Mode I fracture of concrete-mortar repair systems under freeze-thaw cycles

Hokkaido University ○Student member Ye Qian
Hokkaido University Member Dawei Zhang
Hokkaido University Fellow member Tamon Ueda

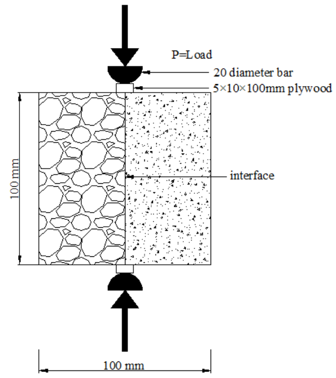
1. Introduction

In cold regions, every year infrastructures such as pavements and dams need to be repaired due to freeze-thaw damage. There is a lot of research on freeze-thaw damage of concrete materials, but less so on that of concrete repair systems. Within the limited study, different results exist among them. Gao and Cheng (2006) found that with only 30 freeze-thaw cycles, the splitting tensile strength of concrete-concrete interface decreased to almost nil. Li et al. (2007) also got the similar results within 45 cycles. However, the test results by Li and Stephens (1999) showed that with up to 300 freeze-thaw cycles, the splitting tensile strength of concrete-concrete interface decreased by only 5 to 30 percent depending on the curing condition and moisture condition of the repairing surface. Naderi (2008) tested the bonding of concrete and ordinary Portland cement mortar, and found that almost no decrease in splitting tensile strength. Although the preceding studies are all based on the splitting tensile test under similar freeze-thaw condition (ASTM C666), the results varied remarkably. The factors affecting the interfacial bond properties under freeze-thaw cycles still remain unclear.

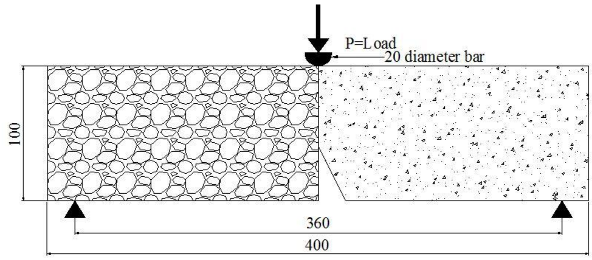
2. Experimental Program

To investigate the effects of water cement ratio and air entraining agent, three kinds of old concrete were chosen. The water cement ratio of normal concrete without and with air entraining agent (marked as N and NA respectively) was 0.55, while that of high strength concrete (marked as H) was 0.32. For the air entrained concrete (NA and H), the fresh air content is 5%. The repair material was ordinary Portland cement mortar (marked as M) with water cement ratio of 0.50, where the ratio of cement to sand was 1:3 by volume, and fresh air content was 3% with air entraining agent.

Concrete prisms with the dimension of 50×100×100mm and 200×100×100mm were casted. One day later, the concrete prisms were demolded and cured in water at a temperature of 20 ± 1 ℃ for 30 days. Then the other half of repairing mortar was cast with the surface of old concrete sandblasted until the coarse aggregate appeared. Two days after casting, these composite prisms with dimension of 100×100×100mm and 400×100×100mm were cured in water for 30 days before subjected to freeze-thaw cycles. They were subjected to splitting tensile test and three point bending test respectively, as shown in Figure 1.



(a)



(b)

Figure 1 the composite specimen and set-up of
(a) splitting tensile test; (b) three point bending test

For splitting tensile test, the splitting tensile strength is defined and calculated according to Equation 1.

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

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

Three point bending test was carried out under displacement control condition and the loading speed was 0.1mm/min. The flexural strength was calculated considering the material behavior as linear-elastic, shown in Equation 2.

$$f_{ft} = 1.5\frac{Pl}{b(d-a)^2} \quad (1)$$

where f_{ft} is the flexural strength, P is the load, l is the span, b, d and a are the width and height of the specimens and the height of the notch.

