

含镁类水滑石及丛林伪装涂层的制备及植物可见-近红外光谱模拟

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摘要: 现有的丛林伪装涂层模拟材料, 与绿色植被相比, 光谱图往往无法同时满足绿峰和近红外水吸收峰特征。本工作采用共沉淀法制备了硫酸根插层镁铬类水滑石等6种材料, 并采用X射线衍射分析、傅里叶红外变换光谱分析、热分析、扫描电子显微镜等手段对该材料进行了结构表征, 然后将其与铬绿颜料复合制备丛林伪装功能涂层, 进行可见-近红外光谱和热成像测试。研究表明, 调变层板阳离子和层间阴离子合成的6种类水滑石(LDHs)材料具有典型的层状结构特征, 其中硫酸根插层镁铬类水滑石的层间距最大, 热失重最多, 对应其层间存储水分子最为丰富。可见-近红外光谱测试结果表明, 镁铬类水滑石显示了490 nm处蓝峰和1400、1900 nm处的近红外水峰特征, 通过将 MgCr-SO_4^{2-} -LDHs包覆 Cr_2O_3 后可形成绿色特征的丛林伪装涂层模拟材料。优化的 MgCr-SO_4^{2-} -LDHs@ Cr_2O_3 与 MgCr-SO_4^{2-} -LDHs质量比为3:7制备的伪装涂层, 其绿峰、近红外吸水特征峰均实现与天然植物叶片的高精度匹配, 光谱相似度高达95.80%, 且热成像测试与植被结果无明显差异。对颜色和近红外水吸收峰双功能模拟材料的研究, 为植被伪装发展提供了一个新的研究方向。

关键词: 丛林伪装涂层; 绿色植被; 水吸收峰; 类水滑石; 光谱相似度

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丛林伪装旨在通过模拟自然环境特征来隐藏军事目标, 使其难以被探测和识别^[1,2]。高光谱遥感能够捕捉到植被在可见光、近红外和短波红外等波段的光谱特征, 可以识别伪装目标与自然背景之间的光谱差异, 在丛林伪装中展现了强大的应用潜力。绿色植被可见-近红外光谱区域具备4个特性, 分别为: 绿峰、红边、高原、水吸收峰。通过功能涂层技术开发, 设计与绿色植被“同色”“同光谱”的材料, 可以实现目标物的伪装和隐蔽的功能^[2]。

水滑石, 又名双金属氢氧化物(Layered double hydroxides, LDHs), 是一种阴离子型层状结构材料。通过层板金属离子和层间阴离子调变, 可形成类水滑石材料, 化学式为 $\text{M}^{\text{II}}_x\text{M}^{\text{III}}_{1-x}(\text{OH})_2(\text{A}^n-)_{x/n}\cdot m\text{H}_2\text{O}$, 在涂料、塑料、药物缓释等领域具有广泛用途^[3-6]。类水滑石具有良好的热稳定性和环保无毒的特性, 适合在涂层材料中作为安全添加剂使用。类水滑石层间丰富的水分子, 在植被光谱中可以模拟近红外水峰, 是一种性能优异的植被可见-近红外光谱模拟材料。

杨玲等^[7]研究表明, 镁铝水滑石在78~2500 nm波段与植被的光谱相似度高于95%。袁乐等^[8]研究了镁铝水滑石在层板掺杂铬离子后, 提高了水滑石与植被的光谱相似度。本课题组^[9,10]前期研究表明, 铬绿和硝酸根插层镁铝水滑石复合, 模拟绿色植物光谱相似度可以达到95%以上; 以茜素绿插层水滑石、柠檬酸根插层水滑石和钼酸铋复合制备涂层, 与树叶光谱相似度超过97%。

镁铬类水滑石既呈现蓝绿色、又具备近红外水吸收峰, 因此在其基础上进行类水滑石层间阴离子调变, 很有可能形成优异的丛林伪装模拟材料。本工作以共沉淀法合成镁铬类水滑石材料, 然后以铬绿颜料和镁铬类水滑石复合, 制备丛林伪装功能涂层, 用于模拟植物可见-近红外光谱。

1 实验

1.1 样品的制备

1.1.1 类水滑石材料合成 MgCr-SO_4^{2-} -LDHs

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采用共沉淀合成^[11, 12]。按照 $n(\text{Mg}^{2+}) : n(\text{Cr}^{3+}) = 3 : 1$ (n 为物质的量), 将 5.24 g 和 2.3 g 的 MgSO_4 、 $\text{CrCl}_3 \cdot 6\text{H}_2\text{O}$ 分别溶解在去离子水中, 制备溶液 A 和溶液 B, 将 4.6 g 的 NaOH 溶解在去离子水中, 标记为溶液 C。在 80 °C 搅拌, 同时加入体积比例为 1 : 1 : 1 的溶液 A、溶液 B、溶液 C, pH 值保持在 9~10 之间, 滴加时间保持在 30 min, 滴完后继续搅拌 30 min, 然后在 65 °C 的烘箱中晶化 8 h。经过滤, 在 65 °C 下干燥 12 h, 粉碎得到样品, 样品被标记为 $\text{MgCr-SO}_4^{2-}\text{-LDHs}$ 。

