Interfacial Tensile Bond between Substrate Concrete and Repairing Mortar under Freeze-Thaw Cycles
Ye Qian, Dawei Zhang, Tamon Ueda

Related Papers Click to Download full PDF!

Fatigue Degradation Properties of PCM-concrete Interface
Dawei Zhang, Hitoshi Furuuchi, Akihiro Hori, Tamon Ueda
Journal of Advanced Concrete Technology, volume 7 (2009), pp. 425-438

Meso-scale Mechanical Model for Mortar Deformation under Freeze Thaw Cycles
Fuyuan Gong, Evdon Sicat, Tamon Ueda, Dawei Zhang
Journal of Advanced Concrete Technology, volume 11 (2013), pp. 49-60

Change of the Coefficient of Thermal Expansion of Mortar Due to Damage by Freeze Thaw Cycles
Evdon Sicat, Fuyuan Gong, Dawei Zhang, Tamon Ueda

Flexural behavior of fire-damaged reinforced concrete slabs repaired with near-surfaced mounted (NSM) carbon fiber reinforced polymer (CFRP) rods
Cao Nguyen Thi, Withit Pansuk, Lluis Torres

Stress analysis for concrete materials under multiple freeze-thaw cycles
Fuyuan Gong, Evdon Sicat, Dawei Zhang, Tamon Ueda

Click to Submit your Papers
Japan Concrete Institute http://www.j-act.org
Interfacial Tensile Bond between Substrate Concrete and Repairing Mortar under Freeze-Thaw Cycles

Ye Qian\(^1\)*, Dawei Zhang\(^2\) and Tamon Ueda\(^3\)

Received 18 March 2016, accepted 31 July 2016 doi:10.3151/jact.14.421

Abstract

Freeze-thaw cycle is one of the major damage factors of concrete patch repair. Not only the material itself but also the adhesive interface is damaged under freeze-thaw cycles (FTC). Air-entraining agent has long been used to increase the freeze-thaw resistance of concrete materials. However, the effect of air-entraining agent on the adhesive interface has not been explored. The degradation mechanism and failure mode of concrete repair system under FTC has not been studied, either.

In this study, three kinds of substrate concrete were casted and repaired by two kinds of ordinary Portland cement mortars and one kind of polymer-modified cement mortar (PCM), respectively. With up to 150 FTC, splitting tensile strength and failure modes of composite specimens were experimented. Results showed that air-entraining agent in the repairing mortar greatly influenced adhesive tensile strength under FTC. The water cement ratio and air-entraining agent of substrate concrete insignificantly affected the adhesive interface, but affects failure mode. The adhesive tensile strength of PCM-repaired composite specimens decreased faster than that of ordinary Portland cement mortar-repaired composite specimens although PCM itself showed stronger freeze-thaw resistance than ordinary mortar.

1. Introduction

As existing concrete structures such as pavements, bridge decks, dams, etc. aging and degrading, the maintenance and rehabilitation of concrete structures has been a worldwide concern. It is one of common repairing methods that damaged concrete was removed, the surface was roughened, and newly cast repairing materials were placed on the treated surface of old concrete. It has been noticed by many researchers that the bonding between old concrete and new repairing material is a major issue since in most cases it is the weakest part of the repair system. According to Emmons and Vaysburd (1993) and Morgan (1996), the compatibility between old substrate concrete and new repairing material is a critical issue to obtain a good bonding. Emmons and Vaysburd (1996) further divided the repair system into three phases: substrate, repairing material and the interface (transition zone) between them. However, as an important component of the repair system, the components and fracture behavior of the interface have not yet been further studied.

Due to close mechanical properties and thus good compatibility to substrate concrete and low cost (Morgan 1996), ordinary Portland cement mortar has been largely used as repairing material. Nowadays, polymer-modified cement mortar (PCM) has also been largely applied in concrete repair. The polymers in PCM form polymer membranes, bridging the cement hydration products. In this way, PCM shows higher tensile strength, higher resistance to water and freeze-thaw cycles, and low permeability, etc (Ohama 1987; Lavelle 1988; Ohama 1995; Medeiros et al. 2009). It’s also concluded that under conventional environment PCM has stronger bonding with substrate concrete in concrete repair than ordinary cement mortar.

