

泡沫混凝土气泡性能与基体材料研究进展

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摘 要: 泡沫混凝土是近年来广泛研究和应用的保温材料。泡沫混凝土制备过程中气泡性能与基体材料是影响其性能的关键。气泡不稳定及基体缺陷制约着泡沫混凝土大规模推广应用。为了揭示泡沫混凝土气泡和基体对其结构与性能影响, 本文围绕气泡性能和基体材料, 全面总结和分析发泡剂和稳泡剂的种类及用量, 基体材料种类和用量以及纤维、外加剂等研究现状, 阐明宏观性能及微观结构关联机制, 以期为中国泡沫混凝土材料和建筑节能事业提供有益参考。

关键词: 泡沫混凝土; 气泡性能; 基体材料

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随着中国城镇化进程的加快, 建筑业得到突飞猛进的发展, 然而建筑制造与运行伴随大量能源消耗。2018 年中国建筑运行总商品能耗达 10 亿 t 标准煤当量, 约占全国能源消费总量的 22%。其中城镇住宅、农村住宅、公共建筑和城镇供暖的商品能耗分别占比 21.4%、21.6%、33.2%和 21.2%^[1]。随着建筑节能需求的强劲增长以及建筑结构和材料要求的提高, 以泡沫混凝土为代表的建筑节能材料得到广泛应用。泡沫混凝土是由气泡和水泥基体组成的混合材料, 由于没有粗骨料且含有大量封闭气孔, 因而具有轻质、保温和隔音的特点。

泡沫混凝土通常被用于节能墙体结构中, 然而在制备和实际使用中通常伴随塌模、产品强度低和易开裂等问题。为了提高泡沫混凝土的力学、保温和耐久性能, 研究者从提高气泡强度、稳定性及机理方面进行了研究; 对于除气泡以外的基体结构, 研究者从水泥与掺合料种类和用量、水灰比和外加剂等角度研究基体提升机制^[2]。此外, 研究者还考察不同养护制度对泡沫混凝土性能的影响, 以期获得高性能泡沫混凝土的制备工艺参数, 提升产品性能^[3]。

为了揭示泡沫混凝土气泡性能和基体材料对其结构与性能影响, 本文全面总结和分析发泡剂、稳泡剂的种类及用量, 基体材料种类和用量以及纤维、外加剂等研究现状, 阐明宏观参数与性能及微观结构关联机制, 以期为中国泡沫混凝土材料和建筑节能事业发展提供参考。

1 发泡剂与稳泡剂对气泡性能影响

泡沫混凝土的各项性质与气泡性能密切相关。其中发泡剂和稳泡剂对气泡性能影响最为显著。目前, 发泡剂主要有物理发泡剂和化学发泡剂。物理发泡剂是指具备较高活性的表面活性剂或活性物质, 通过降低液体表面张力及在液膜表面形成双电子层排列、包围空气进而形成气泡。物理发泡剂主要包括: 松香树脂类、离子型、蛋白质类及复合类^[4]。化学发泡剂通过加入化学试剂(H_2O_2 , Zn 和 $NaHCO_3$ 等)发生化学反应产生气泡。

1.1 发泡剂种类对气泡性质影响

1.1.1 松香树脂类发泡剂 松香树脂类发泡剂是应用最早、最普遍的发泡剂^[5], 内部的松香三环骨架具有优良的疏水性^[6]。松香树脂类发泡剂主要有

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松香皂发泡剂和松香热聚物 2 种。松香皂发泡剂生产工艺简单, 成本低, 与水泥的相容性较好, 通常适用于密度大于 600 kg/m^3 的泡沫混凝土^[7]。但松香皂发泡剂泡沫稳定性通常较差; 松香热聚物发泡剂与松香皂发泡剂发泡性能相差不大, 但生产成本更高。Yan 等^[8]使用丙烯酸松香聚乙二醇酯发泡发现, 泡沫初始高度为 110 mm, 5 min 后相应高度仅为 33 mm。He 等^[9]对比了 α -烯基磺酸钠(AOS)、十二烷基硫酸钠(SDS)、椰子油(CO)、松香液(RL)发泡剂的发泡性能。研究发现, 当发泡剂浓度为 0.6%~0.8% 时, RL 发泡剂具有最高的发泡倍数。其中, 当 AOS、SDS、CO 和 RL 的浓度为 0.8% 时, 发泡倍数分别为 32、35、40、42。值得注意的是, RL 发泡剂在不同浓度下, 具有最高的沉降距离和较高的泌水量。因此, 使用 RL 发泡剂通常需与其他种类发泡剂及稳泡剂复合使用, 以获得最佳效果。

1.1.2 离子型发泡剂 离子型发泡剂属于第 2 代发泡剂, 具有较高的发泡倍数。与松香树脂类发泡

剂相比泡沫稳定性有所提高。目前, 市场上使用较多的是阴离子型和非离子型发泡剂。表 1 为常见离子型发泡剂的泡沫特点和泡沫混凝土性能。

由表 1 可知, 阴离子型发泡剂因其发泡倍数高而被广泛应用。伍勇华等^[10]使用 1.25% 的十二烷基硫酸钠(SDS)制得发泡倍数为 75 倍, 1 h 泌水量为 51 mL, 1 h 沉降距为 33 mm 的泡沫。SDS 具有降低液体表面张力、在气-液界面吸附并防止气泡聚结的作用, 因而 SDS 可以起到细化气泡尺寸, 增加起泡数量及稳定性的效果^[11]; 非离子型发泡剂具有气泡液膜厚度大、泡沫稳定性高的优点, 但也存在发泡倍数低的缺点^[12]。Fei 等^[13]合成了一种非离子型发泡剂 NPS, 其发泡倍数为 3.5, 半衰期为 60 s。研究表明非离子型发泡剂使用时受生成压力影响显著。Ranjani^[14]发现在较低泡沫生成压力下, 非离子发泡剂椰油二乙醇酰胺的初始泡沫密度随着浓度的增加而增加。而在较高泡沫生成压力下, 非离子发泡剂的初始泡沫密度随着浓度的增加而降低。

表 1 离子型发泡剂的泡沫特点和对泡沫混凝土性能影响

Table 1 Foam characteristics of ionic foaming agents and its effects on foam concrete

Foaming agent	Type	Foam characteristics or concrete properties
Anionic foaming agent	0.3% N-lauryl - L-glutamate sodium ^[15]	Foaming ratio, settling distance and bleeding water reached 35 times, 35 mm and 80 mL in 1 h, respectively.
	1% sodium dodecyl benzene sulfonate (LAS) anionic foaming agent ^[16]	Foaming ratio, settling distance and bleeding water were 32 times, 38 mm and 140 mL in 1 h, respectively.
	1% α -olefin Sodium sulfonate (AOS) anionic foaming agent ^[16]	Foaming ratio, settling distance and bleeding water were 46 times, 9.9 mm and 106.2 mL in 1 h, respectively.
	0.3%ORS41 anionic foaming agent	Initial foam volume was 92mL, and the half-life of the foam was 20 min.
	0.3%B-100 anionic foaming agent ^[17]	Initial foam volume was 48 mL, and the half-life of foam was 18.5 min.
	Alcohol ether sulfate (AES) anionic foaming agent ^[18]	Thermal conductivity of foamed concrete with dry density of 440~1 500 kg/m^3 was 0.120~0.421 W/(m·K).
Nonionic foaming agent	Polyethylene glycol fatty acid nonionic foaming agent ^[19]	Surface tension of the prepared foaming agent solution was as low as 25 mN/m, resulting in a stable foam. Ensure minimum strength above 2 MPa and thermal conductivity below 0.2 W/(m·K).

1.1.3 蛋白质类发泡剂 蛋白质类发泡剂是第 3 代发泡剂, 相比离子型发泡剂, 蛋白质基发泡剂具有更高的气泡强度和稳定性^[20~21]。Panesar^[22]用 CF 200 型蛋白质发泡剂制备的气泡密度为 65 kg/m^3 , 膨胀比 15 倍, 湿密度大于 750 kg/m^3 , 产生气泡为孤立的球形小泡。表 2 为蛋白质发泡剂的气泡特点和对泡沫混凝土性能影响。

由表 2 可知, 蛋白质类发泡剂可分为动物蛋白与植物蛋白两种, 目前使用的蛋白质发泡剂以动物蛋白为主。动物蛋白发泡剂以动物蹄角、毛发为原料, 通常具有气泡稳定、泌水量低的优点。Falliano 等^[23]认为不同蛋白质发泡剂对泡沫混凝土抗压强

度影响显著, 尤其是中低密度($300\sim 900 \text{ kg/m}^3$)泡沫混凝土。使用 3% 的 Foamin C[®] 蛋白质发泡剂制备混凝土, 在水胶比(W/C 比)为 0.3 时, 所制备的试件强度显著高于另外两种离子型发泡剂。以 52.5 R 水泥为基体的样品强度增加速率高于 42.5 R 水泥; 不同蛋白质发泡剂对泡沫混凝土的强度、吸水率等影响显著。Jitchaiyaphum 等^[24]研究发现动物蛋白泡沫混凝土的吸水率随抗压强度的增加而增加。而石行波等^[25]使用猪蹄脚为原料的动物蛋白发泡剂制备泡沫混凝土的吸水率随抗压强度的增大而降低。造成以上现象差异的原因可能与不同蛋白质发泡剂对孔隙结构, 尤其是连通孔的影响差异有关。

