

高温环境下超高性能混凝土力学性能及劣化机制研究进展

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摘 要: 高温火灾环境下的超高性能混凝土(UHPC)性能劣化是诱发工程结构损伤失效的主因, 解析其宏观性能与微结构演化间内在关联机制是提升混凝土耐高温性能的关键。本文综述了高温环境下 UHPC 的宏观力学性能与微结构演化特征, 总结了高温环境下 UHPC 性能劣化机制, 探讨了现有研究中关于 UHPC 高温性能存在的关键问题, 并对未来进一步的研究方向提出展望。

关键词: 高温环境; 超高性能混凝土; 力学性能; 微结构特征; 劣化机制

中图分类号: TU528 文献标志码: A 文章编号: 0454-5648(2024)11-3470-12

网络出版时间: 2024-08-22



作为现代工程建设的基础性建筑材料, 混凝土因其优异的工作性能、力学性能、耐久性能、易建造性及安全性被广泛应用于各行业的结构工程中。近年来, 随着现代工程的结构设计逐渐新颖化以及建造技术的难度与需求相应提高, 同时在材料科学快速发展的潜在背景和技术积累下, 超高性能混凝土(UHPC)应运而生, 且其配制与生产技术也得到极大提升^[1]。为此, 针对不同服役环境和场景的建筑材料差异化需求, 多种新型 UHPC 材料被研发并被逐渐应用于重要建设工程中, 如高层或超高层建筑、大跨径桥梁、地下结构工程、核电工程及大型堤坝等。然而, 火灾是现代工程安全最常面临的主要灾害之一, 严重威胁到 UHPC 构件的结构稳定性和使用寿命^[2]。在高温环境下, UHPC 会因其内外温度的骤然失衡出现水化产物脱水、分解、脆化以及热变形不协调等一系列的物理化学破坏现象, 且该破坏现象在强度等级越高的混凝土中尤为突出^[3-4]。因此, 系统开展 UHPC 的高温性能研究并提出切实可行的改善技术措施, 对提升结构工程的防火减灾能力具有重要意义。

综上所述, UHPC 材料的耐高温性能是否稳定

事关火灾环境下建筑结构的长久安全服役大计, 通过系统概述高温环境下的 UHPC 力学性能及劣化机制, 对开发出一种耐高温性能优异的新型建筑材料具有迫切的现实需求^[5-7]。为此, 本文系统整理、分析和总结了 UHPC 在高温环境下的宏观力学性能和微结构劣化特征, 探讨了目前 UHPC 高温爆裂破坏的几种主要劣化理论, 并对未来研究方向进行了展望。基于本文综述结论, 可为 UHPC 材料的耐高温设计与火灾后结构的检测、评估及修复提供一定的参考依据。

1 高温环境下 UHPC 力学性能

1.1 抗压强度

目前, 关于 UHPC 在高温环境中的研究主要涉及高温下的抗压强度和高温后的残余抗压强度, 而由于测试条件受限, 现有多数研究主要集中在后者^[8-9]。在高温下, 由于 UHPC 内部结构致密、游离水含量低且毛细孔较多, 使得 UHPC 内部蒸汽压增加以及温度梯度分布增大, 最终导致高温爆裂现象^[10]。如图 1 所示, 高温后 UHPC 残余抗压强度在 400 °C 内保持稳定或有所增加, 在 400 °C 后则强度损失急速

收稿日期: 2024-03-30。 修订日期: 2024-05-07。

基金项目: 国家自然科学基金(U22B2076, 52078369, 52108241); 2021 年产业技术基础公共服务平台(2021-H029-1-1); 上海市优秀学术带头人计划 (22XD1403300)。

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Received date: 2024-03-30. Revised date: 2024-05-07.

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增大, 当温度超过 800 °C 后则仅剩初始强度的 15% 左右^[11-12]。UHPC 残余抗压强度在初期增加的原因在于其内部的孔隙水在高温作用下被蒸发并加速扩散, 促进了基体内未水化水泥颗粒的二次水化作用, 从而提高了 UHPC 强度^[13]。然而, 影响高温后 UHPC 残余强度的因素众多, 如混凝土强度等级^[14]、冷却方式^[15]、原材料组成^[16]、含水率^[17]、纤维种类^[18]及试件尺寸^[19]等, 均会使得残余强度呈现不同趋势。此外, 纤维的掺入可极大提高 UHPC 的高温力学性能, 并抑制其高温爆裂行为^[18]。通过添加钢纤维或聚丙烯(PP)纤维, 特别是在含硅灰的高强度混凝土中, 可在一定程度上抵消高温对混凝土抗压性能的负面影响, 并改善 UHPC 的残余抗压性能。通过将不同种类的纤维混合掺入 UHPC, 对其高温后残余抗压强度的改善效果最为显著^[20]。采用聚乙烯醇(PVA)纤维制备的工程水泥基复合材料(ECC)具有较 PP 纤维和钢纤维制备的 UHPC 具有更优的耐高温性能, 即使在高温环境下也不会出现爆裂现象^[21]。基于现有研究, 未来还需针对高温下 UHPC 抗压强度及其高温爆裂机制进行针对性研究, 以期为提高 UHPC 耐高温力学性能提供理论支持。

