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A comparison of bending strength between adhesive and steel reinforced concrete with steel only reinforced concrete

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Abstract

Cracking of brittle cementitious composites subjected to excessive loading causes a potential reduction in material performance. Steel bars or metal fibers typically act as tensile reinforcing in concrete composites to increase the material's structural capacity in bending and to delay or prevent matrix cracking.

The goal of this research is to determine whether the performance in bending strength and material integrity of a typically reinforced cementitious composite may be improved through the release of "healing" chemicals, such as adhesives, from hollow fibers into cracks induced by loading in addition to the metal reinforcing. Adhesive-filled repair fibers are intended to break immediately upon cracking in the concrete thereby activating the healing process with the release of a sealing or adhering substance. This self-repair occurs whenever and wherever cracks are generated.

Keywords: Self-repair; Concrete; Fiber reinforcement; Bending strength; Microcracking

1. Introduction: The problem

Concrete is a brittle and permeable material prone to small cracks, which may continue to grow under repeated cycles of loading. Exposing the material over time to environmental forces accelerates its deterioration and threatens its integrity as a structural material. Although concrete is typically reinforced with steel bars or fibers to carry the tensile forces in the matrix, concrete is still subject to cracking. To lengthen the life span of structures, delay repairs, and lower material costs, an inherent system is needed in which cracks, even microcracks, are repaired before their size increases, subjecting the concrete to further environmental deterioration and the subsequent loss of composite action at the rebar/concrete interface, or the steel fiber mat/concrete interface. In these experiments, cracking is repaired by a released chemical, which deters advanced cracking and potentially increases the tensile strength of the matrix. These experiments seek to determine if the internally released adhesive and brittle fiber system will improve the performance of a composite which is also reinforced with the usual steel reinforcing bar, steel fiber mats (Ribtec), or metal fiber reinforcing.

2. Finding a solution: Introductory experimentation and methodology

First stage experiments were performed on two sets of $1 \times 1 \times 6$ in. concrete prism specimens, with a water/cement ratio of 0.5. Sample set #1 contained 24 steel-reinforcing fibers (0.5 mm diameter) and 16 adhesive-filled glass fibers (1.0 mm inside diameter and 1.5 mm outside diameter) running the length of the prisms. Sample set #2, the control set, contained, 24 metal-reinforcing fibers and 16 of the same repair fibers, but the fibers were empty. Each specimen was loaded in three-point bending over a 5 in. span until fracture at which point the repair fibers broke releasing the adhesive agent into the concrete matrix. Load displacements were noted. The adhesive was given 7 days to set. Each specimen then was loaded again in three-point bending. Fig. 1 illustrates the load displacement for both loading events in graph form [1]. Fig. 2 gives the numerical results of these tests [1].

A comparison between the first and second loading for both sets is informative. For specimens in set #1 (adhesive-filled), the slope of the load–displacement graphs for the

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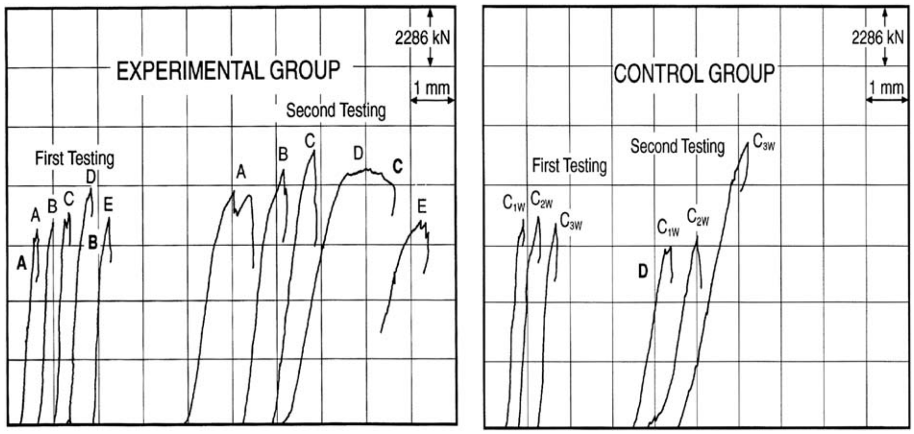

Fig. 1. Load displacement for each sample for first and second three-point bend test [1].

first bending event and the second bending event are parallel, indicating an equal rate of displacement for applied loads. This, however, is not true for specimens in set #2—the control set containing the empty repair fibers. Here, the shallower slope of the second bending event indicates a greater displacement for applied loads than in the first.

