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**Field trial of all-solid-waste stabilized soda residue for roadway
subgrades: mechanical performance and environmental
behavior**

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Abstract: Soda residue (SR), a highly alkaline and saline by-product of the ammonia-soda process, remains difficult to reuse at high dosage because of its high water content and soluble-salt release. Here, an all-solid-waste stabilized soda residue (S-SR) containing 70 wt.% SR was validated in a full-scale roadway subgrade to assess field constructability, engineering performance, and environmental behavior under natural exposure. Under low-temperature natural curing, mean California bearing ratio (CBR) increased from 38.6% at 1 d to 164.6% at 28 d, resilient modulus from 260.8 to 388.6 MPa, and dynamic deformation modulus from 65.6 to 199.9 MPa, while rebound deflection decreased from 0.374 to 0.190 mm. Degree of compaction and initial water content jointly controlled spatial variability. Leached Cl^- decreased from 3028 mg/L at 1 d to 268 mg/L at 60 d and SO_4^{2-} from 286 to 15 mg/L. Over five months, lysimeter leachate pH decreased from 10.87 to 8.32 and electrical conductivity from 15,469 to 4,236 $\mu\text{S}/\text{cm}$ (a 72.6% reduction), indicating gradual decreases in leachate alkalinity and overall dissolved-ion level during the middle-to-late monitoring period. The dynamic cone penetration index (DCPI) showed strong power-law relationships with field mechanical indices ($R^2 = 0.94\text{--}0.99$) and evolved consistently with anion leaching. Compared with reported SR-based systems, S-SR achieved higher SR utilization and 7-d CBR, together with lower material-related cost and production-stage carbon emissions. The study provides field-scale evidence for high-content SR reuse while documenting age-dependent leaching attenuation and field environmental responses under natural exposure.

Keywords: Soda residue; All-solid-waste subgrade material; Recycled construction material; Full-scale field trial; In situ monitoring; Field lysimeter

1. Introduction

Large-volume alkaline and saline industrial residues present persistent environmental and engineering challenges because long-term stockpiling not only occupies land but can also promote the release and migration of soluble constituents into surrounding soil and water (Gong et al., 2026; Gu et al., 2026). Soda residue (SR), a by-product of the ammonia-soda process, is representative of such wastes because of its high salinity, strong alkalinity, and high water content (Gomes et al., 2016). Approximately 0.3-0.6 t of SR is generated per tonne of soda ash, whereas only about 3%-4% is beneficially utilized (Z. Wang et al., 2025). China generated more than 4 billion t of general industrial solid waste in 2024, with an overall utilization rate of about 60% (MEE, 2024), and produced approximately 38 million t of soda ash in 2025, the highest output worldwide (USGS, 2026). In major coastal soda-ash production centers such as Lianyungang, Tianjin, and Weifang, substantial quantities of SR remain stockpiled, potentially causing land occupation, soil and groundwater salinization, and dust generation through salt leaching and particle dispersion (Kasikowski et al., 2007; Zong et al., 2023). Developing high-volume and environmentally responsible reuse pathways for SR is therefore important for reducing both accumulated waste stocks and their associated environmental burdens.

SR is characterized by strong alkalinity, high water content, strong water retention, and abundant fine particles. Its main constituents, including CaCO_3 , CaSO_4 , $\text{Mg}(\text{OH})_2$, CaCl_2 , and NaCl , endow SR with potential filling, cementitious, and alkali-activation functions (Kasikowski et al., 2004). However, the high soluble-salt content, particularly Cl^- , can promote soil and groundwater salinization and corrosion of coastal reinforced-concrete infrastructure, limiting large-scale reuse (Wu et al., 2022). Consequently, large-scale reuse of SR requires not only adequate engineering performance but also evidence that alkalinity and soluble-salt release can be effectively controlled during field application and subsequent environmental exposure.

SR reuse has been widely investigated in geotechnical, environmental, and construction-material applications. SR has been combined with cement, lime, ground granulated blast-furnace slag (GGBS), and fly ash (FA) for stabilization of dredged soil and sludge (He et al., 2020), improvement of marine soft soil (Yang et al., 2025), stabilization of heavy-metal-contaminated soil (Zha et al., 2020), and preparation of composite binders (An et al., 2022). In most cases, however, SR is used only as an amendment or auxiliary component, limiting its consumption. Roadway subgrades require large, continuous fill volumes and are therefore well suited to near-source utilization of industrial solid wastes (Bamigboye et al., 2021; Jiang et al., 2024). Conventional roadway construction relies heavily on natural soils, aggregates, cement, and lime, whose extraction and production consume resources, disturb ecosystems, and generate carbon emissions (Ren et al., 2025; Scrivener et al., 2018). Using SR-based solid-waste mixtures as recycled construction materials can therefore combine stockpile remediation, natural-material substitution, reduced use of carbon-intensive binders, and low-carbon roadway construction (Gu et al., 2023).

Previous studies have made progress toward roadway reuse of SR. Ma et al. (2020) demonstrated the feasibility of preparing and placing SR soil through laboratory and field testing and verified adequate bearing capacity and deformation modulus. Liu et al. (2024) and Wang et al. (2026) prepared SR-based lightweight subgrade fills using cement, GGBS, and SR, and reported that unconfined compressive strength (UCS), California bearing ratio (CBR), resilient modulus, and deflection satisfied relevant design requirements. Zhao et al. (2024) demonstrated favorable field UCS, CBR, and resilient modulus for lime–SR stabilized soil, while Zhang et al. (2025) reported satisfactory expressway performance for SR-phosphate-tailings-modified fishpond soil. Nevertheless, these systems generally rely on conventional binders, contain relatively low SR contents, or lack integrated evaluation of field mechanical performance, environmental behavior, and long-term behavior at high residue contents.

Several issues remain before SR can be reused in roadway subgrades in a large-scale, low-carbon, and environmentally responsible manner. First, most SR-based road materials still depend on cement, lime, or industrial alkali activators, which limits the SR content and makes it difficult to combine high solid-waste utilization with low-carbon construction; local availability and transportation costs have also received limited attention. Second, previous studies have focused mainly on mechanical indices such as UCS, CBR, and resilient modulus, whereas the leaching, migration, and long-term release of characteristic anions (Cl^- and SO_4^{2-}) and heavy metals have received less attention. Long-term field monitoring is especially scarce under actual service conditions involving coupled temperature, water-content, and rainfall effects. Third, most available data were obtained from laboratory specimens under standard curing and cannot fully represent in situ mixing, moisture conditioning, layered compaction, natural curing, and rainfall infiltration. Finally, the high water content, fine particles, and strong water retention of SR make field construction highly sensitive to water content, and construction and quality-control procedures for high-SR-content all-solid-waste subgrades remain insufficiently established.

Accordingly, a full-scale field trial was conducted using locally stockpiled SR with iron tailings (IT), GGBS, and fly ash (FA) to produce an all-solid-waste stabilized soda residue (S-SR). The study aimed to: (1) establish practical procedures for spreading, in situ mixing, water-content conditioning, grading, and compaction; (2) characterize age-dependent field performance using CBR, plate-load resilient modulus (M_R), Benkelman beam rebound deflection (BBD), portable falling weight deflectometer (PFWD) dynamic deformation modulus (E_{vd}), and dynamic cone penetration (DCP) testing and the dynamic cone penetration index (DCPI); and (3) characterize the release behavior of heavy metals and characteristic anions through multi-age core leaching tests, and evaluate the environmental behavior and field environmental response of S-SR by combining field lysimeter pH and electrical conductivity (EC), internal subgrade conditions, and groundwater-quality monitoring before and after construction.

Hydration, microstructural evolution, and ion-stabilization mechanisms are reported in a companion study (Xu, Jin, et al., 2026).

2. Field materials and methods

2.1 Site description

The field trial was conducted on the Nantong Road project in Lianyung District, Lianyungang, Jiangsu Province, China, at approximately 34.76°N and 119.30°E (Fig. 1a). Lianyungang has a warm-temperate humid monsoon climate, with hot, rainy summers and cold, dry winters. The site is near the Yellow Sea coast and approximately 2 km from the SR stockpile and associated treatment facilities. The surrounding area consists mainly of planned roads, undeveloped land, and drainage channels, providing convenient access for material transport.

The S-SR test section occupied K0+050–K0+100 on the eastern side of the site, with a length of 50 m and finished width of 6.0 m (Fig. 1b). The stabilizing wastes were locally sourced: IT from Lianyungang Port Group, GGBS from Yaxin Steel Plant, and FA from Haizhou Power Plant. IT was stockpiled beside the section, whereas GGBS and FA were stored in bulk bags along the alignment for controlled spreading and in situ mixing. Groundwater monitoring wells were installed upstream and downstream of the test section (Fig. 1b) to track changes in groundwater quality before and after construction.

