### Mechanical Properties of Aramid Fiber-Reinforced Composites and Its Performance on Repairing Concrete Beams Damaged by Corrosion

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Original Article

Mechanical Properties of Aramid Fiber-Reinforced Composites and Its Performance on Repairing Concrete Beams Damaged by Corrosion

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Abstract

This study presents an experimental investigation of the mechanical responses of concrete members with partially aramid fiber-reinforced concrete (AFRC). The effect of fiber geometry on mechanical properties of AFRC was investigated to provide the reasonable dimension of the aramid fibers for reinforcing the concrete beams. Additionally, the experiment on the flexural behavior of corroded reinforced concrete (RC) beams repaired by aramid fiber-reinforced mortar or high performance mortar has been carried out. The test results indicate that forty millimeters is the best fiber length for maximizing the tensile strength of AFRC. Furthermore, the twisted fibers can resist...
higher the load capacity in post-peak regions than that by the single plain fibers. In the next part of the paper, both non-repaired and repaired RC beams were tested under the four-point bending. The experimental results demonstrate that the load capacity, ductility of a corroded RC beam repaired using aramid fiber-reinforced mortar was almost restored to the same capacity as that of a non-corroded RC member. The width of cracks in the corroded beam repaired with aramid fibers decreased significantly.

Keywords: Aramid fiber, fiber geometry, corrosion, repairing, flexural capacity.

1. Introduction

Corrosion damage to reinforced concrete (RC) structures is a serious problem and has recently received world-wide attention. Most of previous researches have reported that the steel reinforcement corrosion in the RC members reduces the flexural strength and increases the deflection of RC members (Maaddawy et al., 2005; Chung et al., 2008). Therefore, to avoid the corrosion of the steel reinforcement in a RC structure, the addition of discontinuous fibers into concrete was proposed by Altun et al. (2007), Mansour et al. (2011) and Yoo et al. (2015). This also resulted in the improvement of stiffness (Iqbal et al., 2016) and flexural/shear capacity (Kim et al., 2016; Jongvivatsakul et al., 2011) of the members.

Aramid fiber is a type of synthetic fiber that has high tensile strength, modulus of elasticity, heat resistance, and chemical resistance. There are a number of practical applications for aramid fibers in the actual structures. However, as reported in the past works (Linh et al., 2017; Linh et al., 2018), the members with the aramid fiber-reinforced concrete exhibited a less ductility in the comparison with those reinforced by steel.
Therefore, the repair of the concrete beams by replacing partially fiber-reinforced concrete is considered to enhance the ductility, strength and durability of the existing structures in the comparison to the members with single fiber-reinforced concrete.

Currently, it is seemly only the study by Soroushian et al. (1990) that investigated the effects of the volume fraction and the length of fibers on the strength and toughness of aramid fiber-reinforced cement composites. Their study showed that using the aramid fibers for reinforcing the cement composites, the service strength and ductility is drastically improved. The work, however, tested only the fiber lengths ranging from 3 to 12.7 mm, and the macro fiber length (more than 30 mm) has not been yet studied. Thus, it is difficult to propose the optimum fiber length and fiber configuration for the practical use of aramid macro-fiber. Furthermore, although the aramid fiber is non-corrodible material, the application and the study of the aramid fibers as repair material for corroded RC beams has not been concerned much.

In this paper, the elementary tests are carried out to investigate the effects of fiber length and fiber shape on the mechanical properties of aramid fiber-reinforced concrete. Continue to previous work, the concrete specimens reinforced with the aramid fiber lengths of 30 mm, 40 mm, and 50 mm among the single and twist aramid fibers were tested. The effectiveness of aramid fibers as a repair material is examined to apply for the second part of this study. Continuously, the experimental results of the four RC beams, including non-damaged, damaged, damaged and repaired by aramid fiber-reinforced mortar, and damaged and repaired by high performance mortar, are presented here. The flexural performances by means of the load-deflection relationship and cracking mechanism of all beams are analyzed. This research gains insight into the members’
behaviors repaired by AFRC in the suffer environment, providing a reliable database for
the future study.

2. Mechanical properties of aramid fiber-reinforced concrete

The effects of the length and shape of the aramid fibers on the mechanical
properties of fiber-reinforced concrete are investigated in this Chapter. Five types of the
aramid fibers of differing shapes and lengths were adopted to specimens. The
compressive test and direct tensile test were conducted to determine the properties of
plain concrete (PC) and AFRC.

