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Experimental Study on the Axial Compressive Properties of FRP-Reinforced Seawater Aggregate Concrete Brick Masonry

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Abstract

Seawater aggregate concrete brick is a new type of material for load-bearing walls. To improve the ductility and integrity of its masonry, this paper designs specimens by reinforcing the brick masonry structure with FRP fabrics, and explores the failure characteristics and mechanical properties of FRP-reinforced seawater aggregate concrete brick masonry by testing its compressive strength. The results show that the compressive strength of FRP-reinforced seawater aggregate concrete brick masonry is improved by 28.63% at the most; Compared with non-reinforced masonry, the ductility and integrity of the specimens are improved significantly. Based on the existing design formulas and test results, this paper puts forward the axial compressive strength formula of FRP-reinforced seawater aggregate concrete brick masonry and gives recommended structure of the reinforcement layer.

Keywords

Fiber-reinforced polymer, seawater aggregate concrete brick masonry, reinforcement structure, mechanical properties

1. Introduction

As a porous concrete brick, the seawater aggregate concrete brick is produced in the following way: First, use seawater to mix spherical high-performance water-absorbing resin, cement and other cementitious materials with admixtures, put the mixture into moulds for shaping, and cure the product [1-4]. Compared with ordinary concrete bricks, it has the advantages of energy saving, light weight and ease of construction. However, the seawater aggregate concrete brick masonry features poor ductility and integrity. To promote the application of the new material, this paper designs specimens by reinforcing the brick masonry structure with FRP fabrics, which is extensively used in construction projects thanks to its features like light weight, high strength, ease of construction, strong corrosion resistance, and no impact to the structural form and appearance of the building, etc. Besides, this paper explores the failure characteristics and mechanical properties of FRP-reinforced seawater aggregate concrete brick masonry by testing its compressive strength.

2. Strength mechanism of FRP-reinforced brick masonry

This section introduces the method to construct the FRP-reinforced brick masonry. During masonry construction, arrange fiber mesh or fiber cloth strips in horizontal mortar joints in a mesh pattern to serve as reinforcement [5-6]. See Figure 1. When the masonry is under vertical load, the transverse deformation coefficient and elastic modulus of brick and mortar are different. The interaction between the two leads to additional tensile stress in the brick, which accelerates the cracking of masonry. When laid in a mesh pattern in the horizontal mortar joints, the fiber cloth strips or fiber mesh can restrain the transverse deformation of the mortar and reduce the effect of additional tensile stress to a certain extent, thereby improving the compressive strength of the brick masonry and the stress state inside the masonry under compression.

In comparison to conventional FRP reinforcement applications and reinforced masonry, the FRP-reinforced brick masonry has the following advantages: (1) there is no secondary load on the reinforced structure; (2) there is no need to paste up the fiber fabrics with resin or to make fireproof treatment of the fiber fabrics; (3) there is no adhesive or debonding failure of reinforcement, and no need to take end anchorage measures; (4) There is almost no increase in structural mass or thickness of mortar joints.