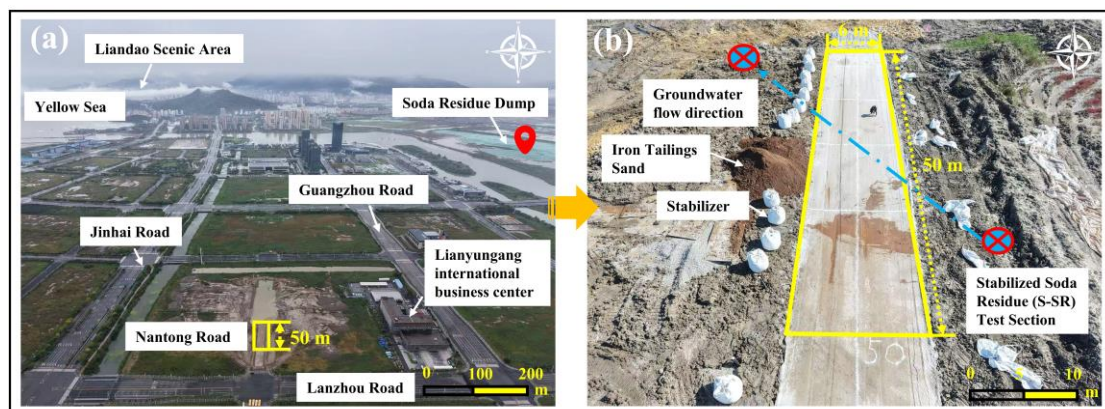


Fig. 1. Location and layout of the field test site: (a) aerial view of the site and

surroundings and (b) layout of the stabilized soda residue (S-SR) test section.

The subgrade cross section is shown in **Fig. S1a**. Considering the potential environmental impacts of soluble-salt release from S-SR, 50-cm-thick modified-clay impermeable barriers were installed beneath and along both sides of the S-SR subgrade (JTG D30-2015, 2015). An approximately 0.8-m-thick layer of quarry crushed-stone soil was then placed and compacted as a bedding layer. After acceptance, the 0.8-m-thick S-SR subgrade was constructed above it with a trapezoidal cross section 6.0 m wide at the top and 8.4 m wide at the base and side slopes of 1.5H:1V. The subgrade was placed in four 0.20-m-thick compacted lifts (Layers I–IV). The target degree of compaction was at least 93% for Layers I–II and at least 95% for Layers III–IV. Temperature, volumetric water content (VWC), and EC sensors were embedded at depths of 0.7 m (Layer I) and 0.3 m (Layer III) to monitor the internal hydrothermal and salinity conditions. Layers I–IV were constructed between November 2 and 23. Field mechanical testing and core sampling were conducted from November 24 to December 21 at the specified ages, followed by long-term in situ monitoring from January 26 to June 29 of the following year (**Fig. S1b**). Construction and early-age field testing were conducted during the late-autumn-to-winter transition. During the 28-d curing and testing period, the mean daily air temperature was approximately 7.0 °C with a minimum of −4 °C, the daily minimum was ≤ 5 °C on 27 of 28 d and below 0 °C on 13 d, and total precipitation was 24.7 mm. Detailed meteorological conditions during construction and curing are provided in **Fig. S2** and **Section S3** of the **Supporting Information**.

2.2 Soda residue and multi-source solid waste binders

Locally stockpiled SR was the primary material. GGBS, FA, and IT were added at a dry-mass ratio of GGBS:FA:IT:SR = 17:3:10:70, without cement or lime. The above mixture proportions were defined on a dry-mass basis, and the actual wet mass of each raw material used in the field was converted according to its measured water content

during construction. All gravimetric water contents reported for the raw materials, mixtures, and field samples were calculated on a dry-mass basis, i.e., as the ratio of water mass to oven-dry solid mass. All three stabilizing components were locally generated industrial solid wastes, enabling regional co-utilization of multiple waste streams. **Table 1** summarizes the basic physical properties and oxide compositions of the raw materials. SR was strongly alkaline and had high water content and EC (pH = 11.47, water content = 42.94%, and EC = 10.48 mS/cm). GGBS and FA were also alkaline (pH $\approx$ 11.2), whereas IT was near neutral (pH = 8.74). SR was rich in CaO (40.55%) and contained 7.21% MgO, providing an alkaline environment and Ca and Mg sources; its SO₃ and Cl contents were 12.49% and 6.34%, respectively, indicating a high salt content. GGBS contained abundant CaO (35.20%), SiO₂ (25.42%), and Al₂O₃ (10.63%) and therefore provided potentially reactive Ca–Si–Al phases. FA contained 37.19% SiO₂ and 33.81% Al₂O₃ and served as a silicoaluminous reactive component. IT consisted mainly of Fe₂O₃ (37.20%) and SiO₂ (28.87%); because of its relatively low chemical reactivity, it primarily provided granular skeleton support and gradation adjustment. It should be noted that LOI represents the total mass loss during high-temperature ignition rather than organic-matter content alone. For SR, which is rich in CaCO₃, Mg(OH)₂, and hydrous mineral phases, the relatively high LOI may be associated with carbonate decomposition, dehydroxylation of hydroxyl-bearing phases, and release of bound/crystalline water, with a possible minor contribution from organic matter.

The median particle sizes increased in the order GGBS (D_{50} = 11.48 μ m), FA (15.14 μ m), SR (39.81 μ m), and IT (104.71 μ m) (**Fig. S3**). The fine GGBS and FA particles can fill voids among SR particles and provide a large reaction surface, whereas the substantially coarser IT improves gradation and forms a load-bearing granular skeleton. The IT fraction also helps mitigate the construction sensitivity associated with the high water content and strong water retention of SR.

Table 1. Physical properties and oxide compositions of the raw materials (GGBS, FA, IT, and SR).

Property	Ground granulated blast-furnace slag (GGBS)	Fly ash (FA)	Iron Tailings (IT)	Soda Residue (SR)
pH	11.27	11.22	8.74	11.47
EC (mS/cm)	0.85	2.54	0.17	10.48
Water content (%; dry-mass basis)	0.00	0.51	14.91	42.94
<i>Oxide content (wt.%)</i>				
SiO ₂	25.42	37.19	28.87	8.94
Al ₂ O ₃	10.63	33.81	7.01	3.33
CaO	35.20	4.76	0.17	40.55
Fe ₂ O ₃	0.34	2.89	37.20	2.13
MgO	6.78	0.53	0.49	7.21
SO ₃	5.25	1.27	0.17	12.49
K ₂ O	0.46	0.42	0.24	0.29
Na ₂ O	6.45	0.27	0.13	0.83
MnO	0.33	0.04	0.51	0.15
P ₂ O ₅	0.02	0.33	0.40	0.09
Cl	1.97	0.02	0.00	6.34
LOI	7.14	18.48	24.82	17.65

Note: Gravimetric water content was calculated as the mass of water divided by the oven-dry mass of solids.

The raw-material leaching results (**Table S1**) showed generally low leached concentrations of heavy metals, whereas soluble-anion release from SR was more pronounced. To provide a consistent screening context for the standardized leaching results, Class IV groundwater values from [GB/T 14848-2017 \(2017\)](#) are listed in **Table S1** as screening references. Cl⁻ and SO₄²⁻ in the SR eluate reached 4870 and 830 mg/L, respectively, both exceeding the 350 mg/L reference value, with the exceedance being particularly pronounced for Cl⁻. The SO₄²⁻ concentration leached from FA (557 mg/L) also exceeded this value. Background Cl⁻ concentration in the native soil was 682 mg/L, while the pre-construction groundwater concentrations were 15,500 and 16,400 mg/L in the upstream and downstream wells, respectively, confirming the pronounced saline

background of the coastal site. Accordingly, the material-level assessment focuses on the release potential of soluble salts, whereas the incremental groundwater response is evaluated using paired upstream–downstream monitoring data before and after construction.

2.3. Construction procedures and monitoring plan

2.3.1 Construction procedures

The S-SR subgrade was constructed by in situ road mixing (**Figs. 2 and S4; Table S2**). Quality control focused on constituent dosage, mixing uniformity, water-content conditioning, and layered compaction.

(1) Material spreading and addition of stabilizing components. The accepted crushed-stone bedding was surveyed and divided into construction grids (**Fig. 2a**), and the mass of each constituent applied per unit area was controlled within each grid to maintain plan-view mixture uniformity. Each lift had a compacted thickness of 0.20 m. With a loose-lift factor of 1.4, the loose thickness was approximately 0.28 m. SR was delivered by dump truck and spread to the required elevation and thickness with a medium-sized hydraulic excavator (**Fig. 2b**). IT, GGBS, and FA were then applied sequentially according to the grid dosage (**Figs. 2c and 2d**). The coarser IT was placed first to improve gradation, followed by the finer GGBS and FA to distribute the reactive components over the surface and reduce local concentration during subsequent tilling.

