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Experimental Study on the Parameters Influencing Modulus of Rupture (MOR) for Masonry Beams and Comparison with Bond Wrench Testing

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ABSTRACT

Currently, the experimental database for Modulus of Rupture (MOR) of masonry beams is limited and current provisions in TMS 402/602-22 use the MOR values from wallette tests. The primary goal of this research is to experimentally determine the parameters that influence MOR for masonry beams. In addition, there are two primary methods for determining MOR in the literature, beam testing and bond wrench testing. As such, the secondary goal is to compare the MOR values from beam- and bond wrench- tests obtained in this study versus those published in literature. The standard ASTM E518 test was used for determining MOR values for beams and a modified approach to ASTM C1072 that nullifies the eccentricity in loading was used in the bond wrench testing. In total, 18 beams and 22 bond wrench prisms were tested with varying grout type, mortar type and masonry units. The results of the testing show that the MOR values significantly increase with the increase in grout strength and are not as influenced by the mortar type. Also, it is worth noting that there was significant variation between MOR values obtained from the two test methods, while the trends remained consistent with respect to the studied parameters among the tests. The obtained data set indicates between a 30% and 59%increase in MOR values obtained from bond wrench as compared to beam tests, and literature confirms a lack of consensus on this topic. Future work will utilize this data and those in the literature to create discrete element method (DEM) models and examine if fundamental differences in stress distributions can be identified to explain these differences.

KEYWORDS

bond wrench, flexural bond strength, grout, masonry beam, modulus of rupture

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INTRODUCTION

Within the TMS 402/602-22 code, the modulus of rupture (MOR) also known as flexural bond strength in masonry beams primarily influences the cracking moment which is used to determine the minimum reinforcement and the effective moment of inertia for calculating deflections. Experimental studies have indicated that the modulus of rupture (MOR) values for fully grouted masonry beams are mainly dependent on the strength of the grout used, however, the increase in the MOR is not proportional to the increase in grout strength (Zohreh Heydariha et al., 2017). The extensive research work consisted of six full-scale reinforced masonry beam specimens along with twenty-five grouted prisms to study the effect of grout type (high strength and normal strength), bond pattern (running and stack bond) and block size (nominal 200 mm (8 in.) and 300mm (12 in.) on structural behavior of masonry beams. The MOR Table 9.1.9.1 provided in the TMS 402/602-22 code (and presented here as Table 1) was derived from tests by Hamid and Drysdale (Hamid Ahmed A. & Drysdale Robert G., 1998) on masonry wallettes, and is referenced in both beam and wall design. The purpose of this study is to gather sufficient data to identify MOR values specific to beam design. In this study, the specimens consist of beams and bond wrench prisms tested oriented so that the head joint is the failure surface to represent the condition where tension is parallel to the bed joint. The specimens are constructed from lintel units or knock out block units. Two different mortars are investigated, masonry cement Type M and N. Finally, the grout strength is also varied.

Table 1: MOR, f_r, psi (kPa) values from TMS 402/602-22 (applicable values in red)

Direction of flexural tensile stress and masonry type	**Mortar types**			
	Portland cement/lime or mortar cement		**Masonry cement or air entrained Portland cement/lime**	
	M or S	**N**	**M or S**	**N**
Normal to bed joints				
Solid units	133 (919)	100 (690)	80 (552)	51 (349)
Hollow units				
Ungrouted	84 (579)	64 (441)	51(349)	31 (211)
Fully grouted	163 (1124)	158 (1089)	153 (1055)	145 (1000)
Parallel to bed joints in running bond				
Solid units	267 (1839)	200 (1379)	160 (1103)	100 (689)
Hollow units				
Ungrouted and partially grouted	167 (1149)	127 (873)	100 (689)	64 (441)
Fully grouted	267 (1839)	200 (1379)	160 (1103)	100 (689)
Parallel to bed joints in masonry not laid in running bond				
Continuous grout section parallel to bed joints	335 (2310)	335 (2310)	335 (2310)	335 (2310)
Other	0 (0)	0 (0)	0 (0)	0 (0)

