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快速响应型防水砂浆自修复微胶囊设计与性能

沈亦超¹, 欧阳瀚梁^{2,3}, 王彦^{2,3}, 高健^{2,3}, 王瑞兴^{2,3,4,*}

(1. 中交二公局第三工程有限公司, 陕西 西安 710016; 2. 东南大学材料科学与工程学院, 江苏 南京 211189; 3. 东南大学重大基础设施工程材料全国重点实验室, 江苏 南京 211189; 4. 东南大学苏州医疗器械研究院, 江苏 苏州 215163)

摘要:针对防水砂浆开裂导致的寿命问题, 研发了一种自修复微胶囊, 其直径为 3.0~3.5 mm, 芯材为磷酸镁水泥、海藻酸钠和聚乙二醇, 壁材为环氧树脂复合硫铝酸盐水泥; 将自修复微胶囊掺进水泥砂浆, 并研究了其自修复效果及机制。结果表明: 自修复微胶囊防水耐碱性能较好, 能与硅酸盐基体产生紧密的界面过渡区, 促使裂缝沿微胶囊发展; 微胶囊破损后海藻酸钠遇水迅速膨胀形成水凝胶网络结构, 15 min 内膨胀面积超 200%, 可以初步封堵裂缝, 随后磷酸镁水泥水化, 于水凝胶中持续作用, 加强裂缝封闭; 该微胶囊 3 d 内可修复 200 μm 以下的裂缝, 7 d 内可修复 450 μm 的宽裂缝, 7 d 内抗渗性能可恢复至 76%, 自修复快速且高效。

关键词: 自修复微胶囊; 海藻酸钠; 磷酸镁水泥; 防水砂浆; 快速响应

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Design and Performance of Rapid Response Self-healing Microcapsule for Waterproof Mortar

SHEN Yichao¹, OUYANG Hanliang^{2,3}, WANG Yan^{2,3}, GAO Jian^{2,3}, WANG Ruixing^{2,3,4,*}

(1. China Communications Construction Second Highway Engineering Co., Ltd., Xi'an 710016, China; 2. School of Materials Science and Engineering, Southeast University, Nanjing 211189, China; 3. State Key Laboratory of Engineering Materials for Major Infrastructure, Southeast University, Nanjing 211189, China; 4. Institute of Medical Devices (Suzhou), Southeast University, Suzhou 215163, China)

Abstract: A novel self-healing microcapsule with a diameter of 3.0 to 3.5 mm was developed to tackle the lifespan issues due to waterproof mortar cracking. The core of the microcapsule was composed of magnesium phosphate cement, sodium alginate, and polyethylene glycol, encapsulated within a shell of epoxy resin composite sulfoaluminate cement. The self-healing microcapsules were incorporated into the cement mortar, and their self-healing effects and mechanisms were studied. The results indicate that the self-healing microcapsules exhibit good waterproof and alkali-resistant properties, facilitating the formation of a cohesive interfacial transition zone with the silicate-based substrate and directing crack propagation along their surface. Upon damage, the sodium alginate component within the microcapsules undergoes rapid hydration-induced swelling upon contact with water, forming a robust hydrogel network structure with an expansion area exceeding 200% within 15 minutes, thereby forming the initial sealing of cracks. Subsequently, the magnesium phosphate cement undergoes hydration within the hydrogel matrix, continuously reinforcing the crack sealing process. These innovative microcapsules demonstrate the capability to repair cracks with widths of up to 200 μm within a period of 3 days and cracks as wide as 450 μm within 7 days. Furthermore, the impermeability of self-healing microcapsules can be restored to 76% within 7 days, highlighting their rapid and highly

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第一作者: 沈亦超(1988—), 男, 江苏扬州人, 中交二公局第三工程有限公司工程师, 学士. E-mail: syc-love@qq.com

通讯作者: 王瑞兴(1978—), 男, 江苏扬州人, 东南大学副教授, 博士生导师, 博士. E-mail: ruixing@seu.edu.cn

efficient self-healing.

Key words: self-healing microcapsule; sodium alginate; magnesium phosphate cement; waterproof mortar; rapid response

防水砂浆常用于地下工程防渗中,裂缝会降低其抗渗性,传统修复方法复杂低效^[1].自修复功能与防水砂浆体系相适配,可智能高效修复裂缝^[2-5].水泥基自修复技术多样,有自体愈合、微生物矿化等^[6-9].为长久维持自修复材料的潜力,封装技术将修复组分包裹于胶囊后掺入水泥基材料.当裂缝出现时,微胶囊释放组分迅速粘合裂缝以短期完成修复,其关键在于芯材与壁材设计、与基材的兼容性、响应速度及修复效率^[10-15].

本文设计制备了一种与砂浆高度兼容、长效的自修复微胶囊.以磷酸镁水泥(MPC)作为胶囊芯材无机增强组分,海藻酸钠(SA)为有机膨胀组分,加入聚乙二醇(PEG)进行造粒,形成了海藻酸钙网络结构,可以促进MPC水化并强化修复效果.壁材采用环氧树脂和硫铝酸盐水泥来搭建复合结构,从而保障力学与防水性能,并延长芯材效能.通过微胶囊破裂释放芯材与膨胀水化,实现裂缝快速自修复.将自修复胶囊掺进水泥砂浆,监测其裂缝修复状况,探究修复产物

的矿物构成、晶体特性与分布情况,揭示快速响应型微胶囊的修复机制,为工程应用开展基础研究.