(2) Mixing uniformity and water-content conditioning. A moldboard plow was first used for one pass (**Fig. 2e**) to fold the surface-applied components into the SR and break down large stockpile agglomerates. A soil stabilizer was then used for the first in situ mixing pass (**Fig. 2f**). After the first in situ mixing pass, the water contents before water conditioning of Layers I–IV were 24.39%, 25.10%, 24.06%, and 25.44%, respectively, all below the OMC of 28.4% (**Fig. S5**). Accordingly, water was added in several small, uniformly sprayed increments with a water truck based on the measured field water content (**Fig. 2g**), followed immediately by a second in situ mixing pass (**Fig. 2h**) to improve the uniformity of both water and solid constituents.

(3) Grading and compaction. A motor grader controlled the surface profile, cross slope, and elevation (**Fig. 2i**). Primary compaction used a single-drum vibratory roller in a static–light vibration–static sequence with overlapping passes from the edges toward the center, followed by a three-wheel static roller for final compaction and finishing (**Figs. 2j and 2k**).

(4) Layer acceptance and curing. Degree of compaction was measured after each lift, and DCP and PFWD were used after 3 d for rapid quality assessment before construction of the next lift. After Layer IV, the surface was geomembrane-covered to reduce water loss and support continued reaction (**Fig. 2l**). Mechanical and environmental tests were then conducted at the specified ages.

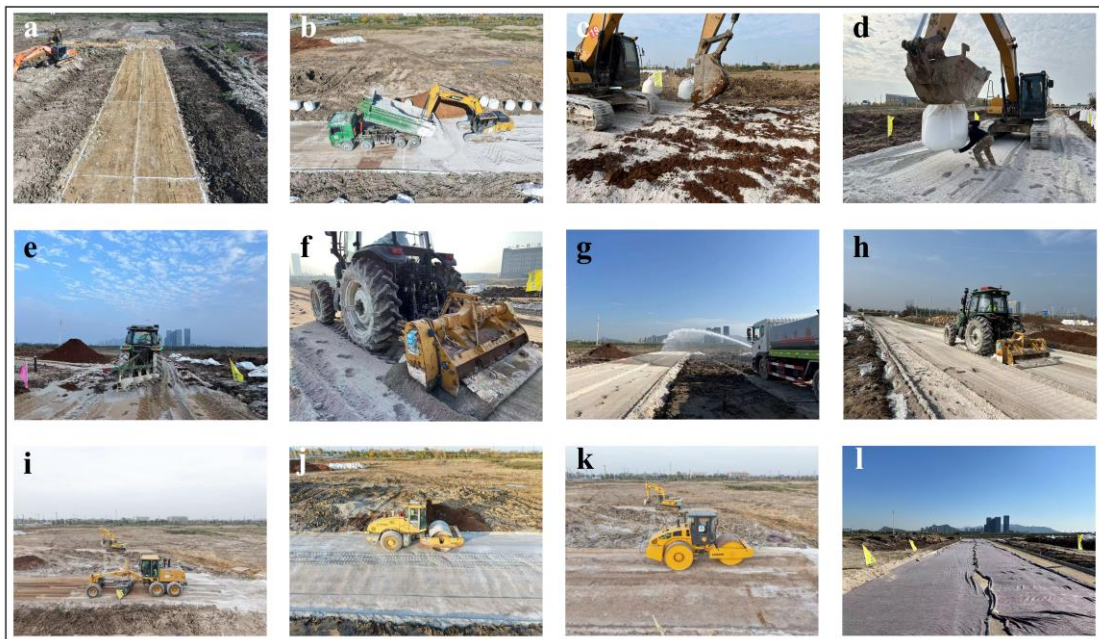


Fig. 2. Field construction process of the S-SR subgrade: (a) subgrade base leveling and grid setting-out; (b) delivery and spreading of the SR; (c, d) unloading and spreading of the solid-waste modifiers (GGBS, FA, and IT); (e) preliminary ploughing; (f) first in situ mixing using a rotary tiller; (g) water-content conditioning via a water truck; (h) second in situ mixing; (i) surface trimming with a motor grader; (j) initial compaction using a smooth-drum vibratory roller; (k) final compaction with a three-wheel static roller; and (l) curing under a geomembrane cover.

2.3.2 Field lysimeter

To characterize leachate generation and physicochemical evolution from the S-SR subgrade under natural rainfall, a field lysimeter was constructed within the test section following [Chen et al. \(2013\)](#); its configuration and field construction are shown in **Fig. 3**. From top to bottom, the lysimeter consisted of the S-SR subgrade, geotextile, drainage layer, high-density polyethylene (HDPE) geomembrane, and polyethylene (PE) drainage pipe (**Fig. 3a**). Infiltrating rainfall percolated through the S-SR layer, passed through the geotextile, and entered the drainage layer, where the PE pipe conveyed the lysimeter leachate to a buried 100-L collection tank for long-term monitoring. The collection tank was continuously monitored for pH and EC. Because time-resolved concentrations of Cl^- , SO_4^{2-} , and heavy metals corresponding to this monitoring period were not obtained, the field lysimeter results are used only to characterize changes in leachate acidity/alkalinity and overall dissolved-ion level.

The field construction sequence is shown in **Figs. 3b–3e**. A 5 m × 5 m collection cell was first excavated within the test section, and the base was graded and compacted to a 2.0% slope to promote gravity drainage along the designed direction. A PE drainage pipe connected to a vertical outlet was then installed at the downslope edge (**Figs. 3b and 3c**). The base and sidewalls were fully lined with an HDPE geomembrane, above which a drainage layer and geotextile were placed to intercept fine particles carried from the overlying subgrade and prevent clogging of the drainage layer and pipe (**Fig. 3d**). Finally, S-SR was backfilled and compacted using the same layered placement, mixing, and compaction procedures as the main subgrade (**Fig. 3e**). The HDPE base and sidewalls formed a closed hydraulic boundary that helped isolate external groundwater and collect vertically infiltrating leachate, while also limiting lateral flow and groundwater exchange. Accordingly, the system was used to characterize S-SR leachate generation and physicochemical evolution under natural rainfall rather than to directly simulate the complete groundwater-migration process of the main subgrade.

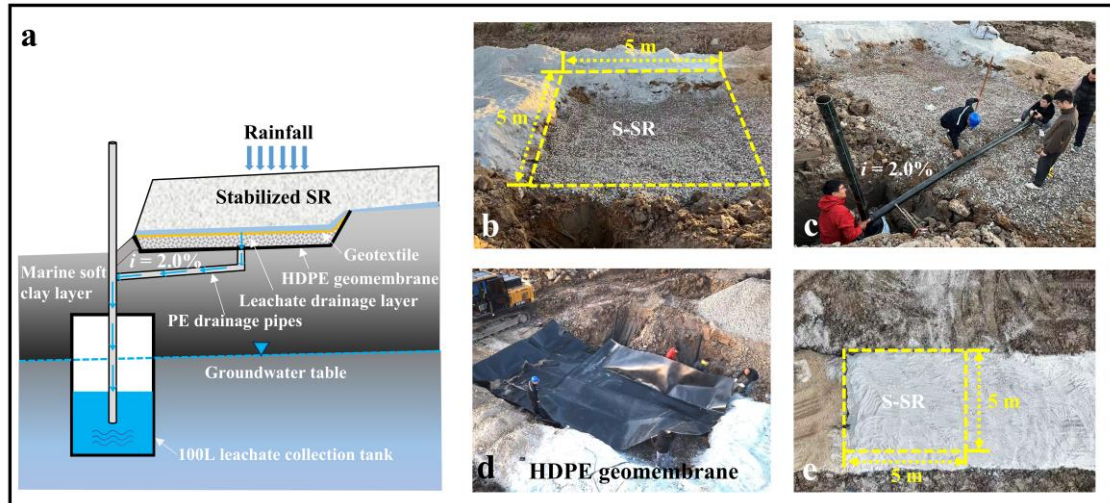


Fig. 3. Construction of the field lysimeter: (a) schematic of the field lysimeter; (b) excavation of the 5 m × 5 m leaching pit for the S-SR section; (c) installation of the polyethylene (PE) drainage pipe at a 2.0% gradient ($i = 2.0\%$); (d) lining of the pit with the high-density polyethylene (HDPE) geomembrane; and (e) placement of the geotextile and drainage layer, followed by backfilling with S-SR.

2.3.3 Monitoring plan

A long-term in situ system monitored the S-SR subgrade and lysimeter (**Fig. S6**). It included embedded temperature/VWC/EC sensors (MEC10; -40 to 80 °C; EC 0 – $20,000$ $\mu\text{S}/\text{cm}$), pH (PH10-1S2S) and EC (ECTDS10) sensors in the collection tank, and a solar-powered wireless transmission system.

