

低温冻融-氯盐环境下钢/纤维增强复合材料筋-混凝土粘结性能

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摘 要: 藏区高原混凝土结构受低温冻融与盐侵的共同作用, 筋材与混凝土的粘结性能是决定结构长期安全服役的关键。为探究低温冻融-氯盐环境对钢/纤维增强复合材料(FRP)筋与混凝土粘结性能的影响, 共设计 144 个试件依次进行冻融循环($-40\sim 20\text{ }^{\circ}\text{C}$)、NaCl 溶液盐侵作用和中心拉拔试验, 试验参数包括筋材类型[钢、玄武岩纤维增强复合材料筋(BFRP)、碳纤维增强复合材料筋(CFRP)、玻璃纤维增强复合材料筋(GFRP)筋]、筋材直径(10、16、20 mm)和冻融循环次数(0、50、100、150)。结果表明: 1) 试件破坏模式主要受筋材类型和筋材直径影响, 冻融循环次数对其影响不大; 2) 试件粘结强度随直径增加而降低, 直径从 10 mm 增加至 20 mm, 钢筋试件粘结强度的降低(51.7%~56.3%)比 FRP 筋试件(<18.2%)更为显著; 冻融循环对粘结强度随直径的变化趋势影响不大, 但 150 次冻融循环后, 钢筋粘结强度下降超过 31.4%, BFRP 筋降幅不超过 22.1%; 3) 直径从 10 mm 增加到 20 mm, 试件峰值滑移增加 5.0%~13.3%, 冻融循环次数从 0 增至 150, 试件峰值滑移降低 13.5%~23.8%, 且直径和冻融循环次数对峰值滑移的交互作用不显著; 4) 在低温冻融-氯盐环境下, 钢筋与 FRP 筋的粘结强度退化虽均与冻融循环相关, 但主因不同, 前者主要因混凝土劣化和钢筋锈蚀, 后者除混凝土劣化外, 还与 FRP 筋和界面性能退化有关; 5) 对试验结果进行归一化处理, 提出了考虑冻融次数和筋材直径的钢、BFRP、CFRP、GFRP 筋粘结强度和峰值滑移预测模型(拟合优度 $R^2>0.86$), 模型预测值与试验结果吻合良好, 可以有效预测粘结性能的退化。

关键词: 低温冻融; 氯盐侵蚀; 粘结滑移; 纤维增强复合材料筋

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为贯彻落实“一带一路”倡议, 实现“治国必治边、治边先稳藏”战略思想, 川藏铁路、新藏铁路等高原地区交通基础设施建设方兴未艾。西藏年最低气温可达 $-45\text{ }^{\circ}\text{C}$, 气温正负交替天数占全年一半以上, 形成极端低温、高频次的冻融环境; 且高原地区桥涵、隧道等结构还常受到除冰盐或土壤中氯盐的侵蚀, 冻融与盐侵共同作用对混凝土结构耐久性造成严重威胁^[1]。碳纤维增强复合材料(CFRP)筋、玄武岩纤维增强复合材料(BFRP)筋和玻璃纤维增强复合材料(GFRP)筋等纤维增强复合材料因其高强与耐蚀特性, 在滨海、盐渍地区等腐蚀性环境中已得到广泛应用^[2-4]。钢/纤维增强复合材料(FRP)-混凝土界面粘结性能显著影响混凝土结构的力学性能^[5, 6]。然而, 现有研究多集中于常温或常规冻融环境, 对高原特有的低温冻融与盐侵共同作用下筋-

混凝土粘结性能的退化规律认识尚不充分。因此有必要针对性开展高原低温冻融-氯盐侵蚀环境下钢/FRP 筋与混凝土界面粘结性能研究。

众多学者已就冻融循环对钢/FRP 筋与混凝土粘结性能影响展开研究^[7-9]。Ma 等^[7]针对冻融环境($-19\sim 10\text{ }^{\circ}\text{C}$)下钢筋与普通混凝土进行了粘结滑移试验, 发现 25 次和 50 次冻融循环后, 粘结强度分别降低了 37%和 55%, 而 50 次循环还导致峰值滑移增加 83.5%。Zhang 等^[8]则模拟了冻融($-14\sim 8\text{ }^{\circ}\text{C}$)与硫酸盐侵蚀共同作用下 CFRP 筋与混凝土的粘结性能, 发现 100 次冻融循环可使粘结强度降低 37.7%, 且最大粘结剪应力位置逐渐从加载端向自由端迁移。Wang 等^[9]基于 33 组拉拔试验得出, 在经历 100、150 次及 200 次冻融循环($-18\sim 2\text{ }^{\circ}\text{C}$)后, GFRP 筋与混凝土的平均粘结强度分别降低了 21.2%、41.2%和

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63.2%。已有研究^[7-9]表明冻融最低温度多设定在 -20°C 左右,然而,文献[10, 11]研究表明,冻融最低温度对混凝土强度影响显著($-160\sim 20^{\circ}\text{C}$ 冻融循环 1 次使混凝土抗压强度和劈拉强度分别下降 29.3% 和 31.7%),且钢筋与混凝土粘结强度随混凝土强度降低而下降^[12]。

在氯盐侵蚀方面,文献[13-15]探讨了其对钢筋与混凝土粘结性能的影响,发现当氯盐致钢筋锈蚀引起混凝土保护层开裂时,粘结强度显著降低。同时,针对氯盐侵蚀下 FRP 筋与混凝土的粘结性能,Zhou 等^[16]发现氯离子浓度是影响粘结强度的关键因素,其中 7% 的 NaCl 溶液中试件的粘结强度比 3.5% 的 NaCl 溶液低 39.8%。

近几年,冻融循环与氯盐侵蚀共同作用对钢筋/FRP 筋与混凝土粘结性能的影响引起学者关注^[17, 18]。Huang 等^[17]研究了冻融($-17\sim 8^{\circ}\text{C}$)与氯离子侵蚀下钢筋与再生粗骨料混凝土的粘结性能,结果表明:相较于单一氯离子侵蚀,冻融-氯盐侵蚀共同作用导致粘结强度降低 28.1%。Lu 等^[18]研究发现:在相同氯盐侵蚀条件下,经历 200 次冻融循环可使钢筋腐蚀速率增加 39.7%,粘结强度降低 73.2%,峰值滑移降低 31.0%。

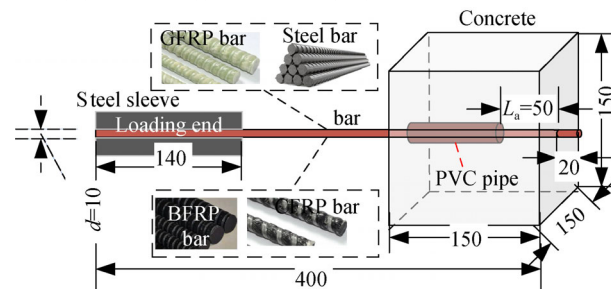
综上,现有研究主要存在以下 2 点不足: 1) 研究对象多集中于单一环境因素(如常温盐侵或常规冻融)或单一筋材,缺乏对低温冻融-氯盐侵蚀环境下,钢筋与多种 FRP 筋粘结性能的横向对比研究; 2) 现有粘结强度模型大多基于常温或常规冻融环境建立,缺乏能够反映低温冻融-氯盐侵蚀影响的预测模型,难以直接应用于青藏高原等特殊地区的混凝土结构耐久性设计与评估。为此,对 144 个试件依次进行冻融循环($-40\sim 20^{\circ}\text{C}$)、NaCl 溶液盐侵作用和中心拉拔试验,探究低温冻融-氯盐侵蚀环境下钢/FRP 筋-混凝土界面的性能退化规律。

1 实验

1.1 试件设计

共浇筑 144 个试件,尺寸及配筋如图 1 所示。钢/FRP 筋总长 420 mm,其中加载端预留 250 mm,自由端保留 20 mm。粘结长度为 5 倍筋材直径。混凝土配合比见表 1,强度等级为 C40,水灰比为 0.41,混凝土立方体 28 d 抗压强度为 42.6 MPa。用于试件制作的水泥(P·O 42.5)和细砂产自唐山燕东水泥公司,碎石由涞水县顺合建材公司生产,减水剂为 YD-A1 多元羧酸、II 级粉煤灰和 S95 级高炉矿渣粉。

钢筋为 HRB 400 带肋钢筋,FRP 筋包括 BFRP、CFRP 和 GFRP。筋材直径采用 10、16 mm 和 20 mm,其中钢筋和 FRP 筋表面形态数据如表 2 所示。



Note: d is bar diameter; L_a is bond length.

