

• 水工岩石力学 •

DOI:10.12454/j.jsuese.202400922



本刊网刊

## 固废基胶凝材料固化盾构渣土的作用机理及路用性能

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**摘要:**盾构施工产生的高含水率、高压缩性渣土难以满足路基填料要求,亟需研发低碳、经济、高效的固化改性材料以实现盾构渣土的资源化利用。本文选用电石渣、赤泥、矿粉、脱硫石膏制备盾构渣土固化用固废基胶凝材料(CRGD),通过无侧限抗压强度(UCS)、水稳定性、加州承载比(CBR)值及孔结构的测试分析,探究了固废基胶凝材料与石灰两种固化剂对盾构渣土的固化效果,并通过扫描电子显微镜-能谱分析仪(SEM-EDS)、X射线衍射(XRD)等手段揭示了固废基胶凝材料对盾构渣土的固化机理。试验结果表明:1)CRGD固化盾构渣土的UCS、水稳定系数、CBR值及经济效益均显著优于石灰;2)养护28 d,掺量为7%的CRGD固化渣土UCS可达4.15 MPa,水稳定系数达83%,较石灰固化渣土提高了20%;3)与未经处理的盾构渣土相比,4%掺量的CRGD固化渣土CBR值可达58.14%,提高了17.40倍,远超规范要求。SEM-EDS、XRD及孔结构分析结果显示,固废基胶凝材料主要水化产物为C-(A)-S-H凝胶、钙矾石等,该材料优化了固化土基体孔隙结构,减小了基体内部的孔隙体积。研究结果可为盾构渣土及工业固废在道路工程中的资源化利用提供参考。

**关键词:**盾构渣土;路基;固废基胶凝材料;加州承载比;水稳定性

**中图分类号:**U416.1

**文献标志码:**A

**文章编号:**2096-3246(2026)01-0156-11

盾构法因其精度高、环境影响小和施工快等优势,被广泛用于隧道施工,但也随之产生了大量的盾构渣土<sup>[1]</sup>。据统计,中国每年产生的盾构渣土在1.19亿t以上<sup>[2]</sup>。在盾构掘进过程中,盾构机常常需要穿越高富水的粉质黏土层、胶结砾岩和闪长岩等复杂地质条件,这使渣土中含有较多的水分和细颗粒。为了提高开挖效率,施工过程中通常添加水、膨润土、泡沫剂或高分子材料等改性剂,以改善土体的塑性、流动性、止水性和保水性<sup>[3-5]</sup>。然而,这些改性剂会改变原有土体性质,进一步导致盾构渣土含水率提高、压缩性增大,从而使后续处理更加困难。目前,中国盾构渣土资源化利用率不足5%<sup>[6]</sup>。盾构渣土主要通过露天堆放或简单填埋处理,严重占用土地资源并可能造成环境污染<sup>[2]</sup>。因此,提升盾构渣土资源化利用率具有重要的现

实意义和应用价值。

盾构渣土由多种粒径的土、碎石或混合碎石构成,具备制备盾构施工辅助材料、再生骨料、工程填料的潜力。Zhang<sup>[7]</sup>、钱鑫<sup>[8]</sup>等验证了将盾构渣土制作成同步注浆材料的可行性;张宁等<sup>[9]</sup>以淤泥质粉质黏土地层中产生的废弃泥浆为基础材料,配置了施工需要的泥浆配方。然而,仅砂土、黏土等细颗粒渣土可用作盾构施工辅助材料,且材料的理想性能受地层土质的影响,需要的渣土规模有限,渣土利用率较低。从盾构渣土中回收符合特定性能标准的砂石颗粒,可以将其用作再生骨料,并进一步用于制造混凝土、砂浆及骨料砌块等产品<sup>[10-11]</sup>;或通过烧制过程将盾构渣土转化为建筑产品,如砖、陶粒和砌块<sup>[12]</sup>。盾构渣土的烧制重塑不可避免地会导致能源的次生浪费,并且在烧制过

收稿日期:2024-11-07 修回日期:2024-12-23 网络出版日期:2024-12-26

基金项目:“十四五”服务山东重点建设项目(2023ZLGX01);国家重点研发计划资助项目(2022YFB2601903);山东省竞争性创新平台项目(2023CXPT080);国家自然科学基金青年项目(52309136);山东省自然科学基金青年项目(ZR2022QE119);山东省博士后创新项目(SDCX-ZG-202203037)

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程中产生的碳排放量难以符合环保标准,因此难以被广泛应用。

将盾构渣土用于路基土回填是实现其大宗量资源化利用的有效途径。盾构渣土的特点是含水率高且压缩性大,未经处理直接用作路基填料难以满足建设性能要求,但经过固化改性后,可满足路基填筑的基本要求<sup>[13-14]</sup>。水泥和石灰等固化材料在土体固化中得到了广泛应用。水泥基固化剂能够显著提升土体的强度和稳定性,从而增强工程的安全性及可靠性<sup>[15]</sup>;石灰则能够与黏土矿物发生絮凝和固化作用,从而改善不良土的物理和力学特性<sup>[16-17]</sup>。然而,水泥的生产过程需要消耗大量的能源,并伴随显著碳排放。同时,仅使用水泥或石灰作为固化剂时,在复杂的工程地质条件下,常常面临强度不足和稳定性差等问题。因此,随着工程需求的多样化和对环境保护要求的不断提高,亟需寻找一种环保的新型功能材料。

利用工业固废材料制备的土体固化剂具有绿色低碳、低成本、高性能的优势,是当前研究的热点<sup>[18-19]</sup>。刘宇翼等<sup>[20]</sup>总结了国内外的相关成果,指出电石渣的主要成分及其含量与石灰相似,且电石渣固化土在工程性能方面优于石灰土,在土体固化时,可以完全替代石灰和水泥等胶凝材料。Wu等<sup>[21]</sup>以电石渣、粒化高炉矿渣、粉煤灰为组分,制备全固废胶凝材料,通过无侧限抗压强度和微观试验,揭示了全固废胶凝材料固化土的力学性能和固化机理,结果表明,固化土的强度受碱激发剂含量和火山灰活性的影响显著,全固废胶凝材料固化土强度是水泥固化土的1.38~2.30倍。吴伟军等<sup>[22]</sup>对赤泥、电石渣和脱硫石膏在低液限粉土固化中的应用进行了探讨,重点分析了固化粉土的力学性能和耐久性的变化趋势,结果显示,赤泥复合固化土的劈裂强度和侧限抗压强度随着养护时间和固化剂掺量的增加而提升,掺入的固化剂在粉土中发生水化反应,生成C-S-H、C-A-H及钙矾石晶体,从而显著改善固化土的性能。

目前,固废基固化土方面已有较为系统的研究,但对固废改良盾构渣土作为路基填料的性能及其改良机理的研究尚不充分。基于此,本文采用电石渣、矿渣、赤泥和脱硫石膏制备固废基胶凝材料(CRGD)对盾构渣土进行固化并与传统固化材料石灰进行对比。通过击实试验、无侧限抗压强度(UCS)试验、水稳定性测试及加州承载比(CBR)试验评估固化渣土宏观路用性能。同时,利用低场核磁共振(LF-NMP)、X射线衍射(XRD)和扫描电镜(SEM)对固化渣土的产物和微观结构进行分析,揭示其固化机制。研究成果可为固废处理提供新的利用途径。

