Comparative Evaluation of Structural and Water Penetration Performance of Three Different Masonry Wall Types for Residential Construction

Ali M. Memari[1], Steve V. Grossenbacher[2], and Lisa D. Iulo[3]

[1]Department of Architectural Engineering, Penn State, 104 Engineering Unit A, University Park, PA 16802, USA

[2]411 Granby St. Apt. 57, Norfolk, VA, 23510, England

[3]Department of Architecture, Penn State University, Stuckeman Family Building, Room 426, University Park, PA 16802, USA

memari@engr.psu.edu

***Abstract*-This paper presents the results of a laboratory experimental study to compare the structural behavior of three types of masonry wall systems suitable for residential construction. The three masonry types chosen consist of concrete masonry unit, autoclaved aerated concrete, and Adobe that have some sustainable attributes. The relative performance of different masonry systems is of interest because of the difference in structure and building technology performance attributes. In this study, a total of 36 wall specimens with dimensions of 1219 mm x 1219 mm were tested in shear and flexure under dry and wet conditions. For wet wall tests, a specially made spray rack was used to simulate rainy condition on the wall specimens before structural tests. This paper initially discusses some aspects of sustainable design guidelines and then presents the test results and observations made during the tests.**

Keywords-Concrete Masonry Unit, Autoclaved Aerated Concrete, Adobe, Lateral Strength, Moisture Test

I. INTRODUCTION

The use of masonry in residential construction has received more attention in the U.S. in light of the devastation following hurricane Katrina in 2005 (FEMA 2006). Furthermore, new masonry materials are being recognized to provide alternatives to wood-frame construction. For example, alternative masonries such as autoclaved aerated concrete are inherently fire resistant and may reduce the necessity for layers of materials and the need for multiple subcontractors for the wall construction.

Although the use of masonry for load-bearing exterior walls is common in low-rise buildings, today's use of load-bearing masonry walls as an alternative to traditional wood-frame in residential construction may stem from energy efficiency and sustainability considerations rather than the need for a better gravity load-bearing or lateral load resisting system. Nonetheless, the structural behavior of the types of masonry walls that may be considered suitable for sustainable design is of interest, given the emerging new masonry products and in some cases, the use of indigenous materials. In particular, because load-bearing masonry walls are usually thick and architectural features of sustainable design such as wall setbacks with respect to the roof or re-entrant corners for shading introduce the more complicated structural response under lateral loads, additional experimental studies seem to be necessary. Along with the added structural complications under dry conditions, thick load-bearing masonry walls that are subjected to rain or moisture and do not have appropriate drainage planes to effectively lead the moisture out are also of concern because of the possible effects water and moisture can have on thermal efficiency and structural capacity. Another issue with potential entrapment of moisture in Adobe or autoclaved aerated concrete walls could be the weakening of the wall due to wet-dry cycles.

In recent literature, there have been many experimental investigations of masonry in both shear and flexural strength (e.g., Abboud et al., 1996; Griffith et al., 2004; Tanner et al., 2005). Many of these experiments dealt with seismic testing of masonry materials leading to proposed design provisions for the use of specific masonry to better assess the dynamic structural capacity. According to Zhuge et al. (1995), experimental values of unreinforced masonry shear wall under lateral cyclic loading provide a more "realistic" estimate of the structural capacity and failure modes of masonry walls than shear-failure calculations. One of the common results of both shear and flexural experimental testing (e.g., Abboud et al., 1996; Fath, 1992; Tanner et al., 2005; Zhuge, Y et al. 1995) is that masonry walls, specifically autoclaved aerated concrete (AAC), and concrete masonry unit (CMU) walls have a higher structural capacity than what would be found just using failure calculations to predict capacity. However, as these masonry materials have become more desirable in residential design for various reasons, the concern of structural performance of load bearing walls in a seismic event has also increased. In severe earthquakes around the world, many masonry structures built from Adobe have seen major cracking and even failure (Adeli & Mohammadi, 1985; Webster & Tolles, 2000; Memari and Kauffman, 2005). Many of these structures were built out of Adobe brick walls because of the availability of the material or the sustainability of the Adobe but neglected the structural behavior of the material. Of course, if proper detailing is used, even Adobe construction can be expected to perform as well as more engineered masonry systems. On the other hand, with poor detailing, even many structures that used CMU (an engineered masonry) wall as the load-bearing structural system have failed in major seismic events, such as the 1994 Northridge earthquake and the 1989 Loma Prieta earthquake.

A general review of masonry materials reveals that many experiments and studies have been carried out on the shear and flexural strength of a single masonry material type, both under static and dynamic loading (e.g., Abboud et al., 1996; Fath, 1992; Griffith et al., 2004; Tanner et al., 2005; Zhuge, 1995). However, not much data is readily available regarding a comparative study of masonry materials concerning shear and flexural strength. There is also a lack of data concerning water absorption of masonry materials and its potential effect on structural capacity.

Given this interest in increased use of masonry for sustainable residential construction and the lack of a comparative study on the experimentally obtained capacity of masonry, a study was undertaken to generate laboratory test data and to compare the structural behavior of three types of masonry that have some of the desirable sustainable attributes. The three masonry types chosen are representatives of a conventional material: CMU, a new material: AAC, and a traditionally indigenous material: Adobe. Although there are interests in exploring and using new materials, some architects have rediscovered the desirable sustainable properties of Adobe as well. Design professionals are interested in the relative performance of masonry wall systems. Of course, evaluation of the thermal performance of such masonry is also of interest to design professionals dealing with sustainable wall systems, but this aspect was not within the scope of this study. In subsequent sections, a brief background and literature review on sustainable design of wall systems, the experimental program, and the test results are presented.

II. BACKGROUND AND LITERATURE REVIEW RELATED TO SUSTAINABILITY ASPECTS OF THE SELECTED MASONRY WALL SYSTEMS

The use of load-bearing masonry walls in sustainable design can reduce energy cost, particularly in climates with high temperature swings over a 24-hour period (Bolin, 2005; Bunz et al., 2006; Van Geem, 2006; Goodhew and Grifith, 2005, The Natural Home, 2008). Although traditional masonry materials such as concrete or clay brick are favored for use in loading bearing design construction, other (new) masonry materials such as AAC with higher insulation property may also qualify as sustainable materials with respect to several attributes.

AAC is a factory-produced lightweight precast concrete product made by mixing portland cement, lime, silica sand or fly ash, water, and aluminum powder, and then pouring the slurry into a large mold (Memari and Chusid, 2003). While still in a semi-cured state, the demolded concrete is wire-cut to configurations and sizes of desired elements such as blocks, beams, slabs, or panels. The members are then placed in a pressurized autoclave for steam curing. The resulting precast units weigh between 400 to 800 kg/m^3 with compressive strengths varying from 2.07 to 6.21 N/mm^2. The insulation property of AAC is approximately an R-value of 1.25 per inch (.05 per millimeter). AAC blocks are laid with thin-bed mortar joints.

Adobe brick is made from a mix of soil (clay, sand, and aggregates), water and straw (for strength) and is molded and sun dried. Adobe and its construction have some useful properties including some thermal insulation but mainly high thermal energy storage capacity (O'Connor, 1999; Newcomb, 2001; Reeve and Reck, 2001; and Witynski and Carr, 2002). Older type Adobe construction is, however, associated with many disadvantages such as large weight, low strength, and brittleness that make traditional Adobe construction with poor detailing extremely vulnerable to damage in earthquakes. With renewed interest in the use of Adobe in some sustainable designs, modern Adobe brick and mortar may include some stabilizer cement or asphalt emulsion. Of course, with the use of such additives, this kind of Adobe cannot be considered an indigenous material. Very little experimental information is available on such stabilized Adobe, and because of the recent interest in its use, this research considered its comparison with CMU and AAC.

The study of the behavior of moist and wet walls in this research would be of interest in cases where there is a possibility of moisture entrapment in the wall. In general, some masonry walls may have an applied exterior finish such as plaster, stucco or cement. Rain water can infiltrate the wall through cracks in a finish surface without proper drainage plane and weep system and get entrapped for some time before it is dried out. In such cases, the thermal efficiency of the wall could be compromised and the lateral load capacity of the wall affected, depending on the type of the masonry and mortar. Furthermore, any entrapped moisture may initiate undesirable mold growth in the walls.