Figure 2 shows the temperature cycle of the center of the specimens according to ASTM C 666-03 procedure A. Theoretically the temperature drops from 4 ℃ to -18 ℃ for 1.5 hours, keeps -18 ℃ for 0.5 hour, rises from -18 ℃ to 4 ℃ for another 1.5 hours, and keeps 4 ℃ for 0.5 hour. The temperature of the center of specimens tested by thermocouples is also shown in Figure 2.

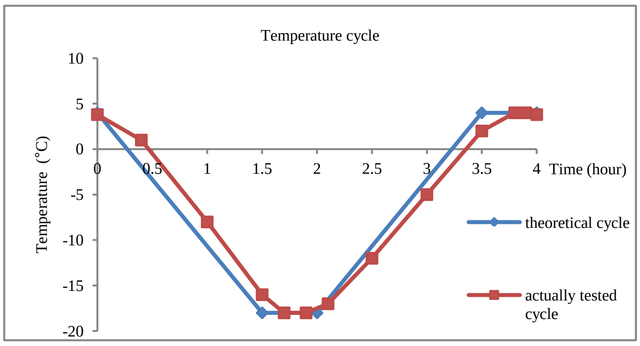


Figure 2 Temperature cycle of the center of specimens

3. Results and Discussions

3.1 Relative dynamic elastic modulus of old concrete and repairing mortar

Relative dynamic elastic modulus (RDEM) was used to quantify the damage of cementitious material under freeze-thaw damage. The results of RDEM of old concrete and repairing mortar are shown in Table 3 and Figure 3. The relative dynamic elastic modulus of air-entrained material (NA, H and M) had nearly no degradation, but that of normal concrete without air entraining agent (N) decreased to 63% with 150 freeze-thaw cycles.

Table 1 RDEM of old concrete and repairing mortar

No. of cycles	N		NA	
	frequency (Hz)	RDEM(%)	frequency (Hz)	RDEM(%)
0	2178	100	2137	100
22	2024	86	2125	99
30	1978	82	2116	98
50	1991	84	2125	99
80	1877	74	2113	98
150	1735	63	2073	94
No. of cycles	H		M	
	frequency (Hz)	RDEM(%)	frequency (Hz)	RDEM(%)
0	2190	100	9571	100
22	2190	100	9686	102
30	2188	100	9637	101
50	2189	100	9487	98
80	2185	100	9504	99
150	2206	101	9525	99