One set of internal sensors was installed at depths of 0.3 and 0.7 m below the subgrade surface (designated S-SR- 0.3 m and S-SR- 0.7 m; **Figs. S6a and S6b**), corresponding to Layer III and Layer I, respectively. Each sensor was installed after mixing and grading but before compaction of the corresponding lift. A narrow slot was excavated, the probe was placed horizontally at the target depth in intimate contact with the mixture (**Fig. S6c**), and the slot was backfilled and lightly tamped with the same mixed material. The cable was routed horizontally to the roadside wireless unit (**Fig. S6d**), after which the lift was compacted so that the sensor remained within the representative compacted subgrade. All sensors were automatically logged at 1-h intervals by a 4G

data-acquisition terminal and remotely uploaded to a cloud platform, enabling unattended continuous online monitoring; the results are presented in **Section 3.3**. It should be noted that the VWC channel of the MEC10 was not specifically calibrated for high-salinity S-SR; therefore, its long-term output was used only as an apparent VWC sensor response for qualitative trend analysis, whereas gravimetric water content was independently determined by oven drying.

2.4. Testing program

A series of age-dependent in situ tests and core-sampling campaigns was conducted within the S-SR section to evaluate field mechanical performance and environmental behavior and to obtain specimens for laboratory analyses (Xu, Liu, et al., 2026). The test layout and field procedures are shown in **Fig. S7**, and the principal test methods, standards, and output parameters are summarized in **Table 2**.

As shown in **Figs. S7a and S7b**, field CBR, Benkelman beam rebound deflection (BBD), and plate-load resilient modulus (M_R) require relatively long test times and disturb larger areas; five points were therefore arranged along the centerline at 10-m intervals from K0+060. Destructive degree-of-compaction measurements and core sampling were conducted at K0+070, K0+080, and K0+090 adjacent to the corresponding mechanical-test locations to facilitate direct comparison of mechanical and physicochemical indices (**Fig. S7a**). DCP and PFWD are rapid, minimally disturbing tests. At each section, three PFWD points and associated water-content sampling locations were arranged transversely at 1.5-m spacing; the K0+080 section was intensified to five PFWD points across the full 6.0-m width and three paired DCP points to assess transverse construction uniformity (**Fig. S7b**). CBR, M_R , and BBD were measured at 1, 3, 7, 14, and 28 d, whereas PFWD and DCP were measured at 1, 3, 7, and 28 d. PFWD and DCP were also performed 3 d after compaction of each of Layers I–IV. The principal output indices were the dynamic deformation modulus (E_{vd}) from PFWD and the DCP index (DCPI) from DCP.

Field mechanical tests were conducted primarily in accordance with the Field Test Methods of Highway Subgrade and Pavement (JTG 3450-2019, 2019) and the Test Methods of Soils for Highway Engineering (JTG 3430-2020, 2020), with relevant ASTM standards used for methodological comparison. Core leaching tests were conducted according to the Solid Waste-Extraction Procedure for Leaching Toxicity-Horizontal Vibration Method (HJ 557-2010, 2010), using deionized water as the extractant at a liquid-to-solid ratio of 10 L/kg. The suspensions were shaken for 8 h, allowed to stand for 16 h, and then filtered through 0.45 μm membrane filters without pH adjustment; the complete procedure is provided in **SI Text S1**. This standardized extraction test was used to characterize the contaminant-release potential of S-SR, and the resulting eluate concentrations should not be interpreted as in situ groundwater concentrations. The Class IV groundwater values specified in the Standard for Groundwater Quality (GB/T 14848-2017, 2017) were therefore used only as screening references. The CBR, plate-load resilient modulus, Benkelman beam rebound deflection, PFWD, and DCP tests reported in this study were all conducted in situ on the full-scale S-SR subgrade, and the field CBR tests were unsoaked. Detailed apparatus, loading parameters, evaluation indices, and calculation procedures for these tests are provided in the Supporting Information (**Text S1** and **Eqs. (S1) - (S7)**).

Table 2. Summary of the field and laboratory testing program (detailed procedures, apparatus and equations are given in **Supporting Information (SI) Text S1**).

Test item	Field / lab	Standard	Key output parameter	Eq. (SI)
Degree of compaction K	Field	JTG 3450-2019 (2019) / JTG 3430-2020 (2020)	Dry density ρ_d , water content	(S1)
Benkelman beam deflection I_T		JTG 3450-2019 (2019)	Rebound deflection (0.01 mm)	(S2)
Resilient modulus M_R (plate load)		JTG 3450-2019 (2019)	Field resilient modulus (MPa)	(S3)
California bearing ratio CBR		JTG 3450-2019 (2019); JTG D30-2015 (2015)	Bearing ratio (%), limit $\geq 8\%$	(S4)
Dynamic deformation modulus E_{vd} (PFWD)		ASTM E2835-21 (2021)	E_{vd} (MPa)	(S5)

Dynamic cone penetration (DCP)		JTG 3450-2019 (2019); ASTM D6951 (2023)	DCPI (mm/blow)	(S6), (S7)
pH, EC and leaching of cores	Lab	HJ 557-2010 (2010); GB/T 14848-2017 (2017)	pH, EC, Cl ⁻ , SO ₄ ²⁻ and heavy metals	—

2.5. Environmental and economic assessment method

Material-production-stage carbon emissions were calculated using the emission-factor method, and material-related costs were estimated from local raw-material unit prices, both referenced to 1 m³ of compacted subgrade material as the functional unit. Component quantities were calculated from the dry-mass proportions and compacted dry density. The system boundary was limited to raw-material acquisition and production and excluded transportation, on-site construction, curing, service, and end-of-life stages; therefore, this assessment does not constitute a full life-cycle assessment. Following GB/T 51366-2019 (2019), SR and IT were treated as locally sourced low-value industrial solid wastes with zero upstream material cost and carbon burden within the adopted boundary; therefore, the calculated cost and emissions were governed mainly by GGBS and FA. No cement or lime was used. For consistent comparison, four representative SR-based subgrade materials reported in the literature were recalculated from their published mixture proportions using the same system boundary and factors. Comparative results are presented in **Section 4.4**. The carbon-emission factors, material unit prices, and calculation procedures are provided in **SI Text S2** and **Tables S4–S5**. A sensitivity analysis was further conducted by varying the field degree of compaction and the principal emission factors and material prices; the detailed method and results are provided in **SI Text S2** and **Table S6**.

3. Results and analysis

3.1. Mechanical performance

3.1.1 Degree of compaction and maximum dry density

The laboratory compaction curve for S-SR is shown in **Fig. 4a**. As the water content increased from 24.5% to 32.1%, dry density followed the expected single-peak trend.

The optimum water content and maximum dry density were 28.4% and 1.26 g/cm³, respectively. The relatively high optimum water content is consistent with the high fines content, porous structure, Ca–Mg-rich composition, and strong water retention of SR. The maximum dry density was only about 70% of that of conventional soil–aggregate fills, which can reduce the additional load imposed on the underlying marine soft clay.

Based on three representative chainages, the mean degrees of compaction of Layers I–IV were $94.83 \pm 0.29\%$, $93.77 \pm 0.25\%$, $93.13 \pm 0.40\%$, and $95.67 \pm 0.29\%$, respectively (**Fig. 4b**). All lifts except Layer III satisfied the corresponding target values, indicating that the adopted in situ mixing and layered compaction procedure could form the high-SR-content subgrade effectively. The standard deviation within each lift did not exceed 0.40%, showing that longitudinal variability within a lift was smaller than the differences among lifts. The corresponding mean field water contents were $29.18 \pm 0.42\%$, $29.66 \pm 0.51\%$, $31.20 \pm 0.55\%$, and $28.69 \pm 0.28\%$ (**Fig. 4c**), which were 0.78, 1.26, 2.80, and 0.29 percentage points above the optimum water content, respectively. Layer III had both the highest water content and the lowest degree of compaction, whereas Layer IV had the water content closest to optimum and the highest degree of compaction.

The layered compaction quality of S-SR therefore showed a clear correspondence with construction water content. As described in **Text S3**, Layer III was constructed during a period of cooling and precipitation, had a relatively high water content (31.20%), and showed the lowest degree of compaction, whereas Layer IV had the water content closest to the OMC and reached a degree of compaction of 95.67%. These results are consistent with classical compaction principles and indicate that, for high-water-content and strongly water-retaining S-SR, construction water content is an important process variable controlling the achievable degree of compaction and should be managed together with compaction. The corresponding field mechanical response is discussed in **Section 4.1**.