1 试验

1.1 原材料

硅酸盐水泥为海螺牌P·I 42.5水泥;MPC和硫铝酸盐水泥均购自诸城市九七建材有限公司,其中MPC由过烧氧化镁(MgO)、磷酸二氢铵(NH₄H₂PO₄)和十水硼砂(缓凝剂)组成.水泥和MgO的化学组成(质量分数,文中涉及的纯度、配合比等除特殊说明外均为质量分数或质量比)见表1.SA购自上海麦克林生化科技股份有限公司,纯度为90%;标准砂购自厦门艾思欧标准砂有限公司;PEG购自国药集团化学试剂有限公司,平均相对分子质量为950~1 050,结晶点约为37℃;黏合剂为昆山化工生产的M02型环氧树脂,环氧树脂和固化剂的配合比为10:3,树脂混合物的黏度为700~1 100 mPa·s,25℃下固化时间为3~4 h.

表1 水泥和MgO的化学组成
Table 1 Chemical compositions (by mass) of cement and MgO

Material	Unit: %							
	CaO	SiO ₂	Al ₂ O ₃	SO ₃	Fe ₂ O ₃	MgO	K ₂ O	Other
P·I 42.5 cement	56.73	19.74	7.94	2.91	3.25	1.70	0.80	1.23
Sulfate alumina cement	47.69	6.55	17.14	16.91	1.51	2.35	0.89	1.30
MgO	7.16	12.63	3.11	0.33	1.67	74.50	0.13	0.24

1.2 微胶囊的制备

设计了3组不同芯材成分的微胶囊,以MPC或SA的质量计,其配合比见表2.SA和MPC均为松散粉末,用PEG造粒且不影响其物化性质.壁材的硫铝酸盐水泥以包衣过程的实际用量为准.微胶囊的制备过程为:将粉体在40℃下用砂浆机预热低速搅拌30 s,加入熔化的PEG(40℃)后,先低速混合60 s,再高速搅拌120 s;拌好后团成球,置于20℃、相对湿度RH=40%下冷却至约32℃,经小型制丸机处理成2 mm直径条状,用轴刀制成球粒,筛取完整芯材;将芯材与环氧树脂混匀静置5~10 min至表面微黏,之后快速(45 r/min)与硫铝酸盐水泥混合10~15 s,包裹1层水泥;将筛选出的微胶囊在室温下静置,直至环氧树脂固化,即可得到自修复微胶囊.

1.3 微胶囊的形貌、性能测试与基体界面分析

利用Xradia 510 Versa型三维X射线显微镜(电压为60 kV,物镜为0.4×,分辨率为8.17 μm)分析干

表2 微胶囊的配合比
Table 2 Mix proportions of microcapsules

Microcapsule	Core material		Wall material	
	MPC	SA	PEG	Epoxy resin
MC	1.00		0.40	0.10
MSA		1.00	0.80	0.10
MSAC	1.00	1.00	1.25	0.11

燥MSAC微胶囊的结构,借助ORS Dragonfly软件(ver.2020.02)重建图像以确认芯壁比.通过胶囊切片与体视显微镜观察壁材特性.依据GB/T 17431.2—2010《轻集料及其试验方法:第2部分:轻集料试验方法》,测试微胶囊的外观密度、粒径分布和尺寸,使用游标卡尺对50颗微胶囊进行测量,并计算粒径系数.通过pH=13的NaOH溶液浸泡试验来评估微胶囊的防水耐碱性,并监测其电导率.

采用FEI Sirion场发射扫描电镜(SEM),设置电压为20 kV,采用二次电子成像观察壁材与砂浆界面过渡

区.选取5 mm³完整立方体试样,双面平滑,真空干燥至恒重后,用导电胶固定于台架,喷金后进行SEM测试.

1.4 水泥基自修复试件制备

设置砂浆水胶比为0.5,自修复微胶囊(等体积替代砂)体积分数为5%,砂浆的配合比见表3.根据GB/T 17671—2021《水泥胶砂强度检验方法(ISO法)》,砂浆的制备过程为:先低速混合水和水泥30 s,快速加入砂与微胶囊并搅拌30 s,暂停90 s以清理挂壁;再高速搅拌60 s,将拌和物立即灌入边长为40 mm的立方模具,振动密实,24 h后脱模;最后将其转移至(20±2)℃、RH≥95%的养护室,养护至特定龄期后进行测试.

表3 砂浆的配合比
Table 3 Mix proportions of mortars

Specimen	Cement	Sand	Water	Microcapsule
PC	160	320	80	0
M-MC	160	286	80	21
M-MSA	160	286	80	21
M-MSAC	160	286	80	21

1.5 自修复效果表征

试件在标准养护室养护7 d后,以手持切割机在其上切出4 mm×4 mm凹槽,形成裂缝并调控其宽度,裂缝两侧用透明胶带固定,随后将试件浸入15~25℃水中进行修复.

