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ASSESSMENT OF STRENGTH PARAMETERS OF URM BLOCKS IN HERITAGE STRUCTURES IN THE PHILIPPINES

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ABSTRACT: Unreinforced masonry (URM) heritage structures, because of their rudimentary building techniques, are vulnerable during extreme environmental events, particularly earthquake. Limited literature involving these structures provide challenges for sound engineering solutions in their preservation, considering their significance in a country's history. Additional studies on the mechanical properties of masonry blocks – compressive, shear, flexural strengths, modulus of elasticity provide an insight on the behavior of structural components subjected to excessive loading conditions, and also establish parameters for seismic vulnerability assessments. The blocks considered are adobe, coralline limestone, and sandstone units, acquired from selected heritage structures in the country. Customized setups for shear and flexure tests were fabricated for lack of standard test methods. Results show that response of earth masonry to different load setup show monolithic behavior, distinct lack of elasticity, and intense deformability. Sandstone, while stronger in performance, exhibited very drastic failure mode in the form of sudden shear and chipping. Nevertheless, the masonry fabric proves to require further strengthening measures in resisting forces, as shown by their strength parameters. Furthermore, stress-strain properties of each sample show that sandstone, the type with greatest material strength, exhibited the smallest plastic deformation and abrupt failure, while adobe, the least average strength, exhibited the longest plastic deformation and gradual failure. Finally, a map is presented to show the spatial scatter of URM fabric used in heritage structures in the Philippines, the most common of which are coralline in Visayas and adobe and clay bricks in Luzon.

Keywords: URM, Heritage structure assessment, Modulus of elasticity, Compressive strength, Shear strength

1. INTRODUCTION

Heritage structures in the Philippines are, at best, representative of the country's rich cultural diversity and lineage, as exemplified by the many churches, chapels, convents, watch towers, bell towers, etc. scattered throughout the archipelago. These structures are also indicative of the state-of-the-art materials and construction methods at the time they were erected, circa 15^{th} to 19^{th} century, utilizing mostly unreinforced masonry (URM), timber, and other indigenous construction materials [1]. Over time, the in-situ condition of the URM fabric deteriorated, increasing the failure probability during extreme environmental events. This failure variability can be determined through analyzing the strength parameters – compressive, shear, flexural strengths, and modulus of elasticity, of individual blocks used to create said fabric.

The shear strength of a masonry block, for one, is a strength parameter not commonly researched upon unlike its compressive and flexural strength, but it is a factor that should not be neglected especially when seismic forces are taken into consideration. A study was conducted [2] wherein a masonry wall, when loaded about the vertical axis, caused a splitting cycle which generated vertical cracks in the upper part of the wall. Furthermore, such kinds of shear failure are commonly observed at vertical corner angles, or near the corners of the wall [3].

Accounting for these detrimental effects, and with the recent 2013 Bohol Earthquake, a multi-hazard vulnerability assessment of heritage structures in the Philippines was conducted using FAMIVE [4]. The procedure consisted of setting up a reliable inventory profile defining the exposure of heritage structures in the region of interest. Identification of relevant building features that affect the structural performance was also considered, leading to a selection of specific case studies with performance-based assessment framework introduced. From then, a quantitative approach for earthquake and typhoon assessment and safety conservation frameworks were considered in the said study. The absence of data for the mechanical properties of URM was compensated by said research through assumptions of values utilizing other studies from foreign literature.

The lack of local references for strength parameters of commonly used URM blocks in the country became the main objective of this paper: to further provide assessment of mechanical properties of in-situ URM fabric used in selected heritage structures and determine by experimentation the range of in-situ values of the most available and ubiquitous URM materials locally – adobe, coralline limestone, and sandstone, whose results can be used for more in-depth assessment on vulnerability and mitigation measures in the country.

2. MATERIALS AND METHODOLOGY

The URM blocks used in the study were gathered from specific regions in Luzon and Visayas where heritage structures of distinct types of masonry are of abundance – coralline limestone in Samar, Southern Philippines; adobe in Intramuros, Manila, and sandstone in Pangasinan, north of Luzon. Five samples for each block were allotted for compression testing; 3 samples for each block type were allotted for shear and another set of 3 samples each for flexure testing. The acquisition of more samples was constrained by the availability of debris that was from the heritage structures themselves.

