

基于近场动力学的冻融混凝土的剩余承载力

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摘 要: 冻融破坏是影响混凝土耐久性的重要因素。为了研究混凝土冻融损伤和剩余承载力之间的关系, 本工作基于近场动力学理论, 推导了孔隙冻胀力与冻胀力态之间的关系, 建立了混凝土冻融模型。研究了孔隙率和孔隙冻胀力对混凝土冻融后剩余承载力的影响, 通过 30、60、90 次和 120 次的冻融试验对模型进行了校核, 单轴受压承载力最大相差 4.7%。研究结果表明: 混凝土的冻融破坏速度呈现早期逐渐加快, 而后期逐渐减缓的趋势; 混凝土冻融损伤与剩余承载力之间有良好的线性关系, 决定系数可达 0.966。

关键词: 近场动力学; 混凝土冻融循环; 单轴压缩; 冻融损伤; 剩余承载力

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冻融损伤是造成寒冷地区混凝土耐久性问题的主要因素之一。针对混凝土冻融破坏机理的研究未有定论, 较为主流的主要有静水压理论^[1]和渗透压理论^[2]。静水压理论描述了混凝土内部水分结冰后产生的静水压力对混凝土的破坏作用, 渗透压理论描述了混凝土内部不同孔径孔隙中溶液的浓度差所产生的渗透压力对混凝土的破坏作用。此外, 学者们还提出了各种冻融破坏理论^[3-5], 但并未达成共识。

现阶段混凝土冻融问题的研究方法主要包括试验研究和数值模拟研究, 研究的侧重点主要可以分为宏观上的结构性能退化研究^[6-11], 微观上孔隙结构研究^[12-16]等。此外, Xiao^[17]基于三参数 Weibull 分布模型, 结合试验数据, 建立了冻融环境下混凝土损伤与冻融循环次数的概率关系曲线。Fu 等^[18]的研究结果表明动态弹性模量衰减模型优于累积冻融损伤模型, 幂函数模型优于指数函数模型, 具有更好的精度和相关性, 能较准确地反映冻融损伤规律和程度。Xie 等^[19]利用 CT 图像识别和三维重建技术, 提取冻融过程中材料内部的孔隙、骨料、水泥基质等组分, 分析了冻融作用下界面过渡区损伤演化规律。Sun 等^[20]提出了一种粘聚折减参数, 提

高了混凝土材料损伤本构模型的准确性, 建立了能反应冻融损伤的混凝土本构模型。

然而, 在冻融裂纹的模拟问题上, 传统的数值模拟方法存在网格依赖问题。近场动力学是 Silling^[21]提出的一种非局部理论, 该理论基于积分方程描述物质点间的相互作用, 最早被用于解决不连续问题。目前为止, 近场动力学已经被应用于很多领域, 包括力学^[22-23]、热学^[24]、化学^[25-26]等。在冻融问题的研究上, Zhang 等^[27]通过引入冻融损伤函数, 对近场动力学模型中的粘结断裂准则进行了修正, 建立了一种用于研究冻融循环条件下寒区隧道的衬砌损伤演化模型。Wu 等^[28]建立了一种施加冻胀力的方法, 实现了对混凝土冻融破坏全过程的模拟。Li 等^[29]在微观层面对水泥材料进行了建模, 模拟揭示了水泥浆体冻融损伤的整个过程, 包括内部裂缝的萌生和扩展, 以及表面冻融剥落。Zhang 等^[30]建立了近场动力学水-热-力耦合模型, 对混凝土的冻结破坏进行了模拟。

随着计算机技术的发展, 目前已有多种数值方法能够对混凝土冻融问题进行模拟, 但大多局限于微观层面, 缺少混凝土冻融后的宏观力学性能研究, 同时在处理裂纹问题时存在网格依赖性。因此本工作

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提出一种介观尺度的近场动力学冻融模型,建立了孔隙冻胀力和冻胀力态之间的关系,将孔隙冻胀力以力态的形式加入近场动力学运动方程中,实现了对冻融混凝土的裂纹模拟和剩余承载力的预测。

1 近场动力学理论

1.1 常规态基近场动力学

常规态基近场动力学的运动方程为^[31]:

$$\rho(x)\ddot{u}(x,t) = \int_{H(x)} T[x,t] \langle x' - x \rangle - T[x',t] \langle x - x' \rangle dV_{x'} + b(x,t) \quad (1)$$

其中: ρ 为质点 x 的密度 (kg/m^3); $b(x,t)$ 为质点 x 的体力密度 (N/m^3); $H(x)$ 表示视距范围; $dV_{x'}$ 为质点 x' 的体积 (m^3); T 是质点 x 和 x' 之间的力状态矢量 (N/m^6), 如图 1 所示。常规态基近场动力学的力状态见表 1^[31-32]。

