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Research Report

Effect of Thickness and Water Content on the Compressive Strength of Mortar

Prepared by

Fernando S. Fonseca
Professor

Johnn P. Judd
Assistant Professor

Theodore J. Moffett, Michael S. Reynolds, and Braden Day
Graduate Research Assistants

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Kurt Siggard
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EXECUTIVE SUMMARY

Mortar compressive strength is determined in accordance with the test method described in the American Society for Testing and Materials (ASTM) standard C109/C109M (ASTM C109 2016), which specifies the size of the specimen as 2-in. cube. However, there is a disparity between the compressive strength of a 2-in. mortar cube and that of a mortar in a bed joint, which is typically 3/8-in. thick. The disparity is due to many factors including differences in thickness and water content. The 2-in. mortar cube is also not confined during testing while the mortar in a bed joint is confined by the surrounding masonry units. It is hypothesized that these differences lead to the mortar in a bed joint to have a higher compressive strength that that obtained from the testing of mortar cubes.

To evaluate the effect of thickness and water content on mortar compressive strength, mortar specimens of different thicknesses and water contents were made and tested. The compressive strength of the mortar was also determined using the conventional 2-in. cube specimen. The cube specimens were tested using the standard compression test method while the thin specimens were tested using the double punch test method.

The test results showed that the mortar exhibited an increased in compressive strength with decreasing specimen thickness. The mortar also exhibited an increase in compressive strength with decreasing water content. The compressive strength of a 3/8-in. thick mortar specimen, which is the typical thickness of a mortar bed joint, was conservatively estimated to be twice the compressive strength of the 2-in. cube.

ACKNOWLEDGEMENTS

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The research would not have been conducted successfully if were not for the managers of the structural and materials laboratories of Brigham Young University, Dave Anderson and Rodney Mayo.

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1 INTRODUCTION

This chapter provides the background and motivation for the research, defines the objective of the research and its scope, and provides a summary of what is included in this report

1.1 Background

Procedures for determining the mechanical and physical properties of mortar are established by the American Society for Testing and Materials (ASTM). The ASTM C109 (ASTM C109 2016) procedures are used for determining the compressive strength of mortar. These procedures involve making 2-in. mortar cubes and testing them in compression. The compressive strength is calculated by dividing the maximum measured load by the cross-sectional area of the cube. The method is a simple and efficient manner of determining mortar compressive strength. Nevertheless, there are three aspects of the method that affect its relevance to mortar joint: (1) the thickness and aspect ratio of a 2-in. mortar cube and a typical 3/8-in. mortar joint are quite dissimilar; (2) the mortar within a bed joint is confined by the surrounding masonry units, i.e., it is under a tri-axial state of stress; and (3) the surrounding masonry units absorb water from the mortar in a bed joint, but the nonabsorbent molds used to cast the 2-in mortar cubes do not absorb water from the mortar. For these reasons, it is thought that the 2-in. mortar cube may not be the best means of determining the compressive strength of mortar in a mortar joint.

1.2 Research Objective

The objective of this research is to develop a relationship between the mortar compressive strength and its thickness and water content. To achieve this objective, the ratio between the compressive strength of 2-in. mortar cubes and that of 3/8-in. thick mortar specimens with different water contents and the ratio between the compressive strength of 2-in. mortar cubes and that of 2 by 4-in. mortar cylinders were determined using two types of tests. Standard compression tests were conducted on 2-in. mortar cubes and 2 by 4-in. mortar cylinders. The double punch test (DPT) method was used to determine the compressive strength of thin mortar specimens.

1.3 Scope of Research

The testing and results of this research program apply to mortar types S and N. Specimens were (a) cured in a fog room at approximately 73° F with 96% humidity and (b) air-cured in the laboratory at approximately 70° F. All mixing and testing took place in a laboratory with controlled humidity and temperature.

Preblended mortar mixes from the same manufacturer and from the same pallet were used in an attempt to reduce variability of materials. The research team used three water contents, to make the mortar. These water contents were selected during a preliminary testing phase, which is not reported herein.

A professional mason also made a mortar and its water content was determined. This mortar was proved to have the necessary workability for laying mortar by being used in the construction several concrete masonry prisms, which were used on another research project.

1.4 Report Organization

This report is organized into four chapters:

- Chapter 1 provides the background and motivation for the research, defines the objective of the research and its scope, and provides a summary of what is included in this report.

- Chapter 2 contains a brief review of the literature regarding the standard compression test and the double punch test. Mortar cube strength versus joint strength is also discussed.

- Chapter 3 describes the test materials and procedures. It describes the mortar made by the research team, including the size of the batch, the water contents, and the mixing procedures, the mortar made by the professional mason, the mortar flow test, and the mortar specimens (cubes, cylinders, thin specimens cut from cylinders, and thin specimens assembled between blocks). It also describes the compression tests and presents the test matrix.

- Chapter 4 presents the results from the compression tests and the double punch tests. The cube specimen and thin specimen compressive strengths are determined, and the properties of the field prepared mortar are determined.

- Chapter 5 concludes the report. The research is summarized and the principal findings are identified.

2 LITERATURE REVIEW

This chapter contains a brief review of the literature regarding the standard compression test and the double punch test. Mortar cube strength versus joint strength is also discussed.

2.2 Standard Compression Test

The standard method for determining the compressive strength of mortar is set forth in ASTM C109 (ASTM C109 2016), which specifies that mortar compressive strength is to be determine using a 2-in. mortar cube. The mortar cube is to be formed in a nonabsorbent, hard metal mold, and is to be cured for 28 days prior to compressive strength testing. The testing is conducted by placing the cube under the loading platens of a compression machine and loading it until failure. The compressive strength is calculated as the maximum load recorded divided by the cross-sectional area of the cube. The same method is used to determine the compressive strength of mortar cylinders.

2.3 Double Punch Test Method

The double punch test (DPT) is a minor destructive test that has been used to estimate the compressive strength of in-situ mortar. The DPT seeks to derive a compressive strength by means of compressing the center area of a specimen with steel rods (or punchers). The DPT has been most widely used to estimate the compressive strength of mortar from historical structures. The DPT has the potential to provide a more accurate estimation of the compressive strength of in-situ mortar because the center part of the specimen, the part being compressed, is confined by the surrounding mortar.

2.3.1 Double Punch Test Method Development

Henzel and Karl (1987) conducted research to develop a straightforward, new test to determine the compressive strength of in-situ mortar. The authors conducted preliminary tests on 40 mm x 40 mm x 62.5 mm prisms and 40 mm x 40 mm x 10 mm thin slices. The thin specimens were capped with a thin layer of gypsum and tested using 20 mm, 25 mm, and 30 mm. diameter punchers to determine the optimal punch diameter for the newly developed test and to establish a calibration curve for the relationship between the strength of the thin specimens and that of the prisms. The results showed a strong relationship between the strength of the small prisms and that of the thin specimens. Based on the results of the tests, the authors suggested that a ratio of 2 between the thickness of the punch and the sample should be used.

The authors then used a 50 mm core drill to extract samples of mortar joints from test walls and 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 the 20 mm metal punches. The process used is illustrated in Figure 2-1.

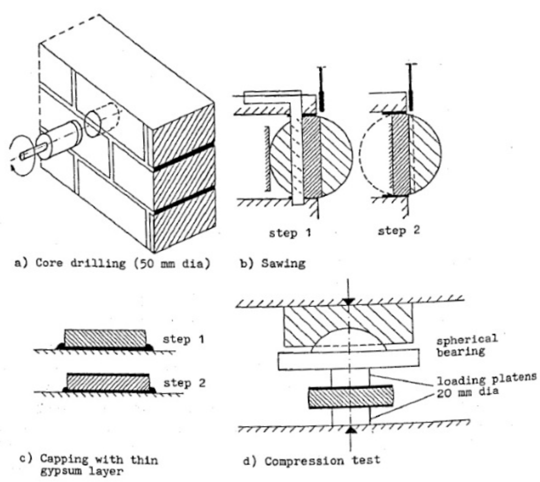

Figure 2-1: Mortar Joint Testing Procedure (Henzel and Karl 1987)

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.

2.3.2 Double Punch Tests and Numerical Modeling

The study by Matysek et al. (2017) compared the results from Double Punch tests to that of a Finite Element Model. The authors used cylindrical mortar samples with a diameter of 50 mm and thickness of 10 mm, 16 mm, and 25 mm. Each sample had a thin layer of gypsum between the mortar and the steel punches. The results obtained using the Finite Element model, shown in Figure 2-2, were compared to those obtained from the physical tests of the mortar, and also to determine the interaction of the mortar, gypsum cap, and steel punches.