The block samples for compression and shear test block have a minimum length-to-width ratio of 2, as prescribed by section 14.7.4.11 of the 2015 New Mexico Earthen Building Materials Code used for masonry blocks in general testing [5] and the Technical Standards in masonry specifications [6]. Using a diamond-brushed saw, the samples were partitioned and cut into 4’’ x 4’’ x 8’’ blocks for compression and shear tests, and 1.5’’ x 4’’ x 8’’ for flexure tests. To ensure even load distribution on the block surface, rough surfaces were smoothened with plaster.

2.1 Shear, Compressive, and Flexural Test Methods

For the shear test, a customized shear setup was fabricated to induce shear failure for each block. One end of the block was constrained and the other half, its free end, was subjected to an area load on the top surface as shown in Fig. 1. Two fasteners held the fixed end on each side to prevent rotation. A steel cube on top of the block transformed the concentrated UTM load into an area load. Loads, including failure load, were recorded at various stages and stored for post-processing. The average shear stress was then calculated by the general shear formula of applied shear force over the shear area.

As for compressive testing, the uniaxial compressive force was applied perpendicular to the bed surface to simulate compression loads experienced by the masonry block in-situ. The results that come from the compressive strength test were also used for the determination of Modulus of Elasticity, computed as the stress over strain or the slope of the linear graph, the graph up to the yield point of the stress-strain diagram for each masonry type. In this regard, a distance-amplifying instrument or a dial indicator was installed on the UTM to measure the displacement of the top fiber during loading until failure.

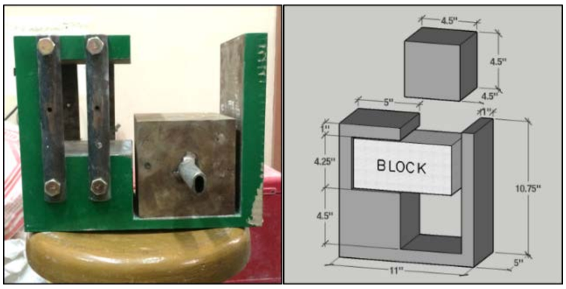


Fig. 1 Loading and instrument setup for the shear test

The flexural strength of the blocks, on the other hand, was obtained as the product of maximum moment and distance of outermost fiber from the neutral axis experiencing the maximum stress, all over the moment of inertia computed from the transverse cross-section of the block. The load rate applied in the testing was at 0.01 MPa/s, with consideration on the block dimensions and the rigidity of the blocks. To obtain this parameter, a customized flexure setup was fabricated as available setups were either too large or too small for the samples. A detailed flexure setup and 3D model with the loading direction can be seen in Fig. 2.

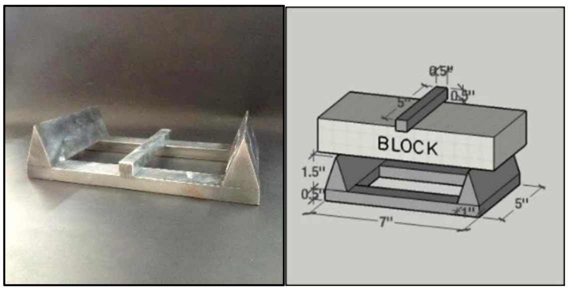


Fig. 2 Loading and instrument setup for flexure

To simulate flexural failure, blocks were made thin enough (1.5’’ x 4’’ x 8’’) to avoid compression strut, an occurrence in which a block loaded on one face develops compression along a diagonal from the support to the applied load, as observed on deep beams defined in 2010 National Structural Code of the Philippines provision 410.8.1 [7].

3. RESULTS AND DISCUSSION

Prior to the shearing test, a shear preload was already introduced in the masonry block, based on the weight of the steel block (0.11625 kN) placed to initiate distributed load on the unconfined half portion of the masonry block and added to the maximum load indicated by the testing machine.

For the shear results shown in Fig. 3, adobe and coralline limestone types from Manila and Visayas, respectively, yielded almost the same strength, resisting almost the same amount of forces throughout the six tested specimens.

