

INVESTIGATING THE EFFECT OF MOISTURE ON NON-RETROFITTED AND RETROFITTED MASONRY STRUCTURES

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Abstract: *The presence of moisture in masonry structures can have significant impact to durability, structural integrity, and aesthetic appearance. Fiber-reinforced paint has been employed, as an alternative retrofitting technique, to enhance the seismic capacity of masonry structures. However, real-world scenarios often involve multiple hazards, including earthquakes and moisture from floods or capillary rise. This study aims to examine the impact of moisture and weathering on both retrofitted by fiber-reinforced paint and non-retrofitted masonry walls. The experimental program involves two types of specimens: masonry wallets for in-plane testing and masonry prisms for compressive and flexural testing. The masonry wallets are subjected to various conditions, including dry (initial condition), wet conditions with water content ranging from 0 to 100%, and both with and without retrofitting. These conditions simulate the effects of water infiltration from capillary rise or floods. Further testing includes compressive strength and flexural tests on the masonry prisms under varying conditions, including dry, wet, and weathered states (5, 10, 15, and 20 cycles). The presence of water within the masonry walls leads to a decrease in the average peak load of masonry wallets. This decrease is observed in both retrofitted and non-retrofitted masonry structures. However, the retrofitted masonry houses still demonstrate promising results compared to non-retrofitted masonry in terms of deformation capacity. The emergence of a white-colored pattern on the masonry surface after weathering cycles indicates salt crystallization, which can occur due to the presence of soluble salts in water. After undergoing 20 cycles, it was observed that the fiber-reinforced paint remained attached to the masonry surface, indicating its strong adhesive properties. The presence of salt within the masonry initially had a beneficial effect, increasing the compressive strength of the masonry prism. However, after a certain number of cycles, the strength began to decrease. The application of fiber-reinforced paint enhances the flexural strength of the masonry prism. However, it was observed that the flexural strength of the fiber-reinforced paint decreased after a certain number of cycles. Although the fiber-reinforced paint is impermeable to water, it is necessary to consider additional measures to prevent water infiltration through capillary action. The findings of this study contribute to the development of robust and durable masonry systems that can withstand the challenges of multi-hazard environments.*

1 Introduction

Masonry is a widely used construction method, especially in developing countries. Poor construction practices have left many structures in earthquake-prone regions vulnerable to lateral loads. Moreover, structures often encounter problems such as rising dampness and salt weathering. Unlike earthquakes, which are infrequent and unpredictable, damage caused by moisture and salt due to rising dampness or floods occurs gradually but consistently over time. Water infiltration can arise from groundwater through capillary rise, rain, or flooding

events. The presence of moisture in masonry poses significant issues, including health problems, mold growth, and the decay of masonry structures (Fusade et al., 2019). Moisture and salt weathering are the most common deterioration mechanisms in porous materials such as bricks or mortar and may lead to severe damage to residential or historical buildings (Binda et al., 2011; Mydin et al., 2017; Padilla-Ceniceros et al., 2017). In general, the influence of salt on structural behavior varies based on the extent of salt penetration into masonry, the type of salt present, and the frequency of weathering cycles. Coastal floods can accelerate salt crystallization in masonry. In addition, the impacts of climate change are expected to lead to severe coastal floods. The low-elevation coastal zone areas in developing countries are considered vulnerable to this impact (McGranahan et al., 2007).

Many studies have explored retrofitting techniques for masonry houses, including methods like grout/epoxy injection, bamboo band, Fiber Reinforced Polymers (FRP), post-tensioning, and polypropylene (PP) band. Each technique has its advantages and disadvantages. The key consideration for implementing any retrofitting technique universally in developing countries is to take into account its cultural relevance and practicality (Yoshimura and Meguro, 2004). This research proposes the use of Fiber-Reinforced Paint (FR-Paint) in a paint form as a retrofitting material. Painting is a common practice in developing countries and is easy to implement. Additionally, it can be modified into transparent paint to preserve the original appearance of heritage buildings. However, further discussion is needed to investigate the material's resistance to salt attack (weathering) and moisture. FR-Paint is impermeable, which means that once water penetrates the masonry, it will be trapped inside. This study explores the influence of moisture and weathering, including exposure to soluble salts, on both non-retrofitted and retrofitted masonry treated with FR-Paint. Weathered specimens will undergo in-plane and out-plane loading tests to assess their mechanical properties.