This behavior is attributed to the decrease in strength from cracking in the first bending test. The rounded peaks of the diagrams for sample set #1 reveal a more elastic failure than is indicated by the sharp points of the diagrams for the controls in sample set #2. Additionally, samples in set #1 carried a greater load in the second bending test than in the first. This was not the case for the controls. Presumably, cracks repaired in the adhesive-repaired test samples are stronger than the original matrix. The adhesive acts to reinforce and strengthen the concrete.

3. Bending test

To measure strength in bending, samples were subjected to three-point bend tests on a universal testing machine.

4. Strength comparison of four reinforcing systems

To measure the strength performance of concrete with the internal adhesive release system against plain metal fibers, steel reinforcing bars, steel fiber mat, the second series of tests compared changes in the flexural strength of these systems as they were loaded until fracture twice. Four reinforcing systems were tested in concrete samples of both slurry and standard mix compositions. Composite concrete matrices contained either piano wire, steel reinforcement bar, steel fiber mat (Ribtec), or the adhesive delivery system coupled with piano wire.

Sample	1st test (kN)	2nd test (kN)	Increase (kN)	% Increase
A	0.7484	0.8845	0.1361	18.2
B	0.7711	0.9526	0.1814	23.5
C	0.8051	1.0297	0.2245	27.9
D	0.8959	0.9888	0.0930	10.4
E	0.7893	0.7666	− 0.0227	− 2.9
Control 1	0.7802	0.6713	− 0.1089	− 14.0
Control 2	0.7938	0.6985	− 0.0953	− 12.0
Control 3	0.7666	1.0660 error	0.2994	39.1

Fig. 2. Capacity of samples to carry a load at first bend and second bend.

5. Test for comparing slurry mix concrete composites with equal weights of reinforcing

5.1. Methodology

Studies were performed on four $2 \times 4 \times 20$ in. concrete beam samples, each containing one of the aforementioned reinforcement systems. The content of the concrete slurry mix, which was equivalent for all samples, was determined by specifications provided by Ribtec [2]. The mix, c/w/s/a: 0.44:0.18:0.20:0.19 [2], ensures adequate infiltration for the proper bonding between the mat and the concrete. The weight of the reinforcement, 0.29 kg, was also kept consistent throughout all samples. Consequently, the strength of each sample varied with each material and its response to the loading. The purpose was to compare the composite's strength before and after the second load test. The compositions were as follows:

Sample #1: The steel wire system was selected as a control for the experiments. Thirty-five steel wires (1.5 mm diameter) were distributed throughout the tensile and compressive zones of the beam, which was tested in three-point bending.

Sample #2: Two #4 (13 mm = 1/2 in. diameter) steel reinforcing bars were placed in the tensile zone representing the industry standard for increasing concrete flexural capacity.

Sample #3: The third sample contained a steel fiber mat system (Ribtec), selected for its potential to reduce shrink cracking and ability to evenly distribute tensile stresses during loading. The Ribtec mat consists of carbon steel fibers spun from molten metal and laid to form an interlaced mat of uniform density. The Ribtec mat is placed within a beam mold into which concrete slurry is added and vibrated. The properties and data for this material are documented in an article titled "Slurry Infiltrated Mat Concrete" [1] and provided by Ribtec.

Sample #4: The fourth test sample contained steel reinforcing wires with an adhesive delivery system, for studying the potential to "repair" and improve the strength of concrete matrices. Eight glass pipette fibers (1.0 mm inside diameter and 1.5 mm outside diameter) and 20 steel reinforcing piano wires (1.5 mm diameter) were contained in the tensile zone of this beam, while an additional 14 steel piano wires reinforced the compression zone, as seen in Fig. 3. Adhesive was injected into the glass pipettes after fracture under the first loading. After the adhesive had set for 7 days, the sample was retested to determine its strength.

Test #1 involved a three-point bending test on virgin members along a 12-in. span. Samples were loaded until failure. After Test #1, adhesive was added to sample #4 and allowed to set for 7 days at which time all samples were retested. In Test #2, the samples were exposed to a second three-point bending test along the same 12-in. span. Test results were recorded in millimeters of deflection versus kilo-Newtons of force and compiled in the chart below (Fig. 4).