裂缝闭合情况通过Mshot软件辅助的体视显微镜进行监测,每1条裂缝选8个点,测量并计算修复时间*t*为0(修复前)、1、3、5、7 d的裂缝封堵率.砂浆M-MSAC修复7 d后,采用三维X射线计算机断层扫描(3D X-CT)进一步分析裂缝表面及内部修复情况.

为测试掺微胶囊水泥基体的抗渗性,用改进的RILEM试验方法^[16],通过定水头法测试试件裂缝的渗水量.抗渗性能测试装置示意图见图1.由图1可

见,PVC管通过硅胶与试件连接,裂缝侧面以石蜡密封,仅允许水从裂缝渗透,利用乳胶管维持100 cm水头差.测试持续10 min,分别于修复时间*t*为0、1、3、5、7 d时进行测试,测试后试件继续浸泡于水中.渗水量由电子天平记录,裂缝宽度与内部状态均对渗水速率有显著影响.抗渗性能恢复率 R_{WT} 计算式为:

$$R_{WT} = \frac{W_n - W_h}{W_n} \quad (1)$$

式中: W_n 为未修复试件渗水的平均质量,g; W_h 是修复后试件渗水的平均质量,g.

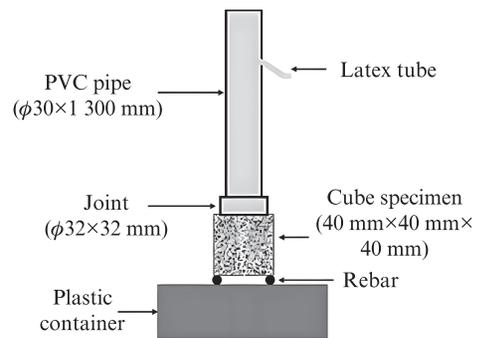


图1 抗渗性能测试装置示意图
Fig. 1 Schematic diagram of permeability resistance performance testing device

1.6 微胶囊自修复过程追踪

为监控微胶囊修复技术对裂缝处理的时效性,设计了含透明玻片的水泥样本模型,并借助体视显微镜进行监测.模拟裂缝装置示意图见图2.追踪试验具体步骤为:使用边长为15 mm的立方体硅胶模具制备了水胶比为1:3的水泥样本,养护7 d;将样本切割为厚度5、6 mm的两部分,前者模拟裂缝面,后者固定玻片并控制裂缝宽度约为1 000 μm;用电钻在模拟裂缝面钻孔,象征胶囊位点,填充修复材料;用速干胶将样本粘贴于塑料盒,并粘贴玻片,注水淹

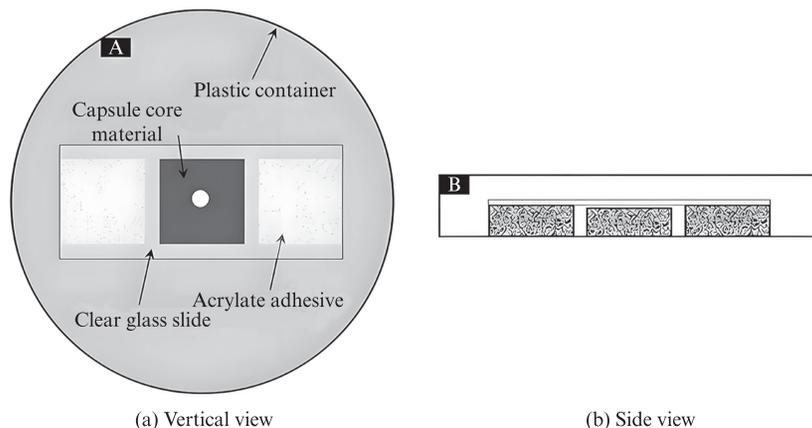


图2 模拟裂缝装置示意图
Fig. 2 Schematic diagram of simulated crack device

没玻片后置于显微镜下,于 t 为0、1、3、5、7 d拍照记录修复进程。

选择20粒制得各类型微胶囊,横向切开,断面朝上放入水中,要求水面刚好没过微胶囊断面.分别在修复时间 t 为0、5、10、15 min时用体视显微镜拍照.区域面积变化率 $A_{ER}(\%)$ 的计算式为:

