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A Relationship Between the Strengths of Type N Cubic Mortar Specimens and In-Situ Mortar

Michael Scott Reynolds

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

A Relationship between the Strengths of Type N Cubic Mortar Specimens and In-Situ Mortar

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Master of Science

The compressive strength of mortar is typically determined using the American Society for Testing and Materials (ASTM) standard method using 2 inch cubes which are compressed till failure. There is however a disparity between the compressive strengths of mortar cubes, and in-situ mortar. This disparity is a result of the differences in thickness, aspect ratio, curing conditions, water content, and confinement between mortar cubes and mortar joints. While these differences lead to mortar joints being stronger than mortar cubes, a relationship between their strengths is desired.

Two less-common mortar strength tests were used to determine more accurately the compressive strength of in-situ mortar. The results of both tests were compared to the results of ASTM standard compressive testing with mortars of the same water content. The first was the Double Punch test which involves the use of two metal punches that compress either side of a thin mortar sample till failure. The Double Punch test is more difficult to perform than the ASTM standard compression test, but was useful because it simulates the confinement that in-situ mortar will experience. The Double Punch test was also used with mortar specimens of varying thickness to determine a relationship between specimen thickness and compressive strength. The second test used was the Helix Pullout test. This test is performed by inserting metal helical screws into a mortar joint, and pulling from the joint while restricting rotation. The maximum load used to extract the Helix is recorded as the Pullout Load, and is used to find the compressive strength by use of a calibration curve. This test was used on a masonry wall panel and mortar cubes were also made with the same mortar for compressive testing.

The tested mortar exhibited decreased compressive strength with increased water content. The mortar also decreased in strength with increasing specimen thickness. Mortar joints were shown to be significantly stronger than mortar cubes based on factors of specimen thickness and confinement by an average factor of at least 2.40. Although results are affected by punch diameter, the Double Punch test was shown to be a consistent and reliable means of estimating mortar compressive strength. The Helix Pullout test exhibited wide variation, and was determined to be primarily useful for qualitative comparison as opposed to quantitative determination of strength.

Keywords: mortar, compressive strength, ASTM, double punch test, helix pullout test

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1 INTRODUCTION

1.1 Background

Some of the oldest structures on earth were made of masonry. Masonry structures are comprised of stones, bricks, or blocks held together by mortar. Masonry structures are still used in modern construction and typically use either concrete blocks or clay bricks separated by layers of mortar. This means the strength of a masonry assemblage is highly dependent on the strength on mortar.

Procedures for finding the strength and other properties of mortar have been set forth by the American Society for Testing and Materials (ASTM). The ASTM C109 (ASTM Standard C109/C109M-16a 2016) standard for finding the strength of mortar involves the making of 2 inch cubes of mortar which are tested in compression. The compressive strength is calculated by dividing the maximum load resisted by the cube by its cross sectional area. This is a simple and efficient manner of determined mortar strength, but there are issues with this method. One issue with the cube test is that it is a poor representation of a mortar joint, which is typically ⅜ inch thick. This mean the thickness and aspect ratio of a mortar cube and a mortar joint are quite dissimilar. Mortar within a mortar joint will also experience a large amount of confinement from the surrounding masonry unit when it is compressed. Mortar joints also let out water to surrounding bricks or blocks when initially placed, which is not provided for in a mortar cube, which is formed in a nonabsorbent mold. These factors make the cube test a weak means of representing in-situ mortar.

With the knowledge that mortar cube strength does not represent mortar joint strength in an accurate manner, one may ask why mortar cubes are used at all to find in-situ mortar strength. Unfortunately, it is quite difficult to extract and properly test mortar joints. Some of the main issues with doing so involve finding a manner in which to extract mortar samples without fracturing or disturbing them. In order to calculate strength, the area of compression is required, which requires more cutting and potential disruption of samples in order to achieve a uniform measurable shape. Some newer tests have been developed to combat this specific issue, such as the Double Punch test, which are discussed later.

The difficulty in extracting representative mortar samples from masonry assemblages gives answer to why lab prepared mortar is used to find compressive strength. But the questions may also be asked why mortar is formed into 2 inch cubes, as opposed to ⅜ inch thick layers of mortar, since a typical mortar joint is that same thickness. But the issue with compressing a thin layer of mortar is that it will not fail in the same manner. Because of the larger aspect ratio, the samples will break in smaller segments, as opposed to all together in one unit. Because of that the actual compressive strength is difficult to determine, because the area in compression is needed to determine strength. But because the whole unit does not fail together, the actual area that fractures at ultimate strength is smaller than the total area of the sample.

1.2 Research Objectives

The objective of the research program is to determine a relationship between the compressive strengths of a mortar cube, and in-situ mortar. The goal is to establish a ratio between the two strengths, so that in-situ mortar strength can be determined from the use of a standard cube compression test, and a known thickness of mortar joint. This is desired because standard cubes tests are simple and widely used, which makes them a useful test so long as the actual in-situ mortar strength can be calculated from the results.

Because of the many variables that affect the differences in compressive strength between a mortar joint and a mortar cube, there is no plausible way to directly measure each with only one test. The author felt that two of the biggest variables leading to the difference in strengths were the thickness, which is essentially a matter of aspect ratio, and the lack of confinement in a standard compression test. Both of these variables are able to be tested with the use of the Double Punch test, and the Helix Pullout test.

The Double Punch test is similar to the standard cube compression test in that mortar samples are loaded in uniaxial compression. The test involves placing a relatively thin mortar specimen between two metal punches, which compress a small portion of the center of the specimen. Because only a small area is loaded, the mortar can fail as a single unit. And the mortar which is not compressed acts to confine the portion that is compressed. The Double Punch test has several advantages in that varying thicknesses of mortar can be tested, and that confinement is simulated in the test.

The Helix Pullout test is also able to test mortar confinement, because it is tested on actual mortar joints within a masonry assemblage. The test involves inserting helical ties into a mortar joint, and pulling them out, shearing a small hole into the joint in the process. The maximum load required to remove the helical ties is the pullout load, which is correlated to the compressive strength. This test is useful because it is actually tested on in-situ mortar. There are potential issues with the test, the greatest of which being the large variation in results, and the fact that compressive strength is not directly measured by the test.

The effects of water loss to surrounding blocks is also a factor leading to the difference in compressive strength, but this was not directly tested by the author through this study. However, multiple water contents were used to simulate the differences that higher or lower water content have on compressive strength. By approximating the amount of water lost from the mortar in an actual masonry assemblage, a relative factor of strength increase could be found to further illustrate the amount by which the cube test is inaccurate.

1.3 Scope of Research

This research program is to test mortar in different configurations, with different tests in order to determine relationships between certain properties of mortar, and its strength. Standard compression tests, Double Punch tests on slices of mortar cubes, and Helix Pullout tests on mortar joints are all performed on mortar with varying water contents. Double Punch test results and Helix Pullout test results are compared to standard cube compression results to establish strength comparisons.

The testing and results of this research program apply only to Type N Mortar. With the exception of wall panels, all mortar specimens were cured in a fog room at 73° F with 96% humidity. All mixing and testing of mortar also took place in a laboratory, making the results more representative of laboratory mortar, and less applicable to field prepared mortar.

All mortar was made from bagged mortar mix, as opposed to a specified mix design. This was chosen because the variables that were to be tested were independent of the mix proportions of the mortar. Thus bagged mortar mix was used because it allowed for faster assembly, and less opportunity for variance. All bagged mortar was of the same brand, and selected from the same palette to reduce the possibility of bag-to-bag variability.

All mortar cubes were 2 inch cubes, and all mortar cylinders were 2 inches in diameter, by 4 inches in height. Although it is generally recommended to cap cylindrical specimens, it was felt that the surfaces of the cylinders were sufficiently smooth and plane to allow the omission of gypsum caps, which is believed to only have caused minor reductions in their overall strength.

Three water contents were chosen for standard compression and Double Punch testing. These water contents were chosen arbitrarily to give an upper water content, a lower water content, and an average water content for the mortar. Water contents were chosen based on workability, which the highest water content causing mortar to splash out of the mixer, and easily flow. The lowest water content was chosen as the driest mix with which the mixer could still be strong enough to mix. The average water content was half way between the upper and lower water contents.

1.4 Outline

The remainder of this thesis is presented in the next five chapters with more detail. Chapter 2 is a review of existing literature pertaining to the subject, which serves as a background and starting point for this research program. In Chapter 3 the specific materials and procedures used for all testing are presented. Chapter 4 is a presentation of the results, and Chapter 5 is an analytical discussion of the results presented in Chapter 4. Concluding remarks and thoughts are presented in Chapter 6.

2 REVIEW OF LITERATURE

The following sections will present a review of the literature related to the Double Punch test, the Helix Pullout test, and other methods, including the standard procedure of determining the compressive strength of mortar. The purpose of these sections is to provide a background on the different test methodologies, and a comparison between those and the standard testing procedure.