其他类水滑石样品 ($\text{MgCr-SO}_4^{2-}\text{-LDHs}$ 、 $\text{MgFe-SO}_4^{2-}\text{-LDHs}$ 、 $\text{MgAl-SO}_4^{2-}\text{-LDHs}$ 、 $\text{MgCr-CO}_3^{2-}\text{-LDHs}$ 、 $\text{MgCr-NO}_3^{-}\text{-LDHs}$) 合成方法同上。 $\text{MgAl-SO}_4^{2-}\text{-LDHs}$ 、 $\text{MgFe-SO}_4^{2-}\text{-LDHs}$ 合成过程与 $\text{MgCr-SO}_4^{2-}\text{-LDHs}$ 区别在于: 采用 $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ 、 $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ 替代 $\text{CrCl}_3 \cdot 6\text{H}_2\text{O}$ 。 $\text{MgCr-CO}_3^{2-}\text{-LDHs}$ 、 $\text{MgCr-NO}_3^{-}\text{-LDHs}$ 合成过程与 $\text{MgCr-SO}_4^{2-}\text{-LDHs}$ 区别在于: 溶液 C 分别用 NaOH 和 $\text{Na}_2\text{CO}_3/\text{NaNO}_3$ 配置。

1.1.2 $\text{MgCr-SO}_4^{2-}\text{-LDHs}@ \text{Cr}_2\text{O}_3$ 合成 $\text{MgCr-SO}_4^{2-}\text{-LDHs}@ \text{Cr}_2\text{O}_3$ 采用共沉淀法合成, 方法同 $\text{MgCr-SO}_4^{2-}\text{-LDHs}$ 合成的差别在于: 称取 1 g 的 Cr_2O_3 分散在去离子水中, 然后在搅拌下包覆合成 $\text{MgCr-SO}_4^{2-}\text{-LDHs}$, 得到 $\text{MgCr-SO}_4^{2-}\text{-LDHs}@ \text{Cr}_2\text{O}_3$ 样品。

1.1.3 伪装涂层制备 将原料 Cr_2O_3 、 $\text{MgCr-SO}_4^{2-}\text{-LDHs}@ \text{Cr}_2\text{O}_3$ 和 $\text{MgCr-SO}_4^{2-}\text{-LDHs}$ 等按 3 : 7 质量比进行研磨拼混, 然后将粉末和聚乙烯醇胶水以 1 : 2 的质量比例混合, 搅拌均匀, 直到混合溶液中没有明显的颗粒为止。然后将上述配置的胶水均匀涂布在氨纶织物上, 然后在 160 °C 烘箱中干燥

10 min, 得到伪装涂层(涂层厚度约 30~50 μm)。

1.2 样品表征

粉末 X 射线衍射(XRD): 采用 XD-6 型 X 射线衍射仪, 测试条件为铜靶, 波长为 0.154 056 nm, 扫描速度为 5 (°)/min, $2\theta = 5^\circ \sim 70^\circ$ 。**傅里叶红外光谱(FT-IR):** 在 Nicolet ET5700 型红外分光光度计上测定, 通过溴化钾压片法制样, 扫描范围为 400~4000 cm^{-1} 。**热重-差热分析(TG-DTA):** 在 Netzsch STA-449C 测试仪上进行, 从室温加热至 700 °C, 升温速率 10 °C/min。**扫描电子显微镜(SEM):** 使用日立 S-3400N 型扫描电子显微镜进行测试, 电压 15 kV, 电流 20 mA。**可见-近红外光谱:** 使用 PerkinElmer LAMBDA 1050+ 型紫外-可见-近红外光谱仪, 波长范围 400~2500 nm。**色差仪(Colorimeter):** 使用美能达 CM-5 型色差仪, 亮度(L^* 值)、绿色-红色轴的分量(a^* 值)、蓝色-黄色轴的分量(b^* 值)的色空间, 波长范围为 380~780 nm。**热成像相机(Thermal Imaging Camera):** 型号(FLIR Sc1050t), 热成像测温, 8~14 μm 红外波段。

2 结果与讨论

2.1 类水滑石的结构

2.1.1 类水滑石的物相组成与结构 图 1a 是硫酸根插层镁铬类水滑石($\text{MgCr-SO}_4^{2-}\text{-LDHs}$)、硫酸根插层镁铁类水滑石($\text{MgFe-SO}_4^{2-}\text{-LDHs}$)和硫酸根插层镁铝类水滑石($\text{MgAl-SO}_4^{2-}\text{-LDHs}$) 的 XRD 谱。XRD 谱中(003)、(006)、(009)面网衍射角呈倍数关系, 体现了层状类水滑石材料的特征衍射峰^[13]。相对而言, 镁铝水滑石的衍射峰强度最高, 镁铬类水滑石的衍射峰强度次之。图 1b 为改变层间阴离子后, 碳酸根插层镁铬类水滑石($\text{MgCr-CO}_3^{2-}\text{-LDHs}$)、