## 1 试验原料及方法

### 1.1 试验原料

试验用土为济南轨道交通4号线某区间掘进粉质黏土地层时产生的盾构渣土(STM)。原状盾构渣土颜色呈褐黄或棕黄色,状态为可塑状态-硬塑状态,土质均匀,含少量铁锰氧化物及结核、姜石,如附录A图A1所示。将取回的盾构渣土风干并粉碎后过4.75 mm标准筛备用。盾构渣土的基本物理性质见表1,根据现行国家标准<sup>[23]</sup>,判定盾构渣土的类别为低液限粉质黏土。盾构渣土的粒径分布曲线如图1所示,粉粒(0.002~0.075 mm)含量为76.14%,黏粒(<0.002 mm)含量为11.77%。通过X射线荧光光谱仪(XRF)获得了盾构渣土的化学组成,如附录A表A1所示,盾构渣土的成分以SiO<sub>2</sub>、Al<sub>2</sub>O<sub>3</sub>、Fe<sub>2</sub>O<sub>3</sub>为主,占总质量的90%以上;由XRD分析结果(附录A图A2)可知,渣土中的主要矿物成分为石英、低钠长石和白云母。

表1 盾构渣土的物理特性

Tab. 1 Physical properties of shield tunnel muck

| 比重/<br>(g·cm <sup>-3</sup> ) | 液限/%  | 塑限/%  | 塑性<br>指数 | 最佳<br>含水率/% | 最大干密度/<br>(g·cm <sup>-3</sup> ) |
|------------------------------|-------|-------|----------|-------------|---------------------------------|
| 2.48                         | 34.49 | 20.57 | 13.92    | 15.90       | 1.81                            |

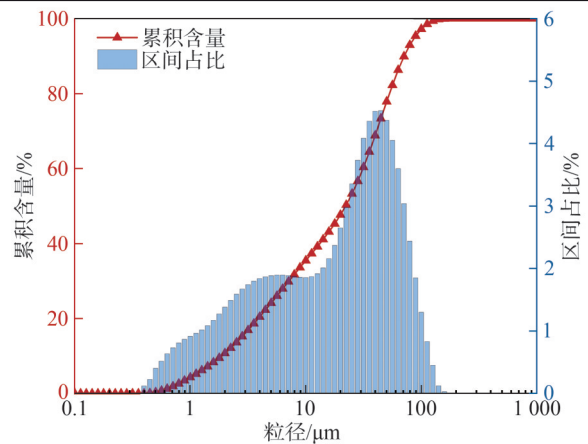


图1 盾构渣土的粒径分布曲线

Fig. 1 Particle size distribution curves of shield tunnel muck

选用山东境内常见的大宗固废赤泥、石膏、矿渣、电石渣作为原料,研制出一种固废基胶凝材料(CRGD)来固化盾构渣土。CRGD由38%电石渣(CS)、25%赤泥(RM)、25%粒化高炉矿渣粉(GGBS)、12%脱硫石膏(DG)组成(质量占比)。电石渣是电石水解获取乙炔气后的废渣,来自山东海天生物化工有限公司,呈干粉状态,粒径偏细,具有较高活性,其主要化学组成为CaO,含量为94%,并含有少量SiO<sub>2</sub>、Al<sub>2</sub>O<sub>3</sub>等杂质;电石渣的主要物相为Ca(OH)<sub>2</sub>,同时含有少量碳化形成的CaCO<sub>3</sub>。所用赤泥为拜耳赤泥,来自山东铝业股份有限公司,主要化学组成为Fe<sub>2</sub>O<sub>3</sub>、Al<sub>2</sub>O<sub>3</sub>、

SiO<sub>2</sub>, 主要矿物为赤铁矿、石英、三水铝石等。S95 级矿渣粉来自山东鲁碧建材有限公司, 主要化学成分为 CaO、SiO<sub>2</sub>、Al<sub>2</sub>O<sub>3</sub>、MgO, 矿物组成以非晶态的硅铝质组分为主, 含钙铝黄长石; 脱硫石膏来自山东魏桥集团有限公司, 化学成分以硫酸钙水合物为主, 同时含有少量的硅铝氧化物。在采用水泥作为盾构渣土的固化剂时, 土粒极易团聚造成材料难以混合均匀, 会严重影响试验结果准确性。鉴于此, 本文采用另一种广泛应用于固化土的材料——石灰, 作为对比试验组。试验用生石灰呈粉末状, CaO 含量 >95%。

通过 XRF、XRD 对 RM、GGBS、DG 和 CS 的化学组成及矿物组成进行分析, 结果如附录 A 表 A1 和图 A2 所示。

## 1.2 试验方法

### 1.1.1 击实试验

击实试验参照《公路土工试验规程》(JTG 3430—2020)<sup>[24]</sup>进行。采用 YDDJ-B 型数显多功能电动击实仪进行试验, 控制混合料含水率按 2% 递增, 将材料加入击实筒内分 5 层进行击实, 每层锤击 27 次。最终绘制击实曲线确定最大干密度和最佳含水率。

### 1.1.2 UCS 和水稳定性测定

按最佳含水率制备用于测定 UCS 和水稳定性的试件。具体参照《公路工程无机结合料稳定材料试验规程》(JTG E51—2019)<sup>[25]</sup>。制件时统一采用 96% 压实度, 每个掺量制备 6 个平行试样, 采用静压成型法制成  $\phi 50 \text{ mm} \times 50 \text{ mm}$  的圆柱形试件, 最后利用制件脱模一体机脱模。脱模后将试件密封并放入温度为  $(20 \pm 2) \text{ }^\circ\text{C}$ 、湿度为 95% 的标准养护室中养护至相应龄期。利用路面材料强度试验机进行 UCS 试验, 加载速率为  $1 \text{ mm/min}$ , 分别测定养护 7、14 及 28 d 龄期试件的强度, 剔除异常值后取平均值, 获得标准养护试件的无侧限抗压强度  $R_u$ 。

水稳定系数  $K$  是评价固化土抗水性的指标, 用以表征在浸水条件下强度的变化规律。在养护龄期的最后一天将 6 个试件浸泡在温度为  $(20 \pm 2) \text{ }^\circ\text{C}$  水中, 使水面超出试件顶部约 2.5 mm, 浸水 24 h 后取出试件并擦干表面水分, 然后在  $1 \text{ mm/min}$  的加载速率下测定试件饱水后的无侧限抗压强度  $R_w$ 。根据测试结果按式 (1) 计算水稳定系数  $K$ :

$$K = \frac{R_w}{R_u} \times 100\% \quad (1)$$

### 1.1.3 CBR 试验

参照文献[24]进行 CBR 试验, 获得固化渣土 CBR 值。设定压实度为 96%, 每个掺量按最佳含水率制备 3 个平行试件, 采用 YDDJ-B 型数显多功能电动击实仪

