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EFFECT OF WET-DRY CYCLING ON BOND BEHAVIOR OF GFRP STRENGTHENED HISTORIC MASONRY STRUCTURES

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Graphical abstract

Abstract

The objective of this research work is to determine the effect of wet-dry cycling on bond behavior of historic masonry structures strengthened by Glass Fiber Reinforced Polymer (GFRP). Shear bond testing was carried out through total 36 specimens exposed to dry, full moisture or wet-dry cycling conditions. The selected samples were then tested at 0, 30, 60 and 90 days. Post-ageing test was also preceded on total sixty masonry prisms exposed to dry, full moisture or wet-dry cycling conditions. The compressive strengths of selected samples were then tested at 0, 40, 70 and 100 days. The test results showed an obvious decrease of the bond strength between GFRP sheets and bricks in the wet-dry cycling condition. For masonry prisms with or without GFRP strengthening, in the first 40 days, the compressive strength of GFRP bonded prism decreased quickly to the value near that of prism without GFRP. After 40 days the rate of decrease became slow, which means that, sheets retrofitted outside the masonry prisms helped to improve their durability by reducing water permeation.

Keywords: Wet-dry cycling, strengthening, historic masonry structures, bond strength, compressive strength, glass fiber reinforced polymer (GFRP)

1.0 INTRODUCTION

Because of lightweight, high strength, corrosion resistance, etc., fiber reinforced polymer (FRP) is gradually used in several fields. In civil engineering, it can be used to repair or retrofit concrete, masonry or steel structures. The bonding property of FRP and structure is the key issue for retrofitting structure by using externally bonded FRP. It is the basic premise for assuring the FRP and structure to resist load and deform together. In FRP strengthened masonry structures, for example, a large number of experimental results showed that, failure often occurred by the debonding between externally bonded FRP and masonry members, which not only caused material waste, but also reduced the reliability of strengthening [1]. The performance of external FRP strengthening systems can be affected by exposure to different environments. Especially the bond at the FRP-substrate interface may degrade when exposed to some environmental agents such as moisture, thermal cycling, freeze-thaw cycling, creep, fatigue and ultraviolet light [2]. Moisture has significant effects on the performance of FRP strengthened structures [3]. A long-term exposure to water may lead to degradation of resins and glass fibers. Moisture also affects the performance of the fiber-matrix interface. Wet and dry cycles can lead to destruction of the concrete base and the ageing of resin. The test results showed that [4], the mechanical properties of resin decreased by about 17% to 43% after wet-dry cycles, which lead to the deterioration of bonding effect.

Thus, the bonding performance between external FRP and structures became hot area of research. Several research works have proceeded about the effects of environmental conditions on quality and performance of the bond between FRP and substrate materials. J.J. Myers and M. Ekenel [5] investigated the effect of surface moisture, relative humidity and temperature on the bond strength between concrete and CFRP reinforcement. Three test methods including a surface pull-off bond test, a surface shear-torsion bond test, and a flexural test were used to evaluate the bond performance of the FRP fabric under various installation conditions. Test results revealed that the high surface moisture content, extreme humidity and extreme low temperature can be detrimental to bond strength. P. Desiderio and L. Feo [6] presented the results of an experimental program focusing on the durability of externally bonded FRP reinforcements (FRP EBR) to tuff masonry structures in the case of outside application (wrapping, planting of masonry walls, vaults and arches) and exposition to climatic agents, particularly to temperature cycling, moisture, and UV light exposure. Oliveira Daniel V. *et al*. [7] discussed some of the most relevant environmental agents and their effect on the durability of FRP-strengthened concrete and masonry constructions. From the results of the ageing tests, it could be derived that, GFRP coupons suffered a strength reduction higher than bricks and epoxy resin due to the reduction in the mechanical properties of epoxy resin and the degradation of the fiber-resin interface.

This paper focuses on the effects of two environmental agents, moisture exposure and wet-dry cycles, for GFRP externally bonded historic masonry structures. Degradation in the bond between the GFRP and the substrate was investigated. Accelerated ageing test was performed to get a better insight into this phenomenon.

2.0 LABORATORY TESTS

2.1 Materials

Specimens from brick, mortar, epoxy resin and glass fiber reinforced polymer sheets were tested to characterize their properties. Solid clay bricks, 300×150×50 mm in size, used in previous experimental works [8], were produced according to the properties of the ancient bricks [9]. The ancient cement mortar was specially prepared according to an original method which involved soaking raw lime in water for at least 60 days, before mixing it with white cement and coarse sand at a ratio of 1:2:9. Table 1 summarized the main properties of each material.