2 Methodology

2.1 Identification of global Earthquake and coastal flood hazard areas

The development of a compound global earthquake and coastal flood hazard map involves the integration of earthquake hazard data, sourced from the International Centre for Numerical Methods in Engineering (CIMNE) with a 475-year Return Period (CIMNE, 2015), and global coastal flood hazard data from with a 5-Year Return Period (Muis et al., 2016). The fundamental process begins with data acquisition and pre-processing, ensuring compatibility of coordinate systems and data format. The mapping simply overlays both data utilizing a Geographic Information System (GIS) while spatial integration is performed, allowing for the superimposition of the earthquake and coastal flood datasets.

2.2 Material and experimental methods

Fiber-Reinforced Paint (FR-Paint)

FR-paint was created by combining fiberglass, paint, and resin. The composition of these materials within the paint significantly influences the properties of FR-Paint (Yamamoto and Meguro, 2017). In this study, a 4% fiberglass composition was used to retrofit the masonry assemblies. The selected paint variant incorporates resin as an essential component and is readily available in the Japanese market. To evaluate its performance, axial tensile testing was conducted, resulting in an impressive average tensile strength of 2.2 MPa.

Bricks and mortar

In the laboratory-scale experiments, the bricks are specified with dimensions of 75x50x35 mm and a compressive strength of 26.10 MPa. Due to equipment limitations, the size of the bricks was reduced to one-fourth of the original dimensions. The experiments employed cement lime mortar, prepared with a precise ratio of cement, lime, and sand (140 g: 1110 g: 2800 g) and a water/cement ratio of 0.14.

Laboratory-scale experimental assemblies

Two types of masonry assemblies were built for different testing purposes: masonry prisms and masonry wallets. Prior to construction, the bricks were soaked for a day, and the mortar was applied with a thickness of 5 mm. Figure 1 illustrates the configurations of the masonry prisms and wallets. All specimens underwent a curing period of 28 days. A total of 42 masonry prism and 12 masonry wallets were constructed (Table 1).

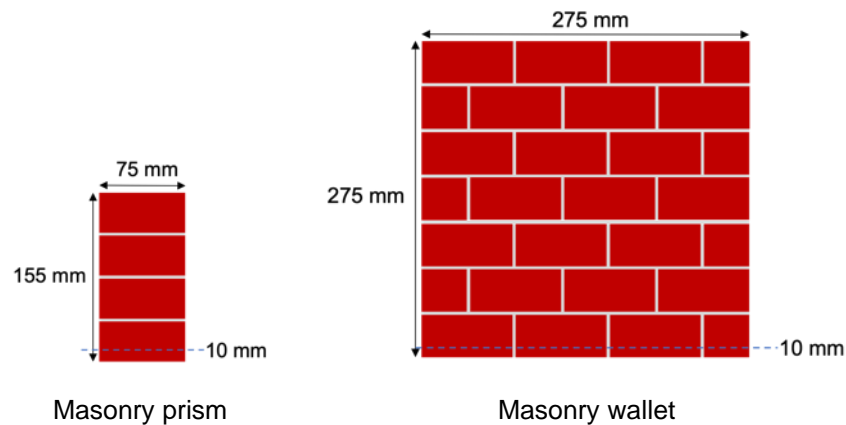


Figure 1 Masonry assemblies submerged in a water depth of 10 mm

Table 1 Specimen detail

Masonry assembly	Testing	Retrofitting	Number of specimens	Label		
Masonry prisms	Compressive strength testing	Non-retrofitted	Dry condition: 3	C-CM0-D		
			Wet condition: 3	C-CM0-W		
			Weathering 5 cycles: 3	C-CM5		
			Weathering 10 cycles: 3	C-CM10		
			Weathering 15 cycles: 3	C-CM15		
			Weathering 20 cycles: 3	C-CM20		
	Flexural bond strength testing	FR-Paint with thickness 2 mm	Non-retrofitted	Dry condition: 3	CM0-D	
				Wet condition: 3	CM0-W	
			FR-Paint with thickness 2 mm	FR-Paint with thickness 2 mm	Dry condition: 3	CMP0-D
					Wet condition: 3	CMP0-W
					Weathering 5 cycles: 3	CMP5
					Weathering 10 cycles: 3	CMP10
					Weathering 15 cycles: 3	CMP15
					Weathering 20 cycles: 3	CMP20
Masonry wallets	Diagonal tension testing	Non-retrofitted	Dry condition: 3	IUD		
			Water content of 20%: 3	IUW2		
			Water content of 50%: 3	IUW5		
			Water content of 100%: 3	IUW10		
		FR-Paint with thickness 2 mm	FR-Paint with thickness 2 mm	Dry condition: 3	IPD	
				Water content of 20%: 3	IPW2	
				Water content of 50%: 3	IPW5	
				Water content of 100%: 3	IPW10	