2.1 Standard Compression Test

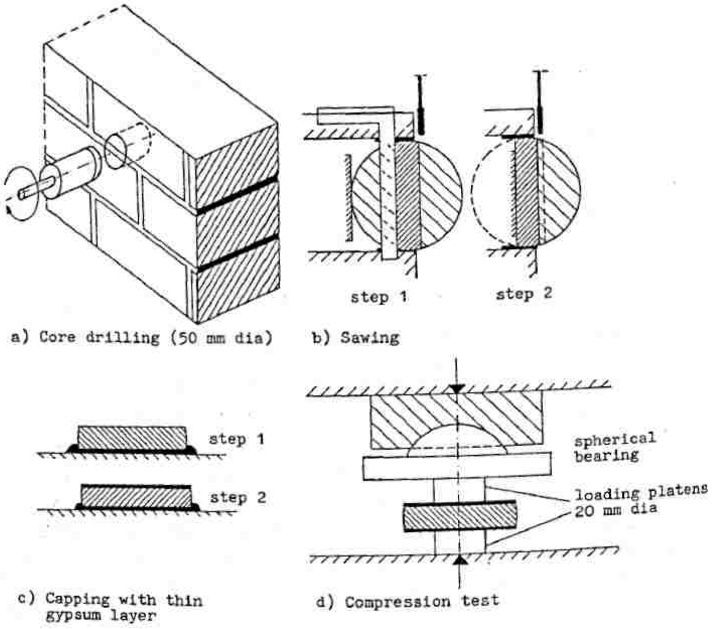
A standard method for determining the compressive strength of mortar is set forth in ASTM C109. The specification designates that mortar compressive strength is to be defined as the compressive strength of a 2-inch mortar cube. The mortar cube is to be formed in a nonabsorbent, hard metal mold. The mortar cubes are to be cured for 28 days prior to compressive testing. The compressive strength is calculated as the maximum load recorded by the testing machine, divided by the cross-sectional area of the cube, typically reported in psi or MPa. The standard compression test is simple, and easy to perform, but is unfortunately not an accurate representation of the strength of in-situ mortar. Several factors include to this disparity, including differences in thickness, confinement, and water loss. Because of this several tests have been developed to more accurately determine the compressive strength of a mortar joint.

2.2 Double Punch Testing

The Double Punch test is a minor destructive test used to estimate the compressive strength of in-situ mortar. It has most widely been used to estimate the compressive strength of mortar from historical structures. The Double Punch test provides for a more accurate simulation of the actual strengths present in in-situ mortar because of the confinement of the mortar surrounding the portion of sample compressed by the steel punches.

2.2.1 Double Punch Development

Henzel and Karl (1987) conducted research to develop a straightforward, new test to determine the compressive strength of mortar. To do so, they used a 50 mm core drill to extract samples of mortar joints from test walls. They removed the layers of brick from the cylinders to expose the rectangular mortar sample. After being isolated, the mortar joints were capped on both sides with a thin layer of gypsum, after which they were compressed between two 20 mm metal punches. This process is illustrated in Figure 2-1.



a) Core drilling (50 mm dia) b) Sawing

c) Capping with thin gypsum layer d) Compression test

Figure 2-1: Diagram of Mortar Joint Testing Procedure (Henzel, Karl 1987)

Further preliminary tests by Henzel and Karl involved the making of mortar prisms of dimension 40 mm x 40 mm x 160 mm. After 2 months of curing the prisms were cut either into smaller prisms (40 mm x 40 mm x 62.5 mm) or thin specimens (40 mm x 40 mm x 10 mm). The thin specimens were capped with a thin layer of gypsum and tested in a similar manner as the specimens extracted from the walls, except that the thin specimens were tested using metal punches of 3 different diameters: 20 mm, 25 mm, and 30 mm. This was done to determine which diameter was optimal for the newly developed test, as well as establish a calibration curve for the relationship between the strength of the thin specimens and that of the prisms, which was determined from tests performed according to DIN 1164 Part 7 (1978). These results showed a strong relationship between the strength of the small prisms and that of the thin specimens. Based on the results the authors suggested that a ratio of 2 between the thickness of the punch and the sample be used. No specific reason was given for this suggestion, but they did produce the most conservative results. Further research is needed to refute or validate their suggestion.

The main set of tests involved the making of miniature walls with varying block types, and mortar mixes. After curing, cores were drilled, mortar layers isolated, and mortar capped and tested with the 20 mm diameter metal punch. The tests were performed to compare the joint strength to the prism strengths. For mortars with lower strength, the joint strength was typically 1.5-2 times that of the prism strength, and for mortars with higher strength, the joint strength was typically 1.15-1.5 times that of the prism. The authors observed, in general, that as mortar strength increased, the difference between joint strength and prism strength decreased.

2.2.2 Double Punch Test Compared to Finite Element Model

A recent study Matysek et al. (2017) compared the results of the Double Punch Test to the results of a Finite Element Model. The authors used cylindrical mortar samples with a diameter of 50 mm and thickness of either 10 mm, 16 mm, or 25 mm. Each sample had a thin layer of gypsum between the mortar and the steel punches to create a cap for even distribution of load. The Finite Element model, shown in Figure 2-2, was used for comparison, and also to determine the interaction of the mortar, gypsum cap, and steel punches.

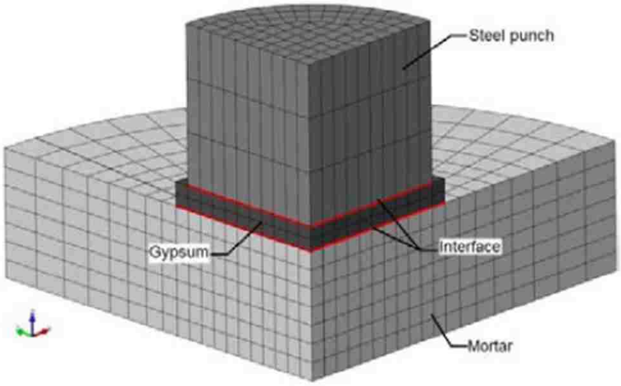


Figure 2-2: Finite Element Model (Matysek, et al. 2017)

The authors found that the physical tests, and numerical model gave very similar results, with the values of calculated and experimental ultimate loads for the 16 mm thick mortar samples differing by less than 2%. The computed vs. experimental results are represented in Figure 2-3. The data does not go through the origin due to initial loading. Additional tests investigate the effects of sample thickness and the strength of the gypsum cap on the mortar strength. The results of these tests are shown in Figure 2-4. The results in Figure 2-4a clearly show that compressive strength is dependent upon mortar thickness to a small degree, with thicker samples also having a higher maximum displacement. The results in Figure 2-4b show that compressive strength is highly dependent upon the strength of the gypsum cap used, with higher gypsum cap strength resulting in higher mortar compressive strength.

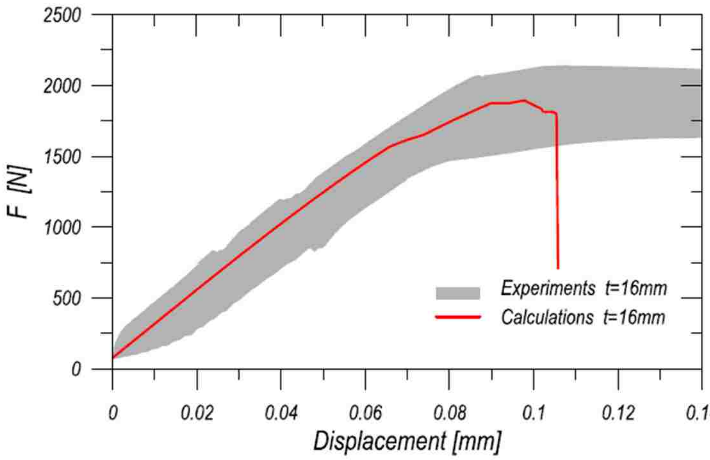


Figure 2-3: Computed Versus Experimental Results (Matysek, et al. 2017)

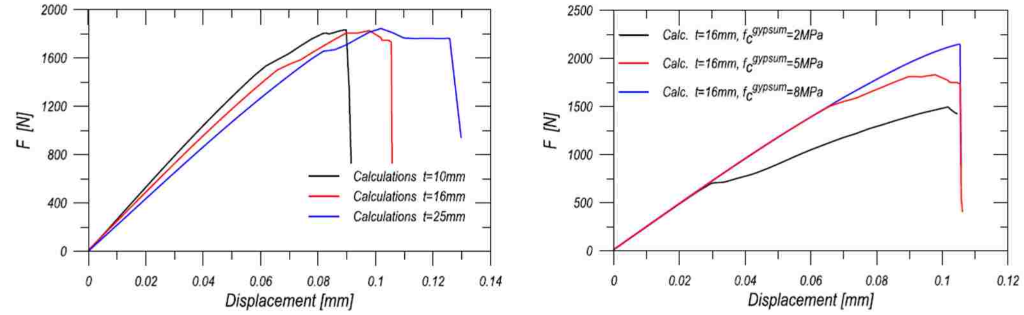


Figure 2-4: Results Based on a) Mortar Thickness, and b) Gypsum Compressive Strength (Matysek, et al. 2017)

2.2.3 Mortar Cube Strength Versus Mortar Joint Strength

A study performed by Sassoni et al. (2013) examined the differences in strengths between weak and strong mortars with both mortar joints and prismatic specimens. Two separate mortar mixes were developed to simulate the "weak" and "strong" mortar. The primary difference between the two mixes was ratio of aggregate to the cement and water. Standard compression testing and Double Punch tests were used and the results were compared to determine the differences in strengths between mortar joints and mortar cubes.

