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Hybrid modified ferrocement under sustained load in flowing sulphuric acid solution

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Abstract

As a part of a research programme on reinforcement corrosion, the behavior of a soluble glass-polyvinyl acetate hybrid modified ferrocement under sustained flexural load was investigated in flowing sulphuric acid solution to better simulate the site condition. Test results showed that corrosion in flowing sulphuric acid was much more severe than in stagnant one, and the behavior of the hybrid modified ferrocement under sustained load and flowing sulphuric acid solution was noticeably better than that of control specimens.

Keywords: Ferrocement; Soluble glass; Polyvinyl acetate; Hybrid modified; Sustained load and flowing sulphuric acid solution

1. Introduction

The deterioration of concrete/mortar due to chemical attack has received increasing attention in recent years because of its widespread occurrence in certain type of structures and the high cost of repair. For instance, in many parts of the world, a large part of the expenditure on sewage drainage system is allocated for improving the structural performances of the existing network [1]. Many failures and stoppages of sewers occurred due to sulphuric acid attack generated by the interaction between bacteria and domestic sewage [2]. The sulphuric acid attacks the alkaline constituents of the hydrated cement paste and converts them into soluble calcium sulphate which can be leached away [2–4]. It should be noted that there is an exponential rise in the permeability coefficient with increasing aggregate size, because transition zone between the cement paste and larger aggregate is much more porous and weaker [4]. Ferrocement is a suitable construction and repair material for relining of sewers. Small aggregate size enables the mortar to be more durable. Small overall thickness has less influence on the flowability and the relining is easy to construct.

Obviously, an increase in corrosion resistance of mortar will lead to an increase in durability of ferrocement. In order to develop a low cost sulphuric acid resistant mortar, soluble soda glass (sodium silicate) and polyvinyl acetate latex (chosen from five kinds of polymer latexes) had been used as the main and supplementary modifying materials, respectively, for producing a hybrid modified cement mortar for the first part of a research programme [5]. A mass loss comparison test indicated that in stagnant sulphuric acid, resistance of the soluble glass-polyvinyl acetate hybrid modified cement mortar was significantly higher than that of the other kinds of modified and control mortars [5]. Based on this, a soluble glass-polyvinyl acetate hybrid modified ferrocement was then chosen for this research.

It is worth noting that deterioration of ferrocement is rarely due to one isolated cause. Practical sewers are often subjected to sustained load and flowing corrosive attack simultaneously. In order that laboratory simulation matched site condition better, further tests were carried out to study the behavior of ferrocement with different types of mortar in flowing sulphuric acid under sustained flexural load. The results of these tests are presented and discussed in this paper.

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2. Experimental investigation

2.1. Materials

Based on the first part of this research programme [5], a soluble soda glass with a specific gravity of 1.44 and a viscosity index of 1.6 was chosen. Na_2SiF_6 was used as hardener for the soluble glass. Ordinary portland cement, sand and class II fly ash in accordance with the Chinese standards were used. Lignosulphonate was used as a dispersing agent and tributylphosphate was used as a defoaming agent. A 10.16 mm × 10.16 mm × 0.8 mm diameter galvanised drawn square weldmesh was used. The yield and ultimate strengths of the mesh were 311 and 443 MPa respectively. Sulphuric acid solution of 1% concentration was chosen for making both stagnant and flowing corrosion environments.

2.2. Specimen groups and comparison test arrangement

Based on the former experimental research [5], four kinds of mortars (with six mixture proportions) were chosen as shown in Table 1. Six groups of corresponding mortar specimens were made as shown in Table 2. Ferrocement specimens were produced for groups 1, 5 and 6 as shown in Table 3.