图 1 试件尺寸及配筋(mm)

Fig. 1 Dimension and reinforcement of specimen (mm)

表 1 混凝土配合比

Table 1 Concrete mixtures							kg/m ³
Cement	Water	Sand	Stone	Water reducer	Fly ash	Slag powder	
260	170	847	995	6.5	58	43	

表 2 钢筋和 FRP 筋表面形态

Table 2 The external dimensions and properties data of steel bars and FRP bars

Bar type	d/mm	h/mm	l/mm	$E \times 10^{-5}/\text{MPa}$	f_u/MPa
Steel	10	0.80	5.50	2.08	668
	16	1.50	9.50	1.95	662
	20	2.34	13.20	1.89	657
CFRP	10	0.65	10.15	1.72	1834
	16	1.74	11.37	1.63	1776
	20	2.17	11.86	1.57	1687
BFRP	10	0.77	9.92	0.48	1344
	16	1.95	10.13	0.45	1173
	20	2.35	11.35	0.42	1156
GFRP	10	0.57	10.29	0.43	853
	16	1.69	11.56	0.39	730
	20	2.03	12.37	0.35	687

Note: h is the horizontal/spiral rib height; l is the rib spacing; E is the elastic modulus; f_u is the ultimate strength.

1.2 试验设计

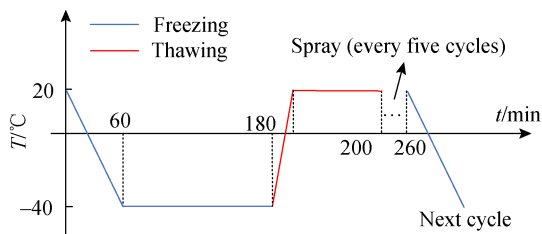
混凝土龄期 28 d 时,对上述试件依次进行低温冻融($-40\sim 20^{\circ}\text{C}$)、NaCl 溶液盐侵作用和中心拉拔试验。试验参数包括筋材类型[钢、BFRP 筋、CFRP 筋、GFRP 筋]、筋材直径(10、16、20 mm)和冻融循环次数(0、50、100、150)。每组工况含 3 个试件。试件命名规则如下:试件编号中首字母 S、B、C、G 分别对应钢筋、BFRP 筋、CFRP 筋和 GFRP 筋; $d10$ 、 $d16$ 、 $d20$ 代表直径;N0、N50、N100、N150 表示冻融循环次数。

具体试验步骤如下:

1) 低温冻融

试件完成 28 d 标准养护后,首先进行为期 4 d

的饱水预处理以确保冻融循环试验前试件达到饱和状态。采用可程式高低温试验箱模拟冻融循环过程,冻融循环制度如图 2 所示,一次冻融循环需 260 min,包含 180 min 冻结和 80 min 融化。每 5 次冻融循环后,将试件置于 20 °C 环境中进行 NaCl 溶液喷淋以维持含水率稳定^[10]。



Note: T is temperature; t is time.

图 2 冻融循环

Fig. 2 Freeze-thaw cycles

2) 氯盐侵蚀作用

试件完成给定次数的冻融循环后,将其浸泡于质量分数为 5% 的 NaCl 溶液中 15 d,通过高浓度 NaCl 溶液加速模拟氯离子侵蚀过程^[19]。

3) 中心拉拔试验

15 d 氯盐侵蚀结束后,采用 300kN MTS 试验机对 144 个试件进行中心拉拔试验,加载速率为 0.5 mm/min。在自由端布置位移计以测得筋材与混凝土相对滑移,数据采集频率 10 Hz。试件粘结强度可通过式(1)计算^[20]。

$$\tau_u = \frac{F}{\pi d L_a} \quad (1)$$

式中: τ_u 为粘结强度(MPa); F 为拔出力(N); d 为筋材直径(mm); L_a 为粘结长度(mm)。

2 结果与讨论

氯盐侵蚀结束后,钢筋试件发生腐蚀,但未引发混凝土开裂,钢筋混凝土试件粘结破坏后,将钢筋取出,测得的质量损失率低于 8.7%;而 FRP 筋试件均未出现腐蚀或开裂现象(图 3)。试件粘结测试结果汇总于表 3,表中结果为每种工况条件下 3 个试件的平均值。

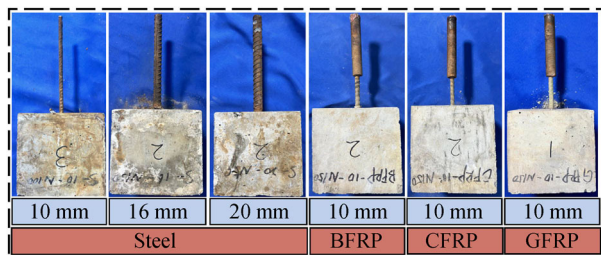


图 3 氯盐侵蚀作用后试件

Fig. 3 Specimens after the chloride attack

表 3 粘结试验结果

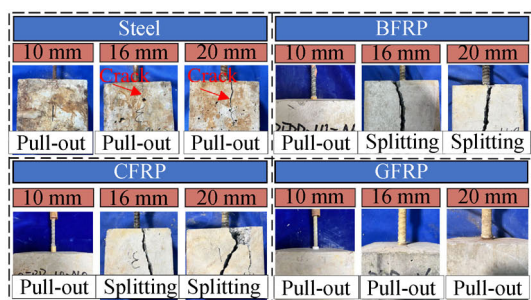
Table 3 Results of the bond test

Bar type	Specimen	Failure mode	F/kN	τ_u/MPa	s_u/mm
Steel	S-d10-N0	P	17.5	11.1	2.1
	S-d16-N0	SP	27.3	6.7	2.3
	S-d20-N0	SP	32.2	5.1	2.5
	S-d10-N50	P	16.2	10.3	1.8
	S-d16-N50	SP	24.6	6.1	2.2
	S-d20-N50	SP	28.3	4.5	2.4
	S-d10-N100	P	13.6	8.7	2.0
	S-d16-N100	SP	22.3	5.5	2.1
	S-d20-N100	SP	26.2	4.2	2.3
	S-d10-N150	P	12.3	7.0	1.6
	S-d16-N150	SP	21.2	4.4	1.7
	S-d20-N150	SP	22.0	3.5	1.9
CFRP	C-d10-N0	P	39.7	25.3	3.6
	C-d16-N0	SP	88.8	22.1	3.7
	C-d20-N0	SP	131.9	21.0	4.0
	C-d10-N50	P	36.9	23.5	3.2
	C-d16-N50	SP	82.4	20.5	3.6
	C-d20-N50	SP	122.5	19.5	3.8
	C-d10-N100	P	31.4	20.0	3.3
	C-d16-N100	SP	71.5	17.8	3.5
	C-d20-N100	SP	106.1	16.9	3.7
	C-d10-N150	P	27.3	17.4	3.0
BFRP	B-d10-N0	P	43.3	27.6	3.3
	B-d16-N0	SP	97.2	24.2	3.6
	B-d20-N0	SP	142.3	22.7	3.8
	B-d10-N50	P	40.5	25.8	3.2
	B-d16-N50	SP	90.5	22.5	3.3
	B-d20-N50	SP	132.3	21.1	3.7
	B-d10-N100	P	38.1	24.3	3.0
	B-d16-N100	SP	83.1	20.7	3.1
	B-d20-N100	SP	125.4	20.0	3.4
	B-d10-N150	P	33.7	21.5	2.7
GFRP	G-d10-N0	P	26.1	16.6	3.7
	G-d16-N0	P	56.7	14.1	3.9
	G-d20-N0	P	82.9	13.2	4.1
	G-d10-N50	P	24.1	15.4	3.4
	G-d16-N50	P	50.2	12.5	3.6
	G-d20-N50	P	71.6	11.4	3.9
	G-d10-N100	P	21.9	13.9	3.3
	G-d16-N100	P	45.0	11.2	3.4
	G-d20-N100	P	63.4	10.1	3.7
	G-d10-N150	P	20.7	13.2	3.2
	G-d16-N150	P	39.8	9.9	3.3
	G-d20-N150	P	56.5	9.0	3.5

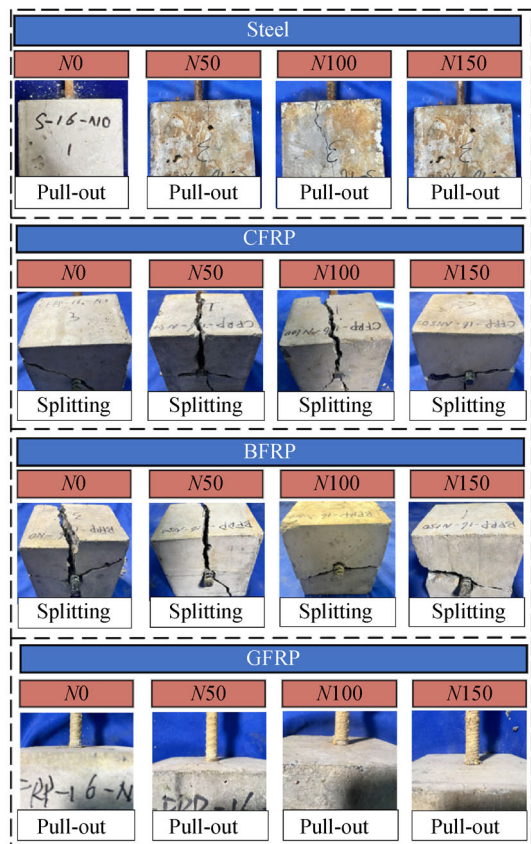
Note: S represents steel bar; B represents BFRP bar; C represents CFRP bar; G represents GFRP bar; N is freeze-thaw cycle; P represents the pull-out failure; SP represents the splitting failure; s_u is the peak slip; τ_u is bond strength.