表 2 蛋白质类发泡剂的泡沫特点和对泡沫混凝土性能影响

Table 2 Effects of protein foaming agent on foam characteristics and foam concrete properties

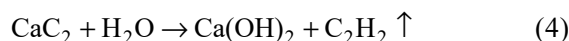
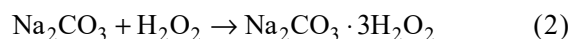
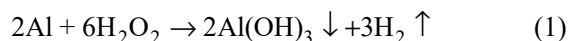
Foaming agent	Type	Foam characteristics or concrete properties
Animal protein foaming agent	Bovine hemoglobin protein foaming agent(H) ^[26]	Bovine hemoglobin improves thermal conductivity and creating a regular cellular structure. The thermal conductivity in the case of a composite with H/C ratio equal to 0.5 and with 3 min of mixing after the introduction of hemoglobin is 0.627 W/(m·K).
	An animal protein foaming agent ^[27]	Defoaming in 1h, the amount of bleeding water and foaming ratio of the animal protein were 36%, 8.5 mL, and 42 times.
	Protein foaming agent prepared from 20–30 g cow hoof horn ^[28]	Foaming ratio reached 13.7 times, and the stabilization time reached 90 min.
	Protein foaming agent prepared by 20 g pig's foot horn and 0.1% gelatin	Half-life of bubble was 47 min, the foaming height was 6.4 cm, the foaming volume was 510 mL, and the stabilization time was 30.33 h ^[25] . The dry bulk density (from 772 kg/m ³ to 581 kg/m ³) and compressive strength (from 6 MPa to 3 MPa) decreased with an increasing foam content (from 1 050 mL to 1 250 mL), while the water absorption increased from 19% to 28% ^[29] .
Plant protein foaming agent	Foam powder for caramel grains ^[30]	Foaming degree was up to 560%.
	Canola meal protein foaming agent ^[31]	Foaming height was up to 110 mm, and stable foaming time was 47 h.

1.1.4 复合类发泡剂 复合类发泡剂是第 4 代发泡剂,是具有协同增效功能的发泡剂。复合类发泡剂兼顾表面活性剂发泡倍数高及蛋白质发泡剂稳定性好的优点^[32]。复合类发泡剂的协同增效作用还体现在降低泡沫混凝土导热系数^[21],提高泡沫混凝土抗压强度,细化泡沫混凝土内部孔隙^[33],延长气泡半衰期^[34],提升起泡力^[35]等作用。

闫秋会等^[21]研究发现当十二烷基硫酸钠(SDS)和动物蛋白发泡剂(APFA)的质量比为 0.67:1.00 时,复合发泡剂的性能最佳,发泡倍数达 50 倍,1 h 泌水量为 0.152 mL。当上述泡沫用量为 2 375 mL 时,导热系数最低为 0.073 8 W/(m·K)。She 等^[33]使用 SDS 与聚乙烯醇(PVA)复配发泡剂制备的泡沫混凝土 28 d 强度为 3.4 MPa,比对照组(2.8 MPa)强度提高 21.4%,样品平均孔径由 289 μm 降至 260 μm。肖红力等^[34]将十二烷基苯磺酸钠(LAS)分别与月桂酰基肌氨酸钠(LS-95)、甲基葡萄糖苷聚氧乙烯醚双油酸酯(DOE-120)复配。实验结果表明,当 LAS 浓度为 1.0%和 0.7%时,复合类发泡剂起泡高度分别增大 8.6%和 12.8%,半衰期增大 22.7%和 36.4%。丁起^[35]将 SDS 与皂素以 3:7 复配。复合发泡剂初始泡沫高为 123 mm,比 SDS 和皂素分别提高 26 mm 和 38 mm。

1.1.5 化学发泡剂 最常见的化学发泡剂是 H₂O₂,此外,Zn、Fe、Al、CaCO₃、Mg(OH)₂和 4MgCO₃·Mg(OH)₂·5H₂O、NaHCO₃等^[36–38]都可作为化学发泡剂使用。Li 等^[39]以磷酸镁水泥(MPC)为胶凝材料、H₂O₂为发泡剂制备 MPC 泡沫混凝土。实验结果表明,所制备泡沫混凝土干密度为 300~1 000 kg/m³时,28 d 抗压强度及导热系数分别为 1.8~21.6 MPa 和 0.136~0.347 W/(m·K)。Djon 等^[38]对比了 Fe 和 Al

粉的发泡性能,实验使用 0, 5%, 10%和 15%发泡剂制备了磷酸活化火山灰泡沫水泥。结果表明,使用 Fe 粉发泡释放的氢气更少,制备的泡沫水泥材料产生孔隙更小、抗压强度更高。部分化学发泡剂的气泡机制见式(1)~式(5)^[40]。



Ma^[37]使用 NaHCO₃ 发泡剂制备而成的泡沫混凝土试件,当干密度由 653 kg/m³增加至 800 kg/m³时,导热系数由 0.078 W/(m·K)增加至 0.100 W/(m·K)。拌和水温是影响化学发泡剂性能的重要因素。使用 6% (质量分数)Na₂CO₃ 在拌和水温为 12、30 ℃和 40 ℃条件下,发泡体积分别为 265、300 mL 和 325 mL,这说明在一定的温度范围,化学发泡剂发泡体积随拌和水温提高而增大^[40]。此外,化学发泡剂通常采用与反应促进剂复配的方式提高其发泡性能。例如,佟建楠^[41]用 HCl 作促进剂与 KHCO₃ 复配成的泡沫发泡倍数可达 29 倍,1 h 沉降距为 17 mm,1 h 泌水率为 22%。

1.2 发泡剂用量对气泡性质影响

发泡剂用量是直接影响泡沫混凝土性能与气泡性质的关键因素。例如,泡沫混凝土强度、吸水率^[29]、气泡密度^[42]、气泡泌水率^[43]和导热系数^[44]等。发泡剂浓度、发泡倍数及完全消泡时间呈正相关,即发泡剂浓度越大,其发泡倍数越高,完全消泡时间越长及气泡稳定性越好。然而,并非发泡剂用量越大

泡沫混凝土各项性能越好。随着阴离子表面活性剂十二烷基苯磺酸钠(LAS)浓度由 0.5%增大至 2.0%, 泡沫混凝土干密度、抗压强度逐渐下降, 吸水率及导热系数则逐渐上升^[45]; 随着 α -烯烴磺酸钠(AOS)浓度由 0.5%增大至 2.0%, 干密度、吸水率及导热系数先减小后增大, 抗压强度逐渐下降。

通常, 随着发泡剂浓度的增大, 泡沫混凝土力学性能和耐久性下降。例如, 石行波等^[29]以猪蹄脚为原料作为动物蛋白发泡剂制备泡沫混凝土。实验结果表明, 发泡剂用量由 1 050 mL 增加至 1 250 mL 时, 泡沫混凝土 28 d 抗压强度由 6 MPa 下降至 3 MPa。吸水率由 19%提升至 28%。Eva 等^[46]研究发现, 低浓度(0.7%)的 FN1 蛋白发泡剂比高浓度(1.4%)的蛋白质发泡剂泡沫稳定性提高 30%, 泡沫膨胀率提高 4.8%。所制备的样品孔隙率更小, 抗压强度更高; 制备复配型发泡剂过程中, 使用不同用量的发泡剂也会对泡沫混凝土性能产生影响。例如, 张磊等^[47]使用十六烷基三甲基溴化铵(CTMAB)与牛蹄角粉、酵母菌互掺制备 2 种发泡剂。研究结果表明, 当 CTMAB 分别为 0.7%和 0.5%时, 复合发泡剂可以显著改善泡沫混凝土力学强度。除了物理发泡剂外, 化学发泡剂用量的变化也会显著影响泡沫混凝土性能。Fu 等^[44]研究发现随着 Zn 粉用量的增加(0.3%~0.8%)样品的 28 d 抗压、抗弯强度、导热系数分别由 13.23 MPa、3.8 MPa、0.28 W/(m·K)下降至 7.15 MPa、2.8 MPa、0.21 W/(m·K)。

1.3 稳泡剂类型对气泡性质影响

由于单独使用发泡剂存在气泡稳定性差、混凝

土强度低等问题。为此, 借助稳泡剂对液膜的增厚、增黏及阻碍排水等作用, 可以提高气泡稳定性、增强泡沫混凝土性能。目前, 稳泡剂主要可分为协同型稳泡剂、增黏性稳泡剂以及纳米固体稳泡剂 3 类^[48]。

1.3.1 协同型稳泡剂 主要协同型稳泡剂有: 硅树脂聚醚乳液(MPS)^[34,49]、月桂醇(LA)^[50]、硬脂酸钙(CS)^[44, 51-54]。协同型稳泡剂的作用机制是通过加强表面分子吸附, 增加液膜强度, 降低透气性, 从而提高泡沫的稳定性。刘昕昊^[55]研究硅树脂聚醚乳液(MPS)对气泡稳定性影响, 实验发现, 6.5%的 MPS 使泡沫沉降由 10.5 mm 降为 3 mm, 泌水量由 36.8 mL 降为 25.5 mL。陈耿等^[49]用 0.6 g/L 的月桂醇提高气泡稳定性, 研究发现月桂醇使发泡体积由 850 mL 增大到 880 mL, 半衰期由 390 s 延长至 2 700 s。Wu 等^[53]发现使用 0.3%的硬脂酸钙(CS)有利于稳定气泡, 并进一步改善超轻质发泡地质聚合物(UFG)的孔隙结构及抗压强度。Cui 等^[54]使用 1%用量的 CS 稳泡剂, 使发泡时间与发泡体积分别增加了 42.8%和 28.6%, 体积密度为 0.31 g/cm³的样品 28 d 抗压强度最低为 1.45 MPa, 满足国家标准 GB 11968—2006《蒸压加气混凝土砌块》要求。表 3 为常见协同型稳泡剂类型、泡沫特点和对混凝土性能影响。

