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轻集料用于超高性能混凝土的研究进展

张高展[1,2], 郭凯正[3], 程华强[4], 丁庆军[3,*]
(1.安徽建筑大学 材料与化学工程学院,安徽 合肥 230601;2.安徽建筑大学 先进建筑材料安徽省重点实验室,安徽 合肥 230022;3.武汉理工大学 材料科学与工程学院,湖北 武汉 430070;4.武汉市市政建设集团有限公司,湖北 武汉 430023)

摘要:轻集料是一种来源广泛、轻质环保的材料,用于超高性能混凝土可以起到降低自重、减少自收缩等作用,近年来成为国内外的研究热点.然而,超高性能混凝土的设计是基于最大堆积密度理论的,而轻集料强度低且多孔的特性为其性能带来不利因素.为此,对比讨论了不同类型轻集料及其制备技术对超高性能混凝土宏观性能的影响,分析了轻集料在超高性能混凝土中的作用机理和增强机制,并结合现有的研究进展,展望了未来的发展前景.

关键词:轻集料;超高性能混凝土;制备技术;作用机理
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Lightweight Aggregate in Ultra-high Performance Concrete

ZHANG Gaozhan[1,2], *GUO Kaizheng*[3], *CHENG Huaqiang*[4], *DING Qingjun*[3,*]
(1. School of Materials and Chemical Engineering, Anhui Jianzhu University, Hefei 230601,China;
2. Anhui Province Key Laboratory of Advanced Building Materials, Anhui Jianzhu University, Hefei 230022,China;
3. School of Materials Science and Engineering, Wuhan University of Technology, Wuhan 430070 ,China;
4. Wuhan Municipal Construction Group Co., Ltd., Wuhan 430023 ,China)

Abstract: As lightweight aggregates are widely used and environment-friendly material that is promising to use in ultra-high performance concrete to reduce self-weight and shrinkage, they have become a hot topic of research at home and abroad in recent years. The design of ultra-high performance concrete is based on the theory of maximum bulk density, and the low strength and porous nature of lightweight aggregates can have a detrimental effect on their performance. The effects of different types of lightweight aggregates and preparation techniques on macroscopic properties are comprehensively discussed and compared, and the mechanisms of lightweight aggregates in ultra-high performance concrete and their enhancement mechanisms are then analysed.

Key words: lightweight aggregate; ultra-high performance concrete; preparation technique; mechanism of action

混凝土的诞生已有200 a历史,随着时代的进步,传统混凝土由于强度低、自重大,已越来越难满足现代建筑的需求.超高性能混凝土(UHPC)经De Larrard等[1]首次提出后便受到广泛关注,UHPC以其超高力学性能和优异耐久性能等优点被誉为21世纪最具前景的建筑材料之一.经过多年发展,UHPC的研究重点不再追求高强度,而是转向绿色、环保、低碳的新目标[2].为此,国内外学者通过使用辅助胶

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第一作者:张高展(1981—),男,河南商丘人,安徽建筑大学教授,博士生导师,博士. E-mail: gaozhanzhang@126.com
通讯作者:丁庆军(1962—),男,吉林蛟河人,武汉理工大学教授,博士生导师,博士. E-mail: dingqj@whut.edu.cn

凝材料减少水泥用量[3-8]、优化配合比提升材料利用率[9-11]等方式降低生产能耗,而对于在UHPC中占据近一半质量的集料[12]研究还较为匮乏,仍大量依赖河砂、石英砂等天然集料[13].鉴于很多国家和地区的天然集料已成为稀缺资源,尤其是中国大规模开采河砂,已经对生态环境和航运造成巨大影响[14],探索新型集料的利用成为UHPC发展的必然趋势[15].

轻集料作为生态环保型材料[16],用于制备轻集料混凝土具有降低自重、隔热降噪等优势,此前多用于LC60以下非承重结构.随着高强轻集料的生产工艺与UHPC设计技术的不断成熟,近年来有学者尝试将轻集料引入到UHPC的体系中,并取得了一系列研究成果,如丁庆军等[17]基于高强度与轻质化的协同设计,使用轻集料完全替代天然砂石集料,制备出具有更高比强度的轻质超高性能混凝土(LUHPC),其能够显著降低建筑物的结构自重、提高承载力和耐久性,目前已在湖北武汉雄楚大道高架桥、重庆新田长江大桥等项目实现了工程应用.