Multi-course beams can be constructed in a variety of ways using a mix of bond beam block for the reinforced courses and stretcher units for the upper courses, or providing a more continuous grout path using all knock out block units or H-block units. In these cases, it would be typical to place the masonry in running bond pattern and the applicable MOR values to gather from Table 1 would be from the row corresponding to "stress parallel to bed joints in masonry laid in running bond". In the case of a single course beam like those tested in this study, one could analyze the beam as within a running bond system and fully grouted using its full cross section for analysis or analyze it with respect to the grout core only (second to last row of the table). For this study the analysis is carried out assuming full cross-sectional properties and the results are compared to Table 1 corresponding to tensile stress parallel to bed joints in masonry laid in running bond for fully grouted hollow units with Type M and Type N masonry cement.

ASTM C1072 and ASTM E518 are the two standard tests used to evaluate the MOR of masonry in the U.S. The bond wrench test due to its simplicity and ease is often used as a tool of quality control in the field whereas the beam test is favored for research purposes to understand the detailed flexural behavior. There has been very limited research directly comparing these test methods. (Nichols et al., 2018) compared the Australian Bond wrench with ASTM E518 beam test and the results from his test showed significant differences with the mean MOR values obtained from Australian bond wrench being 1.5 times higher than the beam tests. Also, (Nichols 2013) showed that bias exists between different types of bond wrench tests, namely; Australian Standard (AS) Bond Wrench, Indian Balanced Bond Wrench, TAMU Unbalanced Bond Wrench, and the ASTM Bond Wrench. The TAMU Unbalanced Bond Wrench and Indian Balanced Bond wrench were developed by Chaudhari, 2010.

In this comparison, the ASTM Bond Wrench provided results that are on average 50% higher than the other wrenches. Work by McGinley (1993) has shown that the ASTM Bond Wrench under certain conditions may have a strain distribution in the masonry that varies significantly from the assumed linear distribution. From these studies, the MOR values obtained from the bond wrench tests tend to be notably higher as compared to the standard beam test as shown in Table 2. Notably some of these tests were performed on ungrouted masonry, rather than grouted masonry which is the subject of the current work.

Table 2: MOR Values from Bond Wrench Tests Directly Compared with Beams or Walls

Reference	Specimen Configuration	Mortar Type (Volumetric Proportion)	Average MOR from ASTM E518 MPa (psi)	Average MOR from Bond Wrench MPa (psi)	Average MOR From Wall Tests MPa (psi)
J. M. Nichols et al., 2018	Texas Brick 194 mm*57.2 mm (8 in.*2.25 in.), Ungrouted, Stress parallel to bed joint	PCL (1:1:6)	0.57 (82.6)	0.82 (119) (Australian)	NA
(Hamid Ahmed A. et al., 1998	200 mm (8 in.) Nominal CMU, Grouted, Stress normal to bed joint	Type S (1:0.38:3.5)	NA	2.13 (310) (ASTM)	1.99 (290)

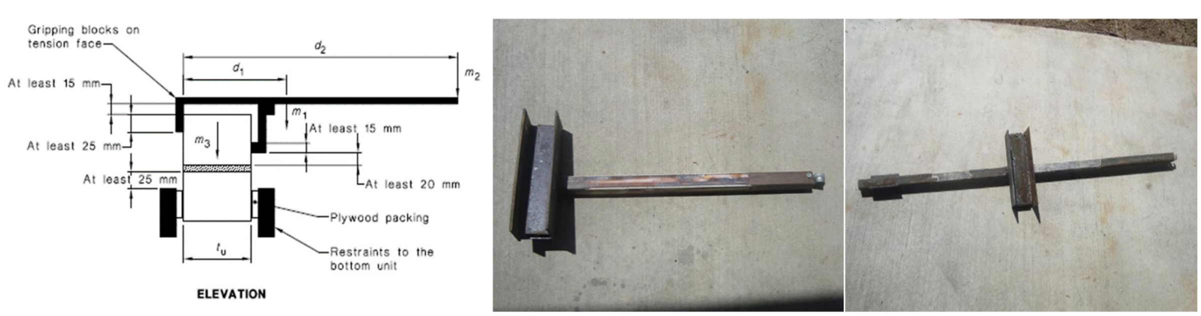

Fig. 1: Australian Bond Wrench AS 3700 (Left), TAMU Unbalanced bond wrench (Mid) after Chaudhari, 2010 and Indian Balanced Bond Wrench (Right) after Chaudhari, 2010