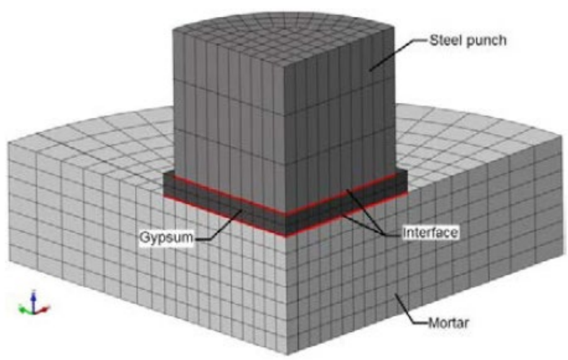

Figure 2-2: Finite Element Model (Matysek et al. 2017)

The authors observed that the predictions of the model were similar to the experimental 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 investigated 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, which indicates that compressive strength depends somewhat on the sample thickness and that thicker samples have a higher maximum displacement. The results presented in Figure 2-4b indicate 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.

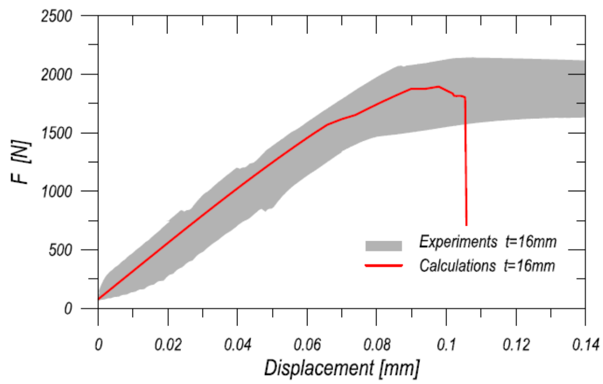

Figure 2-3: Computed vs. Experimental Results (Matysek et al. 2017)

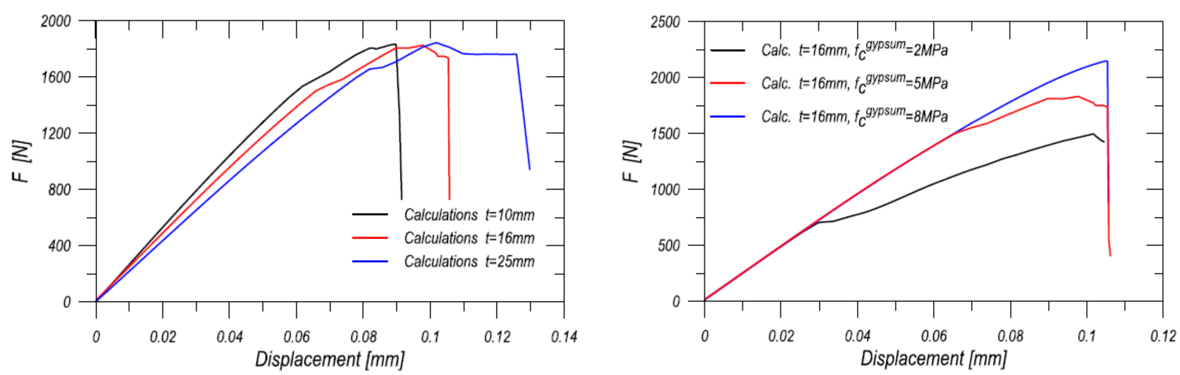

Figure 2-4: Results Based on a) Mortar Thickness, and b) Gypsum Compressive Strength (Matysek et al. 2017)

2.3.3 Mortar Cube Strength versus Mortar Joint Strength

The study conducted by Sassoni et al. (2013) examined the differences in strengths between weak and strong mortars with both mortar joints and prismatic specimens. The primary difference between the weak and strong mortar mixes was the ratio of aggregate to the cement and water. Standard compression tests and DPT were used, and the results were compared to determine the differences in strengths of the sets of specimens.

For the weak and strong mortar, 3 specimen types were made: a standard 40 mm x 40 mm x 40 mm cube, termed M1; a 40 mm x 40 mm x10 mm thin specimen, termed M2; and a 40 mm x 40 mm x10 mm thin specimen extracted from a mortar join, termed M3. To make the M3 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 and cut to the proper dimensions. M1 type specimens were tested using the standard compression test while the M2 and M3 type specimens were tested using the DPT with 20mm punches. The test results are shown in Figure 2-5.

The authors attributed the strength differences between the results of the DPT to that from the standard compression tests to two effects: the difference in aspect ratios and the lack of confinement in the standard compression tests. There is also a large difference in the strengths of the M2 and M3 samples, which were the same size and tested in the same way. The strength difference was attributed to the difference in the microstructures of the 2 sample types. The different microstructures were caused by the differences in compaction between the mortar prism and the mortar joint as well as the absorption of water by the surrounding bricks in the mortar joints, which did not happen in the prisms since they were cast using nonabsorbent molds.

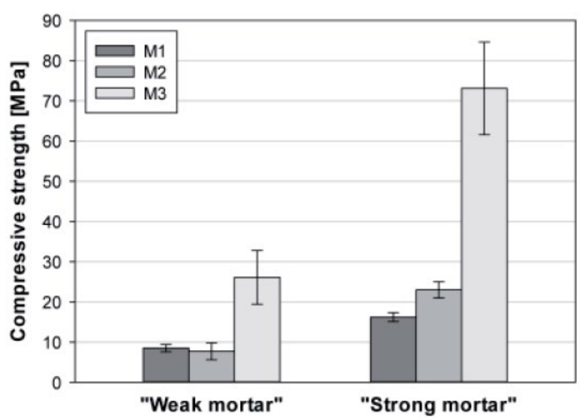

Figure 2-5: Compressive strengths of weak and strong mortar (Sassoni et al. 2013)

3 MATERIALS AND PROCEDURES

This chapter describes the test materials and procedures. The mortar made by the research team, including the size of the batch, the water contents, and the mixing procedures, the mortar made by the professional mason, the mortar flow test, and the mortar specimens (cubes, cylinders, thin specimens cut from cylinders, and thin specimens assembled between blocks) are described. This chapter also describes the compression tests and presents the test matrix.

3.1 Mortar Made by Research Team

To increase the likelihood of consistent mortar properties and in an attempt to minimize ingredient variability, the mortar was made from preblended mortar mixes; and all mortar bags were purchased at the same timer and chosen from the same pallet. Types S and N mortars were used, as represented in Figure 3-1.

Figure 3-1: Preblended Mortar

3.1.1 Mortar Batch Sizes

The mortar was mixed in a mechanical table mixer, which is shown in Figure 3-2, with the dimensions required by ASTM C305 (ASTM C305 2014). Both, the mortar mix and the 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.

Figure 3-2: Mechanical Table Mixer

3.1.2 Mortar Water Contents

Three water contents were chosen to represent a dry, a wet, and an average mix. The wet mix was made with 2.2 lbs of water (22% water content by weight); any more water caused the mix to splash out of the bowl when the mixer was turned on. The average mix was made with slightly less water, 2.0 lbs (20% water content by weight), and the dry mix was made with 1.8 lbs of water (18% water content by weight); any less water made the mix too stiff and appeared to overstress the motor of the mixer.

The amount of water for the dry and wet mixes was chosen so that an upper and lower bound of mortar flows could be obtained. Since mortar compressive strength is inversely affected by the water content, the upper flow bound was expected to correspond to a lower mortar compressive strength bound while the lower flow bound was expected to correspond to an upper mortar compressive strength bound.

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. Since a single batch yielded only enough mortar paste to cast six to seven cylinders and seven to nine cubes, two batches were needed for each mortar water content.

The mixing procedure used was slightly modified from that presented in ASTM C305 (ASTM C305 2005) to accommodate for the fact that preblended mortar mixes were used. 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 mixer speed was increased to medium speed for 30 seconds. The mixer was turned off and the mortar rested for 90 seconds, and within the first 15 seconds of the resting time, the mortar on the sides of the bowl were scraped down. After the resting time, the mortar was mixed at medium speed for another 60 seconds.

3.2 Mortar Made by Professional Mason

The professional mason supervised the mixing of the mortar, and only type S mortar, from the same manufacturer as that made by the research team, was made. One mortar bag was used and mixed on a wheelbarrow as shown in Figure 3.3. The mixing was stopped once the professional mason deemed the mortar to have proper consistency.