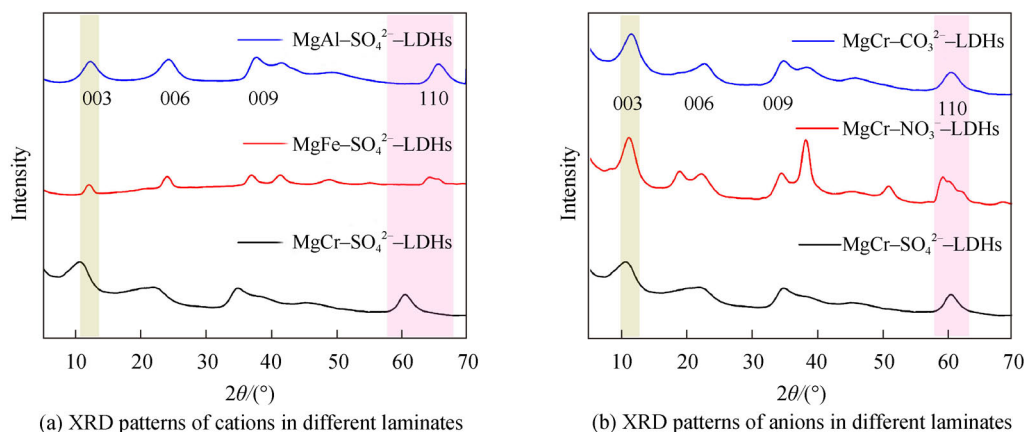


图 1 不同层板阳离子与层间阴离子类水滑石的 XRD 谱

Fig. 1 XRD patterns of different layer cations and intercalated anions of hydrotalcites

硝酸根插层镁铬类水滑石(MgCr-NO₃⁻-LDHs)和硫酸根插层镁铬类水滑石(MgCr-SO₄²⁻-LDHs)的 XRD 谱。3 种类水滑石样品中,硫酸根插层镁铬类水滑石(003)晶面衍射强度较低,峰型较宽,由谢乐公式

$$(D = \frac{K \cdot \lambda}{\beta \cdot \cos \theta}) \text{ 可知, 类水滑石颗粒尺寸相对较小。}$$

根据布拉格公式($2d \sin \theta = \lambda$, d 为晶面间距; θ 为衍射半角; λ 为波长)^[14]计算类水滑石晶胞参数,列入表 1 中,从表 1 中可以看出,MgCr-SO₄²⁻-LDHs [$d_{(003)} = 8.32 \text{ \AA}$]、MgFe-SO₄²⁻-LDHs [$d_{(003)} = 7.74 \text{ \AA}$] 和 MgAl-SO₄²⁻-LDHs [$d_{(003)} = 7.60 \text{ \AA}$] 中, MgCr-SO₄²⁻-LDHs 的层间距最大,由于三价铬离子尺寸较大,增大了八面体及八面体层厚度,从而导致其层间距增大^[15],较大的层间距有利于类水滑石存储层间水分子。在 MgCr-CO₃²⁻-LDHs [$d_{(003)} = 7.72 \text{ \AA}$]、MgCr-NO₃⁻-LDHs [$d_{(003)} = 7.95 \text{ \AA}$] 和 MgCr-SO₄²⁻-LDHs [$d_{(003)} = 8.32 \text{ \AA}$] 中,由于层间阴离子为-2 价,当插层阴离子个数较少时,层间空隙较大,能储存更多的层间水分子^[16],可以更好地模拟植物在 1400~1900 nm 间的近红外水吸收峰特征。

表 1 根据 XRD 谱计算类水滑石晶面间距和晶格参数

Table 1 Calculation of interlayer spacing and lattice parameters from XRD patterns

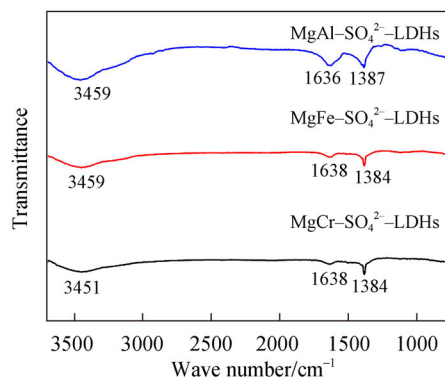
Samples	$d_{(003)}/\text{\AA}$	$d_{(110)}/\text{\AA}$	$a/\text{\AA}$	$c/\text{\AA}$
MgCr-SO ₄ ²⁻ -LDHs	8.32	1.52	3.05	24.98
MgFe-SO ₄ ²⁻ -LDHs	7.74	1.55	3.10	23.24
MgAl-SO ₄ ²⁻ -LDHs	7.60	1.52	3.04	22.81
MgCr-CO ₃ ²⁻ -LDHs	7.72	1.52	3.05	23.16
MgCr-NO ₃ ⁻ -LDHs	7.95	1.55	3.11	23.85

$d_{(003)}$ is Crystal plane spacing of crystal plane with Miller index (003); $d_{(110)}$ is Crystal plane spacing of crystal plane with Miller index (110); a is Lattice constant in the basal plane; c is Lattice constant in interlayer direction.

