Rapid repairing mortar material for corroded reinforced concrete structure

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ABSTRACT: After years of service, many concrete buildings are facing the problem of deterioration. In aging buildings, steel corrosion is one of the major problems causing spalling of concrete cover and loss of strength in the structural members. Traditionally, if the loss in steel area is small, the spalling will be simply repaired by patching. If the loss in steel area is high, the structural members will be repaired by attaching external steel plate with anchors or lapping a new reinforcement to recover the load carrying capacity. However, these methods are labour-intensive, costly and time-consuming. In this paper, an effective and innovative repair method is developed. A repair mortar of sufficient tensile strength will be developed by adding steel fibers into the mortar. Different types of mortar and steel fiber are investigated in terms of mix composition and fiber geometry. Tests are first performed to measure the direct tensile behavior of the fiber reinforced mortar. After identifying mixes with sufficient tensile capacity to compensate for the loss in steel area encountered under practical conditions, bond tests are carried out to study the required bond length of repair mortar patch along the steel reinforcement. The results of this study demonstrate the promise of a new cost-effective approach for the repair of deteriorated reinforced concrete buildings.

1. INTRODUCTION

Many buildings in the world are reinforced concrete structures. The design working life of each building may vary in different countries. However, many buildings over 40-50 years in age are facing the problem of deterioration. The older a building is getting, the higher is the likelihood for it to exhibit problems such as steel corrosion. Cabrera et al. (1997) mentioned that majority of building repair works are caused by reinforcement corrosion and according to Bentur et al. (1997), rusting of the steel bar and expansion of the rust produce internal stresses causing cracking and spalling of the concrete cover. Thus, in order to prevent further deterioration, repair of the structures is needed. In Hong Kong, steel corrosion has been found to be particularly severe for concrete slabs. In current practice, if the loss in steel area is low, the structural load carrying capacity will be considered unaffected and patching of the spalled area with plain mortar is sufficient. If there is significant loss of steel area, the reduced load carrying capacity has to be recovered by lapping a new rebar or attaching an external steel plate. In the lapping process, it is necessary to remove a significant amount of sound concrete to provide sufficient lap length with the un-corroded steel bar Campbell-Allen et al. (1991). As slab repair involves overhead job, attaching of steel plate is difficult to perform. Moreover, fireproofing of the steel plate is required. Due to these disadvantages, the existing methods are labour-intensive, costly and time-consuming.

In this paper, the use of fiber reinforced mortar as a rapid repair material was investigated. As reported by Bentur (2000), fibers have been used increasingly for the reinforcement of cementitious materials to improve its tensile strength and toughness and reduce its sensitivity to cracks. Since fire resistance is one of the concerns in this application, only steel fibers will be used in this study. Bentur et al. (2007) mentioned that reinforcing efficiency will be lower if the diameter of fiber is in the order of 0.1mm or bigger because interfacial stress with the cementitious material may not be sufficient. The diameter of most steel fibers is beyond 0.1mm. To enhance the fiber pull-out mechanism, deformed fiber should be used instead of straight fiber. Hooked end steel fiber pullout tests conducted by Van Gysel (1999), Zhan et al. (2014) and Abdallah et al. (2016) have all shown that the hook is effective in increasing the pullout load. In this work, fibers with different geometries were studied. Apart from the fiber shape, length and aspect ratio were also investigated. A suitable combination of mortar and fiber, including type of mortar, fiber geometry, fiber length and aspect ratio, was identified. With this combination of fiber and mortar, bond test with steel was conducted to find the minimum bond length for design purpose.

2. REPAIR MATERIALS

This rapid repairing mortar material is prepared with different commercial mortars and various types of stainless steel fibers. The mortars are all certified and have been used in many practical applications. All of them satisfy specific performance requirements for repair mortar in Hong Kong on compression strength, tensile strength, modulus of elasticity, bond strength, shrinkage cracking (measured by Coutinho ring)and Figg air permeability. The typical characteristics of mortar and properties of various fibers are summarized in Table 1 and Table 2 respectively.