2.1 Material properties

Figure 1(a) presents pictures of fibers, including five types of aramid fibers having
different lengths (30 mm, 40 mm, and 50 mm) and shapes (S: single and T: twist
configurations). In addition, the characteristics of each fiber type are summarized in Table
1. The specific lengths ($L_f$) tested in this research study were 30 mm, 40 mm, and 50 mm.
The aspect ratio ($L_f/D_f$) was equal to 60, 80, and 100. Table 2 presents the mix proportion
designed for plain concrete (PC) and AFRC. There were five mixes of AFRC with
different fiber types (i.e. 30S, 40S, 50S, 30T, and 40T). The volume fraction of aramid
fibers was 1.0% in AFRC mixes.

2.2 Specimens and test setup

The 150x300 mm cylindrical specimens were prepared for the compressive test.
Compression tests were performed complied to ASTM C-39 (2016). Dumbbell specimens
having dimension as shown in Figure 1(b) were used for the direct tensile test. Direct
tensile tests were undertaken to measure the tensile stress-displacement and ultimate
tensile strength. Two displacement transducers were attached to each side of each
specimen in order to monitor elongation. The equipment setup used in the experimental program is shown in Figure 1(b). For each experimental case, three replicates were tested, and the average values were recorded.

2.3 Effects of shape and length of aramid fibers

2.3.1 Compressive strength

The tested results of compressive strength of the investigated specimens are shown in Figure 2. The specimen with the 30 mm fibers of single shape (30S) provided the highest compressive strength ($f'_c = 41.2$ MPa). While, the compressive strength of the concrete cylinders with 40S, 50S, 30T, and 40T was nearly similar. These observations may be due to the reasonable distribution of aramid fibers in the specimen 30S, triggering the stress transfer between concrete and aramid significantly. The experimental results also indicated that the compressive strength of AFRC was slightly lower than that of the specimen with plain concrete except the AFRC specimen 30S. This implies that although the aramid fibers are brittle material, the use of aramid fibers to reinforce concrete made the strength still assure. Furthermore, as indicated in Figure 2, the strength of the specimens with single shape of aramid fibers decreases as the length of fibers increased; however, the specimens with twist shape of fibers resulted in the similar compressive strength as the fiber length increased. On the other hand, as observed from the tests, in the comparison with the failure mode of the plain concrete, the failure mode of the AFRC specimens resulted in the considerable change from fragile failure to ductile failure since the bridging effect of the fibers occurred in the AFRC specimens. Additionally, multiple fine cracks were visually observed in the AFRC specimens, meaning the stress transfer through the bridging effect was drastically activated.
2.3.2 Direct tensile strength

Figure 3(a) presents the relationship of tensile force and displacement from direct tensile test. It is obvious from Figure 3(a) that the plain concrete (specimen PC) exhibited a brittle behavior during the test. Whereas, the specimens reinforced by aramid fibers resulted in the ductile response since the absorption energy defined by the area under the curves of the AFRC is higher than that of the PC specimen. Generally, Figure 3(a) reveals that the increase of the fiber length implies the enhancement of ductility due to the fiber bridge connection induces the stress activation in the AFRC specimens. Furthermore, the behavior of the specimens during the test is easily separated into two parts after the peak load. However, for the AFRC, the cracks occurred in the specimens, but they still resisted the loads since the aramid fibers have been drastically attended. The results indicate that the brittle tensile failure characteristic of plain concrete is changed so that it becomes tough with the addition of fibers. On the other hand, the maximum loads of the tested specimens occurred at deflection ranging from 0.1 to 0.3 mm. After cracking, the load dropped and all AFRC specimens were able to resist the load at approximately 50 to 60% of the peak load and gradually decreased up to failure as shown in Figure 3(a). This means that the specimens with aramid fibers provided the reasonable resistance to the applied load, making the specimens ductile. Then, the load decreased with the increase of displacement and the cracks can be constrained by the fibers up to very large displacement.

Additionally, there are two types of failure mode of AFRC that are the rupture of aramid fibers and the pull-out from matrix as shown in Figures 3(b) and (c), respectively. The rupture failure is displayed by branching fibers (with many fiber filaments), and the pull-out failure retains the original shape of the fiber. By observing the failure section of
all 30 mm fibers experiments, it can be seen that most of fibers were pulled-out, indicating that 30 mm fibers are not be able to provide sufficient embedded length in the concrete. By inspecting the failed section of 40 mm fibers, it can be observed that the fiber failure was both rupture and pull-out, indicating that 40 mm fibers had sufficient embedded length in concrete.