2.1 破坏模式

图 4 给出了典型试件破坏模式和特征。试件破坏模式分为拔出破坏和劈裂破坏两类, 主要受筋材类型和筋材直径影响, 冻融循环影响不大。图 4a 展示了筋材直径和筋材类型对破坏模式的影响。对于钢筋试件, 所有直径的试件均发生拔出破坏, 但随着钢筋直径的增加混凝土损伤更为严重。当直径为 10 mm 时, 试件仅在自由端钢筋周边产生局部损伤。当钢筋直径超过 10 mm 时, 混凝土表面产生沿筋长方向的未贯穿裂缝, 且裂缝宽度与直径呈正相关, 这主要由表 2 所示的钢筋肋几何特征引起的。随着直径增大, 肋高增加导致钢筋-混凝土界面应力分布不均匀, 肋附近应力集中引起混凝土裂缝宽度增加。



(a) Effect of bar diameter



(b) Effect of freeze-thaw

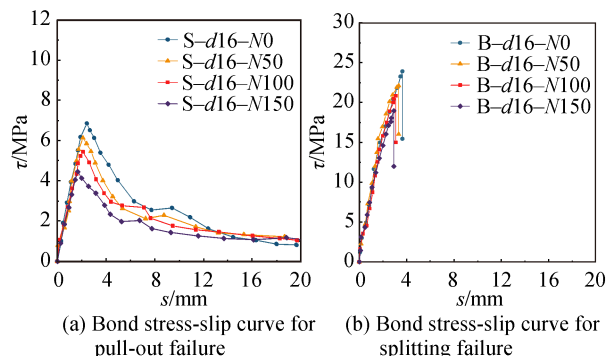
图 4 破坏模式
Fig. 4 Failure mode

对于 BFRP 筋和 CFRP 筋试件, 当直径由 10 mm 增至 16 mm 时, 破坏模式由拔出破坏向劈裂破坏转变。BFRP 筋和 CFRP 筋表面的螺旋肋沿筋长方向均匀分布, 且螺旋肋较为平缓(表 2)。当直径为 10 mm 时, 螺旋肋高度不超过 0.8 mm, BFRP 筋和 CFRP 筋的表面几乎光滑, 试件发生拔出破坏, 混凝土表面未发生损坏。当筋材直径超过 10 mm 时, 螺旋肋沿筋长方向连续均匀分布未引起 BFRP 筋和 CFRP 筋与混凝土界面应力集中, 混凝土在拉拔过程中未出现明显裂缝; 但 BFRP 筋和 CFRP 筋强度较高(表 2), 抑制了肋部剪切破坏, 最终引发混凝土劈裂破坏。与之不同的是, GFRP 筋因其强度小于 BFRP 筋和 GFRP 筋, 所有试件(10、16、20 mm)均发生以肋部剪切破坏为主的拉拔失效, 混凝土内部无裂缝, 这与文献[21]结论一致。

由图 4b 可见, 在低温冻融-氯盐侵蚀环境下, 冻融循环次数对破坏模式影响不大, 文献[22]也得到类似结论。以 16 mm 试件为例, 冻融循环次数从 0 增加到 150, 钢筋试件和 GFRP 筋试件的破坏模式均为拔出破坏, BFRP 筋试件和 CFRP 筋试件均为劈裂破坏。

2.2 粘结应力-滑移曲线

根据试验结果发现, 试件粘结应力-滑移曲线形态取决于试件破坏模式, 图 5 展示了 2 种破坏模式的典型粘结应力-滑移曲线。对于发生拔出破坏的试件, 粘结应力-滑移曲线可分为 4 个阶段: 微滑移阶段、滑移阶段、下降阶段和残余阶段。对于劈裂破坏试件, 仅呈现 2 个阶段, 即微滑移阶段和滑移阶段。上述现象与文献[23-26]中 FRP 筋与混凝土粘结应力-滑移曲线特征相一致。



Note: τ is bond stress; s is slip.

图 5 粘结应力-滑移曲线
Fig. 5 Bond stress-slip curves

2.3 粘结强度

2.3.1 筋材直径对粘结强度的影响 图 6 展示了

筋材直径对钢、BFRP、CFRP、GFRP 筋与混凝土粘结强度的影响。结果表明：钢筋和 FRP 筋试件粘结强度随筋材直径增加而降低，但降低幅度有所不同，这一现象与文献[27–29]中未冻融试件结果类似。具体来说，筋材直径从 10 mm 增加到 20 mm，不同冻融循环次数的钢筋试件粘结强度降低 51.7%~56.3%，而不同冻融循环次数的 BFRP 筋试件粘结强度降低 13.0%~18.2%。对于不同冻融循环次数的 CFRP 筋和 GFRP 筋试件，当直径从 10 mm 增至 20 mm 时，粘结强度分别下降 15.5%~17.0%和 20.4%~31.8%。筋材直径增大导致粘结强度降低的原因可归纳为以下 2 点：1) 大直径筋材可能会在筋材和混凝土界面处形成气泡或空隙等缺陷；2) 与小直径筋材相比，大直径筋材在相同粘结应力下承受更大的拉应力，泊松效应导致筋材的径向收缩更为显著，从而减小摩擦力和机械咬合力^[30]。

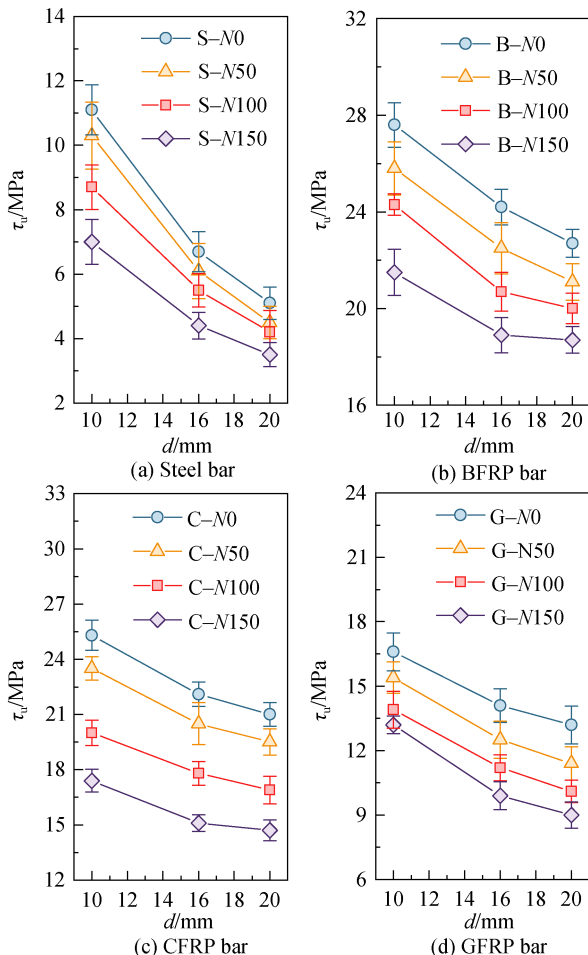


图6 筋材直径对粘结强度影响

Fig. 6 Effect of bar diameter on bond strength

与此同时，对比不同筋材类型下粘结强度随直径增加的降幅可知，钢筋粘结强度降幅比 FRP 筋更为显著，这是由于钢筋肋高通常较高，且肋边缘更

为锋利(表 2)，导致混凝土内部因应力集中而受到更严重的损坏，从而加速粘结失效。此外，由图 6 可见，不同冻融循环次数下粘结强度随直径增加而降低的曲线形态基本一致，即冻融循环次数对粘结强度随直径的变化趋势影响不大。以 BFRP 筋为例，冻融循环次数分别为 0、50、100 和 150 时，直径从 10 mm 增至 20 mm 分别引起粘结强度降低 17.8%、18.2%、17.6%和 13.0%。

