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Experimental Investigation of Traditional Clay Brick and Lime Mortar Intended for Restoration of Cultural Heritage Sites

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Abstract: To properly restore masonry cultural heritage sites, the materials used for retrofitting can have a critical effect, and this requires standards for traditional Korean brick and lime mortar to be examined. This study experimentally investigated the material characteristics of Korean traditional bricks and two types of lime mortar (quicklime lumps and powdered hydrated lime) and the strength of masonry specimens made from those materials. Four different mixing ratios of lime, sand and white cement were considered as material parameters in this study. The experiment included uniaxial compressive testing and flexural testing to examine the mortars' mechanical properties, and compression tests, triplet shear tests and diagonal compression tests for the masonry specimens. The results found that the strength of the masonry specimens was not necessarily associated with the mortar's strength, but rather the cohesion between brick and mortar. In the material test, adding white cement had no noticeable effect on mortar strength. Meanwhile, in the masonry specimen, the effect of the added white cement was significant in terms of compressive and shear strength. This suggests that the bonding ratio between mortar and brick, which is an important factor influencing the behavior of bricks, was stronger with the addition of white cement. Furthermore, it was found that quicklime lumps had a lower strength than powdered hydrated lime. The test specimen with white cement added to powdered hydrated lime exhibited the greatest strength.

Keywords: quick lime; hydrated lime; aerial lime mortar; traditional brick; compression test; triplet shear test; diagonal compression test

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1. Introduction

Masonry refers to a structure that is made up of stones, bricks, tiles, etc. bonded together with mortar. Due to its durability and economy, masonry has been used not only in buildings but also in many other structures such as stone towers, castles, arch bridges and dome structures, from ancient times (Mesopotamian civilization) to the present [1–3]. It is estimated that brick and mortar were first used in the period of the Three States Kingdom of ancient Korea (57 BCE–668 CE) as high-class materials to construct royal facilities such as palaces, tombs and shrines rather than ordinary structures [4–6]. Many ancient and modern masonry structures, e.g., the Royal Tombs, Brick Pagodas, Suwon Hwaseong Fortress (listed as a UNESCO cultural heritage site in 1997), Namhansanseong Fortress (listed as a UNESCO cultural heritage site in 2014) were designed and constructed with the evolving civilization of the country. After the Korean–Japanese Treaty of 1876, the trend of Western style housing was imported to Korea, resulting in the construction of a huge number of brick–mortar masonry buildings. Examples include the Myeong-dong Cathedral (Historic Site No. 258), and Yongsan Seminary, Seoul (Historic Site No. 520) (shown in Figure 1).

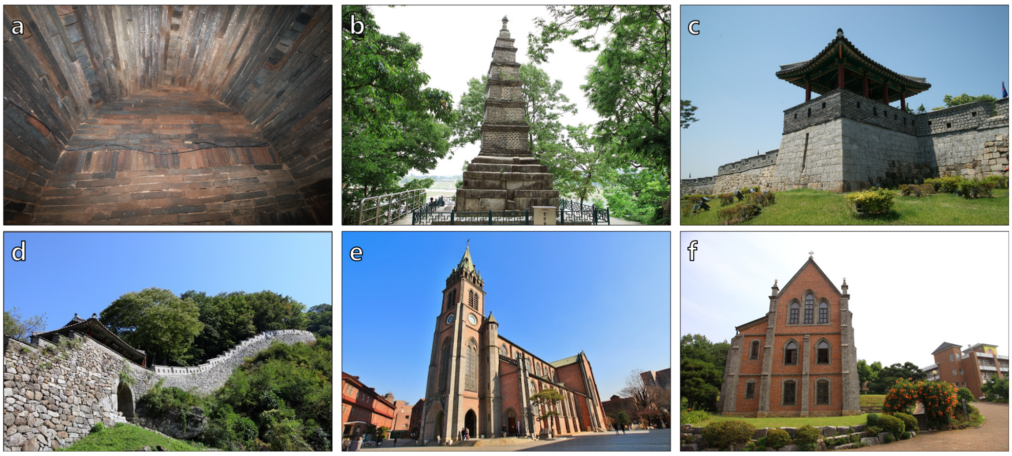

Figure 1. Typical masonry structures in Korea. (**a**) Ancient Tombs in Songsan-ri, Gongju, (**b**) Multi-story Brick Pagoda of Silleuksa Temple, Yeoju, (**c**) Suwon Hwaseong Fortress (listed as a UNESCO cultural heritage site in 1997), (**d**) Namhansanseong Fortress (listed as UNESCO cultural heritage in 2014) (**e**) Myeong-dong Cathedral (Historic Site No. 258), (**f**) Yongsan Seminary, Seoul (Historic Site No. 520).

Over time, maintaining and reinforcing such masonry buildings has become imperative because of deteriorating materials and environmental effects [7,8]. Proper maintenance practices require the appropriate usage of retrofitting materials, not only to guarantee the performance of the re-built components, but also to leave the well-functioning parts unharmed. In this regard, the resemblance of the initial material to the retrofitting material should be considered during the masonry repair process. However, the interruption of traditional manufacturing techniques and traditional construction methods using lime during the Japanese occupation and modernization have caused many difficulties in examining such materials. Furthermore, among materials, lime is less favorable than others due to its fragility and low residual mechanical properties. Without knowledge about traditional lime mortar, the reparation and maintenance of masonry structures was carried out based on the experience and methods of the mason.

Cement mortar has recently been used as a substitute for lime mortar when retrofitting masonry cultural heritage sites, because of its durability and higher strength [9–12]. In addition, several studies have investigated the performance of eco-friendly materials that could be used to preserve and enhance such structures [13–16]. For example, Mosquera, M.J. [17] examined the effect of cement mortar interaction with surrounding materials during restoration. The study showed that mechanical incompatibility between the original bonding material and retrofitting material led to stress concentration and cracks in the weaker part of the masonry structure. Hence, to restore masonry structures, especially those constructed using lime mortar as a binding material, a retrofitting material that is compatible with the original substrate should be utilized [18,19].