Figure 3(d) charts the direct tensile strength of the tested specimens, which is calculated from the maximum tensile force. According to the experimental results, 40 mm fibers provided the highest tensile strength; the maximum tensile strength was 2.2 and 2.92 MPa for the twist and single fibers, respectively. Moreover, the tensile strength of the specimen with 50 mm fibers was lower than that with 40 mm fibers, 2.15 MPa compared to 2.92 MPa. In addition, in the post-peak region, the descending branch of 50S showed a downward trend until failure (Figure 3(a)). It should also be noted that balling may become a problem when fiber length increased, resulting in the worse performance compared to the specimen with 40S of aramid fibers.

As shown in Figures 3(a) and (d), the results presented that in case of same length of fiber the twist fibers provided lower tensile strength than that by the single fibers because the twisted fibers are not perfectly straight. Therefore, when stress occurs in concrete, the twisted fibers pull to straighten themselves and do not effectively resist the micro cracks, while the single fibers can resist propagation of cracks immediately. However, the descending branch of load-displacement curves of twist fibers was more stable than that of single fibers. As presented in Figure 3(a), after the displacement of approximately 1.5 mm was reached, the specimen 40T could resist much strength than 40S because the twisted shape provides a larger surface area for adhesion and frictional bond than the single shape. However, 30 mm twisted fibers did not clearly show this
behavior, due to insufficient length of the fibers. Therefore, based on its positive post-peak behavior, 40 mm twist fibers (40T) were selected and employed in the repair of corroded RC beams explained in the next Chapter.

3. Investigation of corroded RC beams repaired by AFRM and HPM

Based on the results investigated in Chapter 2, the properties of aramid fibers including the shape configuration and optimum length have been provided. This Chapter analyzes the performances of concrete beams repaired by aramid fiber-reinforced mortar (AFRM) and high performance mortar (HPM) under the corrosion environment.

3.1 Experimental program

3.1.1 Beam specimens

Four beams were tested under four-point bending and Table 3 lists the experimental cases. One beam was the control beam, without corrosion, and three beams were corroded using an accelerated corrosion process to reach 10% mass loss of longitudinal reinforcement. Two corroded beams were repaired at the tensile zone using AFRM for one sample and HPM for the other, as shown in Table 3. The HPM, which is available in the market, is the mortar for spalled concrete resulting from reinforcement corrosion.

3.1.2 Specimen layout and detail

The details of the beams are presented in Figure 4(a). Four beams with the same dimension (150 x 200 x 1400 mm$^3$) were prepared with cover concrete of 20 mm on all sides. Two longitudinal reinforcement comprising 16-mm deformed bars (DB16) were arranged at the tension zone, and two 6-mm round bars (RB6) were arranged at...
compression section for each beam. The stirrups were 9-mm round bars (RB9) with spacing of 60 mm.

3.1.3 Materials

The compressive strength of concrete was 32 MPa. The yield strength and ultimate strength of 16 mm deformed steel bars were 537.15 MPa and 673.93 MPa, respectively. The AFRM was used as a repair material with the mix proportion presented in Table 2. Forty-millimeter long aramid fibers with twist shape (40T) were used because they provided the best post-peak behavior, as reported in Chapter 2. The compressive strength of AFRM after 14 days was 56.5 MPa. The average tensile strength of the three dumbbell briquettes was 2.82 MPa, as presented in Table 3. For high performance repaired mortar, the water to powder ratio was 1:7 by weight according to the product data sheet. As shown in Table 3, the compressive strength and tensile strength of HPM were 32.7 MPa and 1.40 MPa, respectively.

3.1.4 Accelerated corrosion and repairing procedures

Figure 4(b) shows the facility required for the process of accelerated corrosion. The main reinforcement was connected to the power supplies with lead wires. Specimens were submerged one-third of the way into 3% NaCl solution. Table 3 summarizes the total time and electric current for each beam. The cracking damage in the beams were observed after the accelerated corrosion process. The damaged concrete, where is 60 mm from extreme tension fiber (Figure 4(c)), was destroyed. The rust around the reinforcing bars was removed by submerging the corroded steel bar in 10% diammonium hydrogen citrate at 60°C for 2 days (JCI, 2004). After that, the repair processes were conducted on two beams (10C-AFRM and 10C-HPM) by cleaning surface and bonding agent (LANKO
751) at the interface between old concrete and repair materials, and then the patch repair
was done with 14 days of curing.