进行重型击实试验, 分 3 层成型, 将试件置于水槽中常温养护 4 d 后采用路面强度测定仪进行贯入试验, 测定其 CBR 值。

### 1.1.4 微观试验

通过 XRD、SEM-EDS、LF-NMR 等微观测试手段分析 CRGD 固化盾构渣土的反应机理及相关影响因素。将测完 UCS 的固化渣土试件破碎后取代表性样品烘干磨细过  $0.075 \text{ mm}$  筛, 采用 Rigaku Ultima IV 射线衍射仪测试样品图谱。测试靶材选择 Cu 靶, 扫描范围为  $5^\circ \sim 80^\circ$ , 扫描速率为  $5^\circ/\text{min}$ 。进行 SEM-EDS 测试时, 选取试件中间部分制成直径  $\leq 1 \text{ cm}$ 、厚度  $< 1 \text{ cm}$  的薄片, 将样品进行干燥处理, 测试时选择新鲜平整的表面为测试面, 喷金处理增加样品导电性, 并对关键区域进行点扫, 分析其化学元素组成, 试验设备为 TESCAN MIRA 场发射扫描电镜。LF-NMR 试验使用纽迈 MacroMR12-150H-I 核磁共振分析仪。将  $\phi 50 \text{ mm} \times 50 \text{ mm}$  的圆柱形试件养护至 28 d 龄期, 试验前将固化渣土试件置于压力  $10 \text{ MPa}$  的真空加压饱和装置中饱和 24 h, 然后将样品放入试样管中进行测试。试验完成后利用系统自带的分析软件进行反演, 导出试样的孔隙率及孔径分布。

上述试验流程如附录 A 图 A3 所示。

## 2 试验结果及分析

### 2.1 击实试验

不同固化剂掺量下固化渣土的击实试验结果如图 2 所示。由图 2 可知, 随着掺量的增加, 击实曲线整体朝着含水率增大、干密度减小的方向移动。固化材料与渣土颗粒充分混合发生表面接触后会消耗渣土颗粒表面的自由水、弱结合水发生水化反应, 同时, 固化材料还会与土中的硅铝质组分反应, 需要更多的水来参与, 加入的材料越多, 需水量越大, 因而最佳含水率 ( $w_{\text{opt}}$ ) 随掺量增加而增大。最大干密度 ( $\rho_{\text{dmax}}$ ) 随掺量增加而降低, 一方面是因为固化材料比重小于土粒比重, 混合后干密度自然会降低; 另一方面, 随掺量的增加, 固化材料与渣土反应生成的凝胶粘附在渣土颗粒的表面, 包裹土粒形成团粒改变了原有级配, 导致混合料干密度降低<sup>[26]</sup>。掺入 4% 的 CRGD 后, 盾构渣土的  $w_{\text{opt}}$  从 15.9% 增加至 17.9%,  $\rho_{\text{dmax}}$  从  $1.81 \text{ g/cm}^3$  降低至  $1.60 \text{ g/cm}^3$ 。掺入 4% 石灰后, 盾构渣土的  $w_{\text{opt}}$  增加至 19.9%,  $\rho_{\text{dmax}}$  降低至  $1.58 \text{ g/cm}^3$ 。在相同掺量条件下, 石灰固化渣土的  $w_{\text{opt}}$  高于 CRGD 固化渣土, 但是其  $\rho_{\text{dmax}}$  低于 CRGD 固化渣土。这是由于石灰与渣土颗粒发生反应, 土粒胶结产生团粒化, 原有的土壤结构发生改变, 团聚体内孔隙增多, 吸收了更多的水分, 土体持水能力增强<sup>[27]</sup>。

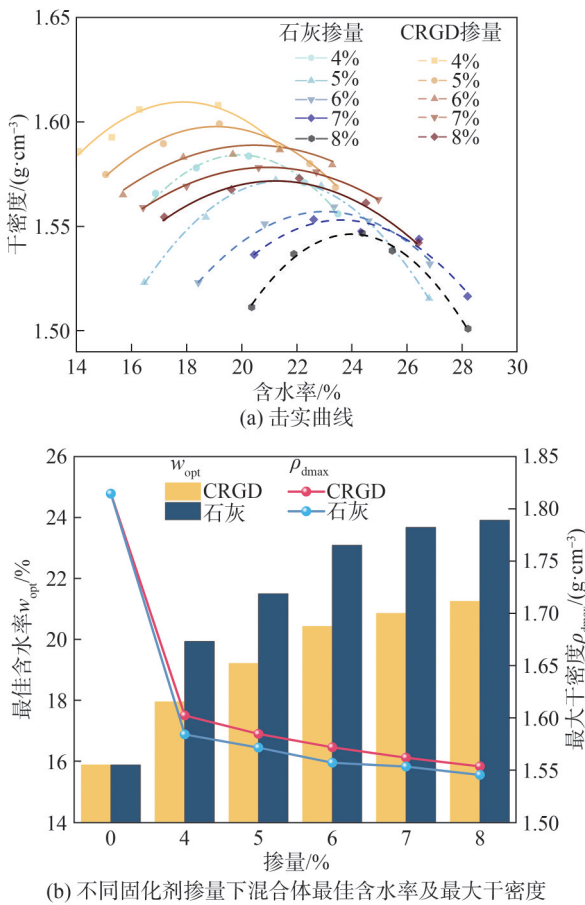


图 2 击实试验结果

Fig. 2 Compaction test results

2.2 UCS和水稳定性

掺量及养护时间对固化渣土 UCS 的影响如图 3 所示。由图 3 可知,未经固化的盾构渣土抗压强度仅为 0.718 MPa,不满足《土壤固化剂应用技术标准》(CJJ/T 286—2018)<sup>[28]</sup>中  $\geq 1.5$  MPa 的要求,无法满足工程建设需要。经固化后,UCS 显著提高,且随着掺量和养护龄期的增加而增加,CRGD 固化渣土的强度增幅比石灰固化渣土更为显著。与未固化渣土相比,养护 28 d 时,4%~8%CRGD 掺量的固化渣土 UCS 提升了 230.5%~525.1%,4%~8%石灰掺量的固化渣土 UCS 提升了 202.6~440.4%,CRGD 固化渣土 UCS 较石灰固化渣土提升了 9%~20%。7%掺量下,养护 28 d 的 CRGD 固化渣土 UCS 达 4.15 MPa,石灰固化渣土 UCS 为 3.47 MPa。主要是因为随着 CRGD 掺量的增加,反应原料增加,产生更多的胶凝物质与膨胀性产物,提高材料整体强度。随着养护龄期增长,反应程度加深,CRGD 水化生成更多的凝胶充填空隙;CRGD 还与渣土中的活性硅铝质反应生成 C-(A)-S-H 凝胶,促进土颗粒与水化产物胶结;部分  $\text{Ca}(\text{OH})_2$  与空气中的  $\text{CO}_2$  发生碳化作用,进一步提高了强度。随着养护龄期延长,石灰固化渣土的 UCS 增长缓慢,这是因