Table 1 Properties of the materials

Material	Solid clay brick	Compressive strength (MPa)	Young's modulus (GPa)	Density (g/cm^3)
		4.012	3.103	1.373
	Cement mortar	Compressive strength (MPa)	Young's modulus (GPa)	Density (g/cm^3)
		1.06	1.461	1.924
	Epoxy resin	Tensile strength (MPa)	Young's modulus (GPa)	Density (g/cm^3)
		55	3.3	1.21
	GFRP sheets	Tensile strength (MPa)	Young's modulus (GPa)	Ultimate elongation
		1700	72	3%

2.2 Shear Bond Testing

For the shear bond testing, two bricks, with a 5cm gap, were used to make up the specimen. One piece GFRP sheet with 150mm width was planted on the full surface of two blocks by using epoxy resin. A special designed steel device (shown in Figure 1) allows the system to be placed under tensile force along the length of bricks in order to mobilized the adhension stresses at interface between GFRP sheet and bricks (shown in Figure 2).

Totally 36 specimens were prepared. Twelve samples (named TD) were left outdoors in sunshine to simulate the totally dry situation. Twelve samples (named TW) were soaked in the water constantly at outdoor temperature. The other twelve samples (named TWD) were cured in wet-dry cycling condition. In each wet-dry cycle, the specimens were soaked in the water at outdoor temperature for 24 hours, followed constant outdoor dry condition for 24 hours. The bond strengths of selected samples were then tested at 0, 30, 60 and 90 days. Three specimens were tested for each period.

Figure 1 Special designed steel device for testing

Figure 2 Shear bond testing

2.3 Post-ageing Tests on GFRP-strengthened Specimens

The bond degradation was also investigated following post-ageing tests on GFRP-strengthened masonry prisms. Totally sixty masonry prisms, 0.31 m × 0.31m square section with 0.45 m in height, were built by using the same type of bricks and cement mortar as that in the shear bonding testing (shown in Figure 3 and 4). Thirty prisms (named CDG, CWDG and CWG, which means the specimens under dry condition, wet-dry cycle and constant moisture, respectively) were strengthened by transversely wounding GFRP sheets on the side surfaces. Other thirty prisms (named CD, CWD and CW according to dry, wet-dry cycle and constant moisture conditions) were used as reference specimens without any GFRP strengthening. The compressive strengths of selected samples after conditioning were then tested at 0, 40, 70 and 100 days.

Figure 3 Masonry prisms for test

Figure 4 Test set-up

3.0 RESULTS AND DISCUSSION

3.1 Bond Strength

The value of the bond strength was established by the following expression:

$$\tau_m = \frac{F}{L \times b}$$

in whihc τ_m is the mean bond strength; F is the applied tension force; L is the anchorage length, which in this test is equal to twice of the length of single brick; b is FRP sheets width, which in this test is equal to the width of single brick.

The experimental results are summarized in Table 2. It is important to note that for both the non-conditioned (dry condition) and conditioned (wet-dry cycle or moisture condition) specimens the failure was at the lamina-substrate interface on the epoxy adhesive layer.

Table 2 Results of shear bond testing

Time (days)	Number of cycles	Bond strength (kg/cm²)		
		TD	TWD	TW
0	0	0.33	0.32	0.32
30	15	0.33	0.32	0.26
60	30	0.33	0.32	0.19
90	45	0.32	0.31	0.13

In order to analyze the bond degradation more clearly, the decrease of bond strength with the cycles are illustrated in Figure 5. In case of exposure to wet and dry cycles, bond strength between GFRP sheet and brick remained stable and the value was about equal to the bond strength under dry condition, which indicated that the bond strength degradation was reversible upon drying during the wet-dry cycles. However, in case of long-term moisture condition, the bond strength decreased in a linear downward trend. After 90 days, the bond strength dropped to about 40% of the value under dry condition. This will have a significant impact on the strengthening effect.

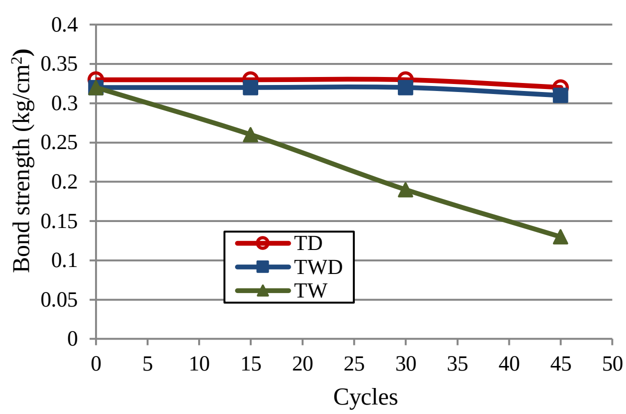

Figure 5 Change of bond strength in different conditioning

3.2 Compressive Strength of Masonry Prisms

The compressive strengths of masonry prisms with or without GFRP strengthening under different conditions were tested and the results are summarized in Table 3.