A bucket full of water was pre-weighted prior of the mortar mixing. Once the mortar was mixed and judged to have the proper consistency by the professional mason, the remaining water was weighted. The water content, in percent, was determined using equation 3.1:

$$WC = \left(\frac{WW_{initial} - WW_{final}}{MW} \right) \qquad 3.1$$

where $WW_{initial}$ and WW_{final} are initial and final water weights, respectively, and MW is the mortar weight. The calculated water content was 20.6%.

Figure 3-3: Mixing of Mortar on the Wheelbarrow

3.3 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 C230 2014). The flow test was performed using the procedures specified in ASTM C1437 (ASTM C1437 2015). The flow is reported as a diameter and also as a percent increase in diameter from the inside diameter of the flow mold. The mortar used for the flow test was then returned to the bowl and re-mixed before making specimens. The flow table with a mortar sample is shown in Figure 3-4.

Figure 3-4: Mortar Flow Test

3.4 Mortar Specimens

There were 4 types of specimens used for testing. Mortar cubes and mortar cylinders were used for standard compression testing. Thin mortar specimens were cut from standard 2-in. mortar cubes and tested using the DPT method. For these, a single batch of mortar was not enough to cast all specimens needed for that specific mortar water content; therefore, two batches were needed for each mortar water content; some batches were used to make both cubes and cylinders while others were used to only make cubes. The fourth type of specimens were also thin specimens but assembled between concrete masonry units. These thin specimens were also tested using the DPT method.

3.4.1 Mortar Cubes

The cube molds were filled with mortar, which was tamped according to the specifications in ASTM C109 (ASTM C109 2016). 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 tested in compression.

3.4.2 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 and each lift was tamped with a metal rod 20 times, according to the procedures set forth in ASTM C780 (ASTM C780 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 28-day curing time. After curing for 28 days in the fog room, the cylinders were tested in compression. Although ASTM C780 (ASTM C780 2018) prescribes capping of cylinder specimens, it was determined that the surfaces of the mortar cylinders were sufficiently smooth and plane to allow the omission of capping.

3.4.3 Thin Mortar Specimens – Cut from Cylinder

Thin specimens were obtained from cutting mortar cubes to various thicknesses using the masonry table saw shown in Figure 3-5. The chosen thicknesses were 1/4 in., 3/8 in., 1/2 in., 5/8 in., and 7/8 in. Because of difficulties in holding the mortar cubes in place while cutting, the actual thicknesses varied slightly from their intended thicknesses. The thin specimens had smooth surfaces such that capping was unnecessary. After cutting, the thin specimens were placed back into the fog room.

Due to the time-consuming task of cutting the thin specimens and the testing of the cubes and cylinders, the testing of the thin specimens was not done at 28 days after curing.

Figure 3-5: Masonry Table Saw

3.4.4 Thin Mortar Specimens – Assembled between CMUs

These thin specimens were made using the mortar prepared by the professional mason. Rings were cut from a 2 in. ABS pipe; the rings thickness were 1/4 in., 3/8 in., and 1/2 in. Half size CMUs were used. A very thin slice was cut from each unit face in order to have a smooth surface, as shown in Figure 3.6, to assemble the thin mortar specimens.

A paper towel was attached to the surface of the CMUs as a bond breaker between the mortar specimens and the CMUs. The paper towel also allowed water from the mortar to be absorbed by the CMUs as it would in the field. Figure 3.7 shows the CMUs with the paper towels and the rings on it. Square metal bars having thickness of 3/8 in., 1/2 in., and 5/8 in. were placed on the edges of the CMUs. These bars were slightly thicker than the ABS pipe rings so mortar could flow over the ABS pipe rings when the rings were filled with mortar.

Figure 3-6: CMU

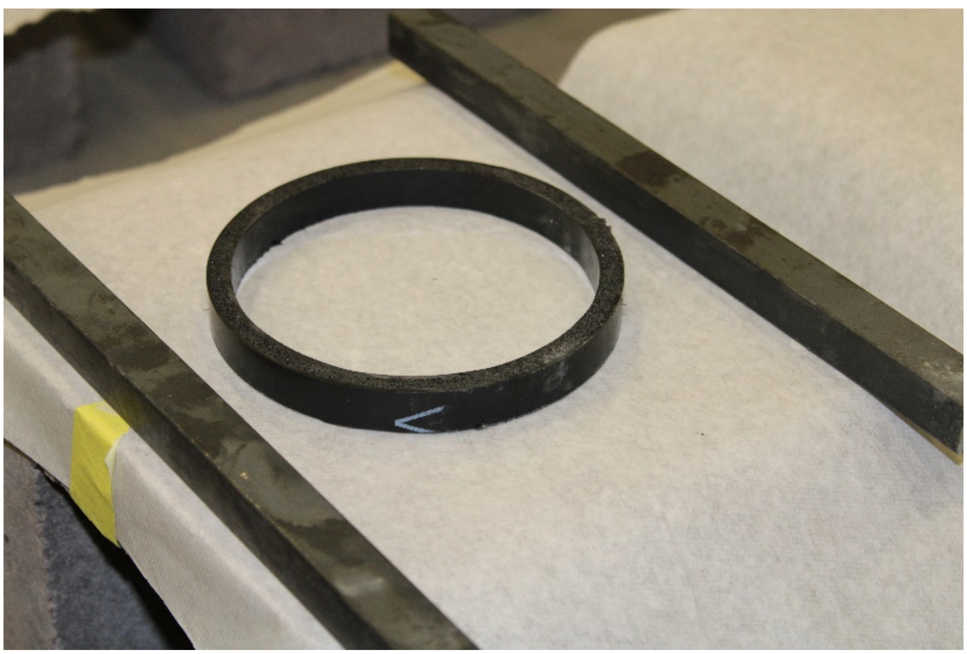

Figure 3-7: CMUs with Paper Towels, Rings, and Square Metal Bars

Mortar was placed inside of the ABS rings as shown on Figure 3.8. A CMU was then placed on top of the mortar and pressed down until it touched the metal bars as shown in Figure 3.9. The square metal bars insure the proper thickness of the final thin mortar specimens.

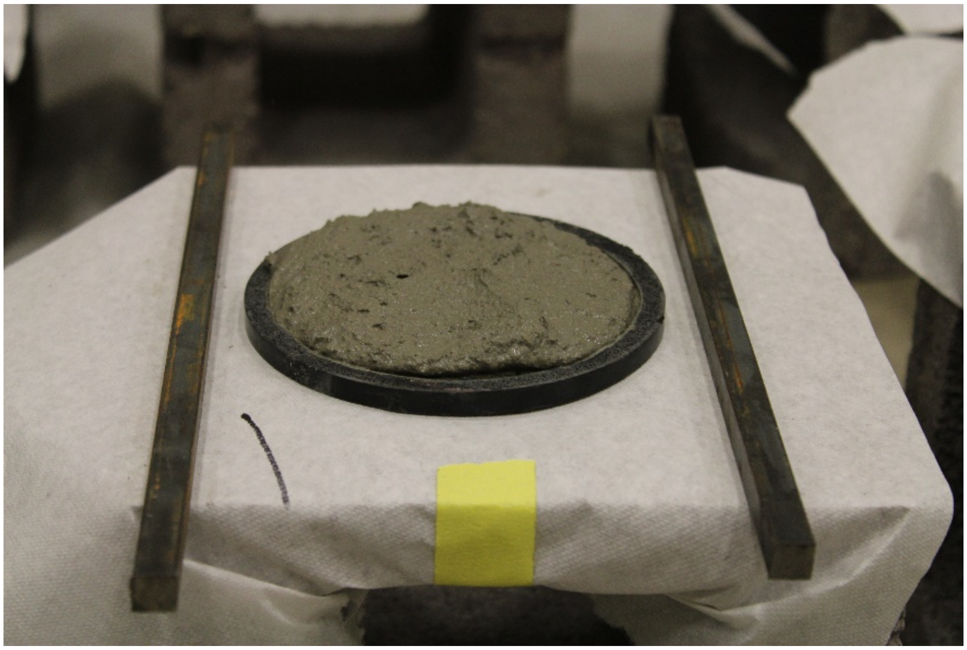

Figure 3-8: Rings Filled with Mortar

Figure 3-9: Mortar Specimen Between CMUs

A preliminary study was conducted to determine the time that the thins specimens could be removed from the assembling setup without breaking. The thin specimens were removed from the setup after approximately 18 hours. A thin specimen is shown in Figure 3.10.