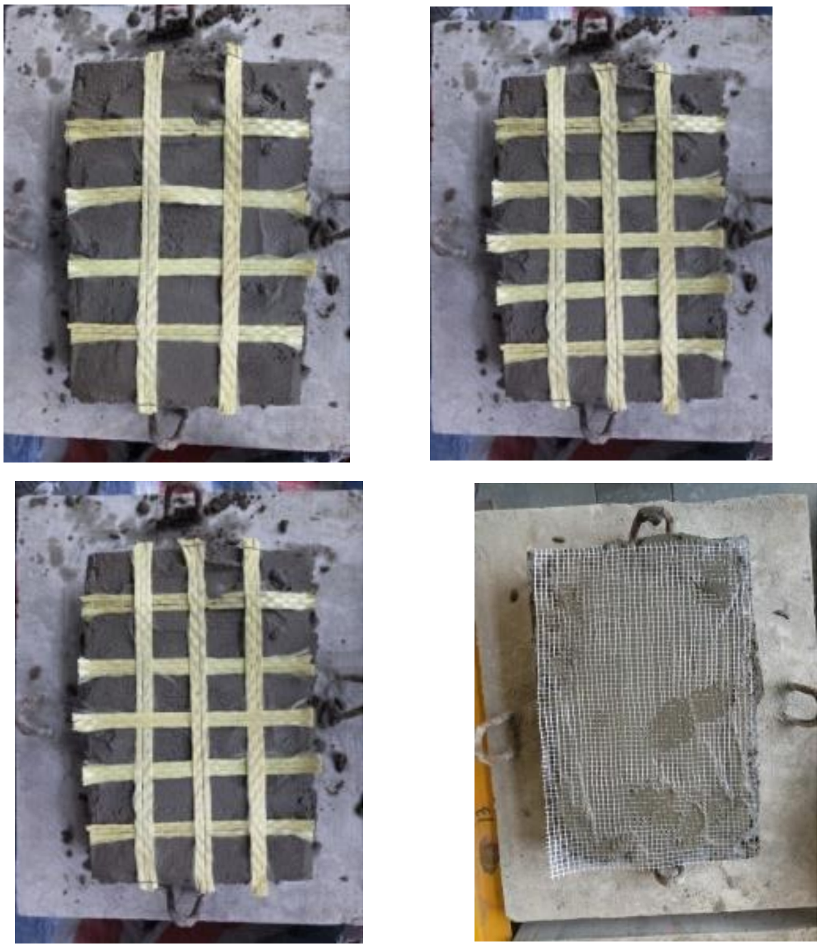
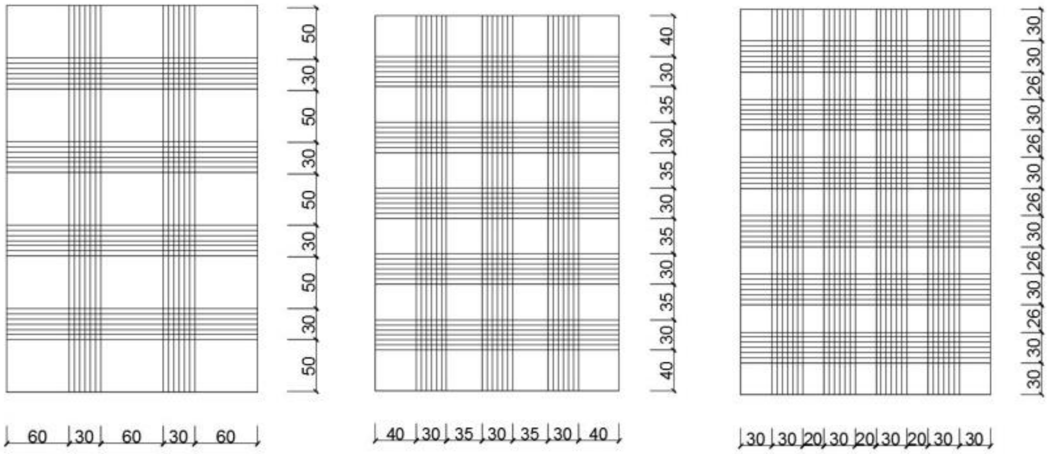