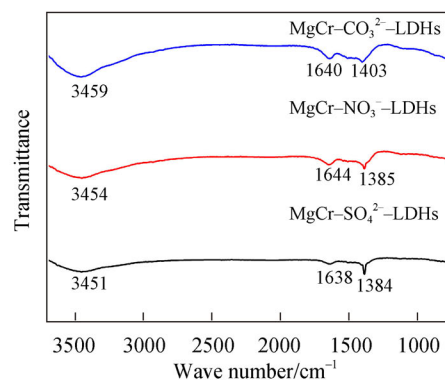
2.1.2 类水滑石的基团性质 图 2 为不同阳离子和阴离子插层类水滑石的 FT-IR 光谱。由于类水滑石存在层间水和层板羟基,在 3200~3600 cm⁻¹ 区域出现了较宽的—OH 红外伸缩吸收峰;在 1600 cm⁻¹ 附近区域中出现的吸收峰,归属于类水滑石中存在结晶水的—OH 弯曲振动峰;在 1380 cm⁻¹ 附近区域出现的吸收峰是因类水滑石中层间阴离子(NO₃⁻和 CO₃²⁻)的伸缩振动而产生。

2.1.3 镁铬类水滑石及丛林伪装涂层的形貌 图 3 为镁铬类水滑石和镁铬类水滑石包覆 Cr₂O₃ 颜料的 SEM 照片。图 3a 为合成的 MgCr-SO₄²⁻-LDHs,材料呈蓝紫色,SEM 照片中显示类水滑石呈现团聚状态、表面有部分细小颗粒物。图 3b 为 MgCr-SO₄²⁻-

LDHs@Cr₂O₃ 的 SEM 照片,当类水滑石包覆铬绿后,样品呈现明显的绿色,并伴有 500~800 nm 的细微颗粒物包覆在类水滑石表面。

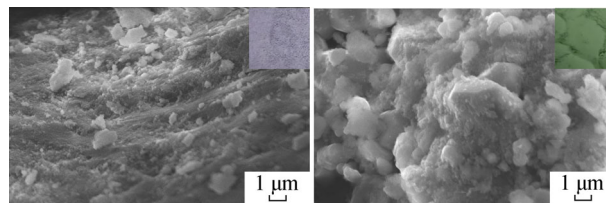


(a) FT-IR spectra of hydrotalcite like compounds intercalated with different cations



(b) FT-IR spectra of hydrotalcite like compounds intercalated with different anions

图 2 不同阳离子和阴离子插层类水滑石的 FT-IR 光谱
Fig. 2 FT-IR spectra of different cations and anions intercalated hydrotalcites



(a) MgCr-SO₄²⁻-LDHs (b) MgCr-SO₄²⁻-LDHs@Cr₂O₃

图 3 类水滑石的 SEM 照片

Fig. 3 SEM images of hydrotalcites

2.1.4 镁铬类水滑石及丛林伪装涂层的热相变 由于伪装涂层的近红外水吸收峰大小与绿色植被的含水量相对应,TG-DTA 技术可以表征类水滑石受热后吸附水、结晶水和层板羟基脱水状况。图 4a~图 4c 分别为 MgCr-SO₄²⁻-LDHs、MgFe-SO₄²⁻-LDHs 和 MgAl-SO₄²⁻-LDHs 的 TG-DTA 曲线,由于类水滑石中存在层间水,在 25~300 °C 时样品出现明显的质量损失,对应类水滑石吸附水、结晶水和层板中

的羟基(结构水)吸热峰。 MgCr-SO_4^{2-} -LDHs 的质量损失比例最大为 26.38%，说明含水量最大，与 XRD 分析层间距最大相一致。在图 4d~图 4e 中，第 1 阶段 MgCr-SO_4^{2-} -LDHs 的质量损失比例大于 MgCr-CO_3^{2-} -LDHs 和 MgCr-NO_3^- -LDHs，同时也

说明 3 种阴离子中，硫酸根插层类水滑石后，类水滑石样品的含水量更大。在 300~600 °C 之间的质量损失峰，会发生类水滑石层板的坍塌及其对应层间阴离子的分解。在超过 600 °C 后，类水滑石会转化为其氧化物，并伴随着质量的损失。