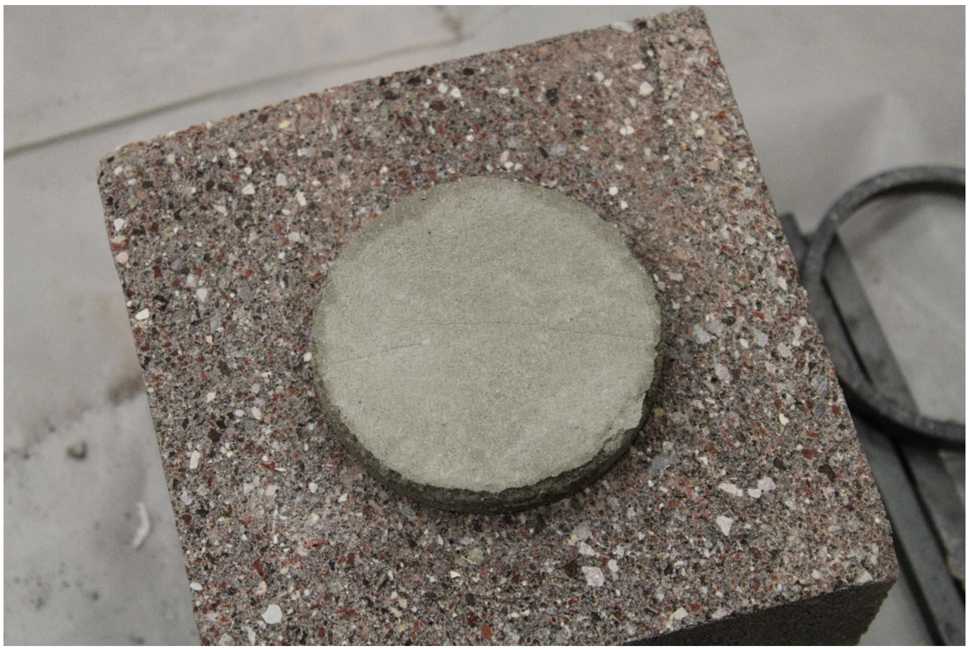

Figure 3-10: Thin Specimen

3.5 Mortar Testing

Two types of test were conducted for the purposes of this research. The standard compression test was conducted on mortar cube and cylinder specimens and DPT was conducted on the thin mortar specimens.

3.5.1 Compression Tests – Cube and Cylinder Specimens

The cube and the cylinder specimens were tested on the Forney Compression machine shown in Figure 3-12 using a controlled displacement rate of 0.13 in./min. Figure 3-13 shows typical failure of mortar cubes and mortar cylinders. The compressive strength was calculated using the procedure specified in ASTM C109 (ASTM C109 2016).

Figure 3-11: Forney Compression Testing Machine

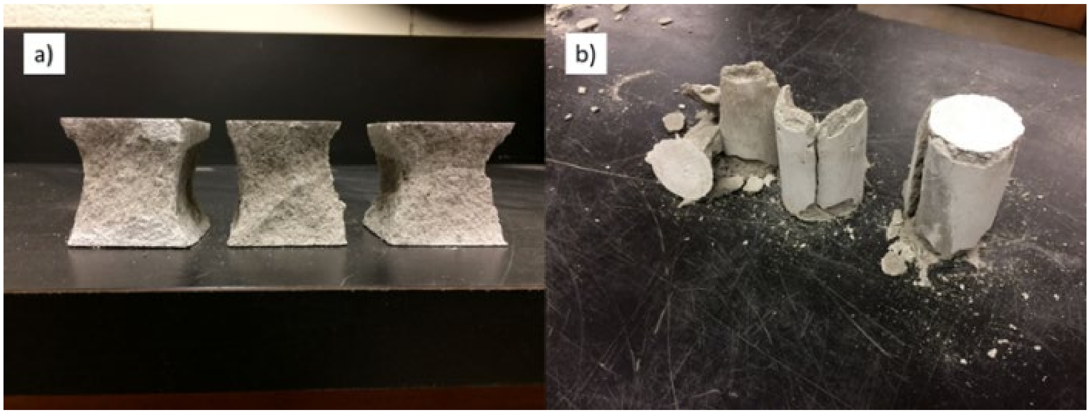

Figure 3-12: Typical Failure Modes of a) Mortar Cubes and b) Mortar Cylinders

3.5.2 DPT – Thin Specimens

The devices used for the DPT were two steel punches, which were manufactured according with the specifications set forth in the standard DIN 18555-9 (1982). Each punch was manufactured from a 1-in. diameter steel rod that was tapered at the edges to produce a 3/4 in. diameter compression surface. The punches are shown in Figure 3-14. The final diameters were slightly larger than 3/4 in., but the tests were not compromised by this fact, as the actual loading surface area was used to calculate the compressive strength of the specimens. The two steel punches differed in diameter by 0.013 in. and the smaller diameter was used for calculating the area of the compression face.

The testing was conducted by securing the punches in the testing machine and then placing the center of the sample between the punches. The specimens were tested at a constant rate of 0.025 in./min. Each sample was compressed slightly past failure. The typical DPT setup is shown in Figure 3-15(a) and a closeup of a thin specimen ready to be tested in shown in Figure 3-15(b).

Figure 3-13: Steel Punches

Figure 3-14: (a) Double Punch Test Setup and (b) Mortar Specimen Ready to be Tested

3.6 Test Matrix

The test matrices are shown in Table 3-1 through Table 3-4. In addition to the specimen type and number of specimens tested, the mortar flows, as determined as aforementioned, and the average final thicknesses of the thin specimens are also presented. As aforementioned, for the mortar made by the research team, three water contents were used, and two mortar batches were made for each water content; the batches were made approximately one week apart from each other. Some batches with the same water content had flows that were near identical and are reported combined while other mortar batches, even thought were made with the same amount of water, have flows that were different enough that they were maintained separated.

The expectation was that the mortar flow would increase with increased water content. The results, however, have some small discrepancies since some of the batches with higher water content, as a percentage of the dry mix weight, had smaller flow than that of some batches with lower water content. Since there were two persons conducting the tests, the discrepancies in flow results can be attributed to the differences in tampering the mortar into the mold and the dropping the flow table as dictated by ASTM C109 (ASTM C109 2016).

Table 3-1: Compression Tests – Mortar Type S

Water Content % of Weight	Mortar Flow in.	Mortar Flow %	Number of Cubes	Number of Cylinders
18	4.50	13	8	7
18	5.00	25	8	7
20	5.41	35	8	7
20	5.94	48	8	7
20.6	5.70	43	3	
22	5.44	36	8	7
22	6.06	52	8	7

Table 3-2: Compression Test – Mortar Type N

Water Content % of Weight	Mortar Flow in.	Mortar Flow %	Number of Cubes	Number of Cylinders
18	4.97	24	5	9
18	5.09	27	5	9
20	5.56	39	8	7
20	5.88	47	7	7
22	6.81	70	8	7
22	6.91	73	8	7

Table 3-3: Double Punch Test – Mortar Type S

Water Content % of Weight	Mortar Flow in.	Mortar Flow %	Thickness in.	Number of Specimens	Curing time
18	4.81	20	0.28	8	56
			0.40	15	
			0.52	7	
			0.67	8	
			0.86	14	
20	6.34	59	0.30	13	50
			0.40	9	
			0.55	10	
			0.66	13	
			0.85	9	
20.6	5.70	43	0.42	10	28
			0.52	10	
			0.65	10	
22	7.48	87	0.29	11	46
			0.41	10	
			0.54	13	
			0.66	14	
			0.88	9	

Table 3-4: Double Punch Test – Mortar Type N

Water Content % of Weight	Mortar Flow in.	Mortar Flow %	Thickness in.	Number of Specimens	Curing time
18	5.13	28	0.28	9	51
			0.39	8	
			0.53	4	
			0.66	7	
			0.87	3	
18	6.56	64	0.27	7	52
			0.39	7	
			0.52	5	
			0.67	8	
			0.86	4	
20	5.77	44	0.29	15	52
			0.36	5	
			0.51	18	
			0.63	12	
			0.86	8	
22	7.06	77	0.28	13	51
			0.38	5	
			0.50	20	
			0.63	12	
			0.87	8	

4 RESULTS

This chapter presents the results from the compression tests and the double punch tests. The cube specimen and thin specimen compressive strengths are determined, and the properties of the field prepared mortar are determined.

4.1 Compression Testing

The average results from the compression tests on cubes and cylinders are presented in Table 4-1 for mortar type S and in Table 4-2 for mortar type N. Because only three cubes were used to measure the compressive strength of the type S, 20.6% WC mortar by the mason, the compressive strength of these cubes are not included in the discussion, plots, and tables presented in this section.