This paper focuses on comparing the MOR of fully grouted concrete masonry with tension parallel to the bed joint, varying parameters like mortar, grout and block type using two different test methods (ASTM E518 and modified Bond wrench C1072). This study focuses on the results obtained from single course bond beam tests as well as the bond wrench prisms and determines how the results from each of these tests compare to each other and the current TMS code provision.

EXPERIMENTAL PROGRAM

Beam Test Procedure

The beam tests were carried out following ASTM E518 (as shown in Fig. 2), which is used to determine the MOR (parallel to bed joints) of unreinforced masonry assemblages. The length of the beams were approximately 163 cm (64 in.) (4-16in. blocks) and thus the clear span of the beam was set to be 152 cm (60 in.), divided into 3 spans making the distance between each support and adjacent distributed point load to be one-third of the span length 50.8 cm (20 in.). Four steel rollers of 2.54 cm (1 in.) diameter were used to support the specimen, and load was applied from a displacement-controlled actuator through a spreader beam. Load was applied at a uniform rate to assure that the peak load was applied in not less than 1 nor more than 3 min (ASTM E518). Because the hydraulic actuator is operated manually, the tested load rate varied slightly between specimens, but all beam tests except one was kept within the specified limits. The one beam that was out of compliance failed after 50 seconds but its results were consistent with those failing between 1 and 3 minutes and so the data was included in the presented set. The peak load and the location of the break of the beam were recorded for each beam test along with the displacements at the mid joint using a string potentiometer.

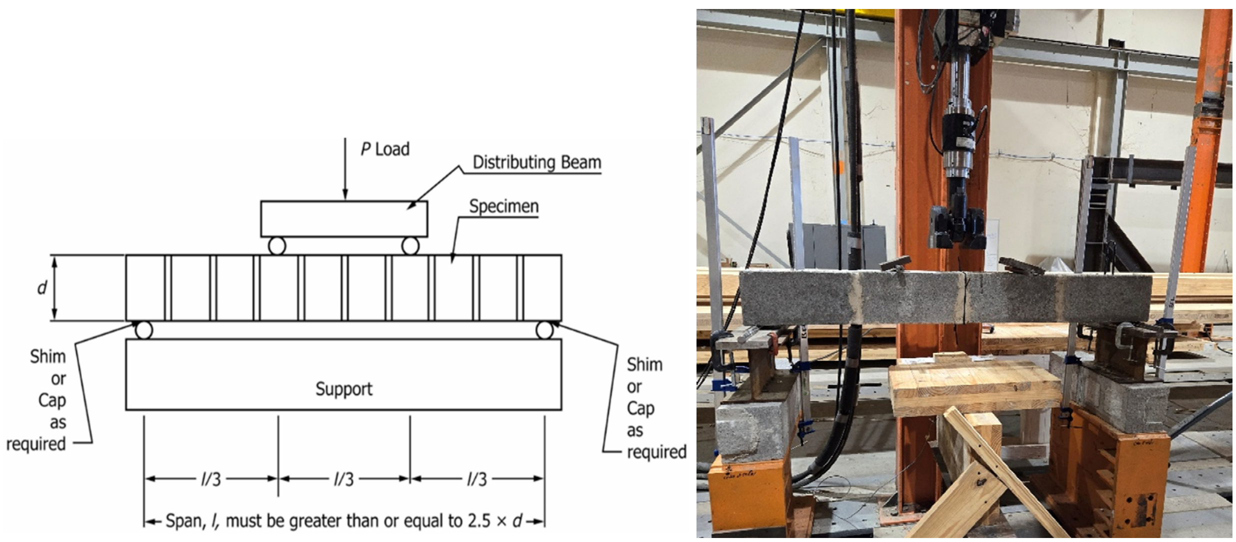

Fig. 2: Third point loading: ASTM E518 (left) and physical test set up (right)