$$A_{ER} = \frac{A_t}{A_{ini}} \times 100\% \quad (2)$$

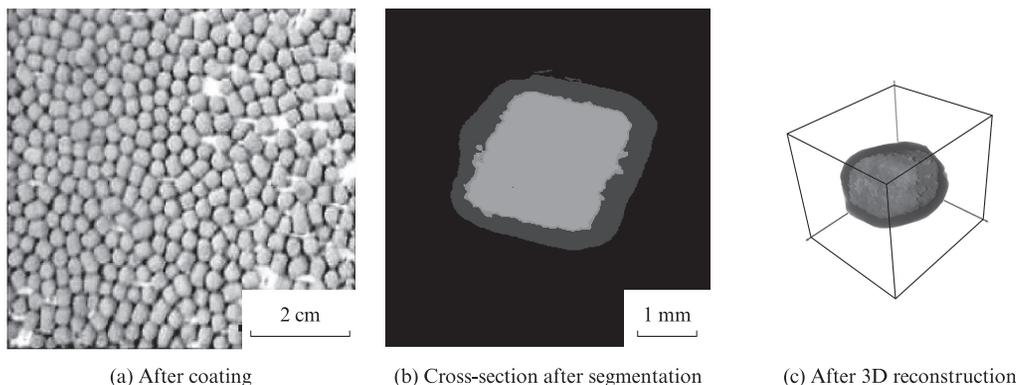


图3 微胶囊的微观结构

Fig. 3 Microstructure of microcapsules

微胶囊的密度和平均粒径系数见表4.由表4可见:微胶囊MSA密度最大,微胶囊MC密度最小,微胶囊MSAC介于二者之间;3组微胶囊平均粒径系数相近.平均粒径系数越接近1,微胶囊形状越趋于球形,越有利于承受各方应力,更能确保裂缝能穿透微胶囊,优化修复效能。

表4 微胶囊的密度和平均粒径系数
Table 4 Density and average particle size coefficient of microcapsules

Microcapsule	Density/($\text{kg} \cdot \text{m}^{-3}$)	Average particle size coefficient
MC	1 376	1.261
MSA	1 838	1.191
MSAC	1 652	1.194

高碱环境下微胶囊的电导率曲线见图4.由图4可见:当浸泡时间小于50 min时,微胶囊的电导率变化较小;当浸泡时间为50 min时,电导率骤降;随着浸泡时间的进一步延长,电导率短时回升后持续下降.可见3组微胶囊均展现出较好的耐碱性,初期电导率稳定或因硫铝酸盐水泥水化致密层与环氧树脂保护芯材,50 min后胶囊破裂,释放芯材成分使其电导率暂时升高.壁材防水性欠佳,可能源于硫铝酸盐水泥层初始疏松,水分可渗至芯材,且芯材遇水膨胀易使壁材破裂,从而削弱了微胶囊的修复效果。

式中: A_{ini} 为微胶囊未遇水时的面积, mm^2 ; A_t 是微胶囊修复 t 时吸水膨胀后的面积, mm^2 。

2 结果与讨论

2.1 微胶囊的结构表征及性能测试

微胶囊的微观结构见图3.由图3可见:微胶囊无团聚,呈独立分散状,粒径约为2 mm;微胶囊形态近似椭球形,其横截面芯材表面平整,壁厚为350~450 μm 。

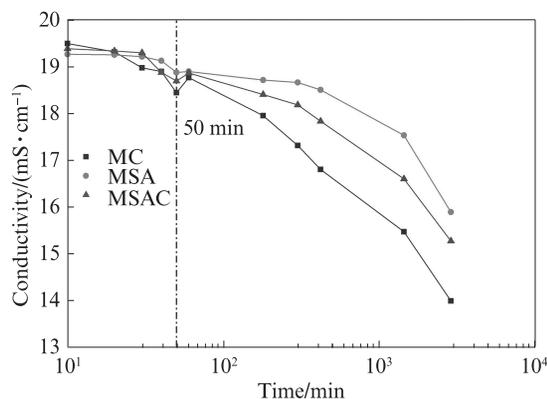


图4 高碱环境下微胶囊的电导率曲线

Fig. 4 Conductivity curves of different types of capsules in high alkaline environment

2.2 微胶囊与基体的界面过渡区

微胶囊与基体界面过渡区的SEM照片见图5.由图5可见,硫铝酸盐水泥壳层与砂浆基体间相容性良好,形成了约100 μm 的紧密过渡区,显著增强了黏结强度^[17-18]。

2.3 微胶囊的自修复效果与机制分析

用裂缝随时间的闭合程度来评估微胶囊的自修复效果.微胶囊对水泥基裂缝宽度的影响见图6.由图6可见:微胶囊组砂浆在3 d内可修复大部分200 μm 以下裂缝;微胶囊MSAC 7 d最大修复裂缝宽度可达450 μm ;砂浆自修复能力排序为M-MSAC>M-MSA>M-MC>PC。