Another aspect of interest in studying masonry walls under wet conditions is to develop a better understanding of the way rain water penetrates through the wall. It is not known for example whether the water leakage would mostly take place through the masonry blocks/bricks or through the mortar for different masonry types. Furthermore, the moisture absorption rate of wetness needs to be determined to yield a measure of the resistance of the wall to water leakage (Choi, 1998). Still another reason for the need to study the water effect on walls is the fact that any moisture entrapped may adversely affect the performance of the building in the long term. For example, water entrapment can lead to corrosion of reinforcement, metal anchors, or other metal attachments to the building. According to Galitz and Whitlock (1998), "Improper handling of rainfall incident upon building surfaces causes innumerable problems, both aesthetic and structural, e.g., efflorescence, mildew, corrosion, and freeze/thaw damage." It is therefore, necessary to better understand the mechanism of water penetration through masonry walls. According to Straube and Burnett (1998), "Despite the importance of driving rain to building performance, very little is known about the magnitude, duration, and frequency of driving rain deposition on buildings." Masonry walls absorb and store some of the rain that falls on the exterior wall surface. Straube and Burnett (1998) further explain that a wall that functions properly, will lose the stored moisture through evaporation drying before any wetness reaches the interior surface of the wall. However, their research has shown that the wetness will reach the other side of the wall; only the amount of moisture will vary depending on the type of masonry used.

Before the presentation of the experimental part of the study, it is also desirable in this literature review and background section to compare the chosen masonry types based on certain sustainable attributes. If we compare the energy efficiency and the reduction of heating and cooling loads of the masonry walls according to the manufacturer's information, 203 mm AAC block wall without insulation thermally performs equally as a 203 mm CMU block wall with R-8.6 insulation, which would mean that the AAC block wall would require less materials to obtain the same energy efficiency. Adobe block walls are also considered to be energy efficient construction material because of Adobe's high thermal mass and the thermal "flywheel" effect, which means the inertia or resistance provided by the Adobe against outdoor temperature fluctuations helps to flatten out the temperature indoors. The thermal flywheel effect is not found in all parts of the United States, and therefore Adobe might be only considered an energy efficient material in places such as the southwest (e.g., Arizona, New Mexico) where the daily swing of low to high temperatures is large. It should be noted that for a more accurate assessment of thermal and energy efficiency of these wall types, additional experimental and simulation studies are needed.

When looking at the materials themselves, AAC can be made out of recycled fly ash from coal plants (Hauser et al. 1999). Typically, AAC is made with sand water and limestone, which are natural raw materials. However, with the manufacturer's process, one unit of raw materials expands to make 5 units of AAC block. Although AAC comes in different densities and CMU can be of normal weight or lightweight, nonetheless, AAC block can be thought to be roughly 50% lighter than CMU block, which reduces the environmental impacts from material transportation and installation. However, because AAC is not a mainstream construction material, the actual materials have to come from few manufacturing plants in the United States, and that would increase the negative transportation effects on the environment.

Adobe block is not only made from earthen materials but they are fully recyclable. However with its large unit weight and lack of availability in most parts of the United States, the environmental impact of transportation of the Adobe material would be relatively high.

CMU block has a chemical manufacturing process, a labor-intensive construction process and a large unit weight, which all contribute to a negative impact on the environment. However, with widespread use in the United States, manufacturing plants can be found in a multitude of places, and if fly ash cement substitute is used, this further reduces the environmental impacts from transporting CMU block.

III. LABORATORY EXPERIMENTAL PROGRAM

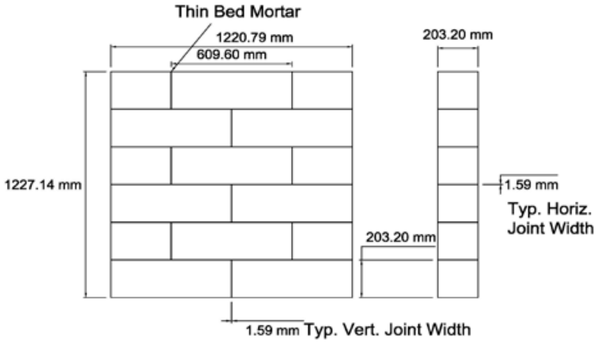
The main objective of the laboratory experimental study was to investigate and compare the structural capacity of the three chosen types of masonry systems to produce technical information with emphasis on structural and moisture penetration performance aspects. The resulting data can be useful to compare load-bearing masonry walls that are more structurally efficient and help determine the appropriate masonry type for certain applications. Specifically, this study aimed to generate laboratory experimental data for comparison of structural capacity and moisture penetration of three types of masonry walls: AAC, Adobe and CMU. An additional objective was to compare the degree of moisture effect (e.g., absorption or saturation) for the three masonry types and the effect of such moisture on strength in comparison with the results from the dry structural capacity tests. The research approach to meet these objectives was to develop the lateral load (flexural and shear) capacity of each masonry wall type. To determine the shear capacity of each masonry wall, an in-plane displacement-controlled load was applied to the top of each wall specimen to produce load and corresponding displacement data. To obtain the flexural capacity of each masonry wall type using load vs. displacement curve, an out-of-plane displacement-controlled load was applied to the mid-span of each test wall specimen. To obtain data for the moisture penetration and its effect on structural integrity, water was sprayed on the specimen, a saturation percentage comparison was done, and then the specimens were subjected to the same displacement-controlled loads to obtain a load vs. displacement curve.

In this study, 36 specimens of unreinforced masonry walls with dimensions of 1219 mm x 1219 mm were tested under in-plane shear loads and out-of-plane flexural loads using the test setup appropriate for the intended purpose. It should be noted that ASTM E72 (ASTM 2005) suggests various test setups for such tests. However, in this study because the mockups were not of actual size used in real life and the objective was comparative study of the three wall systems, there was no need to follow the standard ASTM E72 protocols. 18 of the walls were tested under dry conditions, and the other 18 were tested after a 2-hour moisture saturation test. Table 1 lists the test specimen matrix. To replicate current construction techniques and consistency, commercially available 203 mm nominal width blocks of CMU, AAC and Adobe were used to build the 1219 mm x 1219 mm wall samples. The lengths and heights of the blocks varied depending on the material. Figure 1 shows the block, mortar joint and wall dimensions for each masonry material type used. The cement-lime mortar used for the CMU block walls was structural strength type S mortar with a mixture of 1:1:6 (cement: lime: sand, by volume) and a thickness of 9.5 mm. The mortar for the AAC block walls was thin bed mortar with a thickness of 1.6 mm. Finally, a cement stabilized mortar with a thickness of 25.4 mm was used for the Adobe block walls. The mortar material for AAC and Adobe was provided by respective masonry manufacturers, AERCON Florida LLC (Haines City, Florida) and Clay Mine Adobe (Tucson, Arizona). To acquire consistent results, the walls were constructed by professional masons with some help from the International Masonry Institute (IMI) and were left to cure under laboratory condition (approximately 25°C) for a minimum of 28 days.

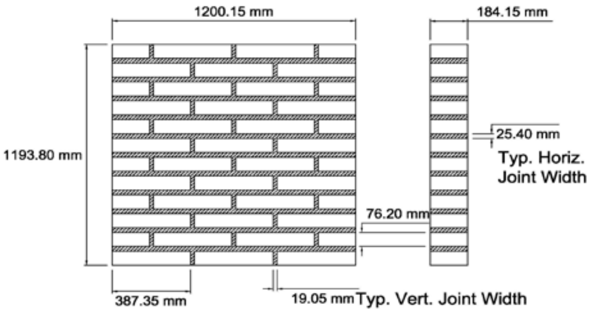
TABLE 1 WALL TEST SPECIMEN MATRIX – ALL SPECIMEN DIMENSIONS 1219 MM X 1219 MM.