由表 3 可知, 协同型稳泡剂具有提高气泡发泡倍数、延长半衰期、减少泡沫沉降及泌水量作用。协同型稳泡剂还可以降低泡沫混凝土干密度, 提升强度^[52]; 值得注意的是协同型稳泡剂的稳泡效果有限, 需与其他稳泡剂共同使用, 进一步提高泡沫稳定性; 且某些稳泡剂(茶皂素)的稳泡效果并不显著^[56]。

表 3 协同型稳泡剂类型、泡沫特点和对泡沫混凝土性能影响

Table 3 Types, foam characteristics and foam concrete properties of synergistic foam stabilizer

Type	Foam characteristics or concrete properties
0.5% modified silicone polyether Emulsion (MPS) ^[57]	Compared with the blank test, the foaming ratio increased from 16.80 times to 17.08 times. The half-life extended to 216.81 min from 20.10 min. When the foam content was 2, 4 mL/g and 6 mL/g, the dry density of FMOC (Foamed magnesium oxychloride cement) prepared by MPS decreased by 6, 16 kg/m ³ and 4 kg/m ³ , and the strength increased by 0.81, 0.19 MPa and 0 MPa, respectively.
1.5% nonylphenol polyoxyethylene ether (TX-10) ^[57]	Compared with the blank test, the foaming ratio increased from 16.80 times to 17.89 times, and the half-life increased to 50.69 min from 20.10 min. The mold collapse phenomenon occurs in the low density of foam concrete due to its large diameter.
Tea Saponin (TS) ^[57]	Compared with the blank test, the foaming ratio increased from 16.80 times to 17.25 times, and the half-life increased to 34.45 min from 20.10 min. The addition of tea saponin had no significant influence on the strength of concrete. While, the dosage of was 0.4% and 0.6%, the dry density of concrete decreased by 33% and 40%, respectively ^[56] .
0.8% silicone amide ^[52]	Strength increased by 31% with 0.8% stabilizer compared with the blank test.
Alkyl alcohol amide ^[58]	Foam concrete prepared with 0.5% alkyl alcohol amide obtained good fluidity and the minimum drop height.

1.3.2 增黏性稳泡剂 增黏性稳泡剂是通过提高泡沫液相黏度以达到降低气泡排液速率, 延长半衰期,

提高泡沫稳定性的目的。典型代表有: 羟丙基甲基纤维素(HPMC)^[33,59]、羧甲基纤维素钠(CMC-Na)^[55,60-62]、

黄原胶(XG)^[63–65]等。其中, XG 对提高气泡黏度和降低排液速率效果显著。Qiu 等^[64]研究发现 0.5 g/L 的黄原胶最有利于提高泡沫稳定性及溶液黏度, 气泡尺寸为 0~200 μm , 且较为均匀, 气泡半衰期随着 XG 浓度的增加由 80 min 增加至 320 min。Sheng 等^[62]研究也发现 XG 对气泡黏度的改善效果优于羧甲基纤维素钠。由表 4 可知, 增黏性稳泡剂对降低气泡泌水率和表面张力显著。例如, 1%明胶可以使气泡半衰期由 20 min 提高到 55 min^[57]。0.5%黄原胶可以显著降低气泡表面张力, 提高气泡稳定性。使泡沫混凝土 7 d 和 28 d 抗压强度分别提高 47.3%和 48.5%, 吸湿率和吸水率分别降至 16.3%和 23.4%^[63]。Yu 等^[12]认为 XG 聚集在气泡液膜之间, 可以降低气泡液膜的排液速率, 从而提高气泡稳定性(见图 1)。

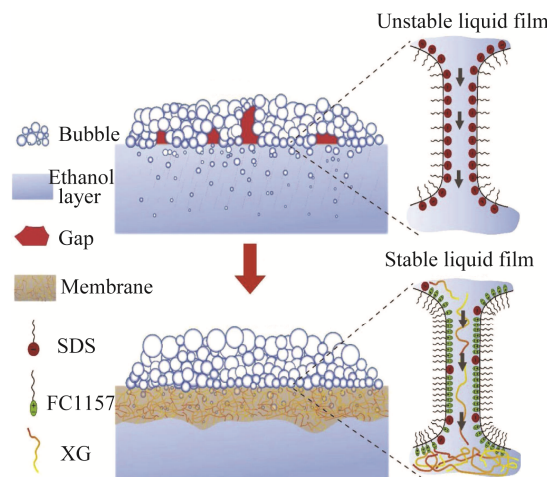


图 1 黄原胶稳泡剂对乙醇层气泡稳定作用^[12]

Fig. 1 Schematic diagram of the synergism of xanthan gum (XG) to stabilize the foam on the ethanol layer^[12]

表 4 增黏性稳泡剂的特点及对泡沫混凝土性能影响

Table 4 Foam characteristics of thickening foam stabilizer and its effects on foam concrete properties

Type	Foam characteristics	Effects on concrete properties
1% gelatin (GA) ^[57]	Foaming ratio was 16.75 times, and the half-life extended from 20.10 min to 55.10 min.	More than 90% concrete pore size was in the range of 50 μm to 200 μm .
0.6 g/L Polyacrylamide (PAM) ^[49]	Compared with the blank test, the foaming volume was increased from 850 mL to 890 mL, and the half-life extended from 390 s to 19 min.	
Hydroxypropyl methyl cellulose (HPMC)	Foam density increased from 50 kg/m^3 to 65 kg/m^3 , and the foam began to bleed after 30 min ^[33] .	When the content is greater than 1%, the dry density was stable at about 570 kg/m^3 . The 28 d strength increased from 2.46 MPa to 2.90 MPa as HPMC increased from 0 to 0.1% ^[59] .
Xanthan gum(XG)	Foam drains little to no water for 80 min with 0.45% XG ^[65] . Compared with the blank test, the surface tension decreased from 31 mN/m to 28.68 mN/m, the foaming ratio increased from 18 times to 21 times, the bubble population density decreased from 56.7 kg/m^3 to 47.5 kg/m^3 , and the bleeding rate decreased from 13.8 mL to 8.6 mL in 60 min ^[63] .	Addition of XG increased the compressive strength of foam concrete by 34% ^[65] . Compared with the blank test, the strength increased from 2.48 MPa to 3.58 MPa, the water absorption decreased from 30.2% to 23.4%, and the film thickness increased from 20 μm to 39 μm ^[63] .
Sodium carboxymethyl cellulose (CMC-Na)	Minimum bleeding volume was 34 mL with 4.5% (in mass) CMC-Na, minimum settling distance reached 9 mm with 6% CMC-Na ^[55] . Foam concrete reached the maximum mobility as CMC-Na dosage was 0.3%, which was 18.3% higher than that of the blank test ^[61] .	Maximum fluidity of foamed concrete with 0.5% CMC-Na is 225 mm, and the maximum 28 d compressive strength of foamed concrete with 0.1% CMC-Na is 2.67 MPa, which is 7.66% and 21.62% higher than that of the base group, respectively ^[60] . Maximum value of 28 d strength and specific strength were increased by 70.1% and 47.9%, while the thermal conductivity decreased by 16.3%. Besides, the dry shrinkage value of 28 d decreased by more than 1mm/m, the water absorption decreased by 18.4%, and the softening coefficient increased by 11.8% ^[61] .
Sodium hydroxide ^[55]	It had a good improvement on the bleeding amount but no significant improvement on the settling distance.	

1.3.3 纳米固体稳泡剂 基于颗粒在气液界面的吸附作用, 纳米固体颗粒具有良好的稳泡作用。纳米固体颗粒使原本的“气-液”泡沫转变为“固-液-气”三相泡沫, 阻碍气泡排水, 从而起到提高泡沫稳定性、细化气泡尺寸的效果。典型代表有: 纳米二氧化硅(NS)^[33, 66–68]、纳米氧化铝(NA)^[69]和纳米碳酸

钙(NLP)^[70]。She 等^[33]用甜菜碱型两性表面活性剂(CAB)、纳米二氧化硅(NS)和羟丙基甲基纤维素(HPMC)制备的发泡剂, 显著降低气泡泌水率、增加气泡黏性、改善其早期塌陷行为。NS 颗粒表面的羟基水解为负氧离子与表面活性剂亲水基团中正离子通过库仑力结合, 从而提高气泡稳定性。Guo 等^[69]

研究了纳米氧化铝(NA)、十二烷基硫酸钠(SDS)与聚乙烯醇(PVA)的复合效果。实验结果表明,随着 NA 在气泡膜边缘聚集, NA 逐渐形成三维网状结构,阻止了液体流动,减缓气泡排液速率。碱性溶液中 OH⁻与 NA 结合,并通过库仑力吸附在表面活性剂周围,致密的表面层结构可以维持气泡形状,