Conditioning procedure

For masonry wallets, the wet-condition samples were immersed under clean water until they reached a constant weight, while the dry samples were left unconditioned. Additional specimens were prepared for the masonry walls to measure both their dry and wet weights. These results were utilized to calculate the average maximum water weight within the masonry walls. The weight of water content was found to be 150 g for 20% water content, approximately 375 g for 50% water content, and reached a stable value for 100% water content. For the masonry prisms, the specimens were submerged in a solution containing soluble salt until they reached a consistent weight. Sodium sulphate and sodium chloride were selected for the tests, as they are recognized

as the most commonly found in buildings (Gentilini *et al.*, 2012). The specimens were immersed in a solution containing salt, comprising a mixture of sodium chloride and sulphate, with each constituting 1% of the total weight. Both masonry wallets and prisms were immersed in a 10 mm layer of water or soluble salt until they attained the desired weight, as depicted in Figure 1. Periodically, more water or soluble salt was added to maintain the 10 mm depth. During the drying process, the specimens were placed in a ventilated oven for three days, maintaining a constant temperature of 56°C. Maintaining a low temperature and ensuring a gradual drying process was crucial to prevent rapid drying, which could lead to the formation of cracks.

Testing procedure

The diagonal tension test, as outlined in ASTM E519/E519M (2020), assesses the diagonal tensile or shear strength of masonry wallets by applying compressive loading along one diagonal. Additionally, for masonry prisms, two tests were conducted: compressive strength (ASTM C140/C140M, 2022) and flexural bond testing (ASTM E518/E518M, 2016). Details regarding the number of specimens and their corresponding conditions are provided in Table 1.

3 Result

3.1 Identification of the most prone region to earthquake and coastal flood

Figure 2 shows the threat of earthquakes and coastal floods leading to salt attacks. Historical earthquake epicenter data and GIS have been acknowledged to generate regional earthquake-prone zone maps. Besides, the weighted overlay approach in ArcGIS, for example, can be used to detect coastal areas that are prone to flooding due to their morphometric disposition, such as river mouths and flat lowlands (Amir and Theilen-Willige, 2022). Identifying the most earthquake-prone regions and regions susceptible to coastal floods on masonry buildings in developing countries requires a comprehensive analysis of various factors, including seismic activity, the vulnerability of masonry structures, and the impact of coastal flooding.

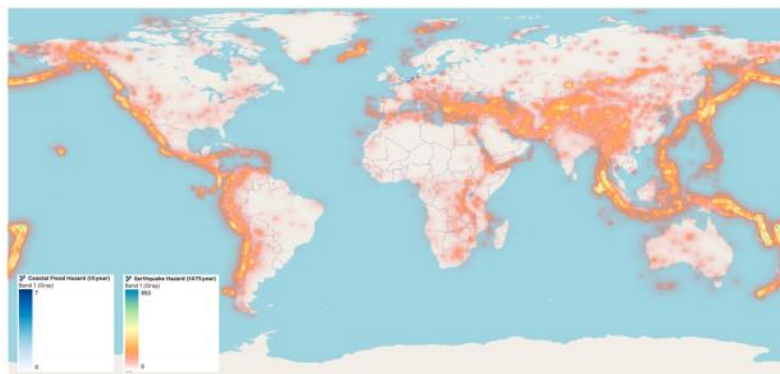


Figure 2 Global earthquake and coastal flood hazard

3.2 Visual assessment of the weathering effect

Figure 3 and Figure 4 show the conditions specimens following exposure to artificial weathering for durations of 5, 10, 15, and 20 cycles. The non-retrofitting specimens (Figure 3) exhibit white-pattern efflorescence on almost the whole surface of bricks, including the uppermost surface. During the 5 to 20 weathering cycles, there is a notable escalation in both the quantity and thickness of efflorescence on the specimen surfaces. After 15 cycles, the flaking also begins on the surface, resulting in a decrease in sharpness. And after 20 cycles, the white pattern efflorescence almost covered masonry prism surface. In the context of the retrofitted specimens presented in Figure 4, an efflorescence with a distinct white pattern was observed on the uncoated side surfaces of masonry prisms. Although the white pattern was not observed on the coated side surfaces, the presence of bubbles on the painted surface suggested a possible delamination of the paint layer, likely caused by the formation of efflorescence.