Table 4-1: Mortar Cube and Mortar Cylinder Strengths – Mortar Type S

Water Content % of Weight	Mortar Flow in.	Mortar Flow %	Cube Strength psi	COV	Cylinder Strength psi	COV
18	4.50	13	3253	6.4	2394	5.0
18	5.00	25	3400	2.2	2498	4.2
20	5.41	35	2681	2.7	1861	5.1
20	5.94	48	2560	4.7	1820	5.7
20.6	5.70	43	1360	—	—	—
22	5.44	36	1849	2.7	1398	6.0
22	6.06	52	2144	2.7	1594	4.4

Table 4-2: Mortar Cube and Mortar Cylinder Strengths – Mortar Type N

Water Content % of Weight	Mortar Flow in.	Mortar Flow %	Cube Strength psi	COV	Cylinder Strength psi	COV
18	4.97	24	3758	4.0	2328	12.0
18	5.09	27	3939	1.8	2295	23.5
20	5.56	39	1797	5.7	1269	10.1
20	5.88	47	1896	1.9	1335	7.3
22	6.81	70	1432	1.8	898	14.6
22	6.91	73	1519	3.8	999	13.1

Higher water content yielded a decrease in compressive strength, which is typical of cementitious materials (Mehta and Monteiro 2006, Mindess at al. 2003). The higher water content also yielded a higher flow, except for mortar type S with 22% water content—the flow of the 1st mortar batch appears to very low and the flow of the 2nd mortar batch appears be low when compared to the flows of mortar type N with the same amount of water. As aforementioned, the discrepancy can be attributed to the differences in the preparation of the specimens since two people were involved in that task.

The average cube compressive strength of mortar type N with 18% water content appears to be significantly high; it is approximately 16% higher than that of mortar type S with 18% water content, and mortar type N should have smaller compressive strength than that of mortar type S, as it is the case for the mortars with 20% and 22% water contents. Although the cylinder compressive strength of mortar type N with 18% water content is not higher than that of the mortar type S with 18% water content, it still appears to be high. Researchers cannot determine the reason for these apparent high values. The only plausible explanation is that the applied testing strain rate was higher than that used for the other tests, which would have caused the ultimate measured load to be an inflated value (Mehta and Monteiro 2006, Mindess et al. 2003).

The coefficients of variation (COV) for the compressive strength results for both types of specimens of mortar type S and for the cube specimens of mortar type N are very low. The COVs for the compressive strength results for the cylinder specimens of mortar type N, however, are relatively high, especially for the 2nd batch of mortar with 18% water content because of two very low compressive strength test results. The low compressive strength values affected the average compressive strengths slightly but affected the coefficients of variation significantly. The average compressive strengths for the cube and cylinder specimens as a function of the water content for Mortar Types S and N are shown in Figures 4.1 and 4.2, respectively.

The plot shown in Figure 4-2 confirms that the cube compressive strength of mortar type N with 18% water content appears to be significantly high as compared with that of the two other water contents.

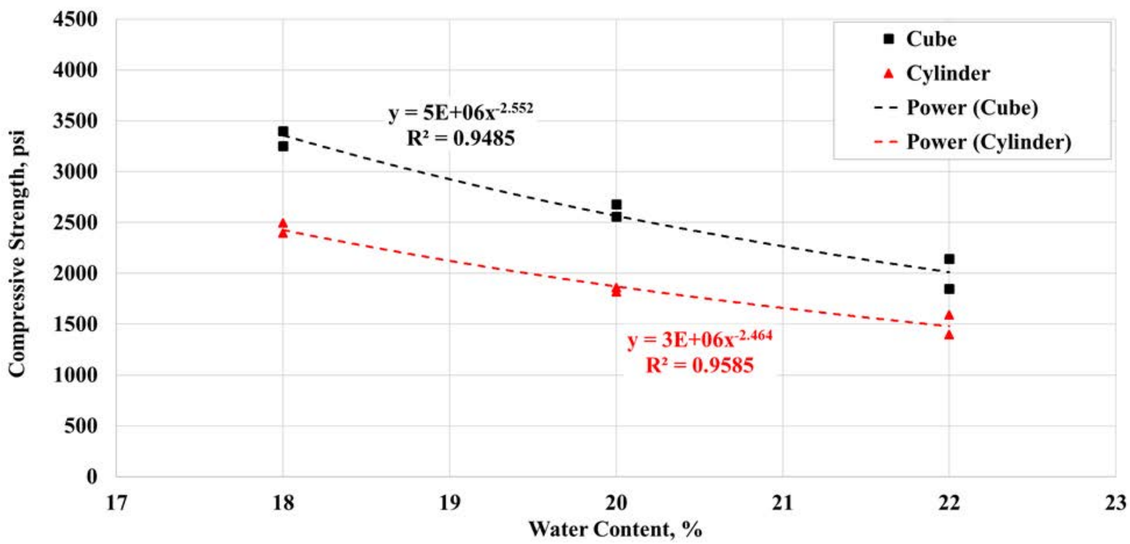

Figure 4-1: Compressive Strength vs. Water Content – Mortar Type S

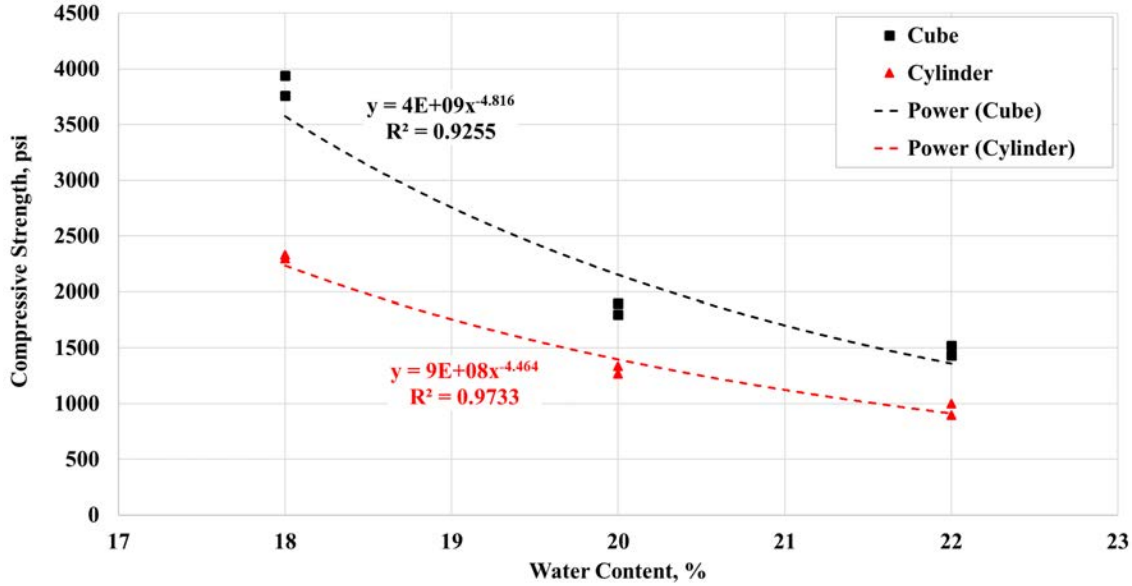

Figure 4-2: Compressive Strength vs. Water Content – Mortar Type N

The compressive strength of the mortars as a function of the water content can be described reasonably well by power curves with very high R^2 value. Power curve relationships were chosen because of Abrams' Law, which has been shown applicable to represent the relationship between the compressive strength of mortar and water content (Mehta and Monteiro 2006, Mindess at al. 2003, Rao 2001).

The ratio between the compressive strengths of the mortar cylinders and that of the mortar cubes are presented in Table 4-3. The results show that the average compressive strengths of mortar cylinders are approximately 73% and 65% of that of mortar cubes for mortars type S and N, respectively; according to ASTM C780 (ASTM C780 2018) standard, that ratio is 85%. Schmidt et al. (1990) mentioned that sensitivity to compaction and misalignment during capping and testing have greater effect on the strength of smaller cylindrical specimens than on the strength of the larger cylindrical specimens—the cylinder specimens tested in this research were smaller cylinders. In addition, specimen size affects the measured strength (ASTM C780 2018) and capping increases the compressive strength (Sassoni et al. 2015, Pelà et al. 2018). Thus, the compressive strength ratios obtained herein, which are lower than that suggested in ASTM C780 (ASTM C780 2018), may have been affected by compaction, misalignment, specimen size, and lack of capping.