增强液膜厚度,并防止气泡合并。Li 等^[70]研究了湿磨废碳酸钙对气泡在浆体中的稳定性影响。研究表明,碳酸钙在液膜表面吸附增加了液体流动阻力,限制了液体的排出,从而提高了泡沫的稳定性。此外,碳酸钙可以吸收液膜的自由能,限制了表面张力的降低,从而提高了气泡的均匀性和强度。

表 5 纳米固体稳泡剂类型、泡沫特点和对混凝土性能影响

Table 5 Types, foam characteristics and effects on concrete properties of nano-solid foam stabilizer

Type	Foam characteristics	Effects on concrete properties
Nano-silica (NS)	Foam density increased from 65 kg/m ³ to 80 kg/m ³ ^[33] . Foam viscosity increased from 2.0 mPa·s to 9.5 mPa·s, the sedimentation rate decreased from 2.50% to 0.63%, and bleeding rate increased from 57% to 59% with 10 g/L NS ^[69] .	Strength of 28 d increased from 3.61 MPa to 6.52 MPa ^[33] .
Ca(OH) ₂ ^[71]	F-PH9(Use 5×10 ⁻⁶ mol/L Ca (OH) ₂ to adjust the pH value of the solution to 9 and mix with the foaming agent) sample group was the best, with 5 min water flow, 60 min water flow and liquidity of 1%, 43% and 172 mm, bubble viscosity and bubble strength of 0.263 Pa·s and 29.84 Pa, and liquid film thickness of 49.52 μm, respectively.	Compressive strength of 7 d and 28 d were 2.2 MPa and 3.1 MPa, respectively. While the water absorption of 28 d and dry shrinkage of 90 d were 4.7% and 2.79 mm/m, the density ratio of bottom to top was 1.12, and the ratio of aperture diameter (100 μm≤d≤500 μm).
Silica fume ^[72]	Foam was 25% higher than that of the blank test in 270 min.	F1 (adding silica fume at the liquid foaming stage) can effectively promote the stability of the foam and the ratio of compressive strength to density than that of F0 (without adding silica fume).
5% (in mass) nano-alumina (NA) ^[69]	There was almost no collapse of foam within 60 minutes. Surface tension was reduced from 30.85 mN/m to 27.83 mN/m, and the foaming ratio was increased from 27 times to 35 times	Concrete strength increased from 2.2–3.4 MPa (without NA mixing) to 3.1–5.2 MPa
10 g/L Graphene (G) ^[66]	Surface tension increased from 31% to 50%, and the sedimentation rate increased from 2.5% to 19.0%.	Thermal conductivity increased from 0.126W/(m·K) to 0.185 W/(m·K).
Hydrophobic Starch Nanoparticles (H-SNP) ^[73]	Compared with the blank test, the foam displacement decreased by 8% in 5 min.	Compared with the blank test, the compressive strength and water absorption increased from 2.35 MPa to 2.77 MPa and decreased from 21.3% to 10.5%, respectively. The dry shrinkage decreased from 2.72×10 ⁻³ to 1.74×10 ⁻³ at 90 d. Percentage of concrete aperture distributed in 100–500μm increased to 63.2%.
6% Wet-ground waste limestone powder(WGWLP) ^[70]	Compared with the blank test, the foam density increased from 65.38 kg/m ³ to 66.24 kg/m ³ . WGWLP refined the small bubbles.	Strength of specimens with 6% WLP was 7.21 MPa, with an increased by 12.2% compared with reference. The maximum density ratio of 1.03 was lower than that of the reference group of 1.09.

表 5 为纳米固体稳泡剂类型、泡沫特点和对混凝土性能影响。由表 5 可知, 纳米固体颗粒通过提升气泡密度^[33,70]、增加泡沫黏度^[69,71,74]和降低气泡沉降距^[69]等方式提升气泡性能, 进而提高泡沫混凝土强度^[33,69,73]。孙乾等^[67]发现 NS 在提高泡沫稳定性方面效果显著, 1.5%的 NS 较对照组起泡体积降低 35%, 但气泡稳定性增加了 6 倍以上。Christina 等^[75]对比了 NS 与 3 种纳米管稳定的气泡发现, NS 稳定的气泡尺寸最小, 气泡排液通道最窄。Xiong 等^[76]研究 NA 对动物蛋白基(AS)、植物蛋白基(PS)及合成类(SS)3 种发泡剂性能的增强效果, 结果发现: 添加 NA 后, AS、PS 和 SS 的气泡密度分别由 21、18 kg/m³ 和 19 kg/m³ 提高到 24、22 kg/m³ 和 76 kg/m³,

气泡黏度由 0.106、0.061 Pa·s 和 0.141 Pa·s 提高到 0.166、0.139 Pa·s 和 0.177 Pa·s。28 d 抗压强度分别由 2.25、1.72 MPa 和 2.05 MPa 提升至 2.42、1.83 MPa 和 2.75 MPa。

值得注意的是, 纳米固体稳泡剂对气泡表面张力的影响不同, NA^[69]、NS^[77]被证明能有效降低气泡表面张力, 而石墨烯(G)^[66]似乎引起了气泡表面张力的增加。气泡表面张力决定了其发泡的难易程度, 通常表面张力越小则发泡能力越好^[64]。实验过程中气泡表面张力的变化可能与纳米材料自身的吸附特性有关, 也可能受到实验操作者对纳米颗粒的分散效果影响。

1.3.4 稳泡剂改性复配 在以上研究基础上, 研

研究者进一步通过稳泡剂改性和复配技术提高气泡的稳泡效果。例如, Zhu 等^[68]使用硅烷改性的 NS 提高了气泡半衰期 27%。Ma 等^[78]通过研究改性聚氧乙烯硅油(MPS)、海藻酸钠(SA)和羧甲基纤维素(CMC) 3 种稳泡剂对铝酸钙水泥(CAC)水化的影响,发现 SA 能加快 CAC 的水化速率,而 MPS 和 CMC 延缓了 CAC 的水化;相较于 MPS 与 CMC, SA 稳定泡沫陶瓷具有更好的结构完整性、更高的孔隙率(87.8%)、更小的平均孔径(283 μm)及更低的热导率(0.277 W/(m·K), 1 000 $^{\circ}\text{C}$)。雷团结等^[79]将 0.2%有机硅稳泡剂(ZT-1)和 0.02%增稠类物质羧甲基纤维素(CMC)复配后发泡倍数达 37.5 倍,1 h 沉降距为 1.8 mm,1 h 泌水量为 26.1 mL,48 h 后泡沫高度仍在 1/2 以上。Xiong 等^[76]将 NA 分别用作植物蛋白质基表面活性剂(PS)、动物蛋白质基表面活性剂(AS)和合成的表面活性剂(SS)的稳定剂,发现 SS、AS 和 PS 在 5 min 时的排水量分别降低 11%、5%和 4%,且纳米改性 SS 混凝土性能优于 PS 和 AS 纳米改性的混凝土。王翠花^[80]将硬脂酸钙与自制稳泡剂复配,制备出满足不同干密度、强度及导热系数的试件。

1.4 稳泡剂用量对气泡性能影响

稳泡剂用量是影响气泡性质及混凝土性能的重要因素。例如,对于协同型稳泡剂,杨冰儒^[81]研究了聚乙二醇、十二醇和三乙醇胺三种稳泡剂对不同发泡剂的稳泡效果不同。其中聚乙二醇对十二烷基二甲基氧化铵(LO)稳泡性能的提高效果最为明显;0.02%的十二醇对 CAB 起泡性能提升效果最佳,0.05%的十二醇对椰油酰胺丙基氧化胺(CAO)和 LO 起泡性能最有提升;当三乙醇胺用量为 0.1%时,对 LO 的起泡性能和稳泡效果最佳。对于 CS,研究者分别考察了用量为 0.1%~0.3%、0~1.0%和 0.4%~4.0%的气泡稳定性变化。Wu 等^[53]研究发现当 CS 含量从 0.1%增加到 0.3%时,UFG 的抗压强度由 1.46 MPa 增加至 1.71 MPa,较 0.1%时试样提高 49%。张燕等^[50]发现当 CS 用量在 0.4%~4.0%时,试件的干密度及抗压强度与用量呈正相关关系。当用量为 1.2%~4.0%时,试件吸水率均<50%,导热系数均<0.08 W/(m·K)。随着 CS 用量的提高,泡沫混凝土抗压强度先升高后降低。由于 CS 具有憎水性,因而随着其用量的增加,泡沫混凝土吸水率逐渐降低^[51]。

对于增黏性稳泡剂,张云飞等^[82]研究了用量 0~2%十二烷基苯磺酸钠(SDBS)、十二烷基硫酸钠(SDS)、羟丙基甲基纤维素醚(HPMC)、聚丙烯酰胺

(PA)4 种稳泡剂对发泡体积的影响。实验发现发泡体积随稳泡剂用量增加分别呈递增、递增、递减及先增后减趋势,最佳用量均为 1.0%~1.5%。Qiu 等^[64]研究发现随着黄原胶用量的增加,溶液黏度增加,黄原胶浓度为 1.1 g/L 时,气泡黏度达最大 18.3 mPa·s,发泡体积随黄原胶浓度增加逐渐降低,当浓度>0.9 g/L 时下降速率显著增大。