For the weak and strong mortar, 3 specimen types were created. The first specimen type, termed M1, was a standard prism with dimensions 40 mm x 40 mm x 40 mm, tested in compression. The second specimen type, termed M2, was a slice from a standard prism with dimensions 40 mm x 40 mm x10 mm. The third specimen type, termed M3, was a layer extracted from a mortar joint, that was cut to the same dimensions as the M2 specimen type. To make these specimens, two brick walls were assembled and allowed to cure for 50 days in laboratory conditions. After curing, 100 mm cores were drilled from the wall, and the mortar was chiseled out, then cut to the proper dimensions. The M1 type specimens were tested using the standard compression test procedure where the M2 and M3 type specimens were tested using the Double Punch Test methodology using 20mm punches. These test results are shown in Figure 2-5.

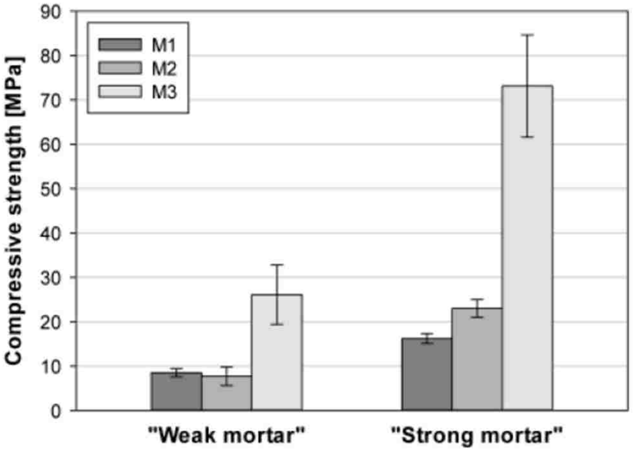


Figure 2-5: Comparison of Compressive Strengths between "Weak" and "Strong" Mortar, and between Mortar Joints and Mortar Cubes (Sassoni, et al. 2013)

The strength differences between the results of the Double Punch tests, and compression tests were attributed to two effects: the large difference in the thickness-to-height ratios and the lack of restraining effect in the compression tests. There were also large differences in the strengths of the M2 and M3 samples, which were the same size, and tested in the same way. This difference was attributed to the difference in the microstructures of the 2 types. The different microstructures are caused by the differences in compaction between a mortar prism and mortar joint as well as the absorption of water from adjacent bricks in mortar joints, which is not present in the prisms, which were cast using nonabsorbent molds.

2.3 Helix Pullout Test

The Helix Pullout Test is another minor destructive test that can be used to find the compressive strength of in-situ mortar. It is described further in the following sections, and relevant research pertaining to it are also presented.

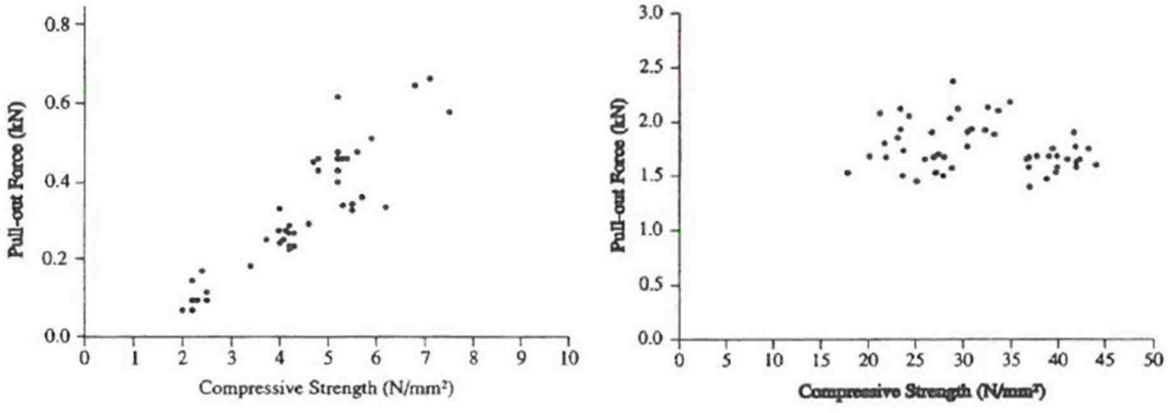
2.3.1 Helix Pullout Test Development

The Helix Pullout test was examined as a method of determining the compressive strength of in-situ mortar by Ferguson and Skandamoorthy (1994). The test determines the force required to pull a helical tie from a mortar joint. The test is performed by drilling a small pilot hole into a mortar joint. The actual diameter of the pilot hole is not important so long as it does not change the failure mode from a shear failure to a compression failure. After drilling, a steel helical tie is inserted into the hole. Figure 2-6 shows an example of a Helical Tie.

Figure 2-6: Helical Tie

After insertion, a special device is threaded onto to the helical tie, and is used to slowly pull the tie, while preventing rotation of the tie. The pulling shears a small hole through the mortar where the tie was inserted. The device measures the load required to pull the tie from the mortar joint, and this value is the Pullout Load. The pullout load is used to determine the compressive strength of the material.

The authors made batches of mortar that were used to make both walls for testing with the Helix Pullout Test and cubes tested in compression. The authors found a positive correlation between Pullout force and the Compressive Strength of the mortar. Unfortunately, this correlation only applied to weaker mortars, with a maximum strength of around 7.5 N/mm^2 (roughly 1000 psi). When medium strength mortars were tested, there was not a significant correlation between Pullout Load and Compressive Strength. These results are shown in Figure 2-7. Another issue that was noticed with the test was that with stronger mortars the gripping device would cut into the steel tie as it was being pulled out. This fact essentially set a limit on the strength of mortar that could accurately be tested.



(a) (b)

Figure 2-7: Comparison Between Compressive Strength and Pullout Load for a) Lower Strength Mortars, and b) Medium Strength Mortars (Ferguson, Skandamoorthy 1994)

2.3.2 Recommended Test Conditions and Procedures

Recommendations for the testing of mortar with the Helix (or Screw) Pullout test were given in MS-D (1997). In particular, the technique was useful for finding data on the following characteristics:

1. Batch-to-batch variability of strength or general quality.
2. Variation of quality in relation to a reference sample.
3. Changes of properties with time, i.e., strength increases due to hardening and the effects of weather conditions and additives.
4. Absolute values of mortar cube strength, provided a suitable calibration data-base is available.

An important note is that the Helix Pullout Test is limited by the yield strength of the helical ties used, typically around 8 MPa. This means that above that strength, the failure is from the yielding of the steel, and isn't proportional to the compressive strength of the mortar.

The test is preferably performed on an area of wall or panel between 1 m^2 and 2 m^2. Within such area, it is recommended to take at least 10 measurements, randomly distributed across the area. It is required that a clear depth of at least 35 mm is given for each standard test, although different tests could use different depths. The Helix Pullout Tests should be performed on dry masonry, which means masonry that has not been wetted in the last 24 hours and also has a dry appearance. This is because pore moisture is likely to have significant effects on the strength measurements.

In order to relate results of the Helix Pullout test to strength properties, such as compressive or flexural strength, a calibration curve is required. From previous tests by Rilem, it has been shown that the relationship between the pull out load and other strength properties is not linear. Therefore, each individual test must be transformed using a calibration curve before an average compressive strength calculation can be made, as a 10% increase in pullout load would not correspond to a 10% increase in compressive strength.

2.4 Combination of Helix Pullout, Double Punch, and Pin Penetrometer Tests

The possibility of using 3 different tests to characterize the strength of in-situ mortar was studied by Pelà et al. (2017). The Double Punch test, the Helix Pullout test, and the Pin Penetrometer test were all investigated because they are Minor Destructive tests. They were also specifically chosen for use in historical masonry, as they produce minimal damage. The tests were performed on two clay brick walls constructed of two different hydraulic lime mortars to simulate the mortar used in historic structures.

The samples used for the Double Punch test were separated from the bricks, and cut into 50 mm x 50 mm pieces, with an average thickness of 15 mm. The samples were not capped as past research has shown that doing so greatly increases the compressive strength. The samples were tested with 20 mm diameter punches.

The Helix Pullout Test was performed in the same manner as Ferguson and Skandamoorthy (1994), except that a 3 mm instead of 4.5 mm drill bit was used to drill the pilot holes. This was done because previous studies by the authors had shown that the use of a larger diameter pilot hole could reduce the results of the Helix Pullout test. Tests with the Double Punch test and the Helix Pullout test were performed on mortar after the same time of curing, so that results could be directly compared.

The Pin Penetration test is another test that can be used to find the compressive strength of mortar. It involves the use of a 3 mm diameter pin that is driven into the face of the mortar by a spring-loaded device. The test leaves an indentation in the mortar, which is measured with a micrometer. The depth of penetration is inversely proportional to the compressive strength of the mortar. The Pin Penetration test was only used with one type of mortar, while both types of mortar were tested with the Double Punch test and the Helix Pullout test.

The tests showed a positive correlation between the age of the mortar, and the Helix Pullout force and the Double Punch strength. As age increased, the depth of indentation from the Pin Penetration test also decreased. Therefore, as Double Punch strength increased, the Pin Penetration decreased. Lastly, as the Double Punch strength increased, the Helix Pullout load increased, and vice-versa.