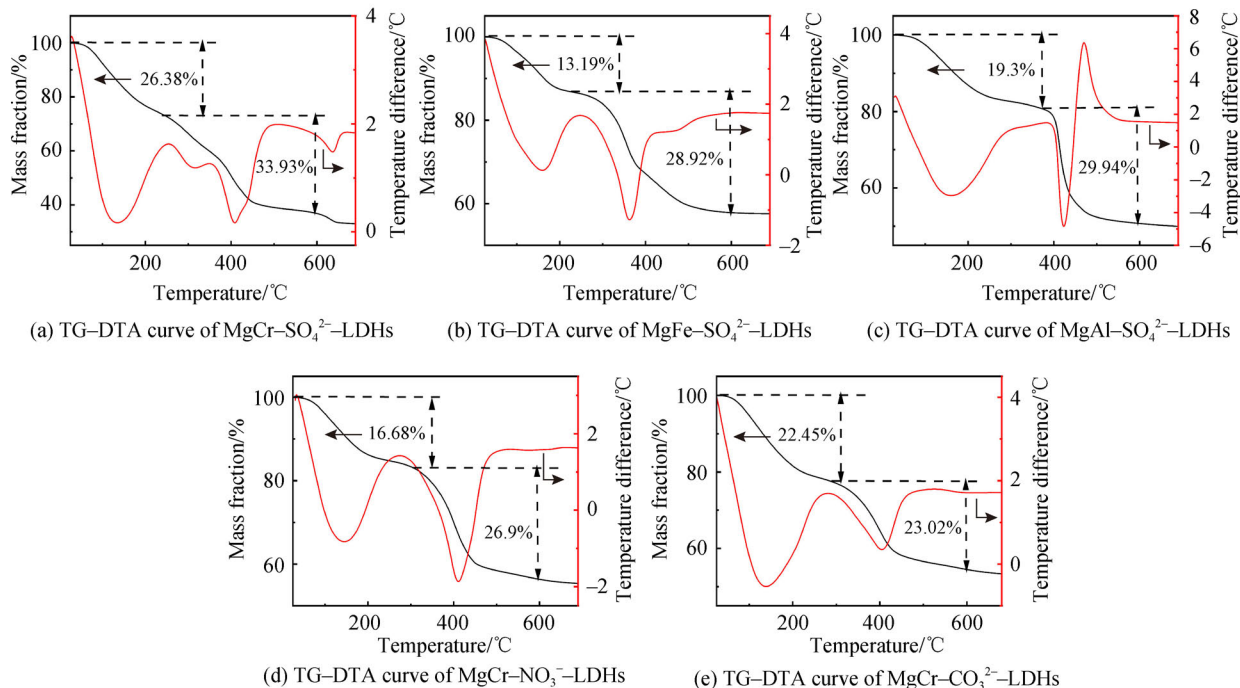


图 4 类水滑石的 TG-DTA 曲线
Fig. 4 TG-DTA curves of hydrotalcites

2.2 实验样品的可见-近红外光谱

不同的层板阳离子和层间阴离子调变会对类水滑石近红外水吸收峰产生影响^[17]。如图 5a 所示，当金属离子调变后，Mg/Cr 组合在 1400 nm 和 1900 nm 附近的近红外水吸收峰最大，Mg/Al 次之，并且镁铬类水滑石还在 490 nm 处出现了蓝峰。 Cr^{3+} 取代 Al^{3+} 之后，由于类水滑石层间距增大

而导致层间水含量增加，引起近红外水吸收峰增强。而在层间阴离子调变后，图 5b 所示的样品光谱图中，硫酸根离子具备更加优异的近红外水吸收峰特征，硝酸根次之，碳酸根插层类水滑石的近红外水吸收峰最小，因此本工作选择 MgCr-SO_4^{2-} -LDHs 作为模拟植物光谱特征的水峰模拟材料。

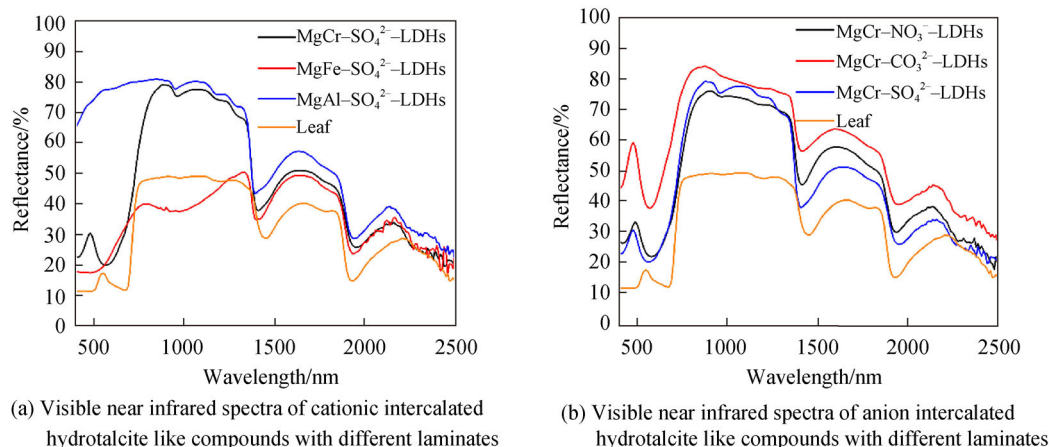
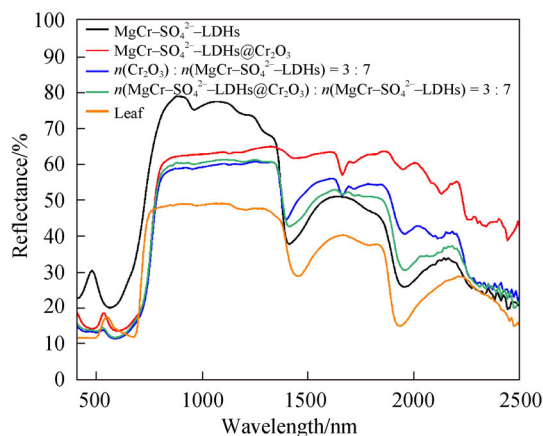


图 5 不同层板阳离子和层间阴离子插层类水滑石的可见-近红外光谱
Fig. 5 Vis-NIR spectra of different layer metal cations and interlayer anions of hydrotalcites

2.3 涂层光谱相似度计算

为了匹配绿色植被 550 nm 左右的绿峰特征,选择在 Cr_2O_3 基础上包覆硫酸根插层镁铬类水滑石 ($\text{MgCr-SO}_4^{2-}\text{-LDHs@Cr}_2\text{O}_3$), 如图 6 所示。在加入铬绿颜料后, 有效改善了类水滑石的绿峰特征, 但由于铬绿的颗粒较小, 会遮盖类水滑石的近红外水吸收峰特征。因此, 本工作将 $\text{MgCr-SO}_4^{2-}\text{-LDHs}$ 包覆 Cr_2O_3 后, 与 $\text{MgCr-SO}_4^{2-}\text{-LDHs}$ 进行拼混后制备伪装涂层, 在保持绿峰特征的同时, 可显著提升光谱近红外水吸收峰效果。



n is in mole.