事实上无论是协同型稳泡剂还是增粘性稳泡剂,除了其用量对气泡稳定性影响外,发泡剂种类和用量影响也会对气泡稳定性产生影响。高鹤^[45]将 0.3%的 CS 分别掺入不同浓度 LAS、AOS 发泡剂,研究泡沫混凝土吸水率和导热系数的变化。当发泡剂用量较低(<0.5%)时,CS 掺入使混凝土吸水率及导热系数有所提高,当发泡剂用量为(1%~2%)时,吸水率及导热系数有所降低。

1.5 其他因素对气泡性能影响

除发泡剂和稳泡剂种类及用量对气泡性质和稳定性产生影响外,泡沫混凝土胶凝材料、纤维、水胶比以及外加剂等都会显著影响气泡的性质和稳定性。例如:胡慧敏^[83]研究水泥对泡沫混凝土性能的影响发现:将普通硅酸盐水泥和硫铝酸盐水泥混掺使用时存在一个平衡点,当硫铝酸盐水泥用量低于此平衡点时,可使泡沫混凝土气泡均匀且稳定。王婷^[84]制备粉煤灰泡沫混凝土时出现浆体流动度增大、气泡结构粗化的现象。分析认为,粉煤灰的“滚珠效应”使泡沫混凝土浆体流动度增加,浆体内部气泡无法独立稳定存在并与周围气泡发生聚合。

在泡沫混凝土中使用纤维可以改善泡沫混凝土各项性能,研究者同时考察了不同纤维对气泡性质影响。例如,范雨茜^[85]研究竹原纤维对化学发泡泡沫混凝土性能的影响发现,竹原纤维通过消除原本可留存的大气泡,抑制小气泡扩展的方式改善泡沫混凝土的孔隙结构,进一步影响其性能。杨瑞环等^[86]通过制备聚乙烯醇纤维泡沫混凝土发现,聚乙烯醇纤维能将混合浆中的大气泡分割为更小而均匀的小气泡,提高气泡稳定性。吴子豪^[87]经研究则发现气泡会聚集在比表面积大的聚丙烯纤维表面,小气泡进一步相互融合成大气泡,影响气泡稳定性;此外,部分聚丙烯纤维贯穿在气泡中易引起气泡破灭。

水胶比是影响泡沫混凝土各项性能的重要因素,研究发现水胶比可以显著影响气泡稳定性。孙赛炜等^[88]研究发现,增大水胶比能够增加浆体流动性,减弱气泡与基体间的摩擦,保证气泡稳定性。梁恺康^[89]研究水胶比对碱激发泡沫混凝土消泡率

影响时得到了相反的结论。结果表明, 当水胶比分别为 0.35 和 0.65 时, 600 kg/m^3 碱激发泡沫混凝土消泡率为 21.1% 和 31.1%。分析认为水胶比变化显著影响着浆体黏度。水胶比的增大会使浆体黏度减小, 从而减少气泡在浆体中吸附的数量。

研究表明, 使用增稠剂和减水剂对提高气泡稳定性有一定帮助。增稠剂可通过其疏水基团与水形成氢键以及极性基团的相互作用搭建三维网状结构^[90]。进而避免气泡的破灭与聚集, 提高气泡稳定性^[91]。Bagheri 等^[92]发现在泡沫混凝土混合料中加入减水剂可减少气泡体积损失, 提高气泡稳定性。减水剂使泡沫混凝土气泡体积损失分别由 84%、68% 和 65% 降低为 75%、58% 和 46%。原因是: 减水剂可通过改善流动性与和易性减弱气泡与基体间的摩擦, 从而减少气泡体积损失^[93]。

2 基体材料对泡沫混凝土性能影响

如前所述, 泡沫混凝土可分为气泡与基体 2 部分。从原料组成上来看, 基体材料主要包括水泥和矿物掺和料体系以及碱激发胶凝材料/地质聚合物体系, 还包括所用纤维和外加剂等。

2.1 水泥

水泥基材料, 是以水泥为胶结剂, 掺加各类集料、外加剂形成的水硬性胶凝材料。其中, 水泥标号及种类决定了制备泡沫混凝土性能差异。

张剑等^[94]研究发现 P.O 42.5 R 水泥制备泡沫混凝土的 3 d 抗压强度为 P.O 32.5 R 水泥所制备试样的 3 倍左右。Xiao 等^[95]对比了硫铝酸盐水泥(SAC)和普通波特兰水泥(OPC)对泡沫混凝土抗压强度和导热系数的影响。实验发现 OPC 可以提高泡沫混凝土的早期抗压强度和导热系数。SAC 可以降低泡沫混凝土的导热系数。Li 等^[96]运用泡沫混凝土导热系数的经验方程, 计算得出了不同类型水泥泡沫混凝土的导热系数(式 6)。

$$\lambda = \frac{(\lambda_2 - \lambda_1)\rho_1}{(5\rho_2 - 4\rho_1)^Z} + \lambda_1 \quad (6)$$

式中: λ 为泡沫混凝土导热系数; λ_1 、 λ_2 分别为发泡气体和水泥浆体的导热系数; ρ_1 为泡沫混凝土干密度; ρ_2 为水泥浆体干密度; Z 为泡沫混凝土封闭孔隙与所有孔隙的比值, 当所有孔隙都关闭时, Z 的值等于 1。

图 2a 和图 2b 为导热系数经验方程式的计算值与实际值对比。随着干密度增大, 泡沫混凝土的导热系数逐渐增大, 保温性能降低。其中 MPC 泡沫

混凝土导热系数最高, SAC 泡沫混凝土最低, OPC 泡沫混凝土导热系数略高于 SAC 泡沫混凝土。对不同水泥泡沫混凝土的孔隙结构(见图 2c~图 2d)分析可知, 当泡沫混凝土干密度为 600 kg/m^3 时, 3 种水泥泡沫混凝土的孔径分布(0.15~0.20、0.20~0.25、0.25~0.30、0.30~0.35 mm 和 0.35~0.40 mm)与平均孔径相差不大, 说明孔隙结构对泡沫混凝土导热系数的影响可以忽略不计。考虑到以往研究认为孔隙结构对泡沫混凝土导热性起主导作用^[97]。不同泡沫发泡所产生气体不同, 因而泡沫混凝土的导热系数还受到气体导热系数的影响。综上, 不同强度的水泥对所制备泡沫混凝土强度和导热系数影响显著。因此, 实际工程与产品应根据硬化时间、流动度、早期强度及导热系数的需要选择水泥种类和用量。

2.2 矿物掺和料

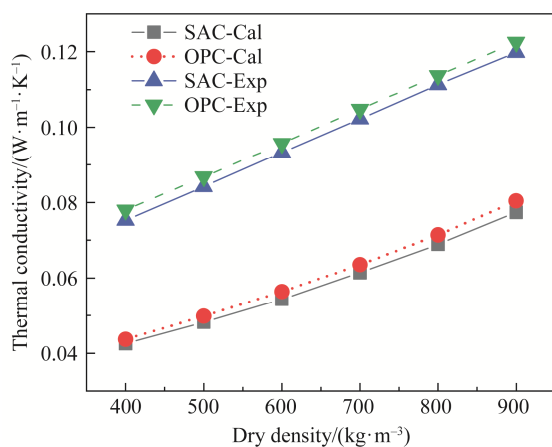
矿物掺和料具有一定的填充效应和活性效应, 可以改善泡沫混凝土微结构, 提高泡沫混凝土抗渗透性能^[98]。由于矿物掺和料种类丰富, 组成复杂, 不同矿物掺和料种类和用量对混凝土性能影响各异。其中, 粉煤灰(FA)是最常用的矿物掺和料。

现有研究表明, FA 最佳用量在 30% 左右。FA 用量、粒度粗细均会影响泡沫混凝土的抗压强度、孔隙结构以及水化进程等。吴丽曼等^[99]研究发现, 不同 FA 用量对泡沫混凝土性能的改善效果不同。当 FA 用量为 50% 时, 试样平均孔径和孔隙率较基准组试样分别减小 21.18% 和 6.80%; 当 FA 用量为 30% 时, 泡沫混凝土 28 d 抗压强度最高, 较基准组试样增加 15.92%。分析认为, 当 FA 用量为 10%~20% 时, 可以起到细化孔径, 提升吸声性能的作用, 而过高用量的粉煤灰则会阻塞孔隙、对吸声产生不利影响。这可能是因为适量 FA 中存在活性的 SiO_2 、 Al_2O_3 可发生二次水化反应, 生成 C-S-H、C-A-H 凝胶, 使结构更加密实并进一步提高混凝土强度。而过高用量的 FA 会使水化产物中的 $\text{Ca}(\text{OH})_2$ 反应过度, 使溶液中 Ca^{2+} 含量减少, 减缓水化反应进程而降低强度。

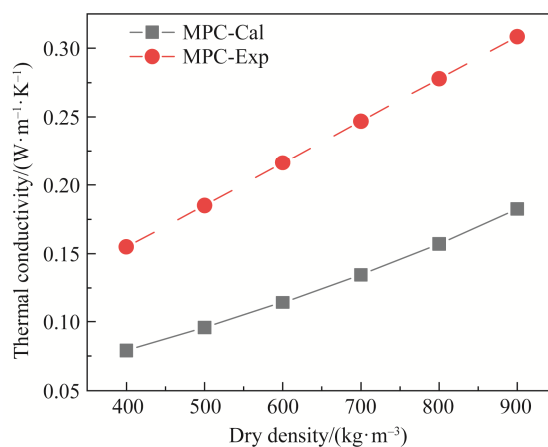
不同粒度的 FA 对混凝土的影响不同, She 等^[100]用平均粒径为 $21 \mu\text{m}$ 的细 FA 替换水泥(替换率 30%), 用平均粒径为 $98 \mu\text{m}$ 的粗 FA 替换砂(替换率 0, 50% 和 100%)。研究发现, 使用粗 FA 代替砂提升了混凝土的流动性和强度, 降低试样固体密度, 提高混凝土干缩及吸水率。Liu 等^[101]分析了 FA 用量对泡沫混凝土干密度、导热系数、收缩率等的影响。实验结果表明, FA 可以不同程度地降低试样的