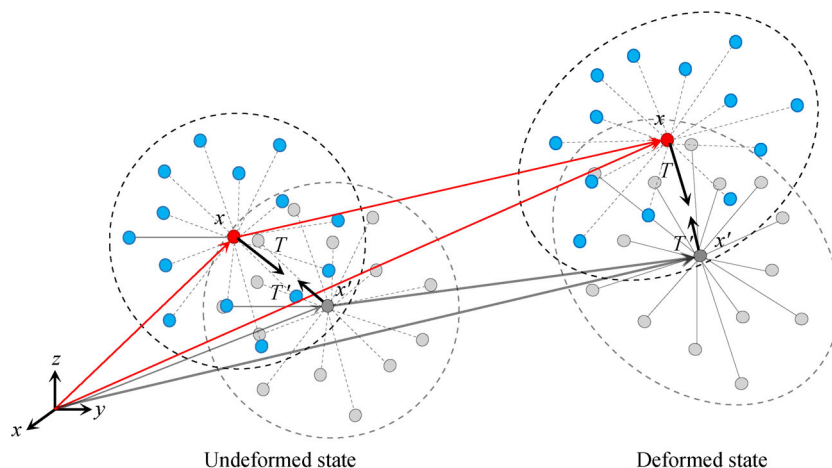


图 1 常规态基近场动力学模型

Fig. 1 Ordinary state-based peridynamics model

表 1 不同维度问题的力态表示

Table 1 Representation of force states for problems with different dimensions

Dimension	Force state T	Volume expansion θ
3D	$T = \frac{3K\theta}{m} \omega x + \frac{15G}{m} \omega e^d$	$\theta = \frac{3}{m} (\omega x) \cdot e$
Plane strain	$T = 2 \left(K - \frac{G}{3} \right) \frac{\theta}{m} (\omega x) + \frac{8G}{m} \omega e^d$	$\theta = \frac{2}{m} (\omega x) \cdot e$
Plane stress	$T = 2 \left(\frac{2\nu-1}{\nu-1} \right) \left[K + \frac{G}{3} \frac{(3\nu-1)(\nu+1)}{(2\nu-1)^2} \right] \frac{\theta}{m} (\omega x) + \frac{8G}{m} \omega e^d$	$\theta = \frac{2}{m} \left(\frac{2\nu-1}{\nu-1} \right) (\omega x) \cdot e$

其中: 加权体积 $m = (\omega x) \cdot x$, 伸长量的偏斜部分 $e^d = e - \frac{\theta x}{3}$ 。近场动力学中, 粗点积表示 $A \cdot B = \int_{H_s(x)} A \langle \xi \rangle B \langle \xi \rangle dV_\xi$ 。 K 和 G 分别为体积模量和剪切模量; ν 为泊松比; ω 为影响函数; x 为键变形前长度; e 为键的伸长量; e^d 为键的伸长量的偏斜部分。

1.2 弹塑性理论

在常规态基近场动力学中, 基于 Drucker-Prager 准则的屈服函数表示为,

$$f(\theta, e^d) = A \sqrt{9K(k)\theta} + \sqrt{\alpha G (\omega e^d) \cdot e^d} - Bc \quad (2)$$

其中: $A = \frac{2 \sin \phi}{\sqrt{3}(3 - a \sin \phi)}$, $B = \frac{6 \cos \phi}{\sqrt{3}(3 - a \sin \phi)}$, ϕ 为

内摩擦角, 单轴压缩时 a 取值为 1。屈服函数中参数的取值见表 2。

将键的伸长量的各向同性部分和偏斜部分均分解为弹性部分和塑性部分,

$$e^i = e^{ie} + e^{ip}, e^d = e^{de} + e^{dp} \quad (3)$$

其中: e^i 为键的伸长量的各向同性部分; e^{ie} 为 e^i 的弹性部分; e^{ip} 为 e^i 的塑性部分; e^d 为键的伸长量的偏斜部分; e^{de} 为 e^d 的弹性部分; e^{dp} 为 e^d 的塑性部分。

力态可以重新表示为^[23],

$$t = \kappa \omega e^i + \alpha \omega e^d \quad (4)$$

流动准则为,

$$\dot{e}^{ip} = \lambda \nabla^i \psi, \dot{e}^{dp} = \lambda \nabla^d \psi \quad (5)$$

表 2 不同维度问题的屈服函数参数取值

Table 2 Parameter values of yield function for problems with different dimensions

Dimension	k	α	κ
3D	$k = K$	$\alpha = \frac{15G}{m}$	$\kappa = \frac{9K}{m}$
Plane strain	$k = K + \frac{G}{9}$	$\alpha = \frac{8G}{m}$	$\kappa = \frac{6}{m} \left(K - \frac{G}{3} \right)$
Plane stress	$k = K + \frac{G}{9} \left(\frac{\nu+1}{2\nu-1} \right)^2$	$\alpha = \frac{8G}{m}$	$\kappa = \frac{6}{m} \left(\frac{2\nu-1}{\nu-1} \right) \left[K + \frac{G}{3} \frac{(3\nu-1)(\nu+1)}{(2\nu-1)^2} \right]$

屈服函数 $f(\underline{e}^i, \underline{e}^d)$ 的 Fréchet 导数 $\nabla^i \psi$ 和 $\nabla^d \psi$ 相关, 分别为,

$$\nabla^i \psi = A \sqrt{K(k)} \underline{x}, \quad \nabla^d \psi = \sqrt{\alpha \omega G} \frac{\underline{t}^d}{(\underline{t}^d \cdot \underline{t}^d)^{\frac{1}{2}}} \quad (6)$$

塑性乘子表示为^[33],

$$\lambda = \frac{\kappa(\underline{\omega} \dot{\underline{e}}^i) \cdot \nabla^i \psi + \alpha(\underline{\omega} \dot{\underline{e}}^d) \cdot \nabla^d \psi}{\kappa(\underline{\omega} \nabla^i \psi) \cdot \nabla^i \psi + \alpha(\underline{\omega} \nabla^d \psi) \cdot \nabla^d \psi} \quad (7)$$

1.3 临界能量密度断裂准则

在近场动力学中, 质点的损伤定义为:

$$\phi(x) = \frac{\int d(\xi) dV_{x'}}{\int dV_{x'}} \quad (8)$$

其中: $d(\xi)$ 表示键的状态, 当 $d(\xi) = 0$ 时, 表示键未受损, 当 $d(\xi) = 1$ 时, 表示键损伤。由此计算得到 $\phi(x)$ 的取值范围在 0~1 之间, 数值越大, 则表示损伤程度越严重。

键所包含的能量密度为^[34]:

$$\omega = \int_0^t T \langle \xi \rangle \dot{\underline{e}} \langle \xi \rangle dt = \int_0^s T \langle \xi \rangle d\underline{e} \quad (9)$$

临界能量密度准则可以表述为: 当键所包含的能量密度 ω 超过临界能量密度 ω_c 时, 键断裂。临界能量密度表示为^[34–35]:

$$\begin{cases} \omega_c = \frac{4G_c}{\pi \delta^4} & 3D \\ \omega_c = \frac{3G_c}{2\delta^3 h} & 2D \end{cases} \quad (10)$$