Emmons and Vaysburd (1994), from the perspective of contractor, pointed out that long-term durability of concrete repair is more important than short-term bonding strength of newly cast concrete repair system. Freeze-thaw cycle (FTC) is one of the major factors affecting the durability of the bonding of concrete repair system. It causes scaling and cracking in concrete structures. Not only the material itself is damaged by FTC, the adhesive interface, which is regarded as the weakest part of composite system, is also possibly degraded under freeze-thaw cycles. Both using splitting prism test, Li et al. (1999) and Li et al. (2007) have presented the degradation of splitting tensile strength of concrete repair system with increasing number of FTC, taking the surface roughness, surface moisture and curing condition into consideration. Most PCM itself has good freeze-thaw resistance over conventional mortar and concrete. This is due to the reduction of porosity as a result of decreased water-cement ratio and filling of pores by polymers, and air-entrained by polymers and surfactants (Ohama 1995). However, the freeze-thaw resistance

---

1Ph.D. Candidate, Department of Civil Engineering and Engineering Mechanics, Columbia University, New York NY, USA. *Corresponding author, E-mail: yq2157@columbia.edu
2Associate Professor, College of Civil Engineering and Architecture, Zhejiang University, Hangzhou, China.
3Professor, Division of Engineering and Policy for Sustainable Environment, Hokkaido University, Sapporo Japan.
of the PCM repaired system has not been studied.

Air-entraining agent is commonly added during concrete mixing to improve the freeze-thaw resistance of concrete materials. Air voids are entrained into concrete materials, decreasing the rate of water absorption (Li et al. 2011) and releasing the pressures during freeze-thaw cycles, and thus decreasing the freeze-thaw damage (Du and Folliard 2005). However, the effect of air-entraining agent in repairing material and substrate concrete has not been fully studied.

In this study, factors affecting the interfacial tensile bond of concrete repair system, such as water cement ratio of substrate concrete, repairing materials (ordinary mortar and PCM), and air-entraining agent in repairing mortar and substrate concrete, were tested and analyzed. The failure mode and degradation of composite specimens under freeze-thaw cycles were presented. The explanation based on microstructural phenomena was introduced for the splitting prism test results including failure mode, splitting tensile strength degradation, and effects of given factors. Meanwhile, the degradation of PCM repaired composite under freeze-thaw cycles were presented and analyzed.

2. Experimental procedures

2.1 Mix proportions of substrate concrete and repairing mortars

To study the effect of water cement ratio of substrate concrete and air content of both substrate concrete and repairing material on the interfacial bonding between substrate concrete and repair material, three kinds of substrate concrete were casted. The water cement ratio of normal strength concrete without and with air-entraining agent (marked as N and NA respectively) is 0.55, while that of high strength concrete (marked as HA) is 0.32. For the air-entrained concrete (NA and HA), the fresh air content is 5%. The repairing material was ordinary Portland cement mortar (marked as MA containing air-entraining agent and MX not containing air-entraining agent) with water cement ratio of 0.50, where the ratio of cement to sand was 1:3 by volume. The fresh air content of air-entrained mortar (MA) was 4%. The PCM is a commercial product widely used for concrete patching in Japan. The polymer is VA VeoVa with the polymer cement ratio (defined as the weight ratio of solids in polymer to cement) as 5–10%. The mix proportions of substrate concrete and repairing mortar are shown in Table 1.

2.2 Preparation of substrate concrete

Concrete prisms with the dimension of 50×100×100 mm were casted. After casting, the molds were covered with wet rags and plastic sheet. One day later, the concrete prisms were demolded and cured in water tank at a temperature of 20 ± 1 °C for 27 days. Then the surface of the concrete prism to be repaired was sandblasted until the coarse aggregate exposed. The roughness was measured by a 3D measurement apparatus and quantified by arithmetic mean value of roughness (Ra) according to JIS standard (Zhang et al. 2009; JIS B 0601 2011). The profile surface roughness parameter Ra was 0.3 to 0.4 mm.

For each kind of substrate concrete, six concrete bulks with the dimension of 100×100×400 mm were also casted for relative dynamic elastic modulus (RDEM) test and splitting tensile test.

2.3 Preparation of composite specimens

Before concrete repairing, the substrate concrete were taken out of the curing tank, wiped off free water on the surface and left in the air for 5 hours. During concrete repairing, the substrate concrete was put into the bottom of the steel mold with the dimension of 100×100×100 mm, with the repairing surface towards up. The repairing material was casted onto top of the substrate concrete in the mold and compacted using a vibrator. It is similar to situations where the bridge decks, dams, and pavements are repaired. Air-entrained mortar (MA) was casted just after the substrate concrete was sandblasted (one month curing time for substrate concrete before repairing); while non-air-entrained mortar (MX) and PCM was casted 8 months later (9 months curing time for substrate concrete before repairing).