Group 1 composed of six 100 mm × 100 mm × 100 mm cubes, six 40 mm × 40 mm × 100 mm prisms and six ferrocement specimens. The six cubes were divided into two sets and tested for 28-day strength, and the strength after exposing 10 weeks to flowing sulphuric acid attack, respectively. The six prisms were divided into two sets and tested for mass loss versus time in the stagnant and flowing sulphuric acid solutions, respectively. The six ferrocement specimens were divided into

Table 1
Mix proportions for different groups of mortar specimens (by weight)

Material	Specimen group					
	Group 1 soluble glass-polyvinyl acetate hybrid modified mortar-1	Group 2 soluble glass-modified mortar	Group 3 polyvinyl acetate-modified mortar	Group 4 unmodified mortar-1	Group 5 soluble glass-polyvinyl acetate hybrid modified mortar-2	Group 6 unmodified mortar-2
Cement	100	100	100	100	100	100
Soluble glass/ lignosulphonate[a]	7/0.05	7/0.05			7/0.05	
Na_2SiF_6	1.05	1.05			1.05	
Polyvinyl acetate	3		5		3	
Lignosulphonate	0.5	0.5	0.5		0.5	
Tributylphosphate	6	1	10		6	
Fly ash	15	15	15	15	15	15
Sand	200	200	200	200	200	200
Water	55	55	55	55	45	45

[a] Soluble glass and lignosulphonate were mixed before producing modified mortar.

Table 2
Comparison test results of different groups of mortar specimens

Test items	Specimen group					
	Group 1 soluble glass-polyvinyl acetate hybrid modified mortar-1	Group 2 soluble glass-modified mortar	Group 3 polyvinyl acetate-modified mortar	Group 4 unmodified mortar-1	Group 5 soluble glass-polyvinyl acetate hybrid modified mortar-2	Group 6 unmodified mortar-2
28-day cube strength (MPa)	20.7	15.1	15.0	20.3	23.3	24.8
28-day density	1.87	1.79	1.78	1.94	1.90	1.98
Mass loss after 10 week flowing acid attack (%)	4.05	9.81	23.11	35.12		
Mass loss after 10 week stagnant acid attack (%)	1.1	2.92	5.11	7.75		
Cube strength after 10 week flowing acid attack (MPa)	19.3				22.7	17.2

The test results of the "28-day cube strength" and "mass loss after 10 week stagnant sulphuric acid attack for specimen groups 1–4" (as the first part of this research) had been reported in Ref. [5] and are repeated in Table 2 of this paper.

Table 3
Comparison test results of different groups of ferrocement

Test items	Specimen group		
	Group 1 soluble glass-polyvinyl acetate hybrid modified mortar-1	Group 5 soluble glass-polyvinyl acetate hybrid modified mortar-2	Group 6[a] unmodified mortar-2
Maximum crack width (mm)/ crack number (before exposure in flowing acid)	0.032/26.2	0.028/24.1	0.035/27.5
Cube strength (MPa) (after 10 weeks in flowing acid)	19.3	22.7	17.2
Calculated moment capacity (kN m) (after 10 weeks in load-flowing acid environment)	0.306	0.310	0.279
Tested moment capacity (kN m) (after 10 weeks in load-flowing acid environment)	0.313	0.324	0.289[b]

[a] The outermost two layers of mesh in one of the unmodified ferrocement specimens were seriously corroded. Two corroded wires were observed in each of the other two unmodified specimens.

[b] The ultimate moment capacity of the specimen with the outermost two layers of seriously corroded mesh was 0.21 kN m and not used for calculation of mean value of tested moment capacity.

two sets. The first set of three specimens was tested for ultimate moment capacity after 28 days of normal curing. The other set of three specimens was used for testing ultimate moment capacity after 10 weeks of exposure in flowing acid solution under sustained flexural load (see Section 2.4).

For groups 2–4, each group of specimens composed of three 100 mm × 100 mm × 100 mm cubes and six 40 mm × 40 mm × 100 mm prisms. The three cubes were tested for density and 28-day cube strength. The six prisms were tested for mass loss versus time in the stagnant and flowing sulphuric acid solutions, respectively.