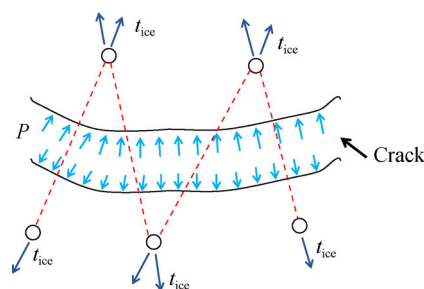
其中: G_c 为能量释放率(N/m); h 为二维问题的板厚(m)。

1.4 近场动力学孔隙冻胀力理论

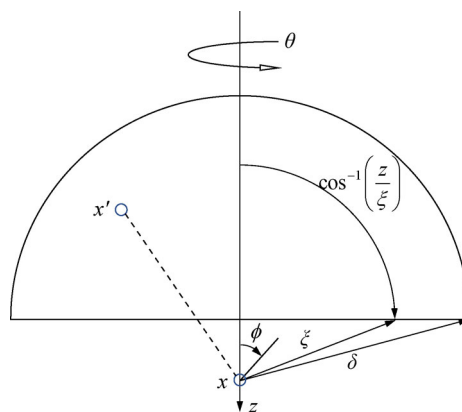
近场动力学中, 键力以将 2 质点拉近为正, 孔隙冻胀力使 2 质点远离, 应为负值。冻胀力态将被施加在受孔隙冻胀力的键上, 如图 2 所示。

定义裂纹面上的孔隙冻胀力为 P , 施加于近场动力学质点间的冻胀力态为 T_{ice} , 该力态不随质点间键的破坏而消失, 且该力态大小与“键”的长度

$$T_{ice} = t_{ice} \cdot (1 - \xi / \delta) \quad (11)$$



(a) Pore frost heaving force diagram



(b) Integration diagram

图 2 近场动力学孔隙冻胀力计算示意图

Fig. 2 Schematic diagram of peridynamic pore frost heaving force calculation

参照近场动力学临界能量释放率的积分表达^[36], 得到孔隙冻胀力 P 与冻胀力态 T_{ice} 的关系:

$$\begin{cases} P = \int_0^\delta \int_0^{2\pi} \int_z^\delta \int_0^{\arccos(z/\xi)} t_{ice} \cdot (1 - \xi / \delta) \cos \phi \xi^2 \sin \phi d\phi d\xi d\theta dz = \\ t_{ice} \left(\frac{\pi \delta^4}{30} \right) 3D \\ P = 2h \int_0^\delta \int_z^\delta \int_0^{\arccos(z/\xi)} t_{ice} \cdot (1 - \xi / \delta) \cos \phi \xi d\phi d\xi dz = t_{ice} \left(\frac{\pi h \delta^3}{24} \right) 2D \end{cases} \quad (12)$$

冻胀力态表示为:

$$\begin{cases} T_{ice} = \frac{30P}{\pi\delta^4}(1-\xi/\delta) & 3D \\ T_{ice} = \frac{24P}{\pi h\delta^3}(1-\xi/\delta) & 2D \end{cases} \quad (13)$$

在混凝土冻融破坏中, 孔隙冻胀力一般被认为是孔隙压力。目前计算孔隙压力常借助有限元方法,

结合断裂能释放原理, 建立冻融循环次数与塑性耗散能密度之间的关系, 并提取孔隙压力。

2 实验

本工作的混凝土采用青岛烨华建中建筑工程有限公司购买的商品混凝土, 混凝土强度为 C40, 尺寸为 100 mm×100 mm×100 mm, 配合比如表 3 所示。

表 3 混凝土配合比
Table 3 concrete mixture proportions

Aggregate	Sand	Cement	Water	Water reducer	Slag powder	Fly ash
960	735	340	175	11	80	40

2.1 开口孔隙率

混凝土的孔隙包括与开口孔隙和闭口孔隙。在冻融问题中, 开口孔隙严重影响混凝土的冻融性能。因此本研究中测定的孔隙率只考虑开口孔隙。开口孔隙率按如下方法测定, 取 3 块混凝土试样, 分别测定干燥质量 m_1 和饱和面干质量 m_2 , 并根据下式计算开口孔隙率,

$$p = \frac{m_2 - m_1}{\rho_w V_c} \quad (14)$$

其中: ρ_w 为水的密度(kg/m^3); V_c 为混凝土的表观体积(m^3)。

2.2 冻融循环

冻融试验机为 TDR-15D 混凝土快速冻融试验机, 冻融循环次数设置为 0、30、60、90 次和 120 次, 温度范围为 $(-18 \pm 2) \sim (18 \pm 2)^\circ\text{C}$, 每个循环次数下设置 3 块混凝土进行重复性试验, 减少随机性。试验开始前, 首先将混凝土浸泡在清水中 4 d, 保证水充分浸透混凝土。随后启动冻融试验机, 按预先设置的循环次数和温度进行冻融循环试验。试验结束后, 取出混凝土试块擦干表面浮渣和水分, 编号并分别称取其质量和检测动弹性模量。

2.3 抗压强度

冻融循环试验结束后, 于 MTS Exceed E64.305 电液伺服万能试验机上进行单轴抗压试验。

3 模型验证

3.1 冻融云图分析

冻融破坏与混凝土的孔隙有很强的相关性^[1], 孔隙尺寸相较于混凝土尺寸有非常大的差别, 若根据孔隙尺寸进行建模将耗费巨大的计算成本。本文参考 Wu^[28]的做法, 用断裂键与所有的键的数量比值来表征孔隙率。由于本模型不涉及温度场, 每个

时间步即代表一次冻融循环。

试验测定的开口孔隙率为 1.68%, 通过有限元方法计算得到的孔隙冻胀力为 58.3 MPa。获得相关参数后, 采用近场动力学理论进行冻融模拟, 模拟通过 Matlab 编程实现。模拟采用平面模型, 划分为 200×200 个质点, 根据开口孔隙率计算初始断裂的键, 并在这些键两端的质点施加冻胀力态, 即式(13)。当裂纹扩展产生的新断裂的键时, 在新断裂的键两端的质点赋予冻胀力态, 以模拟水分迁移引起的孔隙冻胀力。