Korean traditional lime is made of hydrated lime, which is obtained through a calcination process of limestone, quicklime. Limestones which are rich in calcium carbonate are often used for high productivity. Quicklime is highly reactive in the presence of water, and cannot be used until it reacts with water and transforms to calcium hydroxide. Hydrated lime refers to calcium compounds in their hydrated state, or so-called calcium hydroxide, while quicklime or calcium oxide is the pure state. Hydrated lime is regularly produced through the following process. Limestone (calcium carbonate or calcite, $CaCO_3$) is burnt in a kiln at high temperatures above 1000 °C. This firing process removes carbon dioxide from the limestone to produce calcium oxide (CaO), a highly reactive solid known as quicklime or lump lime. Dry slaking of this calcium oxide with water causes a highly exothermic reaction that creates an anhydrous material, namely slaked lime or hydrated lime (calcium hydroxide, $Ca(OH)_2$). The lime cycle can be repeated when hydrated lime is initially hardened by drying, then reacting with carbon dioxide and moisture in the air, to slowly harden in air to form carbonates. However, the air lime hardening and strength developing process takes time. Natural Hydraulic Lime (NHL) is mainly used for cultural heritage conservation because of its relatively quick hardening process [20–22]. In Europe, studies have been conducted on the reparation and maintenance of cultural heritages for a long time, in accordance with BS EN 459-1 [23].

Despite such difficulties, hydrated lime has been commercialized in some countries for use in traditional cultural heritage site reparation. Paulina Faria et al. [24] investigated current hydrated lime. Their work concluded that the hydrated lime has good characteristics for historic building conservation.

Definition and classification of lime materials based on ASTM C5 [25], C25 [26]. According to the structural purposes and chemical composition, quick lime, air lime, hydrated lime, dry hydrated lime, lime putty, pure air lime can be chosen and used for designing, reservation. Air lime can be produced using one of the following processes. (1) Quicklime (obtained with a kiln firing process) is used to form lime putty. Lime putty continues to mature for months to form pure air lime (non-aggregate lime). (2) Powdered Quicklime is used instead of normal quicklime because it has a shorter lime putty maturing process. (3) Commercial Hydrated Lime (powder) is used without a slaking process.

In this study, two types of limes were prepared using the first and second approaches, quicklime lump (LL) and Powdered hydrated lime (PL), respectively. LL is a traditional mortar and has previously been used for cultural heritage restoration. In addition, PL was adopted for the comparison purpose and evaluate their characteristic in this study. These materials were used to investigate the physical characteristics and basic properties of traditional hydrated lime for the repair of cultural heritage sites. Compression and flexural tests were conducted to study the material characteristics of the lime mortar. The strength of the masonry specimens was experimentally investigated using compression testing of prism specimens, shear testing of triplet specimens and diagonal testing of the masonry [27–29]. Valerio Alecci [30] studied the shear strength of brick masonry walls assembled with different types of mortar. A comparison is provided between the values of the masonry shear strength calculated by applying three formulas available in the literature for diagonal compression test data, and those obtained from laboratory tests for shear triplet.

This study focuses on the several mixing ratios of lime mortar which were also used as the material parameters. The results are presented and discussed to better understand the strength of each mortar mixture, and its effects on bonding between the mortar and bricks, which contributes to the masonry specimen's strength. The results of this study can be used as basic data for the manufacture of brick and lime mortar, as required for the renovation and reinforcement of cultural properties.

2. Material and Method

2.1. Lime Mortar Mixture

Quicklime is mainly sourced from Chungcheongbuk-do, an inland province located in the center of the Republic of Korea. Many enormous quicklime mining sites including Samcheok, Taebaek, Jeongseon, Uljin, and Andong reside in this province. The area provides lime supplies for the lime and steelmaking industry of the country. The chemical analysis of some domestic high-Ca limestones from Jecheon-Danyang, as determined by XRF method, are presented in Table 1 [31].

This study used Quicklime lump (LL) and Powdered Hydrated lime (PL) as the main mixing ingredients to create mortar binder for the masonry specimens. Each contained a different proportion of the calcium compound, 85% and 90% for the LL and PL, respectively. The main components of white cement in cement are limestone (CaO), quartzite (SiO_2) and pyrophyllite (AL_2O_3), which account for 92% of white cement. Figure 2. presents images of the mixing materials used in this experiment observed under a 0.5 mm stereoscopic microscope. Figure 2a–c depict the agglomerated forms of LL, PL and white cement, respectively, and show their particle size in decreasing order.

Table 1. Chemical analysis (wt%) deternined by XRF method for some domestic high-Ca limestones in Jecheon-Danyang.

SiO_2	Al_2O_4	TiO_2	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	LOI	Total
1.94	0.39	0.00	0.01	0.00	0.56	52.91	0.00	0.03	44.16	100

Figure 2. Materials used for experiments. (**a**) Quick lime lumps, (**b**) powdered hydrated lime, (**c**) white cement.

For the field application, LL was exclusively prepared and produced by the restoration organization of the Changdeokgung Palace Complex, under the guidance of the Cultural Heritage Administration of Korea. Figure 3 demonstrates the quick lime lump production process. Quicklime was piled up and slaked with water at a 1:1 proportion. The ratio was confirmed through a previous experiment. Water can be added to the quicklime by spraying through a nonwoven fabric to prevent overheating from the exothermic reaction. The lump lime pile was covered with tarpaulin sheets to prevent moisture evaporation, and left for 5 days for the maturing process. Afterwards, the slaked lime was strained using a 3 mm sieve to collect quicklime lumps. The final products can be used after a further month of ripening. Powdered hydrated lime (PL), which was used in this study, is manufactured by Baekkwang Mineral Products company under the same process as quicklime lumps.