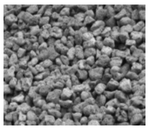
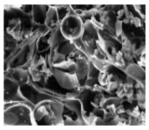
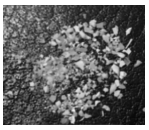
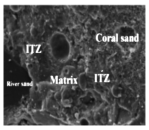
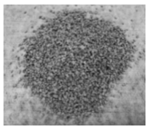
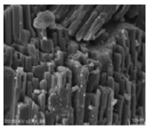
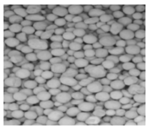
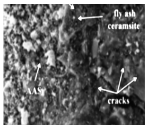
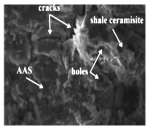
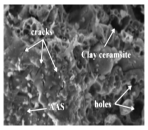
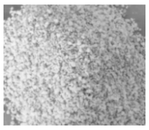
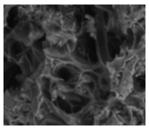
本文归纳整理了国内外关于轻集料在UHPC中应用的相关研究,综述了轻集料对UHPC性能的影响和作用机理,以期为轻集料UHPC技术的发展与应用提供一定的参考.

1　轻集料对超高性能混凝土性能的影响

轻集料是一种堆积密度不大于1 200 kg/m^{3}的多孔材料,按其生产方式可分为:(1)天然轻集料,如珊瑚石、浮石和火山渣等;(2)人造轻集料,如烧结页岩、烧结煤矸石和冷黏粉煤灰等.轻集料含有多种尺度的孔,其表面形貌、孔的连通程度及含水量均会对混凝土性能造成影响[18].不同种类轻集料的物理性能如表1所示.目前,轻集料在普通混凝土中的研究与应用已发展到较高水平[19-23],而在UHPC中还处于起

表1　不同种类轻集料的物理性能

Table 1　Physical properties of different kinds of lightweight aggregates

Type of aggregate	Main raw material	Manufacturing method	Macrostructure	Microstructure	Cylinder compressive strength/MPa	Bulk density/(kg·m^{-3})	Saturated water absorption (by mass)/%	Reference
Natural lightweight aggregate	Pumice				1.1-2.9	358-460	54.0-77.9	[25-26]
	Coral				1.5-4.5	850-1 200	10.0-31.2	[27-28]
	Zeolite				—	950-1 200	40.0-160.0	[29-30]
Synthetic lightweight aggregate	Fly ash	Cold bongding			5.3-15.7	821-1 200	7.8-21.0	[31-32]
	Clay	Sintering			5.3-10.0	539-900	13.4-17.6	[31,33-34]
	Shale	Sintering			4.0-6.8	525-874	7.5-11.6	[31,35-36]
	Perlite	Sintering			0.3-4.4	260-390	33.0-170.0	[37-38]

步阶段.可以确定的是,在UHPC体系中,轻集料的影响与普通混凝土相比存在较大差异[24],鉴于此,本文将从工作性能、表观密度、力学性能、体积稳定性和耐久性方面讨论轻集料对UHPC性能的影响.

1.1 工作性能

良好的工作性能可以降低施工难度,是UHPC推广和应用的重要前提.轻集料对UHPC工作性能的影响主要取决于预处理方式、掺量、粒径级配与形貌等.

由于轻集料是多孔材料,在干燥状态下进行拌和会吸收UHPC浆体中的水分,而预湿后的轻集料能够携带额外的水分,并在拌和过程中释放一部分,对UHPC水胶比的改变是影响工作性能的重要因素.Golias等[39]发现,干燥轻集料除了会从拌和浆体中吸收水分之外,还会吸入一些细小的胶凝材料颗粒,这些颗粒会堵塞轻集料自身的孔隙,导致轻集料在浆体中的吸水量和吸水速率远低于在水中的吸水量.因此,对于孔隙较小的轻集料,应在拌和前进行预湿或适当延长拌和时间,以避免泌水和离析情况出现[40].此外,轻集料掺量的增加使UHPC扩展度出现先增大后减少的趋势[33,41-43],这是由于轻集料密度较小,在重力作用下浆体的流动性能减弱,造成工作性能下降.另外,球形度高的轻集料能减少集料间的咬合摩擦,在集料周围更容易形成润滑层,在"滚珠效应"下可以使UHPC获得更好的工作性能[33,44].