The modulus of rupture was calculated using Eq. [1].

$$(1)\ R = \frac{(P+0.75P_S)l}{bd^2}$$

where, R is modulus of rupture, P is maximum applied load, P_S is weight of specimen, l is span length, b is average width of specimen and d is the average depth of specimen. Each specimen was weighed with a scale to determine self-weight.

Modified Bond Wrench Test

The modified bond wrench device was designed to induce flexural failure across the head joint of fully grouted masonry prisms similar to conventional bond wrench tests (ASTM C1072). This was accomplished by inducing a moment across the head joint of the specimen using two actuators that were pressurized from one hydraulic pump using a T-splitter, as is shown in figure below. The load rate was applied at a uniform rate with a hand pump ensuring the specimens failed between 1 and 3 minutes after loading began, consistent with ASTM C1072.

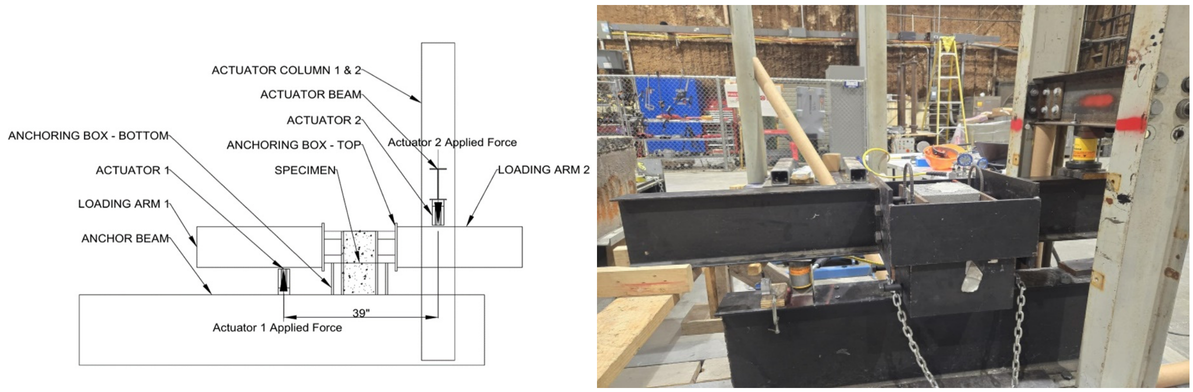

Fig. 3: Schematic of the bond wrench test set up (left) and physical test set up (right)

The state of stress in the masonry prism is a combination of compression (due to the weight of the loading arm, plates, and top half of bond wrench prism) and flexure (due to the moment induced from the actuators). The goal of the design was to ensure that the compression stress induced by the machine was similar to the low level of compression stress induced by the ASTM C1072 bond wrench device. The calculated weights for the bond wrench components are shown in Table 3. It is worth noting the standard ASTM C1072 device is a one-sided lever arm, so the applied axial load also causes eccentricity. In contrast, the bond wrench test device used in this experiment is balanced because it applied two equal axial loads on either side of the test specimen. The actual ratio of the compression stress from loading to the tensile stress at failure is much lower for this device than the ASTM C1072 device (Banks et al., 2023).