图 6 涂层改善过程及植物树叶的可见-近红外光谱
Fig. 6 Coating improvement process and visible-near-infrared spectra of plant leaves

为了计算伪装涂层和绿色植被的光谱相似度, 引入了光谱相似度(SCC)、信息分散度(SID)的计算方法(已做标准化处理)^[9], 计算结果列入表 2 中。将伪装涂层与常见植被在 400~2500 nm 的近红外光谱相似度进行对比。 $\text{MgCr-SO}_4^{2-}\text{-LDHs@Cr}_2\text{O}_3$ 的光谱相似度为 86.69%, $n(\text{Cr}_2\text{O}_3):n(\text{MgCr-SO}_4^{2-}\text{-LDHs})=3:7$ 的光谱相似度为 90.91%, 当铬绿用类水滑石包覆后再与类水滑石混合制备的涂层相似度最高, 达到 95.8%, 分散度最低为 0.0983, 结果表明: $\text{MgCr-SO}_4^{2-}\text{-LDHs@Cr}_2\text{O}_3$ 和 $\text{MgCr-SO}_4^{2-}\text{-LDHs}$ 拼混后制备的伪装涂层具有优异的伪装性能。市场现有丛林伪装涂层主要考虑 400~1100 nm 波段的光谱模拟, 1100 nm 以上波段模拟材料的研究还不是很完善^[18, 19], 此外, 本工作研究的含铬体系有一定毒性, 后续进一步优化配方体系致力于无铬丛林伪装涂层材料及耐候性的研究。

2.4 伪装涂层的色度图和热成像特征

图 7 为 $\text{MgCr-SO}_4^{2-}\text{-LDHs}$ 、 $\text{MgCr-SO}_4^{2-}\text{-LDHs@Cr}_2\text{O}_3$ 、 $n(\text{Cr}_2\text{O}_3):n(\text{MgCr-SO}_4^{2-}\text{-LDHs})=3:7$ 、 $n(\text{MgCr-SO}_4^{2-}\text{-LDHs@Cr}_2\text{O}_3):n(\text{MgCr-SO}_4^{2-}\text{-LDHs})=3:7$

表 2 伪装涂层的光谱相似度(SCC)和信息分散度(SID)

Table 2 Spectral correlation coefficient (SCC) and spectral information divergence (SID) of comparing camouflage coatings with leaf

Different camouflage coatings	SCC/%	SID
$\text{MgCr-SO}_4^{2-}\text{-LDHs@Cr}_2\text{O}_3$	86.69	0.17
$n(\text{Cr}_2\text{O}_3):n(\text{MgCr-SO}_4^{2-}\text{-LDHs})=3:7$	90.91	0.12
$n(\text{MgCr-SO}_4^{2-}\text{-LDHs@Cr}_2\text{O}_3):n(\text{MgCr-SO}_4^{2-}\text{-LDHs})=3:7$	95.80	0.09

$\text{LDHs})=3:7$ 和植物叶片的 CIE chromaticity diagram 色度图, 图 7 中各个涂层的颜色存在明显的差异。涂层的颜色 Laboratory test 测试值列入表 3 中, $\text{MgCr-SO}_4^{2-}\text{-LDHs}$ 的 L^* 值最高为 57.3, 亮度最高, 其他 3 种涂层较树叶颜色偏暗; 4 种涂层的 a^* 值都小于植物的 a^* 值(-0.05), 说明所制备的涂层都偏绿色, 其中: $n(\text{MgCr-SO}_4^{2-}\text{-LDHs@Cr}_2\text{O}_3):n(\text{MgCr-SO}_4^{2-}\text{-LDHs})=3:7$ 的 b^* 值为 -2.52, 最接近植物的 b^* 值(-3.15), 该涂层整体与植物色差最接近。

