial grouting had the most severe corrosion at the edges between exposed and embedded steel [26]. Fully grouted areas surround the steel in a high pH environment while voided areas leave the steel unprotected. Having these two areas adjacent on the same strand can form a local corrosion cell, resulting in

accelerated corrosion. When Schupack examined a 35-year-old post-tensioned bridge, corrosion of the tendons was attributed to poor and incomplete grouting as well [27]. Even though the corrosion was not significant enough to deem the bridge structurally deficient at the time, if not repaired, it may have led to a catastrophe as is the case for the YNS-Y-GWAS bridge discussed in the next section.

2.1.1. Collapse of YNS-Y-GWAS Bridge

The YNS-Y-GWAS Bridge in South Wales over the River Afon, collapsed without warning on December 4, 1985. The bridge, which was built in 1953 had been routinely inspected, with no concerning issues reported. The bridge was even specially inspected in 1981 before an oversized load was allowed across the bridge. The inspections did not discover any indications of corrosion. However, it failed suddenly without any excess loading [4]. After the collapse, the investigation of the bridge remains found severe corrosion of the steel at the joints of the bridge. Corrosion of the steel strand was caused by inadequate protection at the joints; grout leakage during construction was determined to be the primary cause. The voided tendons exposed the steel strands to chlorides from de-icing salts used on the deck to the steel strands. The chlorides penetrated the duct, which lead to the corrosion of the steel strands and eventual collapse of the bridge. It is important to note that this bridge had dry joints, that is, joints that were not epoxied to mitigate potential moisture and chloride ingress.

In the years following the collapse of the YNS-Y-GWAS Bridge, corrosion came to the forefront of PT bridge problems and many countries reconsidered the use of PT bridges. France discontinued use of segmental bridges after five cases of rupture of external tendons protected by cementitious grout in nine years [28]. The average age of the failed tendons was only 15 years. The UK introduced a ban in 1992 on all PT concrete bridges until new standards and procedures were implemented [22]. These bans have since been reinstated after development of specifications by the Federation internationale du beton (fib), also known as the International Federation for Structural Concrete. A decade after the YNS-Y-GWAS collapse, the United States also discovered issues with failed tendons in several bridges, primarily in aggressive environments such as coastal parts of Florida.

2.1.2. Niles Channel Bridge

The Niles Channel Bridge is a 4,500 ft bridge made up of segmental precast post-tensioned concrete box beams. The tendons are made up of 19 strands inside a polyethylene duct. During a routine inspection, it was found that spalling concrete had exposed a wedge plate. Further investigation by Powers revealed all 19 strands had separated due to corrosion at that point [5]. The extent of the tendon corrosion is shown in Figure 2.2.



Figure 2.2 Corroded end-cap from a Niles Channel Bridge tendon [29]

The corrosion evaluation determined the upper trumpet (reference Figure 1.1) circumference had not been in contact with grout, merely grout bleed water. Although the failed tendon was demolished prior to the investigation, subsequent random hammer sounding and visual inspection revealed a high incidence of bleed water and voids in the grout.

2.1.3. Midbay Bridge

The Midbay Bridge is a concrete segmental box structure with external post-tensioned tendons. The bridge utilized 4-inch diameter polyethylene tendons, one containing 19 0.5-inch diameter strands and the other with 27 0.5-inch strands [6]. During construction, the tendons were stressed, and the ducts filled with a cementitious grout to protect the steel. Nondestructive testing was performed using a method developed by the University of Wisconsin Milwaukee based on magnetic flux leakage. During the testing of the tendons, two tendons were found to have corrosion issues [6]. Figure 2.3 shows the corroded tendon with the deviator pipe blown out after its failure.



Figure 2.3 Midbay Bridge tendon failure [30]

The corrosion of the strands was determined to come from water and oxygen entering the duct through a hole. The reason for the hole was speculative; however, the failure of two systems, both the duct and the grout, led to the corrosion.

2.1.4. Sunshine Skyway

The Sunshine Skyway Bridge is located over lower Tampa Bay on the west coast of Florida. The 4.1-mile bridge is constructed of post-tensioned segmental box girders and a cable-stayed midspan. The expected life span of the bridge was 100 years with proper maintenance. Severe corrosion, however, was found in one of the columns.

Further investigation found grout containing salt water in 28 of the high-level approach columns [8], [31]. Figure 2.4 shows the severity of the corrosion caused by the chlorides in the mix water.



Figure 2.4 Corroded tendon found in Sunshine Skyway [30]

It was found that grout had been contaminated with chlorides and a significant number of vertical polyethylene ducts had cracks or hollow surrounding areas. Due to the findings of the investigations, the research team recommended a universal repair plan to reach the bridge's original 100-year service life goal.

2.1.5. Varina Enon Bridge

The Varina Enon Bridge was completed in Virginia in 1990. The bridge was approximately 630 ft long with 480 grouted tendons in the superstructure. In 2001, voids were found in many tendons during an inspection of the bridge, leaving the tendons unprotected. Vacuum grouting was used to fill the voids in 2004. Although the strands were not found to be corroded in 2001 and the voids were eventually grouted, a tendon failed in 2007 [7]. Two of the tendons were replaced, including the tendon shown in Figure 2.5, and 20 tendon sites were inspected using destructive measures. Eleven of the twenty sites investigated were found to have various levels of corrosion.



Figure 2.5 Corroded tendon from Verina Enon Bridge [32]

In 2011, it was determined that the grout used in the tendons contained chlorides. Another problem revealed during the investigations was the water-to-cement ratio (w/c) found in the tendons of the bridge exceeded 0.60 [7]. Typically, the recommended water to cement ratio is less than 0.30 meaning that the water content of the grout was more than double than the qualifying mix design. This exemplifies the need to ensure batching and construction practices are performed to the specified level.

Since the discovery of multiple severe tendon failures in bridges, research efforts have been put forth to solve bleeding and voiding issues in cementitious grout and to better understand the variables affecting the cause of corrosion and long-term durability of the structure.

2.2. Durability

Durability is the ability of a structure to withstand various forms of attack during its service life including weathering, chemical attack, corrosion, abrasion, or any other

form of deterioration [25]. Traditional civil engineering curriculum does not tend to emphasize durability in proportion to the amount of damage that poor durability design can cause. Many graduating engineers have limited background on applying comprehensive durability concepts to their structural designs. Overall infrastructure durability is a pressing issue in the United States. The American Society of Civil Engineers (ASCE) rates bridges at C+ overall [33]. Of the 614,387 bridges in the National Bridge Inventory, about 9% are deemed structurally deficient. It should be noted that only 3% of the structurally deficient bridges in the United States are prestressed concrete bridges [34].

Grouting problems have been found in multiple PT bridges over the last several decades, diminishing the system's resilience to corrosion. In most instances, the failure of the tendons was due to excessive bleed water in the ducts. The water remained or eventually evaporated, leaving voids in the ducts, which allowed chlorides more direct access to the steel. Chlorides are present in coastal marine environments as well as in northern environments where de-icing salts are used on bridges. Chlorides often combine with moisture, from rain or melting snow, to seep into the structure through joints, anchors, or other potential weak points. Temperature and humidity also play a role, where increases in temperature or humidity have an acceleration effect on corrosion [25].

2.3. Corrosion

Corrosion in concrete occurs in two stages [25]. The first being the initiation of corrosion and the second being the propagation of the corrosion. The initiation of corrosion occurs as atmospheric carbon dioxide or chlorides penetrate the concrete causing depassivation of the steel. With today's high-quality concrete, carbon dioxide effects (carbonization) are typically minimal compared to chloride induced corrosion. Penetration of chlorides is accelerated through cracks or any other potential direct ingress points. Chlorides are one of the most significant factors in the corrosion of steel, yet the specific details around the role of chlorides in a reinforced concrete system is not entirely known. Chloride ions may disperse the passive film, make the film permeable to all ions, penetrate the passive film, or reduce the pH making the passive film unstable. It is known

that the concentration of chlorides in the concrete causes a shift in half-cell potential measurements [25].

Cementitious grout provides the last line of defense in the PT system against corrosion. Grout provides a passive (high pH) environment that is good for corrosion protection of steel, by forming an alkaline environment around the strands. The high pH allows for a passive film of iron oxides to form on the steel, protecting the strands from corrosion. Therefore, for corrosion to occur, the passive film must first be penetrated. Then water and oxygen must be present at the cathode and the ionic diffusion between the anode and cathode may not be resisted by the concrete. This process creates a corrosion cell [25].

A basic corrosion cell in concrete is made up of three main elements: an anode, cathode, and electrolytes [25]. An anode is the location that loses metal, a cathode is the location of oxygen reduction and the electrolyte is the conductive medium in which the corrosion takes place. The free moisture in the concrete acts as the electrolyte. The anode and cathode must be connected electrically for the charge transfer to occur. Microcells and macrocells are the occurring corrosion cells. A microcell consists of anodes and cathodes that may only be a micron apart, while corrosion macrocells consist of anodic and cathodic regions separated by larger distances along the length of the steel or reinforcement cage. Macrocells can develop on a single bar or different areas of the structure that are electrically connected. Bonded PT provides the opportunity to electrically isolate the prestressing system from the rest of the structure, depending on the materials used in the duct and anchorage areas.

Corrosion can affect the prestressing strand disproportionately compared to mild steel [25]. The geometry of the prestressing steel strand can increase the effect of corrosion both in material loss and in potential failure mechanism. Seven wire strands have a higher surface area to cross sectional area ratio than a typical steel reinforcement of the same diameter, making it more susceptible to corrosion per unit of cross-sectional area. Secondly, the configuration of the strand may allow water to migrate easier through strand interstices than it would through solid grout, causing a wicking action that can transport aggressive agents more rapidly along the length of the tendon. This same wicking action can amplify bleeding behavior in the grout prior to set. Also, the

configuration of the strand is more conducive to crevice corrosion. This type of corrosion occurs in small spaces, such as the space between the wires. These crevices also enhance the formation of chloride ion concentration cells. Since high strength prestressing steel requires less cross-sectional area in the member than mild steel reinforcement, the loss of cross section due to corrosion of one strand will have a more significant effect on the capacity of the member than the loss of a mild steel bar. High strength steel may be more prone to stress cracking, hydrogen embrittlement, and corrosion fatigue, which are difficult to detect in tendons in the field. With an increase in susceptibility to corrosion of the seven-wire prestressing strand and the potential for sudden failure depending on the type of system and cause of the corrosion, it is of the utmost importance to make sure the strand is protected from the ingress of moisture and chlorides.

The mechanisms of corrosion are important; however, the rate of corrosion drives the service life of a structure susceptible to corrosion. Inspections of bridges across the US and the world have found the presence of chlorides, moisture, voids and even damage in the tendons. These conditions can lead to an accelerated corrosion of the strands. The acceleration of corrosion becomes an issue because it happens so quickly that the steel can degrade to a point where the bridge is no longer serviceable in a short amount of time leading to costly remediation and repairs. The rate of corrosion is a function of many factors; including the presence of moisture and oxygen, concrete permeability and resistivity, gradients in chloride ion concentration, pH of the concrete's pore water, carbonation, and stray currents. The corrosion product (rust) itself can limit oxygen to the system, changing the corrosion rate.