Table 3: Self Weight (SW), Dimensions and Other Dead Weight from Test Device

Unit Type	SW of top course N (lb.)	b cm (in)	h cm (in)	A cm^2 (in^2)	I cm^4 (in^4)	Wt. of Load arm N (lb.)	Wt. of face plates N (lb.)	Total SW N (lb.)	Moment arm cm (in.)
Lintel Units	132 (29.7)	19.4 (7.63)	19.4 (7.63)	375 (58.1)	11725 (282)	845 (190)	214 (48)	1191 (268)	49.5 (19.5)
Knock Out Units	150 (33.7)	19.4 (7.63)	19.4 (7.63)	375 (58.1)	11725 (282)	845 (190)	214 (48)	1209 (272)	49.5 (19.5)

The modulus of rupture was calculated using Eq. [2].

$$(2)\quad f_r = \frac{-SW}{A} + \frac{M\frac{h}{2}}{I}$$

where SW is the self-weight of the masonry and device (268 lbs. for Lintel Units and 272 lbs. for Knock-out units obtained by weighing the specimens), A is the cross-sectional area, M is the moment applied by the two actuators shown in Figure, $\frac{h}{2}$ is the distance to the maximum tensile stress location from the neutral axis (3.81 in), and I is the moment of inertia across the axis of bending.

The load path and the assembly process of this modified bond wrench device is discussed in detail by Banks (Banks et al., 2023).

Specimen Construction and Batch Designation

Four 163 cm (64-inch) long beams were constructed using nominal 200 mm (8-inch) concrete masonry units (CMU) for each batch of test specimens. The beams were grouted approximately 24 hours after the block was laid and were allowed to cure in the laboratory conditions completely covered with a plastic tarp until the day of testing. The tests were done on the 28th day of casting.

Five bond wrench specimens per batch designation were constructed on the same day as the corresponding beam specimens using two saw-cut half CMUs. The half units were grouted and cured in the same manner as the beam specimens. Two or three days before testing, short threaded rods were set into the blocks using epoxy following the method of Banks et al. (2023) to attach the specimen into the bond wrench device. The bond wrench tests were completed within three days after reaching the curing period of 28 days.

Test specimens for material properties including masonry prisms, mortar cubes and C1019 grout specimens were created on the same day as the beam and bond wrench specimens and cured according to their ASTM standards. The slump for each grout mixture was recorded following the provisions of ASTM C476 and was maintained within a range of approximately 20.3-22.9 cm (8-9 in.). The batch designations along with detailed specimen descriptions are given in Table 4.

Table 4: Batch Designation

Designation	Unit Type	Mortar Type	Grout Type
8-LU-MCM-LSG	200 mm (8 in.) high Lintel Units (LU)	Masonry Cement Type M	Low strength Grout (LSG)
8-LU-MCN-LSG	200 mm (8 in.) high Lintel Units (LU)	Masonry Cement Type N	Low strength Grout (LSG)
8-LU-MCN-HSG	200mm (8 in.) high Lintel Units (LU)	Masonry Cement Type N	High strength Grout (HSG)
8-KOBB-MCN-LSG	200 mm (8 in.) high Knock Out Bond Beam Units (KOBB)	Masonry Cement Type N	Low strength Grout (LSG)

Material Properties

Three mortar cubes were prepared for each batch of specimens to determine the compressive strength of the mortar following the provisions of ASTM C109. Four ASTM C1019 specimens were prepared for each grout mix to determine the compressive strength of the corresponding grout. Due to size limitations of the mixer, each batch had to be grouted in two mix preparations. Finally, four fully grouted concrete masonry prisms made by stacking two standard half blocks were constructed for each batch of specimens to determine the specified compressive strength of masonry f'_m, following the procedures as defined in ASTM C1314. All specimens were tested on or within twenty-four hours of the beam tests and within three days of the bond wrench tests. The results of each of these tests are shown in Tables 5 and 6.

Table 5: Compressive Strength of Mortar Cubes (ASTM C109)

Batch	Compressive Strength, MPa (psi) (28 Day)			
	Individual			Average
8-LU-MCM-LSG	13.5 (1955)	13.4 (1942)	13.30 (1930)	13.4 (1942)
8-LU-MCN-LSG	7.54 (1094)	8.36 (1213)	8.59 (1247)	8.16 (1184)
8-LU-MCN-HSG	8.49 (1232)	8.39 (1217)	7.91 (1148)	8.26 (1199)
8-KOBB-MCN-LSG	5.48 (796)	6.00 (871)	5.36 (778)	5.62 (815)

Table 6: Compressive Strength of Grout Specimens (ASTM C1019) and Masonry Prisms (ASTM C1314)