For groups 5 and 6, each group of specimens composed of six 100 mm × 100 mm × 100 mm cubes and six ferrocement specimens. The six cubes were tested for 28-day strength and the strength after 10 week flowing sulphuric acid attack, respectively. The six ferrocement specimens were tested for the ultimate moment capacities after 28 days of normal curing and 10 weeks combined sustained flexural load and flowing acid solution (see Section 2.4), respectively.

The size of the ferrocement specimens was 350 mm long, 125 mm wide and 30 mm thick as shown in Fig. 1. No skeletal steel was used and 5 mm spacers were fastened onto the first layer of reinforcement to obtain a nominal cover of 5 mm. Eight layers of mesh were used for each specimen to provide 1.287% of reinforcement in the stress direction. The specimens were cast horizontally in groups of six.

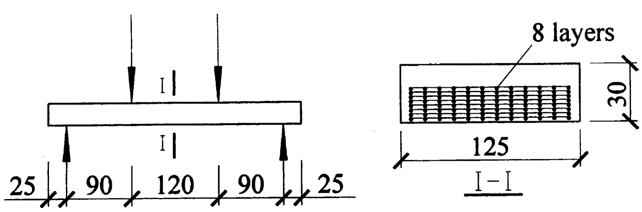


Fig. 1. Ferrocement specimen.

2.3. Curing conditions

Immediately after casting, the specimens were covered with damp hessian, protected by polythene sheeting for 24 h at a temperature of about 19 °C. The specimens were then demoulded and transferred to the curing room for further curing of 27 days at 20 ± 1 °C with relative humidity of 98%. Due to the rearrangement of the equipment in the laboratory, the specimens for flowing sulphuric acid corrosion test were stored in curing room for 30 weeks before testing.

2.4. Sustained load—flowing sulphuric acid attack environment

The test setup for creating flowing corrosive environment is shown in Fig. 2. A 1% sulphuric acid solution was put into a glass fiber tank for storing specimens at room temperature. A water pump worked 8 h every day with a flow velocity of 40 l/min. The solution in the tank was changed every week. In order to ensure that the ferrocement specimens were subjected to severe load–corrosion conditions, they were preloaded with built-in steel equipments made by the authors (Fig. 3) coated with anti-rust paint. The specimens were stressed by tightening the bolts on the top of the equipments to a state of cracking with a maximum allowable steel stress (nominal) of 207 MPa as defined by ACI [6]. The nominal steel stress was calculated by using the elastic-cracked-section method. The maximum crack width and crack number of different groups of ferrocement

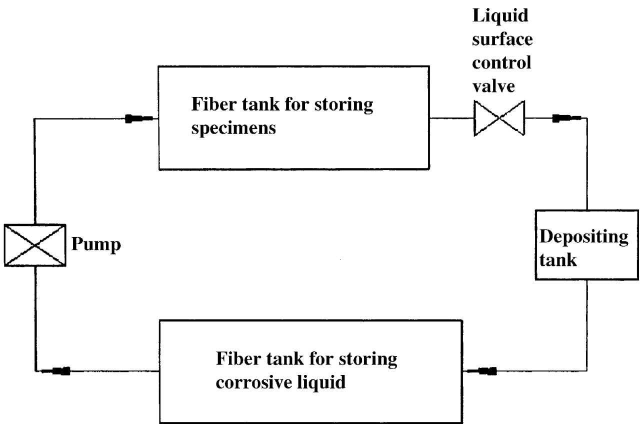


Fig. 2. Flowing corrosion system.

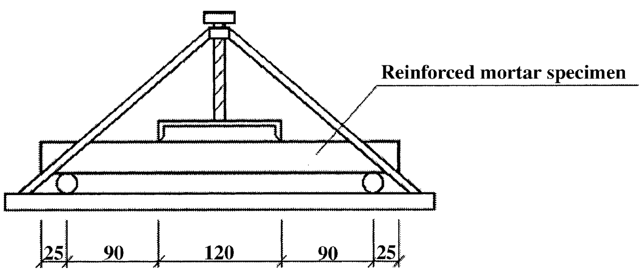


Fig. 3. Sustained flexural loading equipment.

specimens before exposure in corrosive environment are shown in Table 3. It can be seen that the maximum crack width for every specimen was less than the limitation value of 0.5 mm specified by ACI [6]. With the load being sustained they were put into the storage tank and subjected to flowing acid solution.