Recently, research was published to develop a framework to predict the time variant service reliability index, $\beta(x,t)$, of post-tensioned segmental concrete bridges subjected to various structural loading and corrosive exposure conditions [35]. The generalized reliability index, β , is considered a quantitative measure for the safety or serviceability of structural systems. The framework accounts for (1) uncertainties in the tensile capacity and prestress loss, void conditions and damage condition of the tendons, compressive strength and unit weight of the concrete and live load conditions, (2) the effects of different levels of corrosion induced loss in the tension capacity of strands, and (3) the redistribution of loads upon tension failure or complete corrosion of a strand. With

the aforementioned variables, a value of $\beta(x,t)$ was estimated and used as a serviceability indicator for PT bridges. The target reliability index was calculated using acceptable levels of safety and the structure can be evaluated. This research provides a potential indicator of the structures serviceability after tendons have been compromised. However, the non-uniform nature of PT bridge corrosion even in similar environments and the inability to visually access each tendon make this type of prediction potentially non-conservative. It is far better to assure the best possible system from the beginning.

2.4. Materials

The corrosion protection for the system relies on several components including the surrounding concrete, duct, grout, and anchorage protection. Figure 1.1 shows a basic PT anchorage system.

Grout is pumped into the ducts to protect the strand after stressing. Research has been conducted to develop grout mixtures and testing procedures to assure good quality grout is placed in PT ducts. Improvements have been made over the last 20 years in developing proper guidelines and specifications to provide uniform quality grout.

2.4.1. Concrete

Concrete typically forms the first barrier against the ingress of corrosive agents to the steel. In addition to providing a physical barrier, concrete provides a high pH environment as discussed in proceeding sections. The effectiveness of the concrete depends on the concrete material properties and the design and construction practices used. Cracks are the primary path for chloride ingress in concrete. Prestressed concrete has the advantage over mild reinforced concrete in that cracks are typically not an issue due to the induced active compressive stress in the concrete.

2.4.2. Strands

There are two main problems specific to prestressed steel in comparison to mild steel. First, prestressed steel is continuously stressed to 55%-65% of its ultimate tensile strength with a temporary increase as the strands are initially stressed [36] and that fluctuates as load is applied and removed. Thus, loss of cross section (due to corrosion)

increases net tension stress and can lead to local yielding and fracture. In a seven-wire strand configuration, a single wire in the strand can fracture, transferring load to the remaining strands (which may also be corroded). Likewise, with strands bundled in tendons in the same environment, the likelihood that additional strands in the same tendon are susceptible to corrosion is higher. With progressive wire fracture, and potential full strand fracture, the possibility of tendon failure becomes part of a progressive chain as loads are transferred to remaining strands [37]. Secondly, the strength of prestressing steel is four to five times higher than that of mild reinforcing steel. Therefore, smaller diameter reinforcement is typically used, further reduced into 7 individual wires per strand. Thus, the smaller diameter PT strands lose relative cross-sectional area faster than mild bars at the equivalent corrosion rate.

Codes such as AASHTO LRFD Design and Construction specifications as well as ACI 301 and ACI 318 provide standard specifications and code requirements for PT strands. The post-tensioning tendon is typically made using high strength seven-wire prestressing strand. To increase the protection of the strands, epoxy coated steel or stainless steel have been considered. Another material considered for strands is fiber reinforced polymers (FRP).

Steel strands can have an added layer of protection with the addition of an epoxy coat. An epoxy coated strand is applied in two configurations: coated or coated and filled. The coated and filled method surrounds the strands with epoxy and is in the middle of the individual wires. This prevents a wicking effect during pumping and the migration of moisture and chlorides along the strand [25]. Due to the nature of the strand, the forces within it, and the role it plays in the structural system, the additional layer of protection should be considered. However, the epoxy coating can prove challenging at the anchors, as wedges need to be able to accommodate the additional coating to bite into the strand [25]. Additionally, the anchorage area can become a weak point for chlorides to reach the steel at the area where wedges have penetrated the coating.

Kalina performed a study on mechanical and corrosion resistance properties of bridge post-tensioning strands [38]. Conventional steel strands, hot dipped galvanized strands, stainless steel strands, copper-clad strands, stainless-clad strands, and flow-filled epoxy-coated strands were all tested. The epoxy-coated strand “dominated” in

comparison to the others during corrosion resistance testing. The stainless-steel strand was only slightly less effective in corrosion resistance but did not meet any of the requirements for mechanical properties, deeming the material insufficient.

Fiber reinforced polymers (FRP) have also been studied. The advantage of using FRP composites is that they are not susceptible to corrosion. A study of scaled models found that carbon fiber reinforced polymers are feasible as a steel replacement in post-tensioned bridges [39]. However, for the same size strand, their elasticity was less than steel, meaning the bridge had higher deflections and more flexibility. Also, the production and constructability of the FRP strands is more difficult than steel.

Overall, unlike in traditional steel reinforced concrete, alternate metals or coatings have not gained a foothold in the prestressing market. The vast majority of prestressed structures utilize black steel.

2.4.3. Ducts

The post-tensioned duct provides several functions. It's first purpose is to provide the void in the concrete to place the strands for internal tendons. Another important function of the duct is to act as one of the layers of corrosion protection. The duct works as a barrier when an impervious material is used in addition to watertight splices and connections to the anchorage [25].

If the duct is not properly constructed, corrosion of the strand may be expedited. Incidents of corrosion have been found where pathways for moisture and chlorides have been able to penetrate, such as damaged ducts, improper splices between ducts, and corroded ducts which were not intended to be used as permanent ducts [25]. Generally, deterioration of the duct corresponds to severe corrosion and occasionally fracture of the prestressing steel tendon due to chlorides being able to penetrate the grout. Since grouting happens after strand stressing, the grout itself is not prestressed. Cracked grout is not unusual, so when the duct barrier is gone (often accompanied by spalled or heavily cracked concrete), chlorides can penetrate through cracks or reach the strand directly in the presence of voids [17].

Galvanized steel ducts were commonly used prior to 2000, but they presented various issues [40]. While the steel is strong enough to serve as a duct, the corrosion

resistance is inadequate, and galvanization only provides a finite layer of protection for the steel duct. Research and field performance testing have found that corrosion damage is imminent in the presence of moisture, oxygen and chlorides. Crimped seams and splices for galvanized steel ducts are not water-tight or water-proof, allowing for the ingress of moisture. Once moisture gets into the duct, the duct acts as a pathway for the moisture to move along the tendon. Steel ducts should not be used in situations in which exposure to deicing salts or sea water is probable. Instead, plastic ducts should be used in these conditions [25].

Unlike steel ducts, plastic duct systems can provide the highest level of corrosion protection for PT tendons [36]. Plastic ducts, introduced in the early 1990's, are non-corroding and provide an impermeable barrier to the steel. An impermeable duct also can provide tendon encapsulation with full grouting and sealed end caps. This electrical isolation can protect the system from corrosion induced by stray currents in addition to aggressive agents. Added benefits of plastic ducts also include lower friction losses and reduced fretting fatigue in the strand when compared to steel ducts [25]. Properly specified structural plastic ducts have proven to supply sufficient strength, rigidity, abrasion resistance, and bond properties to satisfy performance requirements [36]. The use of watertight and airtight ducts also allows for the use of vacuum grouting for repair of voids, which applies a negative pressure at one end of the duct while the grout is pumped. Overall, robust plastic ducts are superior to steel ducts and should be used in all new exterior PT construction.

2.4.4. Anchorage

PT anchorages and ends (tails) of strands must be protected from corrosion throughout the entire life of the structure, beginning at construction. During construction, contaminants need to be prevented from entering the duct prior to grouting and capping of the anchors. Inadequate protection of the anchors after grouting could be due to lack of cover, filling the anchorage recess with permeable materials, or insufficient bonding between the fill material and the anchorage recess. An ingress of moisture and chlorides can be found where inadequate anchorage protection is used [26]. This, combined with poorly grouted ducts, allows the moisture to move along the length of the tendon.

Attention to detailing and a thorough maintenance plan of the joints can retard the ingress of chlorides and moisture from contacting the anchorage zones. Isecke inspected anchorages of a post-tensioned bridge and found multiple unprotected anchors [26]. At the locations where chloride filled moisture ran off the deck, the anchorages were severely corroded, and the PT bars were also heavily corroded. On the other hand, anchors without deck runoff did not experience any corrosion. In a bonded post-tensioned system, the anchorage corrosion may not be failure critical as the bond between the strands and concrete will still allow for a transfer of stress, preventing a complete loss of prestressing. However, in a segmental bridge using external tendons, for example, the grouted system acts unbonded (except at the anchors and deviator points). Therefore, measures should be taken to prevent the ingress of moisture and chlorides at anchorage locations through proper detailing for runoff as well as anchorage protection layers. If corrosion occurs in the external tendons, there is potential for sudden failure of the strands.

2.4.5. Unbonded/Flexible Fillers

Due to the strand failures in the US and Europe, flexible fillers are gaining traction in the PT bridge industry as an alternative to cementitious grout [3]. Although more common in Europe, flexible fillers such as wax, petroleum gel, and grease were also recently implemented in Florida. These flexible fillers provide corrosion protection without bond to the duct or structure and are thus referred to as unbonded. Flexible fillers are pumped into the tendons at the anchor caps or a pipe saddle, similarly to grouted tendons. As shown in Figure 2.6, the wax filled tendon uses the same concept as grouted tendons. Wax is heated and pumped into the tendons to cover the strands as a physical barrier between potential oxygen, moisture, and chlorides.



Figure 2.6 Tendon injected with wax

Flexible fillers have an advantage when there is a need to adjust prestressing forces in tendons or completely replace tendons (i.e. deck replacement) because the unbonded strand is more easily replaceable. It should be noted, that flexible fillers need to be heated to allow them to flow and completely fill the duct. It is imperative that the filler be kept at an elevated temperature throughout the pumping process. Heating the fillers may cause other issues and cooling of the filler during pumping can lead to a blockage of the duct [3]. Duct blockages can increase the pressure in the duct, leading to damage of the duct.

Inspection techniques for flexible fillers differ from grouted tendons. The use of flexible fillers has opened up the opportunities to utilize monitoring methods not possible with rigid fillers [3]. However, unbonded or flexible fillers are not immune to construction deficiencies of their own. Robson and Brooman reported corrosion related distress in a bridge which utilized 240 tendons in a plastic grease filled sheath. After 20 years of service life, two tendons failed completely, and wire fracture was found in 121 of the remaining tendons. The wire failures and fractures were found to be due to the corrosion in anchorage zones [41]. The corrosion was attributed to a ten-month construction delay during which the tendon ends were left unprotected. The failure of the tendons demonstrates how imperative corrosion sensitive construction practices are.