为早期主要发生离子交换反应, $\text{Ca}^{2+}$  替代低价阳离子,降低了结合水膜的厚度,增强了颗粒的密实程度,从而提高了早期强度。然而,在离子交换过程中,石灰中的  $\text{OH}^-$  和  $\text{Ca}^{2+}$  吸附于黏土颗粒表面,导致活性降低,仅部分  $\text{Ca}(\text{OH})_2$  与渣土中的  $\text{SiO}_2$ 、 $\text{AlO}_2$  发生火山灰反应生成 C-S-H、C-A-H,且火山灰反应速率缓慢<sup>[29]</sup>。

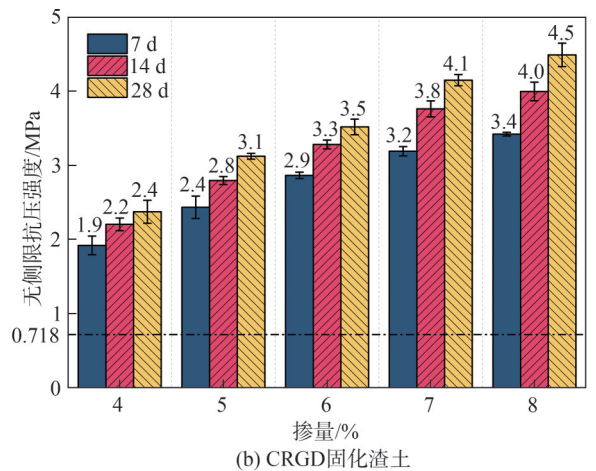
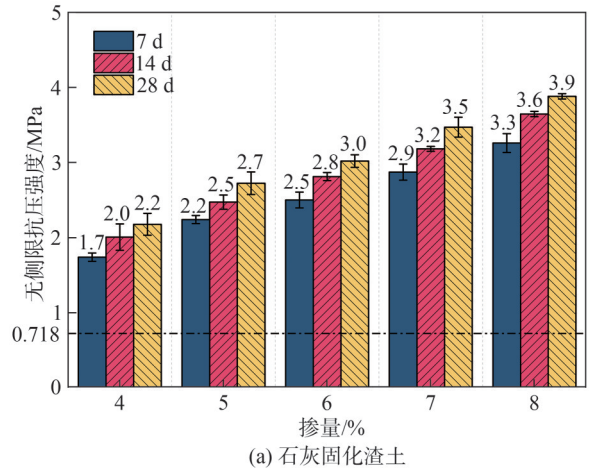


图 3 不同掺量下固化渣土的无侧限抗压强度

Fig. 3 Unconfined compressive strength of solidified muck under different dosage

试样浸水破坏过程见附录 A 图 A4。由附录 A 图 A4 可以看出,未经固化处理的盾构渣土水稳定性极差,试件浸水后无法保持完整性,短时间快速崩解,若直接将盾构渣土用于工程,可能会发生严重的路基沉降。这是因为渣土试件孔隙率大,水进入孔隙后破坏颗粒间结合,且浸水后土粒间结合水膜增厚的速度不同,产生应力集中,使得试件崩解<sup>[30]</sup>。由附录 A 图 A4(b)、(c)可知,固化后水稳定性显著增强,浸水 1 d 后试件完整性良好。图 4 为不同掺量下固化渣土的水稳定系数,由图 4 可知,经固化处理后的盾构渣土水稳定系数与 UCS 变化规律一致,同样随掺量与养护龄期增加而增大,CRGD 固化渣土水稳定系数显著高于

石灰固化渣土。7% 掺量下, 养护 28 d 的 CRGD 固化渣土水稳定系数达 83%, 超过标准<sup>[28]</sup>中  $\geq 80\%$  的要求, 较石灰固化渣土提高了 20%, 这表明 CRGD 对固化渣土水稳定性的提升效果更好。其原因除了 CRGD 水化反应生成 C-S-H 凝胶和 AFt 提高土体黏聚力, 增强体系性能之外, 部分 CRGD 和渣土发生反应也使得固化土结构更致密, 能够更好地抵抗水的侵蚀, 水稳定性更好<sup>[31]</sup>。

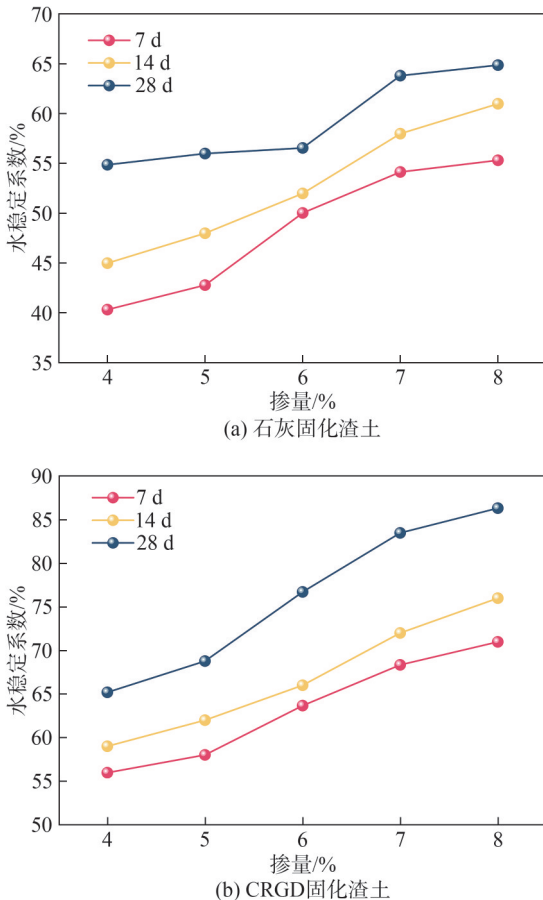


图4 不同掺量下固化渣土的水稳定系数

Fig. 4 Coefficients of water stability of solidified muck under different dosage

### 2.3 加州承载比(CBR)试验结果

CBR 值是评估土体道路使用性能的重要指标。未固化渣土的 CBR 值仅为 3.16%, 不满足《公路路基设计规范》(JTJ D30—2015)中  $CBR \geq 8\%$  的要求。盾构渣土未经固化时, 主要靠黏粒之间的吸附作用力将粉粒聚集在一起, 土体内部含有大量孔隙, 在水进入结构内部后, 结合水膜变厚, 黏聚力降低, CBR 值低。图 5 为不同 CRGD 掺量下固化渣土的 CBR 值拟合曲线。由图 5 可知, CRGD 掺量为 4% 时, CBR 值从 3.16% 增加到 58.14%, 相比未固化渣土提高了 17.40 倍; 石灰掺量为 4% 时, CBR 值为未固化渣土的 12.39 倍, 二者均远高于设计规范要求。CBR 值随掺量增加

而增大, 但增幅逐渐减小。相同掺量下, CRGD 固化渣土的 CBR 值高于石灰固化渣土, 二者差值随掺量增大。掺量为 8% 时, CRGD 固化渣土 CBR 值达 217.98%, 石灰固化渣土为 111.55%, 这表明 CRGD 固化渣土承载能力更优。采用 CRGD 固化后, CRGD 发生水化, 水化产物填充土体中的空隙形成更致密的结构, 而且还增强了颗粒间的结合<sup>[32]</sup>。此外, 碱性环境下, 材料浸水后解离出大量的  $Ca^{2+}$ ,  $Ca^{2+}$  置换土颗粒表面的  $Na^+$ ,  $K^+$ ,  $H^+$ , 减弱了土颗粒之间的静电斥力, 使得在击实过程中, 土体结构更加密实。最后, CRGD 中未反应的颗粒可以吸附在土颗粒表面, 起到填充孔隙的作用, 使土体强度增强。