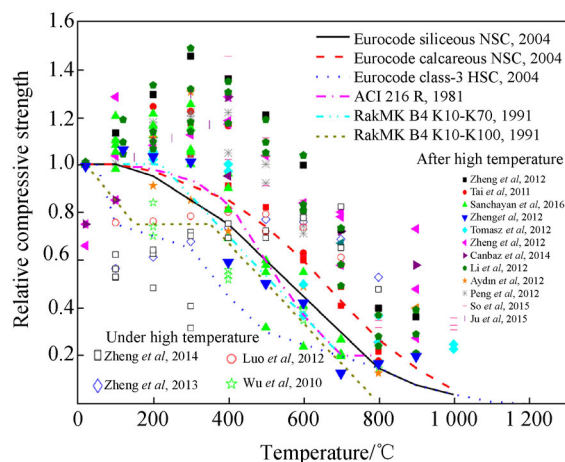


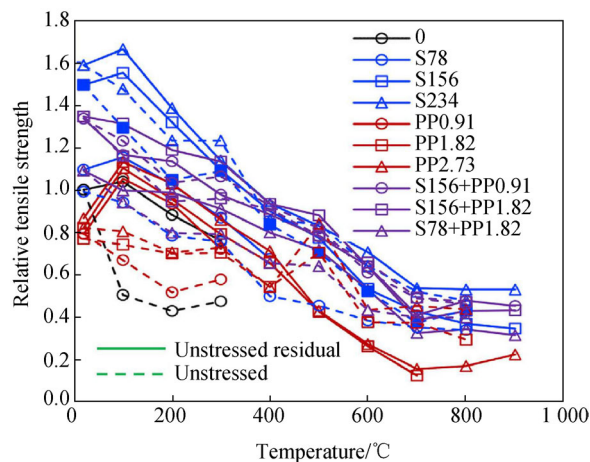
图 1 高温环境下纤维混凝土的抗压强度变化^[9]

Fig. 1 Changes in compressive strength of fiber reinforced concrete under high temperature environment^[9]

1.2 抗拉强度

在高温环境下, UHPC 的抗拉强度通常随温度的升高而呈线性降低的趋势(见图 2)^[22-23]。在室温下, 掺入高强度的钢纤维、碳纤维或玄武岩纤维对混凝土抗拉性能的提升作用较大, 而低强度的 PP 纤维、PVA 纤维或 PE 纤维效果则稍显逊色^[24]。同时, 通过掺入较长的纤维及混杂纤维也能提高 UHPC 的抗拉性能^[25]。高温环境下, 纤维的掺入也可显著改善 UHPC 的抗高温爆裂作用, 特别是钢纤

维与 PP 纤维的组合^[26-27]。钢纤维可提高 UHPC 内部的导热性并降低其温度梯度分布, PP 纤维则会在 145 °C 时熔融并在 UHPC 内部形成多条可供水蒸汽通过的微孔道。钢纤维与混杂纤维不仅可使 UHPC 在高温下仍保持较高抗拉性能, 还能在高温后恢复部分拉伸强度。然而当温度超过一定范围后, 纤维增强效果则会大幅降低。UHPC 在高温下的抗拉强度通常低于高温后, 仅当 UHPC 含有大量 PP 纤维时才会出现少数例外情况^[28]。此外, 当温度从 20 °C 升至 800 °C, 掺入 PVA 纤维的 ECC 抗拉强度先增加后降低, 且在 200 °C 时达到峰值。原因在于 PVA 纤维耐热性较差, 其随温度的增加而逐渐软化且自身韧性降低, 最后造成强度下降^[29]。因此, 提出高温环境下 UHPC 的不同纤维类型与掺量最优组合, 并开展纤维对 UHPC 高温后抗拉恢复特性研究对提升 UHPC 高温抗拉性能至关重要。



S is steel fiber. PP is polypropylene.

图 2 高温环境下 UHPC 的抗拉强度变化^[30]

Fig. 2 Change in tensile strength of UHPC under high temperature environment^[30]

1.3 抗弯强度

目前, 关于 UHPC 在高温下的力学研究主要集中在抗压和抗拉性能, 关于抗弯性能研究则相对较少^[31]。现有研究大多关注常温下的纤维混凝土抗弯性能, 不同几何形状和纤维种类(如钢纤维、PVA 纤维、PP 纤维、棕榈纤维、棒材纤维和碳纤维)的混杂可显著提高 UHPC 的抗弯性能^[32-34]。然而, UHPC 在高温后的抗弯强度与抗拉强度类似, 即随着温度的升高而近乎线性降低(见图 3)^[35]。PP 纤维的掺入与否, 均对高强度 UHPC 弯曲性能的影响较小^[30]。相较于单掺 PP 纤维, 钢纤维的复合掺入可极大提高纤维 UHPC 的高温残余弯曲强度, 其主要得益于钢纤维冷却后的拉伸强度恢复^[26]。此外, 矿物掺合料

也对 UHPC 高温残余抗弯强度有影响, 磨细矿渣对提高 UHPC 高温残余抗弯强度有利, 硅灰则相反^[36]。在 UHPC 中掺入 10% 矿渣和 30% 粉煤灰时, 其 1 000 °C 后试样的残余抗折强度为 8 MPa, 为 200 °C 时强度的 22%^[37]。现有研究主要关注 UHPC 抗弯性能演变规律, 后续研究可从高温下纤维与 UHPC 基体间界面损伤角度来进一步探讨 UHPC 抗弯性能劣化机理。

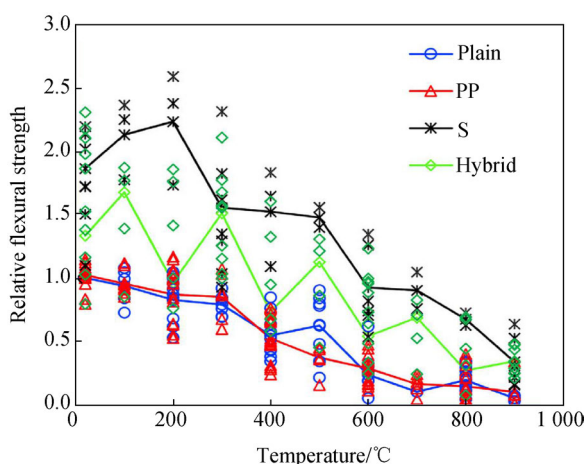


图3 高温环境下纤维混凝土的抗弯强度变化^[30]