Dry Static Shear Strength Test	AAC: DS1, DS2, DS3
	Adobe: DS4, DS5, DS6
	CMU: DS7, DS8, DS9
Wet Static Shear Strength Test	AAC: WS1, WS2, WS3
	Adobe: WS4, WS5, WS6
	CMU: WS7, WS8, WS9
Dry Flexural Bond Strength Test	AAC: DF1, DF2, DF3
	Adobe: DF4, DF5, DF6
	CMU: DF7, DF8, DF9
Wet Flexural Bond Strength Test	AAC: WF1, WF2, WF3
	Adobe: WF4, WF5, WF6
	CMU: WF7, WF8, WF9
Moisture Penetration Test	AAC: MP1, MP2, MP3, MP4, MP5, MP6
	Adobe: MP7, MP8, MP9, MP10, MP11, MP12
	CMU: MP13, MP14, MP15, MP16, MP17, MP18

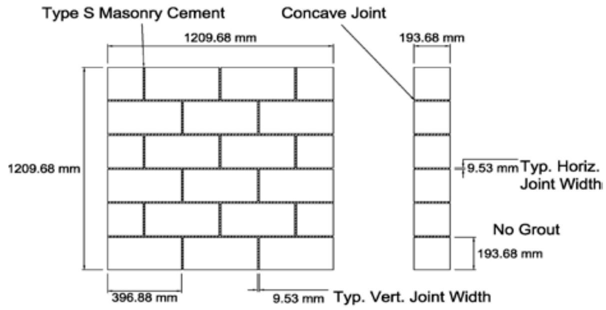
The out-of-plane flexural test setup, as shown schematically in Figure 2, consisted of securing a wall specimen on a strong floor (a concrete platform) and using a steel reaction frame to apply jacking force to the specimen. The walls were placed vertically and tied back to the steel reaction frame at the top of the specimen, using tieback rods attached to a stiff channel. The sliding of the wall was prevented by using steel angles anchored at the base. A rubber pad was inserted at the bottom to prevent direct contact between the angle and the specimen. An ENERPAC loading jack was used to apply a horizontal load to a steel channel that was placed across the center of the wall area to distribute the load. The static monotonic load was increased incrementally until failure. The data and information were recorded by a computer and data acquisition system using a load cell and displacement transducers placed at mid height of the wall specimen.



(a) AAC



（b）Adobe



(c) CMU

Figure 1 Wall specimen details and dimensions; (a) AAC, (b) Adobe, (c) CMU

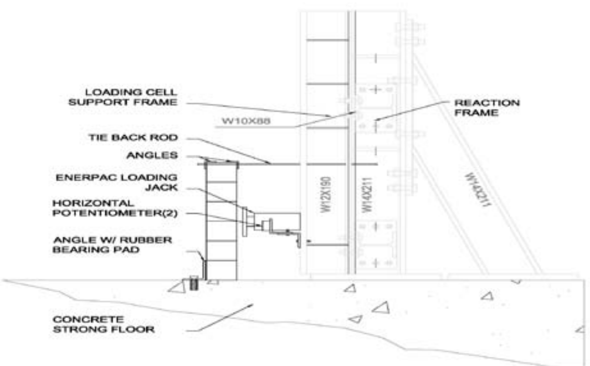


Figure 2 Out-of-plane flexural test configuration

The in-plane shear test setup, as shown schematically in Figure 3, consisted of the same strong floor (platform) and reaction frame as in the out-of-plane flexural test setup. However, the wall was oriented such that the line of action of the loading jack would exert an in-plane load to the specimen. The wall was secured with a steel angle at the base to prevent sliding and another steel angle to secure the vertical tie system. Both angles were bolted to the concrete base. A rubber pad was inserted in the left bottom corner of the wall to prevent direct contact between the angle and the specimen. The vertical tie system was bolted to one of the angle sections at the bottom and was attached to a plate at the top of the wall to prevent overturning of the wall. The load was applied at the center of the wall thickness 102 mm below the top of the wall. An extension of the ENERPAC loading jack and extra plate was provided to allow room for monitoring equipment and to spread out the load across the thickness of the wall. The specimens were subjected to an increasing lateral load until failure. The data and information were recorded by a computer and data acquisition system using a load cell and two potentiometers placed at the loading point for horizontal displacement and two potentiometers placed at the base of the specimen for vertical displacement.

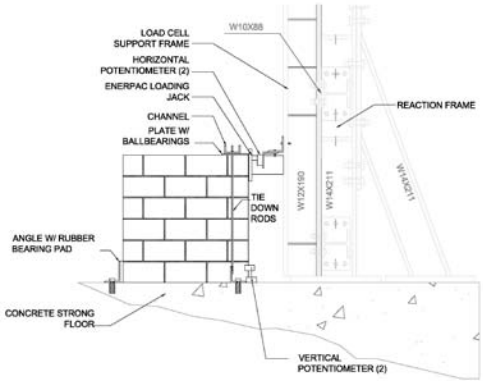
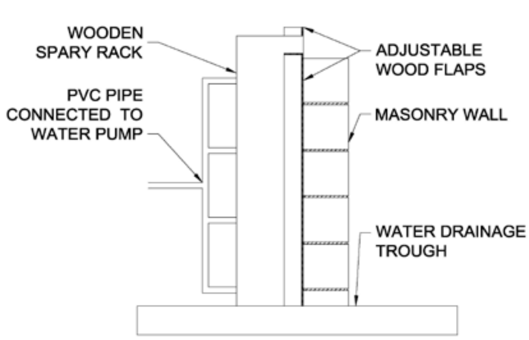


Figure 3 In-plane shear test configuration

The moisture penetration test setup, as shown schematically in Figure 4 (a), consisted of a specially constructed spray rack to simulate rainy conditions on the wall specimens for 2 hours before structural tests under wet conditions were performed. Figure 4 (b) shows photographs of the exterior and interior side of the spray rack. Various methods of applying water spray on wall specimens to simulate rain conditions have been studied by Galitz and Whitlock (1998). Such Methods include water test chamber, spray rack, and calibrated nozzle testing. ASTM C1601, C1403, and E514 (ASTM 2006a, b, and c) all discuss the standard methods of testing moisture penetration of masonry under wind driven rain, field testing of moisture penetration and water absorption of masonry mortars.



（a）Moisture penetration test setup

(b) Photographs of the exterior and interior side of the moisture penetration test rack

Figure 4 Moisture penetration test configuration

The wall specimens were subjected to a constant flow of water to the exterior through the spray rack. Each wall specimen was inspected and the water penetration to the interior side was documented in increments of 10 minutes for 2 hours. Immediately after the 2-hour moisture penetration test, each wall was then tested for in-plane or out-of-plane structural capacity while still wet.

IV. DISCUSSION OF PRISM TEST

To get the compressive strength of the masonry made of AAC, Adobe and CMU, prism tests for each unit type were also performed. The construction and testing of the prisms followed the guidelines of ASTM C1314 (ASTM 2006d). The curing was under the same condition as the wall specimens. Three prism specimens of each material were tested. The average of the 3 tests of each material was used to compare to MSJC (MSJC 2005) calculations for the AAC and manufacturers test results for the Adobe and CMU. The test results are presented in tables displaying the individual prism properties and the average compressive strength of the prism specimens. Table 2 shows the prism test results for the AAC, Adobe and CMU masonry. The average compressive strength (***f'***$_{mt}$) from the prism tests of the AAC, Adobe and CMU were 3.3 N/mm^2, 5.2 N/mm^2, and 7.8 N/mm^2, respectively.