Batch		Grout Specimens (ASTM C1019) Compressive Strength, MPa (psi) (28 Day)			Masonry Prisms (ASTM C1314) Compressive Strength, MPa (psi) (28 Day)		
		Ave. by Mix (4 samples)	Ave. of both Mixes (8 samples)	St. Dev. of both Mixes (8 samples)	Ave. By Mix (2 samples)	Ave. of both Mixes (4 samples)	St. Dev. of both Mixes (4 samples)
8-LU-MCM-LSG	Mix 1	14.4 (2083)	13.3 (1934)	1.72 (250)	16.6 (2409)	17.4 (2526)	2.99 (434)
	Mix 2	12.3 (1785)			18.2 (2643)		
8-LU-MCN-LSG	Mix 1	17.3 (2503)	16.8 (2438)	1.19 (172)	18.4 (2666)	18.8 (2721)	2.66 (386)
	Mix 2	16.4 (2373)			19.1 (2776)		
8-LU-MCN-HSG	Mix 1	23.6 (3422)	21.0 (3051)	3.49 (506.20)	21.9 (3170)	21.6 (3136)	0.85 (122)
	Mix 2	18.5 (2680)			21.4 (3101)		
8-KOBB-MCN-LSG	Mix 1	14.4 (2081)	13.5 (1958)	1.26 (182.68)	18.1 (2626)	18.3 (2649)	0.72 (104)
	Mix 2	12.7 (1835)			18.4 (2671)		

TEST RESULTS AND DISCUSSION

All beam specimens failed in flexure. The failure initiated with the cracking at the bottom of the middle joint and followed by the tension failure of the grout core. The bond wrench specimens went through clean tensile splitting failure across the mortar joint starting from the tension side of the specimen. The typical failure pattern of the beam and bond wrench specimen can be seen in Fig. 4.

Fig. 4: Typical failure of beam (left) and bond wrench specimens (right)

Modulus of Rupture (MOR) Results

Table 7 compares the average results from the beam and bond wrench tests for tested MOR (denoted as f_r) to each other and the predicted MOR (denoted as f_{rp}) currently provided in TMS 402/602-22.

Table 7: Tested MOR Values versus Predicted Values

Batch	Mortar Type	TMS 402/602-22 Predicted MOR, f_{rp} kPa (psi)	Average Tested MOR values, f_r kPa (psi) *Standard Deviation in kPa (psi)*		Ratio f_r/f_{rp}	
			ASTM E518 (4 specimens)	Modified Bond Wrench (5 Specimens)	ASTM E518	Modified Bond Wrench
8-LU-MCM-LSG	Masonry Cement Type S	1103 (160)	1239 (180) *41.2 (5.97)*	1970 (286) *323.71 (47.0)*	1.12	1.79
8-LU-MCN-LSG	Masonry Cement Type N	689 (100)	1140 (165) *110 (16.0)*	1758 (255) *200 (29.0)*	1.64	2.55
8-LU-MCN-HSG	Masonry Cement Type N	689 (100)	1530 (222) *103 (15.0)*	2108 (306) *160 (23.2)*	2.21	3.04
8-KOBB-MCN-LSG	Masonry Cement Type N	689 (100)	1165 (169) *67.6 (9.80)*	1507 (219) *137(19.8)*	1.68	2.17

According to Table 9.1.9.1 (also Table 1 of this paper) of TMS 402/602-22, the predicted MOR for tensile stress parallel to bed joints in running bond for fully grouted beams with mortar Masonry Cement Type N is 689 kPa (100 psi) and with Masonry Cement Type M is 1103 kPa (160 psi).

The data shows bias between these two tests with the values from bond wrench test being considerably and consistently 30-59% higher than the beam test for all four batches of testing. The average ratio of predicted MOR (f_{rp}) to tested MOR (f_r) was 1.67 for the beam test and 2.39 for the bond wrench test.