Fig. 3 Change in flexural strength of fiber reinforced concrete under high temperature environment^[30]

1.4 粘结强度

UHPC 的粘结性能主要包括钢筋与 UHPC 间的粘结强度以及钢纤维与 UHPC 间的粘结强度。由于高温下的粘结测试技术要求较高, 故相关研究主要是围绕高温后的 UHPC 粘结强度开展。高温下钢筋 UHPC 粘结强度的降低不仅与温度有关, 还与测试程序、钢筋直径与形状、混凝土强度等级及受力方向等有关^[38–40]。钢筋和 UHPC 间粘结强度的劣化程度大于 UHPC 抗压强度的破坏, 接近高温下 UHPC 抗拉强度的破坏^[41]。对于低碳(素)和低合金(变形)钢筋, 其强度在 400 °C 范围内略有提高, 在 400 °C 以上时则直线下降, 700 °C 时仅为常温下的 20% 左右^[41]。对于钢筋混凝土, 其粘结强度在 200 °C 内略有增加, 而后随温度升高而逐渐降低^[41–42]。当增加钢筋埋入长度和混凝土强度等级及采用带肋钢筋时, 均能提高残余粘结强度, 水冷相较于自然冷却则会导致 UHPC 残余粘结强度产生更严重的降低^[41, 43]。

针对钢纤维增强 UHPC 而言, 高温不仅会影响钢纤维的强度, 还会对 UHPC 的粘结性能产生影响 (见图 4)。在高温下, 钢纤维不仅会发生拔出模式的改变, 还会大幅降低强度。在 600 °C 内, 钢纤维

表现为拔出破坏, 在 600 °C 之后则变现为拔断破坏^[44]。同时, 钢纤维在 800 °C 时的残余屈服强度和极限强度分别为 20 °C 时的 15% 和 25%^[45–46]。对于不同纤维增强的 UHPC 而言, 高温对直纤维增强 UHPC 的影响要大于钩端纤维增强 UHPC。直纤维 UHPC 的粘结强度随温度增加而直线降低, 当温度从 20 °C 升至 400 °C 时, 暴露在高温下的直纤维试件拔出强度从 3.4 MPa 降至 1.6 MPa。当温度超过 400 °C 后, 其粘结性能因基体会爆炸剥落而影响结果可靠性。当温度从 20 °C 升至 400 °C 时, 钩端纤维增强 UHPC 的平均粘结强度将由 6.4 MPa 增加至 6.6 MPa。然而对于强度等级低于 UHPC 的高强度或普通强度混凝土而言, 高温对钩端纤维 UHPC 的粘结性能则稍显不同, 即其粘结强度在 20~400 °C 内无明显变化, 在 400~800 °C 内则急剧降低。高温下钢纤维和 UHPC 基体间粘结强度的降低还与材料组成及性能劣化密切相关^[45–46]。因此, 通过对钢筋或钢纤维进行界面物理或化学改性, 对改善 UHPC 的高温粘结性能不失为一种较好的技术措施。

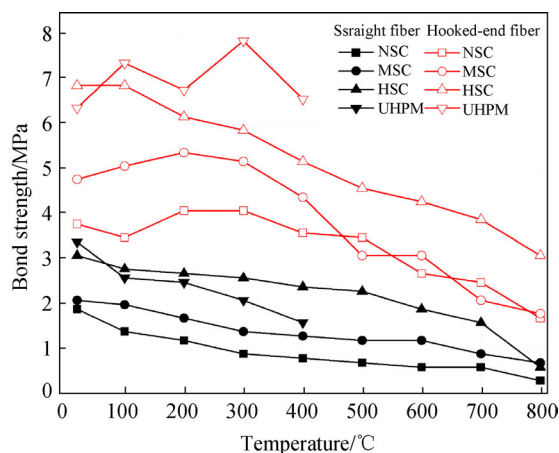


图4 高温环境下钢纤维与 UHPC 基体间粘结强度^[45]

Fig. 4 Bond strength between steel fiber and UHPC matrix under high temperature environment^[45]

1.5 弹性模量

与常温相比, 暴露在高温下的 UHPC 弹性模量损失较为严重。高温下, UHPC 弹性模量随温度的增加而呈降低趋势, 其原因在于 UHPC 内部自由水的损失及高温下内部裂缝演化^[47–48]。该损失程度会随初始温度的升高而迅速加重, 且与残余抗压强度和拉伸强度损失则相反^[20]。通常, UHPC 的弹性模量在 200 °C 内变化不大, 在 200~400 °C 之间会存在较大损失, 400 °C 后将进一步下降, 在 600 °C 后则下降趋缓, 混凝土在 800 °C 时弹性模量将降低至常温时的 20% 左右^[49–50]。纤维的掺入能极大提高 UHPC

的弹性模量, 钢纤维与混杂纤维增强 UHPC 在 200 °C 时仍能保持较高模量, 当温度高于 200 °C 后则迅速下降。当温度高于 200 °C 后, PP 纤维对缓解弹性模量的损失效果一般优于钢纤维和混杂纤维。此外, UHPC 在高温后虽能恢复部分弹性模量, 但在高温下会大幅降低^[51]。可见, 深入探讨高温下 UHPC 弹性模量损失机制, 并开展高温后弹性模量快速恢复措施及机理研究对提高 UHPC 耐高温性能至关重要。