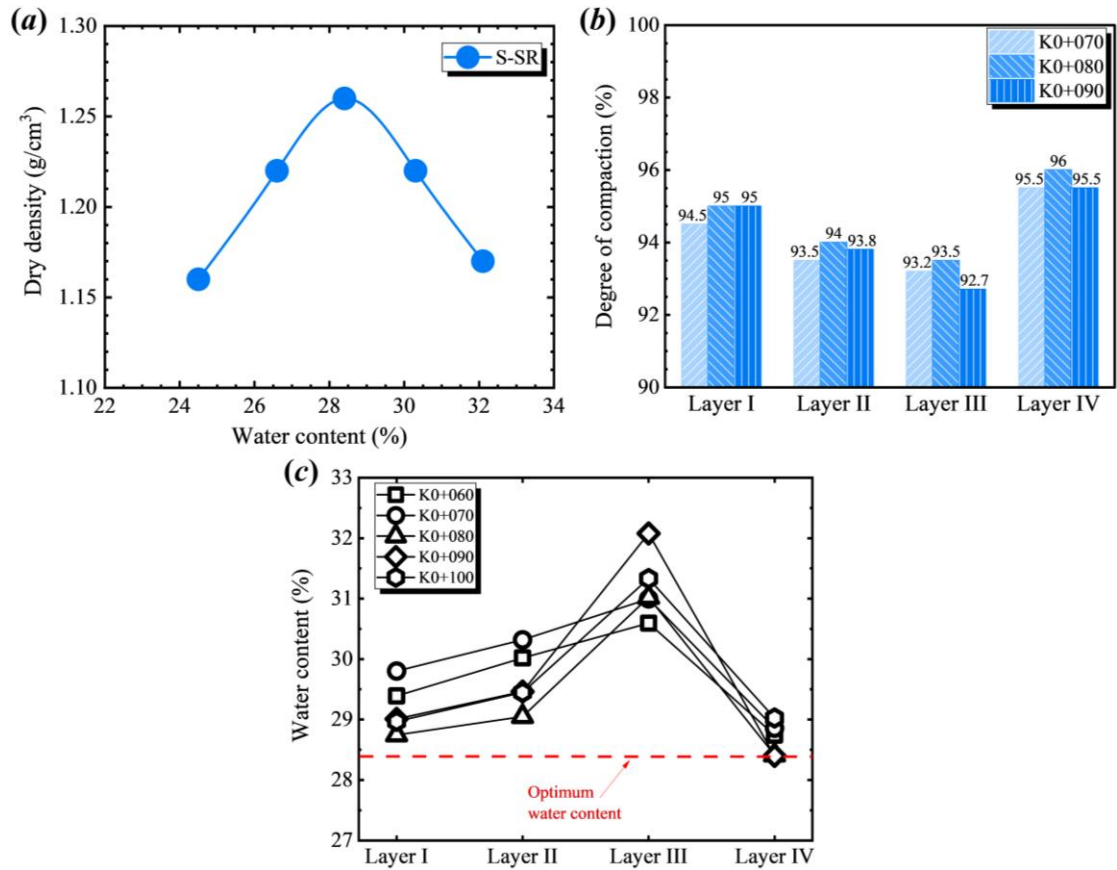


Fig. 4. Compaction characteristics and field quality control of the S-SR subgrade: (a) laboratory compaction curve; (b) field degree of compaction for each subgrade layer (Layers I–IV) at different chainages; and (c) in situ water content of each layer compared with the optimum water content.

3.1.2 In situ California bearing ratio (CBR), Resilient modulus (MR) and Benkelman beam rebound deflection

Field CBR increased continuously with curing age at all chainages (**Fig. 5a**). Mean values at 1, 3, 7, 14, and 28 d were $38.6 \pm 1.95\%$, $63.4 \pm 3.05\%$, $100.8 \pm 4.15\%$, $134.8 \pm 6.18\%$, and $164.6 \pm 7.96\%$, respectively. The increase was fastest during the first 7 d; by 28 d, CBR was approximately 4.3 times the 1-d value. Despite low-temperature curing, the 1-d mean CBR was already 4.8 times the 8% subgrade-top requirement (JTG D30-2015, 2015), and the 28-d mean was 20.6 times the requirement. Coefficients of variation remained approximately 4.1%–5.1%. K0+080 generally showed the highest

CBR, whereas K0+060 and K0+100 were lower, suggesting persistent effects of local mixing, water-content distribution, rolling overlap, and compaction.

Field M_R increased from 260.78 ± 4.73 MPa at 1 d to 388.62 ± 12.32 MPa at 28 d, an increase of about 49% (**Fig. 5b**). All values exceeded the 20-MPa design requirement for the top of secondary- and branch-road subgrades in [CJJ 37-2012 \(2016\)](#), indicating substantial stiffness support for the overlying pavement structure. M_R was already relatively high at 1 d (about 67% of the 28-d value), whereas 1-d CBR was only about 23% of its 28-d value. This reflects their different mechanical meanings: M_R characterizes overall small-strain stiffness, while CBR is a local large-deformation penetration measure that is more sensitive to progressive bonding. The subsequent M_R increase is consistent with continued structural development and the CBR trend ([Feng et al., 2022](#)).

Consistent with the increases in CBR and resilient modulus, Benkelman beam rebound deflection decreased with age (**Fig. 5c**). The mean deflection decreased from 0.3737 ± 0.0050 mm at 1 d to 0.2862 ± 0.0046 mm at 3 d, changed only slightly between 7 and 14 d, and then decreased further to 0.1901 ± 0.0021 mm at 28 d, a total reduction of approximately 49.1%. The decreasing deflection confirms the progressive improvement in resistance to load-induced deformation. Coefficients of variation were only 1.1%–1.4%, the lowest among the three principal mechanical indices, indicating a relatively uniform longitudinal stiffness distribution. The minimum 28-d deflection occurred at K0+080 (0.188 mm), where CBR and M_R were also highest.

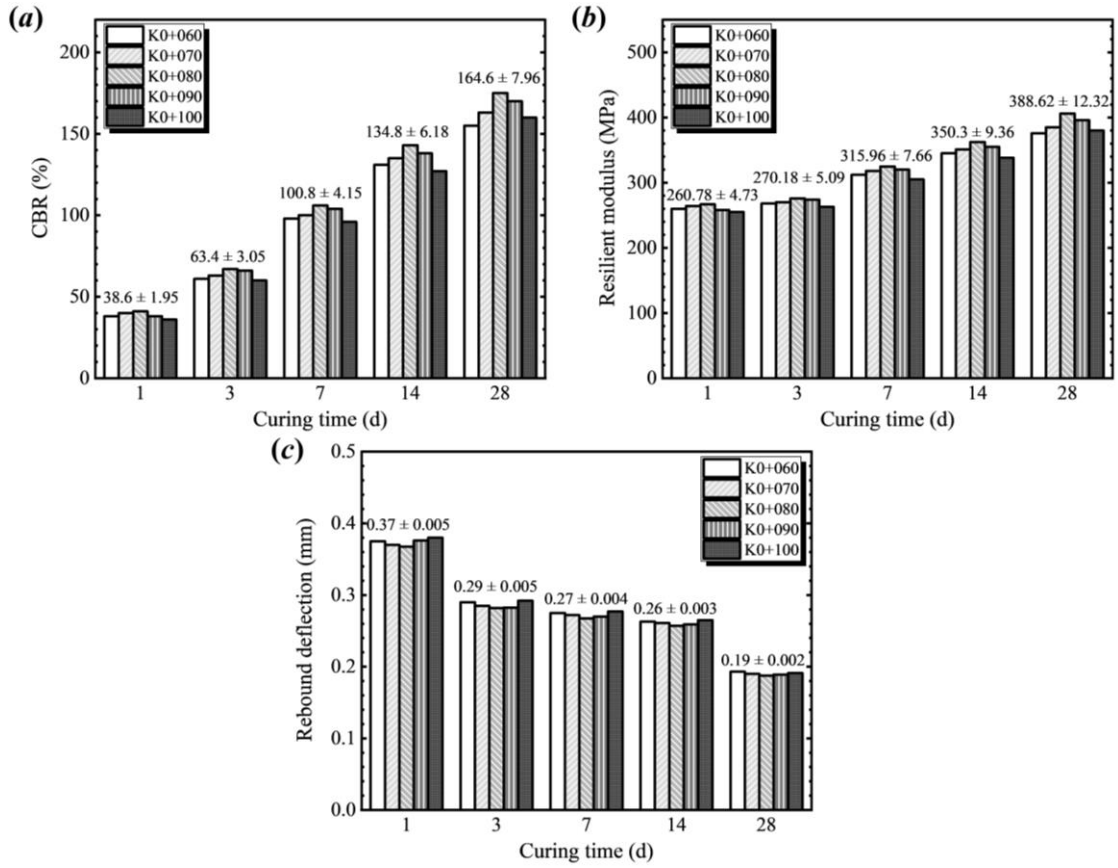


Fig. 5. Mechanical performance of the S-SR subgrade with curing time: (a) CBR; (b) resilient modulus; and (c) Benkelman beam rebound deflection. Values are mean ± standard deviation across five chainages ($n = 5$).

