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MATERIAL AND OUT-OF-PLANE FLEXURAL PROPERTIES OF TRADITIONAL MASONRY WALL

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The October 2013 Earthquake hit the Bohol Island of the Philippines. Many traditional churches were damaged by the earthquake. In this study, material tests were conducted to assess the strength of the Philippines' traditional masonry wall, which is composed of various materials. Additionally, out-of-plane flexural experiments were conducted to elucidate the mechanical characteristics of masonry walls found in traditional churches. The wall specimens used in this study were made of a variety of materials with different compositions. The major findings of this study are summarized as follows: (a) compressive tests and splitting tensile tests were conducted for various test samples having distinct compositions. For both tests, the strength of the cylinders without additional materials was greater than that with contamination, expect for those containing egg whites; (b) out-of-plane flexural experiments were conducted on four specimens to identify their structural characteristics.

Keywords: The 2013 Bohol Earthquake, Masonry structure, Material composition, Material test, Out-of-plane flexural experiments.

1 INTRODUCTION

The October 2013 Earthquake that hit Bohol Island in the Philippines killed 222 people; more than 3 million people were affected in the Philippines (Ministry 2016). According to a previous disaster investigation, 23 churches with masonry structures in Bohol Island were completely destroyed or partially damaged (Japan 2014) due to their poor seismic tolerance.

The walls of traditional masonry churches in Bohol are fixed using a rammed-earth method; in this method, mud containing stones, shells, gravel, and lime paste is piled up into layers and tamped down (Hanazato 2000, Rammed 2016).

These churches are a place of assembly; hence, they must be able to withstand enough seismic activity to minimize earthquake damage. However, they were built without any information regarding their seismic performance. Moreover, some constructions were damaged by the earthquake, whereas some were not.

In this study, material tests were conducted to assess the strength of the walls composed of various materials. Furthermore, out-of-plane flexural experiments were conducted to elucidate the mechanical characteristics of the masonry walls present in traditional churches. The wall specimens were unique compositions of several materials.

2 MATERIAL STRENGTH TEST OF MUD MORTAR

Mud mortar is made up of stones, shells, gravel, and lime paste. In this study, we created test cylinders having various proportions of different materials and conduct strength tests to understand the difference of strength from material combination and proportion.

2.1 Test Cylinders

The material combinations and proportions of the test cylinders are indicated in Table 1. The main materials are slaked lime, sand, and water. Furthermore, we selected cement, egg yolk, egg white, palm fiber, and straw as additional materials. The volume ratio of materials was changed while a combination of 01 to 11 indicated only main materials, and a combination of 12 to 21 indicated main materials with one or two additional materials. The number of each cylinder combination was four or six. Combination 02 was named 'PALETADA' and represented the composition of the traditional wall. The curing period was nominally 28 days based on JIS A 1132, and when it was short, the period was a multiple of 28 days.

Table 1. Combination and proportion of materials (volume ratio).

Comb.	Number	Main materials			Additional materials				
		Slaked lime	Sand	Water	Cement	Egg yolk	Egg white	Palm fiber	Straw
01	6	0.8	3.2	1	0	0	0	0	0
02	6	1	3	1	0	0	0	0	0
03	6	1.17	2.1	1	0	0	0	0	0
04	6	1.47	1.97	1	0	0	0	0	0
05	6	1.5	2.5	1	0	0	0	0	0
06	6	2	2	1	0	0	0	0	0
07	6	2.2	1.64	1	0	0	0	0	0
08	4	2.5	2	1	0	0	0	0	0
09	6	2.94	1.31	1	0	0	0	0	0
10	4	1	3	0.6	0	0	0	0	0
11	4	1.47	1.97	0.8	0	0	0	0	0
12	4	1	3	0.8	1	0	0	0	0
13	4	1.47	1.97	1	0.32	0	0	0	0
14	4	1	3	0.6	0	0	0	0.02	0
15	4	1.47	1.97	1	0	0	0	0.2	0
16	4	1	3	0.6	0	0	0	0	0.02
17	4	1.47	1.97	1	0	0	0	0	0.2
18	4	1.47	1.97	1	0.32	0	0	0	0.2
19	4	1	3	0.6	0	0.5	0	0	0
20	4	1.47	1.97	1	0	0.5	0	0	0
21	4	1	3	0.6	0	0	0.5	0	0

2.2 Material Strength

Material tests were conducted based on JIS A 1108 and JIS A 1113. The compressive strength test and splitting tensile test and main damage are depicted in Figures 1 and 2. The strength of each cylinder is illustrated in Figure 3, excluding cases containing cement. Because the strength of the cylinders with cement were found to be twenty times that of cylinders without cement, the results with cement were excluded from this paper.