综上，钢/FRP 筋与混凝土粘结强度随筋材直径增加而降低，且钢筋试件降幅显著大于 FRP 筋试件，冻融循环次数对粘结强度随直径的变化趋势影响不大。

2.3.2 冻融循环次数对粘结强度的影响 图 7 展示了冻融循环次数对钢、BFRP、CFRP、GFRP 筋与混凝土粘结强度的影响。对于不同筋材类型和直径的试件，冻融循环次数增加均导致粘结强度显著降低，且钢筋试件的粘结强度降幅显著大于 FRP 筋试件。具体来说，经过 150 次冻融循环后，钢筋试件粘结强度降幅超过 31.4%，BFRP 筋试件粘结强度降低了 17.6%~22.1%，CFRP 筋和 GFRP 筋试件粘结强度降幅分别在 16.3%~31.2%和 18.8%~31.0%之间。

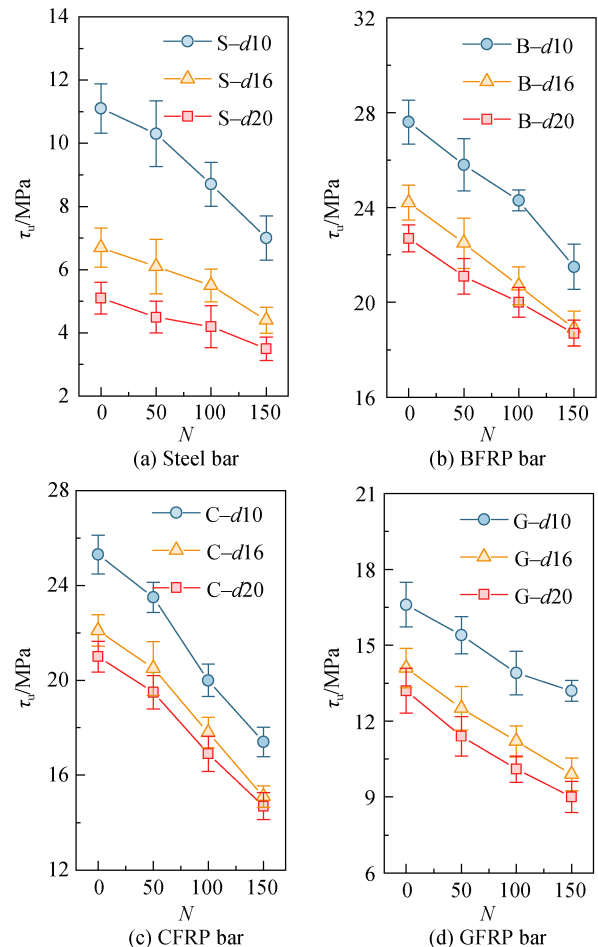


图7 冻融循环次数对粘结强度的影响

Fig. 7 Effect of freeze-thaw cycles on bond strength

2.3.3 粘结强度退化机理 在低温冻融-氯盐环境下钢筋粘结强度退化的主因是冻融循环导致混凝土强度劣化和钢筋锈蚀。混凝土内孔隙水冻结膨胀会在孔隙中产生应力, 当应力超过混凝土抗拉强度时混凝土开裂; 随着冻融循环次数增加, 微观和宏观裂缝数量与宽度随之增大, 导致混凝土强度下降; 混凝土强度降低减弱了其对钢筋的约束作用, 因此粘结强度降低^[31]。

在低温冻融-氯盐环境下 FRP 筋试件粘结强度退化基本源于低温冻融循环, 除混凝土性能劣化外, 还与 FRP 筋及其界面性能退化有关。对于 FRP 筋, 其树脂基体在 0℃以下会发生硬化并产生微裂纹^[32], 冻融循环中交替的高低温会加剧该过程。树脂中平行于纤维方向的微裂纹会逐渐聚集和扩展, 削弱邻近区域的性能, 纤维约束性能下降, 继而导致筋材力学性能降低^[32]。图 8 展示了发生粘结破坏的 FRP 筋混凝土试件中 FRP 筋的表面形貌, 冻融循环导致加载后筋材表面损伤加剧。对于 10 mm 的 BFRP 筋(图 8a), 冻融循环次数增加导致了其螺旋肋损伤程度加剧: 未经历冻融的 BFRP 筋, 其螺旋肋保持相对完整; 而经历 150 次冻融循环后, BFRP 筋在粘结区域的螺旋肋几乎被磨平。对于 16 mm 和 20 mm

的 BFRP 筋, 随着冻融循环次数增加, 筋材表面摩擦划痕加重。图 8b 和图 8c 表明, 随着冻融循环次数增加, CFRP 筋和 GFRP 筋表面螺旋肋损伤程度和表面划痕加剧。

对于 FRP 筋与混凝土界面, 如表 4 所列, FRP 筋热膨胀系数($17.1 \times 10^{-6} \sim 93.0 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$)显著高于混凝土($6 \times 10^{-6} \sim 8 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$)^[33]。因此, 在冻结过程中, FRP 筋的收缩大于混凝土, 导致 FRP 筋和混凝土之间界面形成间隙^[34], 劣化了两者的粘结性能。

表 4 热膨胀系数^[33]Table 4 The thermal expansion coefficient^[33]

Material	Thermal expansion coefficient/ $^{\circ}\text{C}^{-1}$
Concrete	$6.0 \times 10^{-6} \sim 8.0 \times 10^{-6}$
BFRP	17.1×10^{-6}
CFRP	93.0×10^{-6}
GFRP	22.5×10^{-6}

2.3.4 粘结强度预测模型 本研究探讨了钢筋直径和冻融循环次数对钢筋、BFRP 筋、CFRP 筋和 GFRP 筋试件粘结性能的影响。为分析筋材直径对粘结性能的影响, 将参数 D 定义为筋材直径(d)与参考值(d_0)之比, 并据此进行归一化处理, d_0 取 10 mm, 得到式(2)。

$$D = \frac{d}{d_0} \quad (2)$$

参考文献[35, 36], 对粘结强度进行归一化处理, 其表达式为式(3)。

$$R_{\tau} = \frac{\tau_u(N, D)}{\tau_0} \quad (3)$$

式中: R_{τ} 为归一化粘结强度; $\tau_u(N, D)$ 为不同筋材直径的试件在低温冻融-氯盐侵蚀环境下的粘结强度; τ_0 为未受到低温冻融-氯盐侵蚀环境影响的粘结强度; N 为冻融循环次数。参考文献[37, 38]中冻融循环次数和筋材直径与粘结强度的关系, 选择式(4)以表征冻融循环次数和 D 对粘结强度的影响。

$$\tau_u(N, D) = R_{\tau} \cdot \tau_0 = A \exp(BD) \cdot (1 - CN) \cdot \tau_0 \quad (4)$$

式中: A 、 B 和 C 为通过试验确定的参数。

基于式(3), 归一化粘结强度见图 9。结合式(4), 对本工作试验数据进行拟合(图 9), 得到钢、BFRP、CFRP、GFRP 筋与混凝土粘结强度的预测模型, 具体参数列于表 5。

图 10 展示了式(4)中粘结强度计算值与文献[9, 17, 35, 37, 39-42]中的试验值的对比。试验值与计算值之间的误差大多在 10%以内, 验证了本工作的粘结强度计算模型的合理性。对于 Xu 等^[35]和 Liu 等^[41]