2.5. Ultimate capacity test method

The testing rig consisted of a four point arrangement with a span of 300 mm and a pure bending moment region of 120 mm. A force was applied by a 30 kN hydraulic test machine. After the specimens were broken, the cover to outermost reinforcement, the specimen thickness and crack spacing were measured. The reinforcement exposed at the fracture surface was examined for evidence of rust.

3. Results and discussion

3.1. Mass and strength losses of different mortars in flowing and stagnant acid solution

For mass loss test, the samples were weighed once a week. The specimens were brushed softly under water with a nylon brush to remove loose surface debris before weighing. Fig. 4 shows the test results of mass loss versus time for different kinds of mortars. As shown in

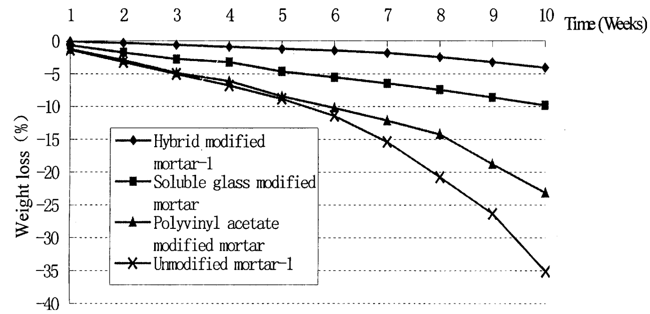


Fig. 4. Curves of weight loss versus time in flowing sulphuric acid solution.

Fig. 4 and Table 2, the 10-week weight losses in flowing 1% acid were 4.05%, 9.81%, 23.11% and 35.12% for the hybrid modified mortar, soluble glass-modified mortar, polyvinyl acetate-modified mortar and unmodified mortar, respectively. However, the 10-week mass losses of the four mortars in 1% stagnant sulphuric acid solution were only 1.10%, 2.92%, 5.11% and 7.75%, respectively. These evidences indicated that degradation of mortar in flowing acid was significantly severer than in stagnant acid solution.

The cube strengths after 10 weeks of exposure in flowing acid for the specimens of groups 1, 5 and 6 were 19.3, 22.7 and 17.2 MPa, respectively, as shown in Table 3. These values were 6.76%, 2.60% and 30.6% lower than those of the corresponding three kinds of cube specimens after 28 day normal curing, respectively.

Both weight loss and strength loss tests indicated that hybrid modification improved the flowing acid resistance of mortar significantly. The significantly higher durability of the modified mortar mainly stemmed from the noticeable improvement of its microstructure and ingredients used as initial materials [5].