1.2 表观密度

相较于普通混凝土,虽然UHPC多方面性能均有大幅提升,但自重仍未得到有效控制(表观密度不小于2 500 kg/m^3),导致UHPC应用范围受到限制[45].采用轻集料制备UHPC对于降低自重具有积极作用.

一般来说,密度越低的轻集料越有利于减少UHPC自重,并随着轻集料取代率的增加而逐渐降低.综合相关文献来看,在满足UHPC力学性能(抗压强度≥100 MPa)的前提下,人造轻集料比天然轻集料更有利于降低UHPC自重,使用700~900级、筒压强度不小于6 MPa的人造高强轻集料可降低20%以上的自重[34,46-49].此外,一些微米级轻集料用于UHPC中,对于降低自重具有更加显著的效果[50].Danish等[51]采用空心玻璃微珠取代部分集料或水泥,在降低表观密度的同时未对工作性能造成影响.胡尧等[27]采用空心玻璃微珠仅取代10%的石英砂,UHPC表观密度即从2 650 kg/m^3降至2 300 kg/m^3.

1.3 力学性能

力学性能是衡量UHPC性能最重要的指标,而轻集料由于自身强度远低于天然砂石及UHPC基体,是影响力学性能的不利因素;但采用合理方法对轻集料UHPC进行设计,可以削弱轻集料强度不足的缺陷,甚至能在一定程度上提升UHPC的力学性能.

Meng等[41]采用最大粒径为1.18 mm的烧结页岩取代0%~75%石英砂,发现随着轻集料取代率的增加,UHPC抗压强度和抗折强度均出现先增大后减少的趋势,轻集料取代率为25%时强度到最大值.Liu等[25,52]研究也证实,人造轻集料与天然轻集料取代部分河砂,均有助于提升UHPC的抗压强度与抗折强度.轻集料自身强度是限制混凝土强度的主要因素,随着人造轻集料技术的提升,采用蒸压养护[53]、核壳结构设计[54]的人造高强轻集料筒压强度可达20 MPa以上且密度等级不高于900级[49],然而更高强度的轻集料对UHPC力学性能的提升并未达到预期效果.朱博等[55]采用最大粒径5 mm、筒压强度15 MPa的免烧高强轻集料取代石英砂,发现随着轻集料取代率的增加,UHPC的力学性能显著降低.这是由于免烧高强轻集料通常采用成球造粒的生产工艺,粒径偏大且多为单一级配或间断级配,直接用于UHPC会破坏原本致密的骨架结构,因此须对轻集料的粒径与级配进行合理设计.修正后的Andreasen&Andreasen模型对于轻集料在超高性能混凝土中级配设计的可靠性已得到证实[56-57],该模型计算出的轻集料颗粒级配既有粗颗粒在体系内形成骨架,又有细颗粒填充空隙形成致密堆积结构.此外,进一步降低轻集料粒径尺寸、改善轻集料的空间分布可以补偿UHPC引入轻集料而造成的强度损失[58].相关研究表明,即使采用筒压强度仅为0.3 MPa的轻集料,也可制备出抗压强度大于等于120 MPa的UHPC[38].

此外,轻集料携带的水分也会对UHPC力学性能产生明显影响[41,59],尤其是对早期强度的影响较大[28].虽然轻集料自身强度较低,但进行适当程度的预湿可以降低轻集料自身对抗压强度的负面影响[60],轻集料的含水量对于UHPC力学性能存在最佳值.魏琦[56]研究表明,随着轻集料携带额外水分的增加,UHPC的抗压强度呈先增后降趋势,进一步说明引入适量的水分有利于提升UHPC的力学性能,然而过量的水分会使轻集料表面形成一层水膜,降低其与基体的黏结性能并增加水胶比,造成UHPC力学性能下降.He等[61]的研究也证实了这一点.

1.4　体积稳定性

开裂是水泥基材料的普遍现象,几乎所有的开裂都是由体积稳定性不足而产生变形所导致的.就UHPC而言,收缩变形是影响体积稳定性的主要因素,而自收缩占总收缩的80%左右,是问题的关键所在.轻集料可以有效减少UHPC的收缩变形,与其掺量、孔结构、粒径和预处理方式密切相关.

