•绿色岩土工程•

DOI:10.12454/j.jsuese.202500528

本刊网刊

生物聚合物协同EICP生态固化裸土扬尘抗风蚀性能及机理

田　威[1,2],李　璐[1],贺文昊[1,2],云　伟[1,2],赵航宇[1],弋郭洋[1]

(1.长安大学 建筑工程学院,陕西 西安 710061;2.自然资源部退化及未利用土地整治工程重点实验室,陕西 西安 710021)

摘　要:为了缓解裸土扬尘引起的空气污染状况,采用生物聚合物(果胶、海藻酸钠)协同脲酶诱导碳酸钙沉淀(EICP)技术固化裸土扬尘。通过碳酸钙含量试验、抗风蚀性试验、表面硬度试验、酸碱度试验、易溶盐含量试验及微观试验,系统对比分析了果胶、海藻酸钠分别联合EICP技术固化裸土扬尘的效果。结果表明:果胶、海藻酸钠的加入对碳酸钙生成量有影响;固化4次后,0.50%果胶–EICP、1.50%海藻酸钠–EICP处理后试样的风蚀质量损失率分别为3.64%、0.37%,经果胶、海藻酸钠联合EICP技术固化后的试样有较好的抗风蚀能力;固化4次后,果胶–EICP、海藻酸钠–EICP处理试样的表面硬度值较对照组(水)分别提高了186.41%、132.66%;经过果胶–EICP、海藻酸钠–EICP处理的试样pH值为7.5～7.8且易溶盐含量均小于1.60%;果胶、海藻酸钠与EICP过程生成的碳酸钙晶体共同作用,通过充填孔隙、黏附裸土颗粒,有效固化了裸土扬尘。研究结果可为生物聚合物联合EICP技术在裸土扬尘治理方面的环保应用提供参考。

关键词:脲酶诱导碳酸钙沉淀;裸土扬尘;木钙;生物聚合物;表面固化

中图分类号:TU411　　**文献标志码:**A　　**文章编号:**2096-3246(2026)03-0134-12

当前,西北地区空气质量已成为中国关注的焦点。西北地区干旱少雨、植被稀疏且裸露地表广泛分布,加之受矿产资源开采、基础设施建设及农牧活动扩张的影响,地表扰动加剧[1–2]。露天矿坑、尾矿堆积场等工程裸土持续产生,农田、退化草场等生态脆弱区地表覆盖丧失,导致大规模地表裸露[3–4]。裸露地表在强风作用下发生风蚀,造成土壤表层松散颗粒扬起,形成裸土扬尘,不仅危害人体健康,还加剧了土地贫瘠化、雾霾天气频发等环境问题[5–6]。尽管洒水降尘、植被修复及化学抑尘等传统治理方法能够在短时间内抑制裸土扬尘污染,但其在实际应用中仍存在抑尘时间短、恢复周期长、环境污染大等局限性,难以实现长期、环保的大规模应用[7]。因此,研究一种环境友好、高效经济的裸土扬尘治理手段是当前的首要任务。

脲酶诱导碳酸钙沉淀(enzyme induced carbonate precipitation,EICP)技术[8]凭借其环境友好性、高效经济等优点被广泛应用于土体加固[9–10]、粉尘治理[11–12]等领域。EICP技术所用脲酶可以从植物中提取,成本较低且对环境影响较小。Sun[11]、Wu[12]等将EICP技术应用于粉尘治理并进行试验研究,均发现EICP技术生成的碳酸钙晶体可以有效胶结颗粒,且试样表面有硬壳层形成,能起到稳固颗粒、减少扬尘的作用,证明了将EICP技术应用于抑制粉尘的可行性。然而,EICP技术中脲酶为游离态,导致EICP过程缺乏特定的成核点位引导碳酸钙晶体有序生长,致使碳酸钙沉淀在土体中难以形成有序的结构,从而影响了EICP技术的固化效果[13]。

为了解决这一问题,有学者将EICP技术与生物聚合物进行结合[14–15]。生物聚合物是一类生物体内的生物化学反应合成的聚合物[16],生物聚合物的种类繁多,包括海藻酸钠、果胶、黄原胶、壳聚糖等。果胶和海藻酸钠是天然高分子化合物,因其具有良好的增稠性、胶凝性、可降解性且生产成本低,而被广泛应用于食品加工、污水治理等领域[17–18]。然而,以往研究常采用黄原胶或壳聚糖联合EICP技术进行固化土体试验,选用海藻酸钠、果胶与EICP技术联合固化土体的试验

收稿日期:2025－05－14　　**修回日期:**2025－10－26　　**网络出版日期:**2025－11－20

基金项目:陕西高校青年创新团队((2022)943);自然资源部退化及未利用土地整治工程重点实验室开放基金项目(SXDJ2024–04);国家自然科学基金项目(52479115);长安大学研究生科研创新实践项目(300103725042)

作者简介:田　威(1981—),男,教授,博士.研究方向:微生物岩土技术、二氧化碳捕集与资源化循环利用、大宗固废高值化综合利用等.E-mail:tianwei@chd.edu.cn

较少[19]。此外，现有的研究多聚焦于生物聚合物联合EICP技术在提升土体强度及耐久性方面的应用[14–15]，针对裸土扬尘治理的研究相对较少。

基于此，本文提出一种环保高效的裸土扬尘治理方法，即果胶联合EICP技术（简称为果胶–EICP）和海藻酸钠联合EICP技术（简称为海藻酸钠–EICP），对裸土扬尘进行固化处理。通过表面硬度、碳酸钙含量、抗风蚀性、酸碱度、易溶盐含量等性能试验，结合扫描电镜（SEM）、X射线衍射（XRD）及傅里叶变换红外光谱（FTIR）试验，从宏观性能和微观作用机制两方面对不同生物聚合物掺量及固化次数下裸土试样的固化效果进行研究，以期为裸土扬尘治理提供新的思路与方法。

1　材料与方法

1.1　试验材料

试验裸土取自陕西省西安市长安区，对取回的裸土进行风干、粉碎、去杂并过2 mm筛。根据《土工试验方法标准》（GB/T 50123—2019）[20]测得裸土的基本物理指标见表1，裸土粒度分布如图1所示。

表1　裸土基本物理指标

Tab. 1　Basic physical indicators of bare soil

密度/(g·cm^{-3})	最大干密度/(g·cm^{-3})	塑限/%	液限/%	比重
1.85	1.73	22.09	39.47	2.7

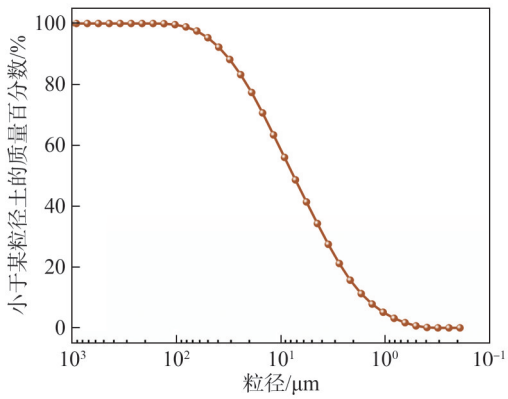


图1　裸土粒度分布

Fig. 1　Particle size distribution of bare soil

海藻酸钠购自天津市众联化学试剂有限公司，为白色或淡黄色的颗粒状物质。果胶为食品级果胶，购自河南中辰生物科技有限公司，为白色至淡黄色的粉末。

EICP溶液由脲酶液和胶结液组成。参考文献[12]，EICP溶液中脲酶液与胶结液体积比为1∶3；参考文献[9]，胶结液中尿素与木钙浓度比为1∶1。

试验所用脲酶提取流程如下：将干燥大豆粉碎成粉末并过100目筛网；取10 g过筛后的大豆细粉与200 mL去离子水混合，使用磁力搅拌机充分搅拌30 min后，将大豆细粉溶液放置在4 ℃的冰箱中24 h；取出溶液搅拌20 min后，用100目纱布过滤，并将过滤后的溶液倒入离心管，置于4 000 r/min的离心机中离心30 min。离心后上清液即为大豆脲酶溶液。

1.2　试样制备

采用控制变量法设置不同果胶及海藻酸钠掺量、不同固化次数，共计5组试验，每组3个平行试样。试验方案见表2。

表2　试验方案

Tab. 2　Experimental schemes

组别	喷洒溶液	生物聚合物	生物聚合物掺量/%	固化次数
1	水		0	1、2、3、4
2	木钙（1 mol/L）溶液		0	
3	EICP溶液		0	
4	EICP溶液	果胶	0.25、0.50、0.75、1.00、1.50、2.00	
5	EICP溶液	海藻酸钠		

注：生物聚合物掺量为生物聚合物与裸土的质量比，掺量及固化次数取值参考文献[21–22]。试样尺寸参考文献[12]及预试验结果，抗风蚀性试验所需试样在直径15 cm、高度2 cm的圆盘模具中制备，其余试验所需试样在直径为90 mm的培养皿中制备。