Parameters Affecting MOR values

Grout Type

Figure 5 demonstrates the trendlines of MOR values from beam and bond wrench specimens with Low Strength Grout (LSG) and High Strength Grout (HSG), holding all other parameters constant (batches 8-LU-MCN-LSG and 8-LU-MCN-HSG). Both sets of data have an increasing trendline that suggest that grout strength has a correlation with the MOR values.

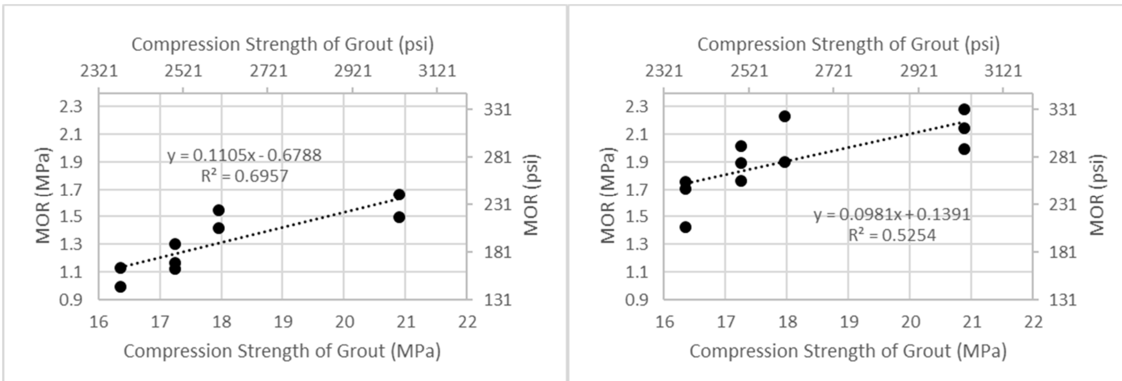

Fig. 5: MOR values for beams(left) and bond wrench specimens (right) with respect to varying grout strength

Mortar Type

The MOR does not appear to be highly influenced by Mortar Type. This box plot in Figure 6 shows the comparison of MOR values between 8-LU-MCM-LSG and 8-LU-MCN-LSG specimens.

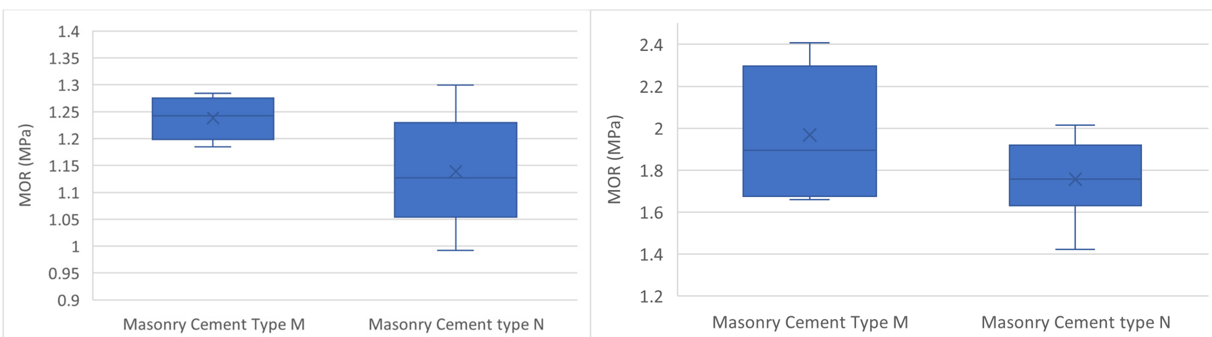

Fig. 6: MOR values for beams(left) and bond wrench specimens (right) varying Mortar

Block Type

The data gathered by comparing the two different types of blocks; lintel units and knock-out bond beam units in this study shows that the block type also does not have a strong influence on the flexural behavior of the beams and bond wrench prisms (Figure 7). It is important to note that the knock-out units used in this study that were readily available from local suppliers resulted in a similar grout area (approximately 135 cm^2 (21 in^2) for lintels and 129 cm^2 (19.9 in^2) for knock out units), as shown in the Figure 8.