2 UHPC 耐高温性能优化

为改善 UHPC 的耐高温性能, 众多学者从混凝土材料组分设计与优化方面开展了大量研究。高温环境下, 通过掺入粉煤灰、矿渣和偏高岭土等矿物掺合料、添加纳米材料、采用轻质骨料或细磨浮石可显著改善混凝土的耐高温性能^[3-4, 52-53], 硅灰则具有不利影响。同时, 掺入纤维也可增强 UHPC 的抗裂性并改善 UHPC 的高温残余力学性能和抗高温剥落性能^[54]。聚合物纤维(如聚丙烯纤维)在高温下会熔融并产生隧洞, 通过降低 UHPC 内部蒸汽压来缓解其高温劣化。钢纤维在高温下则具有较高的导热性与热稳定性, 通过促进 UHPC 内均匀传热来减少其高温开裂和剥落破坏^[55]。此外, 地聚物混凝土内部特殊的类陶瓷网状结构使其具有优异的耐高温性能, 在 600 °C 暴露 2 h 后仍无明显强度损失, 即使

在 900 °C 后仍有 63% 保持率, 其强度损失远小于普通混凝土^[56-58]。然而, 现有方法对 UHPC 耐高温性能提升效果仍不理想, 如何开发出性能优异的耐高温 UHPC 材料, 同时提出相应的配合比设计新方法, 对优化混凝土的耐高温性能至关重要。

3 高温环境下 UHPC 微结构特征演化

3.1 水化产物热分解

高温环境下, UHPC 微结构的破坏则更为复杂, 其破坏主因在于孔隙水的蒸发与扩散、孔结构破坏、水化硅酸钙(C-S-H)凝胶分解及界面过渡区失效^[59-61]等。UHPC 破坏主要包含 3 个阶段^[52, 54, 62-63]: 1) 在 200 °C 内, UHPC 内部组分结构较为稳定, 该阶段主要涉及水分蒸发散失及部分未水化水泥颗粒的二次水化作用。该阶段自由水、毛细水和吸附水快速蒸发并产生一定的蒸汽压是诱使混凝土微结构破坏的主因, 形成的缺陷是离散且不连续的。2) 在 200~400 °C 内, 大部分钙矾石和氢氧化钙晶体会发生脱水分解, 同时部分化学结合水也会随这些水化产物的分解而蒸发, 由此使得硬化水泥浆体和界面过渡区性能降低。3) 在 400~800 °C 内, 氢氧化钙晶体和大部分 C-S-H 凝胶都将分解, 界面过渡区变得松散, 缺陷从不连续到连续的转变使骨料与基体间的粘结性能大幅降低, 最终导致 UHPC 的宏观性能与微结构严重退化。

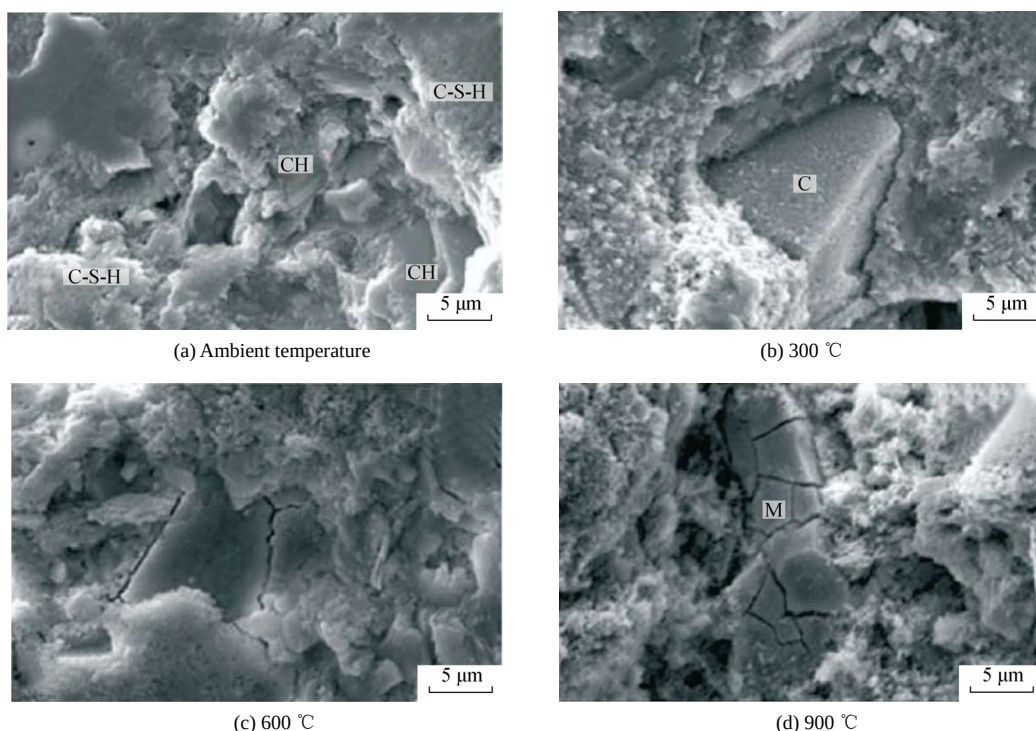


图 5 高温下混凝土内部微观形貌^[63]

Fig. 5 Internal microstructure of concrete at high temperature^[63]

3.2 孔结构和孔隙水

高温环境下 UHPC 孔结构破坏较为复杂, 主要受到水化产物分解、水分蒸发、矿物组成改变、孔隙溶解和膨胀、胶凝材料物理性能变化等多种因素影响^[64]。当温度低于 105 °C 时, 主要发生的是自由水和物理吸附水蒸发, 混凝土中大孔(>200 nm)和毛细孔(10~200 nm)的数量有所增加, 微孔(<10 nm)的数量几乎不变。随着温度上升, 大孔因化学结合水蒸发而数量增加, 微孔中则逐渐充满水蒸汽。此时, 微孔中水蒸汽产生的压力使得微孔壁变形并破坏, 与临近孔连通或形成更大孔径的孔, 微孔数量相对减少^[59–61, 65]。此外, 高温不仅会改变 UHPC 孔隙连通性并使部分孔结构变得更连通或更封闭, 还会造成孔结构变形, 如毛细孔的变细或变粗、裂缝的扩张等。最终, 孔结构的改变使 UHPC 基体发生破坏, 降低其强度^[66]。