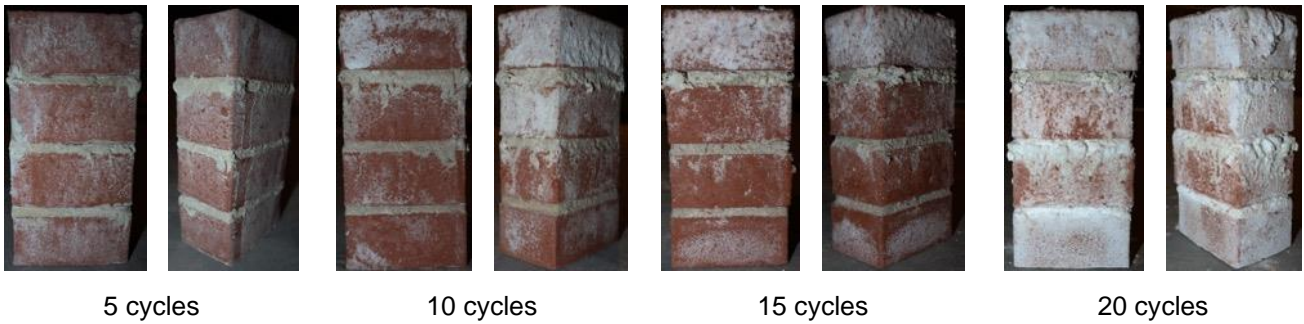


Figure 3. Non-retrofitted masonry prism after weathering cycles.

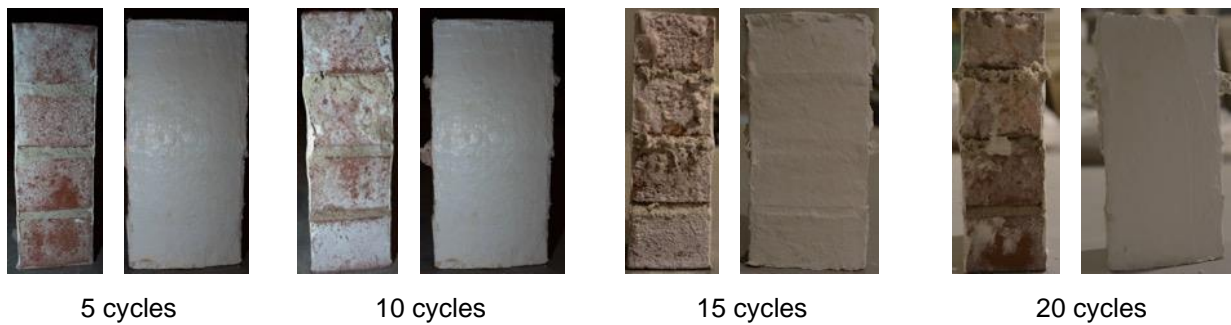


Figure 4. Retrofitted masonry prism after weathering cycles.

3.3 Diagonal tension test (in-plane)

From Figure 5 (a), retrofitted specimens exhibit a higher peak load in comparison to the non-retrofitted. The extent of this strengthening effect, however, depends on both the fiber ratio and the thickness of the coating. Lower fiber ratios and thinner paint layers demonstrate a comparatively modest improvement in masonry strength. In addition, these retrofitted specimens exhibit an increased deformation capacity, as illustrated in Figure 5 (b). The non-retrofitted masonry specimens exhibit a brittle failure mode after reaching their peak load, resulting in a sudden collapse. In contrast, the retrofitted masonry specimens continue to bear loads even after surpassing their ultimate strength. This load-carrying behavior can be attributed to the substantial properties of the FR-Paint, which provide structural support, preventing the bricks and mortar from collapsing.