Table 4-3: Cube Compressive Strength–Cylinder Compressive Strength Ratio

Mortar Type S				Mortar Type N			
Water Content, %	Cylinder Strength, psi	Cube Strength, psi	Strength Ratio, %	Water Content, %	Cylinder Strength, psi	Cube Strength, psi	Strength Ratio, %
18	2394	3253	74	18	2328	3758	62
18	2498	3400	73	18	2295	3939	58
20	1861	2681	69	20	1269	1797	71
20	1820	2560	71	20	1335	1896	70
22	1398	1849	76	22	898	1432	63
22	1594	2144	74	22	999	1519	66
		Average:	**73**			**Average:**	**65**

4.2 Double Punch Testing

Thin mortar specimens were tested using the double punch test method, and the results are presented in this section.

4.2.1 Steel Punch Areas

The measured diameters, average diameters and areas for the double punches are shown in Table 4-4. The area of the smaller punch was used for strength calculations.

Table 4-4: Steel Punch Areas

Measurement	Punch A Diameter, (in)	Punch B Diameter, (in)
1	0.810	0.832
2	0.818	0.828
3	0.821	0.820
4	0.819	0.831
5	0.810	0.827
6	0.810	0.827
Average:	0.815	0.828
Punch Areas (in^2)	0.524	0.540

4.2.2 Typical Specimen Behavior

The typical load-displacement behavior of a thin specimen is presented in Figure 4-2. The load would gradually increase until the sand grains on the surface of the specimen would crush or a crack would initiate causing a sudden but small decrease in load. The load would then continue increasing until the maximum load; it then would gradually decrease.

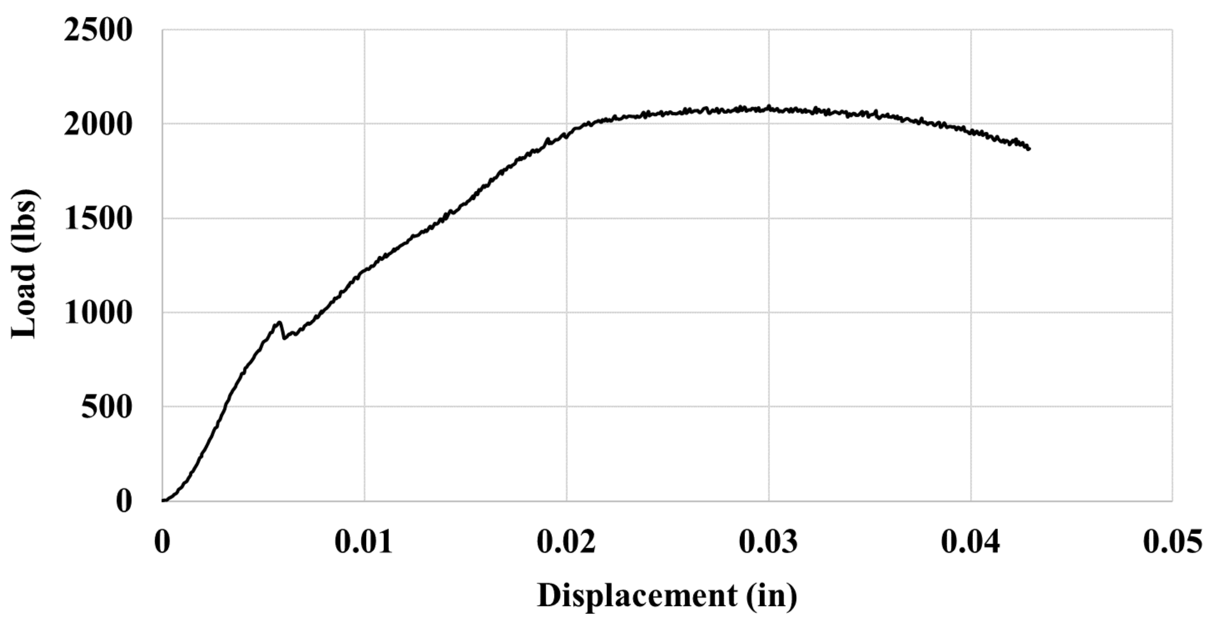

Figure 4-2: Typical Load-Displacement Behavior of a Thin Specimen

The typical failure of the thin specimens is depicted in Figure 4-3: a circular crack matching the diameter of the steel puncher and four or five radial cracks.

Figure 4-3: Typical Thin Specimen Failure

4.2.3 DPT Results

Although the two batches of mortar type N with 18% water content had two slightly different measured flows, the compressive strength results were similar; the reason for the discrepancy in flow measurement is aforementioned. From here on, the two batches of mortar type N with 18% water content are treated as one and the average flow is reported.

The mortar compressive strength for all specimens as a function of specimen thickness is shown in Figures 4.4 and 4.5, for mortar types S and N, respectively. Also plotted are power trendlines. The average mortar compressive strength for each water content as a function of specimen thickness is shown in Figures 4.6 and 4.7, for Mortar Types S and N, respectively. Also plotted are power trendlines, which can describe the data reasonably well, as suggested by the high R^2 values.

An increase in water content resulted in a decrease in strength (Mehta and Monteiro 2006, Mindess at al. 2003), similar to what was observed for the compressive strength of the mortar cubes and cylinders. Even though the compressive strength of the mortar type S with 20% and 20.6% WC are very similar, the compressive strength of mortar type S more accurately captures this relationship, since for mortar type N, the difference in compressive strength between the 18% and 20% water contents appears negligible. Either the results of mortar type N 18% series tests are too low or that of the 20% series are too high.