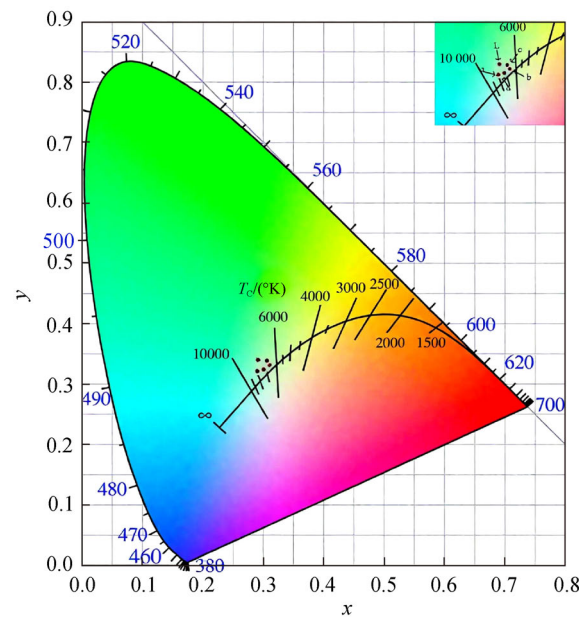


图 7 伪装涂层的色度图

Fig. 7 Chromatic diagram of camouflage coatings

表 3 伪装涂层的 Lab 颜色值

Table 3 The color parameters Lab of camouflage coatings

Samples	L^*	a^*	b^*
$\text{MgCr-SO}_4^{2-}\text{-LDHs}$	57.3	-4.76	-5.14
$\text{MgCr-SO}_4^{2-}\text{-LDHs@Cr}_2\text{O}_3$	46.22	-4.08	-0.75
$n(\text{Cr}_2\text{O}_3):n(\text{MgCr-SO}_4^{2-}\text{-LDHs})=3:7$	41.85	-1.34	-0.04
$n(\text{MgCr-SO}_4^{2-}\text{-LDHs@Cr}_2\text{O}_3):n(\text{MgCr-SO}_4^{2-}\text{-LDHs})=3:7$	42.81	-1.84	-2.52
Leaf	52.02	-0.05	-3.15

L^* is lightness; a^* is green-component of the red axis; b^* is blue-yellow axis component; Leaf is plant leaf.

使用热成像仪对伪装涂层与植物测试热成像图进行对比,如图8所示。图8a和图8b中将伪装涂层做成树叶形状放入树丛以及多种树叶之中,其热成像

图与植物树叶没有显著差异。图8c中将伪装涂层与形状相似的植物放在手臂上对比,伪装涂层呈现清晰的热成像图,说明伪装涂层具有优异的热遮盖能力。

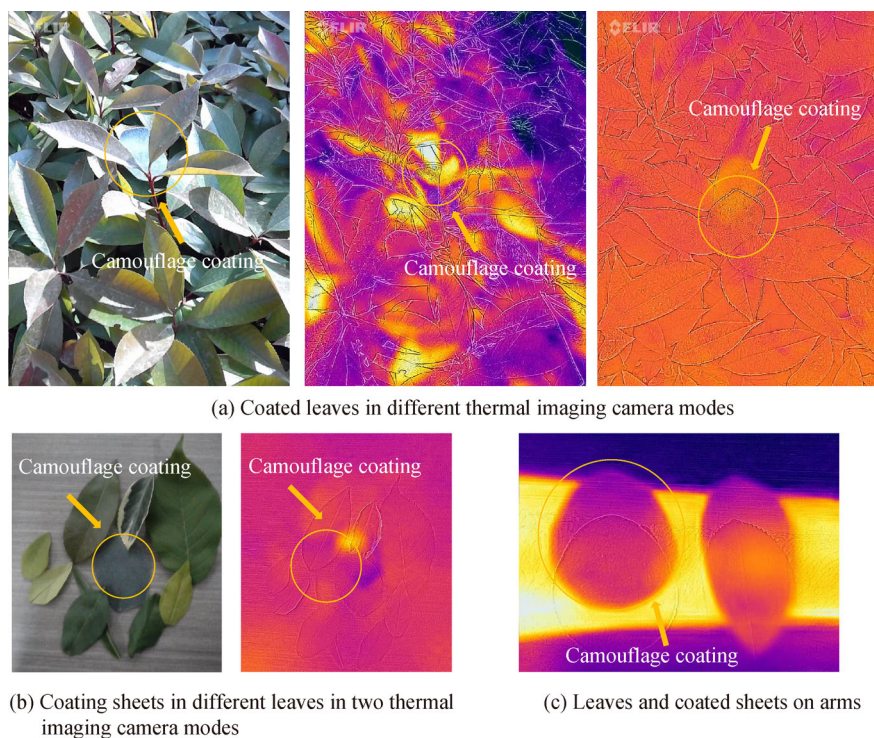


图8 伪装涂层的热成像图

Fig. 8 Thermodynamic imaging diagram of camouflage coating

3 结论

本工作通过共沉淀法制备硫酸根插层镁铬类水滑石等6种类水滑石材料,并应用XRD、FT-IR、SEM、TG-DTA等手段对合成材料进行结构表征,合成材料具有典型的层状水滑石结构,其中硫酸根插层镁铬类水滑石的层间距最大,热质量损失最多,其对应层间存储水分子最多。可见-近红外光谱测试结果表明,镁铬类水滑石显示了490 nm处的蓝峰和1400、1900 nm处的近红外水峰,通过 MgCr-SO_4^{2-} -LDHs包覆 Cr_2O_3 后可形成绿色特征的丛林伪装涂层绿峰模拟材料。优化的 $n(\text{MgCr-SO}_4^{2-}\text{-LDHs@Cr}_2\text{O}_3):n(\text{MgCr-SO}_4^{2-}\text{-LDHs})=3:7$ 比例制备的伪装涂层,绿峰、近红外吸水特征峰均实现与天然植物叶片的高精度匹配,光谱相似度高达95.80%,且热成像测试与植被结果无差异。本工作对颜色和近红外水峰双功能材料的研究,对丛林伪装涂层开发具有较高的参考意义。

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Visible-Near Infrared Spectroscopy Simulation of Jungle Camouflage Coating based on Hydrotalcites Containing Magnesium