Table 1. Typical characteristics of mortar*

	Compressive strength at 28 days (MPa)	Minimum tensile strength at 7 days (MPa)	E (GPa)	Minimum bond strength at 7 days (MPa)	Cracking in Coutinho ring test at 7 days	Minimum figg air permeability (sec)
Requirement	20-40	1.5	9-15	1.5	No crack	150
Mortar A	Complies	Complies	Complies	Complies	Complies	Complies
Mortar B	30	2.7	10	2.2	No crack	216

* The Characteristics of each mortar are provided by corresponding manufacturers.

Table 2. Properties of various fibers

Material	Length (mm)	Diameter (mm)	Aspect ratio	Tensile strength (MPa)
30mm hooked end fiber	30	0.4	45	1200
35mm hooked end fiber	35	0.75	47	1200
60mm hooked end fiber	60	0.75	80	1200
60mm double hooked end fiber	60	0.9	65	2300
Micro steel fiber	13	0.16	81	2500
Crimped fiber	30	0.75	40	1200
Wave-plate fiber	30	0.93[a]	32	1200
Stainless 25mm hooked end fiber	25	0.4	62	1200
Stainless 50mm hooked end fiber	50	0.75	67	1200
Stainless 60mm hooked end fiber	60	0.65	92	1200

[a] Its diameter is equivalent diameter calculated from the cross-sectional area of the wave-plate fiber.

3. DIRECT TENSILE TEST OF FIBER REINFORCED MORTAR

3.1 Specimen preparation and test set up

Several mixes were tested with different fibers shown in Table 2. Tension specimens were casted in steel mold which is 50mm wide, 350mm long and 15mm thick. 6 specimens were prepared in each mix, 3 specimens were tested for 7 days strength and the other specimens were tested for 28 days strength.

Fiber reinforced mortar was prepared by mixing mortar and water first. Then fibers were added into the wet mortar for further mixing. During the casting process, the mortar was squeezed into strips and then cast into the mold in a way that fibers were aligned along the longitudinal direction so tensile strength can be maximized. Hand squeezing of the fiber reinforced mortar also serves to remove entrapped air. It is then unnecessary to compact the specimens through vibration, which may cause the sinking of fiber and affect the fiber distribution. The specimens were demolded after 24 hours and stored in the laboratory environment instead of the curing room, to simulate the situation in real applications where the repair mortar will not be wet cured. Before testing, the specimens were strengthened by glass fiber meshes and metal plates applied at the end on both sides (Figure 1). This is to ensure the occurrence of failure away from the gripped ends. Two LVDTs (linear variable differential transformer) were attached at the edges of the specimen for measuring displacement. Then the specimen was installed in the testing machine for direct tensile test under displacement control at the loading rate of 0.05mm/min.

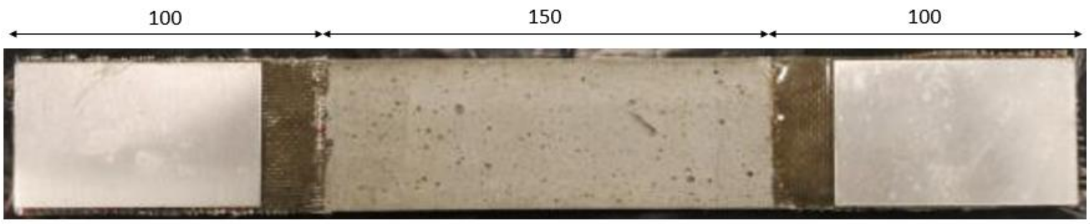

Figure 1. Configuration of strengthened specimen.