2.5 Summary

2.5.1 Double Punch Test

The Double Punch test has been shown to be a reliable method of determining the compressive strength of in-situ mortar. It is preferable to a standard compression test because it better simulates the confinement that in-situ mortar experiences. It has also been shown to result in higher strength than a standard compression test for this reason.

Henzel and Karl (1987) were able to determine an efficient method for performing the test that will give reliable results. Their research showed that samples 10 mm thick were optimally tested with punches 20 mm in diameter. They were also able to show how the results of the test compares between weak and strong mortars.

Matysek et al. (2017) performed highly applicable tests and compare the results of the Double Punch test to the results of a Finite Element model. Their experimental tests differed from the model by less than 2 percent. They were also able to show how the strength of a gypsum cap affects the strength of the sample. They did not perform any tests however, with the double punch test without a gypsum cap.

Sassoni et al. (2013) also performed valuable research determining the strength differences between mortar prisms, slices from a mortar prism, and an extracted bed joint of mortar. They were able to show two important properties of mortar. The first is that for stronger structural mortars, a prismatic compression test will give lower strengths than a double punch test, even with mortar from the same batch, meaning that the only differences are the test method and sample thickness. The second is that strengths from the Double Punch test depend largely on whether the sample came from a slice of a prism, or from an actual bed joint extracted from a wall, with the latter being significantly stronger, which was attributed to the differing microstructures of the 2 types of sample.

2.5.2 Helix Pullout Test

The Helix Pullout Test is another useful way that may be used to find the compressive strength of in-situ mortar. It is especially useful because it does not require mortar cubes of cylinders to be made ahead of time. This application applies in instances where there are no samples to test the strength and minor damage to the structure can be accommodated. There are however limits to its use and accuracy, which will not make it suitable for every situation.

The research performed by Ferguson and Skandamoorthy (1994) provided some valuable relationships between the helix pullout load and the compressive strength of mortar. This work is helpful in determining a calibration curve, so that field results from the Helix pullout test can be correlated to the compressive strength of in-situ mortar. The results from their testing were most accurate with lower strength mortars, but the trend seen with the lower strength mortars was not present with medium strength mortars. Their testing was also limited by the strength of the helical ties.

Some useful guidelines are given in MS-D (1997) to help assure the consistency and accuracy of the Helix Pullout Test. The guidelines include the number of samples, the area in which the test is performed, and the conditions of the masonry, such as that the masonry must be dry. The importance of a calibration curve was also emphasized, as it is the key to finding the compressive strength of mortar.

2.5.3 Combination of Tests

These tests were useful as results were used to determine relationships between all 3 tests. There are limitations however, to the results. For example, there was no data from the Double Punch test for mortar strengths between 1.2 - 4 MPa and for mortar with strength greater than 7 MPa. The authors also noted that results from the Helix Pullout test and the Pin Penetrometer test could potentially be unreliable, because they only evaluate the exterior face of the mortar which is subject to greater weathering.

3 TEST PROCEDURE

The sections that follow introduce the methods used to make mortar specimens, and how those specimens were tested in compression, with the Double Punch Test, or with the Helix Pullout Test. All materials used conformed to ASTM standards, and were used based on availability.

3.1 Mortar Mixing

Research began by determining consistent procedures to be used for all tests in the study. In order to provide consistent results, all mortar was made from bagged mortar mixes. All bags were purchased together, and chosen from the same palette to increase the likelihood of consistent properties between bags.

3.1.1 Mortar Batch Sizes

All mortar was mixed in a table top mixer, with the dimensions required by ASTM C305 (ASTM Standard C305-14 2014). Both the mortar mix and water used to make the mortar, were measured according to weight with a scale precise up to 0.0005 lbs. Because of the size of the mixer, each batch of mortar was limited in size. Preliminary testing determined that a batch containing 10 lbs of dry mortar mix and a variable weight of water were the most that the mixer could handle without over-stressing the motor or causing material to splash out of the bowl. Thus, each batch of mortar contained 10 lbs of mortar mix and one of 3 weights of water.

3.1.2 Mortar Water Contents

Three water contents were chosen to represent a dry mix, a wet mix, and an average mix. Because the actual water contents for testing were irrelevant, they were chosen arbitrarily from preliminary testing. The wet mix, which had the highest water content was made with 10 lbs of mortar mix and 2.2 lbs of water. The amount of water for the wet mix was approximately the maximum that could be used without causing the mix to splash out of the bowl when the mixer was turned on. The average mix was made with 2.0 lbs of water and 10 lbs or mortar mix. Lastly, the dry mix was made with 1.8 lbs of water and 10 lbs of mortar mix. The amount of water for the dry mix was determined based on the fact that less water made the mix too stiff and it appeared to over-stress the motor of the mixer.

The dry and wet mixes were chosen so that an upper and lower bound of mortar flows could be obtained. These flow bounds were expected to correspond to a comparison between mortar strength bounds, since mortar strength is affected by the water content of the mortar.

3.1.3 Mixing Procedure

Each batch of mortar was mixed using the same procedure, except for the amount of water used to make the mortar. The mixing procedure used was slightly modified from that presented in ASTM C305 to accommodate for the fact that the sand and cement were already combined as a mortar mix. After weighing the mortar mix, the water was also weighed. Water was weighed last to reduce the effects of evaporation of the water. Water was added to the mixing bowl first, then the mortar mix was slowly added. The bowl was attached to the mixer, which was turned on at low speed for 60 seconds. After 60 seconds of mixing the mortar at slow speed, the mixer speed was increased to medium speed for 30 seconds. Then the mixer was turned off and the mortar was allowed to rest for 90 seconds. During the first 15 seconds of this resting time, the mortar on the sides of the bowl were scraped down. After the resting interval, the mortar was mixed at medium speed for another 60 seconds.

3.2 Mortar Flow Tests

Immediately after mixing, the mortar flow was determined. The flow table and flow mold used complied with the dimensions specified in ASTM C230 (ASTM Standard C230-14 2014). The flow test was performed using the procedures specified in ASTM C1437 (ASTM Standard C1437-15 2015) . The flow is reported herein as a percent increase in diameter from the inside diameter of the flow mold. The mortar used for the flow test was returned to the bowl and re-mixed before making specimens. This test procedure is demonstrated in Figure 3-1.

Figure 3-1: Mortar Flow Test

3.3 Mortar Specimens

There were 3 types of specimens used for testing. Mortar Cubes were used for full compression testing as well as for the Double Punch test. Mortar Cylinders were used only for full compression testing. A wall panel was also constructed so that the mortar on the bed joint could be tested with the Helix Pullout test. The mortar was used to make either cubes or cylinders, depending upon the needs of each test. Some batches were used to make both cubes and cylinders while others were used to only make cubes. A test matrix showing the number of each specimen type is shown in Table 3-1.

Table 3-1: Test Matrix

Standard Compression			Double Punch Test			Helix Pullout Test		
Mortar Flow (%)	Number of Cubes	of Cylinders	Flow (%)	Thickness (in.)	of Specimens	Helix Size (in.)	Row	of Specimen
24	8	8	28	0.283	9	0.315	1	7
27	8	8	28	0.393	8	0.315	2	7
39	8	7	28	0.531	4	0.315	3	7
47	7	7	28	0.662	7	0.315	4	7
70	8	7	44	0.286	15	0.315	Cube	18
73	8	7	44	0.356	5	0.394	1	7
			44	0.511	18	0.394	2	7
			44	0.626	12	0.394	3	7
			64	0.266	7	0.394	4	7
			64	0.388	7			
			64	0.524	5			
			64	0.665	8			
			77	0.282	13			
			77	0.381	5			
			77	0.504	20			
			77	0.626	12			

3.3.1 Mortar Cubes

The cube molds were filled with mortar, which was tamped according to the specifications in ASTM C109. The cube molds were placed in a fog room for 48 hours, after which the mortar cubes were removed from their molds, and placed back in the fog room for the remainder of the 28 day curing time. After curing for 28 days in the fog room, the cubes were ready to either be tested in compression or to be cut into slices, for testing with the Double Punch Test method.

3.3.2 Mortar Cylinders

Mortar cylinders were made using plastic molds with an inside diameter of 2 inches and height of 4 inches. Molds were filled in 3 lifts, with each lift being tamped with a metal rod 20 times, according to the procedures set forth in ASTM C780 (ASTM Standard C780-18a 2018). The mortar top was cut off with a straight edge, after which a plastic cap was placed on the mold. The mortar cylinders were left in their molds for 48 hours, after which they were removed and placed in the fog room for the remainder of the curing period. After curing, the cylinders were ready to be tested in compression. Because the cylinders were within the dimensions required by ASTM C39 (ASTM Standard C39/C39M-18 2018), the cylinders were not required to be capped.

3.3.3 Wall Panel Construction

The wall panel used for the Helix Pullout test was constructed by a professional mason. The mortar used was also mixed by the mason. After mixing the mortar, a flow test was performed on the mortar. The wall panel was constructed with single cell concrete masonry units stacked 5 high and 12 wide. Figure 3-2 shows a wall panel used for the Helix Pullout Test. After construction, the walls cured for 28 days before testing began. Several cube specimens were also cast for compression testing.