Two days after casting, composite prisms with the dimension of 100×100×100 mm, as shown in Fig. 1, were demolded and cured in water tank for 28 days before being subjected to freeze-thaw cycles. For each repairing mortar, three mortar bulks with the dimension of 100×100×400 mm were also casted for relative dynamic elastic modulus (RDEM) test and splitting tensile test.

2.4 Freeze-thaw cycle experiments

After water curing for 28 days, composite specimens and concrete and mortar bulks were put into the environmental chamber to start freeze-thaw cycles. The container in the chamber is well designed for specimens with the dimension of 100×100×400 mm that the specimen is surrounded by a water layer of 3 mm. One 100×100×400 mm or four 100×100×100 mm specimens

<table>
<thead>
<tr>
<th>Mark</th>
<th>w/c</th>
<th>Water (kg)</th>
<th>Cement (kg)</th>
<th>Fine aggregate (kg)</th>
<th>Coarse aggregate (kg)</th>
<th>Air entraining agent (ml)</th>
<th>Water reducing agent (kg)</th>
<th>Air content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>0.55</td>
<td>160</td>
<td>290.9</td>
<td>897.9</td>
<td>1118</td>
<td>130.9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H</td>
<td>0.32</td>
<td>160</td>
<td>500</td>
<td>817.9</td>
<td>1018.4</td>
<td>187.5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>N</td>
<td>0.55</td>
<td>165</td>
<td>300</td>
<td>888.5</td>
<td>1106.2</td>
<td>0</td>
<td>0</td>
<td>1.8</td>
</tr>
<tr>
<td>MA</td>
<td>0.50</td>
<td>281.9</td>
<td>563.7</td>
<td>1438.1</td>
<td>0</td>
<td>236.8</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>MX</td>
<td>0.50</td>
<td>281.9</td>
<td>563.7</td>
<td>1459.6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

were put in each container. The temperature cycle of the center of the composite specimen accords to ASTM C 666-03 procedure A (ASTM C666-03 2008). The temperature was set to drop from 4 °C to -18 °C for 1.5 hours, kept at -18 °C for 0.5 hour, rise from -18 °C to 4 °C for another 1.5 hours, and kept at 4 °C for 0.5 hour. The tested temperature at the center of specimens by thermocouples was close to the set temperature. During freeze-thaw experiments, the edge of interface in composite specimens was not sealed.

According to ASTM C666-03, the material is regarded to be failing the freeze-thaw test when RDEM decreases under 60%. As could be seen in section 3.1 that for N, RDEM decreased to 63% after 150 cycles. So we considered that 150 cycles was long enough to make the material fail and tested samples up to 150 cycles. Number of freeze-thaw cycles served as a parameter quantifying the extent of degradation of composite specimens under freeze-thaw cycles. After certain number of freeze-thaw cycles, the composite specimens, concrete and mortar bulks were taken out of the environmental chamber to conduct relative dynamic elastic modulus (RDEM) test and splitting prism test.

2.5 Relative dynamic elastic modulus (RDEM) test

During freeze-thaw damage, micro cracks are generated under various pressure: hydraulic pressure (Powers 1945), osmotic pressure (Powers and Helmuth 1953), crystallization pressure (Scherer 1999, Scherer and Valenza II 2005) and etc. With microcracks initiation and propagation, the elastic modulus of cement and concrete decreases. Relative dynamic elastic modulus (RDEM) is used to quantify the extent of damage of cementitious material under freeze-thaw damage: 100% means no degradation, and below 60% means severe damage (ASTM C666-03 2008). After certain numbers of freeze-thaw cycles, the composite specimens, concrete and mortar bulks were taken out of the chamber to conduct RDEM test. The fundamental transverse frequency of concrete prism was recorded. According to ASTM E 1876-09 (ASTM E1876-09 2009), relative dynamic elastic modulus is proportional to the square of the ratio of fundamental transverse frequency of n cycles to 0 cycle, as presented in Eq. 1.

$$\text{RDEM} = \left(\frac{F_n}{F_0}\right)^2$$  \hspace{1cm} (1)

Where $F_n$ and $F_0$ is fundamental transverse frequency after n cycles and 0 cycle of freezing and thawing, respectively.

2.6 Splitting prism test

Geissert et al. (1999) proposed a simple test method to measure the bond strength of composites. It is similar to ASTM C 496 (ASTM C496 1996) for splitting tensile strength. Instead of using cylindrical specimens, it uses prism specimen, which is easier to be made and conducted for splitting tensile test. Especially when subjected to freeze-thaw cycles, prism specimen is suitable to the container of environmental chamber.