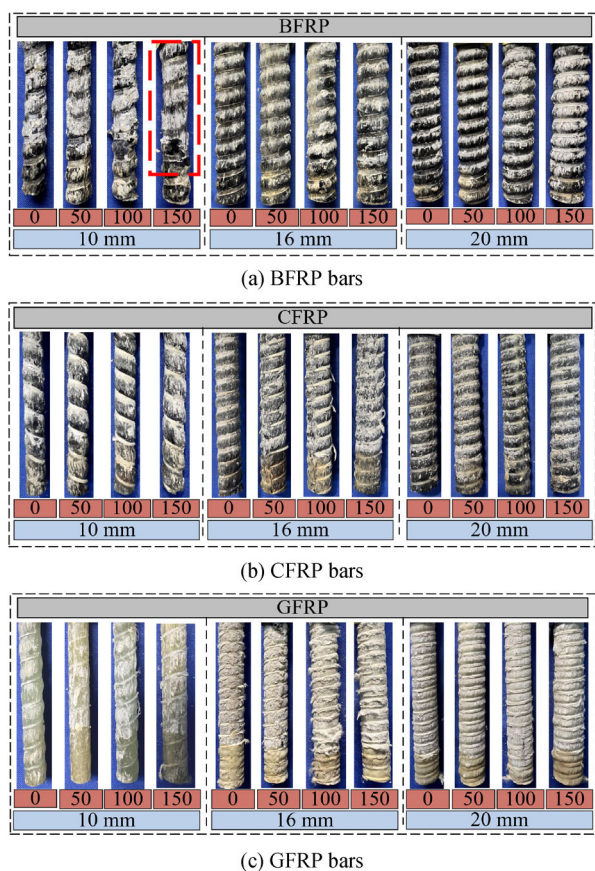
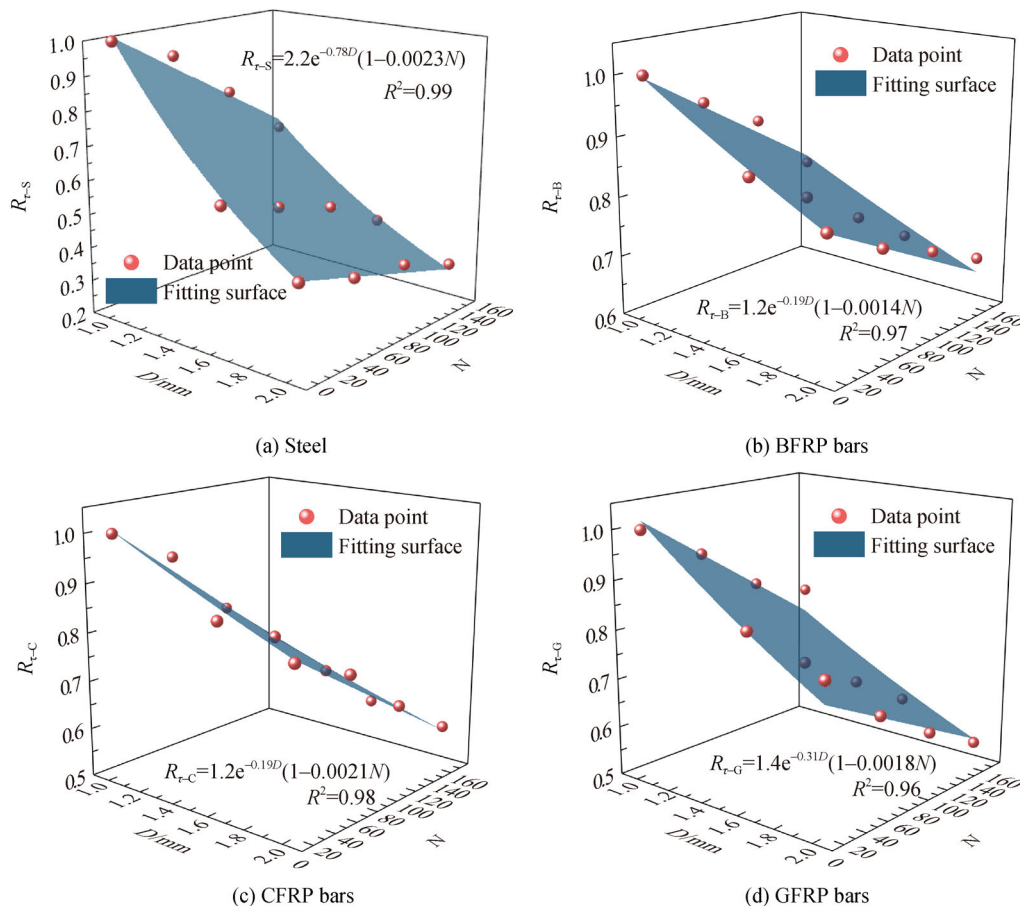


图 8 粘结破坏后 FRP 筋表面形貌

Fig. 8 FRP bars from the bond failed specimens

研究, 部分数据在 25% 误差范围之外, 这主要是由于本工作和文献[35, 41]中冻融最低温度不同(本工作为 -40°C , 文献[35, 41]为约 -18°C)。混凝土强度

随冻融最低温度降低而降低, 低温冻融下粘结强度较小^[10, 11, 43], 即公式(4)低估了文献[35, 41]试件的粘结强度。



Note: R^2 is the coefficient of determination; R_{r-s} , R_{r-B} , R_{r-C} and R_{r-G} are normalized bond strength of steel, BFRP, CFRP and GFRP specimens, respectively.

图 9 归一化粘结强度预测模型拟合

Fig. 9 Fitting of relative bond strength prediction model

表 5 粘结强度预测公式参数

Table 5 Parameters of bond strength prediction model

Bar type	A	B	C
R_{r-s}	2.2	-0.78	0.002 3
R_{r-B}	1.2	-0.19	0.001 4
R_{r-C}	1.2	-0.19	0.002 1
R_{r-G}	1.4	-0.31	0.001 8

Note: A, B and C are parameters determined by experiments.

2.4 峰值滑移

2.4.1 峰值滑移变化特征 图 11 和图 12 展示了钢、BFRP、CFRP、GFRP 筋与混凝土的峰值滑移, 可以发现钢筋试件峰值滑移明显小于 FRP 筋试件。钢筋试件峰值滑移约为 1.6~2.5 mm, 而 FRP 试件峰值滑移在 2.7~4.1 mm 之间, 这主要源于钢筋和 FRP 筋的表面特征(表 2)。根据 Hao 等^[27]的研究, 峰值

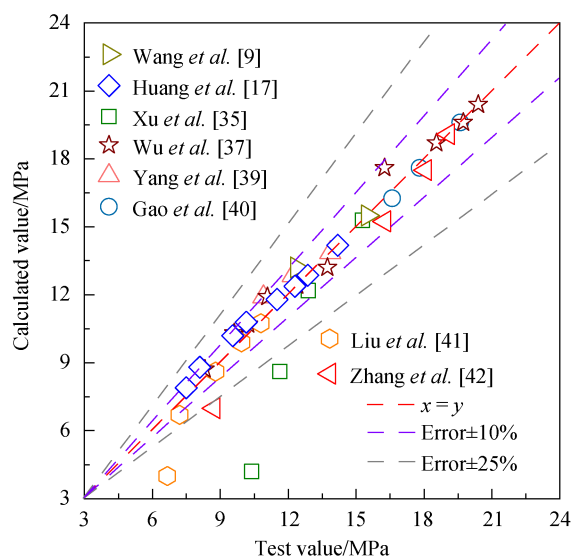


图 10 粘结强度预测模型验证

Fig. 10 Verification of bond strength prediction model

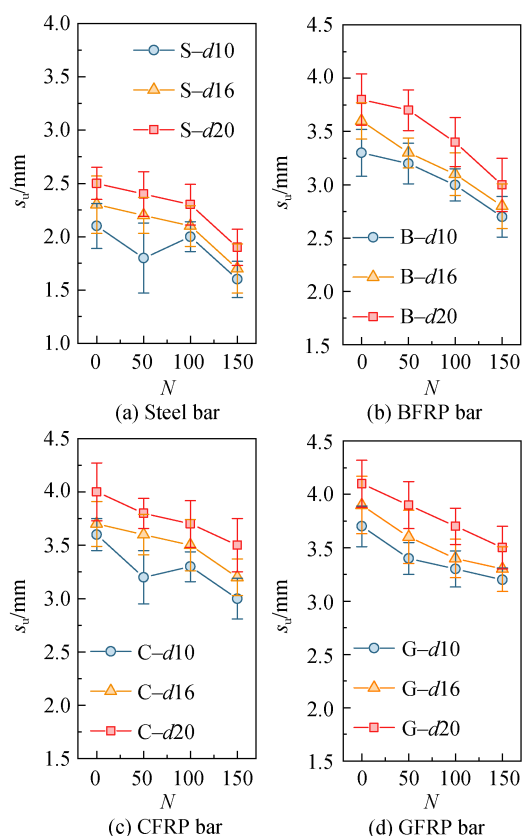


图 11 冻融循环次数对峰值滑移影响

Fig. 11 Effect of freeze-thaw cycles on peak slip

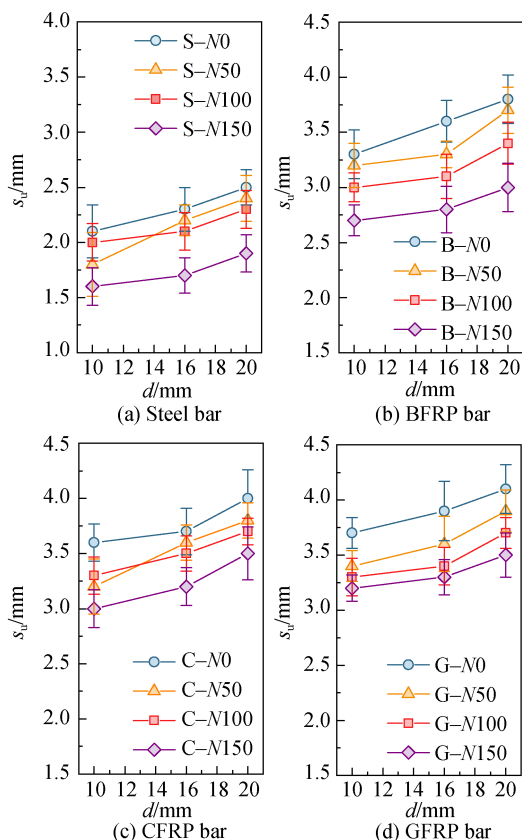


图 12 筋材直径对峰值滑移影响

Fig. 12 Effect of bar diameter on peak slip

滑移随着肋高减小和肋间距增大而增大。具体而言,较大的肋高能增强混凝土对肋的约束,从而限制钢/FRP 筋与混凝土的相对滑移;而较大的肋间距则导致筋材与混凝土在相同应力下的接触点数量减少,每个接触点拥有更大的变形空间,使得达到峰值滑移前可产生较大的位移。如表 2 所示,相同直径下,钢筋肋间距显著小于 FRP 筋,且钢筋肋高较大。