试样制备过程如图2所示。首先，取20 g烘干过筛后的裸土与一定量的果胶或海藻酸钠粉末拌合，果胶及海藻酸钠掺量见表2，拌合后将试样表面轻微刮平而不进行机械压实，以保持与自然裸土状态接近。其次，利用喷壶先后将2.5 mL脲酶液、7.5 mL胶结液均匀喷洒于试样表面，间隔30 min再进行胶结液的喷洒。随后，为确保反应充分完成，将处理完的试样在室温下静置24 h，此为一次固化完成。最后，将固化完成的试样放入65 ℃烘箱中烘干5 h，再进行后续试验。喷洒溶液时，要把控喷壶的倾斜角度及移动速度，以保证喷洒的均匀性。

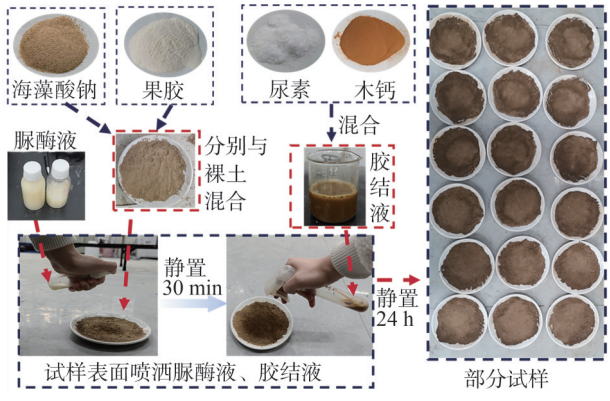


图2　试样制备过程

Fig. 2　Sample preparation process

1.3　试验方法

1.3.1　胶结液浓度的确定

EICP矿化产物的生成量与胶结液浓度有关，通过

测定碳酸钙实际生成量及生成率，确定后续试验的胶结液浓度。配制浓度为0.25、0.50、0.75、1.00、1.25 mol/L的胶结液15 mL，分别与15 mL脲酶液混合，在室温条件下静置24 h，采用酸洗法测量碳酸钙实际生成量。选取碳酸钙生成率峰值处对应的胶结液浓度进行后续试验，以实现最优固化效果。碳酸钙生成率计算公式如下：

$$P=\frac{m_c}{C\times V\times M}\times 100\% \tag{1}$$

式中：P为碳酸钙生成率，%；m_c为碳酸钙实际生成量，g；C为胶结液浓度，mol·L^{-1}；V为胶结液体积，L；M为碳酸钙摩尔质量，取100.09 g·mol^{-1}。

1.3.2 碳酸钙含量测试

采用酸洗法测量碳酸钙含量，取试样表面硬壳层（质量为s_1）放入烧杯，称量试样与烧杯的总质量为s_2，滤纸质量为s_3。向烧杯中加入过量稀盐酸至无气泡，过滤。过滤完成后，将烧杯和滤纸放入烘箱进行烘干，烘干后二者总质量为s_4，根据式(2)计算碳酸钙含量ω：

$$\omega=\frac{s_4-s_2-s_3}{s_1}\times 100\% \tag{2}$$

1.3.3 抗风蚀性测试

抗风蚀性是评价固化扬尘效果的重要指标之一，通过对试样进行模拟风蚀试验，测量试样的质量损失率来分析其抵抗风蚀的能力[23–24]。称量平盘质量记为M_1，烘干后的试样质量记为M_2；利用FD–4012–WG型GREE落地扇3档对试样进行风蚀，将试样放置在距风扇侧面0.5 m处（风力可达7级，风速13.9～15.1 m·s^{-1}）吹风15 min，风扇扇叶中心须正对试样。风蚀试验及风蚀后的试样如图3所示。称量风蚀后试样重量M_3，根据式(3)计算试样质量损失率δ：

$$\delta=\frac{M_3-M_1}{M_2-M_1}\times 100\% \tag{3}$$

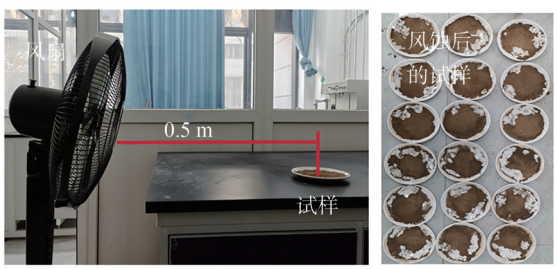


图3 风蚀试验及风蚀后的试样

Fig. 3 Wind erosion test and samples after wind erosion

1.3.4 表面硬度测试

表面硬度可反映试样表面硬壳层抵抗局部变形或压入的能力，可通过数显邵氏硬度计（LX–D型）测量。测量时，将硬度计压针垂直按压在试样表面，使其与试样表面完全贴合，此时读取读数S。每个试样测量5次，取5次的测量均值作为试样表面硬度值。

1.3.5 生态兼容性测试

固化后试样的pH值是评价抑尘剂生态兼容性的核心指标之一。取少量试样于锥形瓶内，按土水质量比1∶5加入去离子水，振荡3 min后再静止30 min；取少量液体于烧杯中，测量溶液的pH值。重复以上步骤3次，取平均值，测量误差不超过0.1[20]。

固化后试样的易溶盐含量也是评价抑尘剂生态兼容性的核心指标之一。按照《土工试验方法标准》（GB/T 50123—2019）[20]，称取11 g试样硬壳层置于锥形瓶中，并加入55 mL去离子水，振荡3 min后过滤溶液；移取50 mL溶液至蒸发皿，完全烘干后，称量蒸发皿质量。根据式(4)计算试样中易溶盐含量：

$$w=\frac{m_2-m_1}{m_0}\cdot\frac{V_1}{V_2}\times 100\% \tag{4}$$

式中：w为易溶盐含量，%；m_0为硬壳层质量，g；m_1为蒸发皿质量，g；m_2为蒸发皿与烘干残渣的总质量，g；V_1为蒸馏水体积，mL；V_2为移液枪吸取溶液体积，mL。

1.3.6 微观测试

采用扫描电子显微镜对固化后试样的微观形貌进行扫描，放大倍数为500～5 000。采用D/max–2500型X射线衍射仪对固化后试样的物相组成进行测试，测量角度为15°～80°。采用傅立叶红外光谱仪测试固化后试样的透过率，波数范围为4 000～500 cm^{-1}。

2 结果与讨论

2.1 胶结液浓度的确定

图4为不同胶结液浓度下碳酸钙的生成曲线。

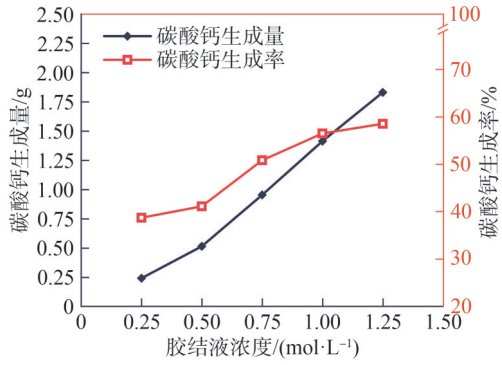


图4 不同胶结液浓度下碳酸钙生成曲线

Fig. 4 Calcium carbonate precipitation curves at different cementing solution concentrations

由图4可知：随着胶结液浓度的增加，碳酸钙的生成量及生成率总体呈上升趋势；当浓度超过0.75 mol/L时，碳酸钙的生成量及生成率增幅逐渐减缓，表明反应在较高浓度区间趋于饱和。为了在试验中实现最佳的反应效率和效果，选取1.25 mol/L进行后续试验。

2.2　性能试验结果

2.2.1　碳酸钙含量

图5为不同固化次数、生物聚合物种类及掺量下试样的碳酸钙含量。

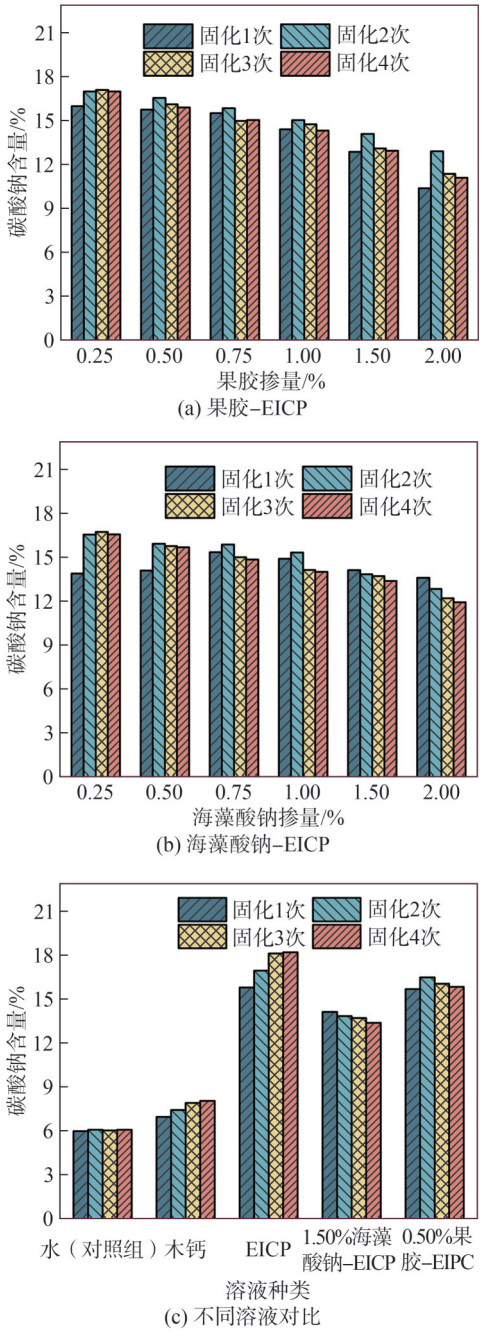


图5　不同固化次数、生物聚合物种类及掺量下试样的碳酸钙含量

Fig. 5　Calcium carbonate contents of samples after different curing times, biopolymer types and dosages