Figure 3-2: Wall Panel with Helical Ties

3.4 Mortar Testing

Three types of test were conducted for the purposes of this research. A standard compression test was conducted on mortar cube and cylinder specimens. Double Punch Tests (DPT) was conducted on slices of mortar. The Helix Pullout Test was conducted on the mortar bed joints of the masonry wall panel.

3.4.1 Compression Tests

Both cube and cylinder specimens were tested in compression. All specimens were tested on a Forney Compression machine as shown in Figure 3-3. The specimens were tested at a controlled displacement rate of 0.13 in./min. Figure 3-4 shows a typical mortar cube after testing, which experienced a standard and expected mode of failure. The compressive strength was calculated using the procedure specified in ASTM C109.

Figure 3-3: Forney Compression Testing Machine

Figure 3-4: Mortar Cube After Compression Testing

3.4.2 Double Punch Test

The Double Punch Test was used in an effort to obtain compression test results that better represent the compression conditions of an actual mortar joint. Before testing could begin, Mortar cubes were first cut into slices. Several thicknesses of slice were used for the test. The Double Punch Test has been used by researchers before, but to the knowledge of the author, it has never been tested with variable thicknesses of mortar joint.

3.4.2.1 Sample Preparation

As previously mentioned, specimens used for the Double Punch Test were obtained from cutting cubes to various thicknesses. This was achieved by using a masonry table saw to cut the cubes as shown in Figure 3-5. The chosen thicknesses were ¼ in., ⅜ in., ½ in., and ⅝ in. Because of difficulties in holding the cubes in place while cutting, the actual thicknesses of mortar slice varied slightly from their intended thicknesses. This however did not compromise the results, because the thickness of each sample was recorded before testing.

Figure 3-5: Masonry Table Saw

3.4.2.2 Test Device

The primary test devices used for the Double Punch Test were 2 steel punches. The steel punches were fabricated specifically for this research. The diameters of the punches were chosen based on the review of previous literature. The specific dimensions of the punches were also given in German standard DIN 18555-3 (1982) for performing the test. Each punch was fashioned from a 1 inch diameter steel rod that was tapered at the edges to produce a ¾ inch diameter compression surface. The actual diameters were determined as an average of 6 measurements of each punch with a digital caliper. The actual diameters were slightly larger than ¾ inch, but the tests were not compromised by this fact, as the actual loading surface area was used. The 2 steel punches also differed in diameter by 0.013 in. Because of this, the smaller of the 2 diameters was used for calculating the area of the compression face. Using the smaller diameter results in higher strength calculations. However, because the punch with the smaller diameter will also experience higher stress, the specimens will fail at that smaller surface. Thus the use of the smaller diameter is accurate. The steel punches were mounted onto an Instron tension and compression machine, and used to compress each sample for the Double Punch Test. A picture of the punches is shown in Figure 3-6.

Figure 3-6: Steel Punches

3.4.2.3 Testing Process

The Double Punch Test was performed for each slice of mortar cube. For each sample, 2 measurements on opposite sides were taken of the thickness. Then, the center of the sample was placed between the 2 punches. After that, the specimens were tested at a constant rate of 0.025 inches per minute. Each sample was compressed past failure, and the load recorded continuously by the data acquisition system. The process was repeated for each sample. Figure 3-7 demonstrates a typical Double Punch Test sample and setup.

Figure 3-7: Double Punch Test Setup

Figure 3-8: Mortar Specimen Tested with the Double Punch Test

3.4.3 Helix Pullout Test

After the wall panels cured for 28 days, pilot holes were drilled along the bed joints at a spacing of 8 in. on center. Two sizes of helix were used for the testing, and thus 2 sizes of pilot hole were used as well. The 2 sizes of Helix were 0.315 in. and 0.394 in. One side of the wall panel was used for 0.315 in. helices and the other side of the wall panel was for 0.394 in. helices. The sizes of pilot hole used were 5/32 in. and 3/16 in. The holes were drilled in approximately the middle of each cell. This was done so that a consistent thickness of mortar would be tested with each helix. After the pilot holes were drilled into the wall panels, the helices were inserted into the holes with a Hammer Drill.

A helix pullout device was used to slowly pullout each helix and the maximum load was recorded. The test device used for initial tests did not have a sufficiently large pulling capacity, as most helical ties reached the capacity of the extraction device before the helix was extracted. Therefore, the test was repeated on undisturbed mortar by drilling new pilot holes 1.5 inches from the original pilot holes. No observed disturbance was found by visual inspection to be more than ¾ in away from any original hole thus, 1.5 inches was determined to be an adequate distance. Figure 3-8 shows, on the left, the hole left after initial Helix tests, and on the right, the pilot hole for the second round of tests. After new helices were inserted, the tests were repeated with a higher capacity device. The higher capacity device is shown in Figure 3-9. The second round of tests did not have any helix that exceeded the maximum capacity of the test device.

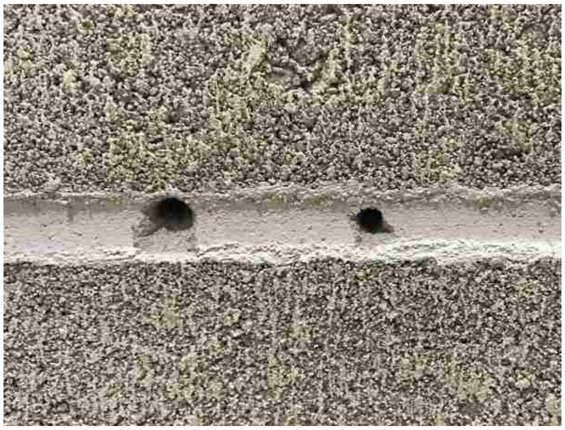


Figure 3-9: Original Helix Hole and Secondary Pilot Hole

Figure 3-10: Helix Pullout Device

3.4.3.1 Compression Cube Tests

As mentioned in Section 3.3.3, several cubes were made from the same mortar used to make the wall panel and these cubes were tested in compression. The testing equipment and process were identical to the equipment and process detailed in Section 3.4.1.

3.4.3.2 Helix Cube Tests

Some of the cubes made from the wall panel mortar were tested using the same Helix Pullout Device. This was done to develop a relationship between the cube compression tests and the Helix Pullout tests performed on the walls. To do this, the cubes were pre-drilled, just as with the wall panel. After pre-drilling, 0.315 in. helical ties were inserted 1.25 in. into the center of the cubes. A depth of 1.25 in. was used to match the face shell thickness of the CMU used to construct the wall panel. The cubes, with helices inserted into their centers, were placed against a metal plate with a small hole in the center. The protruding helix was fed through the hole and connected to the pullout device on the other side of the plate. This test setup is demonstrated in Figure 3-10. The test was performed in the same manner as the Wall Panel tests.

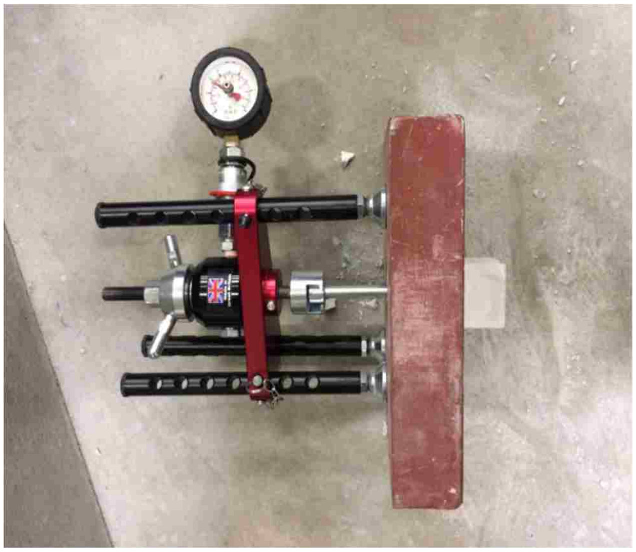


Figure 3-11: Helix Cube Test Setup

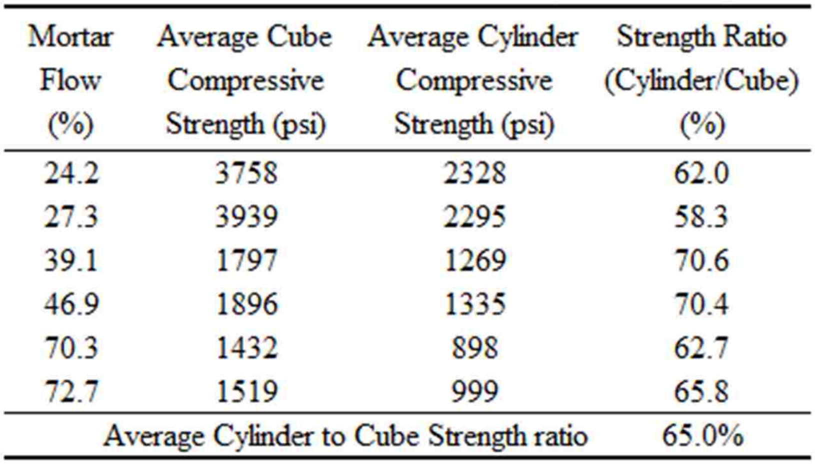
4 RESULTS

The sections that follow present the results from testing performed according to the procedures aforementioned listed. A discussion of the results is presented in the following chapter.