Grouted bonded tendons still offer several advantages over unbonded tendons including a protective alkaline environment, more structural redundancy, and greater

ultimate structure strength leading to a potentially more efficient design [41]. Also, the post-tensioning operation during constructions costs 15% to 26% more for flexible fillers than similar grouted systems, leading to an increase in superstructure cost [42]. With the uncertainty of flexible fillers and the evidence of successful grouting, cementitious grouting is still the preferred method for strand protection in the United States.

2.4.6. Grout

Portland cement grouts have been used since the 1950's in post-tensioning [43]. Grout offers the ability to bond the PT tendon to the surrounding concrete member and to protect the steel strands from corrosion caused by the infiltration of chlorides into the ducts. The grout provides a physical barrier from moisture and chloride penetration and the provides an alkaline environment to form a layer of passive film of iron hydroxides around the steel [36]. The ability to bond concrete structures to the prestressing steel also provides multiple benefits. Bonded structures allow for an increase of the prestressing force in a cracked section and allow the steel to reach the yield or ultimate strength at discrete locations. This has positive effects on the strength of the section, crack distribution in the member, and the energy dissipation of the member [23]. Grout also prevents a complete loss of prestress if the anchor fails (as was the case in the grease filled bridge tendon described previously), by providing a bond between the strand and the concrete, allowing a local defect in the tendon to remain local.

High performance grouts have been developed using fresh property testing, accelerated exposure testing, and large-scale pumping [9]. Important fresh grout properties include: increased fluidity, bleed resistance, decreased volume change, and longer setting time. Fresh grout properties are determined by water to cementitious ratio (w/cm), chemical and mineral admixtures, and cement type; the best grout for post-tensioning combines appropriate fresh properties for ease of placement and long-term performance. One beneficial grout property is thixotropy. Thixotropic grout has the property to stiffen when at rest and to become more fluid as it is agitated [13]. The advantage being the grout has a perpendicular head as it is pumped, thus avoiding the formation of voids due to air trapped by backflow in addition to its anti-bleed property. Corrosion protection and fresh properties require careful consideration during the grout's

design process. The use of high-performance grouts in conjunction with proper construction practices can lead to well protected tendons such as the tendon shown in Figure 2.7.



Figure 2.7 Tendon adequately full of grout

PTI offers guide specifications for grouts for post-tensioning including information on mixture proportioning and admixtures. PTI recognizes four classes of grout: A, B, C, and D. Class A grout is a simple grout made of cement and water, Class B grout allows admixtures, and Class C grouts are prepackaged grouts. In Class D grout mixtures, the engineer specifies the grout design, including the proportions of portland cement, other cementitious materials, water, and chemical admixtures. The specific design requirements and testing procedures for each class are specified in PTI Specification for Grouting of Post-Tensioned Structures [1].

2.4.6.1. Cementitious Materials

Cementitious grout has a long track record of its success when properly used; cementitious grout and prestressing steel have proven to be very compatible in structures over time. Most grout used in construction prior to the 1990's has been a simple mixture of portland cement and water, sometimes containing an expansive agent that was thought to help counteract bleed [44]. Recently, grout with supplemental cementitious materials

and chemical admixtures have been used, especially in aggressive environments such as coastal regions and northern climates where chlorides or sulfates are common. These high-performance grout mixtures are formulated to allow smoother construction processes with reduced chance of bleeding and voids in the grout when properly implemented. ASTM C150 Type I and Type II cement are currently allowed in grout by PTI M55.1. It should be noted that cement of one particular source or supplier should be used for one particular mix [23]. This assures a reasonably small range of cement particle size and chemical composition leading to consistent grout properties.

2.4.6.1.1. ASTM C150

Five different types of cement are classified in ASTM C150 which defines portland cement as “a hydraulic cement produced by pulverizing clinker consisting essentially of hydraulic calcium silicates, usually containing one or more forms of calcium sulfate as an interground addition.” Most grouts utilize Type I, II, and III cement. Currently PTI 55.1 only allows Type I and II cements for post-tensioned structures.

2.4.6.1.2. Pozzolans

Research has shown that the presence of pozzolans can increase compressive strength, reduce bleed, and reduce permeability. Silica fume is often used in prepackaged grout mixes. One tradeoff, however is that workability of the mixture is sacrificed, therefore superplasticizer must be added to maintain fluidity [9]. Fly ash has similar effects on grout as silica fume but to a lesser degree. One difference between fly ash and silica fume is water requirements are reduced when fly ash is used, due to the dispersion and deflocculating of the cement particles, this effect also reduces the dosage of superplasticizer needed.

2.4.6.2. Admixtures

Chemical admixtures are typically liquids, sometimes powders, that are used to manipulate the fresh and hardened properties of grouts. Admixtures can influence set control, water reduction, air-entrainment, bleed control, volume control, corrosion inhibition, and pumpability [1]. Set-controlling admixtures such as superplasticizers can greatly extend the time the grout stays fluid and can be used to maintain a desired fluidity

with a significantly lower water content than without it. It should be noted that these high-range water reducing admixtures have been shown to increase bleed in grouts of the same water to cement ratio. While air-entraining admixtures are allowed to be used in PT grouting, no strong evidence has shown freeze-thaw damage of the grout has been an issue in PT grouts.

Anti-bleed admixtures are permitted in grout and typically are necessary to pass required test parameters for most bridge applications. There is currently no standard specification requiring the use of anti-bleed admixtures in grout. The only standard is that grouts must be able to pass performance requirements for minimal bleed. The standard for grout permits expansion causing admixtures. For corrosion concerns, PTI suggests avoiding any gas forming systems as they have been proven to produce detrimental effects [1]. Corrosion inhibitors have been shown to mitigate steel corrosion in traditional reinforced concrete and are permitted by PTI specifications as long as results for the Accelerated Corrosion Test are included and the dosage is correctly used for grout applications. Typically, a good bleed resistant grout and robust duct/anchor protection system is a better investment than adding a corrosion inhibitor to the grout. PTI's Specification for Grouting of Post-Tensioned Structures details the affects admixtures have on grout in more detail than summarized here. Overall, the addition of admixtures can positively affect the properties of the grout mixtures as long as the proper proportions and combinations are used and tested in advance of field use.

2.4.6.3. Water to Cement Ratios

The water to cement ratio is the main contributing factor to the grout's fresh properties. In the 1960's when the majority of grouts were a simple mixture of water and cement, water-cement ratios (w/c) typically specified were between 0.47 and 0.53 [1]. In general, these grouts seem to be performing satisfactorily. As grouts were used in more aggressive environments, admixtures were used to reduce the chance of bleeding with these high w/c grouts. Generally, the lower the w/c, the lower the permeability of the grout and the amount of bleed water is reduced. The water to cement ratio is not directly proportional to bleed water, rather, there is a threshold at which bleed suddenly becomes significant and the amount of free water then increases the potential bleed volume [23].

With this being the case, the w/c still proves to be helpful as a consistent ratio for proportioning as the preliminary tests will indicate if the grout will perform as designed at a specific water content for a given cement.

Research was conducted suggesting high performance grouts with water-cement ratios of 0.4 [45] down to 0.33 [9] including various admixtures prior to the widespread introduction of prepackaged grouts. Grouts with low w/c tend to be more stable and less likely to bleed. Recently, prepackaged grouts have been specified by design engineers. The constituent materials and their proportions are typically unknown due to the proprietary nature of the product, so the true w/c is unknown. However, the water to solids ratio (w/s) is measurable. Each mixture has a w/s range required by the manufacturer and varies between mixtures. Typically, the manufacturer's recommended water to solids ratio is near 0.25. It is of the utmost importance that the amount of water in the batch during construction lies within the specified amount provided by the manufacturer since the recommended w/s range is used to prequalify grout performance.

Multiple properties, such as permeability, fluidity, bleed, and density are dependent on the water-cement ratio. Corrosion protection provided by uncracked solid grout is primarily related to its permeability [25]. Low permeability of grout inhibits the ingress of moisture and chlorides. Permeability of grouts can be lowered by reducing the water-cement ratio and/or inclusion of pozzolans. The selection of grout proportions and admixtures requires careful consideration of the properties described previously. Hamilton [46] discovered most prepackaged grouts are robust enough to pass bleed tests even when subjected to a 15 percent increase in w/s. However, too much water in the batch can lead to multiple issues with the grout; even causing soft grout or a porous hardened grout layer near the top of the duct with the over addition of water. Too little water in the grout typically results in lack of fluidity and difficulty in pumping.

2.4.6.4. Prepackaged Grout

For the last 15 years, prepackaged grout has made up the majority of the grout placed in tendons in the United States. Prepackaged grout allows grout manufacturers to engineer and produce a grout composition that can pass the specified performance tests. Prepackaged product manufacturers provide assurance of compliance with the physical

properties by producing an Independently Certified Laboratory report at least once per year. Prepackaged grout manufacturers must also implement a quality assurance program that can be employed to show quality control results when necessary. Quality control is particularly important when cement sources change. Hamilton [47] conducted research in 2014 that concluded that none of the commercially available prepacked PT grouts tested produced bleed or soft grout when the grout was mixed in accordance with manufacturer's recommendations and tested well before the printed bag expiration date. The main problem facing grout today is not the design of the grout, but rather, poor quality control on construction practices and grouting operations.

Prepackaged grout materials and proportions are largely unknown due to the proprietary nature of the product. This, along with the varying nature of cement, leads to difficulty testing the grout with design-based specifications, therefore performance-based criteria are better implemented. Performance criteria allow field testers to perform the tests without knowing the cement or admixture content, or size of the cement particles. Performance tests such as fluidity, wet density, and bleed tests are already required by PTI and are discussed further in the next section.

2.4.6.5. Properties and Testing

The viscosity and consistency of grout was judged visually in the field by experienced staff in the early days of grouting. Then, the requirement of the mud balance, flow cone, and other measurements were introduced to quantify the grout's properties. Since the ASBI/PTI grouting committee started in 2000, a series of standardized testing is required to ensure proper procedures are used. These tests must be performed during grout design, prior to field use, and during pumping to ensure the proper design and installation of the grout in the field. Many mixtures of grout are allowed under the specification, but all must meet performance requirements to be able to perform well in the field. PTI M55.1 [1] specifies eleven laboratory tests to ensure quality grout material. Laboratory trial batches of the proposed grout mixture must be prepared and tested using the same materials and equipment as the job site at least eight weeks in advance of scheduled grouting. Field testing is also required one week in advance of the initiation of production grouting. These tests consist of compressive strength, pumpability, and a wick

induced bleed test for Type A grout and grout strength, volume change, pumpability, and Schupack pressure bleed tests for Types B, C, and D grouts. If field mockup tests are required by the Design Engineer, the field trial tests shall be conducted at the same time. Production tests are also required, including a minimum of one pressure bleed test at the mixer, two mud balance tests per day, or when there is an apparent change in the grout, one strength test per day, and two fluidity tests (at inlet and outlet) every 2 hours.