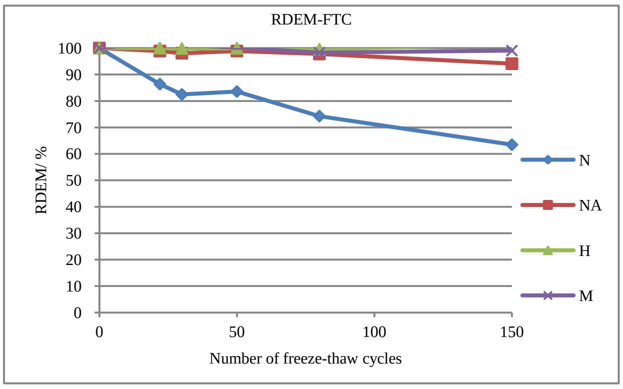


Figure 3 RDEM of old concrete and repairing mortar

3.2 Splitting tensile strength of old concrete and repairing mortar

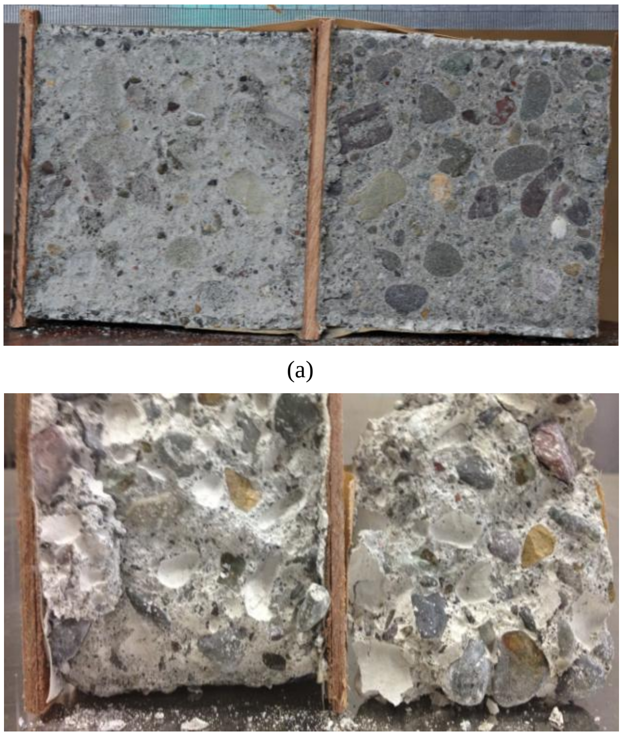
Splitting prism test on old concrete and repairing mortar were conducted to get the splitting tensile strength of constitutive material as shown in Table 2. These data were compared with the splitting tensile strength of repair composite specimens to quantify the weakest part of repair system under freeze-thaw cycles.

Table 2 splitting tensile strength of old concrete and repairing mortar

number of cycles	N		NA	
	mean(MPa)	degradation(%)	mean(MPa)	degradation(%)
0	4.02	100.0	2.95	100.0
30	3.04	75.7	3.06	103.8
50	2.74	68.2	2.87	97.5
100	2.42	60.2	2.82	95.5
150	2.26	56.2		
number of cycles	H		M	
	mean(MPa)	degradation(%)	mean(MPa)	degradation(%)
0	3.93	100.0	4.63	100.0
30	4.30	109.5	3.78	81.5
50	3.57	90.9	3.84	82.9
100	3.67	93.3	4.19	90.5

3.3 Splitting tensile strength of composite specimens

For all the splitting prism tests except N-M composite specimen with 150 cycles, the failure mode was adhesion failure. After splitting failure, the old concrete was distinctly separated from the repairing mortar as shown in Figure 4 (a). For N-M composite specimen with 150 cycles, the failure mode was cohesion failure with fracture happened in old concrete side, as shown in Figure 4 (b).



(a)

(b)

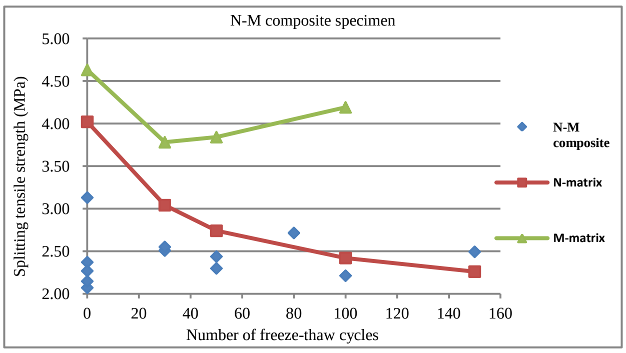
Figure 4 A typical example of fracture surface of composite specimens: (a) adhesion failure; (b) cohesion failure

Splitting prism strength of composite specimens is listed in Table 3. For NA-M and H-M composite specimens, as the failure mode was adhesion failure, results of splitting tensile test are regarded as interfacial bonding strength. By comparison of Table 2 and 3, the interfacial splitting strength is always smaller than either the splitting tensile strength of constitutive material under circumstances with and without freeze-thaw cycles. From figure 5, The interface bonding is the weakest part of the composite specimens with and without freeze-thaw cycles, but did not deteriorate obviously with freeze-thaw cycles.