4.1 Compression Testing

The results from the compression tests on cubes and cylinders at various water contents are presented in Table 4-1. The average compressive strengths of cubes and cylinders are compared to establish a ratio of their strengths.

Table 4-1: Mortar Cube Versus Mortar Cylinder Strength



Mortar Flow (%)	Average Cube Compressive Strength (psi)	Average Cylinder Compressive Strength (psi)	Strength Ratio (Cylinder/Cube) (%)
24.2	3758	2328	62.0
27.3	3939	2295	58.3
39.1	1797	1269	70.6
46.9	1896	1335	70.4
70.3	1432	898	62.7
72.7	1519	999	65.8
Average Cylinder to Cube Strength ratio			65.0%

4.1.1 Mortar Flow Versus Compressive Strength

The results of the compressive testing of both cubes and cylinders were plotted versus the mortar flow, and is shown in Figure 4-1. For both specimen types, a power curve trendline was obtained. The equation of cube strength trendline is given in Equation (4-1) and the R^2 value for this equation is 0.837. The equation of cylinder strength trendline is given in Equation (4-2) and the R^2 value for this equation is 0.788. Power curve relationships were chosen because Abrams' Law, which is a power curve relationship, has been shown to be a valid relationship between the water content and compressive strength of mortar by Gangolu (2001).

$$f'_{m\text{-cube}} = 54{,}349(x)^{-0.86} \tag{4-1}$$

$$f'_{m\text{-cylinder}} = 34{,}334(x)^{-0.85} \tag{4-2}$$

where: $f'_{m\text{-cube}}$ = compressive strength of mortar cube
$f'_{m\text{-cylinder}}$ = compressive strength of mortar cylinder
x = mortar flow in percent

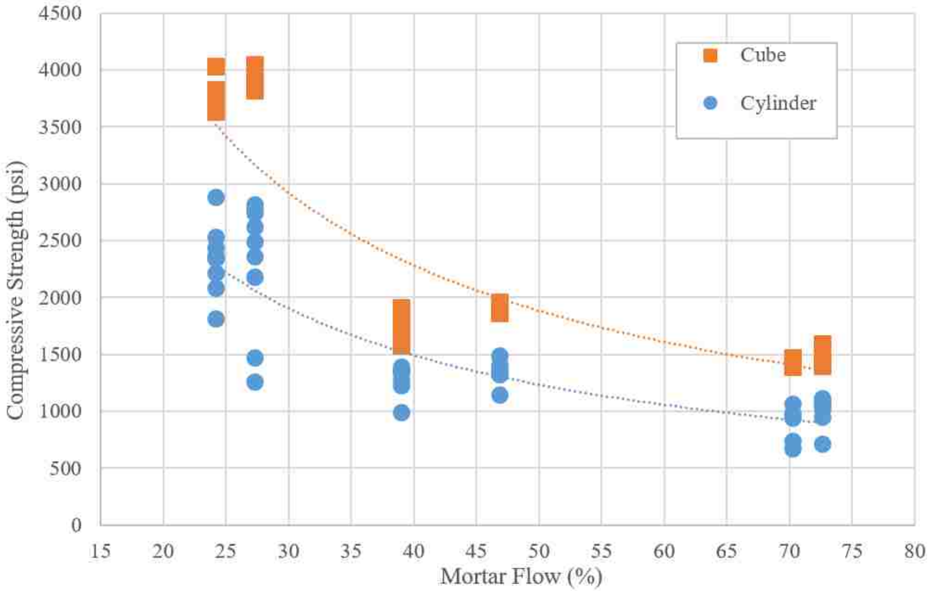


Figure 4-1: Mortar Flow Versus Compressive Strength

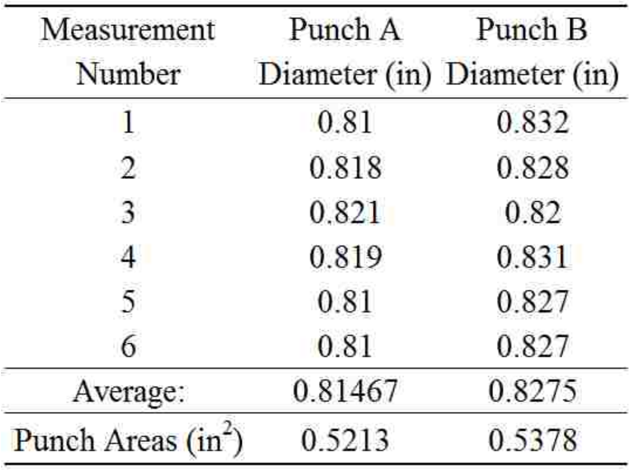
4.2 Double Punch Testing

The results from the Double Punch testing is presented in the following sections.

4.2.1 Steel Punch Areas

The steel punches used for the Double Punch Test were custom fabricated, and designed to be ¾ inches in diameter, but were actually slightly larger. The measured diameters and average diameter and corresponding areas are shown in Table 4-2. The area of the smaller diameter punch was used for strength calculations for the Double punch test.

Table 4-2: Steel Punch Areas



Measurement Number	Punch A Diameter (in)	Punch B Diameter (in)
1	0.81	0.832
2	0.818	0.828
3	0.821	0.82
4	0.819	0.831
5	0.81	0.827
6	0.81	0.827
Average:	0.81467	0.8275
Punch Areas (in^2)	0.5213	0.5378

4.2.2 Typical Punch Test Behavior

During testing of the mortar samples with the Double Punch test, a typical behavior was noticed. For thinner samples, typically less than ½ in. thick, the load would typically gradually increase to the maximum load, then gradually decrease. Occasionally a crack would initiate instantaneously, and the load would make a small drop, then continue to increase. This type of behavior is demonstrated in Figure 4-2 for the Load vs Displacement of a mortar sample 0.419 in. thick.

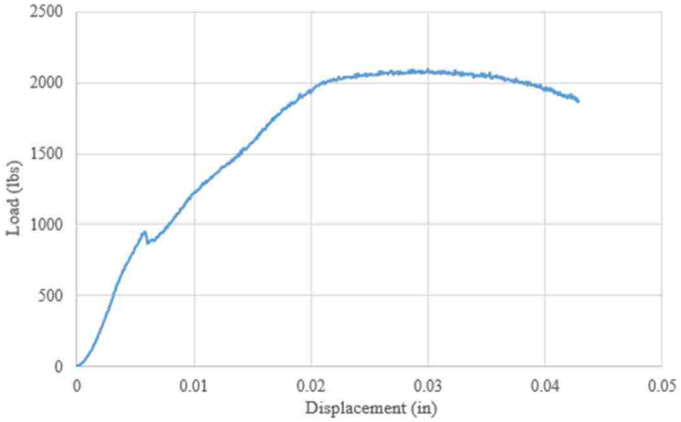


Figure 4-2: Load Displacement Plot For 0.419 in. Thick Sample

4.2.3 Double Punch Strength Results

The strength results for the 4 different flows of mortar are shown in Figure 4-3. This includes all tested specimens at all the measured thicknesses. For each flow a curve was fitted and these same curves are shown again in Figure 4-4 with their respective equations.