干密度及导热系数, 且粒度更细的 FA 更有利于降低导热系数和收缩率。事实上, 矿物掺合料除了影响泡沫混凝土基体性能, 还对气泡稳定性造成影响,

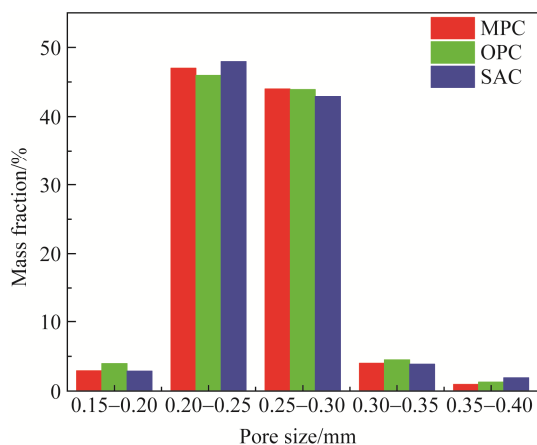
例如, Xiao 等^[102]认为随着 FA 用量增加(5%~20%), 混凝土凝固时间逐渐延长, 进而导致坍落度增大, 不利于气泡稳定。



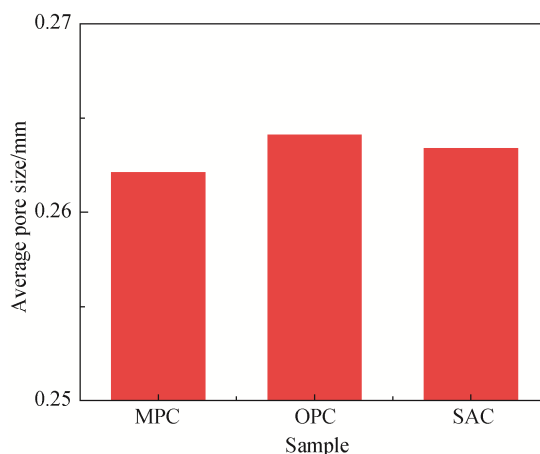
(a) Calculated value and experiment value of SAC and OPC



(b) Calculated value and experiment value of MPC



(c) Distribution of pore size



(d) Average pore size of sample

SAC is sulphoaluminate cement. OPC is ordinary portland cement. MPC is magnesium phosphate cement.

图2 水泥对泡沫混凝土导热系数和微结构影响^[96]

Fig. 2 Influence of cement on thermal conductivity and micro-properties of foam concrete^[96]

考虑到矿物掺合料种类的多样性, 表6总结了典型矿物掺合料对泡沫混凝土性能影响。由表6可知, 硅灰、偏高岭土及凹凸棒土对于泡沫混凝土的强度有不同程度改善, 而再生粉和棕榈油煤灰对强度影响各异。硅灰具有增加密度、改善孔隙结构作用, 而再生混凝土微粉对密度影响不大; 通常, 粉煤灰及硅灰的加入都对降低泡沫混凝土吸水率具有帮助。矿物掺合料种类多样, 形貌和组成各异, 因此, 对泡沫混凝土的影响也不同。Song 等^[103]对比了粉煤灰(FA)、炉渣(FS)、矿粉(MP)3种掺和料对泡沫混凝土抗压强度影响顺序为 MP、FS、FA, 对导热系数的影响顺序为 FS、FA、MP。泡沫混凝土强度随 MP 用量增加而增大, 随 FA、FS 用量增加呈先增大后减小的趋势。MP 中高含量的 CaO 有

助于促进水化反应进行, 同时 MP 粒径最小, 使泡沫混凝土孔隙填充更加快速、致密, 起到提高抗压强度的作用; FS 中 SiO₂ 及 Al₂O₃ 的反应活性高于 FA^[104], 因而 FS 对抗压强度的影响大于 FA; 导热系数方面, FA 加入会使孔隙分布更均匀, 减少连通孔隙数量而使导热系数降低^[105]; 由于 MP 形状的不规则性, 易破坏气泡而使连通孔增加、导热系数增大。因此, 当 MP 用量过大时, MP 颗粒对气泡的破坏作用大于其活性作用的影响。以上分析可知, MP 在改善强度方面效果显著, 而 FS 对导热系数影响较大。由此可见, 考虑矿物掺合料对泡沫混凝土性能的影响要从矿物掺合料组成、粒度、形貌、活性和用量等角度, 建立其特性与泡沫混凝土宏观性能关联。

表 6 掺合料对泡沫混凝土性能影响

Table 6 Influence of admixture on foam concrete performance

Mineral admixture	Influence on concrete performance
Fly ash (FA)	Incorporation of FA reduced the ratio of compressive strength to thermal conductivity ^[106] . When the fixed content of FA is 40%, the maximum compressive strength of concrete is 0.54 MPa, the maximum splitting tensile strength is 0.169 MPa, the maximum thermal conductivity is 0.059 6 W/(m·K), and the porosity, average pore size and pore shape factor are the minimum, which are 85%, 655.07 μm and 1.25, respectively ^[107] .
Silica fume (SF)	SF increased the density of foam concrete by 55% and reduced the water absorption by 67%. SF increased the concrete strength by 4.4 times. Addition of SF increased the thermal conductivity of foam concrete by 37% ^[106] .
Metakaolin(12%)	Compared with the blank test, the compressive strength and average pore diameter increased from 0.11 MPa to 0.22 MPa and 967 μm to 1 156 μm, respectively ^[108] .
Attapulgite(3%)	Maximum compressive strength was 3.33 MPa and the maximum specific strength was 6 488 N·m/kg, which were 148.5% and 127.5% higher than those in the blank test, respectively ^[61] .
Recycled powder (RP)	Addition of recycled powder resulted in little impact on both the wet and dry density of foam concrete. Compressive strength of foam concrete decreased with the increasing content of the recycled powder. Incorporation of recycled powder reduced the thermal conductivity of foam concrete. Porosity and maximum pore diameter of foamed concrete increase with increased recycled powder content ^[95] .
Palm oil fuel ash (POFA, 20%)	POFA had low compressive strength due to its non-volcanic particles, high LOI (Loss On Ignition) content and porous nature ^[109] . It has low water absorption and porosity ^[110] .

2.3 碱激发胶凝材料/地质聚合物材料

除传统水泥基材料外,碱激发胶凝材料和地聚合物胶凝材料也被用于制备泡沫混凝土的基体^[111-112]。

与传统水泥基体不同,碱激发材料和地聚合物材料需要借助激发剂和固废材料制备泡沫混凝土基体。因此,碱激发/地聚合物材料的激发剂种类、用量及固废原料可以显著影响泡沫混凝土性能。

2.3.1 碱激发胶凝材料 常见的激发剂有: NaOH^[59,113-116]、Na₂O^[115,117-118]、Ca(OH)₂^[119-120]等。郑安然^[59]研究发现,2%用量 Na₂O 制备的泡沫混凝土 3 d 抗压强度最高。当 Na₂O 用量增加至 8%时,泡沫混凝土 3 d 强度降低至 10.6 MPa,7 d 和 28 d 抗压强度分别为 13.3 MPa 和 17.1 MPa。实验结果表明,碱激发胶凝材料可以提高泡沫混凝土早期强度,而高含量的激发剂对泡沫混凝土基体抗压强度不利,这可能与 Na₂O 能使水化产物 C-S-H 脱钙有关^[121]。激发剂用量除了影响泡沫混凝土基体的抗压强度,还会对干密度、流动度和凝结时间等产生影响,例如,陈飞屹^[52]使用碱激发胶凝材料作为泡沫混凝土基体,研究发现当激发剂含量为 4%时泡沫

混凝土干密度为 552 kg/m³,强度为 0.08 MPa;而激发剂含量为 7%时,试件干密度达到 250 kg/m³,抗压强度为 0.21 MPa。Liu 等^[117]发现碱激发剂用量可以显著改变基体的流动度,例如,当 Na₂O 含量为 6%时,达最大流动度(178 mm),较初始值提高 21.1%。此外,Feng 等^[115]还证实了 Na₂O 具有促凝作用。当 Na₂O 用量从 3%增加到 7%时,初凝时间和终凝时间分别从 890 min 减少至 118 min、930 min 减少到 129 min。

Ca(OH)₂ 作为常用激发剂,其对泡沫混凝土浆体和性能影响与 Na₂O 具有显著差异。例如,Jiang^[119]使用 5%~25%的 Ca(OH)₂ 为激发剂,实验结果表明当 Ca(OH)₂ 用量为 15%时,泡沫混凝土抗压强度达最大值 4.34 MPa,过高用量 Ca(OH)₂ 使泡沫混凝土内部碳化产物增多,不利于抗压强度的提高。泡沫混凝土干密度随 Ca(OH)₂ 用量增加而增大,而吸水率呈现相反趋势。这表明 Ca(OH)₂ 用量的增加提高固废激发效果,加快水化反应,导致干密度增大,孔隙率降低。浆体流动度随着 Ca(OH)₂ 用量增加,浆体流动度逐渐降低(160~200 mm)。