在低温冻融-氯盐侵蚀环境下,随着冻融循环次数增加,所有试件峰值滑移均呈现降低趋势。如图 11 所示,以 10 mm 试件为例,与未冻融的试件相比,钢筋试件在经历 150 次冻融循环后,其峰值滑移降低 23.8%;对于 FRP 筋,随着冻融循环次数从 0 次增至 150 次, BFRP 筋试件峰值滑移降低 18.2%, CFRP 筋的峰值滑移降低 16.7%, GFRP 筋的峰值滑移降低 13.5%。对于不同直径下冻融循环次数对峰值滑移的影响,以 BFRP 筋试件为例,150 次冻融循环后,10、16 mm 和 20 mm 试件的峰值滑移分别下降 18.2%、22.2%和 21.1%,即筋材直径对峰值滑移随冻融循环次数的变化趋势无显著影响。

此外,随着筋材直径增大,所有冻融循环次数下的试件峰值滑移均呈增长趋势。如图 12 所示,以冻融 100 次试件为例,与 10 mm 试件相比,16 mm 和 20 mm 钢筋试件的峰值滑移分别提升了 5.0%和 15.0%;对于 FRP 筋试件,直径从 10 mm 增至 20 mm 时, BFRP 筋试件峰值滑移增大 13.3%, CFRP 筋试件增大 12.1%, GFRP 筋试件增大 12.1%。关于不同冻融循环次数下筋材直径对峰值滑移的影响,以 BFRP 筋试件为例,直径从 10 mm 增至 20 mm,冻融 0、50、100 次和 150 次试件的峰值滑移分别增加 15.1%、15.6%、13.3%和 11.1%,即冻融循环次数对峰值滑移随筋材直径的变化趋势亦无显著影响。

钢筋试件峰值滑移小于 FRP 试件,且随着直径从 10 mm 增加到 20 mm,试件峰值滑移增加 5.0%~13.3%。随着冻融循环次数增加到 150,试件峰值滑移降低 13.5%~23.8%,但筋材直径和冻融循环次数对峰值滑移无显著交互作用。

2.4.2 峰值滑移预测模型 对 2.4.1 节峰值滑移进行归一化处理得到式(5)。

$$R_s = \frac{s_u(N, D)}{s_0} \quad (5)$$

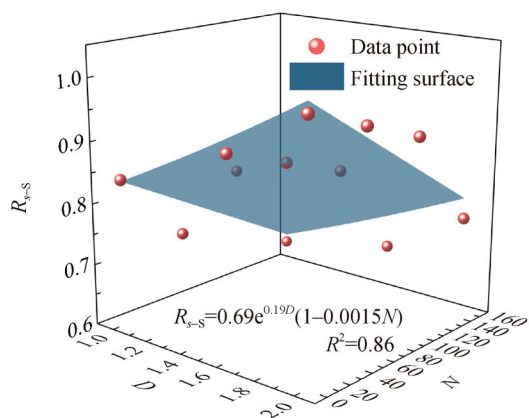
式中: R_s 为归一化峰值滑移; $s_u(N, D)$ 为试件在低温冻融-氯盐侵蚀环境下的峰值滑移; s_0 为未受到低温冻融-氯盐侵蚀环境影响的峰值滑移。参考之前的研究[37, 38]中冻融循环次数和 D 与峰值滑移的关系,

选择式(6)表征冻融循环和直径对峰值滑移的影响。

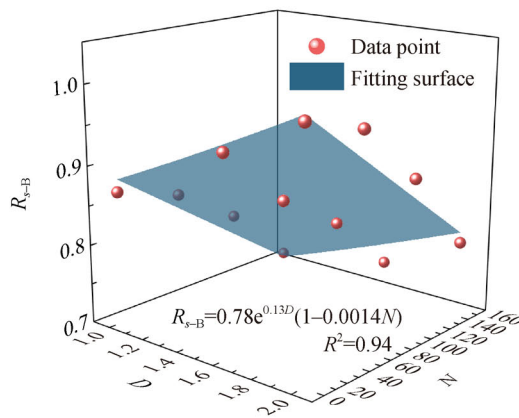
$$s_u(N, D) = R_s \cdot s_0 = k \exp(mD) \cdot (1 - pN) \cdot s_0 \quad (6)$$

其中： k 、 m 和 p 为通过试验确定的参数。

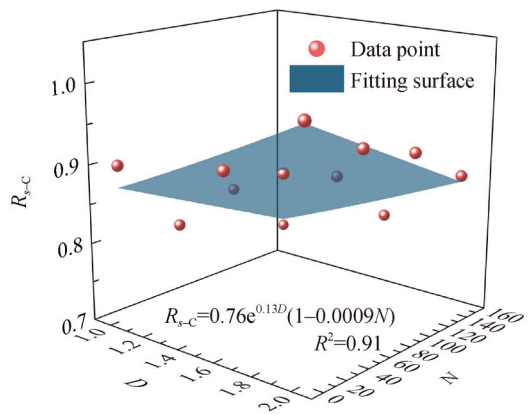
基于式(5)，归一化峰值滑移见图 13。结合式(6)，对本工作试验数据进行拟合(图 13)，得到钢、BFRP、CFRP、GFRP 筋与混凝土峰值滑移的预测模型，具体参数列于表 6。



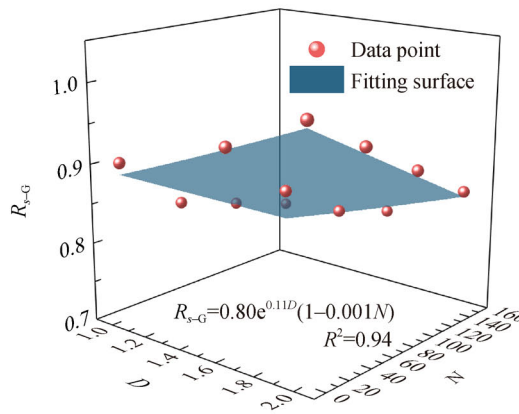
(a) Steel



(b) BFRP bars



(c) CFRP bars



(d) GFRP bars

Note: R_{s-s} , R_{s-B} , R_{s-C} and R_{s-G} are normalized peak slip of steel, BFRP, CFRP and GFRP specimens, respectively.

图 13 相对峰值滑移预测模型拟合

Fig. 13 Fitting of relative peak slip prediction model

表 6 峰值滑移预测公式参数

Table 6 Parameters of peak slip prediction model

Bar type	k	m	p
R_{s-s}	0.69	0.19	0.001 5
R_{s-B}	0.78	0.13	0.001 4
R_{s-C}	0.76	0.13	0.000 9
R_{s-G}	0.80	0.13	0.001 0

Note: k , m and p are parameters determined by experiments.