3.2. Corrosion of ferrocement

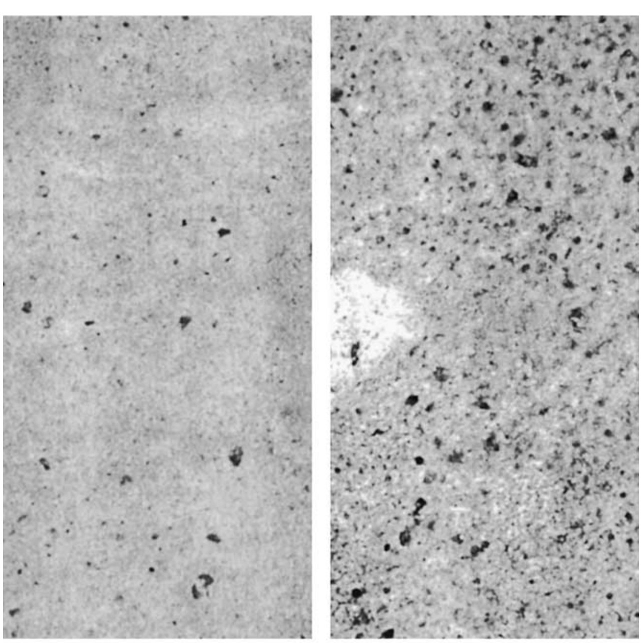
No steel corrosion on the tension face of the hybrid modified ferrocement specimens was found after storing 10 weeks in the sustained load-flowing sulphuric acid environment. The outermost two layers of mesh in one of the unmodified ferrocement specimens were seriously corroded; two out of twelve wires of the third layer of mesh were corroded, and four wires of this layer were slightly corroded. The percentage of wires with red rust of this specimen was 31.2%, leading to an increase of steel stress. Consequently, the maximum crack width increased from 0.35 mm (before exposure) to 0.45 mm (after exposure). Two corroded wires of the outermost layer of mesh were observed at the edges of each of the other two unmodified specimens, showing a percentage of wires with red rust of 2.1%. These evidences showed that the much more durable modified mortar [5] provided better protection to wire mesh.

Rippled corrosion of mortar on the tension side of the three kinds of specimens occurred. However, the corrosion of the unmodified specimens was more severe than that of the hybrid modified specimens (Fig. 5). The reason for the unmodified specimens to be corroded more severely may be two folds. Firstly, the flowing acid resistance of the unmodified mortar was lower than that of the modified mortar. Secondly, the reduction of cross section of steel due to corrosion led to an increase of stress in the tension side of the unmodified specimens. A thin white layer of lime and sulphuric compound was deposited on the compressive side of the hybrid modified specimens; the white layer could be scraped by hand. The retarding of progress of flowing sulphuric attack on compressive side of specimens occurred because some pores, capillaries and microcracks were compressed and partially closed. Because the flowing acid resistance of the unmodified mortar was lower than that of the modified mortar a slight rippled corrosion was observed on the compressive side of the unmodified specimens.

3.3. Moment capacity of ferrocement after exposure test

According to the cube strengths after flowing corrosion presented in Table 3 and a proposed calculated method [7], the residual moment capacities for different ferrocement specimens after 10 weeks of exposure in load-flowing acid solution environment were calculated and shown in Table 3. It can be seen that the calculations show a good agreement with the test results. It can also be seen that even though the cube strength of the unmodified mortar-2 was 32% lower than that of the hybrid modified mortar-2 the calculated moment capacity of the unmodified ferrocement was only 11% lower than that of the hybrid modified ferrocement. This is because the relatively greater difference in cube strength leads only to a small difference in lever arm at the cracked section.

It should be noted that steel corrosion has a significant influence on moment capacity. For instance, the ultimate moment capacity of the specimen with two seriously corroded layers of mesh was about 30% lower than that of the specimens with only two corroded wires as mentioned in Table 3.



Hybrid modified ferrocement | Unmodified ferrocement

Fig. 5. Corrosion on tension side of ferrocement specimens.

4. Conclusions

Within the scope of this study, the following conclusions may be drawn:

1. Corrosion damage in flowing sulphuric acid environment is much more severe than in stagnant acid. The mass losses of various mortars in the flowing 1% sulphuric acid solution was about 3.36–4.53 times as high as those in the stagnant one.
2. Hybrid modified mortar had a significantly higher resistance to flowing sulphuric acid environment compared with unmodified mortar. The decreases of cube strengths for the hybrid modified mortar and unmodified mortar were 2.6% and 30.6% respectively after 10 week flowing 1% sulphuric acid attack.
3. No steel corrosion was observed on the tension face of hybrid modified ferrocement after 10 weeks of exposure in flowing 1% sulphuric acid under sustained flexural load. However, steel corrosion was found on tension face of unmodified ferrocement, leading to a noticeable decrease of ultimate moment capacity.

Acknowledgements

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