Table 3 Results of GFRP strengthened specimens

Number of Cycles	Compressive strength (kg/cm²)					
	CD	CWD	CW	CDG	CWDG	CWG
0	35.83	35.83	35.83	45.25	45.25	45.25
20	35.5	35.09	34.01	45.12	37.15	35.23
35	34.11	21.95	26.21	44.96	33.99	31.28
50	33.77	20.04	22.7	44.58	30.72	25.84

Comparing results of specimens CD and CDG (shown in Figure 6), it can be seen that, after strengthening the compressive strength of masonry prism was significantly higher of around 30% than that before the reinforcement. For the GFRP strengthened specimens exposed to wet-dry cycles (CWDG), the increase of the number of exposure cycles caused large degradation in compressive strength. After 60 days (30 cycles), the compressive strengths of them were equal to those of un-strengthened specimens. However, after 30 cycles, the rate of decline became slow. After 100 days (50 cycles), the compressive strength of strengthened prism decreased 32.1%, about 9% lower than the strength of un-strengthened specimens after 100 days under dry condition.

For strengthened prisms soaked constantly in water (CWG), the rate of compressive strength degradation with time increasing was faster than that of the specimen CWDG. It used only 40 days for the compressive strength of CWG prism decreased to the value of un-strengthened specimens. Moreover, the rate of decline has not slowed. After 100 days, the compressive strength of CWG decreased 43%, about 23.5% lower than the strength of un-strengthened specimens after 100 days under dry condition.

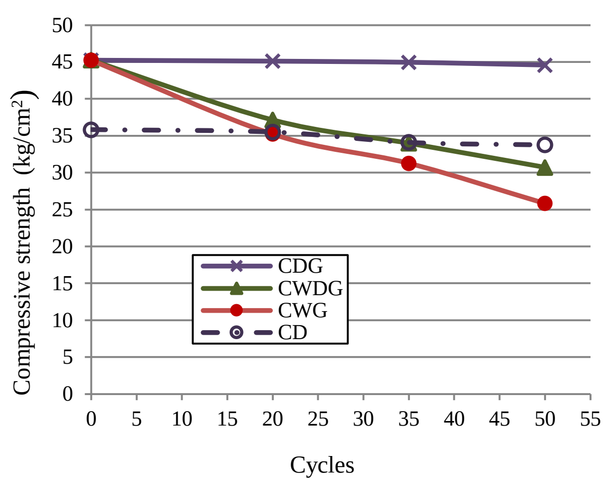

Figure 6 Strength degradation of GFRP strengthened prisms exposed to different conditions

For masonry prisms exposed to wet-dry cycles (CWD) (shown in Figure 7), in a short time (less than 20 cycles) compressive strength remained stable, having the same value as specimens under dry condition (CD). A rapid decrease in compressive strength with increasing cycles was observed after exposure to 20 cycles. 35 cycles of wet-dry ranging originated a 34.5% decrease. However, after 35 cycles, the compressive strength changed few with increasing cycles. To 50 cycles, the strength reached a residual value with 40% reduction when compared to the strength of specimens under dry condition. This shows that, for masonry specimens, the mechanical properties of cement mortar and clay brick decreases after exposure to several wet-dry cycles, which results in the reduction on the compressive strength of masonry prism.

For the GFRP strengthened prisms exposed to wet-dry cycles (CWDG), the compressive strength decreased rapidly with increasing cycles. After 40 days (20 cycles), a decrease of 17.7% was observed. It is because that GFRP sheets are sensitive to moisture. After a short time exposed to wet-dry cycles, the mechanical properties of GFRP sheet degraded, which lead to the reduction on strengthening effect. After 20 cycles, the decrease in compressive strength of specimen CWDG was mainly caused by the degrading of the mechanical properties of clay bricks and cement mortar. At the same period, the influence of the reduction of GFRP tensile strength was reduced and the bond strength between GFRP and prism surface remained stable. Therefore GFRP strengthening effect was obvious when compared to the prisms without GFRP strengthening (CWD) after the same number of wet-dry cycles. After 50 cycles, the compressive strength of CWDG was 53% higher than that of CWD. The results indicate that although there is a reduction in compressive strength for masonry prism strengthened by GFRP induced by wet-dry cycles, it is still a viable method to retrofit masonry structures exposed to such condition. GFRP sheets bonded outside the masonry prisms helped to improve their durability by reducing water permeation.