3.1.3 Dynamic deformation modulus (E_{vd})

At 3 d, mean E_{vd} values for Layers I–IV were 68.48 ± 5.34 , 61.91 ± 5.77 , 52.12 ± 6.20 , and 88.30 ± 8.10 MPa, respectively (**Fig. 6a**), giving the order Layer IV > Layer I > Layer II > Layer III. Layer IV exceeded Layer III by 69.4%. The lowest E_{vd} and greatest spatial variability in Layer III, and the highest E_{vd} in Layer IV, were consistent with their field compaction and water-content states (**Fig. 4**), supporting PFWD as a rapid indicator of lift-to-lift stiffness and construction uniformity (Feng et al., 2022).

Figure 6b shows the age dependence of E_{vd} for Layer IV. The mean E_{vd} increased from 65.6 ± 10.9 MPa at 1 d to 88.30 ± 8.10 MPa at 3 d, 138.0 ± 16.4 MPa at 7 d, and 199.9 ± 15.2 MPa at 28 d; the 28-d value was 3.05 times the 1-d value. All measured ages

exceeded the 40-MPa control value adopted for comparison in this study (TB 10751-2018, 2018). Although the age-dependent trends were similar along the alignment, persistent spatial differences were evident. K0+080 remained relatively high, reaching 158.45 and 222.46 MPa at 7 and 28 d, respectively, whereas K0+100 was lower and reached 184.43 MPa at 28 d. This longitudinal pattern was consistent with the CBR, resilient modulus, and rebound-deflection results and with the measured distributions of water content and degree of compaction.

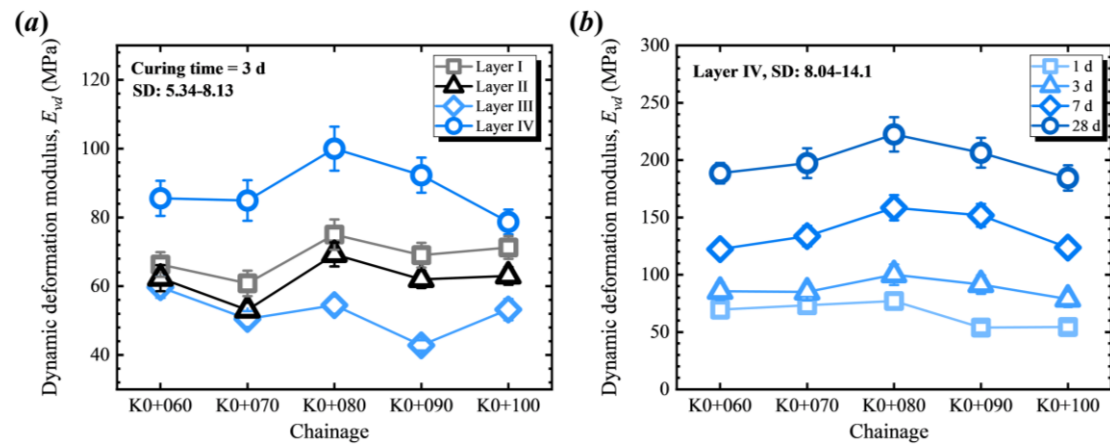


Fig. 6. In situ dynamic deformation modulus (E_{vd}) of the S-SR subgrade evaluated by PFWD testing: (a) spatial variations across Layers I–IV at 3 d; and (b) temporal development in Layer IV at 1, 3, 7, and 28 d. Error bars represent standard deviations of replicate PFWD measurements ($n = 3$).

3.1.4 Dynamic cone penetration index (DCPI)

Figures 7a and 7b show the DCP results for the four lifts after 3 d of curing. Cumulative blow count increased approximately linearly with penetration depth within each lift, indicating relatively uniform penetration resistance through the thickness of an individual lift, but clear differences occurred among lifts. DCPI values for Layers I–IV were 0.87, 1.63, 1.81, and 0.49 mm/blow, respectively, following the order Layer IV < Layer I < Layer II < Layer III. The Layer IV value was only 27.1% of that of Layer III, indicating the greatest penetration resistance in the uppermost lift. This ordering closely matched the degree of compaction and PFWD results: Layer IV had the highest

compaction and E_{vd} , whereas Layer III had the lowest values and the wettest condition. DCP therefore distinguished lift-to-lift construction differences sensitively and complemented the dynamic stiffness information from PFWD.

For Layer IV, DCPI decreased from 1.20 mm/blow at 1 d to 0.49, 0.29, and 0.10 mm/blow at 3, 7, and 28 d, respectively (Figs. 7c and 7d), a 91.7% reduction by 28 d. The corresponding increase in blow count agreed with the increases in CBR, M_R , and E_{vd} and the decrease in rebound deflection, confirming continued strengthening during natural curing.

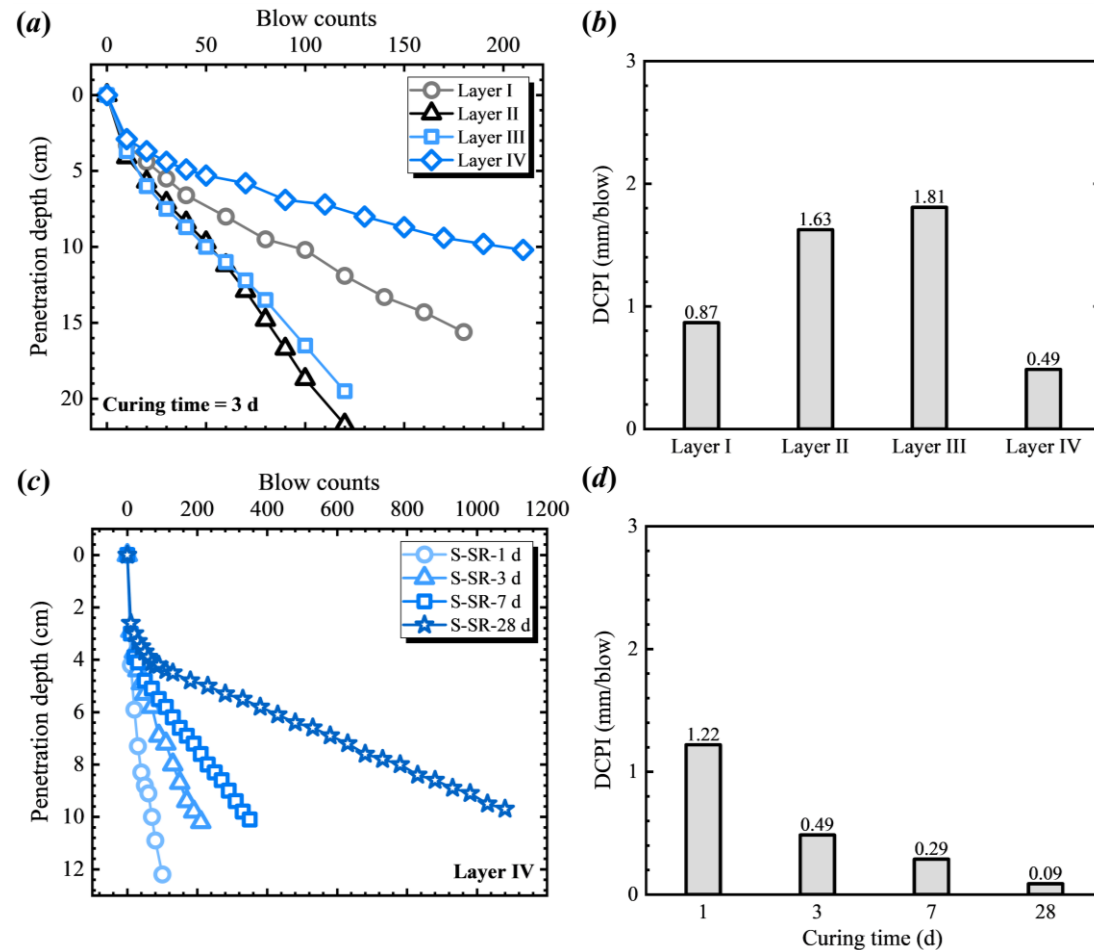


Fig. 7. In situ dynamic cone penetrometer (DCP) test results for the S-SR subgrade section: (a) cumulative blow counts versus penetration depth and (b) corresponding DCPI for Layers I–IV at a curing time of 3 d; (c) cumulative blow counts versus penetration depth and (d) evolution of DCPI for Layer IV at different curing

times (1, 3, 7, and 28 d).

3.2. Leaching behavior and groundwater response

To distinguish the intrinsic pollutant-release potential of the material from the actual groundwater response, multi-age standardized core-leaching tests and groundwater monitoring before and after construction were conducted separately. The former characterized the age-dependent release potential of heavy metals and characteristic anions from S-SR, whereas the latter identified short-term changes in groundwater surrounding the subgrade after construction; the results are presented in **Table 3** and **Table S3**.