试验得到的 120 次冻融循环裂纹图与模拟得到的损伤图如图 3 所示。图 3a~图 3b 分别为冻融试验后混凝土表面出现的剥落和裂纹形貌。图 3c 为模拟的混凝土损伤结果, 可以看出四周出现较为严重的损伤, 即为表面剥落; 位于中间的损伤呈现出放射扩散状, 即为裂纹。近场动力学只描述质点的损伤, 对于一个家族成员完整的质点, 一般认为, 当其一侧所有的键断裂时形成裂纹, 此时该质点的损伤值约为 0.38^[37]。图 3d 将损伤值大于 0.38 的质点设置为白色, 表示此处生成裂纹, 并且将完全脱离的部分删除, 表示混凝土冻融后表面剥落。

3.2 冻融后力学性能分析

荷载作用会使混凝土的裂纹受压闭合^[38], 本工作将受到冻融破坏的键的临界能量释放率设置为 0, 一旦受拉则立刻破坏, 而受压的键能够继续承载。模型的加载示意图如图 4 所示, 前文冻融模拟的结果表明混凝土表面出现了剥落, 为了避免加载模拟中力的传递不平顺, 在加载模拟时恢复边界 3 层断裂的键, 并在上下加载面额外增加 3 层质点厚度的边界层。

图 5a 为冻融后混凝土单轴压缩的试验和模拟应力-应变曲线比较结果。实线表示试验结果, 虚线

表示模拟结果。试验组经过冻融后，弹性模量呈现早期小，随后增大的现象。这是因为裂纹间填充了冰和破碎的混凝土屑，混凝土处于松散的状态，因此在加载前期弹性模量较低，随着荷载增加使裂纹

闭合后，混凝土的刚度随之增加。模拟组则没有考虑裂纹间填充的混凝土碎屑，因此早期弹性模量不变，而随着荷载增大，混凝土存在不同数量的初始裂纹使得弹性模量出现不同程度的下降。

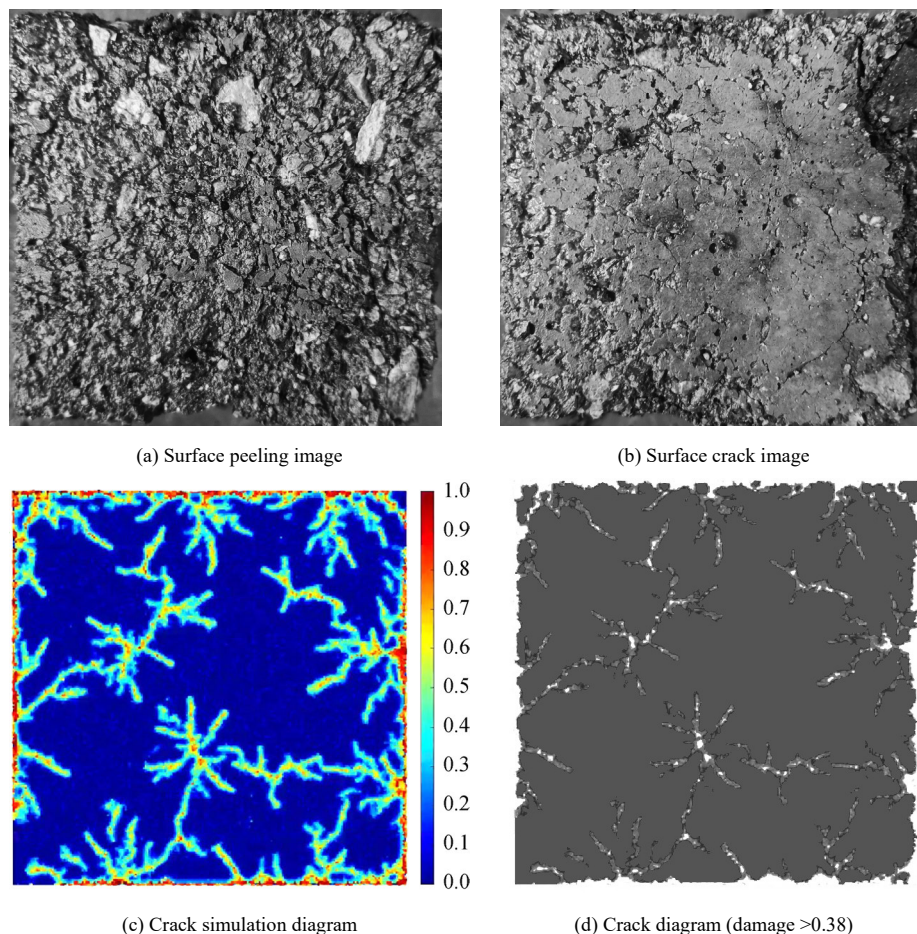


图3 试验与模拟图像比较

Fig. 3 Comparison of experimental and simulated images

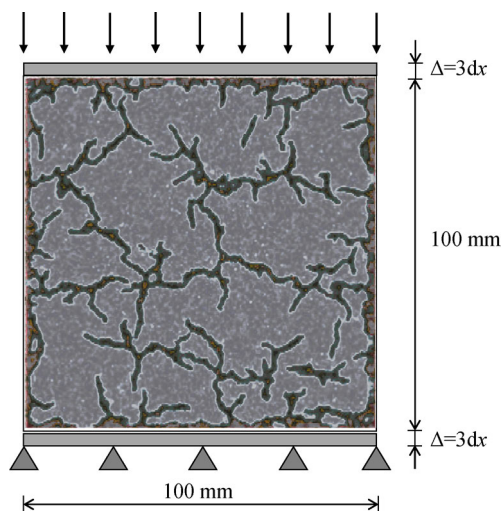


图4 单轴压缩加载示意图

Fig. 4 Uniaxial compression loading schematic diagram

图 5b 为不同冻融循环次数下试验和模拟的极限荷载变化趋势。可以看出试验和模拟结果有较高的吻合度，试验测得的峰值抗压强度分别为 51.15、50.18、48.74、46.14、43.58 MPa，模拟计算得到的峰值抗压强度分别为 50.77、50.71、47.86、43.96、42.22 MPa，最大误差为 4.7%。试验测得的冻融后剩余峰值抗压强度百分比分别为 98.1%，95.3%，90.2%，85.2%，模拟计算得到的冻融后剩余峰值抗压强度百分比分别为 99.8%，94.2%，86.5%，83.1%，最大相差 3.7%。