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Extended Abstract

Introduction The rapid development and practical deployment of hyperspectral detection technology render conventional camouflage materials increasingly inadequate for covert protection in complex forest environments, primarily due to their insufficient spectral matching and limited functionality. A critical challenge in forest camouflage lies in the accurate replication of four characteristic spectral signatures of natural vegetation, i.e., the green peak, the red edge, the near-infrared plateau, and the near-infrared water absorption peak. These features form the unique spectral “fingerprint” of vegetation, which serves as a fundamental basis for evading multi-band, high-precision detection. Among them, the green peak governs a visual concealment within the visible region, while the near-infrared water absorption peak acts as a decisive marker for distinguishing vegetation from artificial materials, which are essential for effective camouflage. However, the existing forest camouflage paints and simulation materials are constrained by inadequate structural design and limited functional integration. Most commercially available products can only partially mimic certain spectral traits of vegetation and commonly exhibit deficiencies in core performance. Note that it remains particularly difficult to simultaneously and accurately match both the green peak of healthy foliage and the near-infrared water absorption peak. This shortfall makes such materials susceptible to rapid identification under hyperspectral imaging, thereby severely limiting the practical effectiveness of the existing forest camouflage technologies. Consequently, there is an urgent need for the research and development of novel camouflage materials capable of comprehensive spectral simulation.

Methods Six types of sulfate intercalated Mg/Cr layered double hydroxides (LDHs) were synthesized by a coprecipitation method. The crystalline structure of the as-prepared materials was examined by X-ray diffraction (XRD). The molecular structures and characteristic absorption features were determined by Fourier-transform infrared spectroscopy (FT-IR). The thermal decomposition behavior and mass loss profiles were analyzed by thermogravimetry–differential thermal analysis (TG–DTA). The surface morphology and particle size distribution were characterized by scanning electron microscopy (SEM). These characterization

techniques provided a comprehensive structural and physicochemical profile of the synthesized LDHs. Subsequently, to meet the requirement of reproducing the green spectral peak in jungle camouflage, a functional camouflage coating was fabricated via blending the optimized LDHs material with chromium-based green pigment. This formulation enhanced the green-peak characteristics in the visible region and preserved the pronounced water-absorption peak in the near-infrared range. The spectral performance of the coating was evaluated by visible–near-infrared spectroscopy (Vis–NIR), and its thermal camouflage capability was assessed by infrared thermographic imaging.

Results and discussion The results systematically indicate that a series of chromium-containing hydrotalcite materials, prepared by a controlled synthesis process, exhibit typical crystalline structural characteristics of layered double hydroxides (LDHs). The XRD patterns reveal sharp and symmetric diffraction peaks, with the characteristic peaks corresponding to the layered structure displaying a high intensity and a regular shape, indicating a good crystallinity and a well-ordered interlayer arrangement. Among the series of chromium-containing hydrotalcites, sulfate-intercalated magnesium chromium hydrotalcite (MgCr-SO_4^{2-} -LDHs) demonstrates unique structural advantages, *i.e.*, its interlayer spacing is significantly larger than that of other intercalated types of magnesium chromium hydrotalcites. Simultaneously, The TG–DTA thermal analysis indicates that this material exhibits the maximum mass loss of 26.38% at 25–400 °C. This is directly related to the content of water molecules stored within the interlayers. The spatial configuration and charge distribution characteristics of the sulfate intercalation ions provide a sufficient space for the stable adsorption and storage of water molecules. As a result, MgCr-SO_4^{2-} -LDHs possesses the most abundant interlayer water content among the prepared samples. This rich interlayer water constitutes the core structural basis for simulating the near-infrared water absorption peak of vegetation. The visible to near-infrared spectra (400–2500 nm) further reveal the optical properties of the Mg/Cr hydrotalcite. In the visible region, the material shows a distinct characteristic absorption peak at 490 nm (blue region), attributed to its intrinsic electronic transition behavior. In the near-infrared region, intense and sharp water absorption peaks clearly occur at approximately 1400 nm and 1900 nm, showing a high similarity to the near-infrared water absorption features of natural vegetation leaves. Sulfate-intercalated magnesium chromium hydrotalcite (MgCr-SO_4^{2-} -LDHs) is modified with chromium(III) oxide (Cr_2O_3) by an *in-situ* coating process via leveraging these characteristics. The near-infrared water absorption properties imparted by the abundant interlayer water in MgCr-SO_4^{2-} -LDHs were combined with the green optical characteristics of Cr_2O_3 . This complementary interaction successfully offset the influence of the intrinsic blue absorption peak at 490 nm from the magnesium chromium hydrotalcite. Ultimately, a jungle camouflage coating simulation material is prepared, having both green visual characteristics and distinct near-infrared water absorption peaks. This provides a key material foundation for subsequent high-similarity spectral matching with natural vegetation.

Conclusions The camouflage coating fabricated with an optimal MgCr-SO_4^{2-} -LDHs@ Cr_2O_3 : MgCr-SO_4^{2-} -LDHs ratio of 3 : 7 could enable a precise spectral matching with natural vegetation leaves. It accurately replicated both the green peak and the near-infrared water absorption peak, achieving a spectral similarity of up to 95.80%. Furthermore, the results of thermal imaging tests revealed no significant difference between the coating and natural vegetation. This study on dual-functional materials that simulated color and the near-infrared water absorption peak could thus offer a promising direction for the development of advanced vegetation camouflage technologies.

Keywords jungle camouflage coating; green vegetation; water absorption peak; hydrotalcite; spectral similarity