To prevent local failure during loading, two thin strips of 5×10×100 mm made of plywood are placed between the loading platen and the specimen to distribute the load. The area of substrate concrete-repairing mortar interface is 100×100 mm. Assuming a uniform tensile stress across the bond plane, the splitting tensile strength is defined and calculated according to Eq. 2 (Nilsson 1961).

$$f_t = \frac{2P}{\pi A}$$  \hspace{1cm} (2)

where $f_t$ is the splitting tensile strength, $P$ is the maximum applied load, and $A$ is the area of the interface.

With certain number of freeze-thaw cycles, the splitting tensile strength of composite specimens and bulks, and the failure mode of composite specimens were recorded, which helped to analyze the fracture behavior of the repair system.

3 Experiment results

3.1 Relative dynamic elastic modulus of substrate concrete and repairing mortar

The relative dynamic elastic modulus (RDEM) of air-entrained material (NA, HA and MA) and PCM had nearly no decrease under freeze-thaw cycles, while that of non-air-entrained material (N and MX) decreased obviously. Since the substrate concrete used in composites repaired with MA, MX and PCM showed little difference in RDEM, the RDEM of three kinds of substrate concrete (NA, N and HA) were averaged and presented in Fig. 2. After 150 freeze-thaw cycles, the RDEM of NA, HA, MA and PCM were 99%, 100%, 99% and 96% of the value of 0 cycle, respectively; while, that of N and MX decreased to 63% and 72%, respectively. The RDEM of PCM did not decrease much, showing good freeze-thaw resistance of PCM. This is due to the low permeability of PCM and airs entrained by polymers and surfactants (Ohama 1995).
3.2 Splitting tensile strength of substrate concrete and repairing mortar

Splitting prism tests on substrate concrete and repairing mortar were also conducted to obtain the splitting tensile strength of each constitutive material. As shown in Fig. 3(a), which gives the results of the materials used for the composite specimens repaired with air-entrained mortar (MA), the mean value of splitting tensile strength of air-entrained material (NA, HA and MA) decreased very little under increasing freeze-thaw cycles, while that of non-air-entrained material (N) decreased obviously. The splitting tensile strength of N decreased to 59.6% with 150 freeze-thaw cycles. On the other hand, Fig. 3(b) shows the results of materials used for the composite specimens repaired with non-air-entrained repairing mortar (MX) and PCM. The mean value of splitting tensile strength of air-entrained material (NA and HA) and PCM under 150 freeze-thaw cycles was 100.4%, 96.6% and 93.1% of those of 0 cycle. The splitting tensile strength of non-air-entrained material (N and MX) decreased to 46.6% and 77.6% with 150 freeze-thaw cycles. All the materials with air-entraining agent, and PCM show good FTC resistance, while the materials without do not. These results will be used in the next section (4.3) to compare with the splitting tensile strength of repair composite specimens to quantify the weakest part of repair system under freeze-thaw cycles. It is interesting to note that the splitting tensile strength of HA increased with longer curing time, and NA did not change obviously, while that of N decreased. For HA, the increase of splitting tensile strength could be related to continuous hydration. However, loss of moisture due to air curing in the summer resulted in decrease of N.

3.3 Splitting prism test of composite specimens

3.3.1 Splitting tensile strength and failure mode of substrate concrete repaired with air-entrained mortar (MA)

For all the splitting prism tests except N-MA composite specimen with 150 cycles, the failure mode was adhesion failure, as shown in Fig. 4(a). The substrate concrete was distinctly separated from the repairing mortar. For N-MA composite specimen with 150 cycles, the failure mode was cohesion failure in which the fracture happened at normal concrete (N) side, as shown in Fig. 4(b).

Results of splitting prism test for composite specimens are shown in Fig. 5. The splitting tensile strength of all three kinds of composite specimens did not change obviously with increasing number of freeze-thaw cycles. Under 150 freeze-thaw cycles, the splitting tensile strength of N-MA, NA-MA and HA-MA composite specimens was 100.6%, 99.7% and 95.9% of the value of 0 cycle respectively.