3.3 C-S-H 凝胶

高温条件下, C-S-H 凝胶分解也是 UHPC 宏观性能退化的重要原因之一^[53, 61]。Peng 等^[67]发现, 即便混凝土暴露在 400 °C 的环境中长达 8 h, C-S-H 仍无明显分解迹象。当温度超过 600 °C 时, C-S-H 的分解速率显著增加。Castellote 等^[68]则认为, C-S-H 凝胶开始脱水时即开始缓慢分解, 分解可能始于 200~450 °C 内, 其取决于脱水速率和升温速率。此外, 方解石和斜钙硅石的含量会随 C-S-H 分解而增加, 这意味着 C-S-H 分解过程中释放出的 Ca^{2+} 参与了其它反应并形成了无水相。

3.4 界面过渡区

高温环境下, UHPC 内部的骨料-浆体以及纤维-基体界面会出现热膨胀变形差异现象, 诱使其界面过渡区出现损伤劣化, 并易形成微裂纹^[69]。400 °C 时, 普通混凝土中的微裂纹密度远小于 UHPC 中的微裂纹密度^[70]。普通混凝土的微裂纹主要出现在粗骨料之间且具有 10 μm 厚度, 而 UHPC 的微裂纹则形成于砂与骨料之间或周围且具有 1 μm 的厚度^[70]。钢纤维的掺入虽然可在一定程度上改善高温后的 UHPC 微结构, 但钢纤维-基体界面粘结强度会随着高温暴露时间的增加而逐渐降低^[12, 71–72]。在经过较长时间的高温作用后, UHPC 内毛细孔水蒸发引起的收缩以及水化产物的高温分裂同样会使得钢纤维-基体界面逐渐开裂, 并逐渐降低钢纤维的活化效率^[73]。

4 高温环境下 UHPC 性能劣化机制

4.1 蒸汽压理论

蒸汽压理论, 也称孔隙水(汽)压力理论。1916

年, Gray^[74]发现在高温下混凝土内部较高的蒸汽压会使其表面发生剥落, 而其破坏程度在越致密的混凝土中则更加明显, 并由此提出了孔隙压力诱导混凝土高温剥落理论。如图 6 所示, 该理论认为: 混凝土内部大量的孔结构富含自由水和结合水, 孔隙水的体积会随温度的升高而发生膨胀。当温度高于 100 °C 时, 一方面, 孔隙水将会以液态和蒸汽的形式向四周扩散并产生一定的压力, 同时该压力会根据孔隙水饱和度和温度的不同而相应变化。另一方面, 水蒸汽向内部移动过程中会因混凝土内外温差较大而出现冷凝成水现象, 并形成饱水层。由于普通混凝土具有一定的渗透性, 部分蒸汽将通过孔隙得到释放。但当混凝土内部含水量足够高时, 孔隙压力将随温度升高而持续增加, 直至在混凝土内部产生破坏应力, 最终导致混凝土剥落爆裂破坏^[75–76]。

随后, 研究人员基于蒸汽压理论提出了 3 种模型来探讨孔隙水压力对混凝土产生的高温损伤机制, 包括: Short 等^[77]的“湿气堵塞模型”、Meyer^[78]的“蒸汽阻力模型”及 Akhtaruzzaman^[79]将孔隙压力视为“理想化的球形孔隙模型”。Kalifa 等^[80]通过采用自行设计的装置测定了 800 °C 内普通混凝土和高性能混凝土的蒸汽压与温度之间的对应联系, 证实了湿气堵塞模型假设。一般而言, 高强混凝土的高温爆裂频率通常和内部含水率和密实程度成正比^[81]。但在实际研究中, 混凝土的爆裂行为存在极大的随机性和不确定性, 而通过试验也难以解释孔隙压力与混凝土爆裂破坏之间的不确定性, 即使是同批次相同制备和养护条件的试件亦不例外^[82–83]。由此可见, 蒸汽压理论主

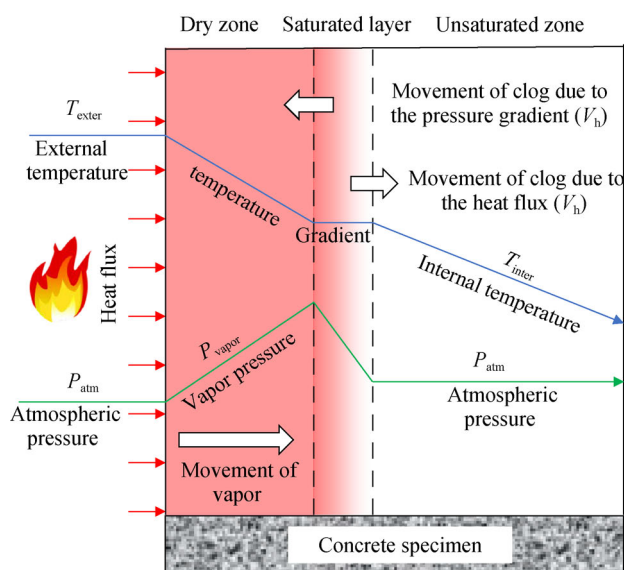


图 6 孔隙水(汽)压力假设^[77, 79]

Fig. 6 Assumption of pore water (vapor) pressure^[77, 79]