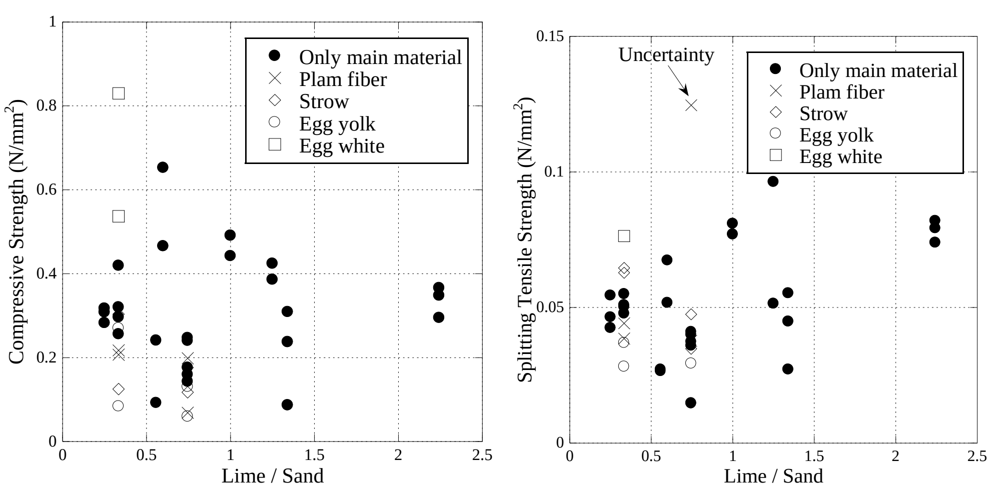
Almost all cylinders were found to be very brittle. The horizontal axis in Figure 3 is the ratio of slaked lime to sand. For compressive strength, the cylinders without additional materials were stronger than contaminated ones, expect for egg white. For the splitting tensile test, the strength increased as the ratio of slaked lime to sand increased up to a value of 1.0, but with high variation. Furthermore, like the compressive test, the cylinders without additional materials were stronger than ones with contamination, expect for those with egg whites. The strength of the cylinder containing palm fiber was uncertain.

(a) Compressive test (b) Compressive fracture (c) oblique fracture

Figure 1. Compressive test and main fracture.

(a) Splitting tensile test (b) Fracture surface (c) Peripheral fracture

Figure 2. Splitting tensile test and main fracture.



(a) Compressive strength (b) Splitting tensile strength

Figure 3. Relationship between material strength and the ratio of lime to sand.

3 STATICALLY DESTRUCTIVE LOADING TEST

Based on former cylinder tests, a statically destructive loading test was conducted on four full-scale wall specimens.

3.1 Wall Specimens

Four wall specimens were constructed at San Carlos University in Philippines on September 15th to 21st, 2015. The walls were 1500 mm high, 650 mm thick, and 1000 mm long. 300 mm were constructed each day, and the curing period was four months. The materials used included lime mortar, slaked lime, sand, water, and rock as indicated in Table 2, based on PALETADA. Lime mortar is commonly used in the Philippines, and is typically cured lime in water for three months at a very high concentration. However, this was very expensive, so we substitute slaked lime, in part, for lime mortar, assuming that slaked lime 2 was equal to lime mortar 1.

We constructed wall specimens A to D as shown in Figure 4. First, we build a raising mold out of timber. Next, coral stone plates were arranged on both sides of the wall. Then, we kneaded the lime mortar, slaked lime, and sand using a mixer. Furthermore, we install knead materials and rock among the stone plates as shown in Figure 4 (a). This same process was repeated five times over as shown in Figure 4 (b). The completed specimen is shown in Figure 4 (c). Additionally, five material test cylinders were made at the same time from the material used to build each wall specimen.

Table 2. Proportion of materials of the wall specimens (volume ratio) and test results.