The data point of 2.5 deflection was chosen carefully to represent a point at which cracks produced were not thought to be repairable by the release of chemicals. Results show that for 2.5 mm of deflection, sample #4 (adhesive and wire) was strongest, followed by sample #1 (wire), sample #2 (rebar), and lastly, sample #3 (Ribtec), which failed completely. All samples experienced a decrease in strength compared to test #1 except for sample #4 (adhesive and wire), which demonstrated a 3% improvement. The strength in sample #1 (wire) decreased by 27%, in sample #2 (rebar) by 36%, and in sample #3 (Ribtec) by 100%.

Sample #	Description	Test #1 (kN)	Test #2 (kN)	Change (%)
	Sample deflection	2.5 mm	2.5 mm	
1	Wire only	22.0	16.0	− 27
2	Reinforced bar #4	12.5	8.0	− 36
3	Steel fiber mat	11.0	0.0	− 100
4	Wire and adhesive	19.0	19.5	+ 3

Fig. 4. First round testing results for bending: four reinforcing systems under bending in slurry mix concrete composite matrices.

5.2. Conclusions

Sample #4 (adhesive and wire) out-performed samples #1, #2, and #3 in its ability to sustain greater loading. Hypothetically, its load-carrying capacity would have increased even more significantly in comparison to the control, sample #1 (wire), had it contained an equivalent weight of metal wires. Moreover, if the weight of the glass pipettes had not been included in the experimental standard of 0.29 kg and the weight of the wires in sample #4 was increased to match that in sample #1, a potential increase in strength for sample #4 would be apparent. The conclusion is that here is a beneficial use of an adhesive-repair system as a complement to steel-reinforced concrete.

6. Test for comparing standard mix concrete composites with equal weights of reinforcing

6.1. Methodology

Basically, the methodology for this series of tests was kept consistent with the previous series of testing, the primary difference being in the composition of the concrete

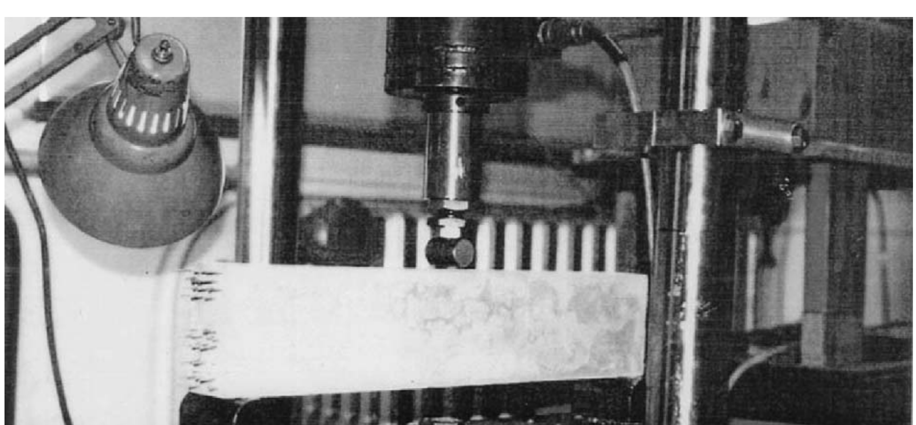

Fig. 3. This is a photo of the concrete test beam, which contained wire and the adhesive release system, sample #4, being subjected to a three-point bending test.

mix, which had been a slurry, and the span, which had been 12 in. Instead, the span was increased to 18 in. and the mix composition was changed to a 0.6 water/cement ratio (c/w/s/a: 1.0:0.6:2.2:0) as an attempt to increase the quality of the cement in the samples. Additionally, a fifth sample was added for study. As before, sample #4 consisted of an adhesive and wire system in which the adhesive was already contained within the specimen. Similarly, sample #5 was of the same composition except that the adhesive was added after the loading, rather than before. The reinforcing systems of the samples were kept at the same weight, 0.29 kg. These specimens are shown in Fig. 5.

6.2. Testing

After the samples had set for 2 days, and then were cured for 28 days, they were removed from their molds, and subjected to a three-point bending test over an 18-in span, as seen in Fig. 3. Adhesive was injected into sample #5 promptly after the first loading. After 10 days, in which time the adhesives in samples were again subjected to a three-point bending test.