目前已有研究证实,天然浮石、珊瑚石和烧结页岩等轻集料均可显著降低UHPC的自收缩[42, 52, 62-65].Liu等[52]发现,在总水胶比固定的情况下,当预湿后的烧结页岩对河砂的取代率从0%增加到5%、10%、15%和20%时,UHPC的净水胶比随着轻集料取代率的增加而降低,3 d自收缩量分别降低了31.9%、47.9%、78.4%和54.6%,且真空饱水后的轻集料减缩效果更好.而Dong等[57]使用天然浮石作为轻集料,在总水胶比相同的情况下,干浮石和预湿浮石均可减少UHPC的自收缩,且随着浮石取代率的提高,减缩效果更明显,这与Liu等[52]的研究结论不一致,可能由于天然浮石比烧结页岩具有更大的孔隙,且保水性较差导致.Liu等[25]研究了净水胶比固定时天然浮石对UHPC收缩的影响,结果表明,使用浮石额外引入适量的水有助于减少收缩,但引水量过高时会增加UHPC的实际水胶比,从而增大UHPC的收缩,研究还发现粒径越大的浮石对减少收缩变形的贡献越高.而Zhutovsky等[66]认为使用粒径较小的浮石对减少UHPC收缩变形的效果更好,究其原因可能是两者所用的天然浮石轻集料产地不同,物理性质存在较大差异,在UHPC内部表现出不同吸释水效果导致的[67].

为了能更好地获得减缩效果,有学者将减缩剂以轻集料为载体加入UHPC中,延长了减缩剂的作用时间,获得了更好的减缩效果,同时避免了减缩剂直接添加所导致的缓凝、早强等不良现象[63, 68-69].

1.5　耐久性

UHPC被誉为耐久性最好的混凝土材料,可有效防止外界有害离子的渗透及内部侵蚀.轻集料的多孔性为水和侵蚀离子提供了潜在的迁移通道,其物理特性及取代率会对UHPC的耐久性产生不同影响[70].

胡俊[71]使用轻集料完全取代UHPC中的河砂并进行了碳化试验和冻融循环试验,结果表明,轻集料UHPC在各龄期的碳化深度均为0 mm,经过300次冻融循环后质量损失仅为0.2%,相对动弹性模量保持在99%以上.魏琦[56]进一步研究得出,随着轻集料取代量的增加,UHPC的抗渗性能、抗冻性能和抗硫酸盐侵蚀性能均呈现先增强后减弱的趋势,当轻集料取代量为100%时,其耐久性仍优于普通UHPC,然而轻集料引入过多的额外水分增加了实际水胶比,使得UHPC密实度降低,削弱了抵抗有害离子渗透和传输的能力,从而导致耐久性下降.王宇譞[72]系统研究了轻集料对UHPC抗氯离子渗透的影响,结果表明:当最大粒径为2.36 mm的轻集料逐渐取代0%~100%的石英砂时,UHPC的氯离子扩散系数从1.0×10^{-13} m^2/s增至1.9×10^{-13} m^2/s;在轻集料取代率相同的条件下,使用粒径较小的轻集料比粒径较大的轻集料表现出了更好的抗氯离子渗透性能,原因是更细的轻集料可以增大UHPC内部曲折度,从而增加氯离子传输路径,在一定程度上削弱了轻集料自身的不利影响.然而这与Shen等[73]的研究结果呈相反趋势,其使用最大粒径为1.18 mm的轻集料取代0%~60%河砂时,UHPC的氯离子扩散系数从2.3×10^{-13} m^2/s降至1.1×10^{-13} m^2/s,这可能是石英砂UHPC比河砂UHPC具有更好的抗氯离子渗透性能,轻集料的掺入对石英砂UHPC的负面影响更大.另外Shen等[73]使用了粒径更小的轻集料,对抗氯离子渗透性能起到改善作用,这也从另一方面印证了王宇譞[72]的结论.此外,轻集料与侵蚀离子(氯离子、硫酸根离子等)的结合能力较强,对于已经侵入UHPC基体中的侵蚀离子,轻集料可以与其发生一系列物理化学反应[70, 74-77],从而避免深层基体受到进一步侵蚀.

2　轻集料在超高性能混凝土中的作用机理

轻集料在UHPC中的作用机理较为复杂,总体上可归纳为对基体内养护的作用、对界面过渡区的强化作用及轻集料自身的火山灰活性作用,这些作用机理在一定程度上可以强化UHPC的性能.