表 7 地聚合物泡沫材料孔隙结构参数

Table 7 Pore structure parameters for geopolymers foam materials

Sample No.	Mass fraction/%			Mean pore size/mm	Most probable size/mm	Average roundness value	Communication porosity/%
	MSW fly ash	Slag	Activator				
a1-20 °C	40	60	10	0.65	0.62	2.14	6.81
c1-20 °C	40	60	20	0.84	0.81	1.88	8.42
a1-30 °C	40	60	10	0.67	0.62	2.06	7.01
b1-30 °C	40	60	15	0.92	0.90	1.91	7.73
a1-40 °C	40	60	10	0.67	0.61	2.07	6.74
a3-40 °C	60	40	10	0.91	0.85	2.01	8.01

2.3.2 地聚合物胶凝材料 Su 等^[122]考察了反应温度、激发剂用量和粉煤灰-矿渣用量对采空区充填泡沫混凝土微结构影响(见表 7)。实验结果表明, 激发剂和粉煤灰用量对孔隙结构有显著影响。与 a1-20 °C 相比, c1-20 °C 的平均孔径和最可几孔径分别增加了 29.23% 和 30.65%, b1-30 °C 的平均孔径和最可几孔径分别增加了 37.31% 和 45.16%。提高激发剂用量和反应温度可以增加钙钒石聚合度及基体密实度, 并降低重金属浸出的风险。Wang 等^[123]以

煤矸石为原料, H₂O₂ 为发泡剂, Na₂SiO₃ 和 NaOH 作为激发剂制备了地聚合物泡沫混凝土。实验结果表明, 地聚合物泡沫混凝土抗压强度随着液固比增加(0.85~0.95)逐渐降低。这可能是液固比提高增加了泡沫混凝土孔隙率, 从而降低抗压强度^[124]。Pasupathy 等^[116]研究了废砖粉地聚合物(BGFC)反应过程(见图 3)。在地质聚合过程中, Al₂O₃ 和 SiO₂ 经溶解、重构、聚合 3 个过程形成了具有 Si-O-Al 键的三维铝硅酸盐聚合物结构。

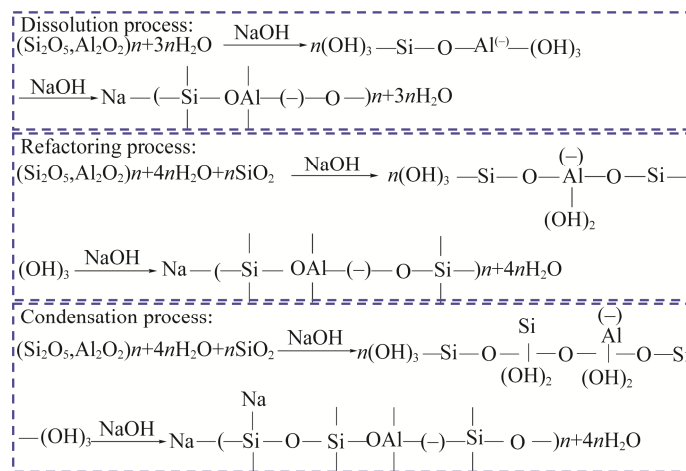


图 3 BGFC 反应过程^[116]

Fig. 3 BGFC Reaction Process^[116]

2.4 其他

2.4.1 水灰比 水灰比(W/C)是影响泡沫混凝土性能的重要因素。Li 等^[125]发现泡沫混凝土抗压强度随着 W/C 比增大(0.4~0.5)而增大。Han 等^[126]研究 W/C 比变化对再生骨料泡沫混凝土性能的影响, 发现随着 W/C 比由 0.45 增大至 0.60, 泡沫混凝土流动度线性增加、干密度逐渐降低、吸水率先减小(0.45~0.55)后增大(0.55~0.60), 抗压强度先增大(0.45~0.50)后减小(0.5~0.6)。对于吸水量, 随着 W/C 比由 0.45 增大至 0.55, 水泥水化反应进程更加充分, 填充了泡沫混凝土孔隙, 增强耐水性; 随着 W/C 比进一步增大至 0.6, 试样中自由水数量增加, 增加了连通孔数量, 提高吸水率。对于抗压强度, 当 W/C 比为 0.45 时, 由于再生骨料吸收了部分水, 使得基体中的自由水无法满足水泥水化需要, 使得泡沫混凝土抗压强度降低; 随着 W/C 比增大至 0.5, 水泥水化反应程度增加, 抗压强度增大; W/C 比进一步增大至 0.6 则会增加连通孔数量, 降低抗压强度。针对碱激发体系, 陈飞屹^[52]研究了 W/C 比对碱矿渣泡沫混凝土性能影响发现, 当 W/C 比为 0.55 和 0.65 时,

其 28 d 强度分别为 0.21、0.18 MPa。降低水灰比通常会提高泡沫混凝土基体的密实性, 例如 Zhang 等^[127]研究不同 W/C 比泡沫混凝土试件的微结构。当 W/C 比为 0.42 时, 试件具有相对致密的基质结构, 表面具有较多封闭孔, 当 W/C 比为 0.58 时, 试件连通孔数量则显著增加。连通孔的增加不仅会降低泡沫混凝土的承载力还会降低其保温性能。针对泡沫混凝土的收缩特性, Li 等^[128]研究 W/C 比对泡沫混凝土收缩开裂的影响, 发现当 W/C 比由 0.4 增大至 0.5 时, 泡沫混凝土开裂时间缩短 1~5 h, 收缩开裂程度增加。

综上所述, W/C 比变化对不同材料基制备的混凝土性能影响不同, W/C 比变化影响着基体内部孔的大小及数量。同时, 也需考虑到不同材料含水量及吸水性对基体的影响, 从而确定最佳的 W/C 比以满足实际需要。

2.4.2 纤维 纤维的加入可有效改善泡沫混凝土的力学性能和干缩性能, 解决泡沫混凝土力学性能差和易开裂的问题。其中, 聚丙烯、聚酯纤维是常用纤维。文献[129]表明, 聚丙烯纤维加入有助于改

善泡沫混凝土干缩性能。Tang 等^[130]对比了未加聚酯(PET)纤维、加入 PET 纤维及加入再生 PET 纤维所制备泡沫混凝土(PRFC、PETRFC 和 RPETRFC)的微观形貌。实验结果表明, PRFC 孔径较大, 孔洞较多, 形成了大量的连通孔。随着纤维的加入, 孔壁断裂现象减弱, 孔壁厚度变厚(纤维表面覆盖的水化产物可有效增强纤维与混凝土基体界面的结合能力)。在以上研究基础上, 研究者进一步考察和对比了生物纤维对泡沫混凝土性能和微结构影响。文献^[131]结果表明, 当甘蔗纤维用量为 1%时, 泡沫混凝土达最大强度, 随着甘蔗纤维用量增加, 泡沫混凝土干缩性能改善效果更加明显。化学纤维与生物纤维的混合使用能够有效改善泡沫混凝土力学性能。Bhagyasree 等^[132]对比了聚乙烯醇(PVA)纤维与椰胶(CG)纤维对泡沫混凝土性能影响。发现 1%PVA 与 1%CG 混合对于泡沫混凝土抗压强度、劈裂抗拉强度及抗弯强度的提升效果最好; 干缩随着 PVA 纤维用量增加(0.3~0.5)而增加。随 CG 纤维用量增加(0.3~0.5)而降低, 2%PVA 与 2%CG 混合对于改善泡沫混凝土干缩效果最为显著。这是由于 PVA 纤维亲水, 在早期反应阶段会吸收水分, 并在混凝土硬化时释放水分产生收缩。CG 纤维由于其具有保水能力, 干缩会随纤维掺量的增加而减小。

综上所述, 纤维对泡沫混凝土强度等性能的提高主要是由于纤维的增韧及抗裂作用。同时, 纤维存在最佳用量, 实际使用过程中应综合考虑纤维种类、长度等参数确定其用量以实现泡沫混凝土性能的提高。