由图5(a)、(b)可知：当果胶掺量不超过0.50%、海藻酸钠掺量不超过1.50%时，对EICP过程碳酸钙生成量影响很小；当果胶掺量超过0.50%、海藻酸钠掺量超过1.50%时，碳酸钙含量减少。这可能是因为果胶、海藻酸钠遇水形成凝胶状物质增加了试样的黏性和稳定性，较高的黏性可能会影响EICP过程中反应物的扩散速率，从而影响碳酸钙沉淀过程[25]。

2.2.2　抗风蚀性

不同方法处理后试样的风蚀结果如图6所示。

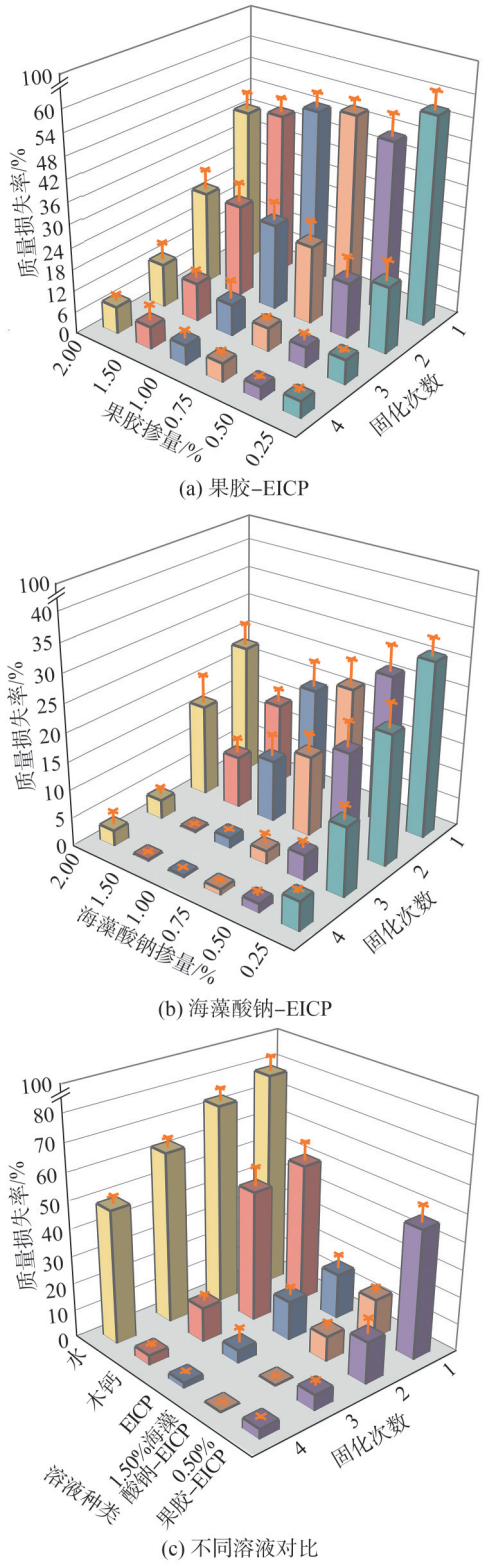
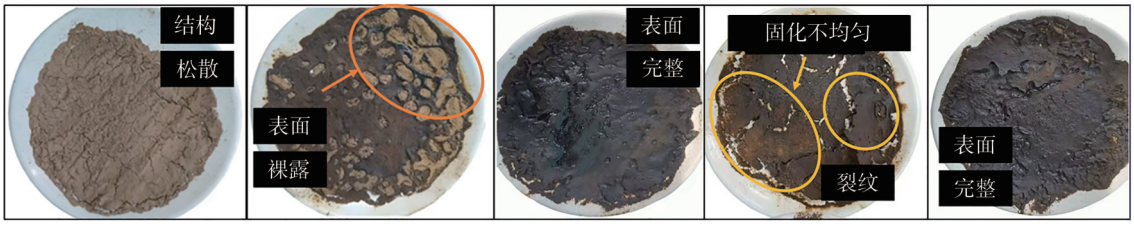


图6　不同方法处理后试样的质量损失率

Fig. 6　Mass loss rates of samples after different treatments

由图6可以看出，同等条件下，对照组（水）质量损失率最高，经过木钙溶液、EICP溶液、海藻酸钠–EICP、果胶–EICP处理后的试样质量损失率明显减小。以水处理组为参照，固化1次后，EICP及海藻酸钠–EICP处理均使试样质量损失率显著降低，相对降幅超过47%；果胶–EICP处理需经两次固化作用方能达到相当的降低幅度，木钙处理则需固化3次及以上才能实现类似效果。由图6(a)及(b)可知，果胶、海藻酸钠的最优掺量分别为0.50%和1.50%，并且1.50%海藻酸钠–EICP的固化效果优于0.50%果胶–EICP。由图6(c)可以看出，经5种不同溶液处理的试样抗风蚀能力分别为1.50%海藻酸钠–EICP>EICP>0.50%果胶–EICP>木钙>水。原因在于水处理后的试样并未形成新的矿物胶结物质，仅依靠暂时湿润作用增强可塑性，随着水分蒸发，土体恢复松散状态，难以形成长期稳定的抗风蚀层[26]，如图7(a)所示。木钙处理在一定程度上提高了试样的抗风蚀性，这是由于木钙中的Ca^{2+}与土体中的CO_3^{2-}结合形成碳酸钙，但其反应速率较慢，固化效果有限（图7(b)）。EICP处理试样的抗风蚀性较优，这是因为脲酶催化尿素水解产生CO_3^{2-}，与Ca^{2+}结合形成碳酸钙晶体，填充孔隙并胶结土粒，使结构更加致密，但EICP缺乏成核位点，晶体分布不均，影响了固化效果[27]，如图7(c)所示。



(a) 水（对照组） (b) 木钙溶液 (c) EICP溶液 (d) 果胶–EICP (e) 海藻酸钠–EICP

图7 不同方法处理后的试样形貌

Fig. 7 Morphology of samples after different treatments

由图6可知，适量果胶的掺入可以明显提升试样的抗风蚀性。这是因为果胶分子表面的带电基团可以作为碳酸钙晶体的成核位点，引导碳酸钙晶体有序生长，从而在颗粒间建立更致密的结构。同时，果胶分子中大量亲水基团吸水后会形成凝胶，与EICP过程生成的碳酸钙晶体共同构成果胶凝胶–碳酸钙复合物（以下简称胶–钙复合物），填充孔隙并增强颗粒胶结力，使试样表层形成稳定硬壳，提高抵抗风蚀的能力[25,28]。

当海藻酸钠掺量为1.50%时，试样抗风蚀性最佳。原因在于EICP反应消耗了部分钙离子，海藻酸钠与溶液中剩余的钙离子通过离子交联作用形成三维网络结构的海藻酸钙凝胶[25]，如图8所示。该凝胶不仅能直接增强颗粒间的黏聚力，还为碳酸钙晶体提供了额外的成核位点，促进晶体稳定沉积与团聚，提升骨架效应及表层硬壳完整性，提高试样抵抗强风吹蚀的能力[29]（图7(e)）。然而，当果胶或海藻酸钠掺量过大时，二者形成的凝胶会覆盖在裸土颗粒的表面，阻碍胶结液渗入试样内部，导致EICP矿化反应不能充分进行，碳酸钙沉淀减少，固化效果减弱[28]。