2.1　内养护作用

根据水胶比理论[78],仅当水胶比大于等于0.42时,水泥基胶凝材料才有可能实现完全水化.由于UHPC水胶比极低(0.14~0.22)且胶凝材料用量高(800~1 300 kg/m^3),拌和水仅能够满足部分水泥水化.水化反应伴随着内部相对湿度的下降,造成混凝土孔隙内凹液面降低,毛细管应力增加,混凝土出现收缩现象[79-81],当收缩应力超过基体的抗拉强度时,在约束条件下UHPC会形成微裂纹甚至裂缝,导致其潜在的开裂风险及结构劣化[82].由此可见,必须引入额外的水分以满足水泥水化需要.图1为外养护与内养护作用示意图.由图1可见:相较普通混凝土,结

构致密的UHPC表现出较低的渗透性，传统的外部养护难以使水渗透到内部中，无法有效地缓解相对湿度的下降[83]；而采用内养护方式可以引入额外的养护水分，并充足地分布在UHPC内部[84]，在水化过程中释放出来，是一种更有效的养护方式.

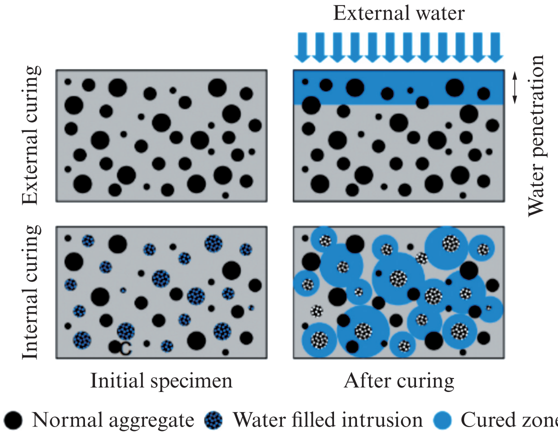


图1 外养护与内养护作用示意图

Fig. 1 Sketch map of external curing and internal curing[85]

由于轻集料具有多孔结构的特点，作为内养护介质可在UHPC内部起到“蓄水池”的作用[86]，能够有效缓解内部相对湿度的下降，使水分从“蓄水池”传输到UHPC各个部位[87]，可以促进水泥熟料的水化反应，改善UHPC的水化进程，生成更多的水化硅酸钙(C-S-H)凝胶并填充了基体孔隙中，从而使UHPC孔隙率和孔径减小，内部结构变得更加致密[88].

内养护作用能够在一定程度上补偿轻集料自身的不利因素，主要取决于其在UHPC内部的释水作用.以往的研究证实，轻集料的释水主要由内部相对湿度及毛细孔的耦合作用所决定[89].随着水化反应的持续进行，一方面内部相对湿度降低、毛细孔压力增高，促进了轻集料中水分的迁移，另一方面由于毛细孔的连通性也不断降低，阻碍了释水通道，反而衰减了水分的迁移[90].轻集料的释水量与迁移距离主要与轻集料的掺量、吸水率和孔结构有关，通常较多的轻集料可以提供更多的内养护水分[88]，而较小的粒径更容易平均分布在基体中[91]，通过优化轻集料的级配设计可以达到最有效的内养护效果[92-93].向玮衡[94]指出，轻集料对基体的养护范围越广，其内养护效果越好，且内养护范围与其粒径尺寸、颗粒级配和释水距离密切相关，并建立了不同级配下预湿轻集料的释水内养护范围模型.预湿球形轻集料在UHPC中的释水距离为0.6～0.8 mm，采用Andreasen & Andersen模型设计的连续颗粒级配可养护90%以上区域.

Trtik等[95]采用中子断层扫描研究了干燥和预湿轻集料的内养护效果，发现水泥浆拌和后4 h内，干燥的轻集料会从水泥浆中吸收孔隙溶液，这些溶液在后期被部分释放回水泥浆；而预湿的轻集料向水泥浆释放更多的内养护水分.Ding等[88]对不同种类轻集料的内养护效果进行了研究，发现轻集料的吸释水能力决定内养护效果，赤泥轻集料比页岩轻集料具有更高的连通孔隙率，因此其饱和吸水量更高，能够提供更多的水分，从而促进水泥水化，内养护效果也更为显著.Kazemian等[96]指出增加轻集料的取代率可以更长时间地保持UHPC中自由水的含量，改善水化过程，从而起到内养护作用.最大内部相对湿度的持续时间也随着轻集料取代率的增加而延长[73].Liu等[97]认为轻集料的孔径不宜过大，否则保水性不足，从而表现出较差的内养护作用.而对于孔径过小，尤其是沸石等具有纳米级孔隙的轻集料，此前认为其纳米孔内的水分无法在水化过程中释放出来，内养护效果较差[98].然而由于UHPC基体的孔径远低于普通混凝土，轻集料纳米孔内的水分还是能向UHPC基体迁移，从而起到内养护作用[38, 96, 99-100].