2.4.6.5.1. Fluidity

Fluidity is the measure of how well the grout can flow or the ability of the grout to be pumped. An insufficient flow leads to difficulties during construction including poor pumpability and the potential for blockages leading to incomplete grouting. The viscosity of the grout can be lowered in two ways. Preferably, during design of the grout, viscosity can be reduced by the addition of a plasticizing admixture. The addition of water, which is unfortunately sometimes done unprescribed during the pumping process, can also reduce the viscosity of the grout. Grout that is too fluid due to water addition above the specified level can cause issues such as voids in crests of tendons resulting in incomplete grouting, as well as higher bleed potential. To decrease the chance of these issues, various testing procedures must be performed.

The flow cone provides a simple testing procedure used both in the lab and the field to determine the time of efflux for a specialized grout. Efflux time is the time it takes for the grout to evacuate the flow cone apparatus. Tests during field mockups are used to establish a range of flow times that are preferable for the grout (with w/s range given by the grout manufacturer) to be sufficiently pumpable in the field. PTI M55.1 specifies using a modified ASTM C939 test wherein the modification specifies “the flow cone shall be filled to the top instead of the standard level [48]. The efflux time of grout, when thoroughly mixed, shall be measured as the time to fill a 1L container placed directly below the flow cone” [1]. There is no required efflux time for grout provided by PTI M55. The only stipulation is the working time after 30 minutes must be within 10 seconds of the original efflux time after remixing for 30 seconds.

2.4.6.5.2. Volume Change

A reduction in volume change or shrinkage of the grout can lead to voids. Volume change is attributed to two effects: shrinkage and sedimentation. Sedimentation can lead to changes in volume up to a few percent and can be controlled by regulating bleed. Shrinkage, on the other hand, depends on the type of cement used and causes volume changes a full order of magnitude lower than sedimentation [23]. Thus, in a study, VSL determined shrinkage is negligible when considering the formation of voids. While sometimes it may be desirable to have an expansive grout to compensate for shrinkage, this is less of a concern than other issues because the grout may be “topped off” allowing voids to be filled from the top of the tendon if needed. Grout is measured for expansion using ASTM C1090 The Standard Test Method for Measuring Changes in Height of Cylindrical Specimens of Hydraulic Cement Grout [49]. The vertical height change must be 0.0% to less than +0.1% at 24 hours and less than 0.2% at 28 days. This test provides a quality assurance measure that the grout will not have unwarranted changes in volume after being pumped into the tendon.

2.4.6.5.3. Bleed and Voids

Bleed refers to the process in which individual particles in a fluid suspension of grout settle out of the solution, leaving excess water on the top of the settled solids [50]. Figure 2.8 shows the void left after the bleed water evaporates from the duct. Bleed is the leading cause of grout voids in ducts, increasing the risk of corrosion.

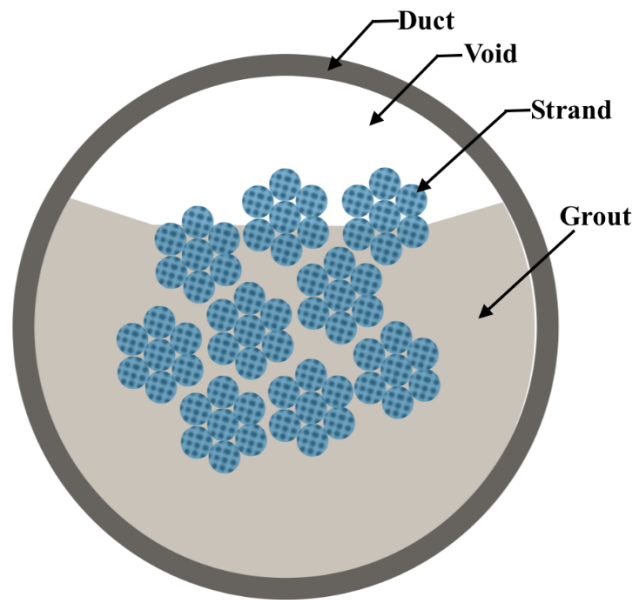


Figure 2.8 Grout Voids in Tendon

Voids in and of themselves do not damage the integrity of the structure, although extensive voids will not bond the strand to the concrete.

Many variables can lead to excess bleed water in the ducts. An increase in pressure within the duct can cause larger volumes of bleed water, especially in vertical applications such as grouted columns [51]. The geometry of the seven-wire strand heightens the process of bleeding by acting as a water transport mechanism [9]. The interstitial spaces between the strand wires allows for water to readily pass through and be filtered from the solids [17]. It should be noted that during the construction process the over addition of water leads to more water in the mixture than is needed to produce a flowable grout and for hydration. Excess water often leads to flocculation and settlement of cement particles, allowing water to move upwards and collect at the highpoints of the tendon. When the water evaporates, void formation occurs in the tendons. To reduce the effects of bleeding, the use of an anti-bleed admixture or gelling agent enables the grout to retain the water even in high pressure situations.

Grout bleed is one of the main reasons for durability problems in tendons. Corrosion was linked to the presence of voids caused by grout bleed water at the anchors of both the Niles Channel Bridge and the Mid Bay Bridges in Florida. Powers conducted

a study of the grout (Type 1 Portland Cement, 1% aluminum based expanding admixture, and 0.45 w/c) with respect to bleeding [52]. The findings showed severe localized corrosion in voids left by bleed water, even with little chlorides present. Additionally, grout tests in the lab showed modest vibration (similar to vibration induced by construction) greatly increased the amount of bleed water of the grout. Since the discovery of failed tendons in these bridges, research has been conducted to reduce the amount of bleed water during construction.

Resistance to bleeding is important for PT grouts. Anti-bleed admixtures, also known as thixotropic admixtures, produce gel-like properties to minimize bleeding while providing adequate fluidity when agitated during mixing and pumping. Three tests are required to assure the amount of bleed is minimized as specified in PTI Specification for Grouting of Post-Tensioned Structures including the wick induced bleed test, Schupack pressure bleed test and the inclined tube test. The wick induced bleed test must be used for Class A, B, C, and D grouts and the Schupack pressure bleed test must be performed per ASTM C1741 for Class B, C, and D grouts [1].

Since high pressure pumping increases the amount of bleed, a pressurized bleed test was developed by Schupack and later modified and developed as a specification by Schokker to simulate conditions where grout ducts experience high pressures (i.e. large changes in elevation) [51]. This test is used in the lab as a qualifying criterion and in the field to assure the proper w/s ratio is used in the ducts. ASTM C1741 Standard Test Method for Bleed Stability of Cementitious Post-Tensioning Tendon Grout is performed to verify the change of bleed at differing w/s ratios. The Schupack pressure bleed test requires the placement of grout in a pressure tube (shown in Figure 2.9) for 10 minutes, then the system is subjected to a specified pressure level within 30 seconds and held for five minutes [53].



Figure 2.9 Schupack Pressure Bleed test apparatus [53]

The pressure bleed limits using the pressure test are specified by PTI M55. For grout to meet these specifications an anti-bleed admixture is typically required.

2.4.6.5.4. Large Scale Incline Tube Testing

The inclined tube test is used to measure bleeding on a more realistic scale, this includes a representative volume of strands, where the grout bleeding must not exceed 0.3% of the initial volume of the grout after three hours. Large-scale inclined tube testing is intended to closely replicate what will be used in practice. The addition of prestressing steel significantly increases the amount of water collected at the high point [23]. The test tendon configuration, grout materials, and the equipment used must match the designed tendon in the field. The inclined tube test performed with the designed grout will detect any tendency of the grout to segregate in the duct, during or after the injection.

Even the use of high-performance grouts can result in bleeding if improper grouting procedures are used during the construction process. The over addition of water

in the field to make the grout more flowable can cause a strong increase in bleeding depending on the amount of available water. It is paramount that proper techniques, inspection, and monitoring are used during pumping of grout on the project.

2.4.6.5.5. Wet Density

The wet density provides an estimate of the amount of water used in the grout mix. Wet density of grout is a suitable predictor of bleed in a pretested grout because density and bleed are related to w/s for a given grout formulation [24]. The mud balance test is a simple test that can be used to ensure proper w/s of the grout. Measuring wet density immediately after mixing allows the inspector to compare the density to the expected values found during initial grout qualification tests. These results can be used to ensure the w/s ratio is between the manufacturers recommendations and falls below the bleed threshold. When the wet density at the end of the duct is compared to the wet density at the pump, the results can be compared to determine if additional moisture is added to the mix as it passes through the duct. The results should be close to identical; Hamilton found less than three percent change in the lab [47]. If they are not close to identical, the grout should continue to be pumped until the densities are reasonably close. Only one mud balance test is required at the end of one duct on a project. This could lead to water in other ducts going unnoticed. When Hamilton added 15% more water in the duct, the wet density, taken at the outlet, of all the grouts in the test matrix decreased by about 50% (near the unit weight of water). A change of this magnitude would be detrimental to the reliability of the grout protecting the structure, thus wet density monitoring is an important assessment.

When segregation and sedimentation occur (resulting from bleeding as discussed earlier), it can lead to a higher density grout near low points and a lower density grout at the high points of the duct. Therefore, densities measured at all locations (grout pump, inlet outlet, etc.) should be reasonably close.

The test equipment currently specified to measure wet density in the field is a Mud Scale. The mud balance test (in accordance with ANSI/API Mud Balance testing procedures) is used at the inlet and outlet of ducts to ensure the grout meets the range for the optimal grout as established in the laboratory. Down-falls of the test include: it is not

precise, it must be recalibrated or thoroughly cleaned often, and results can differ based on the testing technician. Also, the requirements for the test only specify testing twice per day or “when there is a visual or apparent change in the characteristics of the grout at the mixer.” This may not be enough testing to catch detrimental changes in the grout. With the limitations of the mud balance test, a more accurate and continuous density reading procedure should be developed.

The next step to increasing measurement accuracy during quality control of grout in the field is to perform and record in-line measurements throughout the pumping process. Twin Straight Tube Coriolis Mass Flowmeters can be used as in-line density meters allowing the measurement of wet density to be continuously measured and recorded at the inlet of each tendon. This mass flow meter is designed for the direct measurement of mass flow rate, product density, and product temperature [54]. An in-line density analyzer is more efficient and accurate than taking mud balance measurements. In-line measurements also allow for continuous recording of the wet density and records providing project managers, engineers, inspectors, and future researchers access to authentic data about the grout pumped into the tendons during construction.

2.4.6.5.6. Set Time

Set time needs to be considered but is not one of the defining properties of post-tensioning grout. Rapid setting grouts lead to issues during construction hindering placement. A grout that never sets, referred to as ‘soft grout,’ is not acceptable because the tendon is not bonded, and the material is of poor quality. PTI M55 specifies a setting time between three and twelve hours measured by ASTM C953 Standard Test Method for Time of Setting of Grouts for Preplaced Aggregate Concrete in the Laboratory [55]. Set time can be dependent on a number of factors including the particle size of the cement, admixtures used, and temperature. Set time tends to increase as the anti-bleed admixture dosage is increased, sometimes resulting in set times near the twelve-hour PTI M55 limit.