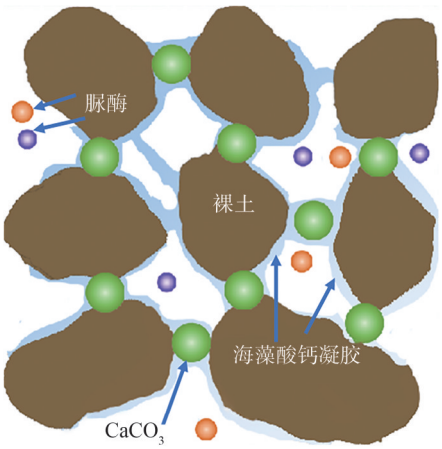


图8 海藻酸钠–EICP固化裸土扬尘作用机制示意图

Fig. 8 Schematic diagram of the bare soil dust solidification mechanism of sodium alginate–EICP

当生物聚合物掺量一定时，增加固化次数有利于进一步提高试样抗风蚀性能；固化4次后，对照组质量损失率为48.79%，经0.50%果胶–EICP处理后的试样质量损失率为3.64%，经1.50%海藻酸钠–EICP处理后的试样质量损失率仅为0.37%。然而，果胶掺量一定时，第4次固化后的试样质量损失率下降幅度明显减缓，部分试样甚至出现裂纹（图7(d)）。这可能是因为过量的胶结液导致局部区域内的碳酸钙过度沉淀引起应力集中，削弱了表层硬度，使得试样表面出现裂纹，抗风蚀能力降低。

2.2.3 表面硬度

不同固化次数、生物聚合物种类及掺量与试样表面硬度值的关系如图9所示。由图9可知，不同溶液处理试样表面硬度大小对比为1.50%海藻酸钠–EICP>EICP>0.50%果胶–EICP>木钙>水。固化1次后，水处理试样的表面硬度仅为8.9 HD，结构松散、裂纹明显，表面缺少抵挡外力变形的硬壳层；木钙处理试样表面硬度提升有限，为12.8 HD，试样表面颗粒仅依靠木钙的物理填充或化学键黏结在一起，表面硬度值较低，相

比之下，EICP、果胶–EICP及海藻酸钠–EICP处理试样的表面硬度值明显提高，表明碳酸钙晶体或其他复合物可以胶结试样颗粒并填充颗粒之间的孔隙，使得试样整体结合更加紧密，表面硬壳层完整程度高。在相同生物聚合物掺量下，随着固化次数的增加，试样表面硬度值增幅呈现先增后减的趋势。从第1次到第3次固化，表面硬度值提升幅度超过50%；而经过第4次固化后，试样表面硬度值较第3次固化增幅不足10%。这是因为经过前3次处理后试样表面已形成较为致密的硬壳层，阻碍后续溶液的渗入，致使第4次固化后试样表面硬度值增幅较小[28]。

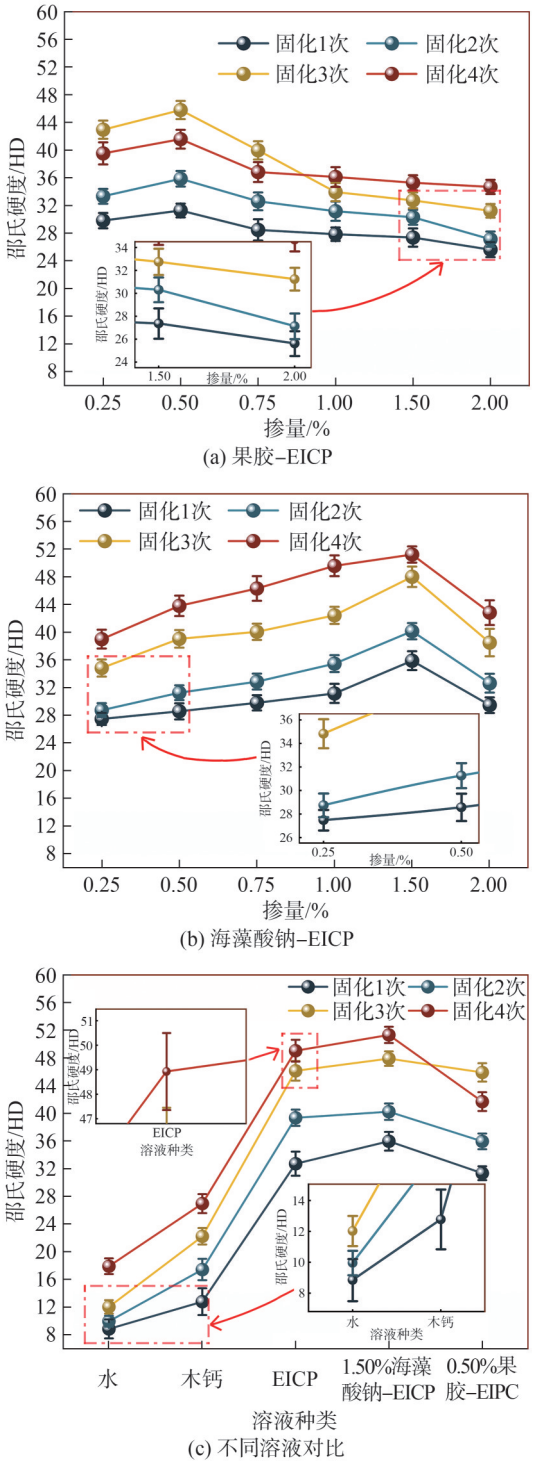


图9　不同方法处理后试样的表面硬度变化规律

Fig. 9　Change of surface hardness of the samples after different treatments

2.2.4　生态兼容性

图10为不同方法处理后试样的pH值。由图10可知：对照组pH值为8.33；经果胶–EICP、海藻酸钠–EICP处理后的试样pH为7.50～7.80，呈弱碱性；相较而言，经果胶–EICP、海藻酸钠–EICP处理后的试样pH值有所下降。这是因为EICP反应过程中，Ca^{2+}与CO_3^{2-}结合形成碳酸钙，消耗了CO_3^{2-}，进而促进了HCO_3^-电离，增加了H^+浓度，试样pH值降低[30]。

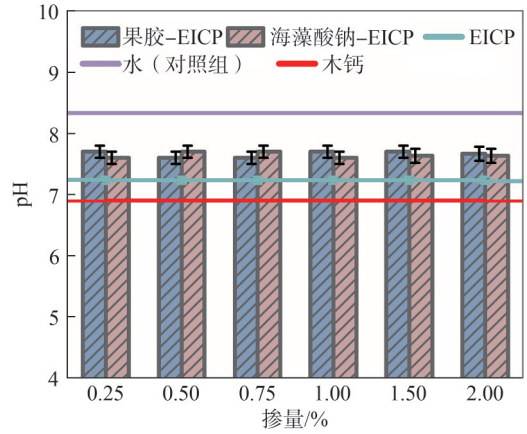


图10　不同方法处理后试样的pH值

Fig. 10　pH of the samples after different treatments

图11为不同方法处理后试样的易溶盐含量。由图11可知，经果胶–EICP、海藻酸钠–EICP处理后的试样易溶盐含量均小于1.60%，与水（对照组）差异较小，表明经果胶–EICP、海藻酸钠–EICP处理裸土并未显著改变其原生态盐分环境，具有一定的环境友好性[31]。

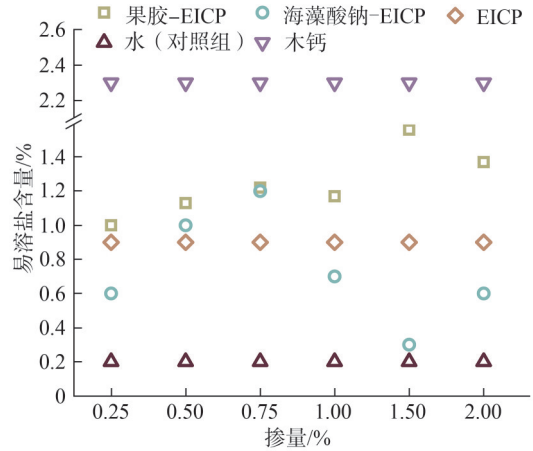


图11　不同方法处理后试样的易溶盐含量

Fig. 11　Soluble salt contents of the samples after different treatments

2.3 微观测试结果

2.3.1 SEM

图 12 为不同溶液固化后样品放大 500 倍及 5 000 倍的电镜扫描结果。图 12(a)为对照组的微观结构，裸土颗粒轮廓清晰且颗粒间存在大量孔隙，整体结构松散。木钙溶液处理试样(图 12(b))的表面孔隙数量有所减少，颗粒表面出现丝状覆盖物，可能是有胶结性的高分子木质素聚合物，在孔隙间能起到一定的填充和胶结作用[32]。EICP 处理后试样(图 12(c))的表面孔隙数量和孔径明显减少，棒状碳酸钙晶体随机散落在试样表面；生成的碳酸钙晶体附着在颗粒表面及孔隙中，形成较为致密的结构，使颗粒结合更紧密，但 EICP 反应缺少成核位点，导致碳酸钙晶体随机分布[33–34]。