要适用于含湿量较高或水胶比较大的混凝土,如普通混凝土和轻质混凝土等。在这些混凝土中,自由水含量较高,容易在高温下形成较高的蒸汽压力。因此,一些研究人员对采用蒸汽压理论来解释混凝土的高温爆裂现象也存在质疑。

4.2 热应力理论

Saito^[84]于 1966 年提出混凝土的高温爆裂破坏是由内部热应力所致, Dougill 等^[85]于 1972 年进一步阐释了该理论的内在破坏机制,后来 Bažant^[86]也进一步完善了混凝土的高温破坏热应力理论。如图 7 所示,该破坏理论认为:在升温过程中,混凝土内外表面之间较大的温度梯度分布使得其内部会产生热应力,且该温度梯度随升温速率的增加而增大。根据混凝土的热力学特性,温度梯度的增大通常会使得混凝土内部产生不同的热应变,其主要包括拉应力和压应力。同时,高温环境下的混凝土将会受热膨胀,而其热变形由于受到内部约束将随之产生较高的热应力。而在混凝土内部,温度梯度通常会使混凝土内部温度较低处产生拉应力,而在靠近表面位置产生压应力,当内部热应力超过靠近受热表面的混凝土的抗压强度时,将会使混凝土表面发生爆裂剥落。

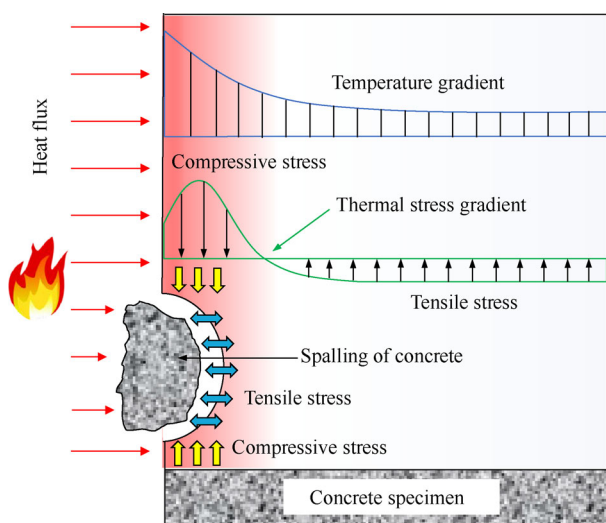


图 7 热应力假设^[77]

Fig. 7 Thermal stress assumption^[77]

然而,该理论存在一定的局限性,即并未考虑混凝土中的水分迁移因素^[87]。该理论认为混凝土表面破坏位置的孔隙水(汽)压力较低,其仅作为引发混凝土爆裂的触发因素之一,而造成混凝土表面爆裂破坏的决定性因素为热应力行为所致。于是 Ulm 等^[88]提出了快速升温混凝土的宏观材料模型,该模型考虑了混凝土在高温下的脱水及其与温度、弹塑性变形间的耦合效应,用于海峡隧道的火灾行为评

估并得出热膨胀受约束是造成混凝土高温破坏的根本原因。由此可见,热应力理论在各种混凝土类型中均具有一定的适用性,尤其是在结构复杂、尺寸较大的混凝土构件中更为显著。其原因在于这些构件在受热时更容易产生温度梯度,从而导致较大的热应力。同时,该理论也适用于解释低含水率的混凝土高温破坏,若将其用于含水率较高的混凝土中则存在诸多难以解释的现象^[87, 89]。

4.3 热开裂理论

混凝土在高温下的爆裂剥落是一项复杂的破坏行为,众多学者采用试验也证实了该破坏并不能完全采用单一的爆裂剥落机制来阐释。因此, Zhukov^[90]于 1975 年首次提出了孔隙压力与热应力联合诱发混凝土爆裂破坏的观点,即高温下混凝土内部的孔隙水产生的蒸汽压与热应力之间的相互作用是导致其发生剥落或爆裂的本质原因(见图 8),并得到了众多学者的认可^[91-92]。高温下,热膨胀和施加荷载会使得混凝土内部纵向应力和裂缝产生一定的均匀应力。同时,垂直于受热表面的高孔隙压力会产生额外的应力,并使混凝土受热面局部区域发生剥落。

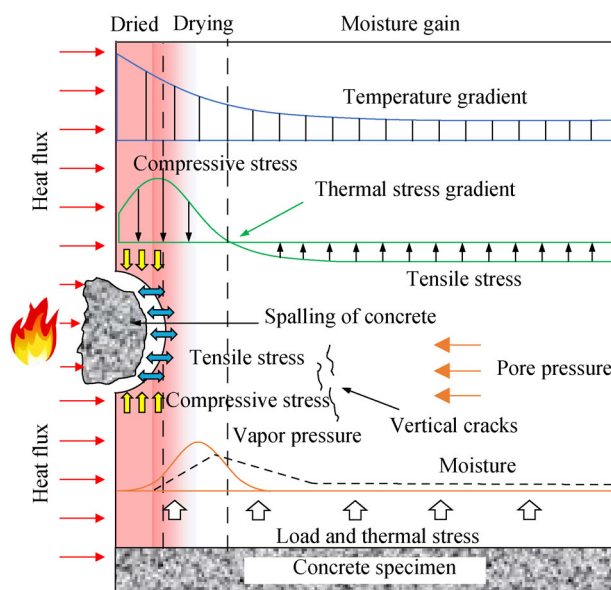


图 8 热开裂假设^[77]

Fig. 8 Thermal cracking assumption^[77]

Zhukov^[90]根据该理论还提出了可预测混凝土高温破坏应力及剥落可能性的函数方程,并发现当混凝土的含水率低于 3% 时混凝土将不会发生剥落或爆裂。傅宇方等^[93-94]认为无论混凝土是否受到外部约束作用或荷载作用,高温下的混凝土均会出现多种破坏裂缝,主要包括:1) 混凝土内部水泥水化产物发生热分解产生的收缩变形裂缝;2) 硬化水泥