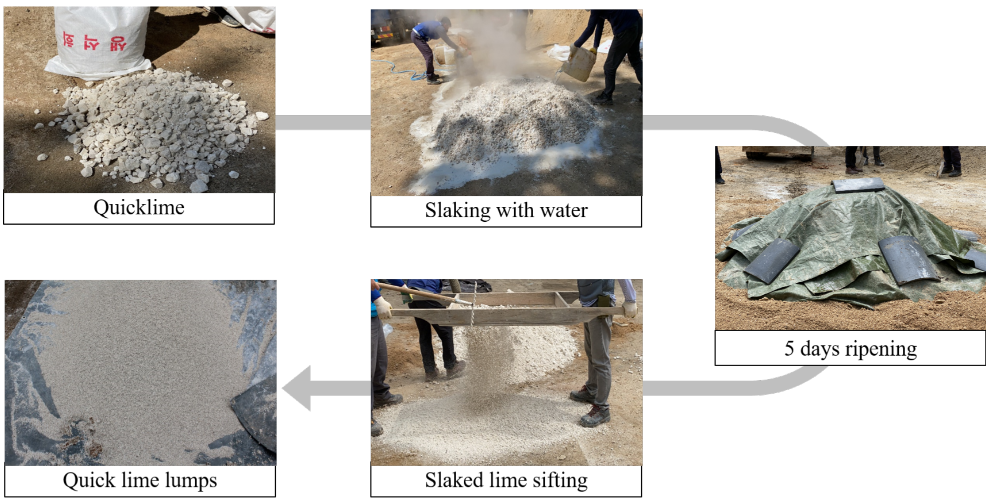

Figure 3. The quick lime lumps production process.

Following the Building structure standards (2017) and the Compression strength experiment standard (ASTM C109/C109M:16a, KS L5105) [32,33], a binder to sand ratio in the range of 1:2.5 to 1:3 was adopted. Various studies of modern masonry structures (Myeongdong Cathedral, Yongsan Theological Seminary and Wonhyoro Cathedral) [34] selected binder to sand ratios of 1:1∼1:3. The Standard Specification of cultural heritage (2019) [35]—brickwork defined the mix proportion of slaked lime:cement:sand as a respective ratio of 1:0.2:4.9 (based on the mass ratio). Nam et al. [36] determined the suitable range of mixing water using a flowability test, depending on the type of hydrated lime and the mixing ratio. The mortar mixing ratios in this research were determined in accordance with those standards and research results [36–38], and are presented in Table 2. Figure 4 presents a flow chart of the tests. Lime and sand were mixed together after quantification by the mortar mixer drill. After the mixing was completed, prior to the casting of specimens, a flow test was performed to ensure the flow of mortar was in the allowable range of 120 mm to 150 mm. The experiments were conducted using mortar material tests (uniaxial compression, flexural tests) and masonry materials tests (compression, triplet, diagonal compression). The material and masonry specimens were cured under an ambient environment condition of (25 ± 3 °C) in temperature and relative humidity and maintained in the dry condition for 56 days.

Table 2. Mixing proportions of lime mortar.

No	Sample Name	Hydrated Lime	Mixing Ratio (by Mass)			
		Preparations	Binder		Aggregate	Water (%)
			Lime	Cement	Sand	
1	LL-1	Quick lime lumps	1	-	1	10
2	LL-2		1	-	3	10
3	LL-3		1	0.2	4.9	14
4	LL-4		1.2	-	4.9	10
5	PL-1	Powdered hydrated lime	1	-	1	28
6	PL-2		1	-	3	17
7	PL-3		1	0.2	4.9	11
8	PL-4		1.2	-	4.9	11

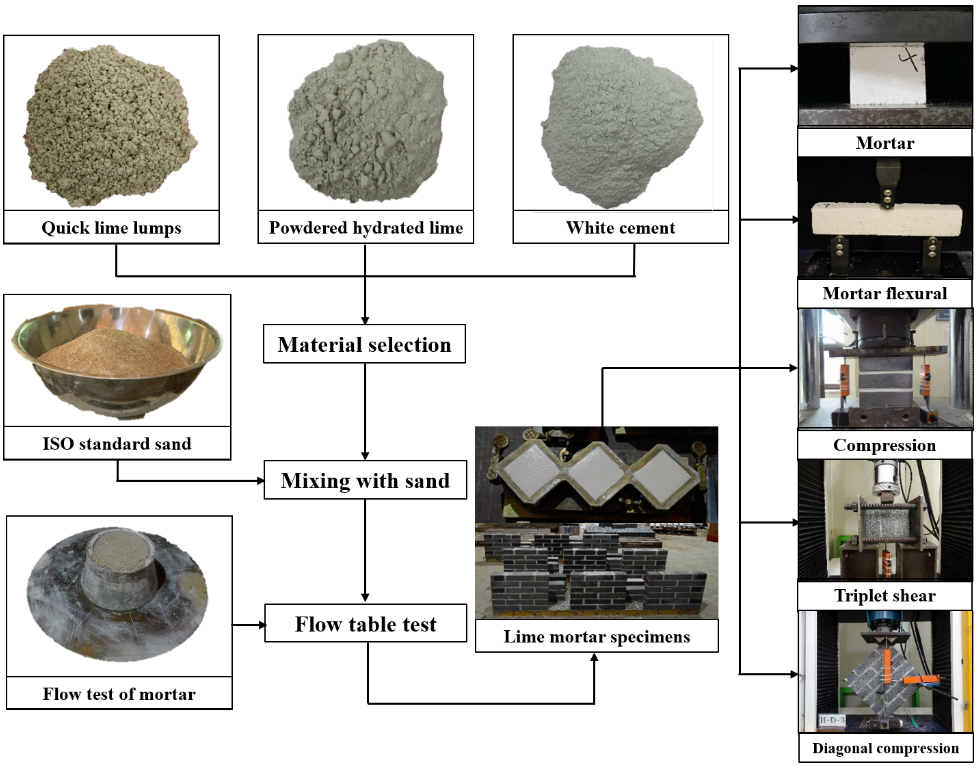

Figure 4. Flow chart of testing.

2.2. Traditional Handmade Brick Test

Traditional handmade bricks were chosen to make the masonry specimens for the experiment. Figure 5 shows the process of traditional handmade bricks manufacturing. Bricks are made manually according to the traditional manufacturing process of forming, heating and cooling. Figure 5a indicates the soiling process, and Figure 5b depicts forming of the brick using the mold. The average measured size of 60 samples was 190 × 90 × 57 mm^3 (±2.0 × 2.0 × 2.0 mm). The compressive strength of the brick was determined by compressive testing of five brick samples to fracture. Axial force was applied in the middle of the largest surface of the brick.