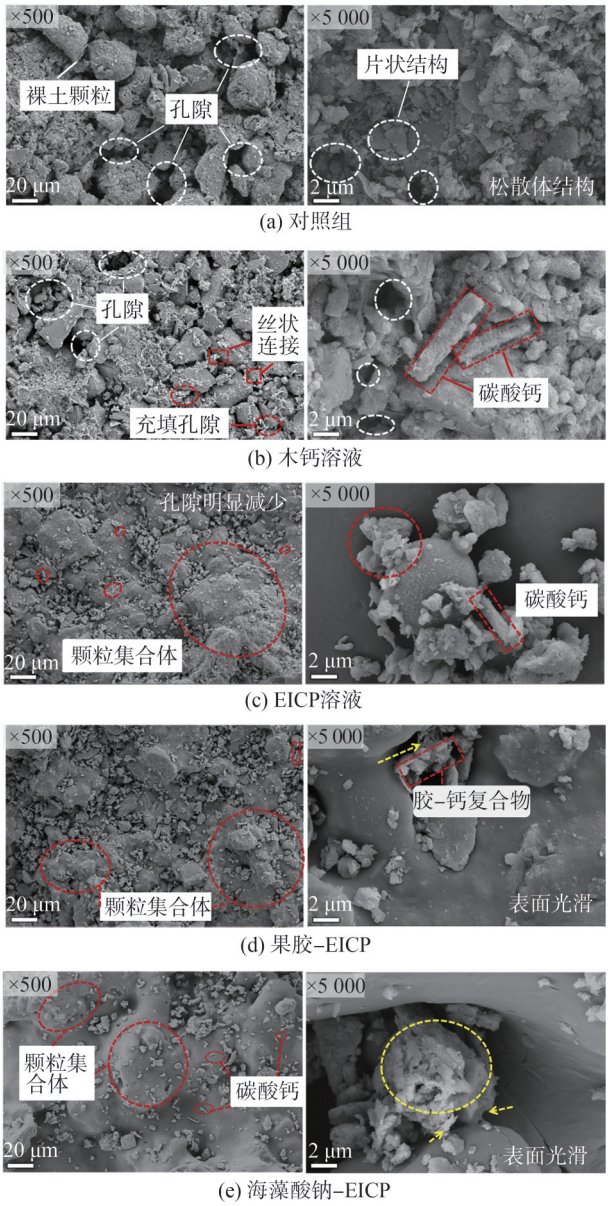


图 12 不同方法处理后试样的 SEM 图像

Fig. 12 SEM images of the samples after different treatments

在图 12(d)中：经果胶–EICP 处理后的试样无明显孔隙，试样表面散落的碳酸钙晶体减少，试样的整体性更高；有胶状物质黏结在颗粒间，这是果胶溶于水形成了果胶凝胶。这种凝胶可以吸附 Ca^{2+} 并作为成核位点，促进碳酸钙有序沉淀，形成块状碳酸钙簇，而且部分块状碳酸钙晶体附着在果胶凝胶上，形成胶–钙复合物，进一步增强颗粒间的胶结作用[25]。

从图 12(e)可以观察到：试样表面更加光滑致密。海藻酸钠分子链的羧基可以捕获 Ca^{2+}，提供了 EICP 反应的成核位点；而且，海藻酸钠分子通过与钙离子的交联作用生成了三维网状结构的海藻酸钙凝胶，这种凝胶网络结构可以作为模板，影响碳酸钙晶体析出的形态和排列方式，促使更规则、更稳定的晶体结构形成[35]。此外，三维网状结构的海藻酸钙凝胶包裹着碳酸钙晶体，形成更大的颗粒集合体填充在孔隙之间，颗粒间的胶结力显著增强，试样的抗风蚀能力大幅提升，优化了 EICP 技术的固化效果。

2.3.2 XRD

不同方法处理后试样的 XRD 图谱如图 13 所示。由图 13 可知，各试样的主要成分基本一致，相较于水和木钙溶液处理后的试样，采用果胶–EICP 及海藻酸钠–EICP 处理后的试样方解石衍射峰强度有所增强，说明果胶–EICP 及海藻酸钠–EICP 有效促进了更多碳酸钙以方解石晶体的形式沉淀。而且，采用海藻酸钠–EICP 处理试样的方解石衍射峰强度高于 EICP 处理的试样，表明适量海藻酸钠的加入提高了 EICP 过程方解石晶体的析出。

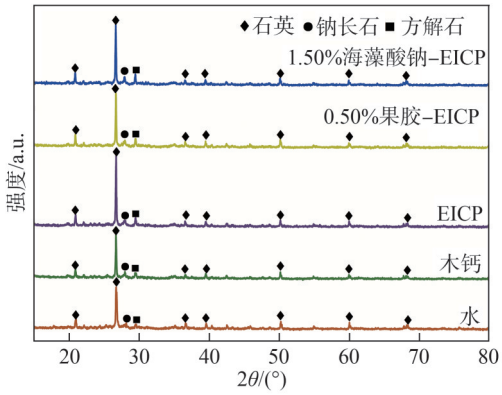


图 13 不同方法处理后试样的 XRD 图谱

Fig. 13 XRD images of the samples after different treatments

2.3.3 FTIR

图 14 为采用不同方法处理后试样的 FTIR 图谱。由图 14 可知：1 632.45 cm^{-1} 附近的峰来源于水的 O—H 弯曲振动，联合处理后试样在此处的峰减弱，这是因为碳酸钙晶体充填孔隙，减少水分吸附，减少了裸土颗粒因失水导致的脱落[36–37]；1 423.21 cm^{-1} 处为 CO_3^{2-}

不对称伸缩峰，经EICP、海藻酸钠–EICP及果胶–EICP处理后的试样该处的峰增强，这说明EICP过程中有很多碳酸钙晶体生成，胶结裸土颗粒[38]；CO_3^{2-}面外弯曲振动峰在873.11 cm^{-1}处产生，经过EICP及联合处理后试样在此处的红外特征峰峰形尖锐化，表明生成的碳酸钙晶体晶型以方解石为主[39]，与XRD分析结果一致；712.57 cm^{-1}处为CO_3^{2-}的面内弯曲振动峰，联合处理后试样的峰强度稳定，说明碳酸钙晶体与裸土颗粒结合紧密，孔隙填充效果显著，进而提高了试样的整体性[37]。

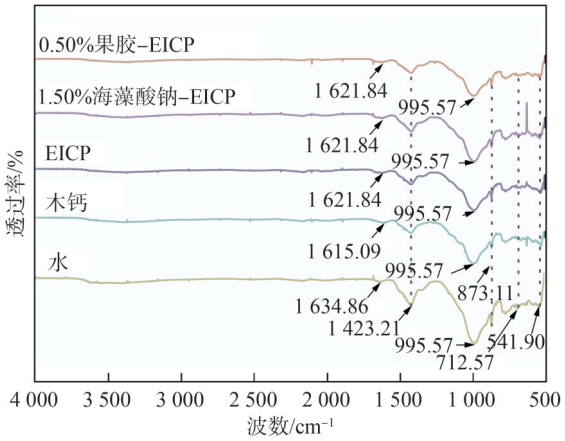


图14　不同方法处理后试样的FTIR图谱

Fig. 14　FTIR images of the samples after different treatments

3　机理分析

生物聚合物协同EICP技术固化裸土扬尘的机理如图15所示。生物聚合物协同EICP技术固化裸土扬尘涉及多个复杂过程，对其固化机理分析如下：

1）海藻酸钠通过分子链上的羧基与钙离子形成的配位键，使海藻酸钠分子链相互缠绕并将水分子包裹其中，生成三维海藻酸钙凝胶网络[40–41]。果胶则是通过分子的氢键及范德华力作用形成果胶凝胶[42]。两种凝胶能够将松散的裸土颗粒黏结在一起，增强颗粒间的黏结力，为后续EICP反应提供稳定的骨架结构。

2）海藻酸钙凝胶和果胶凝胶能够吸附环境中的钙离子，为EICP技术生成的碳酸钙晶体提供成核位点，引导碳酸钙晶体有序生长，从而减少随机散落晶体并提高沉淀均匀性及晶型稳定性[25]。SEM图像证实经果胶–EICP、海藻酸钠–EICP处理后的试样随机散落的碳酸钙晶体减少。

3）海藻酸钙凝胶、果胶凝胶黏结裸土颗粒形成初级骨架，并与EICP过程生成的碳酸钙晶体结合进一步胶结裸土颗粒、填充孔隙，使裸土从松散结构转变为凝胶–晶体–颗粒的多级致密结构。最终试样表面形成硬化的外壳，有效阻止了裸土颗粒被风吹蚀，减少扬尘，从而提升试样抗风蚀能力[43]。