3.2 Test results and discussion

The results of direct tensile test are summarized in Table 3. The typical stress strain curves of short and long fibers are shown in Figure 2 where the short fiber and long fiber are defined as fiber with length below 35mm or above 50mm respectively. Table 3 shows that two different mortars (namely mortar A and mortar B) were used in the test, together with various fibers at different volumes. Some batches can achieve a tensile strength of above 3.5MPa which is the preliminary design tensile strength of the fiber reinforced mortar. It is obvious from the results that fiber reinforced mortar with 60mm long fibers can provide better results. By comparing batch 3 and 4 or batch 13 and 14 at 28 days strength, the tensile strength of batch 3 and 13 are slightly higher than that of batch 4 and 14 respectively. It seems that fibers with the double hooks at their ends do not perform better than single hooked fibers. This is likely due to the low strength of the repair mortar matrix. As the hook will induce high stress in its vicinity, a larger hook may cause microcracking within a larger volume of matrix. Interaction of the microcracking zones will result in matrix failure which renders the anchoring effect of the hook ineffective. As a weaker matrix is easier to fail, the use of the larger double-hooks is not advantageous.

Comparing mortars with short fiber and long fiber in Figure 2, the mortar with long fiber performs better in terms of maximum tensile strength and post-peak behavior. In the pre-peak behavior, multiple cracking can also be observed in the specimen. This observation is in agreement with that in Gopalaratnam et al. (1987).

4. DIRECT TENSILE TEST OF MILD STEEL BAR CASTED WITH FIBER REINFORCED MORTAR

4.1 Specimen preparation and test set up

The fiber reinforced mortar used for this test was from batch 18 of Table 3. The reason for selecting this batch for further testing is that mortar B and 60mm long fibers generally gives better results and stainless steel will be used in practical application due to its corrosion resistance. The geometry and the length of specimens are shown in Figure 3a and Figure 3b respectively. The cross-sectional shape and area of the repair mortar is typical for an old building slab with 10mm mild steel rebars. At the middle of the specimen, the steel bar is grinded to 60% of its original area to simulate a situation with severe corrosion. At the two ends of the specimen, the repair mortar was extended by 100mm, 150mm or 200mm beyond the part with reduced steel area, to study the effect of bond length on the loading that can be transmitted to the repair mortar. More specifically, the required bond length that is sufficient to recover the original load carrying capacity prior to bond failure between fiber reinforced mortar and steel bar needs to be determined. After 7 days of air curing in the laboratory, the specimens were tested under displacement control at the loading rate of 0.1mm/min.

The objective of the work is to develop a repair mortar that can compensate for 40% loss of steel area for a 250MPa rebar, which is commonly used in old buildings in Hong Kong. However, in the experiment, a rebar with 320MPa was employed to ensure the occurrence of failure in the region with reduced steel area. The load carried by the rebar with reduced section was subtracted from the measured load capacity (P) to obtain the contribution by the repair mortar (F).

$$P - \sigma_{320} \times A_s^{'} = F \quad (1)$$

The calculated value was then added to the yield force of a 250 MPa mild steel rebar with 40% area reduction,

$$F + \sigma_{250} \times A_s^{'} = Q \quad (2)$$

and compared to the load capacity of the full rebar (Q) to find the percentage of recovery by adding the repair mortar.

$$\text{Percentage of recovery} = \frac{Q}{\sigma_{250} \times A_s} \times 100\% \quad (3)$$