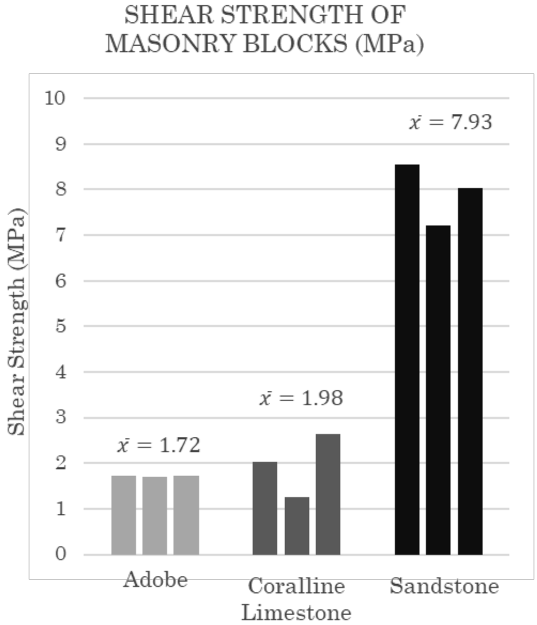


Fig. 3 Summarized shear strengths of masonry samples

These values though were inferior to the strength of sandstone, yielding means shear strength of 7.93 MPa or a little more than twice the combined mean shear strengths of the first two masonry types. The mean maximum load carried by the sandstone samples was 64.716 kN. Theoretically, the shear strength of a single block of sandstone surpasses even the combined material strengths of both adobe and coralline. To fail an adobe brick, it would require almost the same loading and effort as failing a coralline limestone block, but sandstone would require more than three times of the same loading to attain the same failure as that of the previous two types.

These values mean that each individual block has shear strength properties that make them suitable as structural material for low-rise construction, based on the assessment by the World Federation of Engineering Organizations (WFEO) in 2011 [8], although their durability still depends on various factors such as the manner of placement in wall construction and strength of interface between adjacent blocks.

From Fig. 4, some adobe, coralline, and sandstone, were seen to take the shear failure and its internal distribution along the midspan, although more than one shear plane was observed in other adobe and coralline samples. This failure can be most likely attributed to the composition and density, as the two types had an almost equal amount of denseness. Sandstone, being the densest type among the three, yielded to the expected failure plane.

Fig. 4 Failure of masonry blocks due to shear

As for compressive strengths, adobe yielded the lowest mean of 7.488 MPa, the summary of which can be seen in Fig. 5, with recorded values ranging from 6.49 MPa to 8.95 MPa. The mean compressive strength of coralline was not far off, with an average of 7.77 MPa.

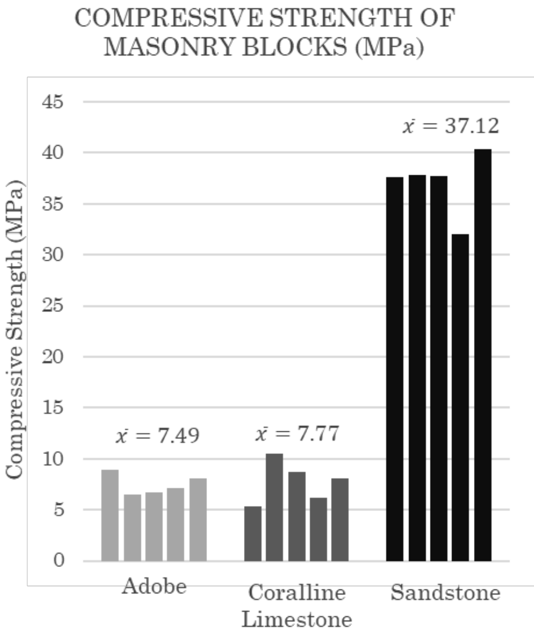


Fig. 5 Summarized compressive strengths of masonry samples

The obtained compressive strength range of adobe, coralline, and sandstone limits them to be used only for single-story structures if they are to remain unreinforced, as these blocks are inadequate alone in sustaining a greater degree of loads especially as structural members or walls [8].

This data was in line with the specifications from the same assessment by WFEO, stating that in unreinforced brick walls for single-story structure for Asia [8], the compressive strength of brick must be at least 30 kg/cm^2 or 2.94 MPa, and wall area that the bricks would cover must not exceed 12 m^2.