Core pH and EC both increased initially and then decreased with age (**Table 3**). The pH increased from 11.32 at 1 d to a peak of 11.66 at 7 d and subsequently decreased to 10.38 at 60 d. EC increased from 4.55 to 6.21 mS/cm over the first 7 d and then decreased to 2.39 mS/cm at 60 d, 61.5% below the peak. The early increases are consistent with release of alkaline and ionic species during initial stabilization, whereas the later decreases indicate progressive consumption or retention of dissolved species and reduced release as the structure developed. Core water content decreased monotonically from 30.60% at 1 d to 22.23% at 60 d, a reduction of 27.4%, reflecting continued water consumption by reaction together with limited water loss under membrane curing.

Heavy-metal leaching remained generally low at all curing ages. Cd and Cr(VI) were not detected throughout, Cu, Ni, Pb, and Hg decreased below their detection limits at later ages, and Zn, As, and total Cr also remained at low levels. These results are consistent with the low heavy-metal background of the raw materials, indicating that heavy metals were not the principal controlling constituents in the standardized leaching tests; subsequent analysis therefore focuses on the mobile characteristic anions.

The leached Cl^- concentration decreased continuously from 3028 mg/L at 1 d to 268

mg/L at 60 d, a reduction of approximately 91.1%. When the Class IV groundwater value of 350 mg/L in [GB/T 14848-2017 \(2017\)](#) is used as a screening reference, core-leachate concentrations at 1-28 d remained above this value and decreased below it at 60 d, indicating that leachable Cl^- attenuated markedly with age but retained a relatively high release potential at early ages. This comparison is used only to characterize the relative leaching risk at different ages and cannot be used directly to determine in situ groundwater quality. SO_4^{2-} decreased rapidly from 286 mg/L at 1 d to 33 mg/L at 28 d and 15 mg/L at 60 d (an overall reduction of approximately 94.8%) and remained below the reference value throughout curing. The more rapid decrease in SO_4^{2-} is consistent with its lower release relative to Cl^- and with the Ca-rich environment, which favors sulfate incorporation into sulfate-bearing hydration phases such as ettringite.

Groundwater monitoring showed no sustained increase in Cl^- , SO_4^{2-} , or heavy metals during the three monthly monitoring campaigns after construction. Before construction, Cl^- concentrations were 15,500 and 16,400 mg/L in the upstream and downstream wells, respectively, confirming a pronounced coastal saline background. At 1, 2, and 3 months after construction, the corresponding upstream/downstream Cl^- concentrations were 15,700/16,500, 15,900/16,700, and 14,900/16,000 mg/L; relative to the pre-construction downstream value, the downstream changes were approximately +0.6%, +1.8%, and -2.4%, respectively. SO_4^{2-} concentrations changed from 216/241 mg/L before construction to 229/251, 234/256, and 218/234 mg/L at 1-3 months (upstream/downstream). Heavy metals likewise showed only limited fluctuations without consistent downstream enrichment. Thus, the paired upstream–downstream data provide no clear evidence of a sustained increase in these groundwater indicators attributable to S-SR during the 3-month monitoring window; however, the monitoring period remains insufficient for long-term groundwater-migration assessment.

Table 3. Physicochemical properties and leaching concentrations of heavy metals and characteristic anions for S-SR at 1, 3, 7, 14, 28, and 60 d, with Class IV groundwater

values shown as screening references.

Heavy metals and anions	S-SR-1 d	S-SR-3 d	S-SR-7 d	S-SR-14 d	S-SR-28 d	S-SR-60 d	Groundwater reference values
pH	11.32	11.53	11.66	11.24	10.67	10.38	/
EC (mS/cm)	4.55	5.38	6.21	4.78	3.65	2.39	/
Water content (%)	30.60	29.32	27.54	25.37	23.59	22.23	/
Cu (µg/L)	1.74	1.48	1.29	0.56	< 0.08	< 0.08	1500
Cr (µg/L)	9.77	2.26	1.94	0.94	0.41	0.30	/
Ni (µg/L)	1.20	1.70	1.64	0.39	< 0.06	< 0.06	/
Zn (µg/L)	13.6	8.26	8.18	5.72	6.74	8.26	5000
Pb (µg/L)	0.56	0.39	0.53	0.22	< 0.09	< 0.09	100
Cd (µg/L)	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	10
As (µg/L)	3.3	4.5	3.6	3.3	2.1	1.7	50
Hg (µg/L)	0.36	0.30	0.30	0.25	< 0.04	< 0.04	2
Cr(VI) (µg/L)	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	100
Cl ⁻ (mg/L)	3028	2445	1566	1040	535	268	350
SO ₄ ²⁻ (mg/L)	286	191	119	46	33	15	350

Note: "Groundwater reference values" are the Class IV values specified in [GB/T 14848-2017 \(2017\)](#).

"<" indicates that the concentration is below the limit of detection (LOD); "/" indicates that no corresponding reference value is specified.

3.3. In situ monitoring

3.3.1 Lysimeter leachate (temperature, pH, and EC)

To characterize the middle-to-late-stage evolution of leachate physicochemical conditions within the closed collection cell under natural rainfall, temperature, pH, and EC in the collection tank were monitored continuously for approximately five months (January 27–June 29), as shown in **Fig. 8**; cumulative rainfall over the same period was 673.4 mm (**Fig. 9d**). The signal-loss intervals shown by the grey shading were excluded from trend analysis. Monitoring began approximately two months after completion of S-SR construction; therefore, the pH and EC records reflect only middle-to-late-stage leachate hydrochemical evolution and do not capture the early-age Cl⁻ release peak after construction. Early-age release of characteristic anions is characterized by the multi-

age core-leaching tests in **Section 3.2**.

Lysimeter leachate temperature increased gradually from 11.2 °C to 17.0 °C with seasonal warming, far less than the variation in air temperature. During the February 6–8 cold spell, for example, daily mean air temperature fell to -3 to -1°C while leachate remained near 12 °C. The buried lysimeter and surrounding subgrade therefore strongly buffered short-term atmospheric fluctuations.

Lysimeter leachate pH decreased continuously with monitoring time, from approximately 10.87 at the beginning to approximately 8.32 at the end of monitoring, with the steepest decline during February-March as spring rainfall increased. The sustained decrease in pH reflects progressive attenuation of the highly alkaline constituents released from S-SR under the combined effects of rainfall leaching and hydration, with alkalinity gradually stabilizing (Chen et al., 2013). By the end of monitoring, the leachate had entered a weakly alkaline range, indicating natural attenuation of alkaline release with service time.

Lysimeter leachate EC decreased from 15,469 µS/cm at the beginning of monitoring to 4,236 µS/cm at the end, a cumulative reduction of 72.6%. The largest single decline followed the continuous rainfall in late February and early March, when EC decreased from 14,930 to 8,800 µS/cm (41%). EC continued to decrease as rainfall increased during April and May and stabilized at approximately 4,200–5,000 µS/cm after mid-May, with only brief downward excursions following intense rainfall. Individual rainfall events did not always produce an immediate monotonic response because of infiltration lag, mixing within the lysimeter collection tank, and antecedent water conditions; nevertheless, EC and cumulative rainfall showed a clear inverse long-term trend. Because EC reflects the overall ionic level rather than individual species, its decline is interpreted only as a decrease in bulk ionic content; age-dependent attenuation of Cl⁻ and SO₄²⁻ is assessed from the core-leaching results.

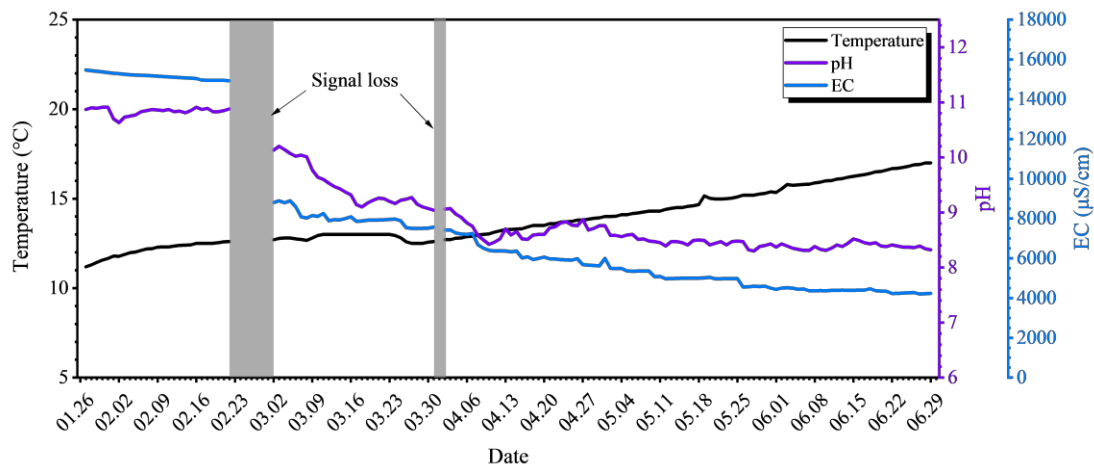


Fig. 8. Long-term monitoring of the leachate from the field lysimeter in the S-SR test section: temporal variations in temperature, pH, and EC. Grey shaded areas denote two short data gaps (approximately 9 d and 3 d), caused by rain-induced short circuits at several sensor-cable connections; monitoring resumed after the connections were repaired.