Table 3. Results of direct tensile test

Batch	Mortar	w/m[a] ratio	Fiber	Fiber volume	Average Tensile Strength (MPa)			
					7days	COV	28days	COV
1	A	0.2	30mm hooked end	1.6%	2.29	0.30	2.36	0.29
2	A	0.2	35mm hooked end	2%	1.88	0.24	2.17	0.18
3	A	0.2	60mm hooked end	1.6%	2.8	0.33	3.76	0.29
4	A	0.2	60mm double-hooked end	1.6%	2.59	0.20	3.52	0.15
5	A	0.2	Micro steel	2.4%	2.62	0.09	2.93	0.26
6	A	0.2	Crimped	2.4%	2.39	0.19	2.81	0.27
7	A	0.2	Wave-plate	2.4%	1.84	0.15	2.43	0.27
8	A	0.2	Stainless 25mm hooked end	2%	2.25	0.08	4.23	0.06
9	A	0.2	Stainless 50mm hooked end	2%	1.98	0.23	3.05	0.15
10	A	0.2	Stainless 60mm hooked end	2%	1.88	0.21	3.15	0.22
11	B	0.183	30mm hooked end	2.4	3.01	0.20	3.24	0.17
12	B	0.183	35mm hooked end	2%	1.93	0.21	3.24	0.06
13	B	0.183	60mm hooked end	1.6%	2.49	0.25	4.33	0.16
14	B	0.183	60mm double-hooked end	1.6%	3.13	0.02	4.12	0.14
15	B	0.183	Crimped	2.4%	2.94	0.19	2.94	0.20
16	B	0.2	Stainless 25mm hooked end	2%	2.99	0.10	3.28	0.14
17	B	0.2	Stainless 50mm hooked end	2%	2.55	0.31	2.9	0.17
18	B	0.2	Stainless 60mm hooked end	2%	3.07	0.16	3.65	0.25

[a] Water to mortar ratio.

4.2 Test results and discussion

The results are summarized in Table 4. For the specimens with 100mm bond length, interfacial bond failure between steel bar and fiber reinforced mortar was observed on all specimens. For the specimens of 150mm and 200mm bond length, the recovered load carrying capacities are 100.5% and 106.1% respectively. These results show good evidence that the fiber reinforced mortar can fully recover the original load carrying capacity of the mild steel bar. Therefore, 150mm bond length can be taken as the required bond length for practical applications. Figure 4 shows a typical load-displacement curve of the test. Although the load is observed to drop after the peak value, it is still above the design yield force of the uncorroded rebar, indicating that full load carrying capacity can still be maintained under tension softening of the steel fiber reinforced mortar. After that, the load starts to increase again due to the strain hardening property of mild steel bar. According to the results, full recovery can be accomplished in the entire loading process.

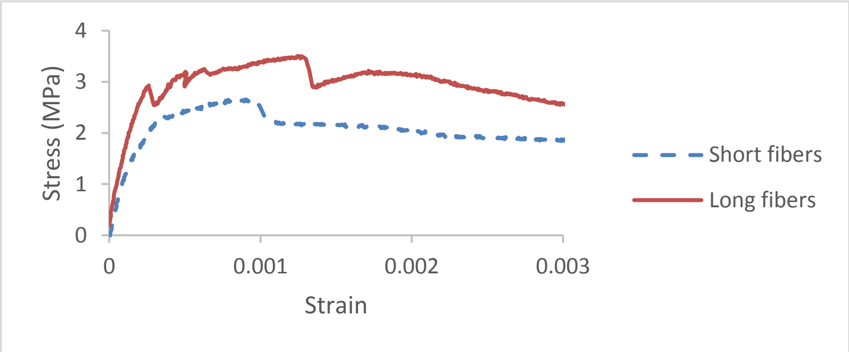

Figure 2. Typical test results for direct tensile test.

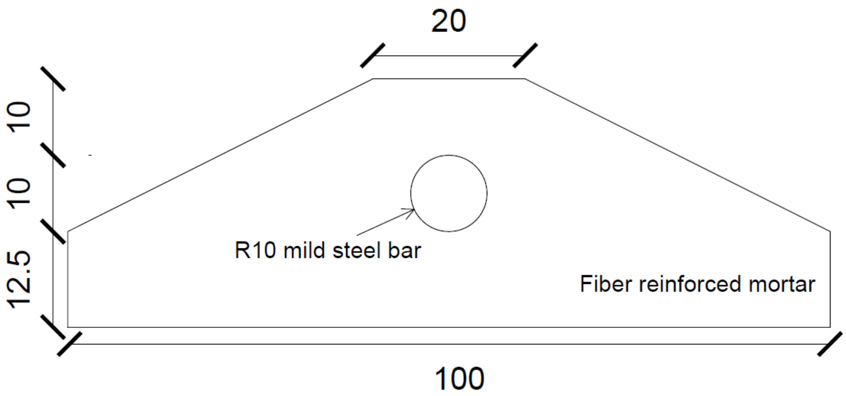

Figure 3a. Geometry of specimen, cross section of repair patch.