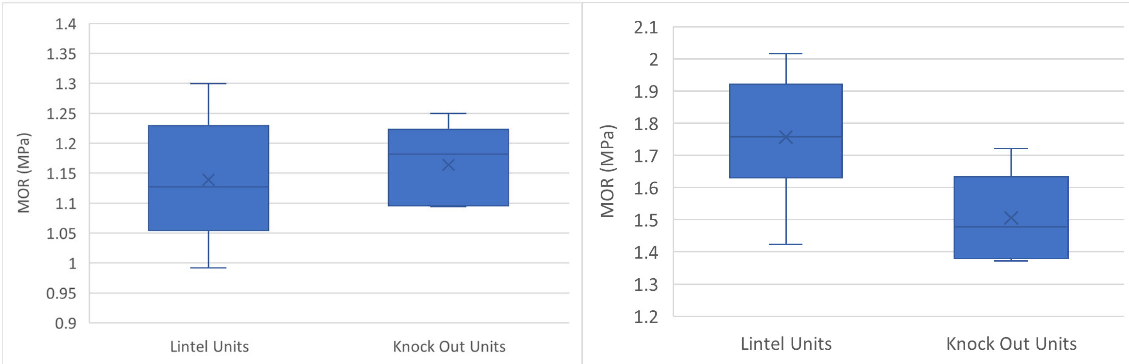

Fig. 7: MOR values for beams(left) and bond wrench specimens (right) varying block

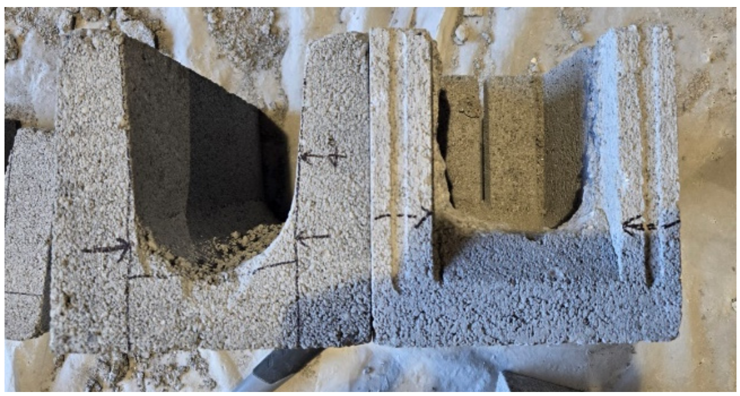

Fig. 8: Cross sections of lintel unit (left) and knock Out unit (right) used in the test

CONCLUSIONS

The MOR values from both the beam test and the bond wrench tests are higher than the values provided in the TMS 402/602-22. Further, experiments showed that grout strength had the largest impact on the MOR values. In contrast, TMS 402/602-22 currently does not account for the influence of grout type on the modulus of rupture of masonry beams. From the experimental data obtained, a significant increase of 25.1% in average MOR values was noted when using High Strength Grout (HSG) instead of Low Strength Grout (LSG). Mortar type and block type both appear to be less influential, but the results were still impacted by these parameters. An average of 10.1% increase in MOR values were achieved when using the stronger Masonry Cement Type M mortar instead of Masonry Cement Type N and an average of 9.4% gain in MOR value was measured with Lintel Units as compared to Knock-out units. The MOR values obtained from beam tests and the bond wrench tests carried out using similar parameters did not align strongly with each other, with the value from bond wrench tests being 30% to 59% greater than that of the beam tests. It is worth noting that the MOR values obtained from the bond wrench tests were significantly and consistently higher than those obtained from the beam tests for all four batches of beam and bond wrench specimens tested in this study. Based on the increased variability observed with the bond wrench test data and the fact that the beam testing is a more representative loading configuration for a masonry building, the team would recommend beam testing over bond wrench testing. Future work will build upon this data set to include multiple course beam tests with different assembly parameters and leveraging the data for an analytical study to examine the differences in the stress distribution and crack propagation behavior between bond wrench specimens and beam tests.

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