The AAC average compressive strength of approximately 3.2 N/mm^2 is 39% higher than the minimum of 2.0 N/mm^2 that is specified in MSJC (MSJC 2005). The mode of failure of each specimen varied slightly, which may be attributed to slight chips or cracks in the blocks themselves. The Adobe average compressive strength was determined to be approximately 5.2 N/mm^2. According to Clay Mine Adobe (2007), the compressive strength of cement stabilized Adobe block is 5.2 N/mm^2, while the mortar strength is given as 4.2 N/mm^2. The prism test results obtained is exactly equal to that of the Adobe block but about 24% higher than the mortar strength. It is normally expected to have the block with higher strength. The mode of failure was consistent throughout the 3 Adobe prism specimens. The CMU average compressive strength of 7.8 N/mm^2 is 24% lower than the 10.3 N/mm^2 stated in MSJC (MSJC 2005). This could be due to lower quality block or a lower strength mixture of mortar. The mode of failure was consistent throughout the specimens except for the lowest compressive strength specimen. ASTM C 1314 (2006d) defines seven different failure modes for

TABLE 2 TESTED PRISM PROPERTIES

Prism No.	Avg. Width (mm)	Avg. Height (mm)	Avg. Length (mm)	Net Area (mm^2)	Max Load (KN)	Net Compr. Strenth (N/mm^2)	hp/tp Ratio*	hp/tp CF**	Corrected Net Strength (N/mm^2)	Mode of Failure***
AAC Tested Prism Properties										
1	200.2	407.9	403.4	80710	273.12	3.39	2.04	1.00	3.39	6,7
2	201.7	409.2	404.9	81613	206.40	2.53	2.03	1.00	2.53	5
3	199.9	407.7	405.1	80903	315.82	3.90	2.04	1.00	3.90	5,6
Avg.	200.7	408.2	404.4	81097	265.11	3.28	2.04	-	3.28	-
Adobe Tested Prism Properties										
1	183.4	408.4	385.1	70581	359.42	5.10	2.23	1.02	5.20	6
2	186.2	412.0	388.6	72322	400.34	5.54	2.21	1.02	5.65	6
3	186.9	392.9	388.6	72645	404.57	5.57	2.10	1.01	5.63	6
4	186.2	402.1	386.8	72000	327.39	4.54	2.16	1.01	4.59	6
Avg.	185.7	403.9	387.4	71871	372.93	5.18	2.18	-	5.27	-
CMU Tested Prism Properties										
1	193.8	404.1	395.0	35677	187.05	5.24	2.09	1.08	5.66	6
2	193.8	405.9	395.7	35677	246.43	6.90	2.09	1.08	7.45	6,7
3	193.8	406.7	395.2	35677	238.42	6.68	2.10	1.08	7.21	6,7
4	193.8	405.1	395.2	35677	440.48	12.34	2.09	1.08	13.33	6,7
Avg.	193.8	405.4	395.2	35677	278.10	7.79	2.09	1.08	8.41	-
* A ratio of height to the least lateral dimension of each prism										
** Height to thickness correction factor from Table 1 of ASTM C 1314 - 03b based on the hp/tp ratio.										
*** Refer to ASTM C 1314 Figure 4 and report number of corresponding mode of failure										

prisms. The failure modes of the prisms that occurred in the testing consisted of a) failure mode 5, which is a semi-conical break in which the sides of the prism shear off in a semi-circle formation, b) failure mode 6, which is a shear break in which a diagonal crack forms in the prism and shears off, and c) failure mode 7, which is a face shell separation in which the face of the prism separates from the center of the prism. Figure 5 shows failure modes for each of the masonry materials.

(a) AAC prism test failure mode

(b) CMU prism test failure mode

(c) Adobe prism test failure mode

Figure 5 Photographs of masonry Prism Failure Modes

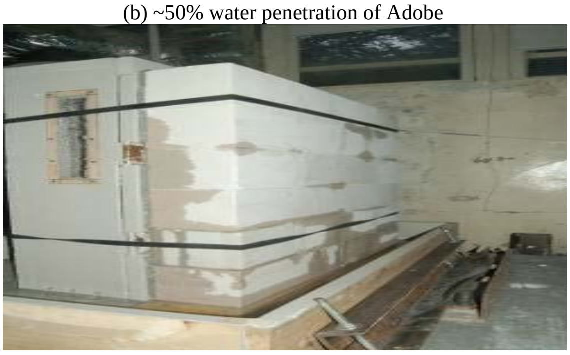
V. DISCUSSION OF DRY AND WET SPECIMENS TESTS

During the water penetration tests, photographs were taken every 10 minutes for 2 hours while the water was being sprayed on the wall specimens. Figure 6 shows photographs of the 3 most saturated wall specimens after the 2 hour spray period. The photographs were used to compare the percentage of wall area where moisture appeared on the opposite side of the water spray. Comparison among the three types of masonry specimens was performed using the average percentage of through-wall moisture penetration. Table 3 shows the average percentage of water penetration for different masonry materials determined from the photographs. Accordingly, the AAC specimens had the least amount of through-wall moisture penetration at an average of 11%, while Adobe had an average of 32% and the CMU walls showed an approximate average of 50% through-wall moisture penetration. The implication of these results is that if these walls are exposed to high precipitation, after 2 hours of heavy rain, one can expect the indicated percentages of the wall area on the interior side to be wet. These tests also showed that the water seepage through the mortar joints was significantly faster than that through the blocks in all 3 wall materials. Because of its small mortar width and solid blocks, the AAC wall specimens had the least through-wall moisture penetration. On the other hand, the Adobe wall specimen showed a much higher 32% through-wall moisture penetration, because of their thick mortar joints. Finally, the CMU walls showed the largest through-wall moisture penetration at an average of 50%. As in Adobe, the water leakage through the joints was larger than through the blocks.

The shear and flexural test results are presented here in the form of load-displacement curves for AAC, Adobe and CMU masonry wall specimens. Comparison of the three dry and three wet responses of different wall systems is made based on such diagrams as well as photographs taken from specimens before and after the tests. Figures 7-12 show the load-displacement plots for shear and flexural tests of AAC, Adobe and CMU specimens under dry and wet conditions. The peak loads and corresponding displacements resulting from shear testing of the dry and wet specimens are listed in Table 4, while the results of flexural tests are listed in Table 5.

（a）~80% water penetration of CMU

(b) ~50% water penetration of Adobe



(c) ~20% water penetration of AAC

Figure 6 Photographs of the water penetration tests for the three masonry types

TABLE 3 2-HOUR MOISTURE PENETRATION PERCENTAGES (SPECIMEN DIMENSION:1219 MM X 1219 MM)

Specimen	%Area Moist	%Average
MP1	30%	11%
MP2	15%	
MP3	5%	
MP4	5%	
MP5	5%	
MP6	5%	
MP7	10%	32%
MP8	15%	
MP9	30%	
MP10	25%	
MP11	50%	
MP12	60%	
MP13	25%	49%
MP14	70%	
MP15	85%	
MP16	30%	
MP17	50%	
MP18	35%	

VI. COMPARISON OF DRY AND WET SPECIMENS TEST RESULTS

The average value of peak load resulting from shear tests (Table 4) for the AAC, Adobe, and CMU specimens are, respectively, 86,533 N, 42,511 N, and 44,928 N for the dry tests and 48,695 N, 28,811 N, 40,762 N for the wet tests. The respective displacements under the peak loads are 46.5 mm, 24.6 mm, and 13.0 mm for the dry tests and 15.8 mm, 19.4 mm, and 17.7 mm for the wet tests. The boundary condition for all wall specimens under in-plane loading was the same as shown in Figure 3.

The dry wall shear test results show that AAC walls had approximately 93% higher strength capacity while Adobe walls had approximately 5% lower strength capacity compared to CMU specimens under the same loading setup. One reason for the relatively larger AAC shear capacity compared to CMU is that AAC masonry used was solid, while the CMU blocks were hollow and not grouted, and thus CMU walls had a much smaller mortared area to resist shear. Although Adobe is generally thought of to be a weak material, the test results show that the cement stabilized Adobe can indeed have shear capacity comparable to that of ungrouted hollow CMU block walls. For the wet wall test results, AAC had approximately 20% higher while the Adobe walls had 29% lower strength capacity compared to CMU specimens. Comparing the dry shear test results to the wet test results, the AAC, Adobe and CMU decrease in in-plane shear strength capacity are, respectively, 44%, 32% and 9%. The larger drop in shear resistance of AAC and Adobe compared to the lower drop in CMU is a significant result of these tests. The reason for the drop in Adobe strength is the change of state of mortar to somewhat plastic form due to water absorption by the mortar. In AAC case, however, it is not the thin mortar but the units themselves mainly absorb the moisture and weaken the wall capacity. Such is not the case, however, in CMU where the moisture easily passes through the mortar and also the units and will not affect their strength significantly. Figure 13 shows the photographs of the dry specimens tested under shear both before and after the shear test. Although there were variations in the failure planes of AAC specimen, the failure mode of CMU and Adobe specimens were consistent.