4 讨论

4.1 开口孔隙率对混凝土冻融性能的影响

混凝土的开口孔隙率是影响冻融性能的关键因

素, 孔隙的数量和大小决定了孔隙水的含量, 本节设置开口孔隙率分别为 1.0%、3.0%、5.0%、7.0% 和 9.0%, 孔隙冻胀力为 40 MPa。图 6 为不同开口孔隙率下 120 次冻融循环的裂纹模拟结果。当开口孔隙率为 1.0% 和 3.0% 时, 混凝土不出现冻融裂纹

或出现很小的冻融裂纹, 对承载能力几乎没有影响; 当开口孔隙率为 5.0% 时, 混凝土出现较多的裂纹, 并且主要集中在外侧, 此时的破坏形式主要为表面混凝土剥落; 当开口孔隙率为 7.0% 和 9.0% 时, 除表面剥落外, 冻融裂纹布满整个混凝土。

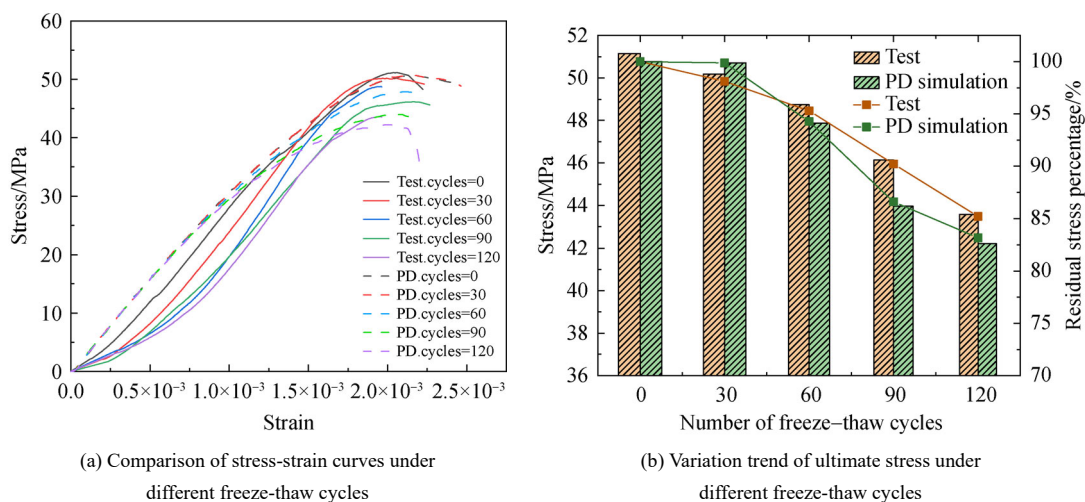


图 5 冻融循环试验与模拟结果比较

Fig. 5 Comparison of freeze-thaw cycle test and simulation results

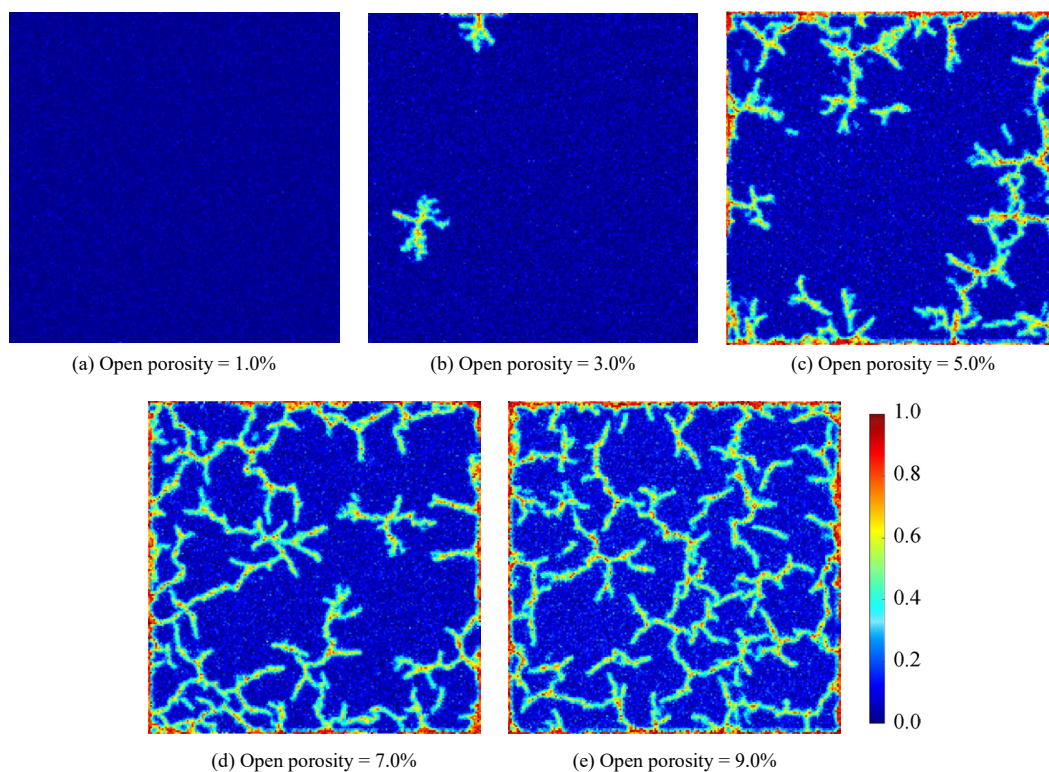


图 6 不同开口孔隙率下冻融裂缝模拟示意图

Fig. 6 Simulation diagram of freeze-thaw crack under different open porosity

图 7 为不同开口孔隙率下的混凝土冻融性能曲线。图 7a 中纵坐标表示损伤值大于 0.38 的质点数量, 图 7b 中纵坐标表示混凝土的单轴受压承载力。

可以看出开口孔隙率为 1.0%、3.0% 和 5.0% 的损伤曲线和应力曲线呈现出相似的变化规律, 即质点的损伤数量与混凝土的承载力呈较为明显的负相关。

值得注意的是, 开口孔隙率为 9.0% 的模型的质点损伤数量在各冻融时期均大于开口孔隙率为 7.0% 的模型, 但二者 120 次冻融循环的承载力却基本相等, 分别为 41.74 MPa 和 41.71 MPa。此外, 对开口孔隙率为 9.0% 的模型, 损伤数量在冻融后期增长缓慢, 90 次冻融循环和 120 次冻融循环的承载力也几乎相同, 分别为 41.80 MPa 和 41.71 MPa, 这说明此时混凝土的冻融破坏几乎达到极限。