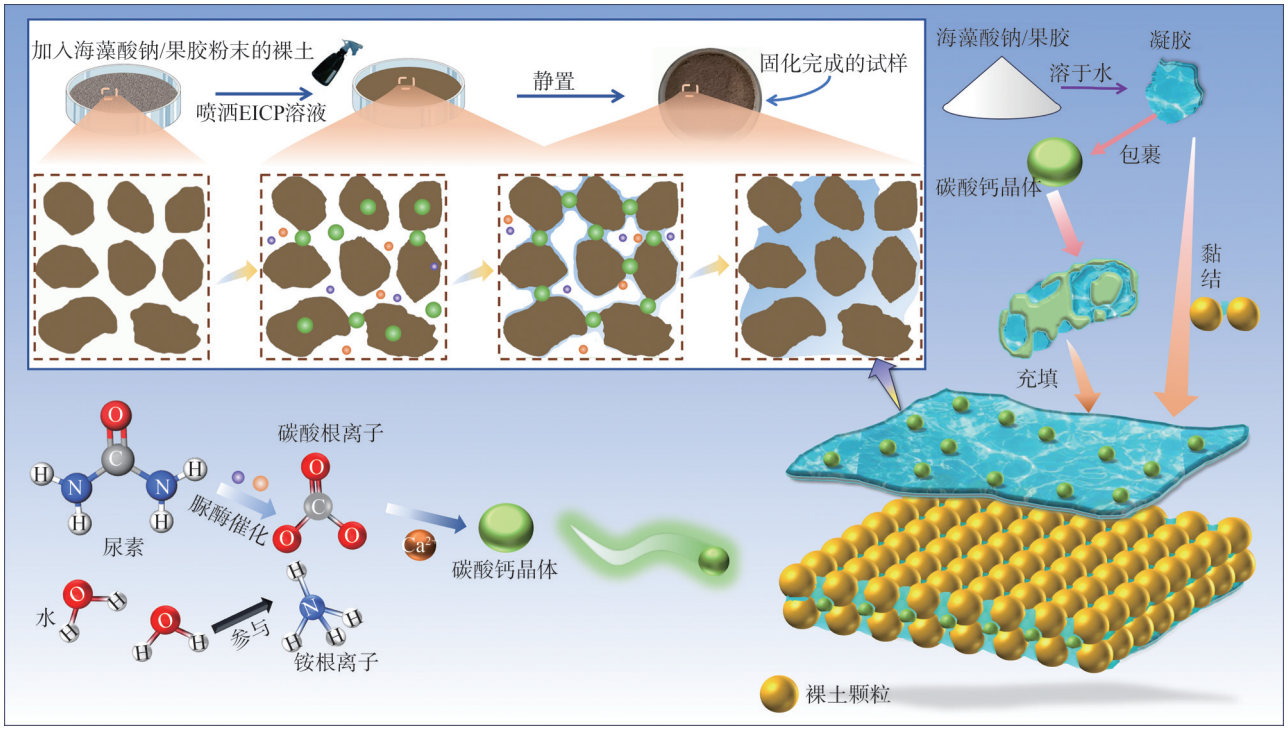


图15　生物聚合物协同EICP技术固化裸土扬尘机理

Fig. 15　Mechanism of bare soil dust consolidated by biopolymer with EICP

4）试样表层生成致密硬壳，有效抑制了裸土颗粒的迁移，与第2.2.2节与2.2.3节试验结果一致，而且海藻酸钠–EICP处理效果优于果胶–EICP。原因在于海藻酸钙网络为离子交联的三维网架，界面黏结与抗剪性

能更强；而果胶凝胶是依靠氢键和范德华力作用形成的，界面黏结力较弱，在荷载作用下凝胶分子链容易发生滑移，导致其整体抵抗变形能力降低[44–45]。此外，经果胶–EICP、海藻酸钠–EICP处理后的试样pH值介于7.5～7.8，为弱碱性，且易溶盐含量均小于1.6%，说明采用果胶–EICP、海藻酸钠–EICP处理试样对环境影响较小，是生态友好的裸土扬尘治理方法。

综上所述，果胶–EICP、海藻酸钠–EICP利用凝胶和碳酸钙进行物理充填、化学黏结及复合胶结等协同作用，改善了裸土试样的致密性及整体性，有效抑制了风力引起的裸土颗粒剥离与迁移，显著提升了裸土的抗风蚀性，为西北地区裸土扬尘治理提供了环保高效的解决方案。

4 结 论

1）果胶、海藻酸钠的掺入对EICP过程中碳酸钙生成量有影响。经果胶–EICP、海藻酸钠–EICP处理后的试样抗风蚀能力显著提高，其中，采用0.50%果胶–EICP、1.50%海藻酸钠–EICP处理试样效果最佳。

2）试样的抗风蚀能力随固化次数的增加而增加；固化4次后，经0.50%果胶–EICP处理后的试样质量损失率为3.64%，经1.50%海藻酸钠–EICP处理后的试样质量损失率仅为0.37%。

3）果胶、海藻酸钠与EICP技术联合固化试样可显著提高试样的表面硬度；经果胶–EICP、海藻酸钠–EICP处理后的试样为弱碱性且易溶盐含量均小于1.6%。

4）果胶、海藻酸钠溶于水分别形成果胶凝胶、海藻酸钙凝胶，二者在充填、黏结裸土颗粒的同时，包裹碳酸钙晶体，使得裸土颗粒、碳酸钙晶体及凝胶之间的胶结更为紧密，有效提高了试样的整体性和致密性，宏观表现为试样抗风蚀能力的提升。

参考文献：

[1] Yang Yanping, Chen Qiang, Wang Lina, et al. Winter pollution characteristics and physicochemical properties of PM in a northwest industrial city[J]. Environmental Science, 2020,41(12):5267–5275.[杨燕萍,陈强,王莉娜,等. 西北工业城市冬季$PM_{2.5}$污染特征及理化性质[J]. 环境科学, 2020,41(12):5267–5275.]

[2] Wang Zhiming, Zhou Wei, Jiskani I M, et al. Dust pollution in cold region surface mines and its prevention and control [J]. Environmental Pollution, 2022,292:118293.

[3] Zhang Haopeng, Wang Feng, Zhou Shenghui, et al. Contribution of dust emissions from farmland to particulate matter concentrations in North China Plain: Integration of WRF-Chem and WEPS model[J]. Environment International, 2025,195:109191.

[4] Meng Yang, Huang Ning, Zhang Chao, et al. Mechanics of wind erosion-induced dust emission from soil crusts: A theoretical predictive model[J]. CATENA, 2024,246:108342.

[5] Zhang Minxia, Liu Feifei, Wang Ruiqi, et al. Research advances of microbial consolidation of bare soil and its resistance of wind erosion dust[J]. Environmental Pollution and Control, 2021,43(2):232–236.[张敏霞,刘飞飞,王瑞琦,等. 微生物固结裸土及其抗风蚀扬尘的研究进展[J]. 环境污染与防治, 2021,43(2):232–236.]

[6] Yang Yukun, Zhou Wei, Wang Zhiming, et al. Accurate long-term dust concentration prediction in open-pit mines: A novel machine learning approach integrating meteorological conditions and mine production intensity[J]. Journal of Cleaner Production, 2024,436:140411.

[7] Li Tingkun, Feng Yinchang, Bi Xiaohui, et al. Main problems and refined solutions of urban fugitive dust pollution in China[J]. Environmental Science, 2022, 43(3): 1323–1331.[李廷昆,冯银厂,毕晓辉,等. 城市扬尘污染主要成因与精准治尘思路[J]. 环境科学, 2022,43(3):1323–1331.]

[8] Zhang Qian, Ye Weimin, Liu Zhangrong, et al. Advances in soil cementation by biologically induced calcium carbonate precipitation[J]. Rock and Soil Mechanics, 2022,43(2):345–357.[张茜,叶为民,刘樟荣,等. 基于生物诱导碳酸钙沉淀的土体固化研究进展[J]. 岩土力学, 2022,43(2):345–357.]

[9] Tian Wei, Yun Wei, Dang Kexin, et al. Study on dynamic characteristics of subgrade loess improved by EICP solution with different calcium sources[J]. Materials Reports, 2024,38(9):53–61.[田威,云伟,党可欣,等. 不同钙源EICP溶液改良路基黄土动力特性研究[J]. 材料导报, 2024, 38(9):53–61.]

[10] Chai Shaobo, Li Xianpeng, Li Yinan, et al. Experimental study on dynamic properties of loess improved by rubber particles and EICP technology[J]. Advanced Engineering Sciences, 2024,56(3): 134–146.[柴少波,李显鹏,李轶楠,等. 橡胶颗粒及EICP技术改良黄土动力特性试验[J]. 工程科学与技术, 2024,56(3):134–146.]

[11] Sun Xiaohao, Miao Linchang, Wang Hengxing, et al. Enzymatic calcification to solidify desert sands for sandstorm control[J]. Climate Risk Management, 2021,33:100323.

[12] Wu Mingyue, Hu Xiangming, Zhang Qian, et al. Preparation and performance evaluation of environment-friendly biological dust suppressant[J]. Journal of Cleaner Production, 2020,273:123162.