2.4.6.5.7. Strength

Strength of grout provides an indication of the quality of grout primarily as a basic indicator of issues with overwatering. High compressive strength does not necessarily benefit the performance of grout. PTI specifies a minimum compressive strength of 21MPa (3000psi) at 7 days and 35MPa (5000psi) at 28 days to assure sufficient bond between the prestressing steel and the structure. Although minimum strengths are stipulated, typical grouts that meet the other performance requirements usually far exceed these minimum strength requirements. VSL studied six mixtures of optimized grouts and found all prepackaged grouts tested at least doubled the required strength [23]. PTI M55 specifies ASTM C942, Compressive Strength of Grouts for Preplaced Aggregate Concrete in the Laboratory to test compressive strength [1], [56]. The specimens used for this test also provide a hardened sample that can be analyzed if questions arise about the grouting material immediately after grouting.

2.5. Specifications

2.5.1. PTI Specification for Grouting PT structures

After reported problems of four bridges in Florida, ASBI and PTI formed the grouting committee discussed previously. The purpose of the committee was to provide grouting guidelines, specifications, and training to eliminate the problems with corrosion in the tendons. In 2000, the grouting committee formed an interim statement on grouting practices. Since then, grouting specifications and annual trainings have been conducted by the groups. The specifications and grouting training sessions have been constantly improving with the increase of knowledge about grout as more research has been conducted.

The industry has accepted the standards to produce more durable structures; yet, some corrosion problems still arise apart from the grouting procedure. Two critical times that may lead to corrosion of the strand during construction are the time after the strands are placed before stressing and the time period after stressing but before grouting. During these periods, the tendon is not fully protected, and moisture and aggressive agents such as chlorides may be able to penetrate the duct if proper care is not taken during

construction to temporarily cap the ends of the ducts. To address these issues, proper construction and grouting plans must be prepared and implemented.

3. Experimental Plan

Through the literature review it is shown that the main cause of corrosion can be traced back to poor grout or poor grouting procedures. The literature review also highlights solutions to the problems related to grout design. The information for contractors and education of construction and inspection practices has increased dramatically, however the test requirements have seen less evolution. Flow cones, mud balances, and other test methods are nearly the same as they were 20 years ago. With the technology available today, easier and more efficient quality assurance and control measures are possible. New technology is needed in the field to help the inspectors and grout operators produce more consistent grout.

The goal of this research is to continuously measure the wet density of the grout by implementing an in-line density analyzer and develop or update specifications to include in-line density monitoring. Therefore, the tests conducted focus on the fresh properties of grout. The test matrix is shown in Table 3.1. Testing was conducted on two types of prepackaged grouts at various water contents to evaluate large volume mixing and pumping properties.

Table 3.1 Test Matrix

		Tests		
Grout	W/S	Flow Cone	Mud Balance	In-line density
1	A	x	x	x
	B	x	x	x
	C	x	x	x
	D	x	x	x
	E	x	x	x
	F	x	x	x
2	A	x	x	x
	B	x	x	x
	C	x	x	x
	D	x	x	x
	E	x	x	x
	F	x	x	x

The test plan, (summarized in Table 3.1) includes mixing full-scale batches in a high shear mixing commercial grout pump. During testing, the flow cone and wet density (mud balance) were measured. Throughout the pumping processes the in-line density was continuously monitored and recorded using a Krohne OPTIMASS 1400C S25 and mud balance tests were performed periodically during the pumping process and compared with the in-line density data.

3.1. Materials

3.1.1. Prepackaged PT Grout

Two types of Class C commercial PT grout were tested. Any reasonable formulation of grout (including non-prepackaged) could be used for the density correlation testing and the results are not intended to compare the two grouts. The goal of testing was to have grouts commonly used in the field tested at a wide range of water to

solids ratios to correlate the in-line meter results to mud balance results. The water demand varied based on the manufacturer’s dosage recommendations. Throughout testing, the recommended and maximum water dosages were tested as provided by the manufacturers. Testing was also conducted on the material at ten, twenty-five, forty-five and sixty-five percent over the manufacturer’s maximum suggested water dosage to determine the sensitivity and range of the density meter. These water contents are referred to as phases (A-F) of the tests.

Table 3.2 shows the water dosage used during testing. Mixtures were tested on various water dosages in accordance with Table 3.1, in order to verify the changes in the grouts’ properties due to various water contents. The findings are discussed in Chapter 4.

Table 3.2 Water Dosage

Dosage/Bag		Grout 1		Grout 2	
Phase	Water Content	Volume (gal)	w/s	Volume (gal)	w/s
A	Recommended	1.5	0.25	1.5	0.26
B	Maximum	1.7	0.28	1.6	0.28
C	Max + 10%	1.9	0.31	1.8	0.30
D	Max + 25%	2.1	0.35	2.0	0.35
E	Max + 45%	2.5	0.42	2.3	0.38
F	Max + 65%	2.8	0.47	2.6	0.43

3.2. Mixing Equipment

The grout plant used to prepare the mixtures is shown in Figure 3.1. The plant is equipped with a 22-gallon mixer to provide high shear mixing (rotating up to 3000 rpm), allowing complete wetting of the particles and adequate dispersion. The plant is outfitted with a 34-gallon agitator tank with a variable speed paddle mixer to prevent the grout from gelling up after initial high-shear mixing. The grout pump is connected directly to the agitator tank. The grout plant powers the components with electricity and hydraulics.



Figure 3.1 Grout Plant [57]

3.2.1. Mixing Procedure

The following procedure was used to mix the prepackaged PT grout.

1. Add required amount of water to mix tank
2. Turn on high shear mixer
3. Add one bag of grout at a time, at a rate of 20-30 seconds
4. Allow mixture of materials in mixer for two minutes after last bag is added to the tank
5. Transfer grout to the agitation tank and start the paddle mixer

Throughout the testing time frame, the grout was pumped through the Coriolis mass flowmeter then circulated back into the agitation tank. Once all the tests for the phase were completed and adequate data was collected from the flowmeter, the grout was pumped back into the high shear mixer. Then a pre-measured amount of water was mixed with the grout for 45 seconds using the high shear mixer to increase the grout's water content to the next testing dosage as shown in Table 3.2. The grout's fresh properties were then retested, and the process was repeated for all phases.

3.3. Experiments

The fresh properties of the grouts were measured to evaluate how varying w/s ratios affect the material's properties. The modified flow cone and density tests were performed in conjunction with the Coriolis mass flow meter as described in this section.

3.3.1. Flow Cone

A modified method of ASTM C939 Standard Test Method for Flow of Grout for Preplaced Aggregate Concrete (Flow Cone Method) [48] was performed in accordance with PTI M-55. The test method is used both in the field and in the lab to determine efflux time [1].



Figure 3.2 Flow Cone Apparatus [58]

The procedure used was as follows:

1. Moisten the inside of the flow cone (shown in Figure 3.2) with water, one minute before testing
2. Fill the apparatus to the top with grout within one minute of pumping
3. Remove stopper from bottom while starting the stopwatch
4. The efflux time, time to fill 1L container, was measured

3.3.2. Density

3.3.2.1. Mud Balance Test

The Mud Balance test was performed according to ANSI/API Mud Balance Test Standards. The grout was tested at the pump outlet four times for each phase at approximately five-minute intervals. A range of wet densities was measured for every phase and repeated for each phase of the test.

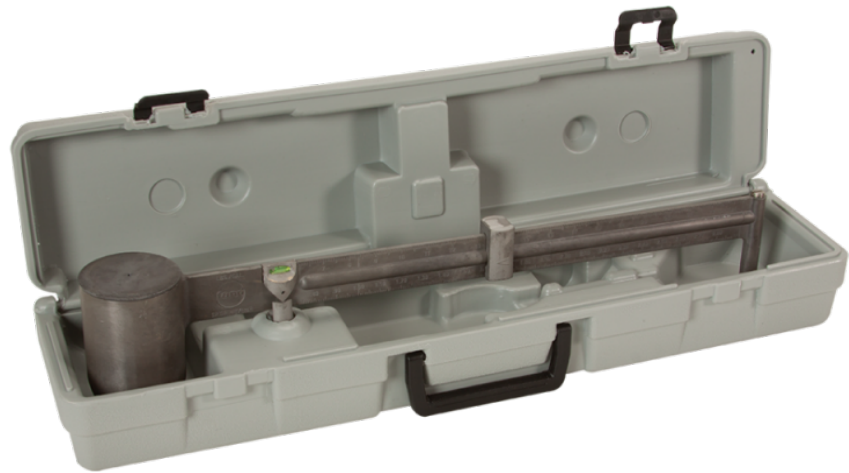


Figure 3.3 Mud Balance Apparatus [59]

The procedures for field testing are as follows:

1. Pour a sample of grout into the cup (shown in Figure 3.3)
2. Tap the side of the cup to ensure air bubbles rise to surface
3. Place cap onto cup and allow grout to flow out through the hole in the cap, ensuring the cup is completely filled
4. Place the mud balance assembly on the fulcrum on the case
5. Adjust the weight on the balance arm until level
6. Record the specific gravity of the grout

3.3.2.2. In-line Density Meter

The OPTIMASS flowmeter is a twin straight tube Coriolis mass flowmeter consisting of two measuring tubes, a drive coil, and two sensors positioned either side of

the drive coil. When the meter is energized, the drive coil vibrates the measuring tubes causing them to oscillate thus, producing a sine wave. The sine wave is monitored by the two sensors. As the grout passes through the tubes, the Coriolis effect causes a phase shift in the sine wave that is detected by the sensors. The phase shift is directly proportional to the mass flow. The density measurement is made by evaluation of the frequency of vibration between the sensors at the beginning and end of the tubes. Temperature is also recorded using a Pt500 sensor embedded in the meter. Live in-line density and temperature measurements provided live feedback on the grout; leading to better quality control. The meter was equipped with a data recorder. The data recorder recorded the measurements onto a micro SD card which was downloaded and analyzed. Continuous monitoring should alleviate the recent concerns of field grouting.

The in-line density meter used throughout testing is shown in Figure 3.4. The meter is placed in-line after the pump. The density, flow, and temperature of the grout was continuously monitored throughout the grouting process.



Figure 3.4 Coriolis mass flow meter [60]

4. Results and Analysis

This section contains test results obtained from the research. Reference Table 3.1 for tests performed on each specimen.

4.1. Fresh Property Test Results

The test results show how performance of the grout varied with water content. As the water dosage was increased, the results show the fluidity of the grout increased and the density of the grout decreased. The main goal of the fresh property testing was to determine if the in-line mass meter adequately measured the grout when compared to the mud balance results. All testing was conducted in a climate-controlled laboratory setting.