6.3. Results

Again, the results are compiled in a table (Fig. 6) relating the millimeter deflection of 2.5 mm to the kN of force.

6.4. Analysis of results

In Test #2, at 2.5 mm of deflection sample #5 (wire and adhesive added after fracture) was the best performer followed by Sample #4 (wire and adhesive before fracture) Sample #2 (rebar) failed completely as did the control, sample #1, which accepted minimal load at greater deflections.

Sample #	Description	Test #1 (kN)	Test #2 (kN)	Change (%)
	Sample Deflection	2.5 mm	2.5 mm	
1	Wire only	10.5	0.0	− 100
2	Reinforced bar #2	8.5	0.0	− 100
3a	Steel fiber mat	6.0	0.22	− 96
3b	Steel fiber mat	5.0	0.1	− 98
4	Wire and adhesive put in before fracture	9.0	1.4	− 84
5	Wire and adhesive put in after fracture	0.5	4.0	+ 700

Fig. 6. Second round testing results: four reinforcing systems under bending in standard mix concrete composite matrices.

A comparison between Tests #1 and #2 at 2.5 mm of deflection shows that each sample experienced decreases in strength following the first loading except sample #5 (wire and adhesive after fracture) which gained 700%. The load capacity for sample #4 (wire and adhesive before fracture) decreased by 84%, followed sample #3a (Ribtec), which decreased by 96%, and then sample #3b, which decreased by 98%. Sample #2 (rebar) and the control, sample #1 (wire), experienced a 100% decrease in load capacity between the first and second tests.

7. Conclusions

Sample #5 (wire and adhesive after fracture) out-performed the other samples. This is attributed to the injection of adhesive into a given crack until cracks were completely filled. The sample relied upon a greater quantity of adhesive not only to “repair” cracks, but also to improve its strength by infiltrating the pores. Sample #4 (wire and adhesive before fracture) that contained a limited quantity of adhesive, out-performed the other samples, due to its ability to “repair.” This is consistent with the first set of samples.

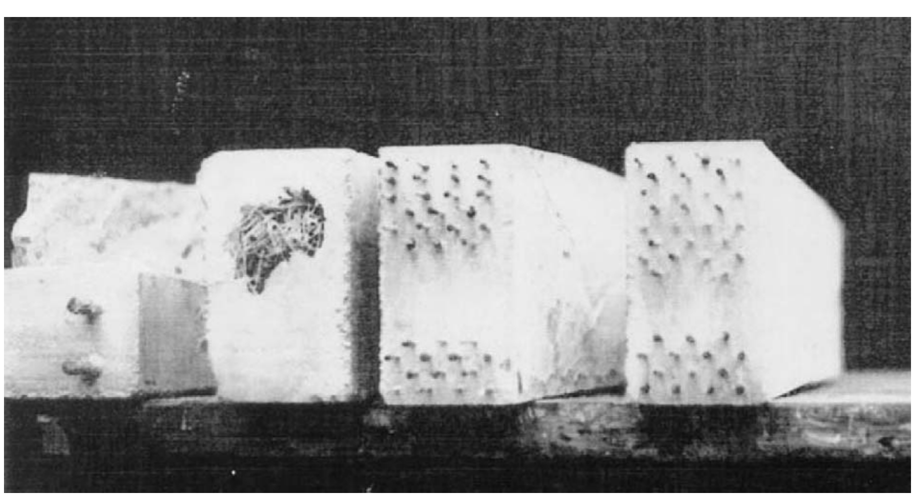

Fig. 5. Concrete beam samples containing (left to right) steel-reinforcing bars, Ribtec (metal fiber mat), and metal wires.

Samples #3a and #3b (Ribtec) performed better than sample #2 (rebar), but not as well as samples #4 and #5 (wire and adhesive). Samples #3a and #3b withstood greater deflections than samples #1 (wire) and #2 (rebar) because of the Ribtec mat's ability to distribute a load over an expansive area. Sample #2 (rebar only) performed significantly lower than the other samples. These results are consistent with those in the slurry mix testing (6-in. prisms), the first tests. The conclusion of the research is that the performance in bending strength and material integrity of a typically metal reinforced cementitious composite was improved through the release of "healing" chemicals, such as adhesives, from hollow fibers into cracks induced by loading.

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