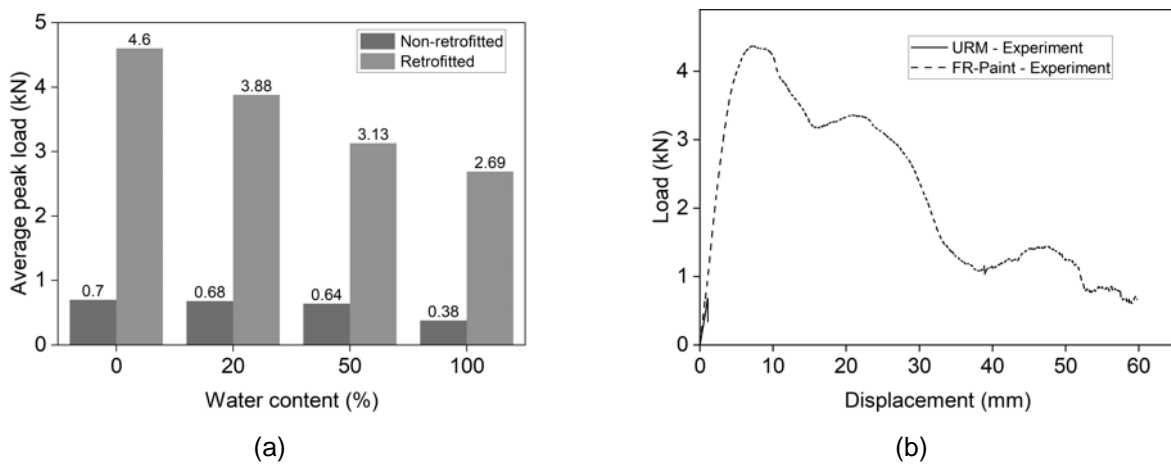


Figure 5. In-plane testing of retrofitted and non-retrofitted masonry wallets: a) average ultimate load b) load-displacement curve

As the water content increased, both retrofitted and non-retrofitted experienced a reduction in average peak load. It indicates that moisture has a weakening effect on the bond between the mortar and bricks. Figure 6

illustrates the thermographic images for masonry walls. In cases where the water content was at 20%, there was a noticeable water accumulation on the bottom surface. This observation aligns with the Digital Image Correlation (DIC) analysis results, as depicted in Figure 7. The failure was primarily localized in the lower layer of masonry walls at the interface between the wet and dry regions. In cases where the water content reached 100%, moisture was evenly distributed in all regions of the masonry structure. Consequently, the failure mode exhibited a more distributed pattern, affecting nearly all regions of the bricks and mortar.