Figure 5. Traditional handmade bricks manufacturing process. (**a**) The soiling process using manpower. (**b**) Handmade bricks processed with a mold. (**c**) Demolded brick

2.3. Compressive Strength of Mortar Cubes Test

Mortar mixtures that were used to assemble the masonry specimens were separately tested to determine their material mechanical properties. Cubic specimens, 50 × 50 × 50 mm^3 in size, were created and cured for 7, 28 and 56 days. Each type of cubic specimen was tested for compressive strength in accordance with ASTM C109 [32]. Since lime mortar generally has a gradual hardening process, the strength of the cubic specimens after 56 days of curing were significantly higher than that of specimens after 7 and 28 days. Therefore, this study only presents results obtained from specimens at 56 days.

2.4. Flexural Strength of the Mortar Test

Three point flexural tests were conducted using 40 × 40 × 160 mm^3 flexural specimens, in accordance with ASTM C 348 [39]. Three units of each type were tested to determine the flexural strength of the mortar mixtures. The flexural strength can be calculated as prescribed in ASTM C 348 [39]. as follows:

$$Flexural\ strength(N/\mathrm{mm}^2) = 0.0028P \tag{1}$$

where, P = Maximum load (N).

2.5. Compressive Strength of the Masonry Prism Test

The masonry prisms consisted of three layers of bricks and two layers of mortar bed joints, which were 10 mm in thickness. The nominal dimensions of the masonry prism were 191 × 190 × 90 mm^3. The prism specimens were tested after curing for 56 days. The compression test was processed in accordance with ASTM C1314 [40], as shown in Figure 6. Displacement measurements were taken from two LVDTs (Linear variable differential transformers) set on both sides of the jig. Displacement control mode was used for the compression tests, where masonry prisms were loaded to failure by applying the load at a rate of 1.0 mm/min

Figure 6. Experimental setups for compression test.

2.6. Shear Strength of Masonry Triplets Test

Triplet shear tests are used to determine the failure behavior and resistance of masonry triplets. The test was conducted according to BS EN 1052-3 [41]. During the test, the triplet was supported vertically by fixing both bricks on their sides, while the center brick was applied a load at rate of 1.0 mm/min. Displacement of the triplet was measured using an LVDT placed under the center brick. Figure 7 shows the set up for the triplet shear test. The shear strength of each specimen can be calculated as follows:

$$f_{voi} = \frac{F_{imax}}{2A_i} \tag{2}$$

where, F_{imax} is the maximum shear force record at failure, A_i is total area of the bed joint equal to the cross-section of the unit.

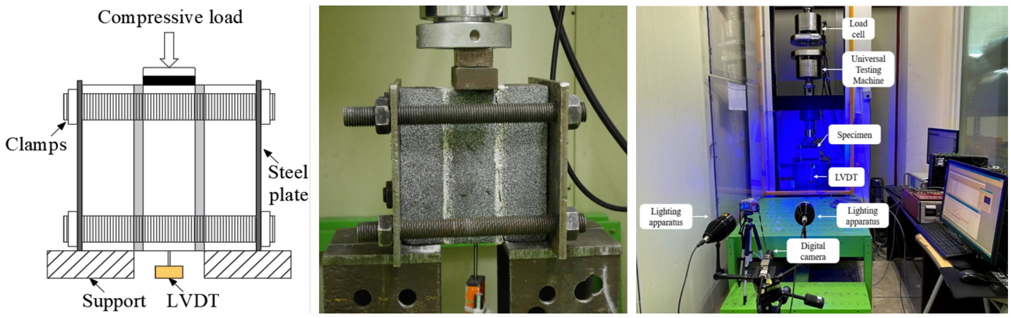

Figure 7. Experimental setups for the Triplet shear.

2.7. Diagonal Compressive Strength of Masonry Panels Test

Diagonal compressive testing is commonly used to determine the shear strength of masonry specimens. This test was conducted according to ASTM E519 [42]. The test setup standard requires the masonry specimen to be rotated by 45°, and the force applied vertically through the top and bottom corners, as shown in Figure 8. LVDTs were placed vertically and horizontally to determine the relative strains. The load was applied in displacement-control mode with the hydraulic actuator loading at a rate of 1.0 mm/min. It is assumed that the stress state at the center of the diagonal specimen is pure shear and the value of the average shear stress s is equal to the principal tensile stress. Based on this assumption, the shear stress of the masonry at an applied load P can be determined as follows:

$$Shear\ stress\ (\tau_s) = \frac{0.707P}{A_n} \tag{3}$$

where P is the applied force and A_n is the net area of the wall panel

$$A_n = \frac{(W+h)}{2t} \tag{4}$$

where W, h and t are width (mm), length (mm) and thickness (mm) of the masonry panel.

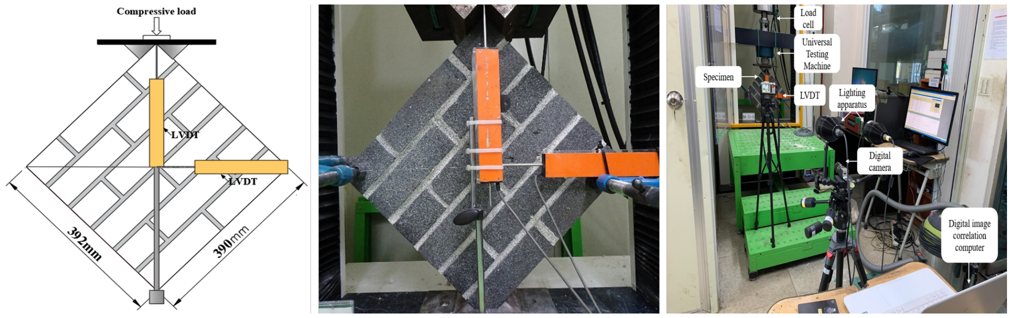

Figure 8. Experimental setups for Diagonal compression.