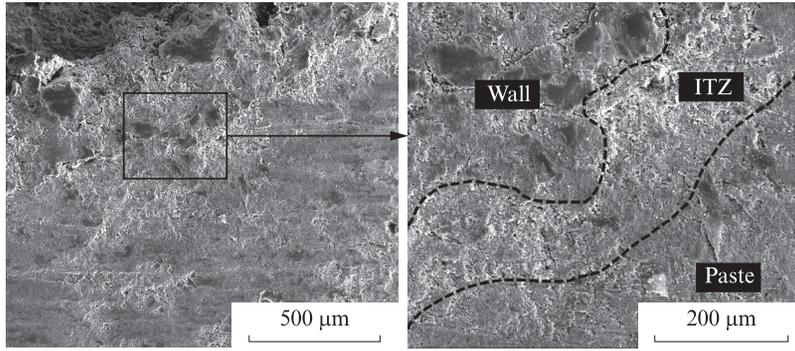


图5 微胶囊与基体界面过渡区的SEM照片

Fig. 5 SEM images of interface transition zone between microcapsules and matrix

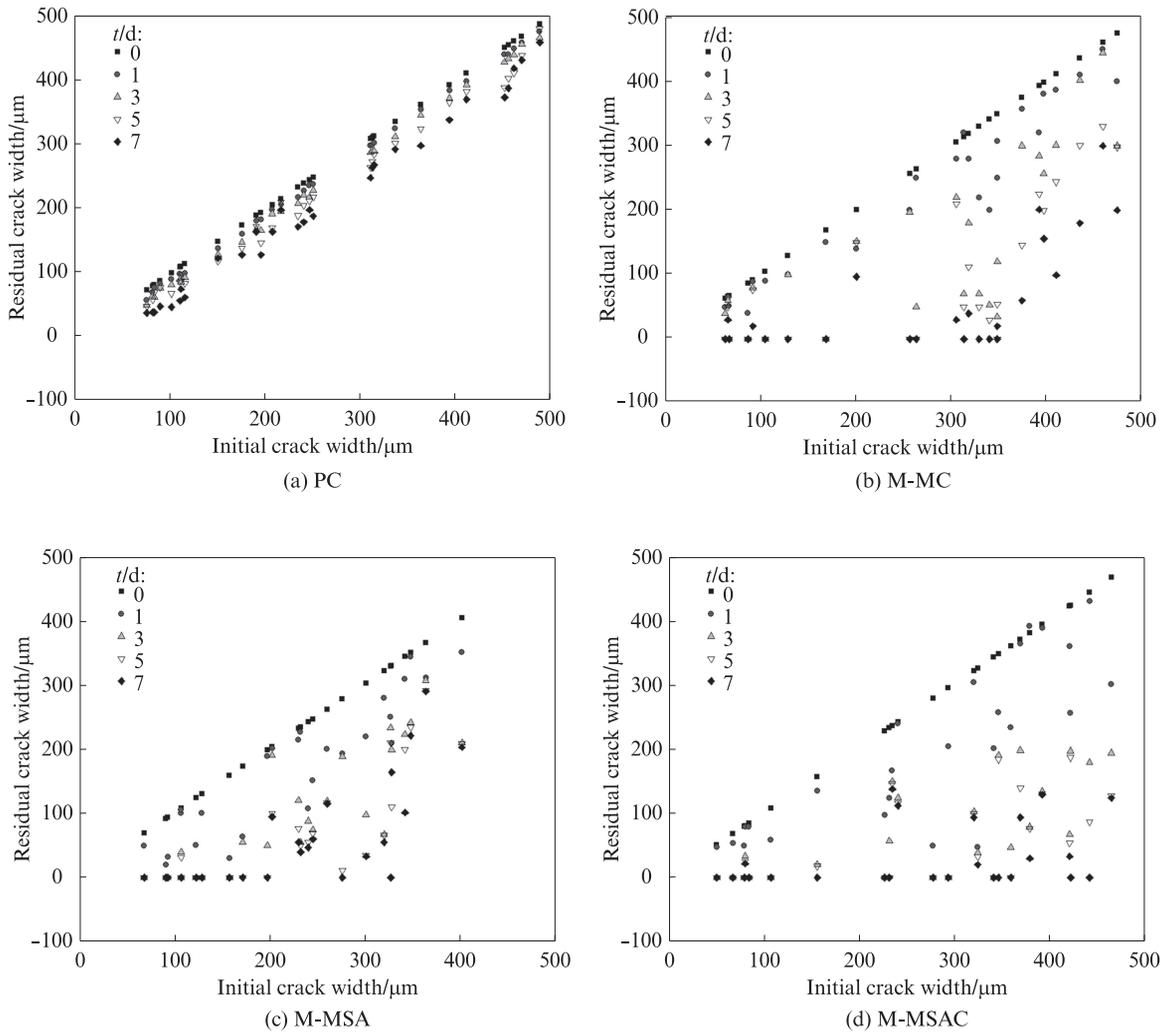


图6 微胶囊对水泥基裂缝宽度的影响

Fig. 6 Effect of microcapsules on cement-based crack width

砂浆 M-MSAC 裂缝的原图像及经过 X-CT 灰度处理后的图像见图 7. 由图 7 可见, 微胶囊 MSAC 修复后, 砂浆裂缝内水凝胶分布均匀. 可见微胶囊在裂缝填补时, 具有早期快速膨胀封堵的特性, 表明 MPC 组分可在海藻酸钙膨胀作用下产生一定程度的迁移.

3D X-CT 图像可识别水凝胶的分布, 但需要注

意的是, 由于部分低密度水凝胶难以精准分割, CT 重建的水凝胶体积可能小于实际体积. 砂浆 M-MSAC 修复后裂缝内部产物的 3D X-CT 图像见图 8. 由图 8 可见, 裂缝边缘有未破微胶囊, 裂缝内水凝胶分布均匀, 有效填充了裂缝, 且微胶囊破裂后, 海藻酸钠与聚乙二醇能扩散至裂缝以外.