For NA-MA and HA-MA composite specimens, from Fig. 5(a) and (b), the splitting tensile strength of composite specimens were always smaller than both of substrate concrete and repairing mortar without and with freeze-thaw cycles. As the failure mode was adhesion failure, the splitting tensile strength of composite specimen was regarded as splitting tensile strength of adhesive interface. The adhesive interface bonding was the weakest part of the composite specimens with and without freeze-thaw cycles, but did not degrade with increasing number of freeze-thaw cycles.
For N-MA composite specimens, until 100 freeze-thaw cycles, the failure mode was adhesion failure. From Fig. 5(c), the splitting tensile strength of composite specimens was smaller than that of both substrate concrete and repairing mortar. However, with 150 freeze-thaw cycles, the splitting tensile strength of normal concrete (N) had decreased to 59.6% of the value of 0 cycle, and RDEM had decreased to 63% of the value of 0 cycle, while the splitting tensile strength of the adhesive bonding did not decrease. The splitting tensile strength of normal concrete (N) became smaller than that of adhesive interface and repairing mortar (MA). The failure mode thus shifted from adhesion failure to cohesion failure happening at substrate concrete (N) side, showing that the substrate concrete (N) became the weakest part of the repair system.

3.3.2 Splitting tensile strength and failure mode of substrate concrete repaired with non-air-entrained mortar (MX)

With increasing number of freeze-thaw cycles, the splitting tensile strength of composite specimens repaired with non-air-entrained mortar (MX) decreased. Under 150 freeze-thaw cycles, the splitting tensile strength of NA-MX, H-MX and N-MX composite specimens decreased to 65.1%, 65.4% and 67.3% of that of 0 cycle respectively, as shown in Fig. 6.

Many composite specimens showed mixed failure mode. Figure 7 shows the fracture surface of NA-MX composite specimen after 100 freeze-thaw cycles. On 70% of the surface, the fracture occurred at the adhesive interface, and the repairing mortar was clearly separated from substrate concrete, while, on the other 30% of the surface (area surrounded by the lines in Fig. 7, whose size was calculated from the image), the repairing mortar bulk fractured. Figure 8 shows the percentage of area for each failure type in all composite specimens repaired with non-air-entrained mortar (MX): at substrate, repair
or interface. Failure happened at substrate or repair material is regarded as cohesion failure mode, and failure at interface regarded as adhesive failure mode.

For NA-MX composite specimens, without freeze-thaw cycle, the fracture happened at the air-entrained normal concrete (NA) side and the adhesive interface, not at the non-air-entrained repairing mortar (MX) side. From RDEM test and splitting tensile test of concrete bulk, it was noted that MX was damaged under freeze-thaw cycles, while NA showed little freeze-thaw damage. With increasing number of freeze-thaw cycles, increasing percentage of fracture happened at the repairing mortar (MX) side, while the percentage of fracture happening at the substrate concrete (NA) and adhesive interface decreased. Under 150 freeze-thaw cycles, most of the fracture surface happened at the repairing mortar (MX) side, while no fracture at the air-entrained normal concrete (NA) side.

For HA-MX composite specimens, the failure mode with 0 cycle was adhesion failure. With increasing number of freeze-thaw cycles, there was increasing percentage of failure happening at the repairing mortar (MX) side, while decreasing percentage at the adhesive interface. There was no fracture happened at the high strength concrete (HA) side. From Fig. 6(b), it was noted that the splitting tensile strength of high strength concrete (HA) was always much higher than that of both non-air-entrained repairing mortar (MX) and the HA-MX composite specimens.

For N-MX composite specimens, with increasing freeze-thaw cycles, the percentage of interfacial adhesion failure decreased, while the percentage of fracture happening at the substrate concrete and repairing material side increased. It was noted that both the substrate concrete and the repairing mortar was non-air-entrained and showed increasing damage under freeze-thaw cycles.

The reason why composites repaired with MX showed mixed failure mode could be related to the similar strength of interface and repair material MX. As could be seen in Fig. 8, without freeze-thaw cycles, most failure happens at the interface for all three composites. However, with freeze-thaw cycles, MX was damaged and composite specimens showed more failure in repair MX part.

For NA-MX, HA-MX and N-MX composites, from 0 to 100 freeze-thaw cycles, most of the fracture happened at the interface adhesion. Meanwhile, the splitting tensile strength of the composite specimens decreased to 92.3%, 88.0% and 89.8% of that of 0 cycle, respectively. It was concluded that the splitting tensile strength of adhesive interface of all composite specimens repaired with MX decreased with increasing number of freeze-thaw cycles.
3.3.3 Splitting tensile strength and failure mode of substrate concrete repaired with polymer-modified cement mortar (PCM)

For all the composite specimens repaired with PCM, the failure mode was adhesion failure. After splitting failure, the substrate concrete was distinctly separated from the repairing mortar as shown in Fig. 9.