It should be noted that during the Test 1 of Grout 1, pressure on the pump started increasing dramatically. The grouting process was stopped after Phase E and the remaining grout was pumped out of the mixer. Residual hardened grout chunks were found deposited in the entrance to the mass flow meter, blocking it. Complete cleaning of the system was necessary. Screening the grout mix and diligent cleaning of all equipment is important for the grouting process to avoid blockages, and this is accentuated when the grout must also flow through the in-line meter. No further issues with blockage of the meter were encountered after Test 1. The test results up until the point of blockage are included and valid.

During the first test of Grout 2, anomalies in the fresh properties of the grout were noticed. After mixing challenges at the manufacturer's recommended water dosage, additional water was added to reach the maximum dosage specified by the manufacturer. During the beginning of the test the grout's temperature quickly rose above 90 degrees (see Figure 4.8) and the grout showed what appeared to be a flash set. The cause for the flash set was unknown as proper storage and handling procedures were followed and cold water was used. The grout was well within the manufacturer's use by date. Although the grout did not pass fluidity and pressure bleed tests and would not be sufficient for field use, the data from the mud balance and flowmeter still showed a strong correlation that proves useful. The results for Phase A of the test are shown as 'NA' because Phase A testing was not conducted. Due to the nature of the grout, it was deemed necessary to acquire new grout from a different batch to continue testing. The second round of testing on Grout 2 produced desirable results will be discussed later.

4.1.1. Flow Cone Test Results

The modified flow cone was performed at each phase for every test. Test results show a relationship between fluidity and w/s shown in Table 4.1. It can be seen that as the water content is increased, the efflux time decreases at a decreasing rate as the flow gets closer to that of water. The correlation between w/s and efflux time for the same prepackaged grout is not linear but does provide a relative indication of added water.

NA=not applicable

Table 4.1 Modified Flow Cone Test Results

W/S	Efflux Time (sec)			
	Grout 1, Test 1	Grout 1, Test 2	Grout 2, Test 1	Grout 2, Test 2
A	12.52	21.41	NA	+ 60
B	7.16	8.14	+ 60	48.00
C	5.84	6.97	+ 60	8.06
D	5.35	6.12	30	6.57
E	4.37	5.16	12.65	5.06
F	NA	4.34	9.68	4.91

A comparison between the first and second rounds of Grout 1 testing reveals that the incomplete mixing and clump formation of the first batch likely had an impact on the remaining water available for the fluid mix as evidenced by the change in flow cone results. Grout 2 had slower flow cone times than Grout 1, particularly at lower w/s, but did not exhibit any increased pumping difficulty compared to Grout 1 in the successful Grout 2 test.

4.1.2. Density

The wet density of the grout was measured two ways during the study.

4.1.2.1. Mud Balance Test Results

The mud balance was taken four times for each phase at approximately five-minute intervals. The grout's specific gravity was recorded to the nearest hundredth and converted into wet density. A consistent mud balance technician was used through a single grout batch to reduce variability. Results are plotted against the in-line density test results in this section.

4.1.2.2. In-line Density Test Results

The OPTIMASS flowmeter was set to measure the density of the grout eight times per second. The in-line results show the density of the grout decreases as water dosage increased. The flowmeter had little variability at each water dosage showing the consistency of the meter. A 10% increase in water leads to a decrease of approximately 0.3 lb/gal in density. The mass meter measures the density to the thousandth of a pound per gallon. Given the preciseness of the mass meter some minor volatility was observed. Therefore, the density figures below show wet density averaged over one minute of pumping. The digital reading in Figure 4.1 shows live readings of density. Live readings allow inspectors and pumping crews to know exactly when the grout's density exceeds the manufacturers pre-approved range or when significant density changes occur.

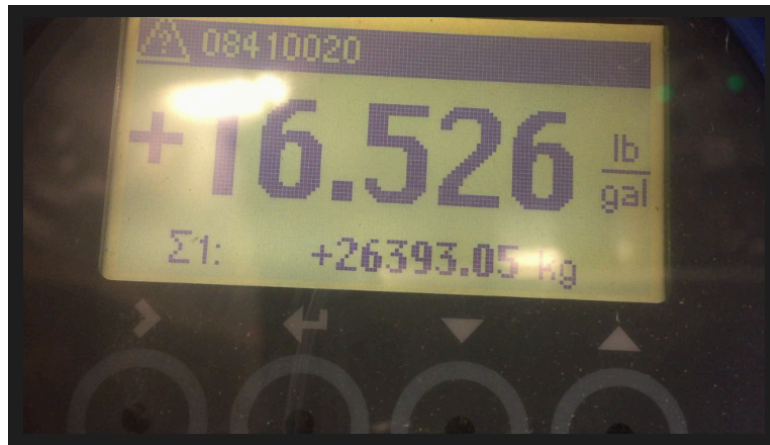


Figure 4.1 Live Density Reading

The density graphs in this section show the one-minute average of wet density recorded by the mass flow meter throughout the duration of each test in yellow. The mud balance was measured at multiple intervals throughout each phase and the time of every

sample of grout was recorded. The mud balance results are plotted alongside the flow meter results in blue. The range error bars on the mud balance results show the range of results measured in each phase. The x-axis shows the time in minutes since the beginning of the test and the y-axis show wet density (lb/gal) and specific gravity.

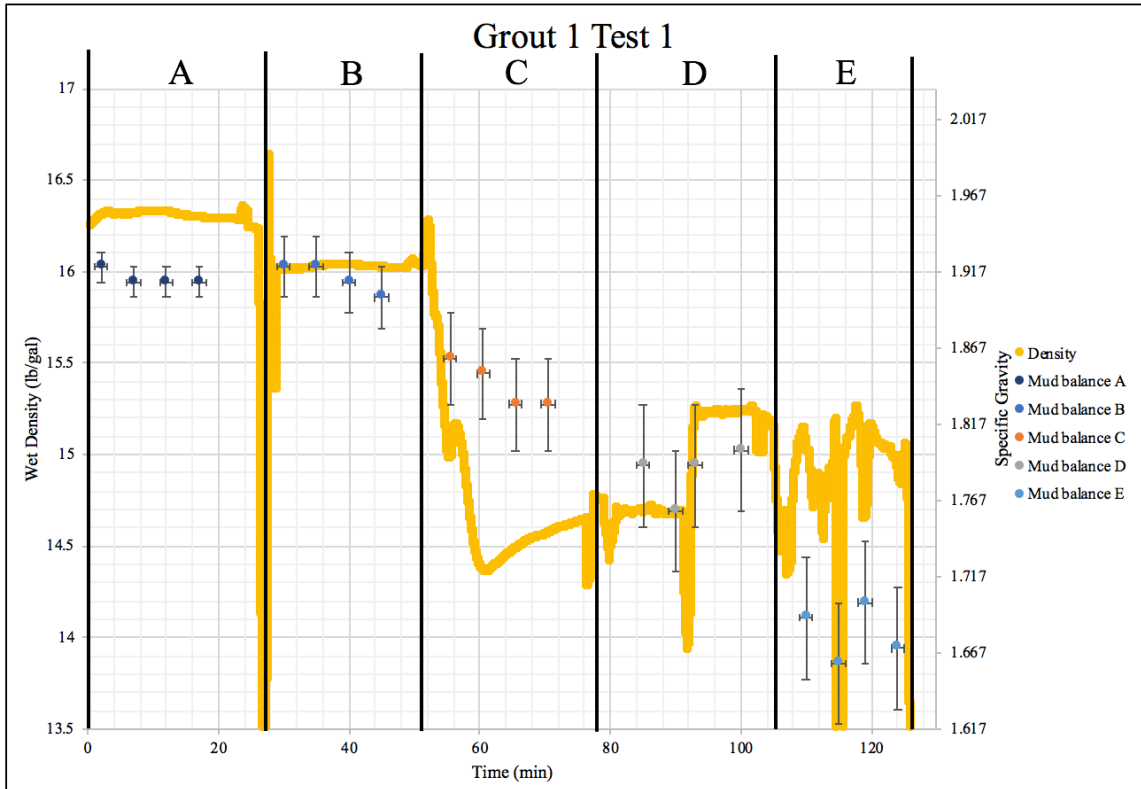


Figure 4.2 Density Results from Test 1 of Grout 1

Figure 4.2 shows the density data for Grout 1, Test 1. Overall, the data followed the same trends between the mud balance and the flow meter. The similar mud balance results between Phase A and B could be due to inadequate mixing. Clumps of unhydrated grout were found on the screen between the mixing tank and agitation tank. The unhydrated grout was then added to the next batch of water. Thus, the water to cement ratio from Phase A to B was similar. PTI M55.1 specifies “If lumps of cement remain on the screen, the mixture is not suitable for grouting.” Therefore, the grout would have been rejected for field use however since the data used in this research is relative, the results are still comparable to each other. During this test, hardened grout chunks were found in the mass meter as discussed previously. It was deduced that the blockage caused the

sudden decrease in measured density as the higher density grout was unable to pass through the blockage. The difference between the mass meter and mud balance during Phase C can be attributed to the blockage decreasing the density of the material allowed to pass through the meter since the mud balance was taken directly from the agitation tank where the density was higher. The pressure increase was noticed at the 110 min mark. At this time researchers fluctuated the pump back and forth between pumping the grout and trying to vacuum grout to release the blockage from in front of the meter. This contributed to the volatility in the graph during Phases D and E. The blockage was unable to dislodge using this method, so the grout was disposed of after Phase E and thoroughly cleaned. It is worth noting that the data recorded and displayed in the graph shows a history of the grouting process. Records like these can be valuable in determining where issues may have occurred and where to look if invasive inspections are needed.