TABLE 4 SHEAR TEST RESULTS

AAC Shear Test Results				
Test Specimens	Max Load (N)	Average Load (N)	Max Horz. Disp. (mm)	Average Horz. Disp. (mm)
DS1	107623	86533	47.4	46.53
DS2	92342		26.5	
DS3	59633		65.7	
WS1	60048	48695	10.7	15.80
WS2	39760		21.5	
WS3	46278		15.2	
Adobe Shear Test Results				
Test Specimens	Max Load (N)	Average Load (N)	Max Horz. Disp. (mm)	Average Horz. Disp. (mm)
DS4	38004	42511	24.5	24.57
DS5	56895		28.4	
DS6	32633		20.8	
WS4	26799	28811	15.7	19.40
WS5	30836		22.6	
WS6	28797		19.9	
CMU Shear Test Results				
Test Specimens	Max Load (N)	Average Load (N)	Max Horz. Disp. (mm)	Average Horz. Disp. (mm)
DS7	44965	44928	17.7	13.00
DS8	53937		5.8	
DS9	35882		15.5	
WS7	47826	40762	20.5	17.67
WS8	38315		17.6	
WS9	36145		14.9	

The average value of peak load resulting from the flexural tests (Table 5) for the AAC, Adobe, and CMU specimens are, respectively, 13209 N, 3505 N, and 3452 N for the dry tests and 8613 N, 3037 N, 4143 N for the wet tests. The respective displacements under the peak loads are 6.0 mm, 22.8 mm, and 26.2 mm for the dry tests and 6.0 mm, 30.7 mm, 11.7 mm for the wet tests. The boundary condition for all wall specimens under flexural loading was the same as shown in Figure 2.

These results show that the Adobe specimens had approximately 2% more flexural capacity in the drywall tests than that of the CMU, while the AAC specimens had 283% more flexural capacity than CMU. In the wet wall tests both the AAC specimens and the Adobe specimens have a reduced flexural capacity while the CMU average flexural capacity slightly increased. The in wet CMU capacity could be attributed to the dry and wet wall specimen # 3 flexural capacity being somewhat lower and higher, respectively, than the other 2 wall specimens. For the AAC case, the drop in wet strength compared to dry strength is about 35%, while the drop for Adobe is 13%. Again, the significant drop in capacity of AAC when it gets wet is quite important to note. In general, efforts should be made in architectural design of the load-bearing AAC and also Adobe to ensurethat they remain dry as much as possible. Comparison of dry wall with wet wall specimens shows that the wet CMU specimens had on average 55% decrease in displacement at peak load. The AAC specimens did not show any change, but the wet Adobe specimens showed 35% higher displacement at peak load compared to the dry specimens. This could be attributed to the formation of increased plastic state in the wet Adobe and its mortar. Figure 14 shows the photographs of the specimens tested under flexure both before and after the flexural test. The photographs consistently show failure plane through the bed joint, except for AAC specimens where failure is also through the masonry itself.