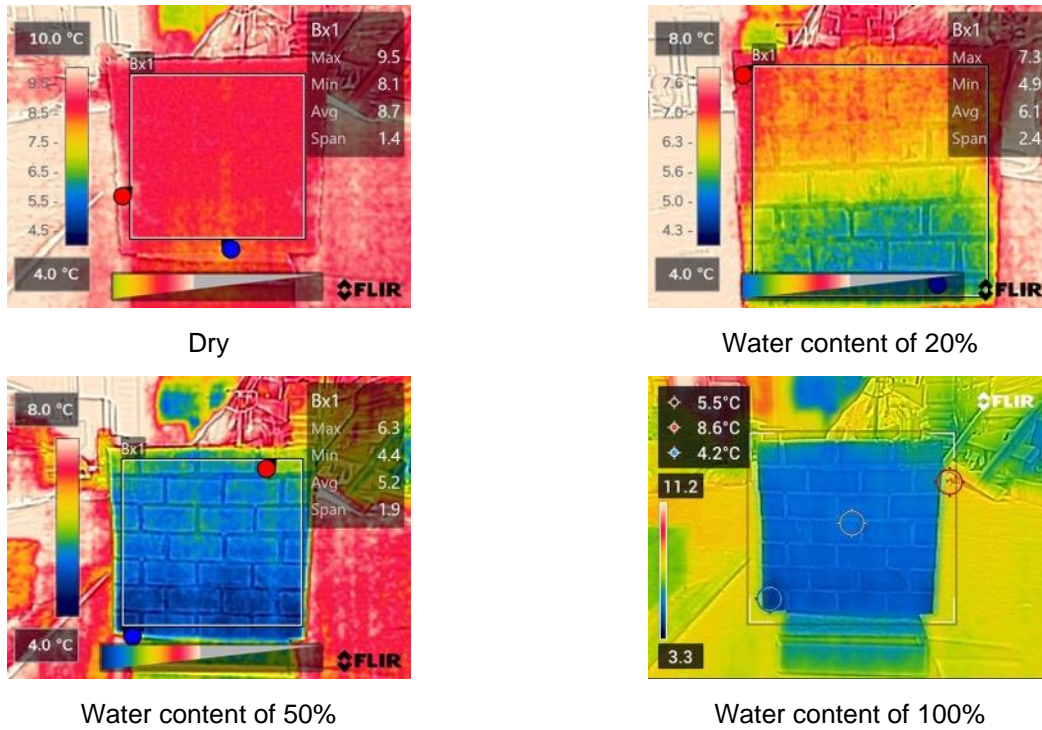


Figure 6 Thermography of masonry wallets under wet conditions

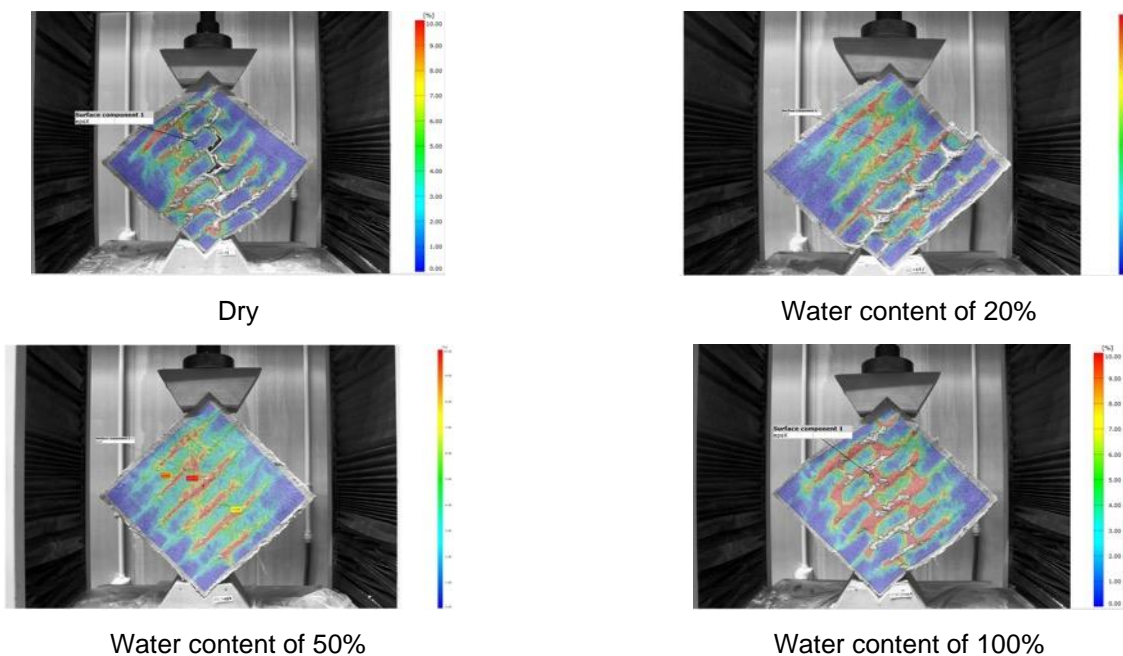


Figure 7 Digital Image Correlation of retrofitted masonry wallets

3.4 Compressive strength test

Compression tests were exclusively performed on non-retrofitted masonry prisms, as the impact of FR-Paint on compression strength is relatively minor. In the case of specimens with 100% water content, denoted as CMO-W (Figure 8 (a)), the compression strength was notably reduced. This reduction can be attributed to the saturation of all pores with water, causing an increase in internal pressure within the material when subjected to a load. In general, weathering can result in a decrease in compression strength. However, during the initial 5 and 10 cycles, there is an observed increment in compression strength, although it remains below the dry conditions. This phenomenon can be attributed to the infiltration of salt, which begins to occupy the material's pores during these early cycles, thereby contributing to the strength of masonry. However, after 15 cycles, the compressive strength was decreasing. This decline occurs because, after 15 cycles, the pores are completely filled with salt, leading to the development of internal cracks due to the presence of salt within the material.