Wall	Volume ratio of material					Material ratio	Cylinder strength [N/mm^2]		Loading test [kN]
	Lime Mortar	Slaked lime	Sand	Rock	Water	Lime / Sand	Compressive	Splitting tensile	Maximum Load
A	1	0	3	4	0	0.33	1.33	0.29	Uncertainty
B	0	2	2	3	0.75	0.50	1.14	0.39	17.4
C	1	2	1	3	0.75	2.0	0.73	0.11	10.1
D	0	3	1.5	3	1	1.0	1.07	0.14	9.4

(a) Containing stone plates and materials (b) Raising mold _ (c) Wall specimen

Figure 4. Construction of wall specimens.

3.2 Material Strength Test

Compressive strength tests and splitting tensile strength tests were conducted. However, some test cylinders broke prior to testing. For splitting tensile strength, when the ratio of slaked lime for sand was 0.5, Wall B, showed the highest strength as indicated in Table 2.

3.3 Loading of Wall

We designed a loading system as shown in Figure 5. Two wall specimens were laid face-to-face of out-of-plane on the steel member, the chain block was used to connect both tops of the walls, and they were pulled against each other. The pulling loads are measured by load cell.

The maximum loads are indicated in Table 2 and the destruction is shown in Figure 6. For Wall B to C, bending destruction was found, but for only Wall A, the foot of the wall was broken, so the maximum loading could not be measured.

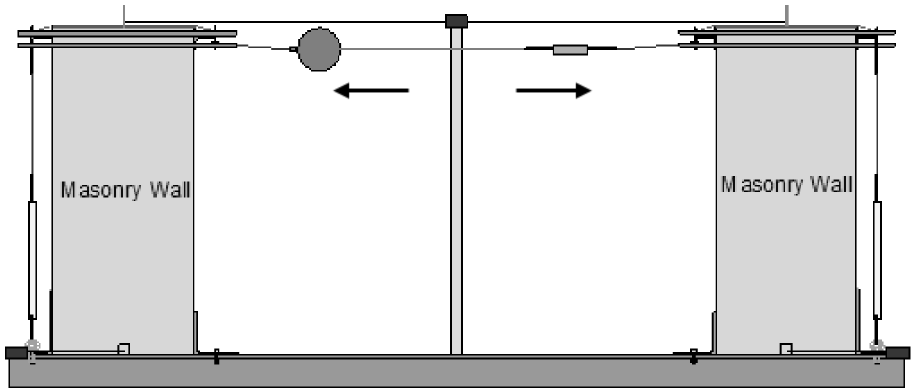


Figure 5. Loading system.

(a) Wall A (b) Wall B (c) Wall C (d) Wall D

Figure 6. Main damage of wall specimens.

4 DISCUSSIONS

The major findings from this study and discussions on them are summarized as follows:

(a) In material tests for various compositions of materials, for compressive tests, the strength of the cylinders without additional materials was greater than that with contamination, expect for the case with egg whites and mortar. And even if the ratio of slaked lime to sand is any value, it is almost constant in 0.3 kN/mm^2. On the other hands, for the splitting tensile test, the strength increased as the ratio of slaked lime to sand increased up to a value of 1.0, but demonstrated high variability.

(b) In case of out-of-plane flexural experiments on four wall specimens, when the ratio of slaked lime to sand was 0.5, the maximum load was the highest

5 CONCLUSIONS

In this study, material tests were conducted to assess the strength of Philippines' traditional masonry walls, which are composed of various materials including slaked lime, sand, and water as the main materials, and cement, egg yolk, egg white, palm fiber, and straw as additional materials. Out-of-plane flexural experiments were conducted to elucidate the mechanical characteristics of masonry walls in traditional churches. The wall specimens were composed of main materials with different compositions. The major findings of this study are summarized as follows:

(a) Compressive tests and splitting tensile tests were conducted for various compositions of materials. For both tests, the strength of the cylinders without additional materials was greater than that with contamination, expect for the case with egg whites. For the splitting tensile test, the strength increased as the ratio of slaked lime to sand increased up to a value of 1.0, but demonstrated high variability.

(b) Out-of-plane flexural experiments were conducted on four wall specimens, and their structural characteristics were investigated. In case of this experiment, when the ratio of slaked lime to sand was 0.5, the maximum load was the highest.

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