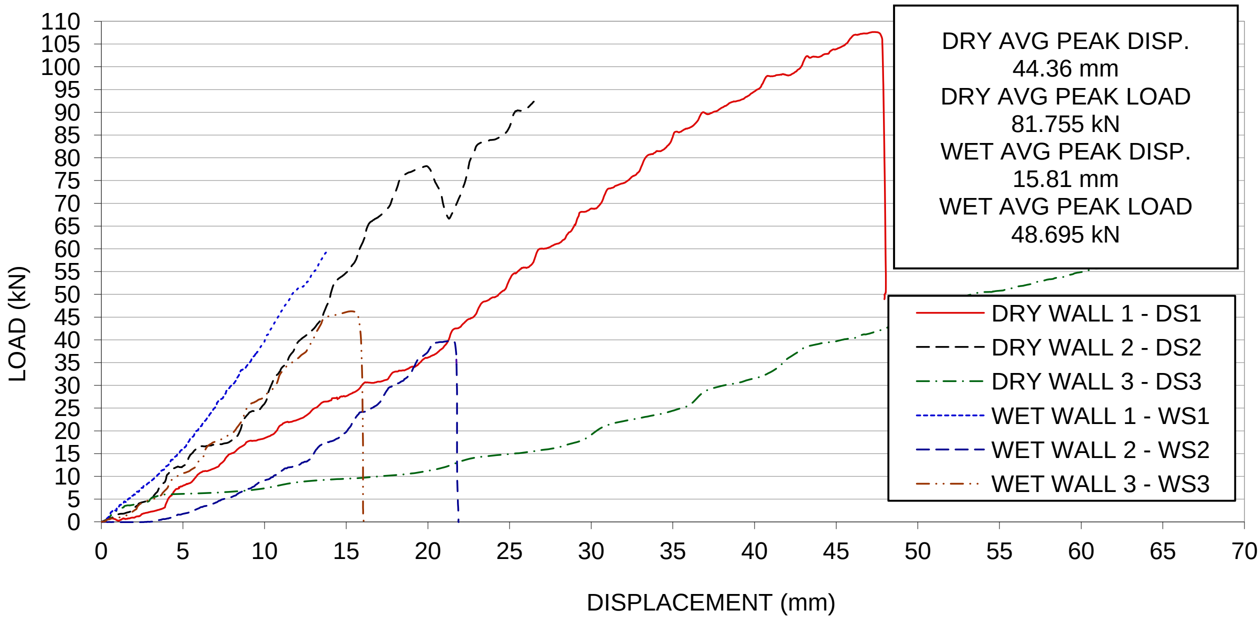


Figure 7 AAC wall shear test load vs. displacement graph

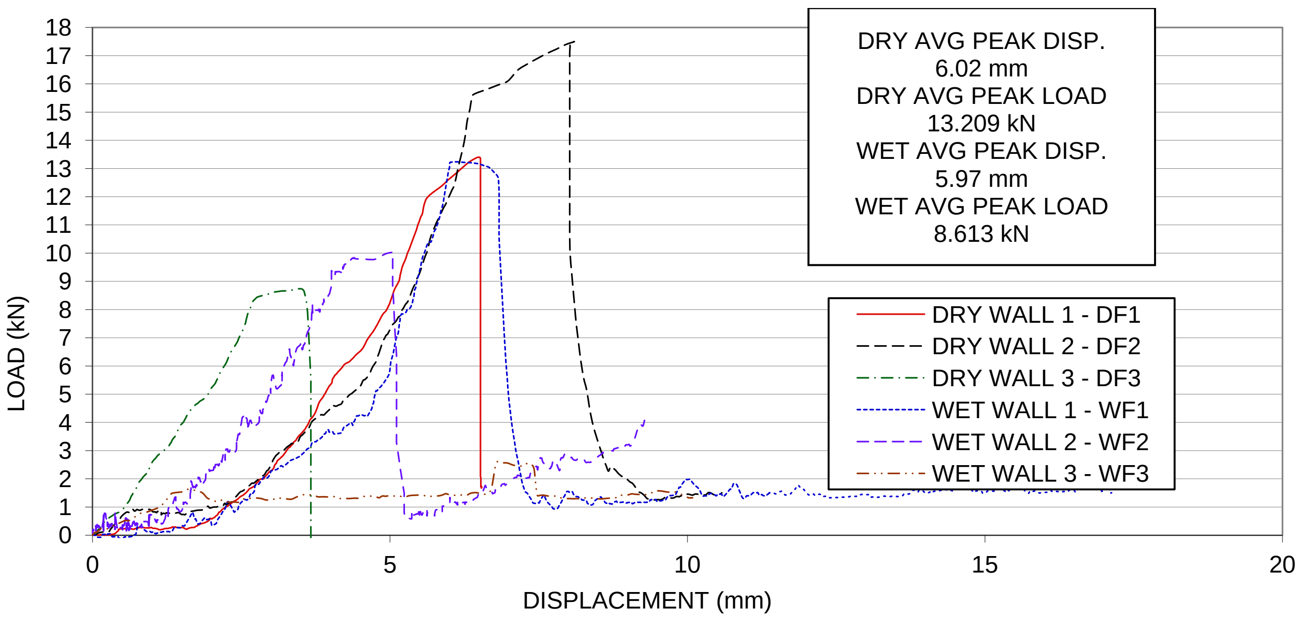


Figure 8 AAC wall flexural test load vs. displacement graph

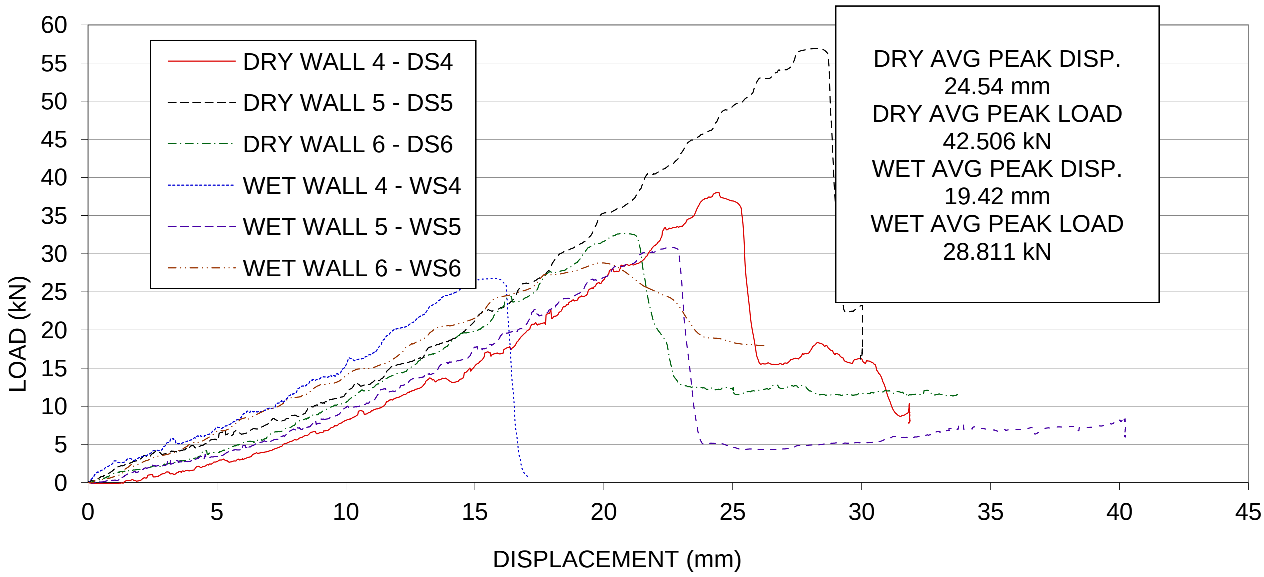


Figure 9 Adobe wall shear test load vs. displacement graph

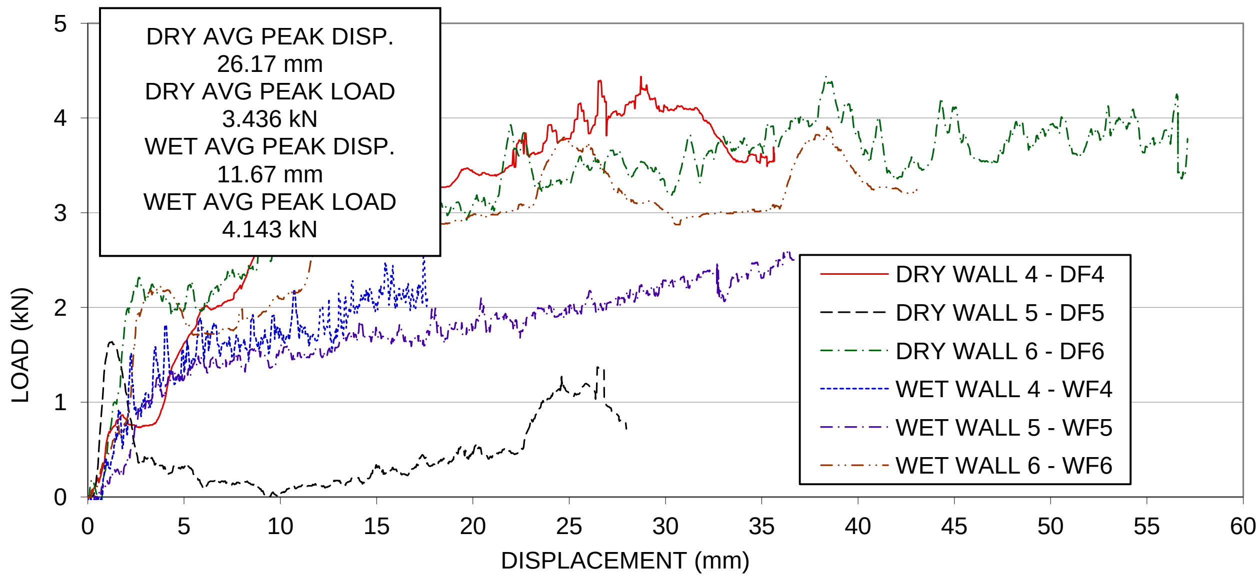


Figure 10 Adobe wall flexural test load vs. displacement graph

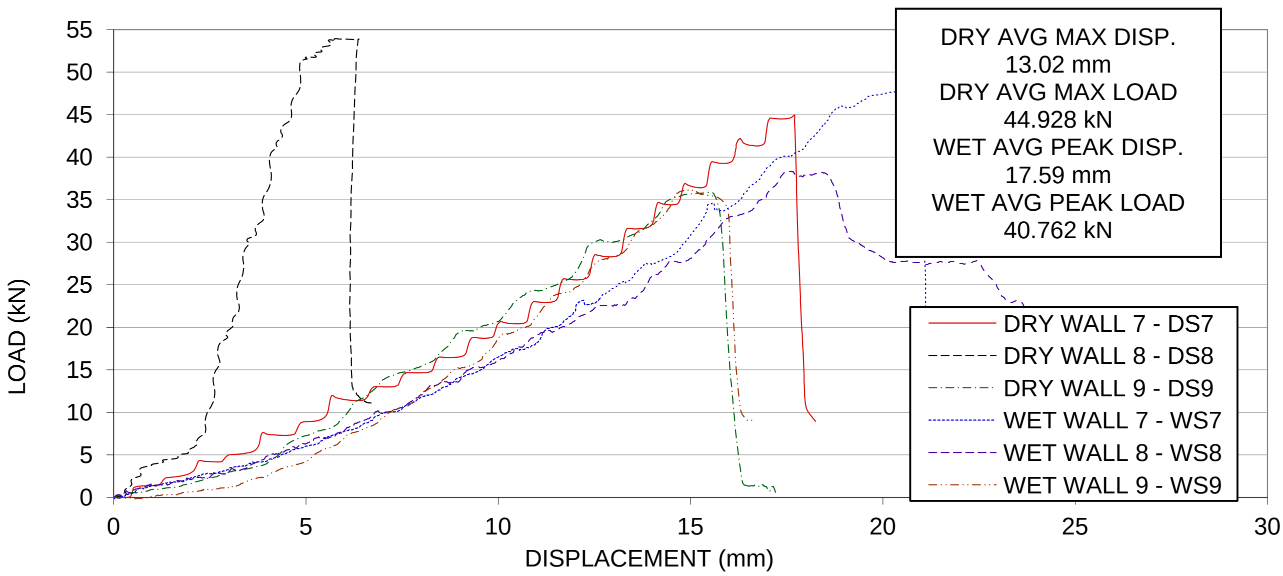


Figure 11 CMU wall shear test load vs. displacement graph

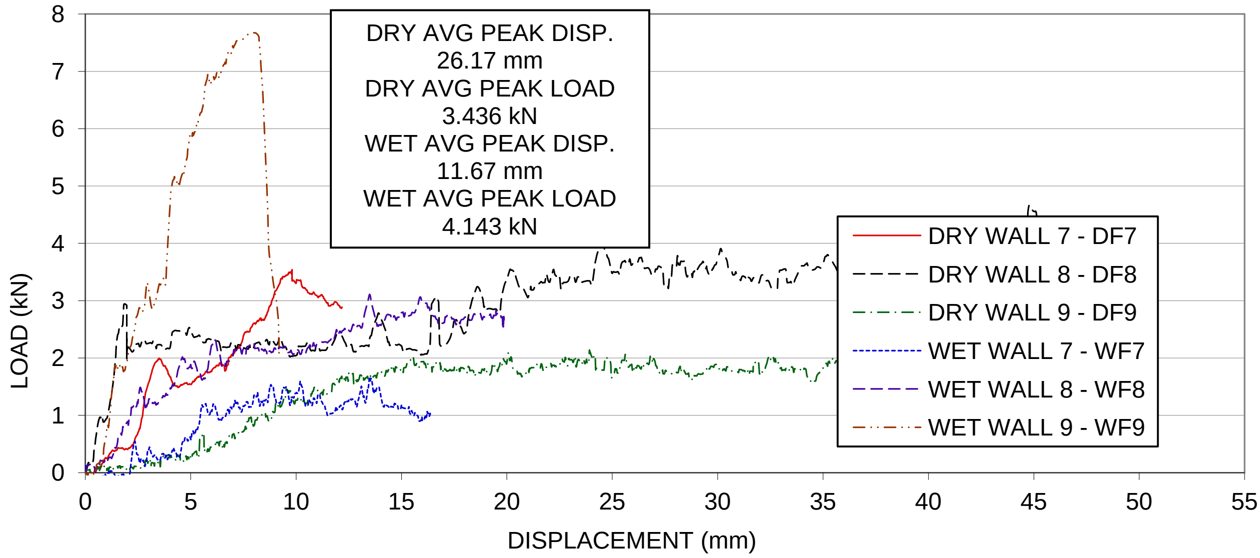


Figure 12 CMU wall flexural test load vs. displacement graph

TABLE 5 FLEXURAL TEST RESULTS

AAC Flexural Test Results				
Test Specimens	Max Load (N)	Average Load (N)	Max Horz. Disp. (mm)	Average Horz. Disp. (mm)
DF1	13396	13209	6.5	6.03
DF2	17495		8.1	
DF3	8737		3.5	
WF1	13237	8613	6.1	5.97
WF2	10030		5	
WF3	2571		6.8	
Adobe Flexural Test Results				
Test Specimens	Max Load (N)	Average Load (N)	Max Horz. Disp. (mm)	Average Horz. Disp. (mm)
DF4	4438	3505	28.7	22.75
DF5	1638		1.25	
DF6	4438		38.3	
WF4	2606	3037	17.4	30.73
WF5	2599		36.4	
WF6	3906		38.4	
CMU Flexural Test Results				
Test Specimens	Max Load (N)	Average Load (N)	Max Horz. Disp. (mm)	Average Horz. Disp. (mm)
DF7	3539	3452	9.8	26.17
DF8	4680		44.8	
DF9	2136		23.9	
WF7	1645	4143	13.5	11.67
WF8	3111		13.5	
WF9	7673		8	

（a）CMU specimen before shear test

(b) CMU specimen after shear test

(c) AAC specimen before shea r test

(d) AAC specimen after shear test

(e) Adobe specimen before shear test

(f) Adobe specimen after shear test

Figure 13: Photographs of shear test specimens before and after the tests

（a）CMU specimen before flexure test

(b) CMU specimen after flexure test

(c) AAC specimen before flexure test

(d) AAC specimen after the flexure test

(e) Adobe specimen before flexure test

(f) Adobe specimen after the flexure test

Figure 14 Photographs of wall flexure test specimens before and after the tests

VII. COMPARISON OF FLEXURAL AND SHEAR STRESSES WITH ALLOWABLE VALUES

Besides the comparison of dry and wet specimen test results, it is also desirable to determine the flexural and shear stresses resulting from dry specimen tests and compare them with available allowable values. Because of the relative small size of the samples, the gravity load effect on the tensile stress calculation can be ignored. The flexural tensile stress can then be obtained based on the following relation f_t = PL/4S for a concentrated load P at mid-height of the wall with height H, where S is the section modulus. For the purpose of this calculation, P can be taken as the average value given in Table 5. The allowable stress values based on test results can be obtained by using a factor of safety of 2.5 as is normally used in masonry structures (e.g., MSJC 2005). The height of the wall is 1219 mm in this case, and the section modulus S is $6.88x10^6$ mm^3/m for AAC and Adobe and $4.71x10^6$ mm^3/m for CMU. The stress calculation based on test results gives the allowable tensile stress values for $f_{t, test}$ of 0.192 N/mm^2, 0.051 N/mm^2, and 0.073 N/mm^2, respectively, for AAC, Adobe, and CMU.

The MSJC (2005) gives the allowable tensile stress value of F_t=0. 172 N/mm^2 for CMU with Type S mortar. The value obtained based on test results (0.073 N/mm^2) is only 42.4% of MSJC value. The reason for such a difference can likely be attributed to the quality of the mortar at the time of the construction. The allowable flexural tensile stress for AAC can be assumed as F_t=0. 165 N/mm^2 (AERCON 2007). The value obtained from the test results (0.192 N/mm^2) is 15.8% higher than the allowable value. For Adobe masonry, no published value was found although the manufacturer (Clay Mine Adobe) gives the modulus of rupture of the units as 0.517 N/mm^2. Since the mortar is also cement stabilized, as an approximation, we could use the same modulus of rupture for the Adobe as well. Based on a FS of 2.5, we obtain an allowable tensile stress of F_t=0.207 N/mm^2. On the other hand, if we take modulus of rupture for the Adobe masonry to be 10% f_m', we get modulus of rupture = 0.527 N/mm^2. In general, without specific test results, the modulus of rupture can be assumed 10% f_m' to 20% f_m'. This value is very close to the manufacturer's value of 0.517 N/mm^2.