Bentz等[101]提出了一种用于计算内养护所需轻集料用量的模型，该模型在普通混凝土中得到广泛应用，并充分证明了其有效性，然而对于UHPC预测的准确性还有待商榷.Justs等[102]认为该模型所计算出的理论用量无法提供足够的水分，用于缓解相对湿度的下降，原因是模型中未考虑水化产物沉淀所需的空间.内养护所引入的额外空间对于普通混凝土来说微不足道，但对内部结构极其致密的UHPC来说，额外的空间才能允许更高程度的水化.因此，在UHPC体系中需要更多轻集料来满足内养护作用[73, 103].

2.2 界面过渡区的强化作用

基体与集料的界面过渡区一般被认为是混凝土内部的薄弱环节.混凝土在外力作用下，由于界面过渡区最先产生裂纹，随之不断扩展、延伸直至结构遭到破坏，因此其是影响混凝土性能的关键环节[104].轻集料与石英砂、河砂等天然砂石的特性存在显著差异，因此轻集料对界面过渡区的作用机制也不同.

天然砂与基体的界面过渡区存在明显缝隙，而轻集料的界面过渡区连续平滑.这主要是由于轻集料的吸释水特性可以促进界面过渡区的水化，使界面过渡区的微观结构得以改善.对比普通UHPC和轻集料UHPC微观力学性能可知，轻集料界面过渡

区的显微硬度明显高于UHPC基体，这是因为预湿后的轻集料会增加界面过渡区的水化程度[75].另外，轻集料UHPC中的C-S-H凝胶平均弹性模量明显高于普通UHPC，这是因为轻集料能够促进界面过渡区生成更多的超高密度C-S-H凝胶，增加了水化产物的填充性和刚度.虽然使用干燥轻集料所生成的高密度/超高密度C-S-H凝胶略低于预湿轻集料[105]，但仍优于普通UHPC[74,106]，这意味着轻集料使界面过渡区从薄弱地带转为了内部强化区.张高展等[35]发现，将烧结页岩轻整形为球形后制备UHPC，会形成拱壳状界面过渡区，如图2所示.这种拱壳界面结构能均匀分散应力，阻碍裂纹的形成和扩展，并抵消UHPC中轻集料与基体弹性模量的差异，从而避免在外加荷载的作用下轻集料与基体变形程度不一致而产生的微裂纹.

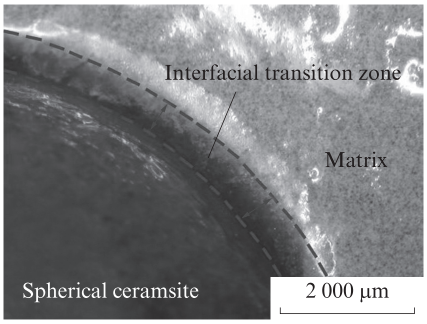


图2　拱壳状界面过渡区
Fig. 2　Arched shell interface transition zone[35]

此外，轻集料的表面粗糙、多棱角且具有高低不平的开孔，水泥浆体可以穿透轻集料表面的空隙，由此产生的机械嵌锁作用可以使轻集料与基体结合得更加紧密，这主要取决于轻集料的表面结构[107]，如表面开放孔隙较多的轻集料能够增大与水泥基体的结合面积，使轻集料与基体粘结得更加紧密.虽然轻集料自身强度较低，远低于水泥石基体，但能够显著强化界面过渡区，在一定程度上弥补了轻集料自身的缺陷.

2.3　轻集料火山灰活性作用

天然砂石含有较高的石英相，在常规条件下表现出极大的惰性，几乎不参与水化反应.在“墙壁效应”下，天然砂石附近存在较高含量的氢氧化钙(CH).CH是水泥石基体中最易受侵蚀的物质，其层间链接较弱，过量CH的堆积极易产生微裂缝并诱导扩展[108]，也是有害离子侵蚀的快速通道.而轻集料属于铝硅酸盐聚集体，主要成分为SiO_2和Al_2O_3，具有潜在的火山灰活性[109-111]，能够与水泥石基体产生二次水化反应，消耗CH并产生额外的火山灰反应产物[112].因此，具有火山灰活性的轻集料能够有效提升UHPC内部结构的密实度[113].