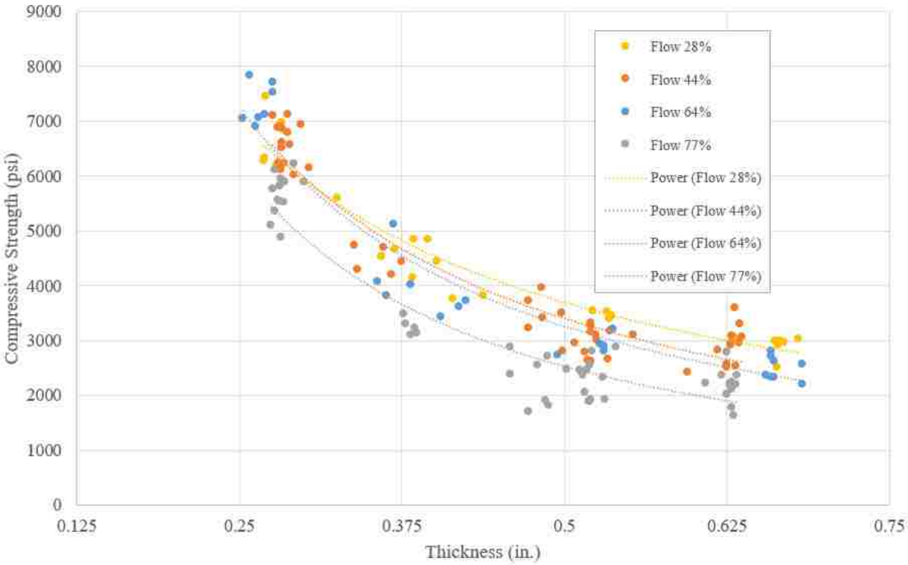


Figure 4-3: Double Punch Strength Results

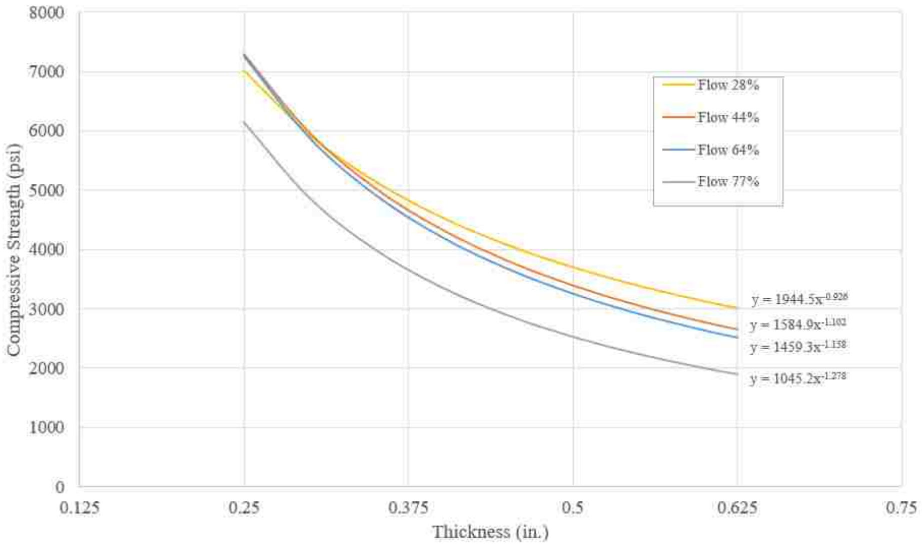


Figure 4-4: Average Strength Results for the Double Punch Test

Comparisons between the average strengths of 3/8 in. thick specimens tested with the Double Punch test, standard cube test, and the recommended strength of Type N mortar cubes of 750 psi, are presented in Table 4-3 for the 4 mortar flows tested.

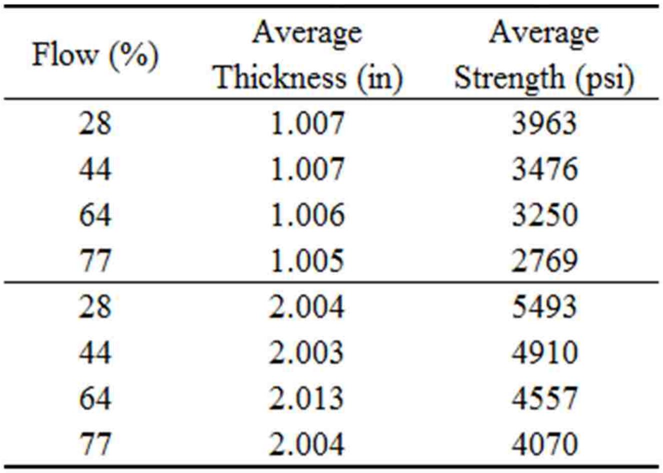
Table 4-3: Strength Comparisons

Flow (%)	DPT 3/8 in. Strength (psi)	Cube Strength (psi)	Strength Ratio (3/8 in. vs Cube)	Strength Ratio (3/8 in. vs ASTM C270)
28	4832	3095	1.56	6.44
44	4615	2098	2.20	6.15
64	4553	1520	3.00	6.07
77	3662	1297	2.82	4.88

4.2.4 Thicker Specimen Testing

For exploratory reasons, thicker specimens were also tested with the Double Punch Test. Both samples cut to a thickness of 1.0 inch and full cubes were tested in the same manner as the other Double Punch Test samples. The results of this testing are shown in Table 4-4.

Table 4-4: Thicker Specimen Strengths



Flow (%)	Average Thickness (in)	Average Strength (psi)
28	1.007	3963
44	1.007	3476
64	1.006	3250
77	1.005	2769
28	2.004	5493
44	2.003	4910
64	2.013	4557
77	2.004	4070

It was also noticed from testing of the thicker specimens that the behavior was significantly different. For the thick samples, load would gradually increase until there was a sudden loss of a large percentage of the load. This behavior is demonstrated in Figure 4-5 for the Load vs Displacement of a mortar sample 2.012 in. thick.

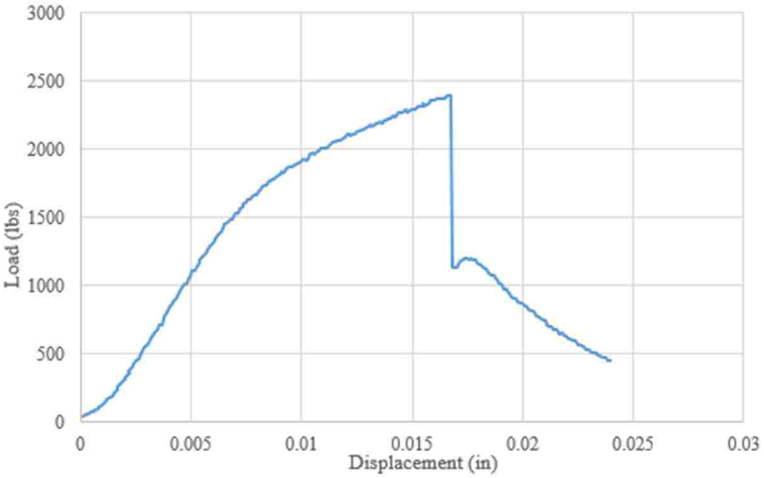


Figure 4-5: Load Displacement Plot For 2.012 in. Thick Sample

4.3 Helix Pullout Testing

The Helix Pullout Test involved measuring the pullout loads from wall panels and mortar cubes. Compression tests of mortar cubes were also conducted to determine the strength correlation between pullout load and compressive strength. The results from these tests are described in the proceeding sections.

4.3.1 Helix Pullout Wall Test Results

The tests were performed on a single wall panel made with Type N mortar. The results of the second trial of pullout testing are shown in Figure 4-6. The average Pullout loads are separated by Helix sizes, as well as horizontal row on the wall panel. The error bars range from the median for each row and helix size, by one standard deviation. The mortar flow was 37% for all Helix Pullout samples.

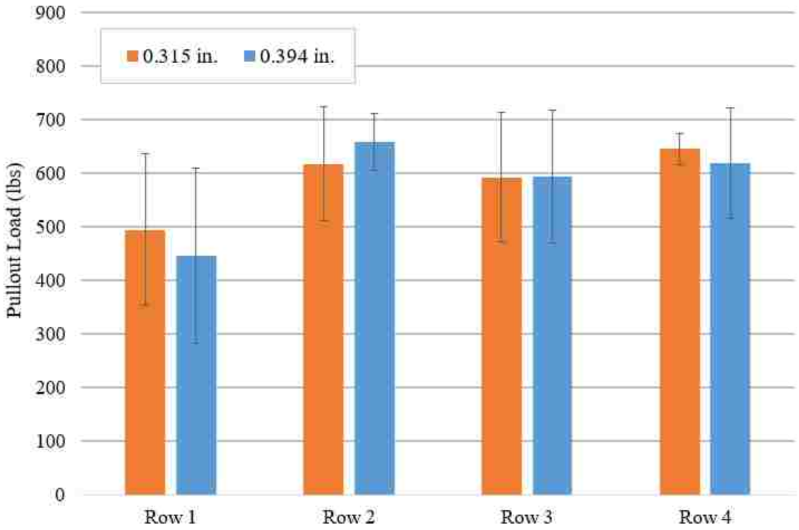


Figure 4-6: Helix Pullout Loads for 0.315 in. and 0.394 in. Helices

4.3.2 Compression Cube Tests

Several cubes were made with the same mortar used to construct the Wall Panel, to determine the unconfined compressive strength of the mortar for comparison to results from the Helix Pullout Test. The results of the compressive strength tests are summarized in Table 4-5.

Table 4-5: Cube Compressive Loads

Sample Number	Compressive Load (lb)
1	9595
2	10415
3	10585
4	11110
5	9275
6	10230
Average	10202
Compressive Strength (psi):	2550.4

4.3.3 Helix Cube Tests

The results of the Helix Cube test described in Section 3.4.3.2 are presented. The average pullout load for all 18 cubes was 521 lbs with a standard deviation of 48 lbs.

5 ANALYSIS

In this chapter the analysis of the results given in Chapter 4 is presented. A discussion of the Compression testing, Double Punch Testing, and Helix Pullout testing is also given.

5.1 Compression Testing

The average compressive strength of the mortar with the highest flow, which corresponded to the second lowest strength, was 1519 psi. This is well above the minimum required compressive strength of 750 psi from ASTM C270 (ASTM Standard C270-14a 2014). The strength recommended by ASTM however, is for a mortar flow of 110% ± 5%. The highest mortar flow measured from all testing done by the author was 73%, which is much lower than 110%, which could explain why the compressive strength was so much higher than 750 psi. Even though the flow for the mortar tested did not reach the levels prescribed by ASTM, the results are still valid because the lower flow values were likely caused by the fact that bagged mortar was used for testing. Bagged mortar contains admixtures that affect strength and workability characteristics. The results are also valuable because bagged mortar is commonly used in the field.

The compression testing results show that mortar cubes were approximately 40-70% stronger than mortar cylinders of the same water content and flow. Furthermore, as the water content and mortar flow increased, the compressive strength of both cubes and cylinders typically decreased. Both of these results were expected, and thus confirmed through testing.