Fig.1. Different reinforcement structures

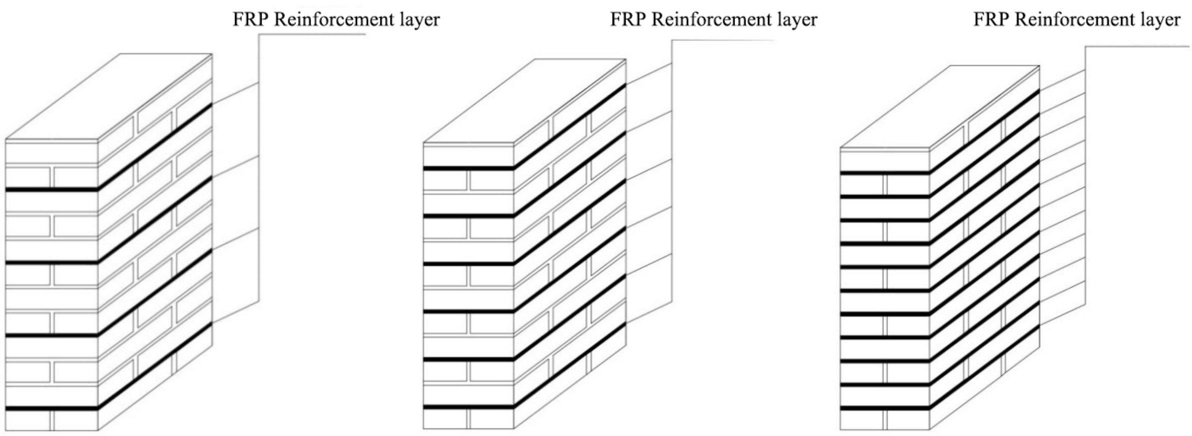
3. Test overview

18 specimens are designed for this test, all of which are 370mm×240mm×746mm in size, i.e. the height-thickness ratio is 3.1. The masonry mortar is of the strength grade M10. The mortar joints are 10mm thick. The average compressive strength of seawater aggregate concrete brick is measured as 28.99MPa. In the test, the brick masonry is reinforced by aramid fiber fabric, glass fiber fabric, and glass fiber mesh. See Figure 2 for the layout and size of fiber fabric. The mesh size of glass fiber mesh is 5mm×5mm. See Tables 1 & 2 for the detailed parameters of the specimens.



Size I Size II Size III

Fig.2. Layout of the fiber fabrics



Form a Form b Form c

Fig.3. Layout of the reinforcement layer

KY0 is the control group is non-reinforced seawater aggregate concrete brick masonry; GKY and AKY specimen groups reinforce brick masonry with GFRP (glass fiber reinforced polymer) and AFRP (aramid fiber reinforced polymer) respectively; GMKY specimen group uses glass fiber mesh to reinforce brick masonry. See Figure 3 for the layout of the reinforcement layer.

Table 1. Parameters of specimens reinforced with fiber fabrics

Specimen No.	Specimen quantity	Fiber fabrics width (mm)	Fiber fabrics thickness (mm)	Fiber ratio by volume (%)	Fiber fabrics layout	Reinforcement layer layout
KY0	2	——	——	——	——	——
AKY1	2	30	0.107	0.085	I	b

AKY2	2	30	0.107	0.146	II	b
AKY3	2	30	0.107	0.255	III	b
GKY1	2	30	0.111	0.088	I	b
GKY2	2	30	0.111	0.151	II	b
GKY3	2	30	0.111	0.264	III	b

Table 2. Parameters of specimens reinforced with fiber mesh

Specimen No.	Specimen quantity	Mesh size (mm×mm)	Fiber fabrics thickness (mm)	Fiber ratio by volume (%)	Reinforcement layer layout
GMKY1	2	5×5	0.146	0.062	a
GMKY2	2	5×5	0.146	0.093	b
GMKY3	2	5×5	0.146	0.185	c

Aiming at measuring the cracking load and the ultimate load of the specimens, the test is carried out in the Structure Hall of Logistical Engineering University. A 500-ton hydraulic long-column testing machine is used for staged loading. See Table 3 for test results. The increase of ultimate stress is determined by comparing the average compressive strength measured of each group with that of Group KY0.