微胶囊对砂浆抗渗性能恢复率的影响见图 9. 由

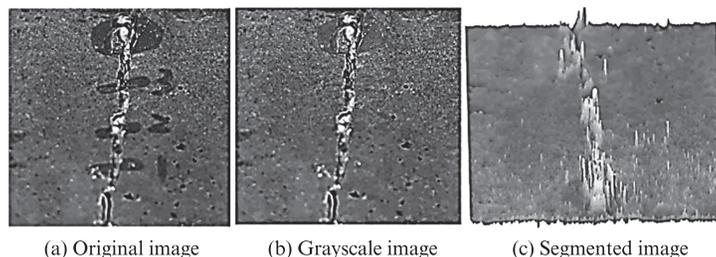


图7 砂浆 M-MSAC 裂缝的原图像及经过 X-CT 灰度处理后的图像

Fig. 7 Original image of mortar cracks and images after X-CT grayscale processing of M-MSAC mortar

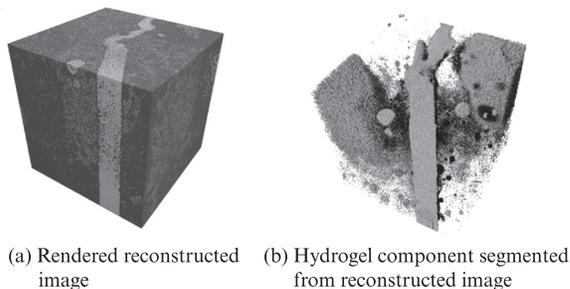


图8 砂浆 M-MSAC 修复后裂缝内部产物的3D X-CT 图像

Fig. 8 3D X-CT images of internal products of cracks repaired of M-MSAC mortar

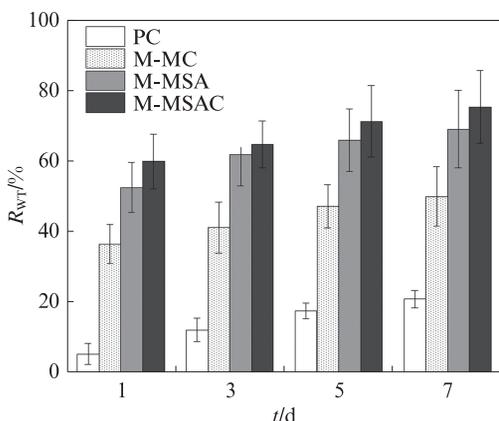


图9 微胶囊对砂浆抗渗性能恢复率的影响

Fig. 9 Effect of microcapsules on R_{WT} of mortars

图9可见:与对照组砂浆PC相比,微胶囊组砂浆的抗渗性能恢复率提升显著;砂浆M-MSAC的恢复率最高,其7d修复后的 R_{WT} 可以达到76%,砂浆M-MSA居中,砂浆M-MC最低.由此可见,微胶囊可快速强化裂缝封堵修复,微胶囊MSAC的优异性凸显了有机膨胀成分对水密性提升的关键作用.

不同修复时间下微胶囊MSA和MSAC形貌的变化情况见表5.由表5可见:微胶囊MSA中海藻酸钠迅速膨胀,其在1d内即完成膨胀;微胶囊MSAC膨胀面积超200%,表明水分渗入后,海藻酸钠快速膨胀促使MPC迁移布满裂缝,伴随MPC持续水化生成水化物于凝胶中持续修复裂缝.通过观察,7d后微胶囊MSAC中MPC颗粒仍具有持续增强修复效果.

微胶囊的膨胀形貌见表6,区域面积变化率见图10.由表6及图10可见:微胶囊MC在水中的膨胀效果一般;微胶囊MSAC膨胀效果较好,其遇水15min即胀破外壁,可见壁材防水的必要性,微量渗水即可导致微胶囊快速破裂,提前释放芯材.

表5 不同修复时间下微胶囊MSA和MSAC形貌的变化情况

Table 5 Morphological changes of microcapsule MSA and MSAC under different repair time

Microcapsules	0 d	1 d	3 d	5 d	7 d
MSA					
MSAC					

表6 微胶囊的膨胀形貌

Table 6 Expansion morphologies of microcapsules

Microcapsules	0 min	5 min	10 min	15 min
MC				
MSA				
MSAS				

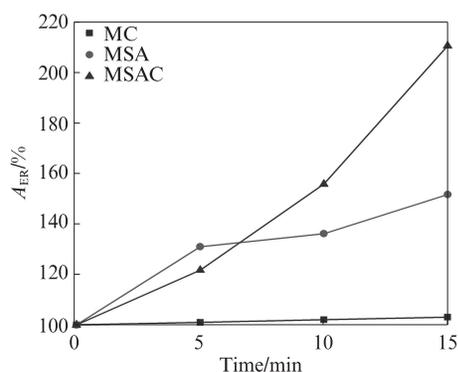


图10 微胶囊的区域面积变化率

Fig. 10 Area change rate of microcapsules

修复后裂缝产物的SEM照片和EDS分析分别见图11和表7.结合图11和表7可知,修复后裂缝产物可能为鸟粪石,呈片状与棒状;同时,观测到水凝

胶网络结构,该结构可为水化沉积提供成核位点.但是,经XRD测试分析未发现鸟粪石晶体,可能是因为峰强过弱,产物多以无定形形式存在^[19].