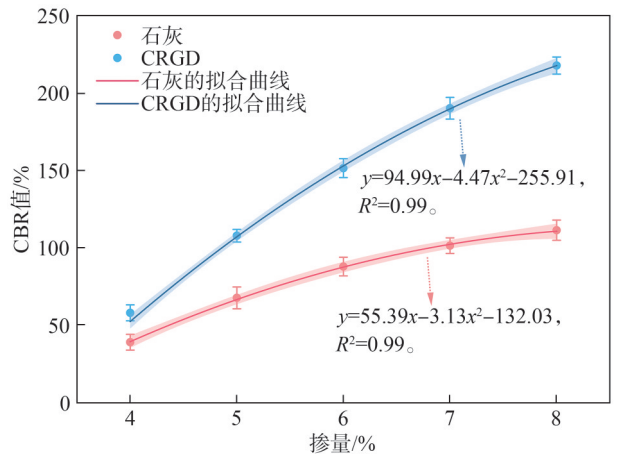


图5 不同掺量下固化渣土的 CBR 值拟合曲线

Fig. 5 CBR value fitting curves of solidified muck under different dosage

### 2.4 微观试验

#### 2.4.1 LF-NMR

图 6 为浸水后固化渣土试件的孔隙率, 孔隙率随石灰和 CRGD 掺量增加而降低, 整体变化幅度较小。对比两种材料, CRGD 水化生成更多的 C-S-H 和 C-A-S-H 凝胶, 且相互胶结填充孔隙, 因而 CRGD 固化渣土的孔隙率明显低于石灰固化渣土, 进一步解释了 CRGD 固化渣土强度和水稳定系数更高的原因。

浸水后, 石灰和 CRGD 固化渣土试件的孔径分布如图 7 所示。由图 7 可知, 两种固化渣土的孔径分布曲线都呈现出两个波峰, 孔隙主要分布在  $[0.001, 0.1) \mu m$  和  $[0.1, 1.0) \mu m$  两个区间, 主要以  $[0.001, 0.1) \mu m$  区间的孔隙为主。随着掺量增加, 峰值整体呈现向左的移动趋势, 即向孔隙减小的方向转移, 这表明随掺量增加, 反应产物逐步填充孔隙, 使得孔径减小。由图 7(b) 可知, 随着 CRGD 掺量增加,  $[0.001, 0.1) \mu m$  区间的孔隙相对减少,  $[0.1, 1.0) \mu m$  区间的孔隙则相对增加。这是因为 CRGD 水化反应生成更多胶凝产物, 胶结土粒发生团聚, 使得土颗粒间的微小孔隙数量减少, 土颗

粒间胶结更加紧密,但这也使得团聚形成的聚集体之间孔隙数量增加<sup>[33]</sup>。

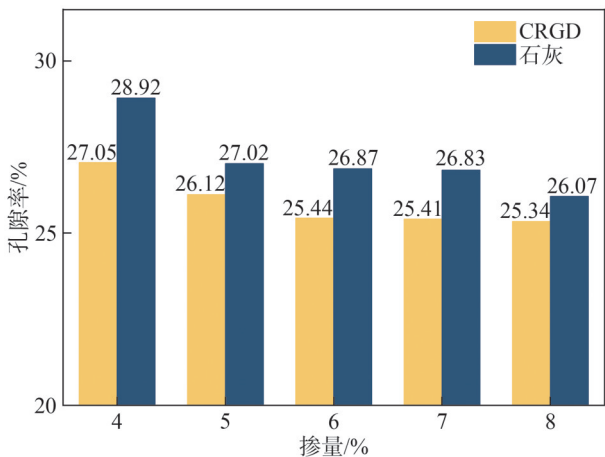


图 6 浸水后固化渣土试件的孔隙率

Fig. 6 Porosity of solidified muck specimen after soaking in water

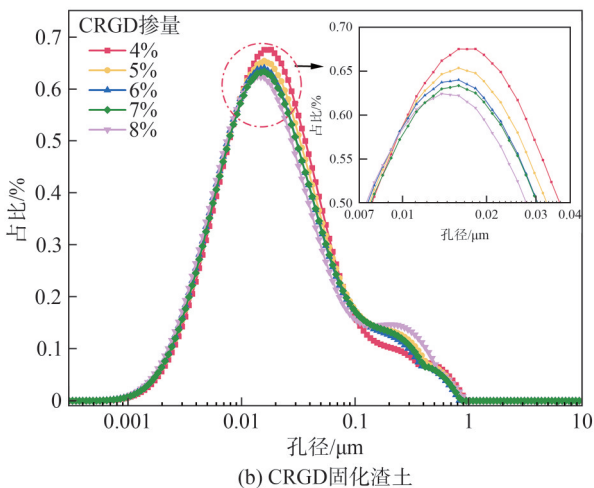
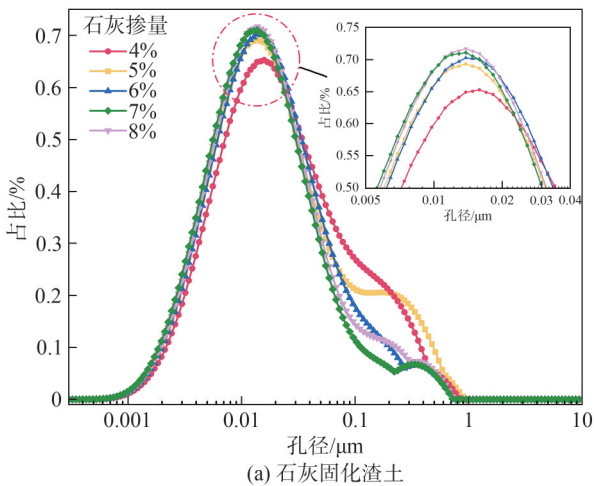


图 7 浸水后固化渣土试件的孔径分布

Fig. 7 Pore size distribution of solidified muck specimen after soaking in water

2.4.2 XRD

固化渣土的 XRD 图谱如图 8 所示。

由图 8 可知,经 CRGD 固化后,体系中生成了 CaCO<sub>3</sub>、AFt 及 C-(A)-S-H 凝胶等物相。与 STM 矿相相比,两种固化渣土中均出现了 CaCO<sub>3</sub>,CRGD 固化渣土体系中由于 CS 和 RM 的掺加使固化土体系碱性上升,从而与 CO<sub>2</sub> 发生碳化反应,CaCO<sub>3</sub> 在基体中通过挤压生长促进基体组分之间相互啮合,产生机械结合力,从而提高了力学性能。值得注意的是,固化材料的差别会对固化渣土体系的矿相组成产生影响,与石灰固化渣土相比,CRGD 固化渣土中还出现了 AFt,这说明该体系中的钙铝质活性物质与 DG 发生了反应,这也是导致 CRGD 固化渣土强度高于石灰固化土强度的重要原因。