Table 3. Test results

Specimen No.	N_{cr}(kN)	$N_{m,t}$(kN)	$N_{cr}/N_{m,t}$	$f_{m,t}$ (MPa)	$\bar{f}_{m,t}$ (MPa)	Ultimate stress increase (%)
KY0-1	553	901	0.61	10.15	10.44	0
KY0-2	548	953	0.58	10.73		
AKY1-1	582	986	0.59	11.10	11.14	6.73
AKY1-2	675	993	0.68	11.18		
AKY2-1	689	1044	0.66	11.76	11.78	12.88
AKY2-2	661	1049	0.63	11.81		
AKY3-1	688	1127	0.61	12.69	12.51	19.84
AKY3-2	756	1095	0.69	12.33		
GKY1-1	598	1014	0.59	11.42	11.46	9.75
GKY1-2	715	1021	0.70	11.50		
GKY2-1	732	1093	0.67	12.31	12.10	15.90
GKY2-2	665	1056	0.63	11.89		
GKY3-1	689	1130	0.61	12.73	12.94	23.99
GKY3-2	772	1169	0.66	13.16		
GMKY1-1	623	1093	0.57	12.31	12.17	16.55
GMKY1-2	651	1068	0.61	12.03		

GMKY2-1	724	1131	0.64	12.74	12.61	20.76
GMKY2-2	765	1108	0.69	12.48		
GMKY3-1	759	1205	0.63	13.57	13.43	28.63
GMKY3-2	602	1180	0.51	13.29		

4. Test results and analysis

According to the comparative analysis of test phenomenon and data, the FRP laid in a mesh pattern in horizontal mortar joints is capable of enhancing the mechanical properties of seawater aggregate concrete masonry and improving the overall performance of the structure.

4.1 Failure characteristics

See Figure 4 for the failure modes of seawater aggregate concrete brick masonry specimen reinforced with FRP laid in a mesh pattern. According to test phenomena and cracks, the failure modes of FRP-reinforced brick masonry are similar to those of common reinforced brick masonry laid in a mesh pattern [7].

Fig.4. Typical failure modes of specimens

The axial pressure is applied to non-reinforced seawater aggregate concrete brick masonry. When the pressure is increased to 50%~70% of the failure load, some bricks in the masonry begin to crack under the combined action of tensile, bending and shearing forces. At this stage, the cracks have not penetrated through the mortar layer. If the loading is stopped, the cracks would cease to develop. When the pressure is increased to 80%~90% of the failure load, the initial cracks continues to grow and pass through several pieces of bricks, forming continuous cracks on the masonry. Even if the loading is stopped at this point, the cracks would continue to develop and the specimens are on the verge of failure. If the load continues to increase, the cracks would extend and widen rapidly and eventually form penetrating cracks which separate the masonry into small columns.

When it comes to FRP-reinforced brick masonry, the cracks appear in a single brick initially with the increase of load. At this stage, the FRP-reinforced brick masonry share similar stress characteristics with non-reinforced masonry, but boasts higher initial cracking load than the latter. The FRP reinforcement structure has little impact on the development of the initial cracks of brick masonry. However, as the cracks develop, the FRP reinforcement structure restrains the transverse deformation of the mortar and limits the lateral expansion of brick masonry. After continuous loading, it is discovered that cracks develop slowly despite the increase in the number of cracks. Thanks to the existence of FRP reinforcement structures, the cracks are prevented from forming continuous cracks along the vertical direction. This forms a sharp contrast with crack development of non-reinforced masonry under compression. Moreover, the cracks concentrate in the middle of the specimens and the brick surface bulges. When the load approximates the failure load, some bricks in the masonry are severely cracked and even crushed, a prelude to the complete destruction of the masonry. At the failure stage, FRP-reinforced brick masonry is not divided into small columns by the cracks and the strength of the bricks is fully displayed. During the failure process, cracks are formed evenly in FRP reinforced seawater aggregate concrete masonry specimens accompanied by the sound of fiber fabrics breakage. After the failure of the specimens, it is observed that the fiber fabrics in some mortar joints are broken.