Nie等[110]发现，轻集料在混凝土成型后能够连续向基体释放Al^{3+}和Si^{2+}，并且其浓度随着养护时间的延长而不断增高，因此轻集料附近的水泥石基体具有较高的Al与Si含量，而河砂附近表现出较高的Ca含量.Liu等[74]对轻集料与河砂附近5～20 μm处的基体进行EDS分析，得到轻集料UHPC中的铝钙比(n(Al)/n(Ca))与硅钙比(n(Si)/n(Ca))，结果见图3(图中AFt为高硫型水化硫铝酸钙、AFm为单硫型水化硫铝酸钙).由图3可见，轻集料(LWFA)附近基体的C-S-H凝胶具有更高的n(Al)/n(Ca)和n(Si)/n(Ca)，说明轻集料参与了水化反应，其释放出的Si^{2+}与Al^{3+}能够嵌入到C-S-H链中.此外，虽然轻集料中Si含量远高于Al，但Al在UHPC内的溶解度更强，导致水泥石基体中Al的浓度高于Si[114].较高浓度Al可以取代C-S-H中的部分Si[115]，从而延长了C-S-H结构的平均链长并生产额外的水化硅铝酸钙(C-A-S-H)凝胶[116]，这也是轻集料能够增强界面过渡区的原因之一.

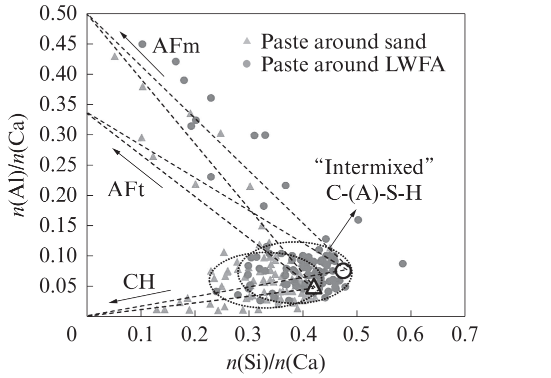


图3　轻集料UHPC的n(Al)/n(Ca)与n(Si)/n(Ca)
Fig. 3　n(Al)/n(Ca) and n(Si)/n(Ca) of lightweight aggregate UHPC[74]

养护温度与龄期也对轻集料的火山灰反应产生一定影响.王俊颜等[117]采用漂珠代替部分石英砂制备UHPC，研究发现：标准养护28 d时轻集料与基体内壁光滑，未产生水化产物；继续养护至120 d时，轻集料与基体内壁生成须状C-S-H凝胶；而采用蒸汽养护后，基体内壁额外生成片状水化产物，这说明高温养护会加剧轻集料的火山灰活性反应.Lu等[47,118]进一步研究认为：室温养护下轻集料的火山灰活性较低，与基体结合能力较弱，断裂时轻集料通常沿着表面从基体中剥落；随着养护温度的升高，轻集料火山灰反应增强，升至250 ℃时生成新的水化产物，此时断裂基本发生在轻集料颗粒之间，而非与基体的

界面处.此外,一些以粉煤灰或矿渣为原料的冷黏轻集料具有更强的活性[119],有利于生成更多的水化产物,从而使UHPC内部结构更加密实[120-121].

3 结论与展望

(1)制备技术是影响轻集料UHPC的关键因素,也是目前研究的瓶颈.充分发挥轻集料的内养护作用、界面过渡区增强机制和火山灰效应可以最大程度上降低轻集料自身强度不足的缺陷,甚至在一定程度上提升UHPC的各项性能.

(2)轻集料完全取代天然砂石集料,可实现抗压强度不小于100 MPa、表观密度不大于2 100 kg/m^{3}的UHPC的稳定制备,并且具有优异耐久性和工作性能,其自收缩远低于普通UHPC.将其应用于大跨度桥梁等复杂建筑能够提升结构效率和耐久性,具有较高的经济价值与社会效益.

(3)未来对于天然轻集料在UHPC中的应用,应以就地取材、因地制宜为主,如跨海大桥、岛礁建设等工程可采用珊瑚轻集料和浮石轻集料制备UHPC.而对于人造轻集料,应大力开发工业固废轻集料在UHPC中的应用研究,有助于推动国家"双碳"目标.

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(下转第905页)