5.1.1 Mortar Flow Versus Compressive Strength

The comparison between mortar flow and compressive strength produced some interesting results. Cementitious materials generally experience decreased strength with increased water content. This behavior was noticed in results of the mortar testing, with only minor variations. The mortar flows for both cubes and cylinders can basically be broken into 3 groups, each with similar flows. Of the 3 groups, those with higher flow experienced lower compressive strength. Within all 3 of the groups however, the opposite effect was observed: the higher flow specimens had slightly higher strength. This is likely the cause for the relatively low R^2 values of 0.837 and 0.788 for cubes and cylinders, respectively.

5.2 Double Punch Testing

The results of the Double Punch testing including steel punch areas, typical test behavior, Double Punch strength results, and thicker specimen testing, is discussed and evaluated in the following sections.

5.2.1 Steel Punch Areas

Although the two steel punches did not have the same diameter and area, their areas differed by only 3%, which was determined to be a sufficiently small deviation. The smallest punch area was used because both punches are always used together, and they must compress each side of the mortar sample with the same force (excepting for the weight of the mortar, which was nominal), meaning that the smaller area punch will deliver a higher, and more critical compressive stress.

5.2.2 Typical Test Punch Behavior

The typical loading behavior of the double punch samples indicated some interesting results. A trend that was noticed was that as the thickness of samples increased, the sudden drops in load also became larger, and more frequent. This loading pattern is compared to the loading pattern of thicker samples.

5.2.3 Double Punch Strength Results

Several things are determined from the results of the Double Punch testing. Firstly, it is shown that as specimen thickness increased, the compressive strength decreased. Possible explanations for this relationship include the increased aspect ratios leading to lower strength, and also that larger specimens will contain a greater number of slippage planes and material defects, increasing the probability of failure.

Secondly, it was also shown that compressive strength generally decreased with increased water content and mortar flow. This conforms to conventional knowledge of cementitious materials. This effect also experienced variation, as observed in Figure 4-4, that some of the curves occasionally crossed each other. A likely cause for this was in the variability of the flow of mortar. Despite mixing each of the high, medium, and low water content batches with the same proportions, the flow always varied. This could indicate that the bagged mortar mix was not completely homogeneous. There could have been higher concentrations of fine aggregate, or cement in different portions of the bag.

Despite the minor variations, the results reflect what the author expected to find from the testing. Mortar, and cementitious materials in general, are extremely sensitive to minor variations, and thus small differences in trends and results were expected.

From Table 4-3 it is seen that the mortar cube test is highly conservative. On average the 3/8 in thick specimens tested with the Double Punch test were 2.40 times as strong as mortar cubes of the same flow. The 3/8 in. thick specimens had an average of 5.89 times the strength recommended for Type N mortar in ASTM C270.

5.2.4 Thicker Specimen Testing

The thicker specimens tested with the Double Punch Test displayed similar behavior patterns to the thinner specimens. As the flow increased, strength decreased for both specimen thicknesses. There is a reversed relationship however, with the thicker specimens. The full 2 inch cube specimens had higher compressive strengths than the 1 inch thick specimens. On average, the full cubes were 42% stronger than the 1 inch slices. A likely reason for this is that the thicker samples deviated from the punch diameter even further, making them less appropriate for testing with that size of punch, as determined by Sassoni, et al. (2015). Further testing is necessary to determine the reason why the thicker specimens observed higher strength.

5.3 Helix Pullout Testing

The results of the Helix Pullout testing, including pullout loads, cube compressive strengths, and cube pullout loads, are discussed and evaluated in the following sections.

5.3.1 Helix Pullout Wall Testing

From the wall testing, a clear relationship between strengths from 0.315 in. and 0.394 in. helices could not be determined. For half of the rows the 0.315 in. helices were stronger, and for the other half they were weaker. The average pullout load from the 0.315 in. helices was 588 lb, and the average pullout load from the 0.394 in. helices was 579 lb. This indicated that the 0.315 in. helices are stronger, but by a nominal amount, and based on the variation in pullout loads further testing could indicate that the 0.394 in. helices were actually stronger. This suggests however, that the pullout load is not dependent on helix size. Despite this there was a slight trend of increasing pullout load with lower rows, indicating that the compressive load on the sample will affect the pullout load. This trend is not definite though, with only really a difference between the top row, and the bottom 3 rows.

Overall, the large variations in pullout load do not allow the determination of any strong relationships between helix size, compressive load, and pullout strength. As shown in Figure 4-6, sometimes the error bars show a range in strength almost as much as the average strength. This underlies the importance of using the Helix Pullout test as only a qualitative, and comparative test, as opposed to a quantitative test.

5.3.2 Compression Cube Tests

The average compressive strength of the cubes made from mortar used to build the wall for Helix Pullout testing was 2550 psi. This is well above the minimum required compressive strength of 750 psi from ASTM C270. This compressive strength is also significantly higher than the maximum recommended mortar strength of 1450 psi obtained by researchers Ferguson and Skandamoorthy (1994). They determined that mortars with a compressive strength above this range did not show any strong relationship between pullout load and compressive strength. This is a likely reason for the large variations in pullout load. These conclusions make the Helix Pullout load difficult to recommend for many structural mortars, as several mortar types have recommended strengths in excess of 1450 psi.

5.3.3 Helix Cube Tests

The average pullout load for the cube specimens was 521 lbs. This is lower than the pullout loads of 588 lbs and 579 lbs for the 0.315 in. and 0.394 in. helices respectively. It was expected that the cubes would experience a lower pullout load, as the mortar in the wall released water to the surrounding blocks, and was confined by surrounding mortar and bricks, both of which would increase the strength. These results are increasingly useful when used in comparison with the results of Type S mortar testing done in conjunction with testing of Type N mortar. The author and Moffett (2018) performed the same tests on the two mortar types. Moffett determined that for Type S mortar the compressive strength was at least 3795 psi, the 0.315 in. helix pullout load was 703 lbs, the 0.394 in. helix pullout load was 745 lbs, and the cube pullout load was at least 612 lbs. This shows a positive correlation between compressive strength and pullout loads. But as stated earlier, the correlation is to be used only comparatively.

6 CONCLUSIONS

6.1 Summary

A laboratory study was performed to determine the effects of thickness and confinement on the compressive strength of mortar. The study was performed primarily to determine a relationship between the compressive strengths of ASTM standard compression cubes, and in-situ mortar. Two tests were performed to determine such a relationship. The Double Punch test was performed on slices of varying thickness of cured mortar cubes. The Helix Pullout test was performed on a wall panel, and cubes comprised of the same mortar as the wall were tested in compression as well as with the Helix Pullout test. Test results were examined and individually compared.

6.2 Findings

Though not a comprehensive study of the compressive strength of mortar, several conclusions can be made from the results and findings. With further testing, the results presented herein can be refined and further built upon. The following conclusions can be drawn based on the results of this study, which are limited by the range of thicknesses and water contents tested:

1. The water content, and resulting mortar flow, of a mortar mix will affect the compressive strength of that mix. Specifically, as the water content and mortar flow

increase, the compressive strength of the mortar will decrease. This was verified with the testing of 3 water contents tested in mortar.

2. The average compressive strength of mortar cylinders was approximately 65% of the compressive strength of mortar cubes. This is lower than the suggested ratio of 85% recommended in ASTM C780. This difference could have been caused by the lack of caps on the cylinders, which would increase their strength.
3. The compressive strength of mortar specimens decreases with increased specimen thickness. This effect was determined using the Double Punch test. There was some slight variation in the results, likely caused by material inconsistencies, but in general the effect was observed for all specimens. On average the mortar specimens that were 3/8 in. thick were 2.40 times as strong as a mortar cube with the same flow. This illustrates the degree to which the cube compression test is conservative.
4. The thickness of a mortar specimen will affect its failure mode. As observed with the thicker samples tested with the Double Punch test, thicker samples failed in a more sudden manner, as opposed to thin samples, for which the compressive load gradually increased then gradually decreased.
5. With wide variation in results from the Helix Pullout test, definitive trends or relationships were unable to be made between helix size, pullout load, and compressive strength. This makes the use of the Helix Pullout test primarily suitable for qualitative comparison rather than quantitative determination of strengths.

6.3 Recommendations for Future Research

Additional testing on the subject would be beneficial to better understand mortar compressive strength and how it is affected by important variables. The following suggestions based on this research study will aid the further study of mortar compressive strength:

1. Test actual extracted mortar joints as opposed to slices of mortar cubes, with the Double Punch test. Although the results from testing with the Double Punch test were useful and revealing, the complex nature of in-situ mortar could be more accurately represented by testing samples extracted from mortar joints.
2. Test mortar cylinders with caps on both ends to remedy the lower compressive strengths, which were caused by rough contact surfaces. Doing so could likely produce results more in line with the suggested cylinder strength of 85% the strength of a similar mortar cube.
3. Perform the Double Punch tests with punches of varying diameters to determine the effect and relationship of punch diameter compared to specimen thickness, and compressive strength.
4. Perform further testing with the Helix Pullout Test in an attempt to determine better trends and relationships between pullout load and compressive strength. The Helix Pullout test is relatively easy to perform, which would make it an appealing test if better strength determinations could be obtained.

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