Results of splitting prism test for composite specimens are shown in Fig. 10. The splitting tensile strength of composite specimens repaired with polymer-modified mortar (PCM) decreased with increasing number of freeze-thaw cycles. With up to 150 freeze-thaw cycles, the splitting tensile strength of all composite specimens decreased almost to nil. The specimens could be split up easily using hand.

With increasing number of freeze-thaw cycles, the splitting strength of composite specimen decreased much quicker than those of concrete and PCM bulk. The splitting tensile strength of composite specimen was always smaller than that of both substrate concrete and PCM. As the failure mode was adhesion failure, results of splitting tensile test are regarded as splitting tensile strength of the adhesive interface (adhesive tensile strength). The adhesive interface bonding was the weakest part of the composite specimens with and without freeze-thaw cycles, and decrease with increasing number of freeze-thaw cycles.

The results could be related to the polymer added in the PCM used in this study. Further explanation will be discussed in the next section.

4. Discussions

4.1 Weak layer in composite specimen

The aggregate-cement paste interface in concrete was firstly studied by Farran (1956), who observed a weak transition zone exhibiting a different mineralogy and microstructure which existed in the interface between aggregate and cement paste. The interfacial transition zone in concrete is the region of the cement paste around the aggregate particles. Cement grains range in size from less than 1 micron to 100 microns. Aggregate particles are larger in several orders of magnitude than cement.
grains. This difference in size makes the aggregate a wall that disrupts the allocation of cement grains. The zone closest to the aggregate surface (interfacial transition zone) contains predominately small grains and has a higher porosity (Scrivener, Crumbie et al. 2004).

Many studies (Mehta and Monteiro 2006) disclosed the interfacial transition zone as the weakest part of concrete materials. Micro cracks tend to initiate and propagate firstly at the interfacial transition zone. At the aggregate surface, a thin layer of C-S-H was observed more often (Scrivener and Pratt 1986). Within 5 μm of the aggregate surface there was much higher percentage of C-S-H than that of 5-15 μm away from the aggregate surface. Within 10 μm of the aggregate surface, Scrivener, Crumbie et al. (2004) stated that there were higher percentage of calcium hydroxide. Monteiro and Mehta (1985) measured higher percentage of ettringite in the interfacial transition zone. The microstructure of layer within 20 μm from aggregate surface was similar to that of cement paste bulk.

Pigeon and Saucier (1992) stated that the interfacial zone between old and new concrete was very similar to the interfacial transition zone between aggregates and cement paste. Their research showed that similarly wall effect between substrate and repairing material resulted in a transition zone that created a layer of weakness. Studies by Van Mier (1997) showed that on the interfacial transition zone between aggregates and cement matrix, fracture did not happen exactly at the physical boundary between aggregate and cement matrix, but rather slightly away from the aggregate surface in the cement matrix. Also, Beushausen and Alexander (Beushausen and Alexander 2008) reasoned that in adhesion failure, fracture of the composite specimen happened not at physical boundary between substrate concrete and repairing material, but at the repairing material side slightly away from the boundary.

Through SEM observation, Xie, Li et al. (2002) found that the hydrates (such as Ca(OH)₂, ettringite and C-S-H) in the fresh repairing material grew into the cavities and pores at the surface of substrate concrete during cement hydration. They also proposed a model of microstructures of the interfacial zone between substrate and repairing material. The first layer, called the penetration layer, is formed in the cavities and pores at the surface of substrate concrete. They are mainly C-S-H and a little of AFt (ettringite) or Ca(OH)₂ (calcium hydrate), with tight structure and no harmful influence on the strength of the interface. The second layer, called the strongly-affected layer, is adjacent to the physical boundary between substrate and repairing material and is characterized by high porosity and highly oriented crystal constituents: mainly Ca(OH)₂ and needle-shaped AFt crystal. This layer is regarded as porous and the weakest layer of the interfacial zone. The third layer, called the weakly-affected layer, is located inside the new repairing material and has almost the same microstructures as the new repairing material, therefore is stronger than the second layer: strongly-affected layer. When the failure mode is adhesion failure, the fracture happens at the second layer, not at the physical boundary between substrate and repairing material. Since the second layer is constituted by hydrates of new repairing material, the strength of adhesive interface thus was greatly influenced by the repairing mortar. The adhesive interface contained more

Fig. 10 Splitting tensile strength of composite specimens compared to splitting tensile strength of bulk substrate and repairing materials: (a) NA-PCM; (b) HA-PCM; (c) N-PCM.
air-entrained voids if the repairing mortar contained air-entraining agent. Therefore, the adhesive interface with the air-entrained cementitious concrete material had good resistance under freeze-thaw cycles. The adhesive interface containing air-entrained voids did not degrade under freeze-thaw cycles, while the adhesive interface of less porosity degraded under freeze-thaw cycles. Additionally, the splitting tensile strength of composite specimens was smaller than either substrate concrete or repairing mortar due to the weak second layer of interfacial transition zone.