[13] Yuan Hua, Ren Guanzhou, Liu Kang, et al. Experimental study of EICP combined with organic materials for silt improvement in the Yellow River flood area[J]. Applied Sciences, 2020,10(21):7678.

[14] Arab M G, Omar M, Almajed A, et al. Hybrid technique to produce bio-bricks using enzyme-induced carbonate precipitation(EICP) and sodium alginate biopolymer[J]. Con-

struction and Building Materials,2021,284:122846.

[15] Soldo A, Miletić M, Auad M L. Biopolymers as a sustainable solution for the enhancement of soil mechanical properties[J].Scientific Reports,2020,10:267.

[16] Babatunde Q O, Yoon H K, Byun Y H. Rheological behavior of zein biopolymer and stiffness characteristic of biopolymer treated soil[J]. Construction and Building Materials,2023,384:131466.

[17] Jha A, Mishra S. Exploring the potential of waste biomass-derived pectin and its functionalized derivatives for water treatment[J]. International Journal of Biological Macromolecules,2024,275:133613.

[18] Zhao Yong, Zhuang Jianqi, Wang Ying, et al. Improvement of loess characteristics using sodium alginate[J]. Bulletin of Engineering Geology and the Environment,2020,79(4): 1879–1891.

[19] Chang I, Lee M, Tran A T P, et al. Review on biopolymer-based soil treatment(BPST) technology in geotechnical engineering practices[J]. Transportation Geotechnics, 2020, 24:100385.

[20] 中华人民共和国住房和城乡建设部.土工试验方法标准:GB/T 50123—2019[S].北京:中国计划出版社,2019.

[21] Lemboye K, Almajed A. Effect of varying curing conditions on the strength of biopolymer modified sand[J]. Polymers,2023,15(7):1678.

[22] Hu Wenlu,Liu Peng.Experimental study on mineralization cementation and dust suppression of red mud by urease spraying process[J]. Journal of Forestry Engineering, 2025, 10(2): 173–179.[胡雯璐,刘鹏.脲酶喷洒工艺对赤泥矿化胶结及抑尘效果试验[J].林业工程学报,2025,10(2):173–179.]

[23] Jiang Yaodong. Research on new dust-depressor of calcite precipitation induced by microbe and enzyme[D]. Nanjing: Southeast University,2018.[蒋耀东.微生物及活性酶诱导碳酸钙沉淀新型抑尘剂实验研究[D].南京:东南大学,2018.]

[24] Tan Huiming, Zhao Xiangyun, Xu Ye. Experimental study on wind erosion resistance of sandy soil stabilized by enzyme-induced carbonate precipitation with urease from soybean skin[J].Journal of Disaster Prevention and Mitigation Engineering,2024,44(6):1408–1417.[谭慧明,赵祥运,徐烨.豆皮脲酶诱导碳酸盐沉淀固化砂土抗风蚀性能试验研究[J].防灾减灾工程学报,2024,44(6):1408–1417.]

[25] Cao Lianqi,Lu Wei,Mata A,et al.Egg-box model-based gelation of alginate and pectin: A review[J].Carbohydrate Polymers,2020,242:116389.

[26] Hamdan N, Kavazanjian E. Enzyme-induced carbonate mineral precipitation for fugitive dust control[J]. Géotechnique, 2016,66(7):546–555.

[27] Xu Jian,Li Xihu,Liu Yonghao,et al.Evaluation of wind erosion resistance of EICP solidified desert sand based on response surface methodology[J].Construction and Building Materials,2024,447:138119.

[28] Zhang Jingwei, Jia Hualing, Li Jia, et al. Bio-gel formation through enzyme-induced carbonate precipitation for dust control in Yellow River silt[J].Gels,2025,11(6):452.

[29] Almajed A, Lemboye K, Arab M G, et al. Mitigating wind erosion of sand using biopolymer-assisted EICP technique [J].Soils and Foundations,2020,60(2):356–371.

[30] Cui Mingjuan,Lai Hanjiang,Hoang T,et al.One-phase-low-pH enzymeinduced carbonate precipitation(EICP) method for soil improvement[J].Acta Geotechnica,2021,16(2):481–489.

[31] Xie Yixin,Cheng W C,Wang Lin,et al.Biopolymer-assisted enzyme-induced carbonate precipitation for immobilizing Cu ions in aqueous solution and loess[J].Environmental Science and Pollution Research,2023,30(54):116134–116146.

[32] Wang Jia, Wang Fei, Li Guoyu, et al. Microstructure characteristics of modified loess before and after drying–wetting cycle[J]. Science Technology and Engineering, 2024, 24(23): 10096–10104.[王佳,王飞,李国玉,等.干湿循环前后不同改性黄土的微观特性[J].科学技术与工程,2024,24(23): 10096–10104.]

[33] Ahenkorah I, Rahman M M, Karim M R, et al. Enzyme induced calcium carbonate precipitation and its engineering application: A systematic review and meta-analysis[J].Construction and Building Materials,2021,308:125000.

[34] Gitanjali A, Jhuo Y S, Yeh F H, et al. Bio-cementation of sand using enzyme-induced calcite precipitation: Mechanical behavior and microstructural analysis[J]. Construction and Building Materials,2024,417:135360.

[35] Hu Chuhuan, Lu Wei, Mata A, et al. Ions-induced gelation of alginate: Mechanisms and applications[J]. International Journal of Biological Macromolecules,2021,177:578–588.

[36] Albenayyan N, Murtaza M, Alarifi S A, et al. Optimization of calcium carbonate precipitation during alpha-amylase enzyme-induced calcite precipitation(EICP) [J]. Frontiers in Bioengineering and Biotechnology,2023,11:1118993.

[37] He Jia,Huang Anguo,Ji Jiafeng,et al.Enzyme induced carbonate precipitation with fibers for the improvement of clay soil slopes against rainfall and surface runoff erosions [J].Transportation Geotechnics,2023,42:101074.

[38] Chen Yanbo, Wang Qingyang, Bian Yi, et al. Effects of enzyme-induced carbonate precipitation(EICP) with different urease sources on the zinc remediation[J]. Journal of Hazardous Materials,2024,480:136321.

[39] Bian Yi, Chen Yanbo, Zhan Liangtong, et al. Effects of enzyme-induced carbonate precipitation technique on multiple heavy metals immobilization and unconfined compressive strength improvement of contaminated sand[J]. Science of the Total Environment,2024,947:174409.

[40] Yuan Hua, Li Jin, Shen Wenbo, et al. Application of Yellow River sediment in the preparation of bio-bricks by sodium alginate+EICP[J/OL]. Advanced Engineering Sciences, 2025:1–9[2025–07–01].http://kns.cnki.net/kcms/detail/51.1773.TB.20240928.1332.001.html.[原华,李瑾,沈文博,等. 黄河泥沙在海藻酸钠+EICP 制备生物砖中的应用[J/OL]. 工程科学与技术,2025:1–9[2025–07–01].http://kns.cnki.net/kcms/detail/51.1773.TB.20240928.1332.001.html.]

[41] Cheng Liang, Yang Yang, Chu Jian. *In-situ* microbially induced Ca^{2+}-alginate polymeric sealant for seepage control in porous materials[J]. Microbial Biotechnology, 2019, 12(2): 324–333.

[42] Ali Z S, Fattah M Y, Al–Gharbawi A S A. Strength and compressibility characteristics of clay treated by pectin biopolymer[J]. Transportation Infrastructure Geotechnology, 2025,12(5):158.

[43] Du Changbo, Tao Han, Yi Fu, et al. Experimental study on plant-derived urease-induced calcium carbonate precipitation for immobilizing limestone dusts[J]. Materials Reports, 2025,39(2):67–74.[杜常博,陶晗,易富,等. 植物源脲酶诱导碳酸钙沉积固化石灰石粉尘试验研究[J]. 材料导报, 2025,39(2):67–74.]

[44] Azimi M, Soltani A, Mirzababaei M, et al. Biopolymer stabilization of clayey soil[J]. Journal of Rock Mechanics and Geotechnical Engineering, 2024,16(7):2801–2812.

[45] Abd T, Fattah M, Aswad M. Improvement of soft clayey soil by bio-polymer[J]. Engineering and Technology Journal, 2021,39(8):1301–1306.

Experimental Study on the Anti-wind Erosion Performance and Mechanism Research of Biopolymer Synergistic EICP Ecological Curing of Bare Soil Dust

TIAN Wei[1,2], *LI Lu*[1], *HE Wenhao*[1,2], *YUN Wei*[1,2], *ZHAO Hangyu*[1], *YI Guoyang*[1]

(1.School of Civil Engineering, Chang'an University, Xi'an 710061, China;
2.Key Laboratory of Degraded and Unused Land Consolidation Engineering, Ministry of Natural Resources, Xi'an 710021, China)

Abstract:

Objective Wind erosion of bare soil is a major source of atmospheric particulate matter pollution in arid and semi-arid regions, posing significant threats to environmental quality and human health. Therefore, an environmentally sustainable and efficient soil stabilization approach is developed by combining biopolymers (pectin and sodium alginate) with enzyme-induced calcium carbonate precipitation (EICP) technology. The research aims to examine the synergistic effects of pectin and sodium alginate on the EICP process, clarify their influence on calcium carbonate crystallization and bonding behavior, and identify the mechanisms responsible for enhancing the wind erosion resistance of treated soils. This study provides a scientific basis for the large-scale ecological application of biopolymer-EICP technology in dust suppression and soil stabilization.