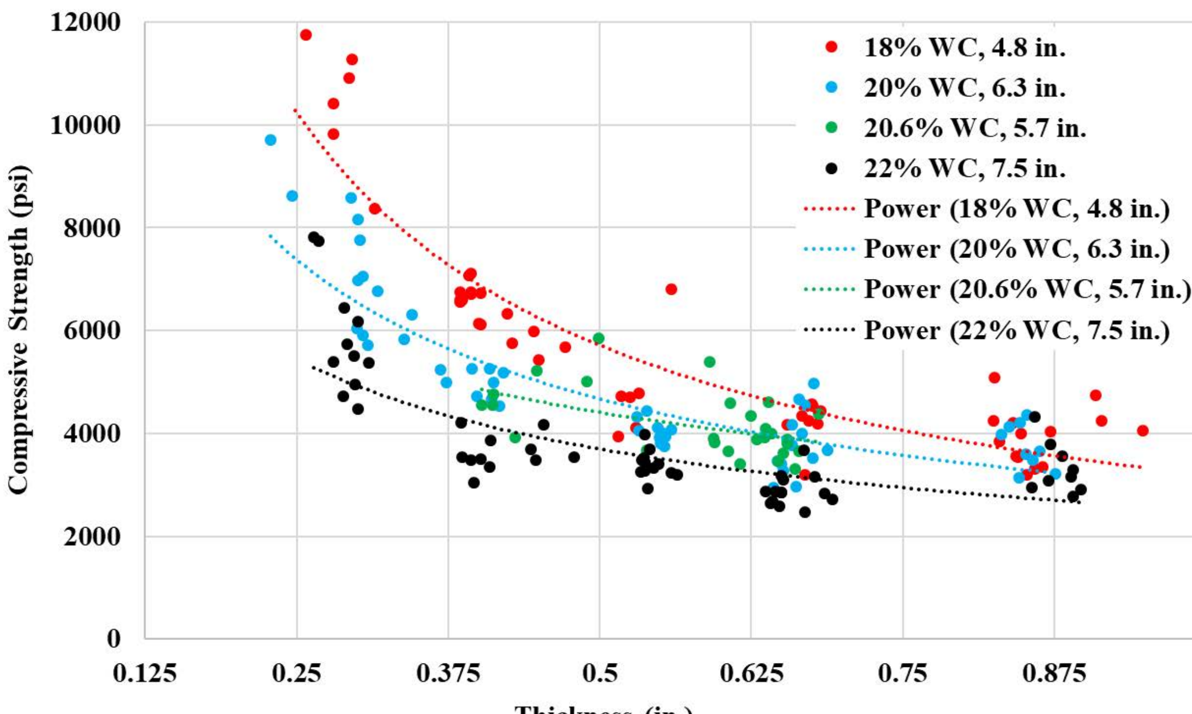

Figure 4-4: Double Punch Strength Results – Mortar Type S

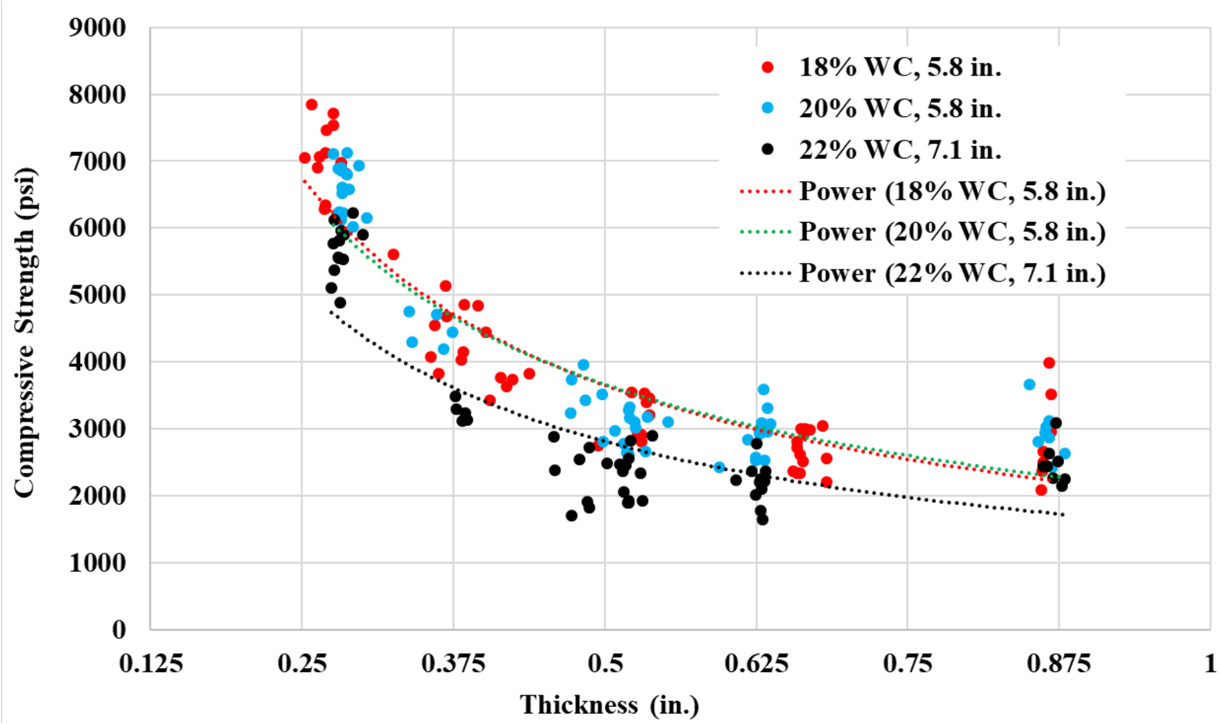

Figure 4-5: Double Punch Strength Results – Mortar Type N

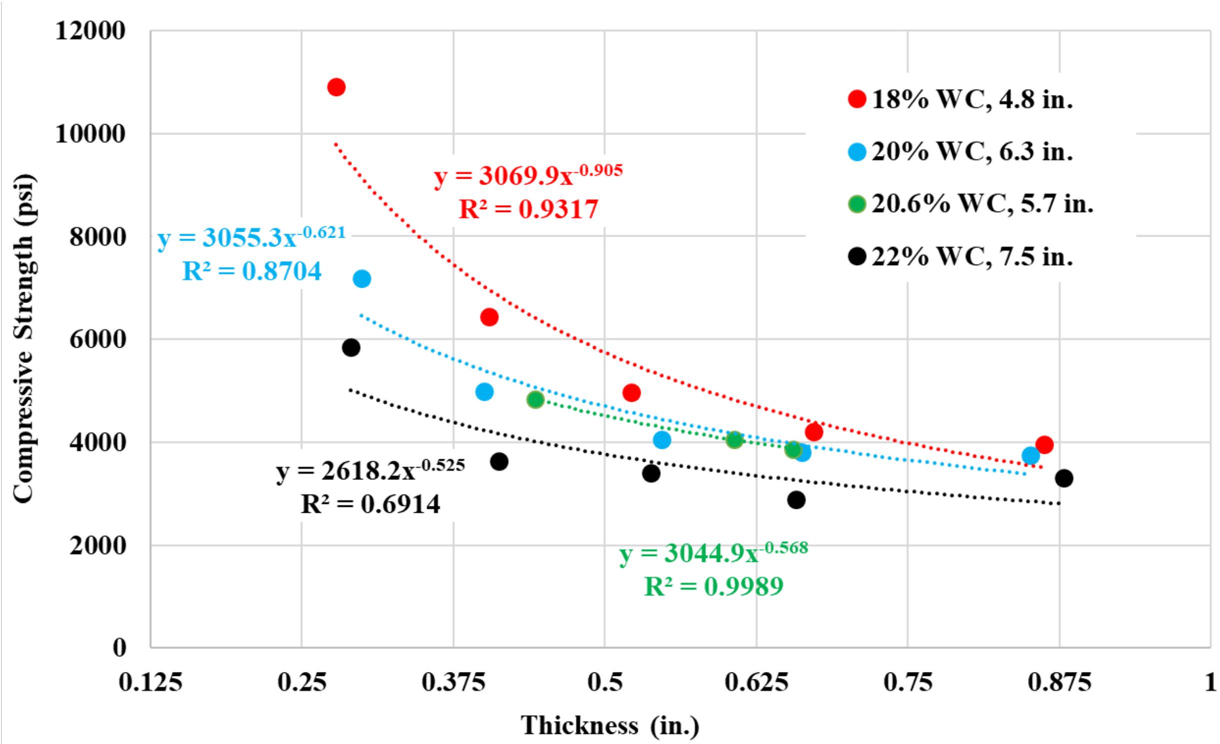

Figure 4-6: Average Compressive Strengths – Mortar Type S

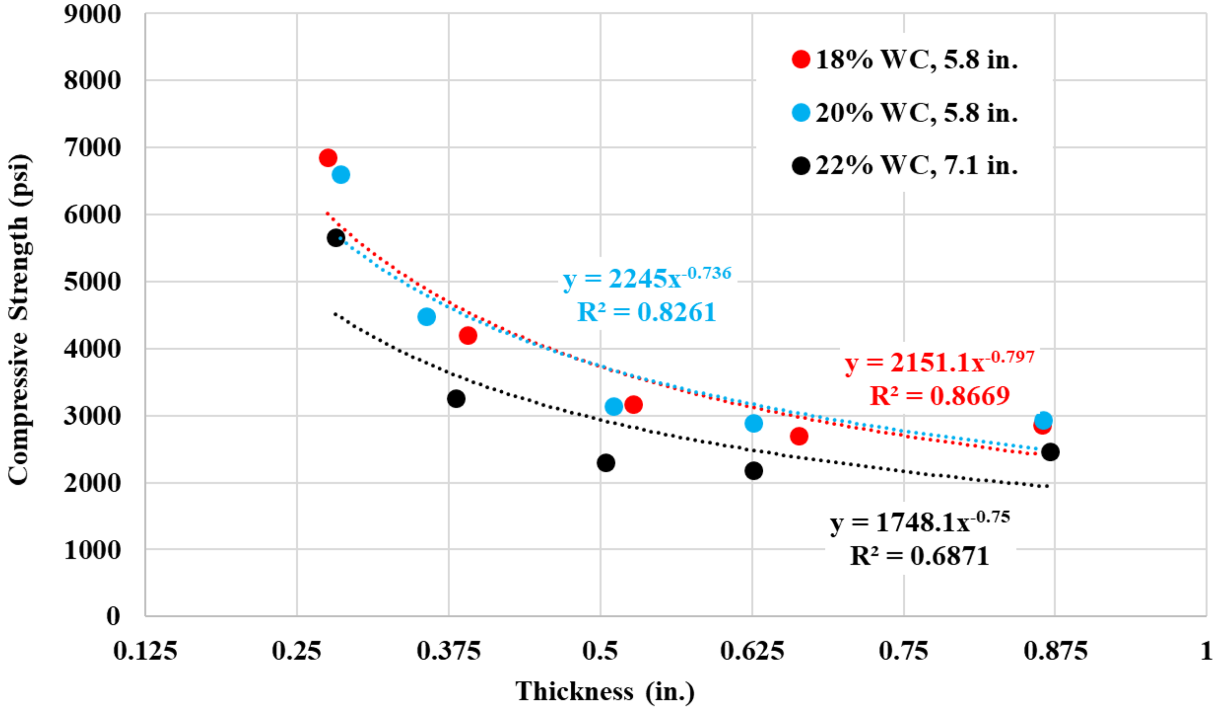

Figure 4-7: Average Compressive Strengths – Mortar Type N

For both mortar types, a decrease in thickness is accompanied by an increase in strength. Pelà et al. (2018), Drdácký (2011), and Sassoni et al. (2015) observed similar trend, which, among other factors, is due to smaller height-to-width ratios, which result in greater capacity, and smaller specimens, which possesses fewer material defects. The material defects are manifest in the slipping planes between adjacent grains. Thus, as specimen thickness becomes smaller, the number and paired probability of slipping planes decreases.