4.2 孔隙冻胀力对混凝土冻融性能的影响

混凝土的孔隙冻胀力受到孔隙孔径大小、温度

变化范围等因素共同影响, 同样是影响混凝土冻融性能的关键因素。本节设置孔隙冻胀力分别为 40、50、60、70 MPa 和 80 MPa, 开口孔隙率为 1.68%。图 8 为不同孔隙冻胀力下 120 次冻融循环的裂纹模拟结果。当孔隙冻胀力为 40 MPa 时, 在 120 次冻融循环次数内未达到开裂条件。当孔隙冻胀力达到 70 MPa 时, 在 120 次冻融循环次数内裂纹已经完全贯穿混凝土。

图 9 为不同孔隙冻胀力下的混凝土冻融性能曲线。图 9a 中纵坐标表示损伤值大于 0.38 的质点数

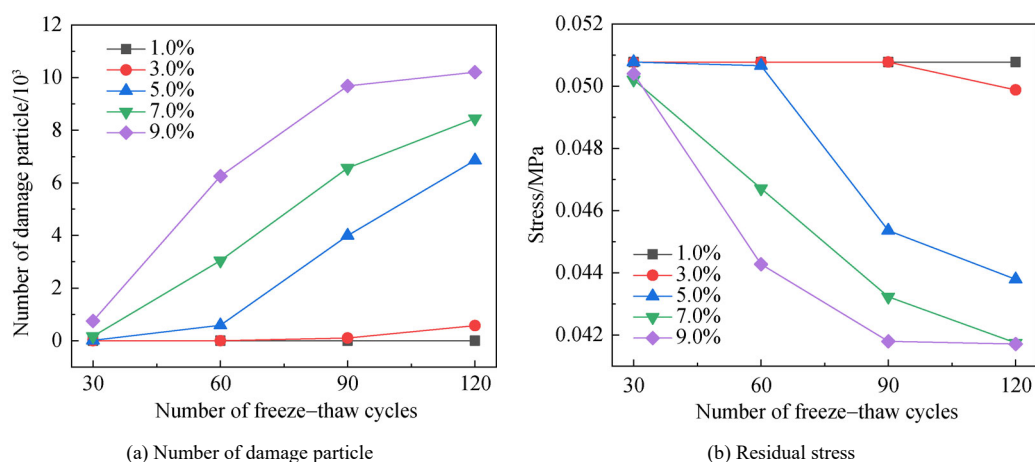


图 7 不同开口孔隙率的混凝土冻融性能
Fig. 7 Freeze-thaw performance with different opening porosity

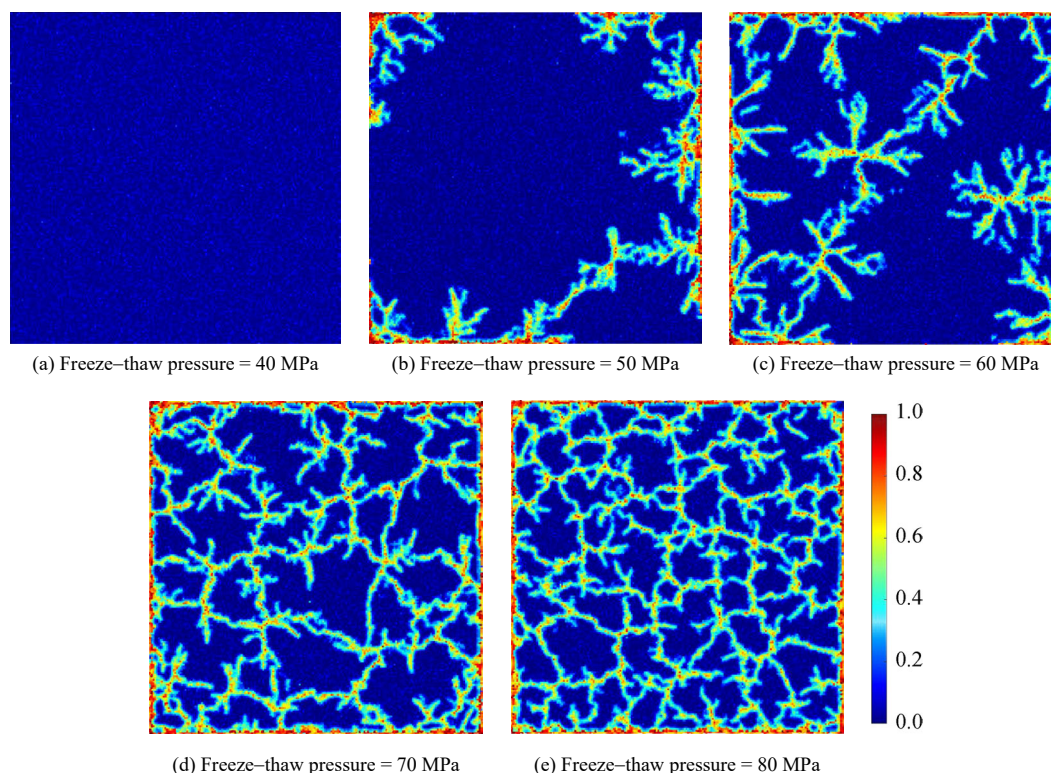
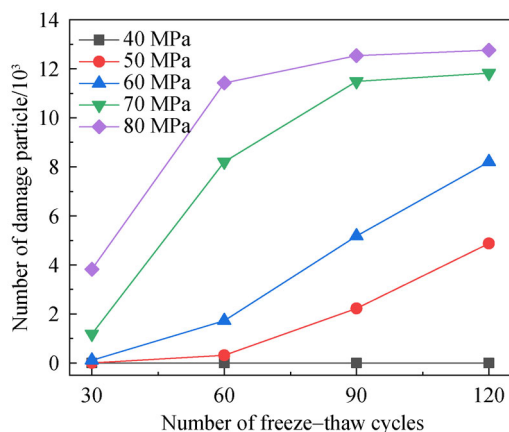
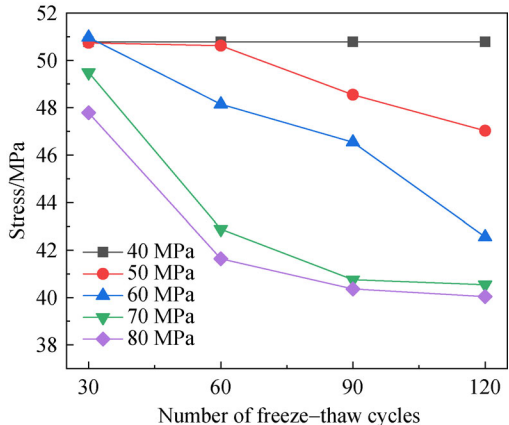