At the final phase after bending tests, the reinforcements were taken off to
measure the mass loss of the corroded bars (as shown in Figure 5(a)). The mass of
corroded longitudinal bars is compared with un-corroded longitudinal bars. The actual
corrosion ratio is presented in Table 3. The measurement expressed that all corroded
reinforcement reached approximately 10% of mass loss.

3.1.5 Test method

Figure 4(c) illustrates the experimental setup. The linear variable differential
transducers (LVDTs) were set at mid-span and the supports to measure the vertical
displacements. A crack displacement transducer (PI-gauge) was attached at the bottom of
each beam. Concrete strain gauges were attached at the compressive zone to measure
compressive strain at the middle of the beam. Strain gauges were also attached on
longitudinal bars and stirrups as presented in Figure 4(d).

3.2 Experimental results and discussions

3.2.1 Load-deflection relations and failure mechanism

The load-deflection behavior of beams (Figure 5(b)) consists of three stages of
pre-cracking stage, pre-yielding and post-yielding until failure. These stages are separated
by the cracking and yielding load. Table 4 summarizes the results of cracking, yielding,
ultimate load and deflection of each beam. The cracking load is defined as the load at
which flexural cracking is initiated and the cracking load was identified through
observation during the test. While, the yield load is defined as the load at which the tensile
steel yielded. Indeed, at the pre-cracking stage, the stiffness of 0C and 10C was the same,
while the stiffness of repaired beams (10C-AFRM and 10C-HPM) was relatively lower
than that of the control beam, as shown in Figure 5(b). The cracking load of 10C-AFRM was comparable with those of 0C and 10C as presented in Table 4. Compared to the non-corroded beam (0C), the yield load of 10C, 10C-AFRM and 10C-HPM decreased 9%, 6%, and 22%, respectively. The yield load of the beam which was repaired using aramid fiber-reinforced mortar increased 3% compared to the beam without repair (10C). This occurred because aramid fibers help to resist some tension force; thus, the yielding was delayed. On the other hand, the yield load of 10C-HPM decreased 15% compared to that of 10C due to the high stiffness of the repaired HPM made the re-distribution of the stress, resulting in the lower yielding load of the specimen 10C-HPM. After yielding, the load slightly increased before reaching the ultimate load. The non-corroded beam provided the highest load capacity among the four beams. When compared to 0C, the ultimate load decreased 6%, 2%, and 16% for 10C, 10C-AFRM, and 10C-HPM, respectively. The load capacity of 10C-AFRC was nearly the same as the load capacity of the non-corroded beam. However, repair using high performance mortar (10C-HPM) did not increase the load capacity of the beam. In addition, based on the absorption energy values displayed in Table 4, the specimen 10C-HPM exhibits in the greatest ductility in the comparison to the other specimens. The specimens with the yielding load relative lower than the ultimate load resulted in the better ductility defined by the absorption energy. This finding is also agreed well to the study by Linh et al. (2018). The above discussion presents that the effectiveness of the beam repaired by AFRM is greater not only in the load capacity improvement but also in the ductility of member by comparing to the same aspects of the beam 10C.

It was found that all steel bars yielded before the ultimate load, as presented in Figure 5(c). As shown in Figure 5(c), the strain in longitudinal bar of 10C is rather low
compared to those of other specimens. This might be the result of bond deterioration between the concrete and corroded bar. On the other hand, the bonding condition of bars in 10C-AFRM and 10C-HPM was better than that of specimen 10C since the rust and the damaged concrete of these two specimens were removed and patched with repair materials. Therefore, the strain of bar in these specimens was similar to that of the control specimen (0C). After exceeding ultimate load, the load dropped due to crushing of concrete in compression zone. As a result, all four beams exhibited the reasonable failure mode of the concrete crushing in the compression zone.

3.2.2 Cracks pattern and crack width

As presented in Figure 6(a), the crack pattern of 0C was symmetrical with respect to the y-axis at mid-span. The flexural cracks initiated first at mid-span, followed by the cracks in shear span and uniform crack spacing was appeared. With an increase in load, flexural cracks propagated vertically into the compression zone and, ultimately, the crushing of concrete occurred at the failure of beam. Flexural cracks were also observed on the non-repaired corroded beam (10C). However, due to the corrosion effect, which results in variation of the area of longitudinal bars, the crack pattern was not symmetrical. In the specimen repaired with AFRM, many fine cracks were observed. The crack width of 10C-AFRC was significantly smaller than that of other beams because of the presence of fibers in the tension zone of the beam, limiting the cracking triggering through the fiber bridge. Some small horizontal cracks were also observed near the repair interface. These findings imply that the toughness of the beam repaired with AFRM was enhanced. On the other hand, the crack pattern of 10C-HPM was different from that of the other beams. There were few flexural cracks, and crack spacing increased and horizontal cracks near
interface were exhibited. The aforementioned observation may mainly due to the stiffness of HPM affecting the stress distribution in the beam.