图 14 展示了文献[9, 17, 35, 39, 40, 42]中的试验值与峰值滑移计算值[式(6)]的对比，误差基本在 10% 左右，验证了本工作中峰值滑移预测模型的合理性。

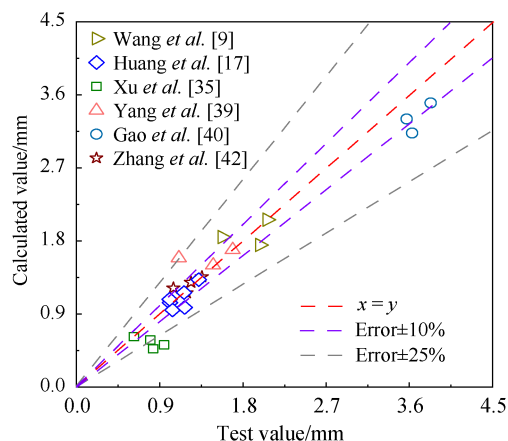


图 14 峰值滑移预测模型验证

Fig. 14 Verification of peak slip prediction model

3 结论

通过中心拉拔试验,探究了钢、BFRP、CFRP、GFRP筋与混凝土在低温冻融($-40\sim 20\text{ }^{\circ}\text{C}$)和氯盐侵蚀环境下的粘结性能。主要结论如下:

1) 试件破坏模式主要受筋材类型和直径影响,受冻融循环次数影响不大。低温冻融($0\sim 150$ 次)-氯盐侵蚀作用后,钢筋试件均为拔出破坏,并伴随沿筋长方向的裂缝(裂缝宽度随直径增大);GFRP筋试件均为拔出破坏,混凝土未开裂;BFRP筋和CFRP筋试件,当直径增至 16 mm 时,破坏模式由拔出破坏转变为劈裂破坏。

2) 钢筋和FRP筋试件粘结强度均随直径增加而降低,直径从 10 mm 增加至 20 mm ,钢筋试件粘结强度降低($51.7\%\sim 56.3\%$)比FRP筋试件($<18.2\%$)更为显著;冻融循环次数对粘结强度随直径的变化趋势影响不大,但 150 次冻融循环后,钢筋粘结强度降幅($>31.4\%$)大于FRP筋试件。

3) 在低温冻融-氯盐环境下,钢筋与FRP筋粘结强度的退化机理存在差异。钢筋粘结强度退化的主因是冻融循环导致混凝土强度劣化和钢筋锈蚀。而BFRP/CFRP/GFRP筋粘结强度退化,除混凝土性能劣化外,还与冻融循环引起的FRP筋树脂基体损伤和筋材与混凝土热膨胀系数差异所导致的界面空隙有关。

4) 钢筋试件峰值滑移约为 $1.6\sim 2.5\text{ mm}$,而FRP试件峰值滑移在 $2.7\sim 4.1\text{ mm}$ 之间;随着直径从 10 mm 增加到 20 mm ,钢/FRP筋试件的峰值滑移增加 $5.0\%\sim 13.3\%$;随着冻融循环次数从 0 增加到 150 ,钢/FRP筋试件的峰值滑移降低 $13.5\%\sim 23.8\%$;但筋材直径和冻融循环次数二者对峰值滑移的交互作用并不显著。

5) 建立了考虑冻融循环次数和归一化筋材直径的粘结强度和峰值滑移的预测模型,可准确预测钢、BFRP、CFRP、GFRP筋在低温冻融-氯盐环境下的粘结性能。

参考文献:

[3] ROBERT M, COUSIN P, BENMOKRANE B. Durability of GFRP

reinforcing bars embedded in moist concrete[J]. J Compos Constr, 2009, 13(2): 66-73.

[4] ROBERT M, BENMOKRANE B. Combined effects of saline solution and moist concrete on long-term durability of GFRP reinforcing bars[J]. Constr Build Mater, 2013, 38: 274-284.

[5] TORRE-CASANOVA A, JASON L, DAVENNE L, et al. Confinement effects on the steel-concrete bond strength and pull-out failure[J]. Eng Fract Mech, 2013, 97: 92-104.

[6] CHEN J F, TENG J G. Anchorage strength models for FRP and steel plates bonded to concrete[J]. J Struct Eng, 2001, 127(7): 784-791.

[7] MA Z M, ZHU F Z, BA G Z. Effects of freeze-thaw damage on the bond behavior of concrete and enhancing measures[J]. Constr Build Mater, 2019, 196: 375-385.

[8] ZHANG J W, LI H, LIU S W, et al. Effects of sulfate and freeze-thaw cycles on the bond behavior of CFRP-concrete interface[J]. Constr Build Mater, 2023, 368: 130368.

[9] WANG H, WU L L, XU X, et al. Experimental study on bond durability of GFRP bar/engineered cementitious composite exposed to freeze-thaw environments[J]. J Build Eng, 2024, 84: 108592.

[10] LONG X, XUE H Q, TAN Y, et al. Effect of ultra-low temperature freezing-thawing cycles on bending fatigue properties of PE-ECC[J]. Case Stud Constr Mater, 2023, 19: e02603.

[11] LI Y, ZHANG Y G, LIU W, et al. Effect of ultra-low temperature freeze-thaw cycle on the flexural performance of hybrid fiber RC beams subjected to monotonic and repeated loading[J]. Structures, 2024, 59: 105751.

[12] WU J Q, YANG J, GUO L, et al. Experimental study on the bond capacity of RC beams incorporating concrete strength, corrosion and loading rate[J]. Structures, 2023, 53: 228-239.

[13] ZHAO Y X, LIN H W, WU K, et al. Bond behaviour of normal/recycled concrete and corroded steel bars[J]. Constr Build Mater, 2013, 48: 348-359.

[14] BISWAS R K, IWANAMI M, CHIJIIWA N, et al. Effect of non-uniform rebar corrosion on structural performance of RC structures: A numerical and experimental investigation[J]. Constr Build Mater, 2020, 230: 116908.

[15] ZHANG P, CONG Y, VOGEL M, et al. Steel reinforcement corrosion in concrete under combined actions: The role of freeze-thaw cycles, chloride ingress, and surface impregnation[J]. Constr Build Mater, 2017, 148: 113-121.

[16] ZHOU J L, LI D S, ZHANG Z K. Bond durability of GFRP and BFRP bars embedded in PVA fiber-reinforced seawater and sea-sand concrete under seawater freeze-thaw cycles[J]. J Compos Constr, 2024, 28(5): 04024050.

[17] HUANG X T, SU T, WANG J X, et al. Bond performance of corroded steel reinforcement and recycled coarse aggregate concrete after freeze-thaw cycles[J]. Sustainability, 2023, 15(7): 6122.

[18] LU X C, GUAN B, CHEN B F, et al. The effect of freeze-thaw damage on corrosion in reinforced concrete[J]. Adv Mater Sci Eng, 2021, 2021: 9924869.

[19] CHEN M, QIAN H. Effects of natural minor corrosion levels on mechanical property and bond anchorage behavior of CRB600H steel bars[J]. Constr Build Mater, 2022, 340: 127660.

[20] 欧阳霖泽, 宋晓滨, 尹从儒, 等. 不同表面形式CFRP筋与混凝土间黏结性能研究[J]. 土木工程学报, 2026, 59(03): 47-58.

OUYANG Linze, SONG Xiaobin, YIN Congru, et al. China Civ Eng J, 2026, 59(03): 47-58.