图 8 不同孔隙冻胀力下冻融裂缝模拟图
Fig. 8 Simulation diagram of freeze-thaw crack under different freeze-thaw pressures

量, 图 9b 中纵坐标表示混凝土的单轴受压承载力。当孔隙冻胀力为 50 MPa 和 60 MPa 时, 损伤曲线增长的速度和应力曲线下降的速度均随冻融循环次数增加。这是因为冻融损伤较小时, 每产生新的损伤都可能成为冻融裂纹的起点, 因此损伤会促进新的损伤。当孔隙冻胀力为 70 MPa 和 80 MPa 时, 损伤曲线增长的速度和应力曲线下降的速度均随冻融循环次数降低。这是因为此时混凝土内部的损伤和裂纹数量已经趋于极限, 混凝土已为碎块, 应该被认为完全丧失承载能力。



(a) Number of damage particle



(b) Residual stress

图 9 不同孔隙冻胀力下的混凝土冻融性能

Fig. 9 Freeze-thaw performance with different freeze-thaw pressure

4.3 损伤与剩余承载力的联系

由 4.1 节和 4.2 节的分析可知, 混凝土冻融破坏与开口孔隙率和孔隙冻胀力有关, 且由不同的初始条件计算得到的破坏稳定值也有所不同。因此针对不同情况的冻融问题, 要建立不同的冻融破坏界限。图 10 为任意 3 组模型的冻融损伤百分比-冻融循环次数曲线及其导函数曲线。原函数曲线斜率

先增后减, 最后达到稳定, 本工作认为混凝土冻融破坏的界限应处于曲线斜率降低的区间内, 因此取导函数曲线峰值点和右侧斜率为 0 的点的中点视为临界冻融循环次数, 作为混凝土冻融破坏的界限, 如图 10 中虚线所示。

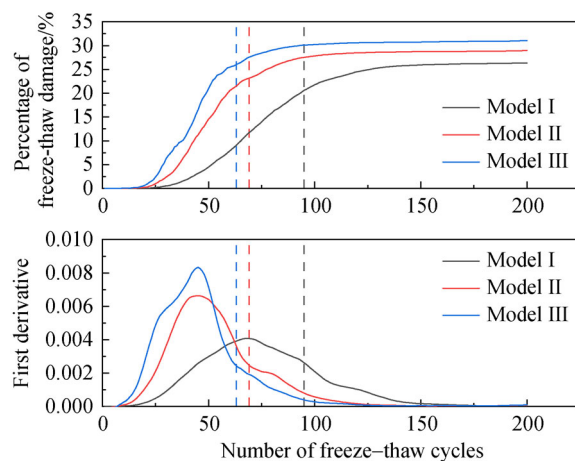


图 10 冻融损伤百分比-冻融循环次数曲线及其导函数曲线
Fig. 10 Freeze-thaw damage percentage-freeze-thaw cycles curve and its derivation curve

确定混凝土冻融破坏的界限后, 建立混凝土失效前损伤与剩余承载力的联系。如图 11 所示为冻融损伤百分比-剩余承载力百分比回归曲线, 数据来源于 4.1 节和 4.2 节模拟结果, 并删除相同的点, 得到共 33 组数据。回归曲线的决定系数 R^2 为 0.966, 表明由近场动力学冻融模型计算得到的混凝土损伤百分比和剩余承载力有显著的线性关系。结合混凝土冻融破坏界限的研究, 即可实现对冻融混凝土全寿命剩余承载力的预测。

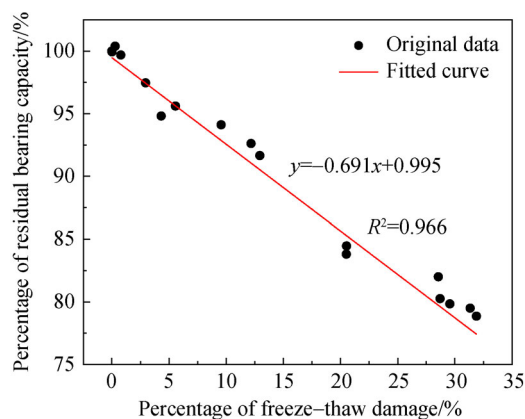


图 11 冻融损伤百分比-剩余承载力百分比回归曲线
Fig. 11 Freeze-thaw damage percentage-residual bearing capacity percentage regression curve