Furthermore, for earthquake-prone countries, particularly in Japan, it requires that masonry units should be applied only for walls not exceeding 10.8m, with slenderness ratio between length and thickness more than 1/12. Each masonry unit must have an allowable compressive strength of 1/3 of the sustained forces and 2/3 of the temporary forces specified by their Code.

The flexural strengths of the masonry samples, meanwhile, are summarized in Fig. 6.

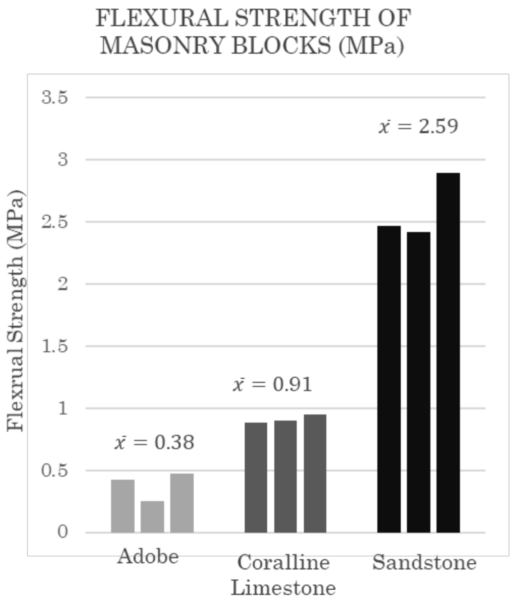


Fig. 6 Summarized flexural strengths of samples

Average flexural strengths of 0.3808 and 0.9116 MPa were observed for Adobe and coralline limestone samples, respectively, while sandstone still exhibited the most resistance of 2.5946 MPa. Adobe samples were weakest in shear, compression, and flexure, while coralline limestone remained to be an average material for flexure.

From actual observations, specimens did not take long to fail in flexure, where an abrupt collapse after reaching peak load was observed in all specimens, coinciding with the expected output and in contrast to the gradual failure induced by compression.

Experiment-wise, a single crack propagating from the bottom fiber of the specimens was generally observed for all samples. These failures verify the homogeneity as observed from similar studies [9]. The cracking patterns were generally the same for almost all specimens, as shown in Fig. 7.

Fig. 7 Failure of masonry blocks due to flexure

Concerning the stress-strain curve, a long continued shortening after the elastic limit was observed for adobe specimens in Fig. 8a, indicating the less brittle property compared to other samples. The elastic region and the elastic limit were identified through the sudden plunge in the curve that signifies the start of plastic deformation. The respective equations on the elastic region take a generally linear form.

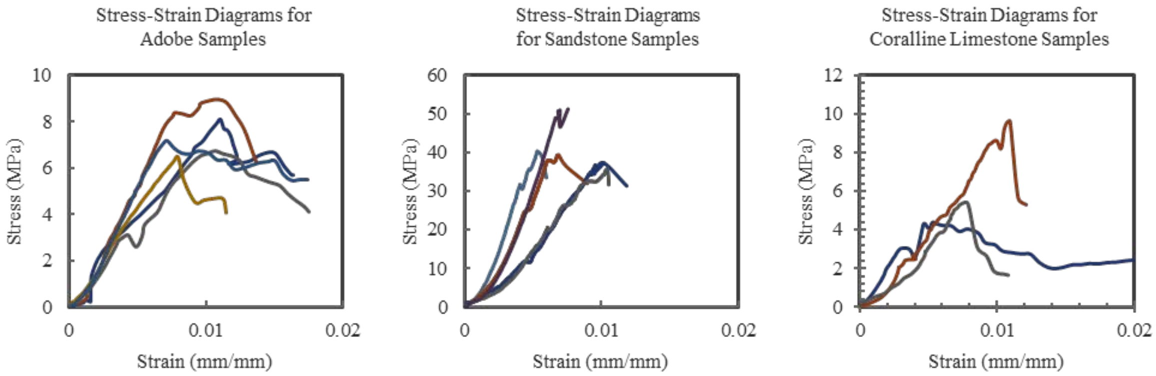
Values for slopes of the graphs ranged from 721.27 MPa to 1058.9 MPa for adobe blocks. Mean Modulus of Elasticity was then taken to be 869.78 MPa or 0.87 GPa. A low gradient of the straight line at the elastic region means that at low compressive stress, a considerable amount of deformation was apparent.