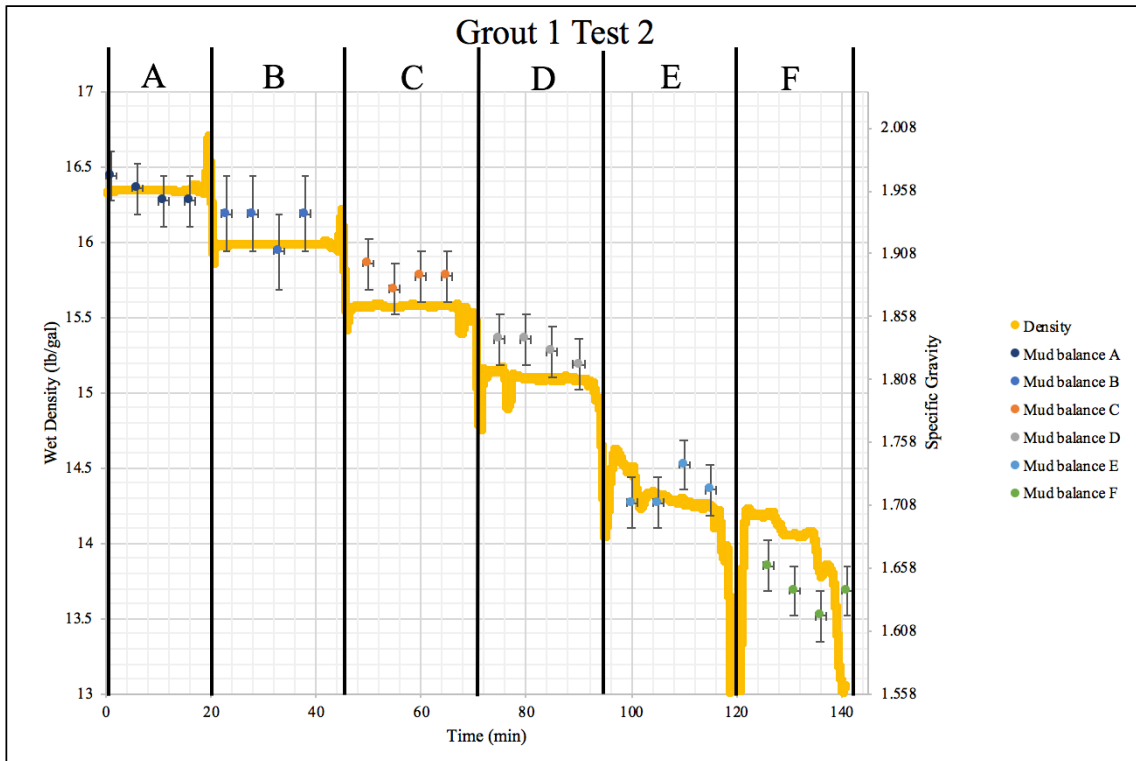


Figure 4.3 Density Results from Test 2 of Grout 1

The graph of Grout 1 Test 2 shows the expected variation of density over time. It can be seen that as water is added in each phase the density decreases. The steps in the density occur when additional water was added to the mixture. The mud balance results follow the trends of data recorded by the density meter giving confidence in the meter results. Additionally, the results are at values expected for this grout at the water ranges used. Note that only Phases A and B represent the allowable water contents for this grout – these show the expected density over 1.9. As water is added, the grout density has a clearly distinguishable drop at each water addition.

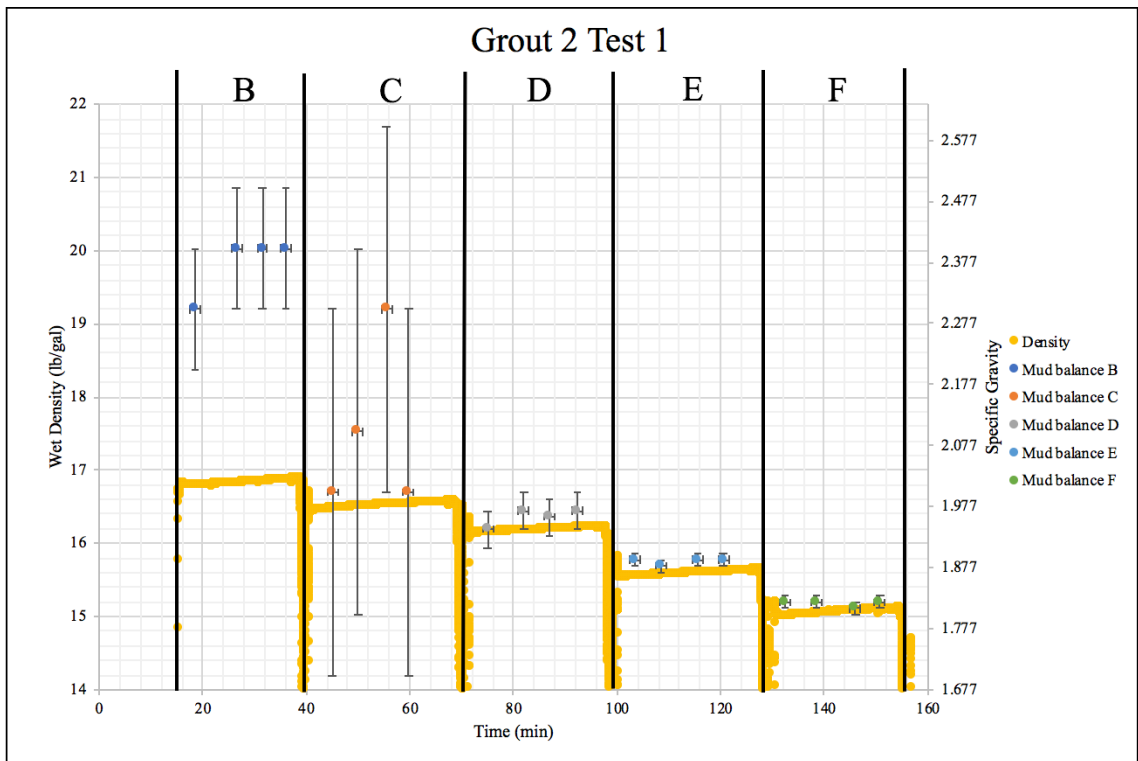


Figure 4.4 Density Results from Test 1 of Grout 2

The data in this figure represents the results of the grout that exhibited flash set behavior. The mud balances in Phases A and B of the tests are further from the graphs than the rest of the water contents. This is likely due to a testing procedure error. As the grout was nearly instantly entering a non-fluid state, the excess grout in the mud balance did not allow grout to flow out through the small vent hole in the cap leading to a higher

volume, higher weight, and thus higher apparent density. Even though the grout was flash setting, the results show the stepping of density described above as long as the grout was able to be pumped. At the end of this test, the mixer seized due to another flash set and could not be water flushed. The mixer had to be disassembled and pumping parts replaced. In the field, any grout exhibiting this behavior should immediately be flushed from the mixer and discarded.

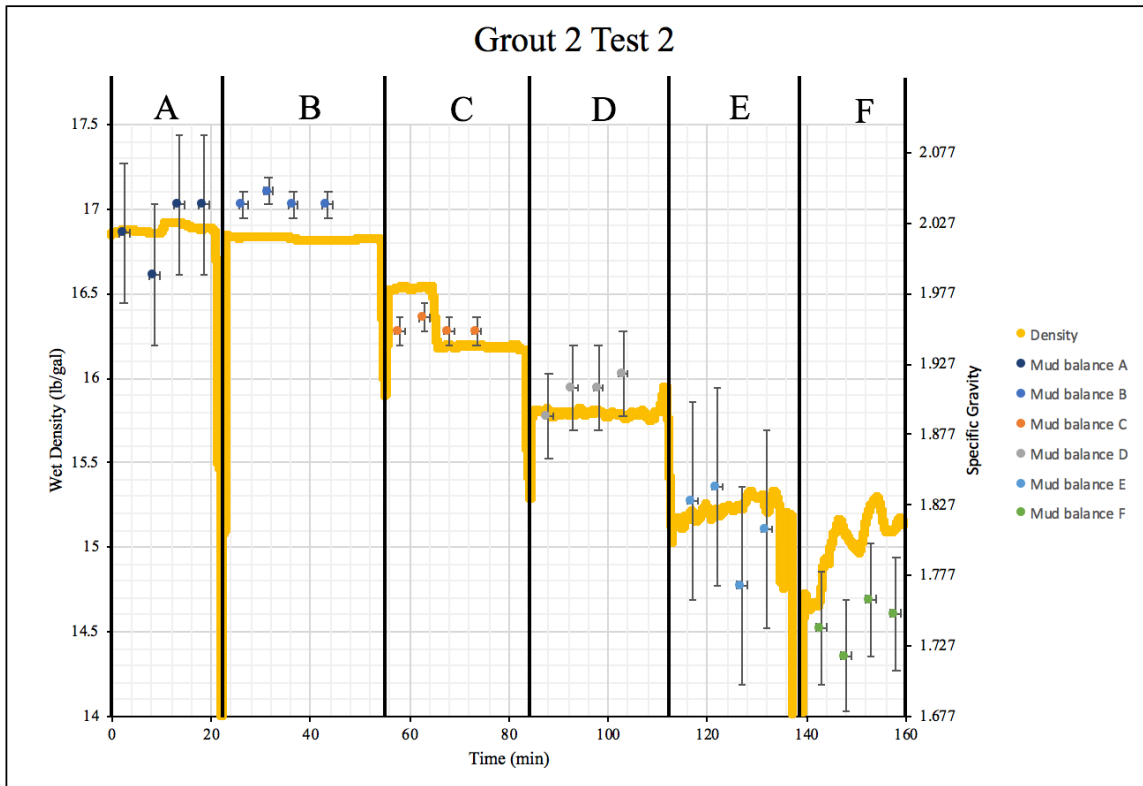


Figure 4.5 Density Results from Test 2 of Grout 2

Grout 2, Test 2 also shows the similar densities in Phases A and B due to clumping of dry grout as described above. The stepping in the density is also seen. The step in Phase C around the 60-minute mark can be attributed to inadequate mixing. Once the grout was fully mixed the density remains constant.

4.1.3. Temperature

The in-line mass meter measures and records temperature using a Pt500 sensor. The temperature was studied to further detect possible issues during the grouting process. PTI M55.1 specifies special precautions shall be used to ensure the temperature of grout is kept below 90 degrees Fahrenheit. The results show the temperature of the grout rising as the cement begins to hydrate. Grout 1 started around 86 degrees and rose slightly during each phase. At the change of each phase, the temperature drops slightly as cold water is added to the grout. During Test 1 of Grout 1 the temperature is seen to increase dramatically at 110 minutes. This was due to the blockage of the meter described above. Heating of the equipment due to blockages or clumping can also contribute to the heat rise.

Grout 2 started with an ambient temperature around 74 degrees and rose quickly in both tests. In Test 1 of Grout 2 the temperature immediately increased over the recommended 90 degrees and passed 100 degrees reaching approximately 105 degrees. This temperature rise was a good indicator of the issues to come. Even when cold water was added to the grout the temperature remained above 90 degrees for the entirety of the test showing flash setting behavior described above. During Test 2 of Grout 2 the temperature rose above 90 but as more cold water was added the temperature decreased to an acceptable quantity. The temperature data is shown below.