Next, to determine shear stresses, the following relation can be used: f_v = 3V/2A_n, where V can be taken here as the average value of failure shear force given in Table 4, and A_n is the mortar area. The values for A_n are as follows: $20.32x10^4$ mm^2/m for AAC and Adobe, and $8.78x10^4$ mm^2/m for CMU. The result of calculation gives the following allowable shear stresses: 0.210 N/mm^2, 0.096 N/mm^2, and 0.252 N/mm^2, respectively for AAC, Adobe, and CMU. MSJC (2005) value for allowable shear stress is 0.255 N/mm^2, which is just about the same as the test result (0.252 N/mm^2). For AAC, a value of 0.103 N/mm^2 can be assumed based on AERCON (2007). MSJC (2005) suggests 0.15 f'_{AAC} for the modulus of rupture, which results in 0.492 N/mm^2. If we use FS=2.5, we obtain an allowable shear stress of 0.196 N/mm^2, which is closer to the test result (0.210 N/mm^2). The allowable shear stress for Adobe may be approximated based on UBC 1991 (ICBO 1991) equation for masonry shear wall, $F_v=0.3(f'_m)^{1/2}$, which results in a value of 0.057 N/mm^2. This value is about 60% of the allowable value obtained based on test results (0.096 N/mm^2). It should be noted, however, that MSJC (2005) has modified this equation to take into account the moment to shear ratio at the critical section.

VIII. CONCLUDING REMARKS

Although limited in scope, number of specimens, and the choice of the test setup, this laboratory experimental study has shown results that would be of interest to design professional in considering masonry wall construction for low-rise residential buildings, especially in regions where large lateral load (such as an earthquake or hurricane) as well as high precipitation (rain) are expected. The results have shown that walls made with the relatively new AAC masonry can have favorable shear and flexural capacity compared to the conventional CMU used in both dry and wet conditions. However, the CMU prism tests in this study showed 24% lower compressive capacity compared to what is normally expected. If the CMU prism tests had the compressive capacity that matched the expected values given by MSJC (2005), the performance of CMU masonry walls would have been more favorable. Nonetheless, considering that the density of AAC is 1/3 to 1/5 that of concrete, the strength to weight ratio for these walls should be quite attractive in seismic design. Another result of the study is the high strength that the cement stabilized Adobe brick shows in the dry shear and flexure tests.

This study has also shown that subjecting these walls to water and moisture to simulate rain, the structural capacity is decreased in both shear and flexural load capacity in all cases except the CMU flexural test, which increased slightly. The results also show that moisture has the least effect on CMU strength compared to the other two masonry types. Water penetration into a masonry wall without proper drainage system may have adverse effects on a structure if not properly dried out and water gets trapped in the wall system. In particular, wet AAC walls as well as Adobe walls will have a significant drop in their shear and flexural strengths, and therefore, should be kept dry as much as possible. Although the test results presented here clearly show some favorable attributes for AAC and Adobe, further tests with full size wall specimens and with more realistic boundary conditions are necessary before any definitive conclusions can be drawn on these masonry types for practical applications. Finally, in follow-up studies, comparison of such wall systems should consider the thermal performance over time as well as the embodied energy as a basis for comparing the sustainability of the masonry types.