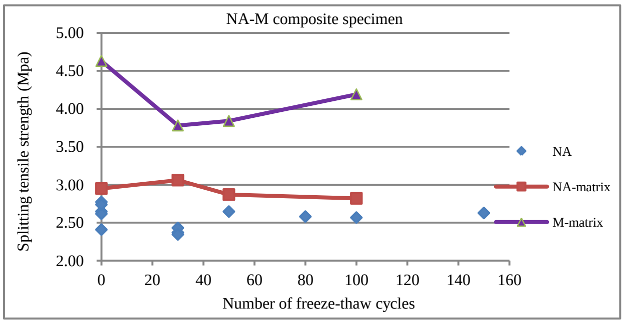
For N-M composite specimens, the failure mode was adhesion failure as interface bonding was the weakest until 100 freeze-thaw cycles. But up to 150 freeze-thaw cycles, the splitting tensile strength of normal concrete (N) had decreased to 56.2% of the value of 0 cycle, and RDEM had decreased to 63% of the value of 0 cycle, while the splitting tensile strength of the interface bonding did not deteriorate obviously. The failure mode shifted from adhesion failure to cohesion failure, showing old concrete (N) was the weakest in the repair system.

Table 3 Splitting tensile strength of composite specimens

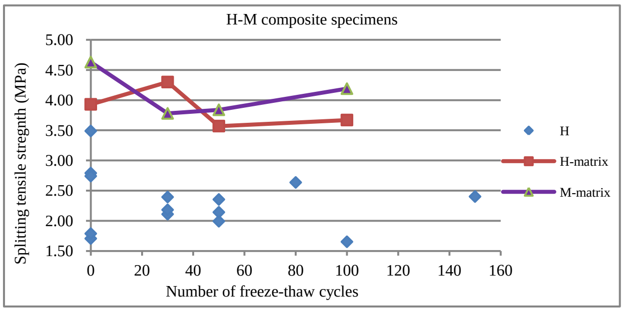
number of cycles	N-M			NA-M			H-M		
	strength (MPa)	mean value(MPa)	degradation(%)	strength (MPa)	mean value(MPa)	degradation(%)	strength (MPa)	mean value(MPa)	degradation(%)
0	3.13	2.40	100	2.77	2.64	100	3.49	2.50	100
	2.07			2.41			2.79		
	2.15			2.65			2.74		
	2.37			2.62			1.71		
	2.27			2.74			1.79		
30	2.51	2.53	105.5	2.37	2.38	90.3	2.39	2.23	89.0
	2.55			2.43			2.11		
				2.34			2.18		
50	2.44	2.37	98.8	1.97	2.18	82.8	1.99	2.16	86.4
	2.30			2.65			2.35		
				1.93			2.14		
80	2.71	2.71	113.2	2.58	2.58	97.9	2.64	2.64	105.3
100	2.21	2.21	92.3	2.57	2.57	97.4	1.65	1.65	66.0
150	2.49	2.49	104.0	2.63	2.63	99.7	2.40	2.40	96.0



(a)



(b)



(c)

Figure 5 splitting tensile strength of composite specimens: (a) N-M composite specimen; (b) NA-M composite specimen; (c) H-M composite specimen.

For all three kinds of old concrete, little degradation of splitting tensile strength of composite specimens with up to 150 freeze-thaw cycles was observed, showing that under freeze-thaw cycles, ordinary Portland cement mortar has good bonding to both normal concrete and high strength concrete. Morgan (1996) discussed that ordinary Portland cement mortar has good compatibility to old concrete, such as modulus in tension, coefficient of thermal expansion, adhesion in tension, etc. The good compatibility between concrete and ordinary Portland cement mortar contributes to the strong bonding between concrete and repairing mortar without freeze-thaw cycles.

Regarding freeze-thaw damage, Powers (1945) proposed a theory that the damage in concrete was caused by hydraulic pressure during ice formation and volume expansion. (Scherer and Valenza II 2005) reasoned that crystallization pressure is the primary cause of freeze-thaw damage. In this study, for the repairing mortar, air entraining agent was added, so that repairing mortar has good frost resistance. The hydraulic pressure or crystallization pressure due to freeze-thaw cycles in the interface could be released by the good void system of the repairing mortar. Further studies are to be carried out to clarify this point.