3. Results and Discussion

3.1. Traditional Handmade Brick Compressive Strength

Figure 9 illustrates a brick specimen before and after the compressive test. Brittle fractures can be observed in the bricks. Cracks occurred shortly after applying force and the brick exhibited sudden failure. Table 3 shows the brick compressive strength results. The minimum and maximum applied forces that caused brick samples to fracture were 766 kN and 1128 kN, respectively. The relative compressive strengths of the bricks were 44.81 MPa and 65.96 MPa. The deviation of the maximum load is 137 kN, which is considered to be an error caused by the soiling process and mold work [43,44]. The mean compressive strength was calculated to be 60.56 MPa, which is about four times stronger than the reference strength of 15 MPa for traditional hand-made bricks proposed in the Cultural Heritage Repair Standard Specification (2020) [45].

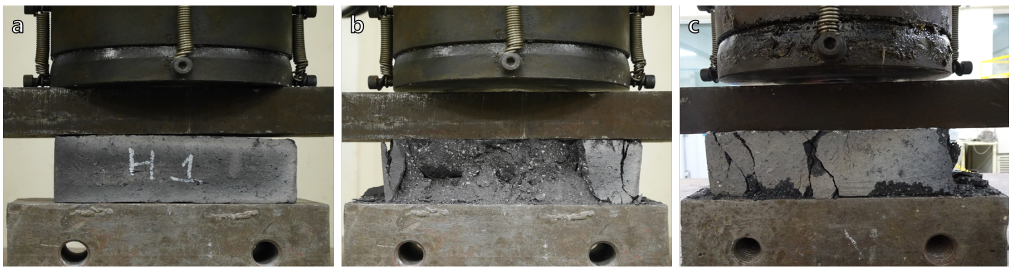

Figure 9. Brick compression test. (**a**) Before testing, (**b**) after testing—front view, (**c**) after testing—back side view.

Table 3. Brick compressive strength results.

No	Maximum Load (kN)	Compressive Strength (MPa)
1	1024	60.97
2	766	44.81
3	1001	62.19
4	1063	65.96
5	1128	58.49
Average	1000	60.56
Deviation	137	7.25

3.2. Compressive Strength of Mortar

Figure 10 presents the set up for the compression testing, and mortar cube failure after testing. Figure 11 depicts the compressive strength of the mortar cubes with respect to lime mortar types (LL and PL) and mixing ratios. The highest strength of the LL mortar specimens was 3.11 MPa (LL-1 mixing ratio) and the lowest strength was 2.53 MPa (LL-3). For the PL mortar cubes, it was 3.08 MPa (PL-3 mixing ratio) and 2.29 MPa (PL-2), respectively. It can be inferred from the results that, without white cement, the LL mortar specimens exhibited greater compressive strength compared to their PL mortar counterparts under the same mixture ratio. The compressive strengths of LL-1, LL-2 and LL-4 were 24.4%, 16.6% and 8.6% greater, respectively, than PL-1, PL-2 and PL-3. In contrast, with the addition of white cement, the compressive strength of the PL mortar specimen was 21.7% greater than that of the LL specimen.

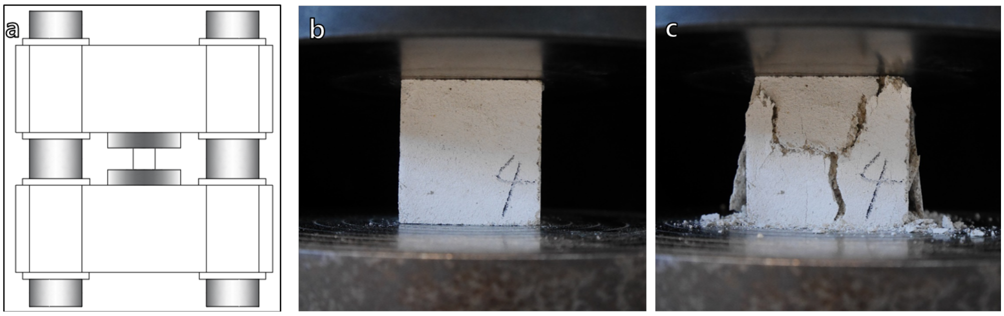

Figure 10. Mortar compression test (**a**) setup for the compression test of mortar (**b**) before testing, (**c**) after testing.

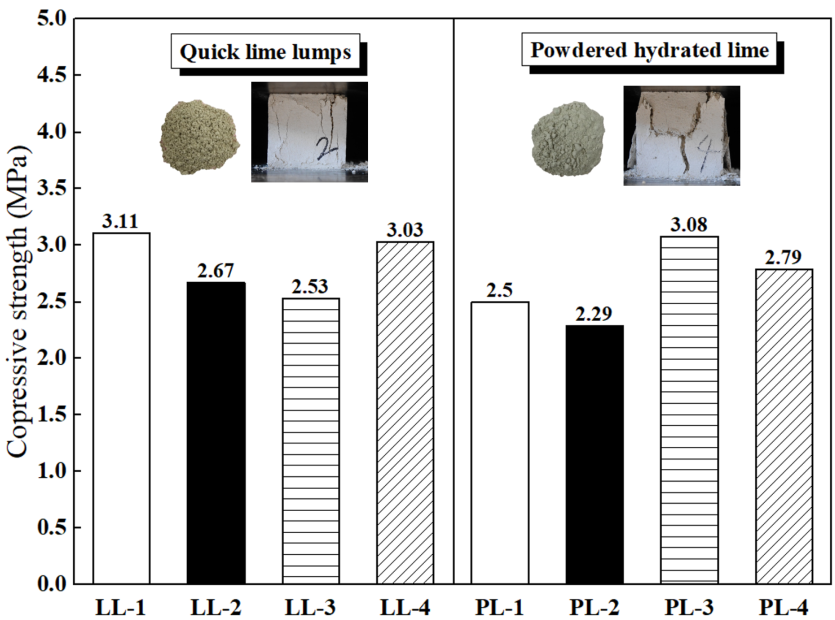

Figure 11. Compressive strength at 56 days.