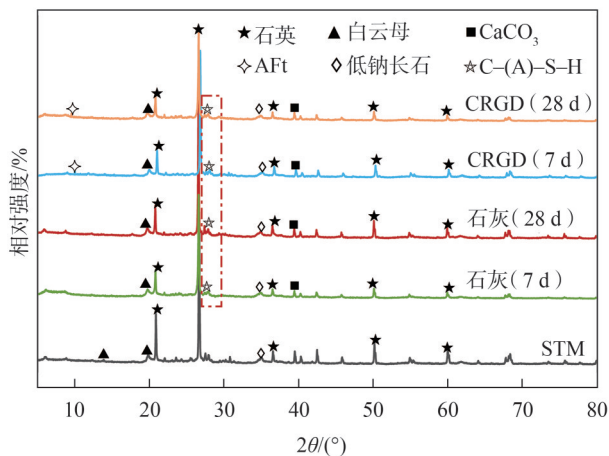


图 8 固化渣土的 XRD 图谱

Fig. 8 XRD patterns of solidified muck

2.4.3 SEM-EDS

盾构渣土及固化渣土的 SEM-EDS 图像如图 9 所示。固化渣土水化产物元素占比见表 2。STM 存在较多的孔洞和裂隙,在加入石灰进行固化后,可以观察到孔洞和裂隙减少,土体表面较为光滑平整。这是由于石灰与盾构渣土中的活性硅铝质产物发生反应,生成了较多的水化凝胶,水化凝胶发挥胶结作用和孔隙填充作用,形成了更加紧密的整体结构。结合 EDS 分析可知,水化产物主要为 C-(A)-S-H 凝胶<sup>[34]</sup>。由图 9(c) 可以观察到,盾构渣土在经过 CRGD 固化后形成了较多的无定型水化凝胶及针棒状产物,结合 P2、P3 能谱分析可知,产物为 C-(A)-S-H 凝胶和 Aft,可有效地填充土体孔隙,提高固化土密实度与强度。土体中的活性硅铝质组分与胶凝材料中的氢氧化钙发生火山灰反应,从而产生更多的水化凝胶。与图 9(b) 对比可知,CRGD 固化土整体微观结构相对紧实,针棒状钙矾石与土壤基质相互作用形成骨架结构,以及水合硅酸钙和水合铝酸钙的协同作用,大大增强了土体的稳定性,这与固化渣土强度试验的结果相对应。

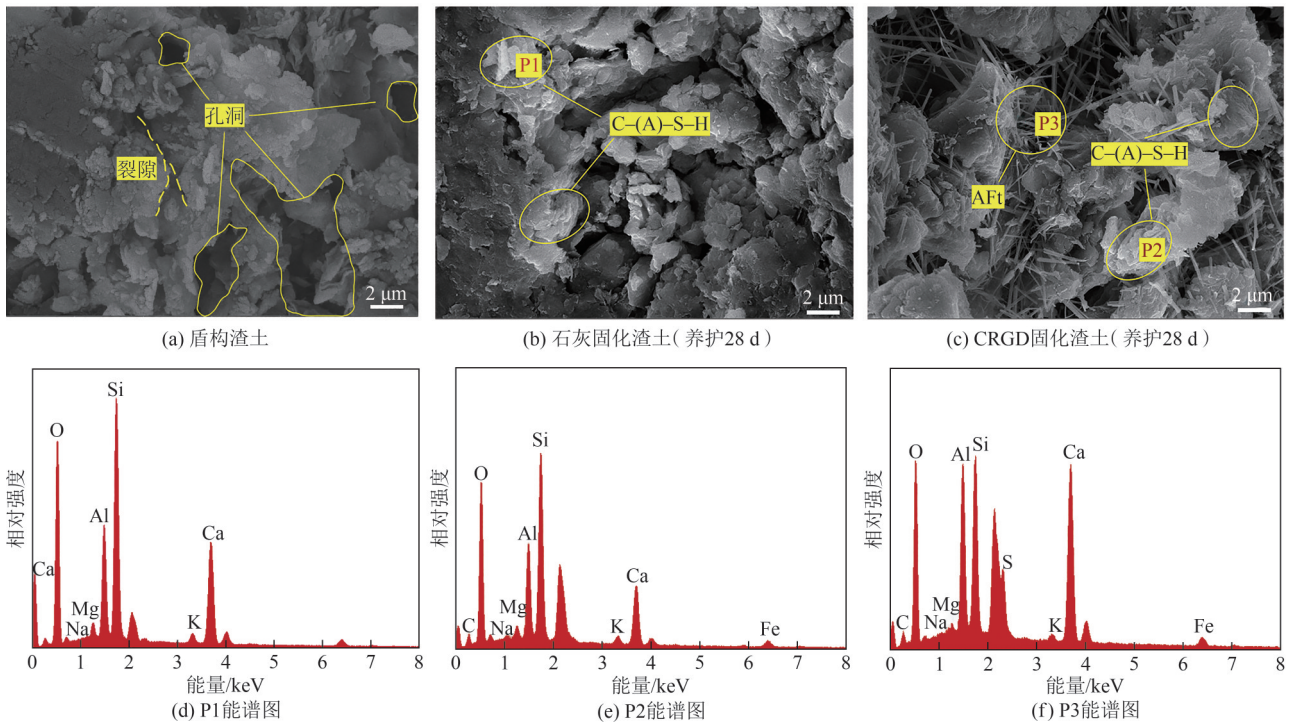


图9 盾构渣土及固化渣土的SEM-EDS图像  
Fig. 9 SEM-EDS images of shield muck and solidified muck

表2 固化渣土水化产物元素占比

Tab. 2 Elemental proportion of hydration products in solidified muck

| 元素 | P1       |          | P2       |          | P3       |          |
|----|----------|----------|----------|----------|----------|----------|
|    | 相对原子分数/% | 相对质量分数/% | 相对原子分数/% | 相对质量分数/% | 相对原子分数/% | 相对质量分数/% |
| C  | —        | —        | 12.80    | 7.41     | 10.94    | 5.92     |
| O  | 67.10    | 50.86    | 54.96    | 42.40    | 52.81    | 38.08    |
| Na | 0.04     | 0.04     | 0.39     | 0.43     | 0.13     | 0.13     |
| Mg | 1.07     | 1.23     | 0.97     | 1.14     | 0.44     | 0.49     |
| Al | 6.48     | 8.28     | 6.95     | 9.04     | 8.33     | 10.13    |
| Si | 14.87    | 19.78    | 13.98    | 18.94    | 9.08     | 11.50    |
| K  | 0.78     | 1.45     | 0.80     | 1.52     | 0.48     | 0.84     |
| Ca | 9.67     | 18.36    | 7.25     | 14.01    | 14.25    | 25.75    |
| Fe | —        | —        | 1.90     | 5.12     | 1.92     | 4.83     |
| S  | —        | —        | —        | —        | 1.62     | 2.34     |

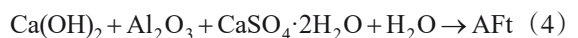
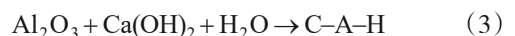
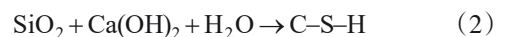
### 3 讨论