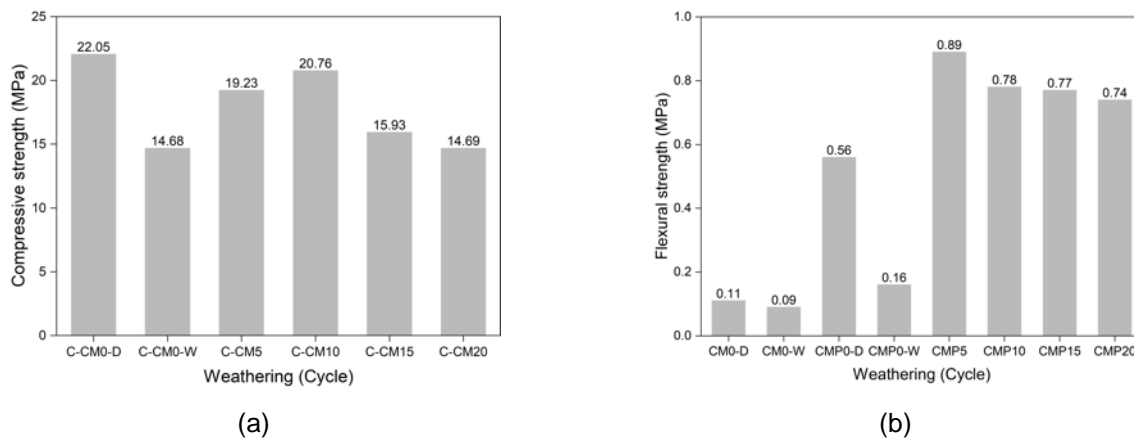


Figure 8. a) Compressive strength of non-retrofitted masonry prism. b) Flexural bond strength of retrofitted masonry prism

3.5 Flexural bond strength test

This testing is exclusively for retrofitted masonry walls, because non-retrofitted specimen is very weak in the out-of-plane direction, so it is difficult to conduct measurement. The summarized results are presented in Figure 8 (b). The water presence can reduce the flexural bond strength of masonry prisms. However, the flexural strength of retrofitted specimens increased after weathering cycles. It occurs due to the drying process, which enhances the strength of FR-Paint. The strength began to decline after 10 cycles, so the weathering effect and soluble salt started to weaken the flexural strength of masonry walls.

4 Discussion

4.1 Failure behaviour

The water content influences the failure behavior of masonry walls. In Figure 6, thermography image of masonry wallets, the specimen with a water content of 20% showed water accumulation in the bottom layer of masonry, aligning with the failure behavior of the 20% water content specimen depicted in Figure 7 (Digital Images Correlation). Sliding failure occurred at the very bottom of the masonry. When moisture was evenly distributed within the masonry, cracks were visible in all parts of the structure. Water weakened the bond between mortar and bricks, leading to cracks that were initiated from the joints. The load-displacement curve (Figure 5 (b)) clearly illustrates that retrofitted specimens have significant deformation capacity. In contrast, non-retrofitted masonry experienced brittle failure.

4.2 Effect of moisture presence

Diagonal tension (In-plane) testing was conducted to examine the shear strength of masonry under varying levels of water content, without weathering and exposure to soluble salt. From Figure 5 (a), the ultimate strength declined with the escalation of water content. However, the deformation capacity remained consistent in the specimens coated with FR-Paint, indicating a strong connection of the paint to the masonry surface. In the case of non-retrofitted specimens, the failure pattern is also the same; the masonry experienced a brittle

failure, resulting in a sudden collapse after reaching the peak load. The presence of moisture in masonry weakens the bond between mortar and bricks, leading to decreased strength of masonry. Volumetric changes triggered by moisture are likely contributors to this strength reduction. The expansion or contraction of the mortar due to moisture weakens the entire masonry structure (Dias, 2002).

4.3 Weathering effect: efflorescence formation

This experiment explored how sodium chloride and sodium sulphate affect masonry prisms. Efflorescence, seen as a white residue, appeared on brick surfaces and the mortar-brick interface (as depicted in Figure 3 and Figure 4). Sodium chloride and sodium sulphate led to different efflorescence patterns due to their mobility differences. Chloride ions, being small and highly mobile, quickly reached the top surface, initiating efflorescence. On the other hand, sulphate ion, a less mobile, concentrated efflorescence primarily in the mortar-brick interface (Gentilini *et al.*, 2012). Masonry exposed to sodium chloride exhibited surface efflorescence, extending into the structure. On the other hand, sodium sulphate is primarily formed near the mortar-brick interface.