3.3. Flexural Strength of Mortar

Figure 12 shows the flexural test set up for mortar specimens. Figure 13 illustrates the flexural strength of the mortar specimens. For the quicklime lump mortar specimens, the highest and smallest observed values of flexural strength were 0.49 MPa (LL-4) and 0.24 MPa (LL-3), respectively, and 0.45 MPa (PL-4) and 0.27 MPa (PL-2) for the powdered hydrated mortar specimens. In comparison, LL mortar provided stiffer specimens than the PL mortar in term of flexural strength, except for the mixture with additional white cement. The effect was likely similar to that observed in the compression test in the previous section. Specifically, flexural strength of the LL-1, LL-2 and LL-4 specimens were greater by 2.5%, 40.7% and 8.8%, while the flexural strength of the PL-3 specimen was 58.3% greater than LL-3. There was no noticeable increase in flexural strength after the addition of white cement compared with the compressive strength.

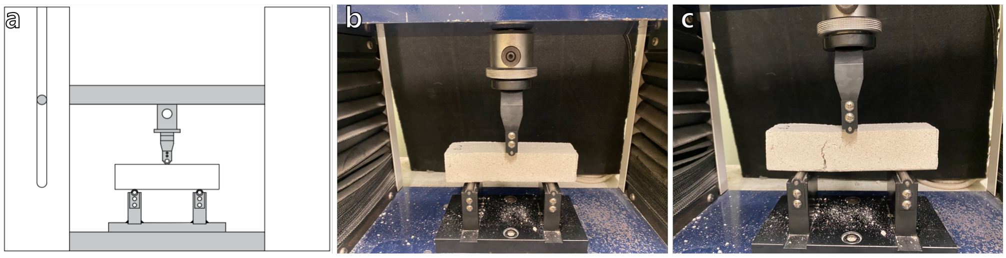

Figure 12. Mortar flexural test. (**a**) Setup for the mortar flexure test (**b**) before testing, (**c**) after testing.

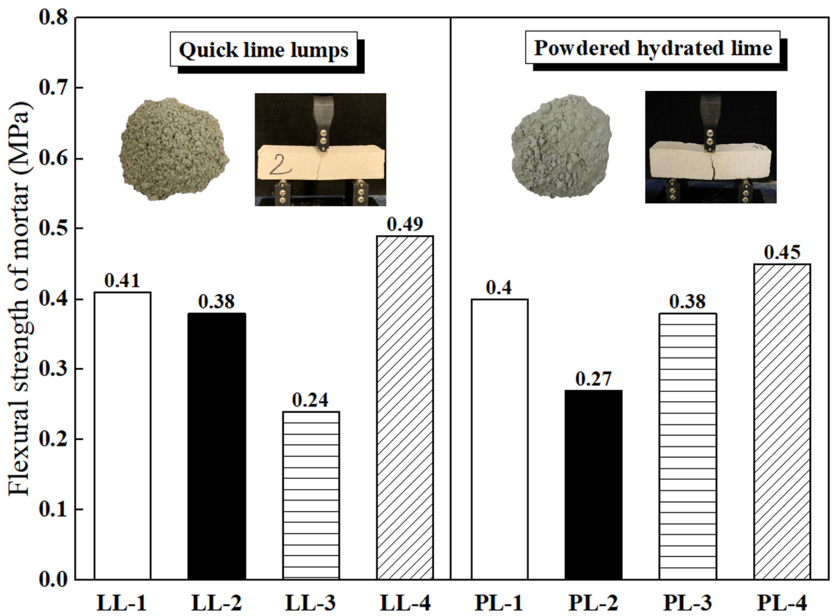

Figure 13. Flexural strength of mortar at 56 days.

3.4. Compressive Strength of the Masonry Prism

Figure 14 shows a masonry prism at failure. Vertical cracks were propagated in the bricks and spalling of mortar can be observed. Figure 15 presents the state of stress generated during the prism compression test. The mortar layers are laterally confined by the brick layers, which develop an internal state of stresses, in which the mortar layers are under triaxial compression while the brick layers are subjected to bilateral tension coupled with axial compression [46,47].

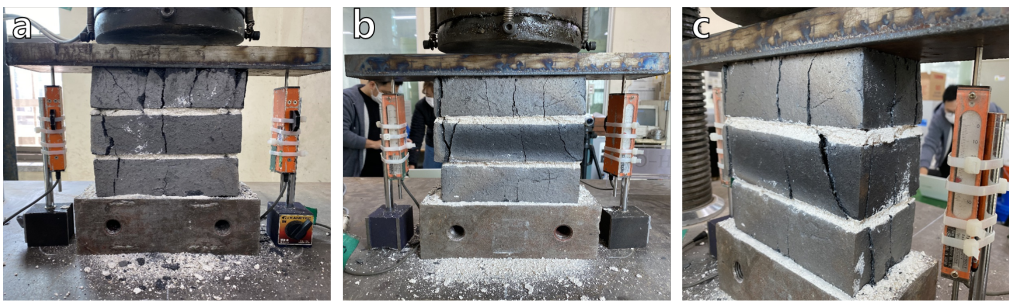

Figure 14. Failure mode compression test. (**a**) Front view (**b**) backside view (**c**) side view.

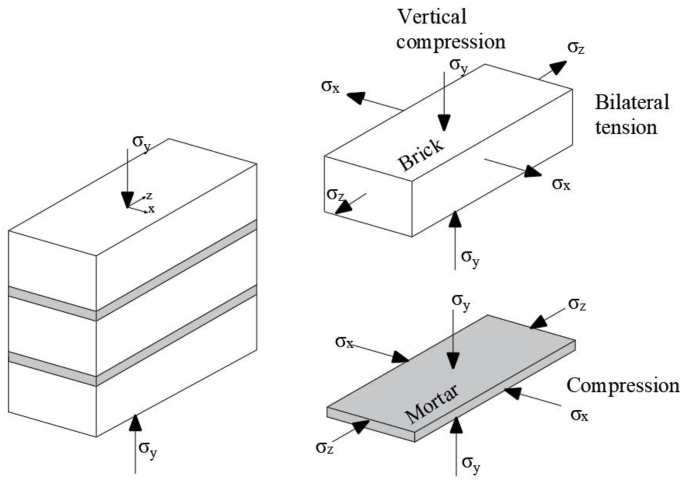

Figure 15. State of stress of brick and mortar in the masonry prism.