浆体与粗细骨料之间的热力不相容性导致的开裂, 如径向开裂、切向开裂和骨料开裂; 3) 混凝土内部温度梯度分布诱发的基体开裂, 主要由表面开裂裂缝和内部开裂裂缝。由于混凝土高温开裂产生的裂缝类型和位置具有一定的随机性, 为解决该问题, 不少研究人员开展了大量相关研究, 但结果仍收效甚微。由此可见, 热开裂理论主要适用于水泥基材料含量较高的混凝土, 如传统的高强度混凝土和 UHPC 等。因为这些混凝土中含有较多的水泥基材料, 在高温下更易发生热分解反应。

4.4 3 种理论在 UHPC 中适用性分析

综上所述, 蒸汽压理论、热应力理论及热开裂理论均涉及混凝土在高温下的性能变化, 且都与温度有直接关系。然而, 蒸汽压理论主要关注混凝土内部蒸汽压力的变化, 热应力理论关注混凝土内部温度分布的不均匀性和热应力的产生, 而热开裂理论则关注水泥基材料在高温下的热分解反应和体积变化。尽管上述 3 种理论可在一定程度上解释普通混凝土的高温破坏机理并相继衍生出不同的预测模型, 但由于混凝土的剥落具有随机性和不确定性, 因此并未得到统一论定且仍具争议。此外, UHPC 具备优异的综合性能, 其高温下的性能劣化是一个较为复杂的物理和化学过程, 其高温破坏机理亦存在争执。

一些学者认为^[95–97], UHPC 含水量越高, 其在高温下的高温爆裂程度则愈剧烈, 并通过试验证明了 UHPC 的高温爆裂与蒸汽压理论密切相关。UHPC 极为致密的内部使得内部水蒸汽在高温下难以逃逸出去并在混凝土内部形成了较高的蒸汽压作用, 进而破坏混凝土。而另一些学者^[98]通过试验和数值模拟手段研究了 UHPC 的高温破坏机理, 并认为其高温爆裂行为与热应力机理密切相关。研究表明, 随着温度的升高, UHPC 内部热应力逐渐增大, 试件外侧的最大拉应力为 6.2 MPa, 内部最大拉应力为 11.5 MPa。模拟试验发现, UHPC 在高温下的破坏是由试件内部能量聚集与释放以及热应力共同影响导致的剥落现象, 并由最初的外表面剥落或爆裂破坏逐渐向试件内部进行扩展演化。对于含粗骨料 UHPC, 其高温爆裂破坏则是沿着 UHPC 基体与骨料间的界面过渡区进行发展的^[99]。还有学者认为除了前述 2 种破坏机理外, UHPC 的高温破坏还与其制备或养护过程中预先产生的随机微裂缝及混凝土内部的微结构密切相关^[28, 100]。由此可见, UHPC 不同于普通混凝土, 虽然普通混凝土的高温破坏机

制可从一定角度解释 UHPC 的高温破坏, 但目前仍缺乏适用于 UHPC 的高温爆裂机制。

5 结论与展望

5.1 结论

火灾环境作为现在建筑结构最常面临的安全风险之一, 会使 UHPC 发生高温爆裂破坏并导致构件承载能力迅速丧失, 极大考验结构工程的服役性能、使用寿命及结构稳定性与安全性。开展相关研究, 对突破 UHPC 材料与构件的耐高温性能极限及防火减灾能力具有现实的应用价值。本文主要结论如下:

1) 高温环境下, UHPC 的强度主要与其强度等级、温度、冷却方式、原材料组成、含水率、钢筋或纤维种类及试件尺寸有关。随着温度的升高, UHPC 的抗压强度、抗弯强度、抗拉强度与粘结强度均会随之降低, 其强度损失在不同温度范围内呈现不同趋势。

2) 高温环境下, UHPC 内部会出现孔隙水蒸发和扩散、孔结构破坏、C-S-H 凝胶分解以及界面过渡区失效, 诱发微裂纹形成并加速扩展。

3) 高温环境下, 学者们针对混凝土的高温爆裂行为提出了蒸汽压理论、热应力理论和热开裂理论。相关理论虽能在一定程度上解释极端温度环境下的普通混凝土劣化机制, 但仍存在诸多争议, 特别是在 UHPC 中。

5.2 展望

纵观目前研究, 尽管各国学者们已经对建筑火灾和高温环境下的 UHPC 开展了大量研究, 在混凝土材料或结构的火灾试验与理论分析方面亦取得重要研究成果, 但对于如何提高 UHPC 的耐高温性能仍缺乏有效的技术措施, 还有待进一步深入研究。该领域存在诸多亟待研究和解决的关键问题:

1) 高温环境会对 UHPC 性能产生不可避免的负面作用, 而现有耐高温性能提升研究获得的改善效果仍不明显, 后期如何从混凝土材料的组分设计、配合比优化、结构定向调控等方面研发出可高效防火、阻热、隔热且兼具快速火灾预警响应功能的新型智能耐高温混凝土材料迫在眉睫。

2) 高温环境下, UHPC 内部会同时发生未水化水泥颗粒的二次水化增强作用和水化产物相的高温劣化作用。如何实现高温下水化产物相的原位微观表征, 并准确定量出 2 种作用对 UHPC 强度的贡献比例及其发展规律, 是深入解析和全面理解 UHPC 在高温作用下劣化本质的关键。