#### 3.1 CRGD固化渣土的协同增效机制

固化剂-土粒-水的相互作用关系是决定固化渣土强度的关键因素。基于上述宏观及微观试验结果的分析,CRGD固化渣土的强度形成机理可归纳为:离子交换作用、水化反应、火山灰反应及碳酸化作用<sup>[35-38]</sup>。

CRGD中各组分溶于水电离出 $\text{Ca}^{2+}$ 、 $\text{Al}^{3+}$ 等高价阳离子,可与渣土中的 $\text{Na}^+$ 、 $\text{K}^+$ 发生等电荷交换,降低黏土颗粒表面结合水膜的厚度,使得颗粒间结构更加致密,减小孔隙率,增加土体强度。CRGD自身发生水化反应,CS溶解,释放大量 $\text{Ca}^{2+}$ 与 $\text{OH}^-$ ,形成碱性环境,激发

GGBS与RM中的活性硅铝组分溶出,这些组分与 $\text{Ca}^{2+}$ 结合,生成C-(A)-S-H凝胶;同时,DG溶解提供 $\text{SO}_4^{2-}$ ,与体系中的 $\text{Al}^{3+}$ 、 $\text{Ca}^{2+}$ 反应生成钙矾石(Aft)。CRGD中的OH<sup>-</sup>能够与土体中的活性氧化硅、活性氧化铝成分发生火山灰反应,生成C-S-H、C-A-H凝胶。胶结物质会包裹土粒形成骨架结构,充填孔隙。 $\text{Ca}(\text{OH})_2$ 还可吸收空气中的二氧化碳或土中的碳酸盐,发生碳酸化反应,生成碳酸钙,进一步填充孔隙。其主要反应方程式如下:



### 3.2 经济效益评价

按照目前固化剂的市场价格,得到不同固化剂的成本,见表3。表3中,渣土处理成本都按照原料掺量为4%进行估算。在固化剂掺量为4%的情况下,处理每吨渣土所需石灰成本为18.000元,而所需CRGD的成本仅为5.160元。由此可知,使用CRGD每吨土可节省成本12.840元,显示出更优的经济效益。

表3 固化剂成本

Tab. 3 Curing agent cost

| 原料   | 每吨原料成本/元 | 处理每吨渣土所需成本/元 |
|------|----------|--------------|
| CS   | 70       | 1.064        |
| GGBS | 160      | 1.600        |
| RM   | 120      | 1.200        |
| DG   | 270      | 1.296        |
| 石灰   | 450      | 18.000       |

## 4 结论

1)随着CRGD掺量的增加,渣土最佳含水率增大,最大干密度减小;经CRGD固化后,渣土UCS和水稳定系数显著提高且均优于石灰固化渣土。CRGD掺量为4%的固化渣土养护28 d后UCS为2.37 MPa,与未固化的盾构渣土相比,显著提高230.5%;7%掺量下,养护28 d的CRGD固化渣土水稳定系数达83%,较石灰固化渣土提高了20%,超过规范要求。

2)CRGD掺量为4%时,CBR值从3.16%增加到58.14%,远超设计规范要求。CBR值随掺量增加而增大并逐渐趋于平缓,CRGD固化渣土CBR值与石灰固化渣土的差值也随掺量逐渐增大。掺量为8%时,CRGD固化渣土CBR值达217.98%,为石灰固化渣土的1.95倍。改良后的盾构渣土满足路基性能要求,可以有效地用于路基填筑。

3)CRGD各组分相互协同发生水化反应,并与土体中的活性硅铝质组分发生火山灰反应,主要生成C-(A)-S-H凝胶及针棒状钙矾石,能够有效地填充土体孔隙,降低孔隙率,提高固化土密实度与强度。并且使用CRGD处理每吨渣土仅需5.160元,具有良好的经济和环境效益。

附录见本刊网络版,扫描标题旁的二维码可阅读网络全文。

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## Study on the Mechanism and Road Performance of Solid Waste-based Cementitious Material for Curing Shield Tunnel Muck

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### Abstract:

**Objective** Backfilling of subgrade soil is an important approach for the resource utilization of shield tunnel muck, but the muck produced by shield construction, which exhibits high water content and high compressibility, is challenging to meet subgrade filling requirements. At present, commonly used soil stabilizers such as cement and lime present issues that include high energy consumption, high carbon emissions, insufficient strength, and poor stability. Therefore, it is urgent to develop low-carbon, economical, and efficient curing modified materials to achieve the resource utilization of shield tunnel muck. In this study, the whole solid waste curing agent (CRGD) prepared from industrial wastes such as carbide slag, red mud, ground granulated blast furnace slag, and desulfurized gypsum is utilized to solidify shield tunnel muck, and the performance and improvement mechanism of the improved shield tunnel muck as roadbed filler are examined.

**Methods** The test soil was the shield tunnel muck produced during the excavation of the silty clay stratum in a section of Jinan Rail Transit Line 4. A solid waste-based cementitious material (CRGD) was developed to solidify the shield tunnel muck by using the common solid waste red mud, desulfurized gypsum, granulated blast furnace slag, and carbide slag in Shandong Province as raw materials. It consisted of 38% carbide slag (CS), 25% red mud (RM), 25% granulated blast furnace slag powder (GGBS), and 12% desulfurized gypsum (DG) in mass ratio. Lime, a material widely used in solidified soil, was used as a comparative experimental group. First, the compaction curve was drawn through the compaction test to determine the maximum dry density and the optimum moisture content. Then, the specimens were prepared based on the optimum moisture content for the determination of the CBR value, unconfined compressive strength (UCS), and water stability. The UCS of the specimens was measured based on the specification after curing the specimens for 7 d, 14 d, and 28 d, and the water stability coefficient was calculated. Finally, low-field nuclear magnetic resonance (LF-NMR), X-ray diffraction (XRD), and scanning electron microscopy (SEM) were utilized to analyze the hydration products and microstructure of the solidified muck and to reveal its curing mechanism.