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REFERENCES

[1] Abboud, B.E., Hamid, A.A., and Harris, H.G., (1996). "Flexural Behavior of Reinforced Concrete Masonry Walls under Out-of-Plane Monotonic Loads", ACI Structural Journal, V. 93, No. 3, pp. 327-335.

[2] Adeli, H. and Mohammadi, J., (1985). "On the Performance of Masonry Buildings During Earthquakes," Proceedings of the Third North

American Masonry Conference, 1985, Arlington, TX, The Masonry Society.

[3] AERCON Florida LLC. "Aerocon AAC Tech Manual." AERCON AAC. 2007. Aercon Florida, LLC. June 2007. <http: //www. aerconaac. com/>.

[4] ASTM Standard E72, (2005). Standard Test Methods of Conducting Strength Tests of Panels for Building Construction, ASTM International, West Conshohocken, PA, www.astm.org.

[5] ASTM Standard C1403, (2006a). Standard Test Method for Rate of Water Absorption of Masonry Mortars, ASTM International, West Conshohocken, PA, www.astm.org.

[6] ASTM Standard C1601, (2006b). Standard Test Method for Field Determination of Water Penetration of Masonry Wall Surfaces, ASTM International, West Conshohocken, PA, www.astm.org.

[7] ASTM Standard E514, (2006c). Standard Test Method for Water Penetration and Leakage through Masonry, ASTM International, West Conshohocken, PA, www.astm.org.

[8] ASTM Standard C1314, (2006) d. Standard Test Method for Compressive Strength of Masonry Prisms, ASTM International, West Conshohocken, PA, www.astm.org.

[9] Bunz, K. R., Henze, G. P., and Tiller, D. K., (2006). "Survey of Sustainable Building Design Practices in North America, Europe, and Asia", Journal of Architectural Engineering, ASCE, Vol. 12, No. 1, pp. 33-62.

[10] Bright, N.J. and Luckin, K.R., (1983). "Effects of Moisture on the Lateral Strength of AAC Masonry When Tested in the Form of Wallettes", Autoclaved, Aerated Concrete, Moisture and Properties, Editors: F.H. Whittmann, pp. 283-294.

[11] Clay Mine Adobe Incorporated, (2007). "Adobe Test Results." Clay Mine Adobe: Mud Adobe Brick, Mortar and Plaster Mix, Tucson Arizona. Clay Mine Adobe. June 2007. <http: //www. claymine Adobe.com/testing_results.html>.

[12] Choi, E. C. C., (1998). "Criteria for Water Penetration Testing," in Water Leakage through Building Facades, ASTM STP 1314, Editors: R. J. Kudder, and J. L. Erdly, American Society for Testing and Materials, pp. 3-16.

[13] Fath, F., (1992). "Shear Capacity of Mortar Joints in Masonry with AAC-Precision Blocks", Advances in Autoclaved Aerated Concrete, Editors: F.H. Wittmann, pp. 259-261.

[14] FEMA, (2006). Hurricane Katrina in the Gulf Coast – Mitigation Assessment Team Report; Building Performance Observations, Recommendations, and Technical Guidance, Federal Emergency Management Agency, Washington, D.C.

[15] Galitz, C. L. and Whitlock, A. R., (1998). "The Application of Local Weather Data to the Simulation of Wind-driven Rain" in Water Leakage through Building Facades, ASTM STP 1314, Editors: R. J. Kudder, and J. L. Erdly, American Society for Testing and Materials, pp. 17-32.

[16] Goodhew, S. and Griffiths, R., (2006), "Sustainable Earth Walls to Meet the Building Regulations", Energy and Buildings Journal, Vol. 37, pp. 451-459.

[17] Griffith, M.C., Lam, N.T.K., Wilson, J.L., and Doherty, K., (2004). "Experimental Investigation of Unreinforced Brick Masonry Walls in Flexure", ASCE Journal of Architectural Engineering, Vol. 130, No. 3, pp. 423-432.

[18] Hauser, A., Eggenberger, U., and Mumenthaler, T., (1999). "Fly Ash from Cellulose Industry as Secondary Raw Material in Autoclaved Aerated Concrete," Cement and Concrete Research, Vol. 29, pp. 297-302.

[19] Houst, Y., Alou, F., and Wittmann, F.H., (1983). "Influence of Moisture Content on Mechanical Properties of Autoclaved Aerated Concrete", Autoclaved, Aerated Concrete, Moisture and Properties, Editors: F.H. Whittmann, pp. 219-232.

[20] ICBO, (1991). Uniform Building Code, International Conference of Building Officials, Whittier, CA.

[21] Magenes, G. and Calvi, M.G., (1997). "In-Plane Seismic Response of Brick Masonry Walls", Earthquake Engineering and Structural Dynamics, Vol. 26, pp. 1091-1112.

[22] Masonry Standards Joint Committee (MSJC), (2005). 2005 Building Code Requirements for Masonry Structures (ACI 530-05/ASCE 5-05/TMS 402-05), ACI, Farmington Hills, MI, www.concrete.org.

[23] Memari, A. M. and Kauffman, A., (2005). "Review of Existing Seismic Retrofit Methodologies for Adobe Dwellings and Introduction of a New Concept," Proceedings of the SismoAdobe2005 Conference, Lima, Peru, May 16-19, 2005, CD-ROM, 15 pages.

[24] Memari, A. M. and Chusid, M. T., (2003). "Introduction to Architectural Aspects and Developments in Research on Structural Performance of Autoclaved Aerated Concrete (AAC) Products," Proceedings of 2003 Architectural Engineering Conference -- Building Integration Solution, ASCE-AEI, September 17-20, 2003, Austin, TX, CD-ROM, 5 pages.

[25] The Natural Home, (2008). "Sustainable design, zero-energy, passive solar, high thermal mass HTM, practical Earthhome construction consultation for homeowner-builders," http: //www. thenaturalhome. com/passivesolar.html, TheNaturalHome.com, Silverthorne, CO.

[26] Newcomb, D., (2001). The Owner-Built Adobe House, University of New Mexico Press.

[27] O'Connor, J. F., (1999). The Adobe Book, Ancient City Press.

[28] PhaseOne Marketing & Design. "Welcome to Beavertown Block." Beavertown Block Co., Inc.2009. June 2007. < http: //www. beavertown block.com/index.html>.

[29] Reeve, A. and Reck, R., (2001). The Small Adobe House, Gibbs Smith, Publisher.

[30] Straube, J. F. and Burnett, E. F. P., (1998). "Driving Rain and Masonry Veneer," in Water Leakage through Building Facades, ASTM STP 1314, Editors: R. J. Kudder, and J. L. Erdly, American Society for Testing and Materials, pp. 73-90.

[31] Svanholm, G., (1983). "Influence on Water Content on Properties", Autoclaved, Aerated Concrete, Moisture and Properties, Editors: F.H. Whittmann, pp. 119-128.

[32] Tanner, J.E., Varela, J.L., Klinger, R.E., and Brightman, M.J., (2005). "Seismic Testing of Autoclaved Aerated Concrete Shearwall: A Comprehensive Review", ACI Structural Journal, V. 102, No. 3, pp. 374-382.

[33] VanGeem, M., (2006), "Achieving Sustainability with Precast Concrete", PCI Journal, January-February, pp. 42-61.

[34] Webster, F.A. and Tolles, E.L., (2000). "Earthquake Damage to Historic and Older Adobe Buildings During the 1994 Northridge, California Earthquake," Twelfth World Conference on Earthquake Engineering, Auckland, New Zealand, January 30-Feburary 4, 2000, CD-ROM, 8 pages.

[35] Witynski, K. and Carr, J. P., (2002). Adobe Details, Gibbs Smith, Publisher.

[36] Zhuge, Y., Corderoy, J., and Thambiratnam, D. (1995). "Behavior of Unreinforced Brick Masonry under Lateral (Cyclic) Loading", The Masonry Society Journal, December, pp. 55-62.