Emmons and Vaysburd (1996) proposed the three phases in the repairing system, including substrate material, repairing material and the interface; furthermore, Xie et al. (2002) proposed the three layers of the interface, including penetration layer, strongly-affected layer and weakly-affected layer, as shown in Fig. 11. Based on the aforementioned findings in the previous studies, the following discussions can be made. In this study, for composite specimens repaired with air-entrained mortar (MA), the adhesive interface was constituted by cement hydrates of the fresh repairing mortar, which contain air-entraining agent and air-entrained voids. The splitting tensile strength of the adhesive interface, which is the strength of the second layer, did not decrease during freeze-thaw cycles because the mechanical property of MA did not degrade during freeze-thaw cycles. For NA-MA and HA-MA composite specimens, as both substrate concrete and repairing mortar were air-entrained and not damaged during freeze-thaw cycles, the adhesive interface (second layer) was always the weakest part of the composite specimen, resulting in always adhesion failure. For N-MA composite specimens, with increasing freeze-thaw cycles, the splitting tensile strength of substrate concrete (N) decreased. Until 100 freeze-thaw cycles, the splitting tensile strength of N and MA were bigger than the adhesive interface (second layer), causing the adhesion failure at the adhesive interface. While under 150 freeze-thaw cycles, the splitting tensile strength of N was smaller than that of the adhesive interface (second layer), thus making the failure mode shifted from adhesion failure to cohesion failure in the substrate concrete (N) side.

For composite specimens repaired with non-air-entrained mortar (MX), the adhesive interface was not air-entrained. During freeze-thaw cycles, the adhesive interface was subjected to freeze-thaw damage, and the splitting tensile strength of the adhesive interface decreased. The splitting tensile strength of the composite specimens after 150 cycles of freeze-thaw cycles decreased to 65.1%, 65.4% and 67.3% of that of 0 cycle for NA-MX, HA-MX and N-MX composite specimens respectively.

By comparison of composite specimens repaired with ordinary Portland cement mortar containing and not containing air-entraining agent (MA and MX), it was concluded that the air-entraining agent or the air-entrained void in the repairing mortar made the second layer of the adhesive interface air-entrained, having a big effect on the splitting tensile strength of the adhesive interface and failure mode of the composite specimen, while the air-entraining agent in the substrate concrete (NA and HA) did not show obvious influence on the splitting tensile strength of the adhesive interface. The water cement ratio and air-entraining agent in the substrate concrete affect the splitting tensile strength and the freeze-thaw damage of substrate concrete, which have a negligible influence on the splitting tensile strength of the composite specimens when showing adhesion failure. This is because the splitting tensile strength at adhesive interface (or weak layer) is smaller than those of substrate and repairing materials. While, the failure mode shifts from adhesion failure to cohesion failure when the substrate concrete is damaged to a lower strength than the adhesive interface. Under this circumstance, the water cement ratio and air-entraining agent of substrate concrete have big effect on the splitting strength of the composites.

Considering the discussion above, the composite specimen is regarded to be three parts: substrate concrete, adhesive interface and repairing mortar. The fracture happened at the weakest part of the composite specimen. The failure mode of the composite system is determined by which part is the weakest under freeze-thaw cycles.
4.2 Reasons of weakened splitting strength of composite specimen with PCM

As to composite specimens repaired with PCM, the polymer in this study is VA VeoVa, which has quite similar physical and chemical property as a kind of commonly used polymer: EVA. Previous studies (Ohama 1995, Silva and Monteiro 2005, Maranhão, Loh et al. 2011) have reported that EVA (Ethylene-vinyl acetate) modified mortars and concretes showed decreased flexural strength, modulus of rupture when they are under high humidity or fully saturated with water. Possible reasons are as follows: 1) Water absorption causes the swelling of the EVA membrane throughout the polymer film, leading to its plasticization and resulting in lower mechanical strengths (Du Chesne et al. 2000). 2) The chemical interaction of acid groups is released by alkaline hydrolysis of EVA with Ca\(^{2+}\) ions in the pore water (Silva et al. 2002). The products of this interaction are calcium acetate and polyvinyl alcohol. Calcium acetate is an organic salt with high hygroscopicity, and polyvinyl alcohol is water-soluble. 3) EVA increases the pores in the range of 10–50 nm (Silva et al. 2001). Pores in this size range would be moderately or greatly affected by the surface tension of the aqueous phase, meaning that the moisture could cause the mechanical strengths to decrease (Mehta and Monteiro 2006). As to PCM bonding with substrate materials under moisture, Jenni et al. (2005) talked about the weak interface between adhesive mortar with polymers and tiles. According to the above information the following discussion can be made.