Figure 6(b) shows the width of cracks from the PI-gauge at the middle bottom face of each beam. As expected, the same load-crack width relationship is found for each of the four beams at the first stage (0 to 22 kN). The specimens 10C and 10C-HPM have the same load-crack width relationship at the second stage (38 kN to 117 kN). For 10C-AFRM, the crack width was significantly reduced from the load of 80 kN up to its ultimate state (176.6 kN) due to the presence of AFRM in the tension zone of the beam. This means the corroded RC beam repaired by AFRM provided an improvement of the safety requirement due to the small crack widths occurred during the test, enhancing the serviceability of the beam in the aggressive environment.

4. Conclusions

Based on the results of mechanical properties and beam tests, the following conclusions can be drawn.

(1) There was improvement in tensile property with the use of aramid fibers in concrete with the reasonable length provided. Fibers with 30 mm in length were not be able to provide sufficient embedded length in the concrete because the fibers mainly pulled-out at the peak load. Fibers with 50 mm in length showed relatively lower tensile strength in the direct tensile test because of fiber balling. Forty-mm fibers provided the highest direct tensile strength among all fiber lengths. Furthermore, although the single shape fibers yield the highest tensile strength, twist fibers were able to resist higher loads in the post-peak region.
(2) The flexural capacity of the corroded beam repaired using high performance mortar, which is the mortar product in the market, decreased 11% compared to the corroded unrepaired beam. Large crack width was observed before the ultimate stage, leading the early yielding of steel reinforcement. Repairing beams by using only mortar cannot recover the flexural capacity of the corroded RC beam.

(3) The use of aramid fibers for repairing the corroded RC beams provides the capability to recover load capacity and ductility of the RC beams. Repairing these beams with aramid fiber-reinforced mortar could slightly delay the yielding of longitudinal reinforcement, which induced the good toughness of the specimens. In addition, it was observed that the number of cracks increased but the width of crack significantly decreased in the corroded beam repaired using aramid fiber-reinforced mortar, which met to the safety requirement of the structures.

Acknowledgement

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Table 4 Summary of test results
### Table 1 Properties and geometry of aramid fibers

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Tensile strength (MPa)</th>
<th>Density (kg/m³)</th>
<th>Length, $L_f$ (mm)</th>
<th>Diameter, $D_f$ (mm)</th>
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### Table 2 Mix proportion of concrete and mortar

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<th>Mix</th>
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<th>Cement (kg/m&lt;sup&gt;3&lt;/sup&gt;)</th>
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<th>Aggregate (kg/m&lt;sup&gt;3&lt;/sup&gt;)</th>
<th>Sand (kg/m&lt;sup&gt;3&lt;/sup&gt;)</th>
<th>Water (kg/m&lt;sup&gt;3&lt;/sup&gt;)</th>
<th>SP&lt;sup&gt;2&lt;/sup&gt; (g/m&lt;sup&gt;3&lt;/sup&gt;)</th>
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<sup>1</sup>Water-binder ratio,  <sup>2</sup>Super plasticizer
Table 3 Experimental program of beam repairing

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<th>Beam ID</th>
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<th>Corrosion ratio (Mass loss) Target</th>
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Table 4 Summary of test results

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<td>Load (kN)</td>
<td>$\Delta_y$ (mm)</td>
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Note: $\Delta_{cr}$ is deflection at concrete cracking, $\Delta_y$ is deflection at yielding state, and $\Delta_u$ is deflection at ultimate state.
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Figure 1 Aramid fibers and direct tensile test setup
Figure 2 Compressive strength of PC and AFRC
Figure 3 Experimental results of direct tensile tests

(a) Tensile force – displacement relationship

(b) Rupture failure of aramid fiber

(c) Pull-out failure of aramid fiber

(d) Direct tensile strength of tested specimens

Cracks occurred but they still resisted load at about 50% of the ultimate load.
(a) Beam configurations

(b) Accelerated corrosion setup

(c) Test setup

(d) Locations of strain gauges

Figure 4 Details of beam specimens (unit: mm)
Figure 5 Experimental results of beam tests
(a) Cracks patterns at ultimate load (the numbers next to cracks indicate their corresponded applied load in kN)

(b) Load-crack width relationship

Figure 6 Crack properties