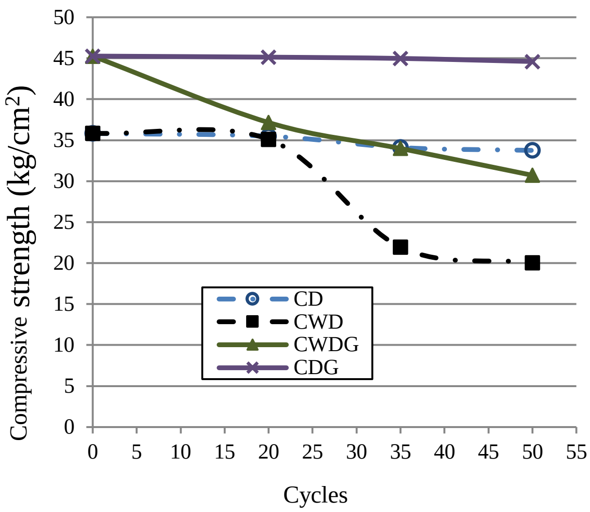

Figure 7 Compressive strength of strengthened or un-strengthened specimens under wet-dry cycles

For masonry prisms exposed to constant moisture condition (CW) (shown in Figure 8), the decrease of compressive strength behaved a similar trend to that of specimen exposed to wet-dry cycles (CWD), in a lower rate of decline. It indicated that wet-dry cycle conditioning has greater impact on the mechanical properties of materials when compared to the moisture conditioning. However, in terms of the GFRP strengthened specimens, the compressive strength of prisms exposed to wet-dry cycles (CWDG) was higher than that of prisms soaked in water constantly (CWG). One reason is that, long time exposure to moisture originated the degrading of the mechanical properties of GFRP sheets. The more important reason is that, deduced from the shear bonding test aforementioned, serious degradation in bond strength occurred with the increasing of time when prisms were soaked in water, which significantly affect the strengthening effect of GFRP sheets.

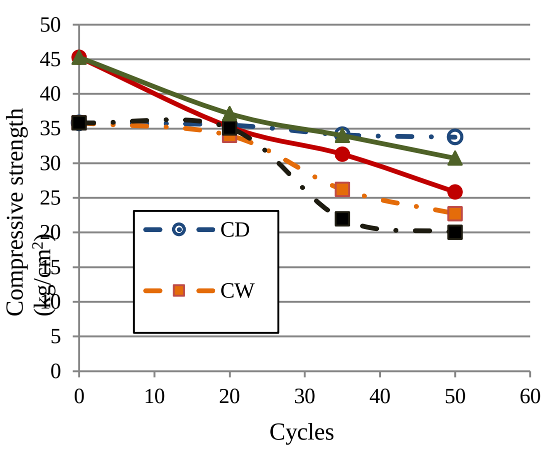

Figure 8 Compressive strength under Long-term moisture environment or wet-dry cycles

Although after 40 days, the compressive strength of the strengthened prism exposed to moisture condition (CWG) reduced to the value near that of the un-strengthened prism (CW), but from the later development trend, it can be observed that the compressive strength of specimen CWG was still significantly higher than that of specimen CW. It indicates that, it is feasible to strengthen masonry structures under water by using GFRP sheets. During the design calculations, it should fully consider the impact of environmental change on the bond strength and mechanical properties of materials. Some special factors should be used for considering the durability under different conditionings.

4.0 CONCLUSIONS

The conclusions of the two tests are summarized below:

1) A significant reduction (40% degradation) of bond strength was observed after 90 days of moisture exposure. However, relatively stable bond strength was observed after 45 wet-dry cycles, which indicated that the bond strength degradation was reversible upon drying during the wet-dry cycles.

2) For the GFRP strengthened prisms exposed to wet-dry cycles, although the compressive strength decreased rapidly with increasing cycles, GFRP strengthening effect was still obvious when compared to the prisms without GFRP strengthening after the same number of wet-dry cycles. It indicates that, it is a viable method to retrofit masonry structures exposed to wet-dry cycling condition by externally bonded GFRP sheets. GFRP sheets could help to improve their durability by reducing water permeation.

3) After 100 days the compressive strength of prisms exposed to wet-dry cycles was higher than that of prisms soaked in water constantly. It is because that serious degradation in bond strength occurred with the increasing of time when prisms were soaked in water, which significantly affect the strengthening effect of GFRP sheets. Also the long term exposure to moisture originated the degrading of the mechanical properties of GFRP sheets.

4) Because GFRP sheets are sensitive to moisture, so after exposed to few wet-dry cycles, the mechanical properties of GFRP sheet degraded, leading to the reduction on the GFRP strengthening effect. After 20 wet-dry cycles, the decrease in compressive strength of strengthened prism was mainly caused by the degrading of the mechanical properties of clay bricks and cement mortar, whereas the influence of the reduction of GFRP tensile strength was reduced.

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