对于本工作研究的混凝土模型, 计算冻融损伤

用时约 30 s, 计算单轴受压承载力用时约 10 800 s。若结合图 11 的回归结果, 预测冻融损伤后混凝土的剩余承载力效率可以提高约 360 倍。

5 结论

建立了混凝土冻融破坏的近场动力学模型, 通过推导孔隙冻胀力和冻胀力态之间的关系, 实现了近场动力学冻融问题中力态的统一表示形式。模拟了混凝土冻融裂纹的萌生和扩展, 以及混凝土冻融后的剩余承载力。此外, 采用边长为 100 mm 的 C40 混凝土立方体试块进行了冻融循环试验和加载试验。结果表明:

1) 近场动力学冻融模型在模拟混凝土冻融的表面剥落和裂纹扩展现象上与试验相似。冻融混凝土的单轴受压模拟结果与试验结果吻合较好, 应力值最大相差 4.7%, 剩余承载力百分比最大相差 3.7%。

2) 混凝土的冻融损伤速率呈现早期逐渐增大, 而后期逐渐变缓的趋势。混凝土的冻融破坏表现为表面损伤剥落, 内部裂纹交错扩展。

3) 通过回归分析, 确定了冻融损伤与剩余承载力之间的线性关系, 决定系数可达 0.966。相比采用力学模型计算, 根据冻融损伤情况采用回归曲线对剩余承载力进行预测, 可将效率提高约 360 倍。

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Residual Bearing Capacity of Freeze–Thawed Concrete Based on Peridynamics

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Extended Abstract

Introduction Freeze–thaw damage is a significant factor affecting the durability of concrete in cold regions. The research on the mechanisms of freeze–thaw damage in concrete remains inconclusive. Currently, the primary methods for investigating freeze–thaw issues in concrete include experimental research and numerical simulation studies. The research focus can be categorized into two areas: macro structural performance degradation and micro pore structure analysis. However, most current value methods are limited to the micro level when simulating the freeze–thaw behavior of concrete, and there is a lack of research on the macroscopic mechanical properties of concrete following freeze–thaw cycles. At the same time, grid dependence arises when addressing crack problems. Consequently, this work proposes a mesoscopic-scale peridynamic freeze–thaw model. The relationship between pore frost heaving force and frost heaving force state is established. The pore frost heaving force is incorporated into the peridynamic motion equation as a force state, enabling the simulation of cracks and the prediction of residual bearing capacity in freeze–thaw damaged concrete.

Methods The commercial concrete purchased by Qingdao Yehua Jianzhong Construction Engineering Co., Ltd. is used. The concrete size is 100 mm × 100 mm × 100 mm, the concrete strength is C40, and the water-cement ratio (W/Cs) is 0.51. The freeze–thaw cycle test was carried out by TDR-15D concrete rapid freeze–thaw test machine. The number of freeze–thaw cycles was set to 0, 30, 60, 90 times and 120 times, and the temperature range was (−18±2)–(18±2) °C. Three concretes were set up for repeated tests under each cycle. Before the start of the test, the concrete was first immersed in water for 4 d to ensure that the water fully penetrated the concrete. Then the freeze–thaw test machine was started, and the freeze–thaw cycle test was carried out according to the preset cycle times and temperature. After the test, the concrete test block was taken out to dry the surface scum and water, numbered and weighed, and the dynamic elastic modulus was detected. The uniaxial compression test was carried out on the MTS Exceed E64.305 electro-hydraulic servo universal testing machine.

The open porosity measured by the test is 1.68%, and the pore frost heaving force calculated by the finite element method is 58.3 MPa. After obtaining the relevant parameters, the freeze–thaw simulation is realized by matlab programming based on the peridynamics theory.

Results and discussion The results of the freeze–thaw tests and uniaxial compression tests were compared with the simulation

outcomes. The diagram illustrating simulated freeze–thaw damage depicts the phenomenon of surface spalling and internal crack propagation, which aligns with the test results. The uniaxial compression stress–strain curves exhibit a similar trend, with a maximum difference in peak stress of 4.7%. After undergoing freeze–thaw cycles, the elastic modulus of the test group was initially low but subsequently increased. This is due to the cracks being filled with ice and broken concrete chips, resulting in a loose state of the concrete, which leads to a low elastic modulus during the initial stages of loading. As the load increases, the stiffness of the concrete also increases once the crack has closed.

The open porosity and pore frost heaving forces of concrete are critical factors influencing its freeze–thaw performance. The freeze–thaw damage and residual bearing capacity of concrete with open porosities of 1.0%, 3.0%, 5.0%, 7.0% and 9.0%, as well as pore frost heaving forces of 40, 50, 60, 70 MPa and 80 MPa, are discussed in detail. The influence of open porosity and pore frost heaving forces on the freeze–thaw performance of concrete follows a similar pattern. When the two values are low, there are no freeze–thaw cracks or minor freeze–thaw cracks in the concrete. When the two values are large, the freeze–thaw cracks cover the whole concrete. The rate of decrease in the residual bearing capacity of concrete initially increases and then subsequently decreases. This is because when the freeze–thaw damage is small, each new damage may become the starting point of the freeze–thaw crack, so the damage will promote the new damage. The damage caused by freezing and thawing in the later stages reaches saturation, resulting in a limited number of cracks and overall damage in the concrete. The concrete has been damaged and should be regarded as having completely lost its load-bearing capacity.

Conclusions The main conclusions of this paper are summarized as following. The peridynamic freeze–thaw model closely resembles the test used to simulate surface spalling and crack propagation in concrete subjected to freeze–thaw cycles. The simulation results of uniaxial compression for freeze–thaw concrete align closely with the experimental findings. The maximum difference in stress values is 4.7%, while the maximum difference in residual bearing capacity is 3.7%. The rate of freeze–thaw damage in concrete increases gradually during the early stages and then slows down in the later stages. The freeze–thaw damage of concrete is characterized by surface damage spalling and internal crack staggered expansion. Through regression analysis, the linear relationship between freeze–thaw damage and residual bearing capacity is established, with a coefficient of determination reaching 0.966. Compared to the mechanical model calculations, the regression curve is utilized to predict the residual bearing capacity based on freeze–thaw damage, resulting in an efficiency increase of approximately 360 times.

Keywords peridynamic; concrete freeze–thaw cycle; uniaxial compression; freeze–thaw damage; residual bearing capacity