The mortar type S data shows that as the thickness becomes smaller, the difference in compressive strength between the mortar with different water contents becomes less pronounced; the data for mortar type N does not indicate the same behavior.

4.3 Cube and Thin Specimen Strengths

Equations 4-1 and 4-2, also shown in Figures 4-1 and 4-2, represent the cube strengths as a function of the water content for mortar types S and N, respectively:

$$f_{mortar,S} = 5E+06wc^{-2.552} \tag{4.1}$$

$$f_{mortar,N} = 4E+09wc^{-4.816} \tag{4.2}$$

where $f_{mortar,S}$ and $f_{mortar,N}$ are the cube compressive strength of mortar types S and N in psi, respectively, and *wc* is the water content, in percent.

Equations 4-3 through 4-6, also shown in Figure 4-5, and Equations 4-7 through 4-9, also shown in Figure 4-6, represent the strengths of thin mortar specimens as a function of the thickness of the specimen for mortar types S and N, respectively, for the different amounts of water content:

$$f_{mortar,S18} = 3,069.6t^{-0.905} \tag{4.3}$$

$$f_{mortar,S20} = 3,055.3t^{-0.621} \tag{4.4}$$

$$f_{mortar,S20.6} = 3,044.9t^{-0.568} \tag{4.5}$$

$$f_{mortar,S22} = 2,618.2t^{-0.525} \tag{4.6}$$

$$f_{mortar,N18} = 2,151.1t^{-0.797} \tag{4.7}$$

$$f_{mortar,N20} = 2,245t^{-0.736} \tag{4.8}$$

$$f_{mortar,N22} = 1,748.1t^{-0.75} \tag{4.9}$$

where $f_{mortar,S}$ and $f_{mortar,N}$ are the compressive strength of thin mortar specimens for mortar types S and N in psi, respectively, and *t* is the thickness of the specimen, in inches.

For mortar types S and N, Equations 4.1 and 4.2 can be used to calculate the compressive strengths for a mortar cube having different water contents and Equations 4.3 through 4.9 can be used to calculate the compressive strength for a 3/8-in. thick specimen, which is the typical thickness of a mortar bed joint. The results are presented in Table 4-5. Also presented are the ratios between the compressive strength of the 3/8 in. thick specimen to that of a cube.

The cubes specimens were tested at 28 days while the thin specimens were tested at different ages, as presented in Tables 3-3 and 3-4. According to Shariq (2018), there is an approximate increase of 8% in compressive strength from 28 to 56 days of age. Herein, it was assumed that the thin specimens experienced an increase in compressive strength identical to that suggested by Shariq (2018) and that the increase beyond 28 days was linear. The compressive strengths of the 3/8-in. thick specimen presented in Table 4-5 were normalized to a 28-day compressive strength by reducing the values accordingly.

Table 4-5: Mortar Compressive Strengths

WC	Type S				Type N			
	Cube	DPT			Cube	DPT		
	Strength (psi)	Thickness (in)	Strength (psi)	Strength Ratio, %	Strength (psi)	Thicknes s (in)	Strength (psi)	Strength Ratio, %
18	3,130	0.375	6,906	221	3,603	0.375	4,411	122
20	2,392	0.375	5,286	221	2,169	0.375	4,324	199
20.6	1,360	0.375	5,315	391				
22	1,875	0.375	4,167	222	1,371	0.375	3,423	250

The data are very consistent except for that of mortar type S with 20.6% water content and that of mortar type N with 18% water content. There is one apparent problem with the type S with 20.6% WC: the compressive strength of the cube is too low. The researchers, however, cannot pinpoint the reason for the low compressive strength, especially because all the procedure and methods to both prepare and test the specimens were exactly the same as followed for the other specimens.

There are also two apparent problems with the mortar type N with 18% WC: the compressive strength of the cube is too high and the compressive strength of the 3/8-in. thick specimen is too low. As aforementioned, the cube compressive strength of mortar type N with 18% water content appears to be significantly high. The average cube compressive strength of mortar type N with 18% water content is approximately 16% higher than that of mortar type S with 18% water content; mortar type N, however, should have smaller compressive strength than that of mortar type S, as is the case for the mortars with 20% and 22% water contents. The researchers could not determine the reason for such a high compressive strength. The only plausible explanation is that the applied strain rate was higher, which would cause the ultimate measured load to be an inflated value (Mehta and Monteiro 2006, Mindess at al. 2003.)

Contrary to expectations, there was not a noticeable increase in compressive strength for the thin mortar type N specimens with 18% water content from that with 20% water content. The increase in compressive strength for the thin mortar type N specimens with 20% water content from that with 22% water content is approximately 26% while the increase in compressive strength for the thin mortar type N specimens with 18% water content from that with 20% water content is only approximately 2%. For mortar, a cementitious material, a lower water content yields an increase in compressive strength (Mehta and Monteiro 2006, Mindess at al. 2003.)

If the data for the mortar type S with 20.6% WC and that of the mortar type N with 18% WC are ignored, the remaining data show that the compressive strength of a 3/8-in. thick mortar specimen, which is the typical thickness of a mortar bed joint, can be conservatively estimated as twice as that of a mortar cube.

4.4 Field-Prepared Mortar Properties

Each mortar batch prepared by the research grout contained 10 lbs of dry mortar mix and a variable weight of water; the “wet” mix was made with 2.2 lbs of water. This amount of material was the most the mixer could handle without over-stressing the motor or causing material to splash out of the bowl.

For mortar type S, the flow of the wet mix used to make the thin specimens was 7.48 inches or 87%. For mortar type N, the flow of the wet mix used to make the thin specimens was 7.06 inches or 77%. These flow values are slightly lower than the value specified, i.e., 110 ± 5% or 8.4 ± 0.2 in., for a mortar to meet the minimum required properties of ASTM C270 (ASTM C270 2014). The smaller flows obtained herein, however, does not compromise the overall results.

The reason for the low flow values for the wet mix is simply because the researchers wanted the make the largest batch possible to minimize the number of batches to reduce the variability of the results. Even with the largest possible batch, two batches were still needed for each mortar water content. Smaller batches with a flow of 110 ± 5% or 8.4 ± 0.2 in. could have been made, but that would have increased the number of mortar batches and the variability of the results.

According to ASTM C270 (ASTM C270 2015), the amount of water to produce laboratory prepared mortar with a flow of 110 ± 5% or 8.4 ± 0.2 in. is not enough to produce a mortar with a workable consistency suitable for laying masonry units in the field. Mortar for use in the field must be mixed with an amount of water to provide the necessary consistent and to satisfy the initial rate of absorption (suction) of the masonry units. The mortar laboratory flow of 110 ± 5% or 8.4 ± 0.2 in. is intended to approximate the flow of field prepared mortar after it has been placed and the suction of the masonry units has been satisfied (ASTM C270 2014). Thus, the flow of a field prepared mortar should typically be greater than 110 ± 5% or 8.4 ± 0.2 in. Drysdale and Hamid (2008) suggests that to satisfy the mason's requirements, a mortar flow value of up to 130% or 9.2 in. is required.

The interesting occurrence is that the flow of the type S mortar prepared under the supervision of a professional mason had only 20.6% water content and a flow of 5.70 inches or 43 percent. These values are comparable to the values obtained herein for the type S mortar prepared by the research group with 20% water content. Not only the water content and the flow but also the double punch compressive strength results are very similar, as shown in Figure 4.6.

5 CONCLUSIONS

This chapter concludes the report. The research is summarized and the principal findings are identified.

5.1 Summary

Standard compression tests and double punch tests were conducted to investigate the effect of mortar thickness and mortar water content on the compressive strength of mortar in a joint. Four types of mortar specimens were cast: mortar cubes, mortar cylinders, mortar discs cut from cylinders, and mortar discs cast in masonry blocks. The ratio between the compressive strength of 2 by 4-in. mortar cylinders to that of 2-in. mortar cubes was determined.

5.2 Principal Findings

Within the scope and parameters defined for this study and based on the results and relevant discussion, the principal findings are as follows:

1. The water content of the mortar mix affected the compressive strength of the mix. As a result, the compressive strength of the mortar increased as the water content decreased.
2. The average compressive strength of mortar cylinders was approximately 73% and 65% of that of mortar cube for mortar type S and N, respectively.
3. The compressive strength of mortar increased with decreasing specimen thickness.
4. The compressive strength of a 3/8-in. thick mortar bed joint was conservatively estimated to be twice the compressive strength of a field-prepared mortar cube.

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