3.4 Young's modulus and flexural strength of composite specimens

Table 4 and Table 5 show the flexural strength and Young's modulus of composite specimens under three point bending test respectively. With up to 100 freeze-thaw cycles, the Young's modulus had much bigger degradation than flexural strength. Although bonding strength of composite specimens degraded a little, Young's modulus decreased severely. More experiments are needed to quantify the damage of Mode I fracture behavior with increasing freeze-thaw cycles.

Table 4 Flexural strength of composite specimens

	number of cycles	flexural strength(MPa)	mean (MPa)	degradation (%)
N	0	2.61	2.95	100.0
		2.52		
		3.72		
	100	2.29	2.29	77.6
NA	0	3.045	3.03	100.0
		2.52		
		3.51		
	30	1.83	1.83	60.5
	100	2.36	2.36	78.0
H	0	3.015	2.56	100.0
		2.01		
		2.64		
	30	2.07	1.95	76.3
		1.83		
	50	1.8	1.80	70.5
	100	2.53	2.53	99.0
	150	2.36	2.36	92.4

Table 5 Young's modulus of composite specimens

	number of cycles	E(GPa)	mean (GPa)	degradation(%)
N	0	19.2	23.4	100.0
		25.8		
		25.1		
	100	9.0	9.0	38.3
NA	0	31.8	23.1	100.0
		15.0		
		22.6		
	30	30.0	30.0	129.7
	100	13.8	13.8	59.7
H	0	19.6	23.9	100.0
		21.8		
		30.2		
	30	18.5	18.1	75.6
		17.6		
	50	18.4	18.4	77.1
	100	14.5	14.5	60.8
	150	8.1	8.1	33.7

4. Conclusions

Based on the experimental results in this study, the following conclusions can be drawn:

1. The splitting tensile strength of the interface did not decrease obviously with up to 150 freeze-thaw cycles for both normal and high strength concrete.
2. For composite specimens with air entrained old concrete (NA-M and H-M), the splitting tensile strength of interfacial bonding is smaller than both constitutive materials, showing that interfacial bonding is the weakest in the repair system.
3. For composite specimens with old concrete non-air entrained (N-M), with increasing freeze-thaw cycles, the splitting tensile strength of the interface did not deteriorate obviously although the RDEM and splitting tensile strength of old concrete (N) decreased. When the splitting tensile strength of old concrete decreased to be smaller than that of the interface, the failure mode changed from adhesion failure to cohesion failure.
4. Young's modulus of composite specimens with increasing freeze-thaw cycles decreased obviously, while, flexural strength degraded less.

Acknowledgements

This study was conducted with the financial support of Grant-in-Aid for Scientific Research (A) No. 22246058 as well as the research grant from Kosoku Doro Kanren Shakai Koken Kyogikai (Council on Social Contribution Related to Expressway) and Japan Institute of Construction Engineering (JICE). The authors are grateful.

References

ASTM C666-03. "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing." 2008.

ASTM E 1876-09. "Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Impulse Excitation of Vibration." 2009

Gao, D. and H. Cheng (2006). "Freeze-thaw cycle influencing on the bonding properties of new to old concrete [J]." Concrete.

Li, P., G. Zhao, et al. (2007). "Freeze-thaw bond properties of new-old concrete." Journal of Harbin Institute of Technology: 06.

Morgan, D. (1996). "Compatibility of concrete repair materials and systems." Construction and Building Materials **10**(1): 57-67.

Naderi, M. (2008). "Adhesion of Different Concrete Repair Systems Exposed to Different Environments." The Journal of Adhesion **84**(1): 78-104.

Powers, T. C. (1945). A working hypothesis for further studies of frost resistance of concrete, ACI.

Scherer, G. W. and J. J. Valenza II (2005). "Mechanisms of frost damage." Materials Science of Concrete VII **60**: 209-246.

Shigen Li, D. G. G., Gregory C. Frantz, and J. E. Stephens (1999). "Freeze-thaw bond durability of rapid-setting concrete repair materials." ACI Materials Journal **96**(2).