4.2 Test data analysis

As shown in Table 3, the axial compressive strength of brick masonry is improved by laying fiber fabrics in a mesh pattern in horizontal mortar joints. In this test, the compressive strength of the specimens is improved by 28.63% at the most. When the same fiber material is used, the higher the fiber ratio by volume, the more the compressive strength of the specimens is improved. The author also compares specimens of different fabric materials when the fiber ratio by volume remains the same. The results show that the compressive strength of specimens in Group GKY is improved more than that of specimens in Group AKY due to the differences in elastic modulus and strip width. The GFRP fabric of Group GKY has a higher elastic modulus than the AFRP fabric of Group AKY. Comparing the compressive strengths of Group GMKY and Group GKY, the author finds that the specimens reinforced with fiber mesh have a higher compressive strength than the specimens reinforced with fiber cloth strips. The finding demonstrates that the compressive strength is not only affected by the elastic modulus and fiber ratio of FRP, but also the adhesive strength of the mortar and FRP. The stronger the adhesive strength, the more the compressive strength of brick masonry is improved by FRP fabrics.

Comparing the results of specimens (GMKY1, GMKY2 and GMKY3) with different layouts of reinforcement layers, the author notes that the compressive strengths of the specimens are improved in varied degrees. That is because the upper and lower plates and the ferrule of the glass fiber mesh reinforcement layer have different effects. The compressive strength of specimens with lower fiber ratio by volume is improved to a smaller extent because the ferrule of the fiber reinforcement layer has a weaker effect.

The results also indicate that the initial cracks of FRP-reinforced brick masonry appear late, exhibiting obvious signs of the ultimate failure of the specimens. Besides, the specimens boast good energy storage capacity and ductility in the failure process.

5. Calculation of axial compressive strength

5.1 Calculation of axial compressive strength of non-reinforced seawater aggregate concrete brick masonry

The average compressive strength of non-reinforced seawater aggregate concrete brick masonry is calculated by the following formula [8]:

$$f_m = 3.28 f_1^{0.2}(1 + 0.07 f_2)k_2 \tag{1}$$

Where, f_1 is the compressive strength of block material (MPa), f_2 is the compressive strength of mortar (MPa), and k_2 is the mortar strength correction coefficient, which is set as 1 in this test.

According to the current specifications, the compressive strength of the pressure bearing members of common mesh-reinforced brick masonry is calculated by the following formulas:

$$N \leqslant \varphi_n f_n A \tag{2}$$

$$f_n = f + 2\left(1 - \frac{2e}{y}\right)\frac{\rho}{100} f_y \tag{3}$$

$$\rho = 100(V_s/V) \tag{4}$$

Where, N is the design value for the axial force; φ_n is the influence coefficient of height-thickness ratio β, axial force eccentricity$e$ and the reinforcement ratio on the compressive strength of the pressure bearing members (brick masonry under axial compression is only affected by height-thickness ratio β); f_n and f_y are respectively the designed compressive strength of masonry and the designed compressive strength of reinforcement material under tension; A is the cross-sectional area of masonry, and ρ is the reinforcement ratio by volume.

The calculation shows that there is a big difference between the test results and the results obtained by the calculation method for the compressive strength of non-reinforced masonry. Therefore, the calculation method does not apply to the axial compressive strength of FRP-reinforced seawater aggregate concrete brick masonry.

5.2 Calculation of axial compressive strength of FRP reinforced brick masonry

Under axial pressure, the pressure bearing condition of FRP reinforced brick masonry is similar to that of mesh-reinforced masonry[9-11]. Hence, the author corrects the axial compressive strength formula of mesh-reinforced brick masonry. Considering the effect of material properties on reinforcement, the author introduces the coefficient related to material properties α_f, and gets the axial compressive strength formula of FRP-reinforced seawater aggregate concrete brick masonry:

$$N \leq \alpha_f \varphi_f f_f A \tag{5}$$

$$\varphi_f = \frac{1}{1 + (0.0015 + 0.45\rho_f)\beta^2} \tag{6}$$

$$f_f = f_m + 2\rho_f f_{f0} \tag{7}$$

Where, α_f-the influence coefficient of fiber ratio and material properties on the compressive strength of brick masonry; φ_f-the influence coefficient of heath-thickness ratio and axial force eccentricity on the compressive specimens; f_f-the average compressive strength of FRP-reinforced brick masonry; f_{f0}-the designed tensile strength of the FRP materials in the reinforcement layer, which is set as 320 MPa.