2.4.3 外加剂 泡沫混凝土制备的过程中, 易发生塌模、收缩、吸水率大等问题, 针对上述问题可采取加入外加剂方式解决, 例如, 使用具有早强、

促凝、减水作用的早强剂、速凝剂和减水剂等^[133-134]。胡驰^[135]系统研究了 GK-3B 促凝剂(0.05%~4.00%)、GK-3A 速凝剂(0.05%~2.00%)及 P-2 聚羧酸减水剂(0.05%~0.3%)用量对泡沫混凝土孔隙率及抗压强度的影响(见表 8), 结果表明: 干密度 500 kg/m³ 的泡沫混凝土中分别加入 0.2%速凝剂、0.3%促凝剂及 0.1%减水剂时, 28 d 抗压分别提高了 32.23%、36.77%和 19.01%, 速凝剂及促凝剂对改善孔隙分布有益, 而减水剂增大了混凝土开口孔隙率。Zhang 等^[136]研究了合成淀粉磺酸盐减水剂对水泥浆体流动性的改善效果。结果表明, 当合成淀粉磺酸盐减水剂用量由 0 增加至 3%时, 水泥浆体流动性由 65 mm 增加至 301 mm。其原因在于减水剂分子在固液界面分布填充了水泥分子间的缝隙, 减缓了水泥对水的吸附作用, 故在用水量相同时可大大提高水泥浆体流动性。Pan 等^[137]通过实验研究了一种促凝剂(以硫酸铝为主要成分, 固含量 40%, SA)对泡沫混凝土成型效果的影响, 发现 SA 用量在 3.6 g 和 6.3 g 时(占水泥用量的 1.2%~2.1%时), 泡沫混凝土成型效果好, 不发生坍塌及下沉, 流动性良好。为进一步提升外加剂作用效果, 可将烷醇胺掺入水泥基材料中以提升应用性能^[138]。Xie 等^[139]通过实验研究发现, 在水泥浆体内分别加入 8%的二乙醇胺(DEA)和 0.25%三乙醇胺(TEA)对加快水泥浆凝结最为显著, 水泥浆体的初凝和终凝时间分别由 119 min 和 232 min 缩短至 1 min 41 s、1 min 49 s 和 5 min 38 s、5 min 24 s。这可能是 DEA 和 TEA 会络合大量 Al³⁺, 促进了 AFt 的形成, 促进水泥浆体凝结。值得注意的是使用某些外加剂(如聚羧酸盐基减水剂(PCE))时可能会出现与水泥不相容^[140]的问题, 降低水泥浆体流动度。

表 8 外加剂对泡沫混凝土孔隙率及抗压强度的影响

Table 8 Influence of admixtures on porosity and compressive strength of foamed concrete

Sample No.	Open porosity/%	Closed porosity/%	28d compressive strength/MPa	Compressive strength ratio
500-fa	49.65	28.75	2.42	100.00
500-s3	45.90	32.50	3.20	132.23
500-c3	39.25	39.15	3.31	136.77
500-j2	53.70	24.70	2.88	119.01

3 泡沫混凝土应用实例

泡沫混凝土具有轻质、保温隔热、整体性好、环保经济等特点, 使其在房建^[141]、路桥^[142]、隧洞^[143]、矿井^[144]等众多领域应用广泛。

在房建领域, 青浦钢结构住宅示范工程^[145]采

用带外装饰保温板的现浇泡沫混凝土复合墙, 加快了施工速度 20%~30%, 相比常规装饰保温墙体节省 100~145 元/m², 气密性及水密性均满足要求。浙江某大厦工程^[146]采用现浇泡沫混凝土填充墙。经现场泡沫混凝土填充墙结构尺寸偏差检验, 均符合验收标准。采用泡沫混凝土填充墙可加快施工进

度、缩短工期,减少人工成本。

在路桥领域,某高速公路路堤病害治理工程中采用泡沫混凝土浇筑回填^[147]。结果表明,采用泡沫混凝土可显著减少回填材料的荷载,具有抑制软基侧移及沉降的作用。同时,采用泡沫混凝土浇筑回填极大程度地提供了施工便利,无噪音污染、扬尘等出现;广州快速路与广州地铁三号线重叠部分的路桥工程同样采用泡沫混凝土用于道路减荷^[148]。

在隧洞领域,引黄工程洞穿管回填中^[149]以 525#硫铝酸盐水泥及粉煤灰为胶凝材料,使用发泡高度>500 mm、稳泡时间>4 h 的 CCW-95 型发泡剂以及 CCW-2001 型缓凝剂制备了泡沫混凝土用于现场施工。结果表明,泡沫混凝土相对密度及强度完全满足标书要求。研究发现泡沫质量不佳容易导致堵管现象,为此,进一步提高泡沫质量是加快施工进度措施之一。

在矿井领域,早在 1992 年美国矿业局就将低密度泡沫混凝土用于某矿井封闭^[150]。事实证明,由于泡沫混凝土质量为同体积标准混凝土的 30%,施工时可大大降低支承结构的成本。

4 结束语

泡沫混凝土的各项性能与气泡性质和基体材料密切相关。发泡剂种类对气泡性质影响最为直接,而借助稳泡剂的增黏、增厚等作用机制可以增强气泡及混凝土的性能,尤其是纳米固体颗粒稳泡剂研究和应用受到广泛关注;基体材料中水泥、矿物掺和料以及碱激发胶凝材料/地质聚合物材料是制备具有高强度基体的关键,此外,协同调整水灰比、纤维用量和外加剂也是提高泡沫混凝土性能的重要因素。

泡沫混凝土优异的性能使其在建筑节能、路基和矿坑填充等领域具有良好的发展前景和应用空间。尽管发泡剂与稳泡剂种类多样,机制不同,研究者进行了不同发泡剂和稳泡剂对气泡性能影响研究,然而如何在种类多样的发泡剂和稳泡剂中实现二者复配获得高性能气泡,以及考虑不同基体材料与浆体对气泡性能改善,实现基体与气泡的协同增强仍需要系统探讨;考虑到固废材料的广泛性和低廉价格,不同固废材料被用于泡沫混凝土制备,然而如何实现泡沫混凝土中固废基体材料大掺量利用以及多固废协同利用,是实现泡沫混凝土推广的关键;由于泡沫混凝土在应用过程中普遍存在易开裂、吸水率高、耐久性差等问题,如何进一步提高泡沫

混凝土耐久性仍需要系统讨论。此外,针对泡沫混凝土在结构工程应用不足以及制备过程碳排放问题,仍有必要深入探讨泡沫混凝土绿色多用途应用,为建材高质量发展提供理论和数据支持。

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Research Progress on Foam Performance and Matrix Materials for Foam Concrete

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Extended Abstract

Foam concrete can be used as a non-load-bearing structure material due to its low density, high porosity and heat and fire resistance, and foam concrete consists of a foaming agent, water, cement, sand and admixture. Air bubbles generate the pores in foam concrete, and the hydration products of the cement, sand, and admixture form a supporting structure. Foam concrete often involves foam collapse, low product strength and susceptibility to cracking during its preparation and practical use. This review was to reveal the foam property of foam concrete and the influence of the matrix materials on the structure and performance. This review also summarized the types and amounts of foaming agents, foam stabilizers, matrix materials, fibers, and additives, and clarified the correlation mechanism between macro- parameters and performance/microstructure.

The property of foam concrete is closely related to its foam performance and matrix materials, and foaming agents and foam stabilizers have a dominant impact on the foam performance. At present, foaming agents mainly include physical foaming agents and chemical foaming agents. Physical foaming agents refer to surfactants or active substances with a high activity, forming bubbles *via* reducing the surface tension of the liquid and producing a double electrical layer on the surface of the liquid film. Physical foaming agents mainly include rosin resin, ionic, protein and composite. Chemical foaming agents produce bubbles *via* chemical reactions by adding chemical reagents (*i.e.*, H_2O_2 , Zn and $NaHCO_3$, *etc.*). Rosin resin foaming agents are the earliest and most commonly used foaming agents, but they have problems such as a low foaming ratio and a poor foam stability. Ionic foaming agents increase the bubble foaming ratio. Protein-based foaming agents have higher strength and stability, but have shortages such as higher foaming costs. Compound foaming agents are the fourth-generation foaming agents with synergistic effects and take into account ionic foaming agents. The foaming agent has some advantages like high foaming multiple and good stability of protein foaming agent.

As the single-use of foaming agents produces a poor stability of foam and results in a low strength of concrete, the foam stability is used to promote the performance of foam concrete by the foam stabilizing agent with its thickening and increase the viscosity of the liquid film and block drainage. Foam stabilizers can be divided into three categories, *i.e.*, synergistic foam stabilizers, tackifier foam stabilizers, and nano-solid foam stabilizers. The mechanism of action of the synergistic foam stabilizer is to enhance the adsorption of

surface molecules, increase the strength of the liquid film, and reduce air permeability, thereby improving the stability of the foam. Viscosity-increasing foam stabilizers are used to increase the liquid phase viscosity of foam to reduce the bubble drainage rate, extend the half-life, and improve foam stability. Based on the adsorption of nanoparticles at the gas-liquid interface, nano-particles have a good foam stabilizing effect. Nano particles transform the original "gas-liquid" foam into a "solid-liquid-gas" three-phase foam, hindering bubble drainage, thereby improving foam stability and refining bubble size.

The matrix mainly composed of cement, mineral admixtures and alkali-activated cementitious materials/geopolymer materials is an important factor affecting the performance of foam concrete. Comprehensive consideration of the cement grade and type, the type and amount of mineral admixtures, and the ratio of activators and solid waste materials of alkali activating materials and geopolymer materials is a key to preparing a matrix with a high strength. In addition, the water-cement ratio (W/C), fiber dosage and admixtures are also a key to improving the performance of foam concrete.

Summary and prospects The superior performance of foam concrete has promising applications in the fields of building energy saving, roadbed and mine filling. Although the effects of foaming agents and foam stabilizers on the bubble performance are investigated, the bubble performance by different matrix materials and slurries still needs to be further improved, achieving a synergistic enhancement of matrix and bubbles. The large-volume utilization of solid waste matrix materials in foam concrete is a key to realizing the promotion of foam concrete considering the wide range and low price of solid waste materials. The durability of foam concrete still needs to be systematically discussed. In addition, it is also necessary to conduct in-depth exploration of the green multi-purpose application of foam concrete to provide theoretical and experimental supports for the high-quality development of building materials.

Keywords foam concrete; foam performance; matrix materials