The compression strengths of the masonry prisms are illustrated in Figure 16. Generally, the PL mortar prisms specimens exhibited higher compressive strength than the LL mortar specimens. The maximum and minimum compressive strengths of the masonry prisms were 11.38 MPA (LL-3) and 8.87 MPa (LL-2) for the quicklime lump mortar specimens. The strengths of the powdered hydrated lime mortar specimen were 15.39 MPa (PL-3) and 9.92 MPa (PL-4). The average strengths of the PL-1, PL-2 and PL-3 were 37.5%, 47% and 35.2% higher than those of LL-1, LL-2 and LL-3, respectively. The PL-4 specimens and LL-4 specimens had similar compressive strengths, with only 3.3% difference. In both the LL and PL mortar prisms, mixture with white cement provided higher compressive strength than other non-cement mixtures. Furthermore, the white cement performance was higher in PL mortar than LL.

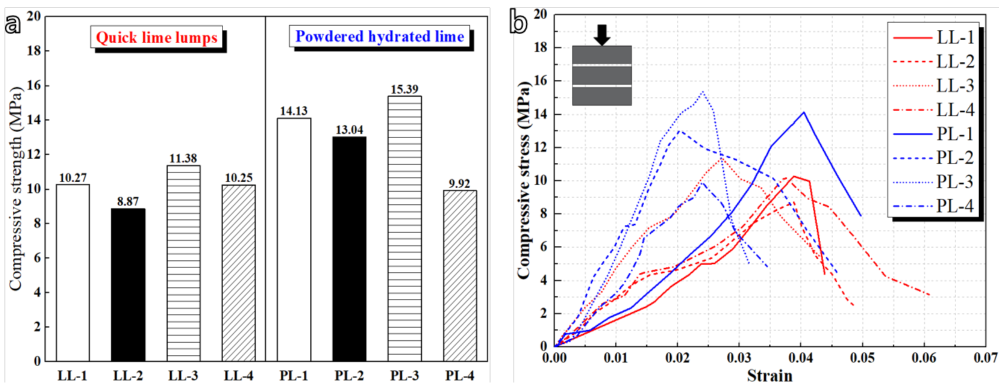

Figure 16. Compressive strength of masonry prism test results. (**a**) Compression strength (**b**) strain–stress curve.

3.5. Shear Strength of Masonry Triplets

Figures 17 and 18 present the shear strength and failure mode results obtained from the triplet tests of the mortar specimens, respectively. Generally, all of the mortar triplets exhibited minor values of shear stress, below 0.11 MPa. In other experimental results, when lime mortar was used, it had a low triplet shear strength value [30,48–50]. Two types of failure mode were observed: (1) detachment of the mortar bed joint and bricks, and (2) detachment of the mortar layer. It can be inferred that the minor shear strengths for LL-3 (0.06 MPa) and PL-1 (0.063 MPa) are associated with the failure mode where the mortar bed joint was promptly detached from the bricks. White cement barely enhanced the performance (shear strength) of the LL mortar specimens, and only slightly in PL. In terms of triplet shear strength, the white cement also showed better results in the PL mortar than in the LL mortar specimens.

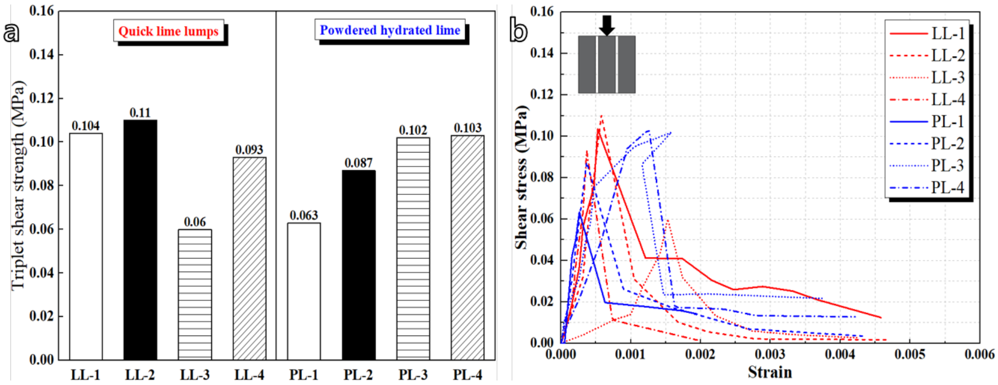

Figure 17. Triplet test results. (**a**) Triple shear strength (**b**) strain–stress curve.

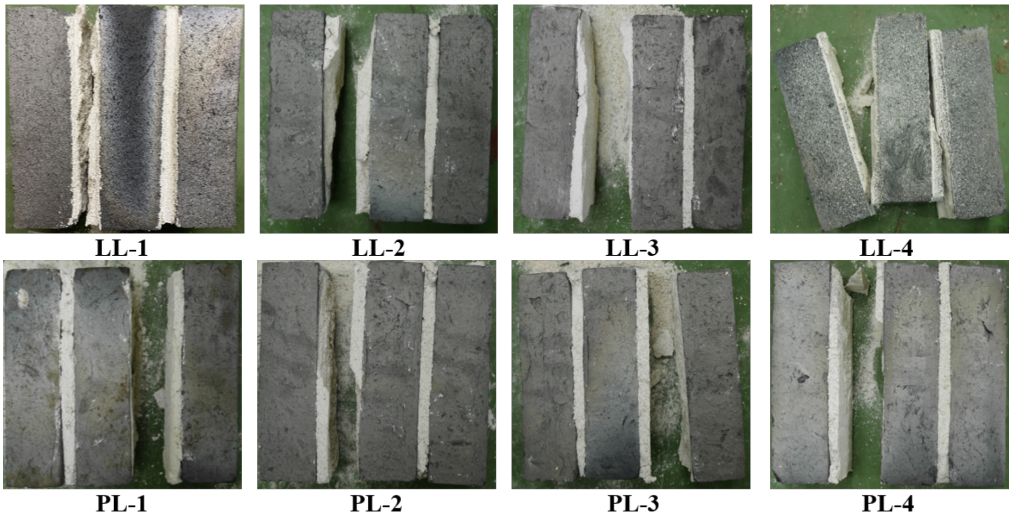

Figure 18. Failure mode of Triplet shear test.