Since polymer film is an important mechanism to bond the components of PCM and increase the tensile strength of PCM, the weakening of polymer under water or freeze-thaw cycles would weaken the PCM. The internal part of PCM or the PCM bulk was not obviously damaged under freeze-thaw cycles, because of the low permeability and high percentage of polymer film. But the surface area of PCM and interface of composite specimen were subjected to damage under freeze-thaw cycles. From Fig. 12(a) and (b), it is observed that with freeze-thaw cycles, a lot of flakes of PCM dropped out or got loosen at surface and the interface. The interface is porous due to wall effect and thus water absorption takes place easily. In fact the splitting failure surface was still wet after the splitting test. Under freeze-thaw cycles, the surface and interface of PCM was subjected to freeze-thaw damage first and more easily, making the flakes at the surface and interface dropped out. The dropping out of flakes at the interface greatly weakens the adhesive bonding. By the given materials used in this study, as all composites repaired with PCM showed adhesion failure in splitting tensile test, and the splitting tensile strength of both substrate concrete and PCM was higher than that of the composite, the adhesive interface was always the weakest part of the composite repaired with PCM during freeze-thaw cycles. Plus, the adhesive interface decreased dramatically with increasing number of freeze-thaw cycles. Therefore the PCM repairing needs careful waterproof to guarantee its bond to the substrate in a freeze-thaw environment.

The authors’ group is conducting another experimental study on interfacial bond property under moisture effects but under climatic high temperature with different PCM. The moisture effects can be found in interface bond failure mode as observed in this paper, however the reduction in bond strength is less than what we observed in this paper. It seems that how much strength reduction as the moisture effects could depend on types of PCM and temperature. Further outcomes will be reported on separate papers.

5. Conclusions

Based on the experimental results on tensile bond property of interface between repairing mortars and substrate concretes under freeze-thaw cycles in this study, the following conclusions can be drawn:

1) The splitting tensile failure happened at the weakest part of the composite specimen, which is constituted by three parts: substrate concrete, adhesive interface and repairing mortar. The failure mode of the composite system is greatly affected by the weakest part.

2) The splitting tensile strength of adhesive interface did not decrease with up to 150 freeze-thaw cycles for both air- and non-air-entrained substrate concrete repaired with air-entrained mortar (MA); while that of adhesive interface decreased for both air- and non-air-entrained substrate concrete repaired with non-air-entrained mortar (MX).

3) The air-entraining agent of repairing mortar greatly affects the degradation of adhesive interface.
(4) The water cement ratio and air-entraining agent of substrate concrete affect insignificantly the adhesive interface under freeze-thaw cycles when the failure happens at the adhesive interface.

(5) The water cement ratio and air-entraining agent of substrate concrete affected the tensile strength and freeze-thaw resistance of substrate concrete, thus affecting the failure mode.

(6) The adhesive interface is the weakest part of the composite repaired with PCM used in this study. The splitting tensile strength of PCM repaired composite specimen under freeze-thaw cycles decreased more quickly than that of composite specimens repaired with ordinary Portland cement mortar with and without air-entraining agent.

(7) The reason of the quicker strength reduction of PCM repaired composite specimen is considered to be the moisture effects on PCM, which would happen only at PCM surface and PCM-concrete interface. This implies the importance of waterproof for its interface.

Acknowledgments
The authors are grateful to “The Research and Development Grant of Japan Institute of Construction Engineering (JICE)” and the “Express Highway Research Foundation of Japan” for funding this study. The first author is also appreciative of the “Ministry of Education, Culture, Sports, Science and Technology - Japan (MEXT)” for the scholarship grant. The second author is also appreciative of the open fund of state key laboratory of coastal and offshore engineering of Dalian University of Technology (LP1406).

References


Ohama, Y., (1987). “Principle of latex modification and some typical properties of latex-modified mortars and concretes adhesion; binders (materials); bond (paste to aggregate); carbonation; chlorides; curing; diffusion.” *ACI Materials Journal, 84*(6), 511-518.