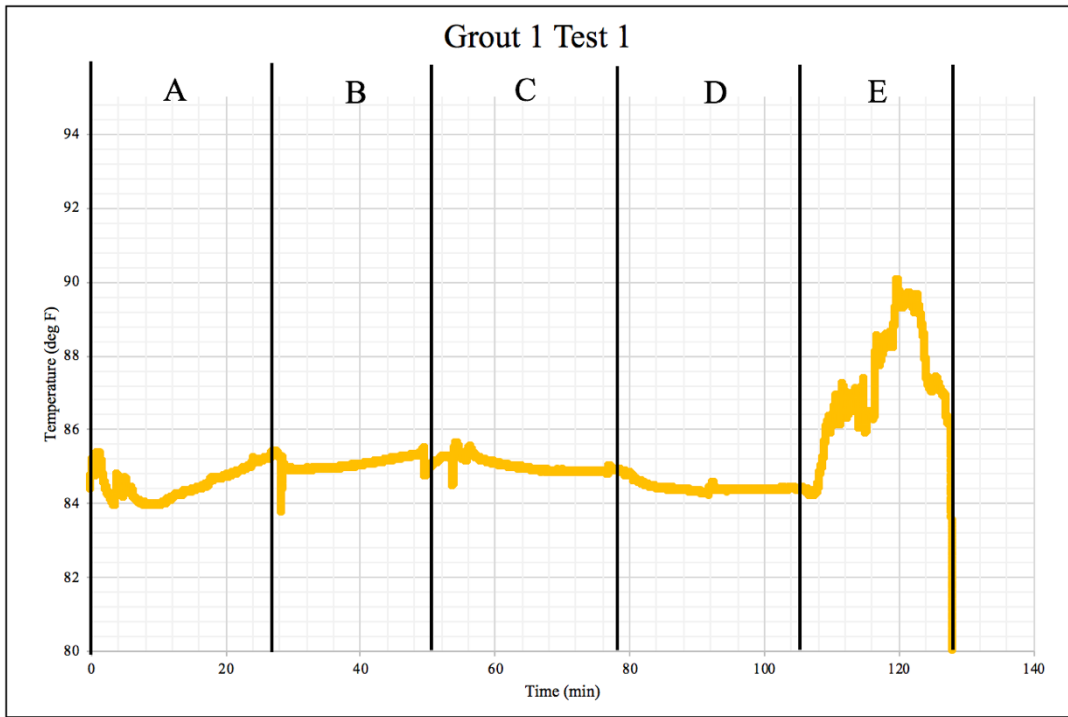


Figure 4.6 Temperature Results from Test 1 of Grout 1

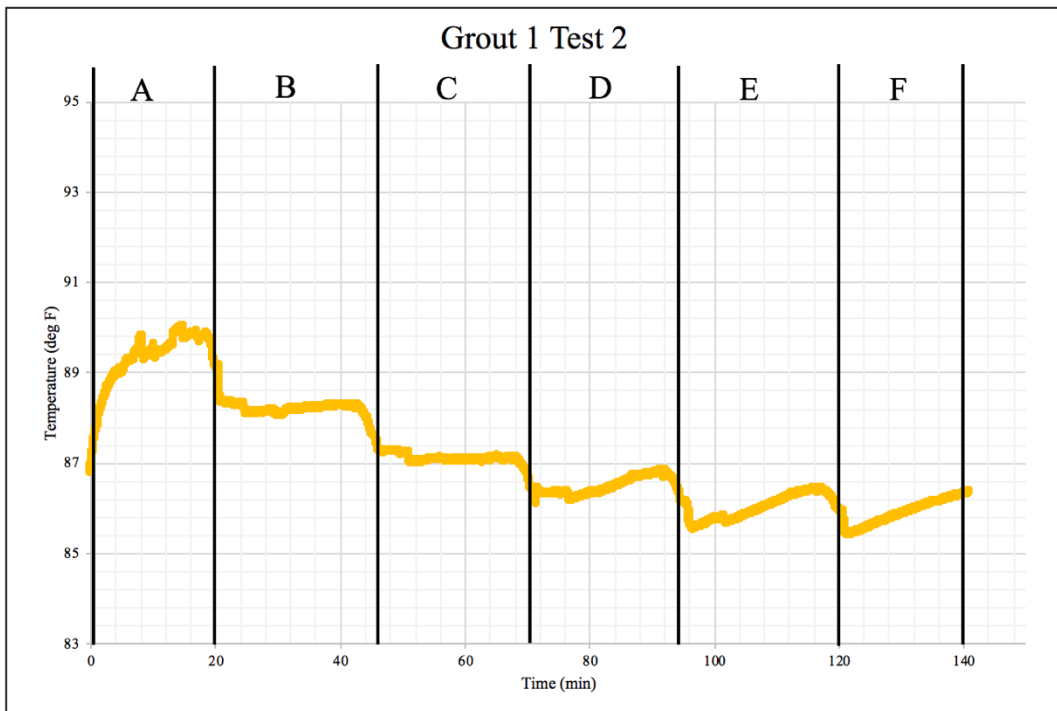


Figure 4.7 Temperature Results from Test 2 of Grout 1

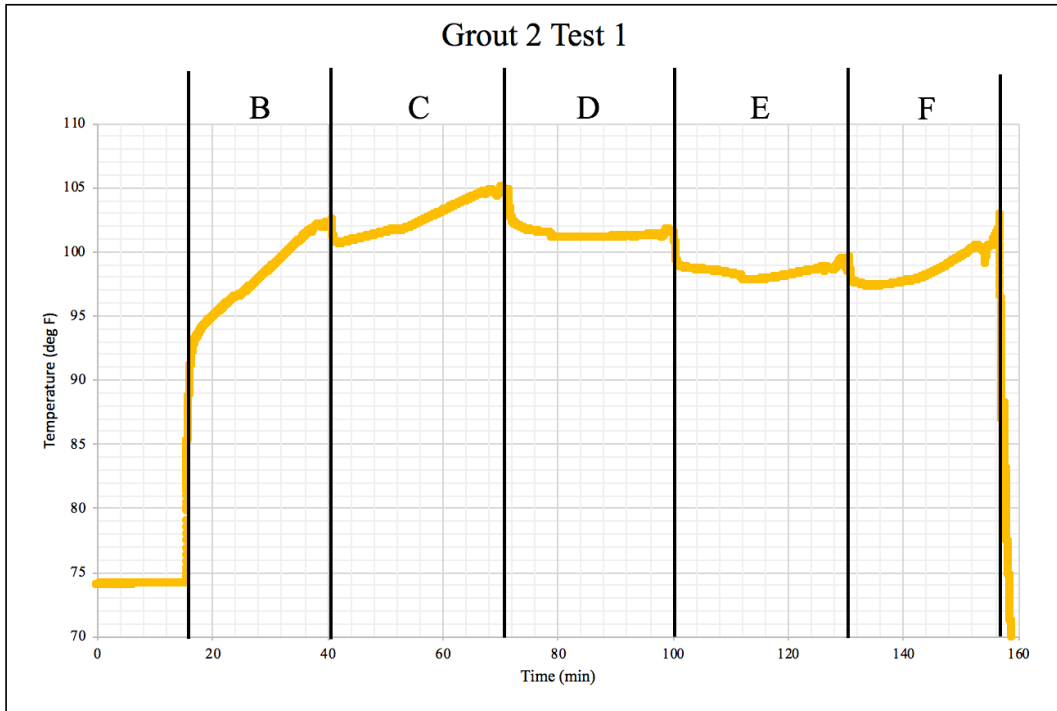


Figure 4.8 Temperature Results from Test 1 of Grout 2

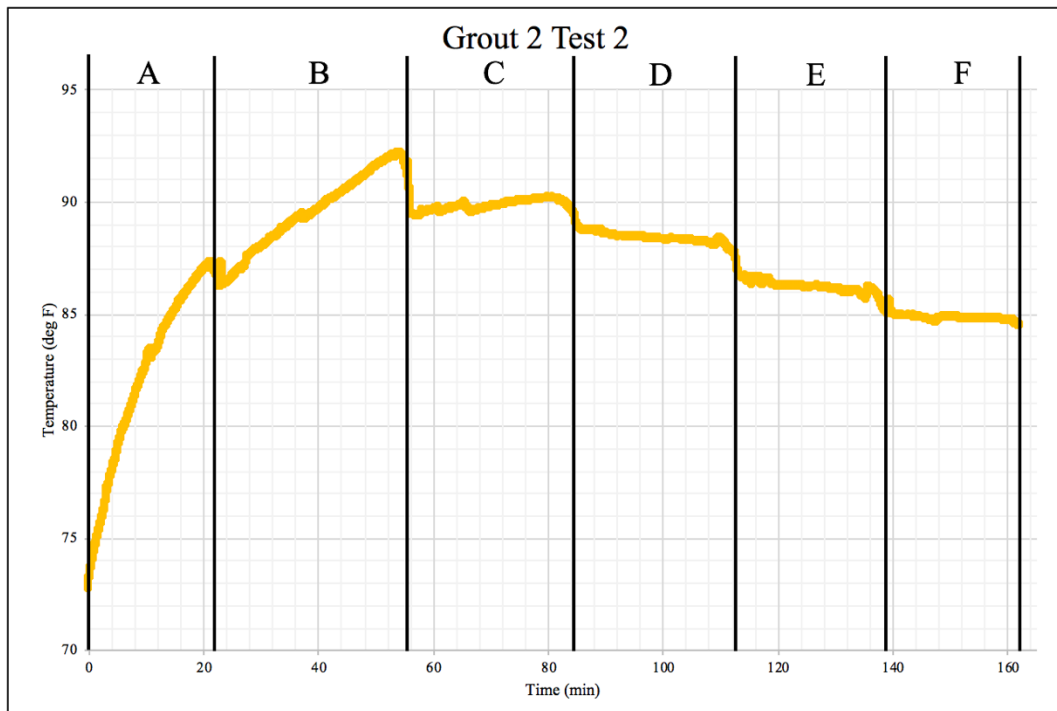


Figure 4.9 Temperature Results from Test 2 of Grout 2

5. Recommended Specifications

Based on the results of this study, there is a clear benefit to using the flow meter in-line during field pumping of post-tensioning grout. The mud balance method that is currently used provides only a snap shot in time, is more prone to operator error, and is not practical to use for frequent measurements during pumping of a single tendon. The in-line flow meter provides nearly continuous density and temperature measurements which provides a live readout for the grouting crew and inspector. Additionally, the data can be downloaded as an electronic record of the full grouting procedure.

Given that the flow meter can provide a single indicator during construction of grout performance of a pretested grout, it is recommended that the flow meter be used on every grouted PT tendon that is using the grout as a protection level, including all bridge tendons. For pretested grouts, this test can replace all other required field tests. Before the grout hose is attached to the tendon, flow meter readings would be taken. This also allows an indication of when any water in the mixing plant or hose is cleared from the line. Pretested grouts must establish a window of acceptable density for approved use.

6. Summary and Conclusions

6.1. Summary

In summary, this project studied wet density of grout in-line during pumping. Specifically, the feasibility of using a mass meter to constantly and consistently measure wet density of grout. Density is a great indicator of the water to solids ratio of prepackaged grout. The goal of this project was to determine if the addition of an in-line flow meter would allow for more accurate and reliable test methods. Two Class C grouts were tested at multiple water to solid ratios. Fresh property measurements were conducted to ensure the mass meter could show issues with the grout as reliably as current test methods. The in-line density meter allows for constant monitoring of density allowing inspectors to determine if the water dosage is within the manufacturers recommended range to prevent bleeding and voids in the ducts. The implementation of the in-line meter as recommended can solve the single biggest construction issue for grouting of post-tensioning tendons.

6.2. Conclusion

Based on the results and observations of the tests performed on the grout, the following are the primary conclusions from this work:

The flow meter provides a practical indicator of grout density nearly continuously during pumping.

The flow meter provides an electronic record of the density and temperature of the grout throughout pumping. This can point to anomalies in the process, even long after the construction is complete. Addition of water or stoppage of pumping is clearly recorded.

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