Sandstone samples, meanwhile, exhibited smallest plastic deformation with stress-strain diagrams propagating to rapid failure, as shown in Fig. 8b. The slopes from the graphs of the elastic regions were relatively higher compared to those of adobe and coralline limestone, while the elastic modulus yielded a mean of 5083.86 MPa or 5.83 GPa, from the range of 3.3-7.0 GPa. A higher elastic modulus indicates that its stiffness is greatest among the three types, especially when compared to coralline limestone.

For the latter, a plunge was observed after the samples have reached the elastic limit as shown in Fig. 8c. At this point, the material could no longer resist loads without permanent deformations. Elastic modulus for coralline limestone yielded a mean of 816.33 MPa or 0.82 GPa from the range of 0.6-1.0 GPa.

3.1 Distribution of URM Heritage Structures in the Philippines

To further complement the study, the distribution of masonry was illustrated using Quantum GIS in a Philippine Map containing points that indicate the typology and prevailing material per region of interest. Based on the available data gathered, it was found out that the most common material was coralline limestone found in the Visayas, in some regions in Luzon, and in northern Mindanao. The abundance of said material was also confirmed by the Philippine Statistics Authority, where limestone accounted for 39% non-metallic resources of the country, as shown in Fig. 9. Coralline limestone is also used for cladding to rubble cores, most notable structures of which are: Bolioon Church and Carcar Church in Cebu; Loboc Church, Loon Church, and Punta Cruz Church in Bohol.



(a) (b) (c)

Fig. 8 Stress-strain curve for (a) adobe, (b) sandstone, and (c) coralline limestone masonry blocks

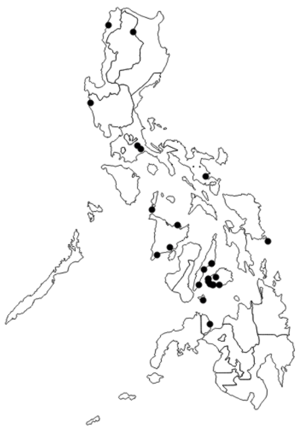


Fig. 9 Locations of coralline limestone masonry heritage structures

Clay brick, on the other hand, was the next common masonry material found in all major island groups of the Philippines, next to adobe which is abundant in Luzon and has been commonly used in construction since the Spanish era [10], [11], as shown in Fig. 10 and Fig. 11, respectively.

Fig. 10 Locations of clay brick masonry heritage structures

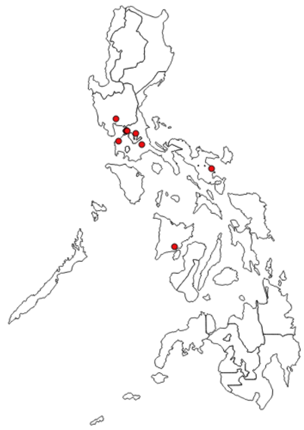


Fig. 11 Locations of adobe masonry heritage structures

Other types of masonry in abundance include Riverstone and sandstone, commonly found in Iloilo, where notable churches made of such are Sta. Barbara Church and Sto. Tomas de Villanueva Church.

4. CONCLUSIONS

The results of the study are shown in the table below.

Indications for the strengths of the most commonly used masonry materials for heritage structures are highlighted. The study has shown that in terms of strength, as compared from various literature [6], [8], and [12], the masonry fabric may further be improved and strengthening measures may be brought out towards heritage structures which, though aesthetically preserved, may have a rather deteriorating structure and pose potential risk in the long run for both multiple lives and the cultural significance of said structures.

Table 1 Material properties based from experiment

Strength (MPa)	Type		
	Adobe	Limestone	Sandstone
Shear	1.71-1.73	1.25-1.65	7.21-8.55
Compressive	5.32-10.56	6.15-10.56	32.06-40.33
Flexure	0.249-0.471	0.883-0.954	2.42-2.89
Elastic Modulus (GPa)	0.72-1.06	0.64-0.989	3.33-7.01
Density (kN/m^3)	12.5-14.52	12.11-14.71	24-25.07

5. ACKNOWLEDGMENTS

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