3) 高温环境下的 UHPC 爆裂行为较为复杂且涉及诸多学科领域, 现有高温破坏理论仅能部分解释 UHPC 的高温破坏现象, 难以预测 UHPC 高温剥落的随机性和不确定性并建立起关联机制。如何在材料力学基础上, 结合热动力学、断裂力学、爆破学等多学科体系, 全方位探析 UHPC 的高温破坏机理至关重要。

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Review on Mechanical Properties and Degradation Mechanism of Ultra-High Performance Concrete in Elevated Environment

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Extended Abstract

As a fundamental construction material in modern engineering, concrete is extensively utilized in structural buildings across various industries due to its exceptional workability, mechanical properties, durability, constructability, and safety. In recent years, the pursuit of increasingly innovative structural designs and the escalating demands and complexities of construction technologies, coupled with the rapid advancements in materials science, have led to the emergence of Ultra-high Performance Concrete (UHPC), whose preparation and production techniques have undergone significant enhancements. Consequently, catering to the diverse requirements of construction materials in different service environments, multiple novel UHPC materials have been developed and gradually introduced into pivotal construction projects, encompassing high-rise or super high-rise buildings, long-span bridges, underground structures, nuclear power projects, and massive dams. Nevertheless, fire remains one of the primary risks confronting modern engineering safety, posing a severe threat to the structural stability and service life of UHPC components. Under elevated temperatures, UHPC experiences a sudden imbalance between internal and external temperatures, triggering a series of physicochemical degradations such as dehydration, decomposition, embrittlement, and thermal deformation incompatibility of hydration products. Notably, these detrimental effects are more pronounced in UHPC with higher strength grades. Therefore, conducting systematic research on the elevated performance of UHPC and proposing feasible enhancement measures are of paramount importance for enhancing the fire resistance of structural engineering.

The elevated stability of UHPC is paramount to ensuring the long-term safe service of building structures in fire environments. Therefore, there is an urgent practical need to develop novel construction materials with exceptional elevated performance through a systematic overview of mechanical properties and degradation mechanisms of UHPC at elevated temperatures. In this paper, the macro-mechanical properties of UHPC at elevated temperatures, encompassing compressive strength, tensile strength, flexural strength, bond strength and elastic modulus, were comprehensively reviewed. The thermal decomposition of hydration products, pore structure and pore water, C-S-H gel, and the interfacial transition zone characteristics of UHPC at elevated temperatures were further summarized. Additionally, the degradation mechanisms of concrete properties at elevated temperatures and their applicability in UHPC were discussed, and the critical issues pertaining to UHPC's elevated performance in existing research were elucidated. Lastly, some insights into future research directions and prospects were proposed. Based on the conclusions summarized in this paper, valuable references can be provided for the design of UHPC materials with enhanced elevated resistance, as well as for the inspection, evaluation, and repair of structures after fire events.

Summary and prospects As one of the most prevalent safety risks faced by modern building structures, fire can lead to elevated spalling failure of UHPC, resulting in rapid loss of load-bearing capacity, posing significant challenges to the serviceability, lifespan, structural stability, and safety of structural engineering. Conducting relevant research holds practical application value in pushing the limits of UHPC materials and structures in terms of elevated resistance and fire prevention capabilities. The main conclusions of this paper are as follows: 1) At elevated temperatures, the strength of UHPC is primarily influenced by factors such as its strength grade, temperature, cooling method, raw material composition, moisture content, reinforcement or fiber type, and specimen dimensions. As the temperature increases, the compressive strength, flexural strength, tensile strength, and bond strength of UHPC decrease, with the loss of strength exhibiting distinct trends within different temperature ranges. 2) At elevated temperatures, UHPC undergoes phenomena such as evaporation and diffusion of pore water, deterioration of pore structure, decomposition of C-S-H gel, and failure of the interfacial transition zone, which initiate the formation of microcracks and accelerate their propagation. 3) Regarding the spalling behavior of concrete at elevated temperatures, scholars have proposed theories including the vapor pressure theory, thermal stress theory, and thermal cracking theory. While these theories can, to some extent, explain the degradation mechanisms of ordinary concrete in extreme temperature environments, they remain controversial, particularly when applied to UHPC.

Despite the extensive research conducted by scholars worldwide on UHPC in the context of building fires and elevated environments, as well as the significant achievements made in experimental and theoretical analyses of fire resistance for concrete materials or structures, the current literature reveals a lack of effective technical measures to enhance the elevated resistance of UHPC, necessitating further in-depth investigation. This field is plagued by numerous critical issues that urgently require research and resolution: 1) The elevated environment inevitably exerts negative effects on the performance of UHPC, and the enhancements achieved through existing research on improving the thermal resistance remain insufficient. It is thus imperative to develop novel intelligent elevated-resistant concrete that can efficiently prevent, resist, and insulate heat, while also integrating rapid fire warning response capabilities, through advancements in concrete material composition design, mix proportion optimization, and structural directional control. 2) At elevated temperatures, UHPC undergoes simultaneous processes of secondary hydration enhancement from

unhydrated cement particles and elevated degradation of hydrated product phases. The key to deeply analyzing and comprehensively understanding the degradation mechanisms of UHPC at elevated temperatures lies in achieving in-situ microscopic characterization of hydrated product phases and accurately quantifying the contribution ratios and development patterns of these two processes to the strength of UHPC. 3) The spalling behavior of UHPC at elevated temperatures is complex and multidisciplinary. The current theories on elevated failure can only partially explain the elevated degradation of UHPC, making it difficult to predict the randomness and uncertainty of UHPC's elevated peeling and establish a correlation mechanism. It is crucial to comprehensively explore the elevated failure mechanisms of UHPC by integrating multiple disciplines such as material mechanics, thermodynamics, fracture mechanics, and blast dynamics.

Keywords elevated environment; ultra-high performance concrete; mechanical properties; microstructural characteristics; deterioration mechanism