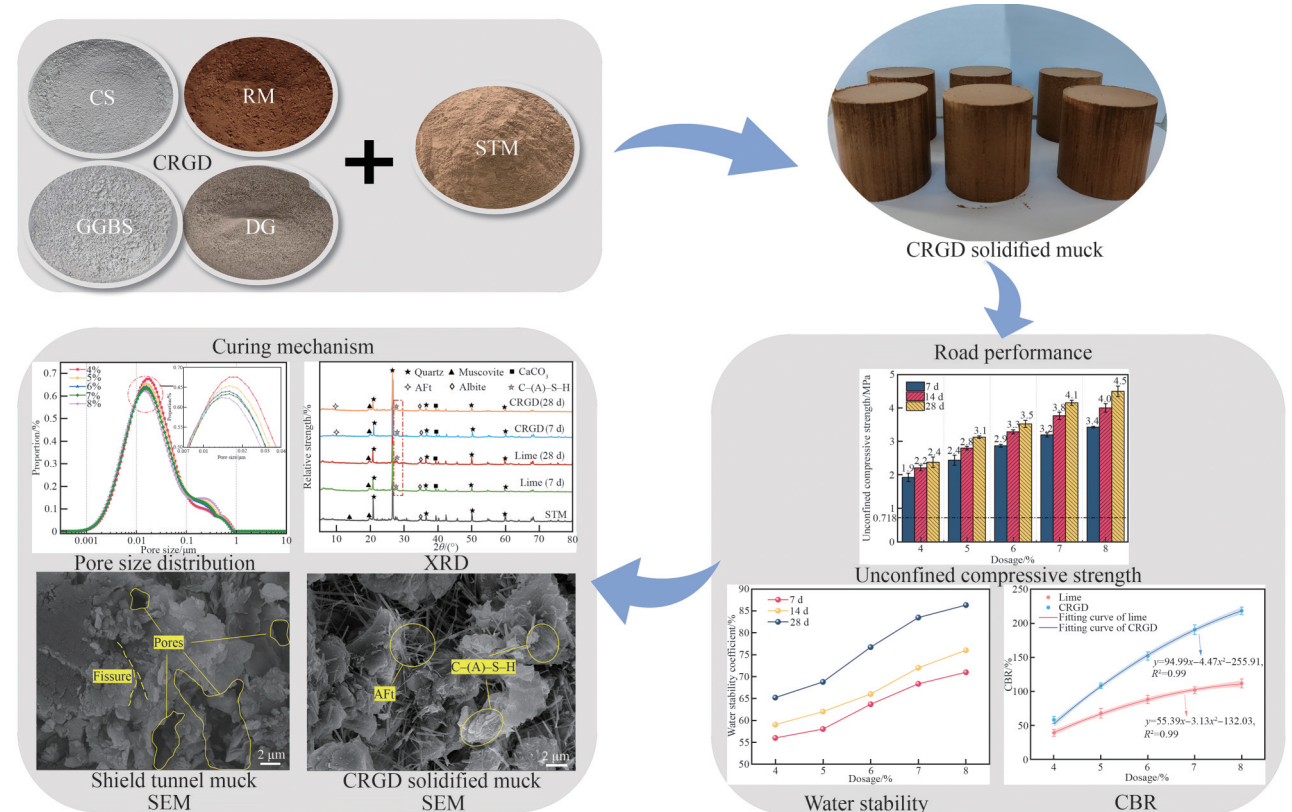
**Results and Discussions** The results of the compaction test showed that with the increase in dosage, the compaction curve shifted toward higher water content and lower dry density. After adding 4% CRGD, the wopt of the shield tunnel muck increased from 15.9% to 17.9%, and the  $\rho_{dmax}$  decreased from 1.81 to 1.60 g/cm<sup>3</sup>. Under the same dosage conditions, the wopt of lime-solidified muck was higher than that of CRGD-solidified muck, but its  $\rho_{dmax}$  was lower than that of CRGD-solidified muck. The unconfined compressive strength of the uncured shield tunnel muck was only 0.718 MPa, which did not meet the requirement of 1.5 MPa in the specification. After curing, the UCS increased significantly and increased with higher dosage and longer curing age. The strength increase of CRGD-solidified muck was more significant than that of lime-solidified muck. At 28 days of curing, the UCS of the solidified muck with 4% to 8% CRGD content increased by 230.5%, 334.8%, 389.8%, 477.6%, 525.1%, respectively. At 7% dosage, the UCS of CRGD-solidified muck cured for 28 days reached 4.15 MPa. At the same time, the water stability of the un-solidified shield muck was extremely poor, and the specimen did not maintain its integrity after soaking in water, disintegrating quickly in a short time. The water stability was significantly enhanced after CRGD curing, and the specimen maintained good integrity after immersion for 1 day. The water stability coefficient of the shield tunnel muck after curing treatment was consistent with the change pattern of the UCS and increased with higher dosage and longer curing age. At 7% dosage, the water stability coefficient of CRGD-solidified muck after 28 days of curing reached 83%, which was 20% higher than that of lime-solidified muck. In addition, the bearing capacity of CRGD-solidified muck was also higher than that of lime-solidified muck. At 4% dosage, the CBR value increased from 3.16% to 58.14%, which was 17.40 times higher than that of un-solidified muck and far higher than the design specification requirements. Under the same dosage, the CBR value of CRGD-solidified muck was higher

than that of lime-solidified muck, and the difference between the two increased with dosage. When the content reached 8%, the CBR value of CRGD-solidified muck was 217.98%, while that of lime-solidified muck was 111.55%. The porosity of the solidified muck after immersion decreased with increasing content, and the porosity of the CRGD-solidified muck was significantly lower than that of the lime-solidified muck. With higher CRGD content, the pores in the range of 0.001~0.1  $\mu\text{m}$  were relatively reduced, while the pores in the range of 0.1~1.0  $\mu\text{m}$  were relatively increased. After curing, the diffraction peak intensity of minerals such as quartz and mica in the sample weakened, and some mineral peaks almost disappeared, which indicated that the curing agent had a pozzolanic reaction with the silicon-aluminum active minerals in the muck. Compared to lime-solidified muck, Aft also appeared in CRGD-solidified muck, which indicated that the calcium-aluminum active substances in the system reacted with DG, and this reaction was an important reason why the strength of CRGD-solidified muck was higher than that of lime-solidified muck. SEM images showed that shield tunnel muck contained many holes and cracks. After CRGD curing, more amorphous hydration gels and needle-like products were observed. Combined with EDS analysis, these products were identified as C-(A)-S-H gel and Aft. The needle-like ettringite interacted with the muck matrix to form a skeleton structure, which effectively filled the muck pores and improved the compactness and strength of the solidified muck. Based on the current market price, the cost of lime required to treat 1 ton of shield tunnel muck with 4% dosage was 18.000 yuan, while the cost of CRGD required was only 5.160 yuan, saving 12.840 yuan per ton of shield tunnel muck.

**Conclusions** The results show that the UCS, water stability coefficient, and CBR values of the modified shield tunnel muck used as roadbed filler are significantly higher than those of lime-solidified muck. This improvement is achieved by using carbide slag, red mud, granulated blast furnace slag, and desulfurization gypsum to prepare the solid waste-based cementitious material (CRGD) for shield tunnel muck solidification. The components of CRGD interact with each other and react with the active silicon-aluminum component in the muck through a pozzolanic reaction, mainly generating C-(A)-S-H gel and needle-like ettringite. These products effectively fill the muck pores, reduce porosity, and improve the compactness and strength of the solidified muck. In addition, treating 1 ton of shield tunnel muck requires only 5.160 yuan, indicating favorable economic and environmental benefits.

**Key words:** shield tunnel muck; subgrade; solid waste-based cementitious materials; CBR value; water stability

**Graphical Abstract:**



(编辑 陈雪)

引用格式: Li Xuan, Li Zhaofeng, Zhang Haolong, et al. Study on the mechanism and road performance of solid waste-based cementitious material for curing shield tunnel muck[J]. *Advanced Engineering Sciences*, 2026, 58(1): 156-166. [李璇, 李召峰, 张昊龙, 等. 固废基胶凝材料固化盾构渣土的作用机理及路用性能[J]. *工程科学与技术*, 2026, 58(1): 156-166.]