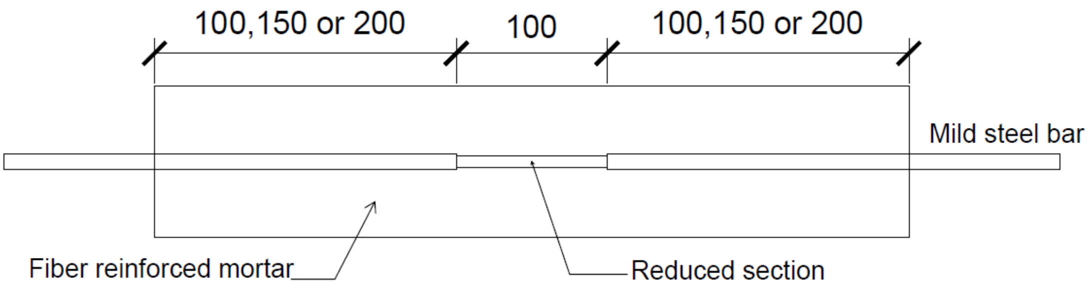

Figure 3b. Different length of specimen.

Table 4. Results of direct tensile test of mild steel bar casted with mortar B and 60mm hooked end stainless steel fibers

Bond length (mm)	Specimens	Maximum tested load (kN)	COV	Bond failure	Load contributed by repair mortar (kN)	Calculated load capacity for member with 250MPa strength steel bar (kN)	Percentage of recovery
100	1	18.1		Yes			
	2	17.5		Yes			
	Average	17.8	0.02		4.2	14.8	14.8/17.7= 83.6%
150	1	24.8		No			
	2	18.6		No			
	3	25.5		Yes			
	Average	23.0	0.17		7.9	19.7	19.7/19.6= 100.5%
200	1	23.7		No			
	2	24.4		No			
	3	24.1		Yes			
	Average	24.1	0.01		9.0	20.8	20.8/19.6= 106.1%

[a] The yield strength obtained from experiment is 320MPa.

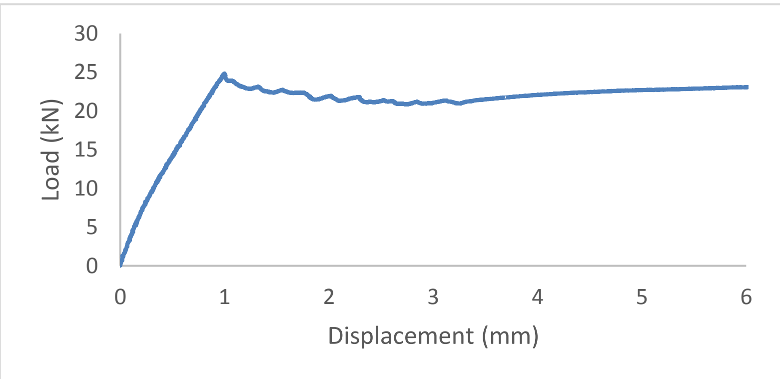

Figure 4. Typical load-displacement curve for 150mm bond length.

5. Conclusion

In this paper, a new repair method for corroded reinforced concrete structure by using steel fiber reinforced mortar is proposed. The direct tensile test of fiber reinforced mortar was conducted to show that sufficient tensile strength can be provided by adding certain type and amout of steel fibers into the mortar. After a suitable combination of mortar and fiber has been obtained, mild steel bars with grinded area at the middle of the bar were cast with fiber reinforced mortar for further load test. With bond length of 150mm on each side of the reduced section, the loading can be fully recovered with a reasonable safety margin. The results show that this method is feasible and applicable for the repair of reinforced concrete members.

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