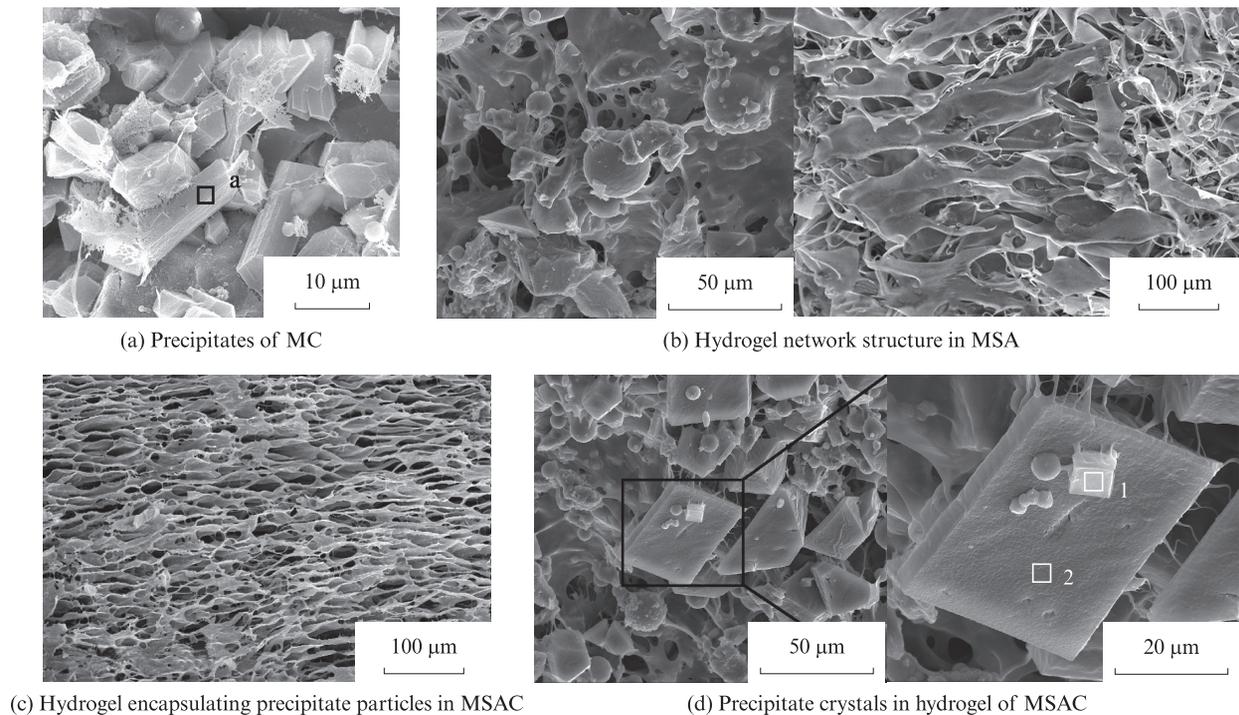


图11 修复后裂缝产物的SEM照片

Fig. 11 SEM images of crack products after repair

表7 图11中选中区域的元素组成

Table 7 Element compositions of selected regions in Fig.11

Region	C	O	Mg	P
a	25.22	49.09	13.93	9.56
1		63.25	14.73	17.66
2	53.65	12.43	6.70	18.31

Unit: %

3 结论

(1)研发的自修复微胶囊直径为3.0~3.5 mm,微胶囊MSA中海藻酸钠能够在1 d内完成膨胀;微胶囊MSAC在15 min内膨胀面积超200%,且7 d后磷酸镁水泥颗粒仍具有持续增强修复效果.

(2)当微胶囊壁材为有机环氧树脂和硫铝酸盐水泥时,壁厚为350~450 μm,具有防水耐碱性,与硅酸盐基体产生紧密过渡区,有利于裂缝沿微胶囊发展.

(3)自修复微胶囊3 d内可修复大部分200 μm以下裂缝,7 d最大修复宽度达450 μm,砂浆M-MSAC的7 d抗渗性能恢复率达76%;砂浆自修复能力排序为M-MSAC>M-MSA>M-MC>PC.

(4)微胶囊破裂后,海藻酸钠遇水迅速膨胀形成

水凝胶网络结构封堵裂缝,且磷酸镁水泥迁移水化持续封堵.