Through the regression analysis of the test results, the author obtains the following formulas:
For Group AKY:

$$\alpha_f = 0.20\rho_f \times 100 + 0.37 \tag{8}$$

For Group GKY:

$$\alpha_f = 0.21\rho_f \times 100 + 0.38 \tag{9}$$

For Group GMKY:

$$\alpha_f = 0.27\rho_f \times 100 + 0.41 \tag{10}$$

With constant brick strength and specimen height-thickness ratio, the coefficient α_f is calculated by three different formulas because the two kinds of FRP fabrics differ on elastic modulus and tensile strength. The basic form of the calculation formula for α_f is:

$$\alpha_f = k\rho_f \times 100 + C \tag{11}$$

Suppose the slope k is relevant to the elastic modulus of FRP fabrics, and the constant C is relevant to the tensile strength of FRP fabrics. Since the slope and the constant are dimensionless, the author introduces the designed tensile strength of FRP materials in the reinforcement layer f_{f0} . After analyzing the test values, the author obtains the following equations for k - E_f / f_{f0} and C - f_{tf} / f_{f0} :

$$k = 0.00057 \frac{E_f}{f_{f0}} + 0.00664 \quad (12)$$

$$C = 0.019 \frac{f_{tf}}{f_{f0}} + 0.24 \quad (13)$$

Substitute Formulas (12) and (13) into Formula (11) to deduct the calculation formula of the influence coefficient α_f :

$$\alpha_f = (0.057 \times E_f / f_{f0} + 0.664)\rho_f + (0.019\ f_{tf} / f_{f0} + 0.24) \quad (14)$$

5.3 Comparison between test results and calculated results

The results of the calculation method proposed in this paper are in good agreement with the test results and can provide preliminary basis for the design. See Table 4 for the results.

Table 4. Results of comparative analysis

No.	$\bar{N}_{m,t}$ (kN)	Corrected	
		$N_{m,c}$ (kN)	$\frac{N_{m,c}}{\bar{N}_{m,t}}$
KY0	927	——	——
AKY1	990	987	0.997
AKY2	1047	1028	0.982
AKY3	1111	1103	0.993
GKY1	1018	1030	1.011
GKY2	1075	1080	1.004
GKY3	1150	1171	1.019
GMKY1	1081	1082	1.001
GMKY2	1120	1108	0.989
GMKY3	1193	1185	0.994

6. Conclusion

Exploring the compressive strength of FRP-reinforced seawater aggregate concrete brick masonry, this paper draws the following conclusions:

(1)This paper introduces a new type of masonry structure to the seawater aggregate concrete brick masonry because the FRP reinforcement layer can improve the compressive strength and integrity of the brick masonry. The results show that the FRP's reinforcement effect depends on the fabric materials, mortar strength, fabric ratio and the layout of the reinforcement layer.

(2)This paper also studies the effect of different layouts of FRP and reinforcement layer on the compressive strength of the reinforced brick masonry. The results show that, within a certain range, the FRP's reinforcement effect increases with the fabric ratio. To maintain a good reinforcement effect, it is recommended that the fabric ratio by volume of the reinforced brick masonry should be greater than 0.09% and the reinforcement layer should not be taller than 3 pieces of bricks.

(3) On the basis of the exiting design formula of masonry compressive strength, the author puts forward a corrected compressive strength formula for FRP-reinforced seawater aggregate concrete brick masonry in light of the test results. The calculated results are in good agreement with the experimental data and can provide a good reference for engineering application.

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