- [21] SHAKIBA M, BAZLI M, KARAMLOO M, et al. Bond-slip performance of GFRP and steel reinforced beams under wet-dry and freeze-thaw cycles: The effect of concrete type[J]. *Constr Build Mater*, 2022, 342: 127916.
- [22] KHANFOUR M A, EL REFAI A. Effect of freeze-thaw cycles on concrete reinforced with basalt-fiber reinforced polymers (BFRP) bars[J]. *Constr Build Mater*, 2017, 145: 135–146.
- [23] SUN Z Y, FENG D C, SUN Y L, et al. Bond-slip behavior of bundled steel/FRP bars and its implementation in high-fidelity FE modeling of reinforced concrete beams[J]. *Constr Build Mater*, 2021, 286: 122887.
- [24] CUI Y F, QU S H, TEKLE B H, et al. Experimental and finite element study of bond behavior between seawater sea-sand alkali activated concrete and FRP bars[J]. *Constr Build Mater*, 2024, 424: 135919.
- [25] WANG J Z, XIAO F D, YANG J L. Experimental study on bond behavior between epoxy-coated reinforcement (ECR) and seawater sea-sand concrete (SSC) under FRP-steel confinement[J]. *Constr Build Mater*, 2023, 385: 131426.
- [26] ZHOU C H, YANG B, ZHANG Z H, et al. Bond-slip behavior of the FRP bar-sea sand concrete interface and its effect on the finite element analysis of RC beam[J]. *Constr Build Mater*, 2024, 436: 136917.
- [27] HAO Q D, WANG Y L, HE Z, et al. Bond strength of glass fiber reinforced polymer ribbed rebars in normal strength concrete[J]. *Constr Build Mater*, 2009, 23(2): 865–871.
- [28] F M FAHMY M, A S AHMED S, WU Z S. Bar surface treatment effect on the bond-slip behavior and mechanism of basalt FRP bars embedded in concrete[J]. *Constr Build Mater*, 2021, 289: 122844.
- [29] WANG Q, ZHU H, TONG Y X, et al. Bond-slip behaviour of the CFRP ribbed bars anchored with the innovative additional ribs in concrete[J]. *Compos Struct*, 2021, 262: 113595.
- [30] ALVES J, EL-RAGABY A, EL-SALAKAWY E. Durability of GFRP bars' bond to concrete under different loading and environmental conditions[J]. *J Compos Constr*, 2011, 15(3): 249–262.
- [31] WARDEH G, MOHAMED M A, GHORBEL E. Analysis of concrete internal deterioration due to frost action[J]. *J Build Phys*, 2011, 35(1): 54–82.
- [32] CHEN Y, DAVALOS J F, RAY I, et al. Accelerated aging tests for evaluations of durability performance of FRP reinforcing bars for concrete structures[J]. *Compos Struct*, 2007, 78(1): 101–111.
- [33] AYDIN F. Experimental investigation of thermal expansion and concrete strength effects on FRP bars behavior embedded in concrete[J]. *Constr Build Mater*, 2018, 163: 1–8.
- [34] BELARBI A, WANG H Z. Bond durability of FRP bars embedded in fiber-reinforced concrete[J]. *J Compos Constr*, 2012, 16(4): 371–380.
- [35] XU S H, LI A B, WANG H. Bond properties for deformed steel bar in frost-damaged concrete under monotonic and reversed cyclic loading[J]. *Constr Build Mater*, 2017, 148: 344–358.
- [36] ZHENG Y X, FAN C C, MA J J, et al. Review of research on Bond-Slip of reinforced concrete structures[J]. *Constr Build Mater*, 2023, 385: 131437.
- [37] WU Y Z, TANG P, LV H L, et al. Degradation of the bond performance between composite limestone powder concrete and steel bars under a sulfate freeze-thaw environment[J]. *Constr Build Mater*, 2023, 369: 130515.
- [38] WU J Q, GUO L, JIN L, et al. Experimental investigation of the bond performance between nonuniformly corroded reinforcing bar and concrete[J]. *J Mater Civ Eng*, 2022, 34(12): 04022346.
- [39] YANG Q, YANG S T, LIU Q, et al. Study on bond properties between near-surface mounted BFRP bars and concrete under freeze-thaw cycles in seawater[J]. *Ocean Eng*, 2024, 299: 117274.
- [40] GAO S L, ZHANG S L, JING X K. Study on the effect of strain rate on the bond performance between GFRP bars and ECC after seawater freeze-thaw cycles[J]. *J Build Eng*, 2024, 90: 109387.
- [41] LIU K H, YAN J C, MENG X X, et al. Bond behavior between deformed steel bars and recycled aggregate concrete after freeze-thaw cycles[J]. *Constr Build Mater*, 2020, 232: 117236.
- [42] ZHANG Q, LI S Y, GONG S S, et al. Study on flexural properties of basalt fiber textile reinforced concrete (BTRC) sheets including short AR-glass fibers[J]. *Front Mater*, 2020, 7: 277.
- [43] 陆采荣, 戈雪良, 梅国兴, 等. 冻融温度对水工混凝土抗冻性的影响[J]. *水力发电学报*, 2013, 32(6): 228–232.
- LU Cairong, GE Xueliang, MEI Guoxing, et al. *J Hydroelectr Eng*, 2013, 32(6): 228–232.

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Bond Performance between Steel/FRP Bar and Concrete under Low-Temperature Freeze-Thaw and Chloride Attack

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Extended Abstract

Introduction The construction of transportation infrastructure in plateau regions, such as the Sichuan-Tibet Railway and the Xinjiang-Tibet Railway, China, is progressing rapidly under the national development strategies. The annual minimum temperature in Tibet can reach -45°C , and the number of days with alternating positive and negative temperatures accounts for more than half of the year, forming an extreme low-temperature, high-frequency freeze-thaw environment. Furthermore, structures such as bridges, culverts, and tunnels in plateau areas are often subjected to erosion from de-icing salts or chlorides in the soil. The combined action of freeze-thaw and chloride attack poses a serious threat to the durability of concrete structures. Fiber-reinforced polymer composites, such as carbon fiber reinforced polymer (CFRP), basalt fiber reinforced polymer (BFRP), and glass fiber reinforced polymer (GFRP)

bars, are widely used in corrosive environments like coastal and saline areas due to their high strength and corrosion resistance. The bond performance of the steel/FRP bar-concrete interface significantly affects the mechanical behavior of concrete structures. However, the existing research mostly focuses on the room-temperature or conventional freeze-thaw environments, and the understanding of the degradation mechanism of the bar-concrete bond performance under the combined action of low-temperature freeze-thaw and chloride attack specific to plateau regions remains insufficient. It is thus necessary to conduct a targeted research on the bond performance of the steel/FRP bar-concrete interface under low-temperature freeze-thaw and chloride attack environments in the Tibetan plateau.

Methods A total of 144 pull-out specimens were fabricated. The test parameters included bar type (*i.e.*, steel, BFRP, CFRP, and GFRP bars), bar diameter (*i.e.*, 10, 16 mm, and 20 mm), and the number of freeze-thaw cycles (*i.e.*, 0, 50, 100, and 150). After 28 d standard curing, the specimens were first subjected to a 4 d water saturation pretreatment to ensure that they reached a saturated state before the freeze-thaw cycle test. A programmable high-low temperature test chamber was used to simulate a freeze-thaw cycling process. Each freeze-thaw cycle lasted for 260 min (*i.e.*, consisting of 180 min of freezing and 80 min of thawing). After every 5 freeze-thaw cycles, the specimens were placed at 20 °C and sprayed with a NaCl solution to maintain a stable moisture content. Following the designated freeze-thaw cycles, the specimens were immersed in a 5% NaCl solution for 15 d to accelerate chloride ingress. Finally, the central pull-out tests were conducted by a 300 kN MTS testing machine at a loading rate of 0.5 mm/min, with the free-end slip measured by a displacement transducer at a data acquisition frequency of 10 Hz.

Results and discussion The failure modes of the specimens are primarily governed by bar type and diameter, with freeze-thaw cycles showing negligible influence. All the steel bar specimens exhibit a pull-out failure accompanied by longitudinal cracks, with crack width increasing alongside bar diameter. The GFRP bar specimens also fail due to pull-out without concrete cracking. In contrast, for the BFRP and CFRP bars, the failure mode transitions from pull-out to splitting failure when the diameter increases from 10 mm to 16 mm. The bond strength decreases with increasing bar diameter for all bar types. When the diameter increases from 10 mm to 20 mm, the bond strength reduction for steel bars (*i.e.*, 51.7%–56.3%) is significantly greater than that for FRP bars (*i.e.*, below 18.2%). After 150 freeze-thaw cycles, the bond strength of steel bars is decreased by more than 31.4%, while the reduction for BFRP bars does not exceed 22.1%. The degradation mechanisms differ between steel and FRP bars. For steel bars, the bond degradation is mainly attributed to concrete deterioration and steel corrosion induced by the coupled environment. For FRP bars, in addition to concrete deterioration, the degradation involves resin matrix damage from freeze-thaw cycles and the formation of interfacial gaps due to the mismatch in thermal expansion coefficients between FRP and concrete. For peak slip, steel bar specimens exhibit the values between 1.6 mm and 2.5 mm, which are considerably lower than those of FRP bar specimens (*i.e.*, ranging from 2.7 mm to 4.1 mm). As the diameter increases from 10 mm to 20 mm, the peak slip is increased by 5.0%–13.3% for all the specimens. Conversely, as freeze-thaw cycles increase from 0 to 150, the peak slip is decreased by 13.5%–23.8%. Note that no significant interaction effect between bar diameter and freeze-thaw cycles on peak slip occurs. Based on the experimental data, the prediction models for bond strength and peak slip are proposed through normalization, incorporating the effects of freeze-thaw cycles and bar diameter. The data by the models are in reasonable agreement with the experimental results, with coefficients of determination (R^2) of exceeding 0.86.

Conclusions This study investigated the bond performance of steel and FRP bars with concrete under low-temperature freeze-thaw and chloride attack. The failure mode was primarily determined by bar type and diameter. The bond strength decreased with increasing diameter, and steel bars had a more pronounced reduction than FRP bars. The freeze-thaw cycles significantly reduced the bond strength for all bar types, the underlying degradation mechanisms differed between steel and FRP bars. The peak slip increased with diameter but decreased with more freeze-thaw cycles, with no significant interaction between these two factors. The proposed prediction models, which could account for freeze-thaw cycles and normalized bar diameter, effectively captured the degradation of bond strength and peak slip, providing a valuable tool for durability design and assessment of concrete structures in harsh plateau environments.

Keywords low-temperature freeze-thaw; chloride attack; bond-slip; fiber reinforced polymer bar