Methods The experimental investigation was performed using natural loess-type bare soil collected from arid regions in Northwest China. The soil samples were air-dried, passed through a 2 mm sieve, and homogenized to ensure uniformity. Cementation solutions containing various calcium lignosulfonate concentrations of 0.25~1.25 mol/L were prepared and mixed with urease solutions to initiate EICP reactions. The acid-washing method was applied to determine the actual calcium carbonate yield, and an optimal cementation concentration of 1.25 mol/L was selected based on reaction efficiency and cost-effectiveness. Mechanical and physicochemical properties, including calcium carbonate content, wind erosion resistance, surface hardness, pH, and soluble salt content, were evaluated after each curing cycle. Wind erosion resistance was determined using a laboratory wind erosion simulation apparatus, and the mass loss rate of each specimen was recorded to quantify erosion resistance. Surface hardness was measured using a digital Shore hardness tester, while pH and soluble salt contents were analyzed to evaluate the environmental compatibility of the treatments. Microstructural and mineralogical characteristics were examined using scanning electron microscopy (SEM), X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FTIR) to characterize morphological features, mineral phases, and functional group interactions. The integration of macro- and micro-scale characterization provided a comprehensive understanding of the influence of biopolymers on the EICP-induced cementation mechanism.

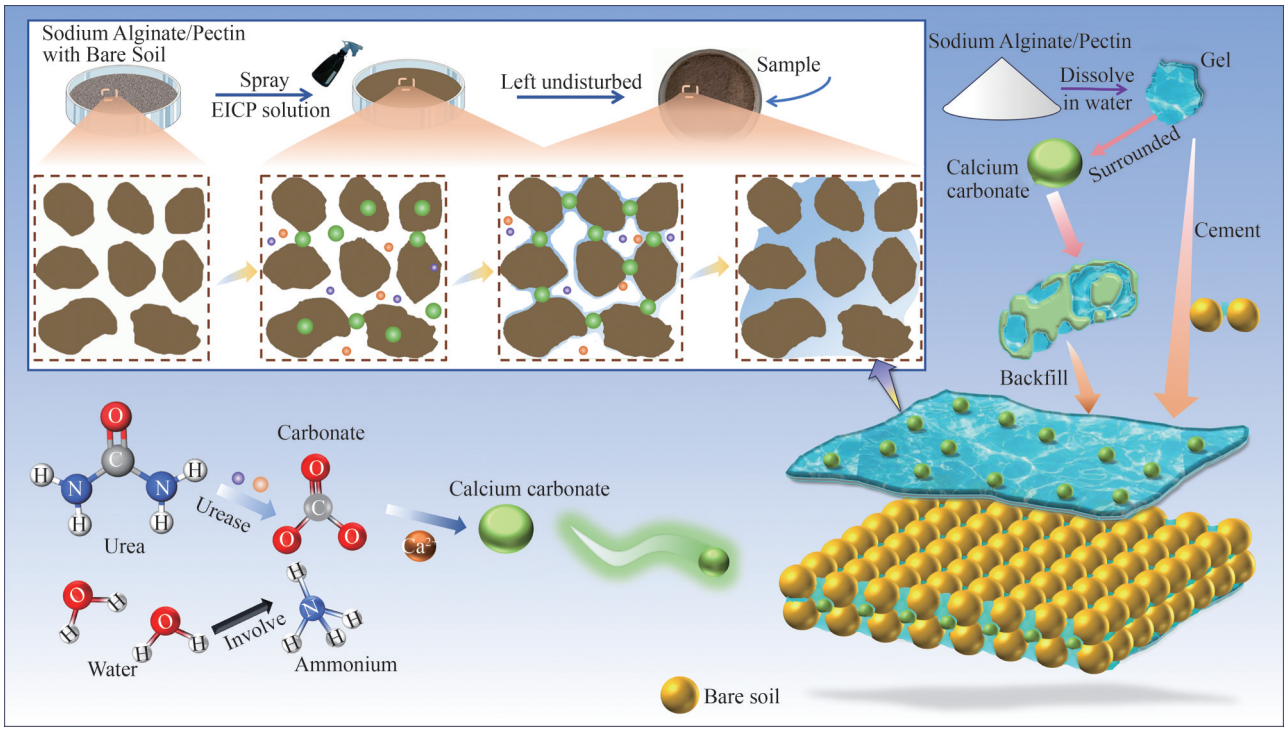
Results and Discussions When the pectin concentration was below 0.5%, and the sodium alginate was below 1.5%, the presence of biopolymers exerted minimal inhibition on the EICP reaction. Beyond these limits, the calcium carbonate yield decreased due to increased solution viscosity, which hindered ion diffusion. The wind erosion resistance of the treated specimens improved significantly with increasing curing cycles. After four cycles, the mass loss rate of the pectin-EICP-treated specimen decreased to 3.64%, and that of the sodium alginate-EICP-treated specimen decreased to 0.37%, compared to over 48% for the water-treated group. The surface hardness values increased by 186.4% and 132.7%, respectively, relative to the water-treated group. These results demonstrated that both biopolymers markedly enhanced the bonding strength among soil particles through the formation of gel-crystal-particle composite structures. The SEM images revealed that in pectin-EICP-treated specimens, hydrogen bonding and van der Waals forces enabled pectin molecules to form a dense gel network that encapsulated soil grains. In sodium alginate-EICP-treated specimens, calcium ions crosslinked alginate chains to form calcium alginate gels with a stable three-dimensional network. These gels not only filled soil pores but also served as nucleation sites for calcium carbonate crystals. The EICP process then deposited calcite crystals preferentially along the gel network, which created a compact and continuous cementation matrix. The resulting composite structure transformed

the loose granular arrangement of the original soil into an integrated and cohesive solid matrix with enhanced resistance to wind-induced particle detachment. XRD and FTIR analyses confirmed that calcite was the dominant crystalline phase of calcium carbonate in both treatments, which indicated that biopolymer addition did not alter the mineral composition but promoted the orderly growth of calcite. Mechanistically, the cooperative action between biopolymer gelation and enzymatic mineralization was identified as the key factor that enhanced soil stabilization. Pectin primarily provided physical encapsulation through hydrogen-bonded gels, while sodium alginate contributed ionic crosslinking with calcium ions, which formed calcium alginate complexes that strongly bonded with calcite crystals. This difference explained the superior erosion resistance of the sodium alginate-EICP system. The gel matrix not only strengthened particle bonding but also regulated the spatial distribution of precipitated calcium carbonate, which improved its uniformity and continuity within the soil matrix. Therefore, the treated soil surface developed a hardened crust layer that was capable of resisting wind shear stress, minimizing dust release. The pH values of all treated specimens ranged between 7.5 and 7.8, and soluble salt contents were below 1.6%, which demonstrated the environmental compatibility of both biopolymer-EICP systems. The treatments did not introduce significant alkalinity or salinity, which made them suitable for large-scale ecological restoration and dust mitigation projects in arid environments.

Conclusions This study establishes an ecological soil stabilization method by coupling biopolymers with enzyme-induced calcium carbonate precipitation. The results reveal that both pectin and sodium alginate effectively enhance the EICP-induced cementation process through synergistic physical filling and chemical bonding effects. The developed gel-crystal-particle composite structure improves soil compactness, increases surface hardness, and significantly reduces mass loss caused by wind erosion. Therefore, the biopolymer-assisted EICP approach combines the advantages of biogenic mineralization and renewable organic polymers, providing an environmentally sustainable solution for bare soil dust control. The findings provide both theoretical and technical support for the large-scale application of EICP-based ecological curing technologies in dust suppression, slope stabilization, and desertification control. In addition, the findings contribute to understanding the organic-inorganic synergistic mechanism in bio-mediated soil stabilization and provide theoretical and practical support for the development of sustainable geotechnical engineering techniques.

Key words: urease-induced calcium carbonate precipitation; the dust of bare soil; calcium lignosulfonate; biopolymers; surface curing

Graphical abstract:



（编辑　李轶楠）

引用格式：Tian Wei,Li Lu,He Wenhao,et al.Experimental study on the anti-wind erosion performance and mechanism research of biopolymer synergistic EICP ecological curing of bare soil dust[J]. Advanced Engineering Sciences, 2026, 58(3): 134–145.
[田威,李璐,贺文昊,等. 生物聚合物协同EICP生态固化裸土扬尘抗风蚀性能及机理[J]. 工程科学与技术,2026,58(3):134–145.]