4.4 Weathering effect: mechanical properties

In this experiment, sodium chloride and sodium sulphate were used as soluble salts to simulate the worst-case scenario for degrading masonry walls and assess their impact on a proposed retrofitting technique. In the compression test (Figure 8 (a)), the wet specimen (C-CM0-W) without exposure to wet-dry cycles exhibited a lower compressive strength. This decrease is attributed to the complete saturation of the brick (water fills the pores). When the load is applied, the absorbed water leads to a transverse bursting effect within the solid matrix of the brick (Sathiparan and Rumeskumar, 2018). By cycle 5 (C-CM5), the compressive strength decreased further but remained above that of the fully wet sample (C-CM0-W). Expansion and contraction during heating or wetting, combined with crystallization due to soluble salt presence, can create microcracks within the brick structure. These microcracks contribute to a reduction in the overall strength and durability of the masonry. However, there was an increase in compressive strength in C-CM10 compared to C-CM5, due to the salts filling pores adequately, enhancing the strength of masonry. In cycles 15 and 20, the compressive strength consistently declined as the salts inside the pores grew larger, leading to internal cracks in the structures. In the analysis of the flexural bond strength test (depicted in Figure 8 (b)), it was observed that the retrofitted masonry exhibited an increase in flexural strength after 5 cycles. This result was unexpected, as it contradicted the anticipated decrease because of sodium chloride and sulphate on FR-Paint quality. A possible explanation could be the drying process and curing period of FR-Paint. To gain deeper insights, conducting experiments with fresh water is essential. These experiments will allow us to evaluate the impact of the drying process on FR-Paint. Additionally, extending the cycles beyond the initial 20 cycles is essential for a comprehensive understanding. However, after ten cycles, the strength started decreasing, indicating the paint quality was deteriorating due to weathering and exposure to sodium chloride and sulphate.

5 Conclusion

This study was conducted to assess the mechanical properties of retrofitted and non-retrofitted masonry assemblies exposed to moisture and weathering cycles involving sodium sulfate and chloride. While most retrofitting techniques primarily focus on earthquake resistance, this paper takes a comprehensive approach, considering the challenges posed by multiple disasters, including earthquakes and floods, in the retrofitting process. Water presence significantly degrades the quality of masonry houses. During diagonal tension tests (masonry wallets), the peak load decreases with increasing moisture presence. Moisture weakens the brick-mortar interface, influencing failure behavior. At a 20% water content, moisture mostly accumulates at the bottom layer of the masonry, initiating cracks that lead to sliding failure. With 100% water content, moisture spreads across all parts of the masonry. Before complete collapse, cracks are uniformly observed on all surfaces. However, an interesting observation lies in the deformation capacity of retrofitted specimens, which perform remarkably well. As long as FR-Paint adheres to masonry surfaces, this deformation capacity remains intact. The impact of FR-Paint is particularly significant in flexural bond strength testing (out-of-plane testing), where it enhances the flexural strength of masonry (Albert *et al.*, 2001; Gilstrap and Dolan, 1998; Willis *et al.*, 2009)(Albert *et al.*, 2001; Gilstrap and Dolan, 1998; Willis *et al.*, 2009). The FR-Paint utilized in this study has a high tensile strength, thereby positively affecting the overall strength of the masonry assemblies.

The subsequent experiment aimed to examine the impact of weathering on non-retrofitted and retrofitted masonry. In compression testing of non-retrofitted specimens, the presence of water significantly decreased

the compression strength of specimens. In the weathering cycles, the compressive strength increased in cycles 5 and 10 but then declined. This pattern indicates that a certain amount of salt inside the pores can be beneficial for masonry. However, when salt deposits inside the pores grow larger, they can generate cracks. In flexural bond strength testing, moisture presence had a notable effect on masonry, leading to an overall decrease in flexural strength. Interestingly, for retrofitted specimens, the flexural strength increased initially but decreased after 10 cycles. This could be attributed to specific drying processes in certain cycles that might enhance the strength of FR-Paint. Further investigation is needed to identify the factors influencing this increase. Generally, FR-Paint exhibited excellent performance in this experiment. However, additional measures are necessary to prevent water infiltration into masonry walls.

According to research and literature, it is important to stress the extra damage that can be caused when coastal floods and earthquakes happen at the same time, especially to buildings made of stone or brick. If buildings experience gradual damage from moisture or salt weathering, there's a higher risk of collapse during earthquakes. Retrofitting materials need to be long-lasting and resistant. Many experiments only test materials initially or after curing, without considering moisture or weathering effects over time. In future retrofitting plans and strategies, it is crucial to adopt a multi-hazard approach, addressing both earthquake and flood risks, especially in vulnerable areas. Research and retrofitting methods should concentrate on developing strategies to address the complex interactions among different factors leading to damage. This focus will enhance the resilience of masonry structures, enabling them to withstand these threats. Further research is essential to assess the extent of property damage and determine the degree of damage inflicted on buildings, known as property damage degree.

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