参考文献:

- [1] 于群,王涛,衣淑丽,等.地下复合型防水技术研究及应用[J]. 居舍, 2022(3):82-84.
YU Qun, WANG Tao, YI Shuli, et al. Research and application of underground compound waterproof technology[J]. Jushe, 2022 (3):82-84. (in Chinese)
- [2] 张鸣,陈令坤,邢锋,等.用于自修复水泥基材料的微胶囊体系性能研究[J]. 建筑材料学报, 2013, 16(5):903-907, 918.
ZHANG Ming, CHEN Lingkun, XIN Feng, et al. Study on properties of microcapsule system for self-healing cementitious composite [J]. Journal of Building Materials, 2013, 16(5): 903-907, 918. (in Chinese)
- [3] 刘士雨,俞缙,刘文强,等.基于MICP的珊瑚砂砂浆裂缝自修复新型细菌载体[J]. 建筑材料学报, 2021, 24(4):687-693.
LIU Shiyu, YU Jin, LIU Wenqiang, et al. New bacterial carrier for the crack self-healing in coral sand mortar based on MICP [J]. Journal of Building Materials, 2021, 24(4):687-693. (in Chinese)
- [4] 王信刚,夏龙,扶兴国,等.环氧树脂/乙基纤维素微胶囊的颗粒特性与缓释性能[J]. 建筑材料学报, 2020, 23(2):396-400, 484.
WANG Xingang, XIA Long, FU Xingguo, et al. Particle characteristics and sustained release properties of epoxy resin/

- ethyl cellulose microcapsule[J]. *Journal of Building Materials*, 2020, 23(2):396-400, 484. (in Chinese)
- [5] 张猛,王永海,冷发光,等.水泥基材料裂缝自修复技术的研究与进展[J].*混凝土*,2023(4):149-154.
ZHANG Meng, WANG Yonghai, LENG Faguang, et al. Research and progress of crack self-repairing technology for cement-based materials[J]. *Concrete*, 2023(4):149-154. (in Chinese)
- [6] SHENG M, WANG X F, HUANG Y J, et al. Dynamic splitting behavior of microcapsule-based self-healing cementitious composites under SHPB impact loading[J]. *Journal of Building Engineering*, 2024, 91:109638.
- [7] DIDIER S, KIM T V, STIJN S, et al. Self-healing cementitious materials by the combination of microfibrils and superabsorbent polymers [J]. *Journal of Intelligent Material Systems and Structures*, 2014, 25(1):13-24.
- [8] 宋炳辰.自修复水泥基材料功能组分的胶囊化研究[D].哈尔滨:哈尔滨工业大学,2016.
SONG Bingchen. Research on the encapsulation of functional components for self-healing cementitious materials[D]. Harbin: Harbin Institute of Technology, 2016. (in Chinese)
- [9] PELTO J, LEIVO M, GRUYAERT E, et al. Application of encapsulated superabsorbent polymers in cementitious materials for stimulated autogenous healing [J]. *Smart Materials and Structures*, 2017, 26(10):105043.
- [10] LEE H X D, WONG H S, BUENFELD N R. Self-sealing of cracks in concrete using superabsorbent polymers[J].*Cement and Concrete Research*, 2016, 79:194-208.
- [11] LÜ L Y, YANG Z X, CHEN G Q, et al. Synthesis and characterization of a new polymeric microcapsule and feasibility investigation in self-healing cementitious materials [J]. *Construction and Building Materials*, 2016, 105:487-495.
- [12] FENG J H, YAP X Y, GAO J, et al. Rapid self-sealing of macro cracks of cementitious composites by in-situ alginate crosslinking [J]. *Cement and Concrete Research*, 2023, 165:107074.
- [13] HONG G, CHOI S. Rapid self-sealing of cracks in cementitious materials incorporating superabsorbent polymers[J]. *Construction and Building Materials*, 2017, 143:366-375.
- [14] 毛倩瑾,伍文文,梁鹏,等.海藻酸钙/环氧微胶囊在水泥基材料中的自修复作用[J].*材料导报*,2018,32(11):4016-4021.
MAO Qianjin, WU Wenwen, LIANG Peng, et al. Self-healing effect of calcium alginate/epoxy microcapsules in cementitious materials[J]. *Materials Review*, 2018, 32(11):4016-4021. (in Chinese)
- [15] SNOECK D, SCHAUBROECK D, DUBRUEL P, et al. Effect of high amounts of superabsorbent polymers and additional water on the workability, microstructure and strength of mortars with a water-to-cement ratio of 0.50[J]. *Construction and Building Materials*, 2014, 72:148-157.
- [16] TZIVILOGLOU E, WIKTOR V, JONKERS H M, et al. Bacteria-based self-healing concrete to increase liquid tightness of cracks [J]. *Construction and Building Materials*, 2016, 122:118-125.
- [17] GILBERT F, GAROZ D, PAEPGEM V W. Stress concentrations and bonding strength in encapsulation-based self-healing materials[J]. *Materials and Design*, 2015, 67:28-41.
- [18] 魏玉伟,程培峰,刘满,等.自修复混凝土修复效果影响因素的试验研究[J].*建筑材料学报*,2018,21(4):588-594.
WEI Yuwei, CHENG Peifeng, LIU Man, et al. Influencing factors of self-healing performance of concrete [J]. *Journal of Building Materials*, 2018, 21(4):588-594. (in Chinese)
- [19] 刘佳辉,周新涛,罗中秋.镍铁渣基磷酸镁水泥的制备及其机理研究[J].*建筑材料学报*,2020,23(2):255-262.
LIU Jiahui, ZHOU Xintao, LUO Zhongqiu. Preparation and formation mechanism of ferronickel slag-based magnesium phosphate cement[J]. *Journal of Building Materials*, 2020, 23(2):255-262. (in Chinese)