3.6. Diagonal Compressive Strength of Masonry Panels

Figure 19 shows the shear stress of the masonry panels, and the failure modes of each are depicted in Figure 20. The maximum shear strength was 0.242 MPa (LL-3) and the minimum shear strength was 0.098 MPa (LL-2) for the quicklime lump specimens, and 0.284 MPa (PL-3) and 0.111 MPa (LL-2) for the powdered hydrated lime specimens, respectively. White cement significantly affected the mortar mixtures by increasing the shear strength of the masonry panel for both the LL and PL mortars, by 2.46 times and 2.56 times, respectively, compared to the smallest values. In addition, the shear strength of PL-3 was 17% greater than that of LL-3, which implies that white cement had a pronounced effect, improving the performance of the PL mortar specimens more than the LL specimens. Most of specimens' failure modes followed a similar pattern, with bricks detached from the masonry panels along the mortar bed joint path.

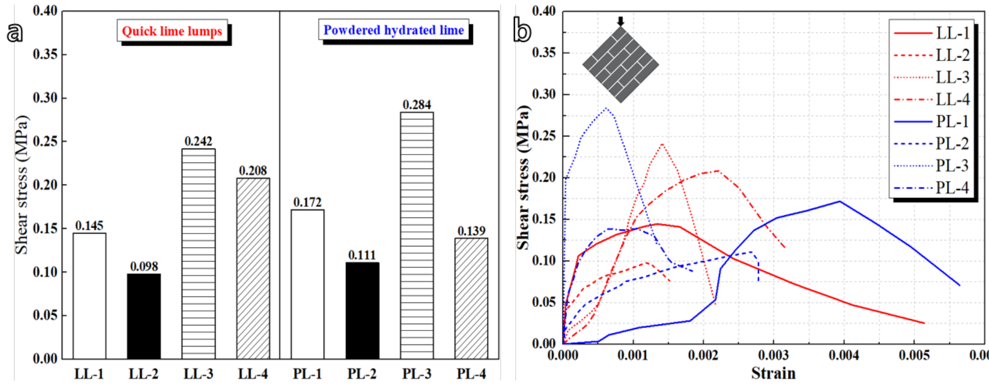

Figure 19. Diagonal compression test results. (**a**) Shear strength, (**b**) strain–stress curve.

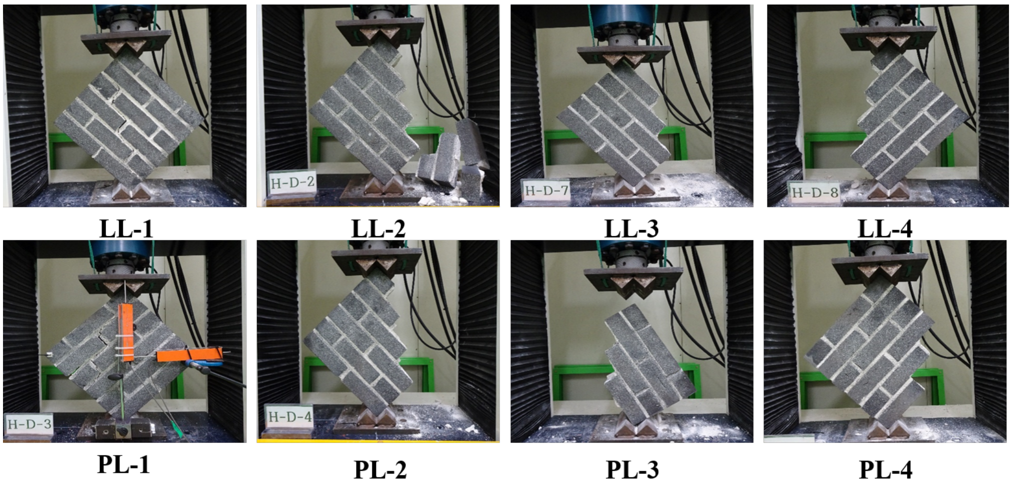

Figure 20. Failure mode diagonal compression test.

4. Conclusions

This study investigated the material properties of different types of mortar and their effects on masonry specimen's performance. The research results can contribute to the reparation and maintenance practices used for masonry cultural heritage sites. Two kinds of mortar (quick lime lumps, powdered hydrated lime) were used at four different lime:sand:cement mixing ratios. The experiments included material tests of the mortar and brick and performance tests of masonry specimens. The following conclusion can be drawn from the experimental results.

1. In the material tests, the addition of white cement resulted in almost no noticeable enhancement of mortar strength. However, in the masonry specimens, this effect was more pronounced. This can be interpreted to mean that the bonding between mortar and bricks, which is a critical factor affecting the masonry's behavior, was stronger with additional cement in the mixing ratio.
2. For each type of mortar (LL and PL), mixtures with white cement exhibited superior behavior in terms of compressive strength and diagonal shear strength compared to non-cement mixtures. However, this effect was barely observed in triplet shear tests, where the change in shear strength of most of the masonry specimens was minor (below 0.11 MPa), which led to prompt failure by detachment of either the mortar layer or the mortar bed joint and bricks.
3. The results also implied that the white cement had a greater effect on PL mortar than LL mortar.The compressive strengths of the LL-3 and PL-3 masonry prisms were 11.38 MPa and 15.39 MPa, respectively, and the PL-3 compressive strength was 35.2% greater than that of LL-3, while the diagonal shear strength of the masonry panels were 0.242 MPa and 0.284 MPa, respectively. Therefore, the mixing ratio of PL-3,

which provided the most favorable performance among all ratios, can be considered for the repair and maintenance of masonry cultural heritage sites. Future research can investigate further effects of different ratios of added cement.

The lime mortar generally exhibited minor strength in specimens, compared to other alternative materials such as cement mortars. However, for most masonry cultural heritage sites, lime mortar is considered a compatible material that associates well with the original substrate. To further evaluate the practical application of lime mortar to such structures, additional studies on material properties and masonry specimens and mixing ratios will be required.

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