3.3.2 S-SR subgrade (temperature, apparent VWC response, and EC)

Temperature, VWC, and bulk EC were monitored continuously at 0.3 m (Layer III) and 0.7 m (Layer I) to characterize the internal S-SR state (**Fig. 9**). Subgrade temperature increased from approximately 8.6–9.6 °C in winter to 28.5–29.6 °C by late June (**Fig. 9a**), broadly following air temperature. The 0.3-m sensor responded faster and fluctuated more, whereas the 0.7-m record was smoother and showed the expected attenuation and phase lag with depth.

The apparent VWC sensor response (**Fig. 9b**) increased overall during monitoring. The 0.3-m sensor reached the upper measurement range in mid-April, whereas the 0.7-m sensor reached it in late May. As noted in **Section 2.3.3**, these uncalibrated readings are interpreted only as qualitative moisture responses rather than true VWC or saturation. The earlier shallow response is consistent with the expected downward progression of rainfall infiltration.

Bulk EC evolved differently with depth (**Fig. 9c**). At 0.7 m, EC rose from 1,518 $\mu\text{S}/\text{cm}$ to a late-February peak of 1,845 $\mu\text{S}/\text{cm}$ and then declined to 1,169 $\mu\text{S}/\text{cm}$ by late June. At 0.3 m, it increased from 1,666 $\mu\text{S}/\text{cm}$ to a May peak of 2,724 $\mu\text{S}/\text{cm}$ and ended at 2,156 $\mu\text{S}/\text{cm}$. Because bulk EC depends jointly on pore-water ionic strength, water content, and hydraulic connectivity, the stronger shallow response is consistent with the lower compaction and greater rainfall sensitivity of Layer III, whereas the deeper decline suggests progressive depletion and downward export of mobile salts. These water–salt interactions are discussed in **Section 4.3**.

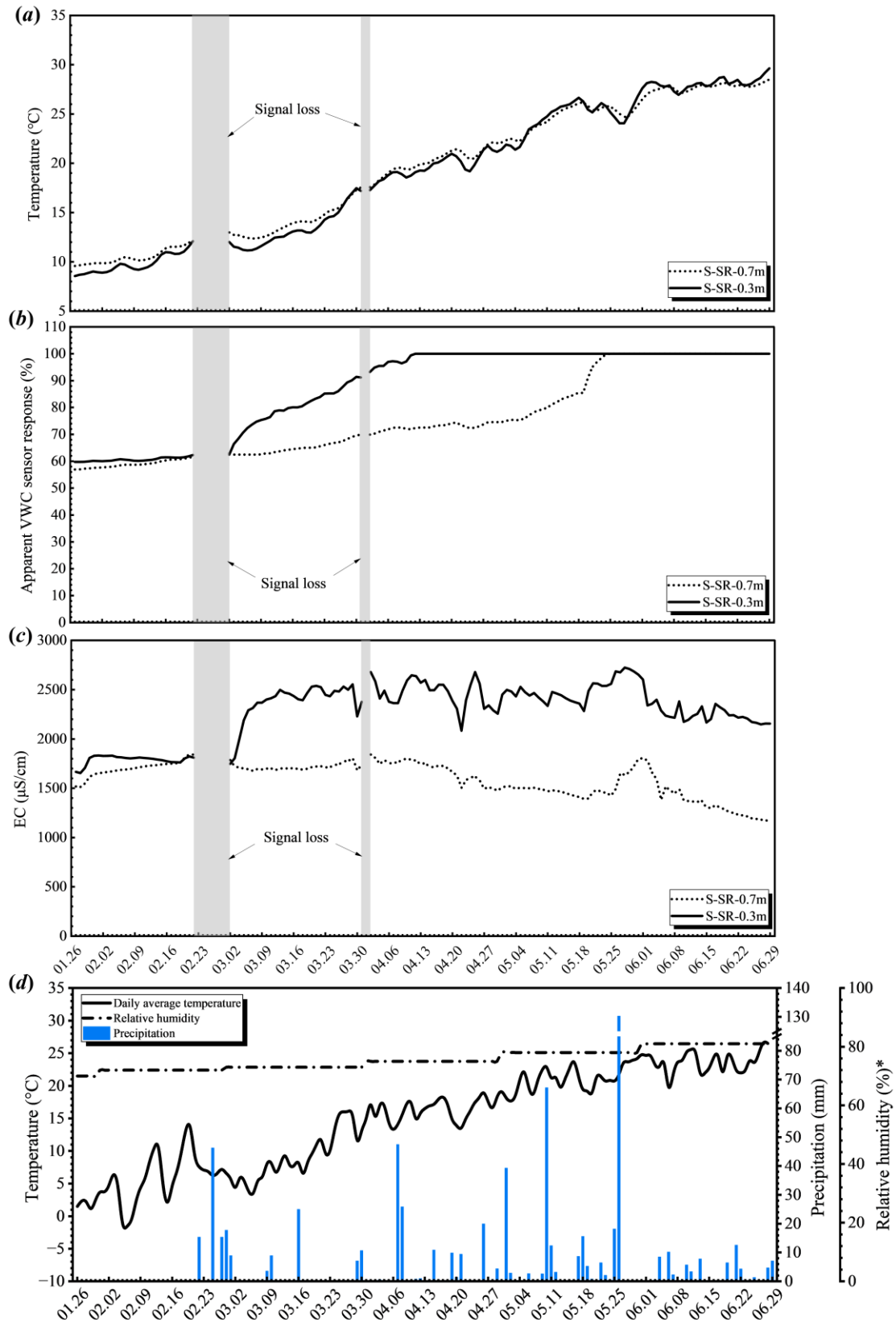


Fig. 9. Long-term in situ monitoring of the S-SR subgrade at depths of 0.3 and 0.7 m: (a) temperature, (b) apparent VWC sensor response, and (c) EC; and (d) corresponding ambient weather conditions. Grey shaded areas denote two short data gaps

(approximately 9 d and 3 d) caused by rain-induced short circuits at several sensor-cable connections; monitoring resumed after the connections were repaired.

4. Discussion

4.1. Effects of the degree of compaction and initial water content on field mechanical performance

The field results indicate that differences in degree of compaction and initial water content established during construction continued to influence the subsequent mechanical performance of S-SR. As shown in **Fig. S8**, degree of compaction correlated positively with E_{vd} ($R^2 = 0.93$) and negatively with DCPI ($R^2 = 0.98$); the corresponding R^2 values for initial water content were 0.79 and 0.77. Layer III had the highest water content (31.20%) and the lowest degree of compaction (93.1%), together with the lowest E_{vd} (52.12 MPa) and highest DCPI (1.81 mm/blow). In contrast, the water content of Layer IV (28.69%) was closest to the optimum (28.4%) and coincided with the highest degree of compaction (95.7%), highest E_{vd} (88.30 MPa), and lowest DCPI (0.49 mm/blow). Longitudinally, K0+080 also remained relatively strong in CBR and M_R and low in deflection. Thus, spatial differences in water content and compacted state established during construction persisted in the later bearing and deformation response.

(1) Degree of compaction showed the strongest association with the early field mechanical differences. As compaction increased, E_{vd} increased and DCPI decreased (**Figs. S8a and S8b**). Higher dry density promotes particle rearrangement, reduces large voids, and increases particle contacts and frictional interlock ([N. C. Consoli et al., 2011](#)). Shorter interparticle distances also favor the development of a more continuous cemented framework as reaction products bridge neighboring particles, consistent with relationships between porosity, binder content, and the strength or stiffness of stabilized soils reported in the literature ([Horpibulsuk et al., 2010](#)).

(2) Initial water content provided an additional coupled influence. At water contents above optimum, excess free water reduces matric suction and effective particle

contact and can lower the dry density achieved under a given compaction effort (Nilo Cesar Consoli et al., 2011). A higher water-to-solids ratio can also dilute reactive species in the pore solution and delay early development of the cemented structure (Horpibulsuk et al., 2010; Wei et al., 2020). These effects are particularly relevant to S-SR because raw SR has strong water retention and a high soluble-salt content; changes in water content therefore alter both the physical compaction state and the ionic environment of the pore solution. High ionic strength can modify particle-surface interactions (Ying et al., 2021), and changes in OH^- concentration and ionic strength can affect activation of GGBS and FA in SR-based systems (Modmoltin & Voottipruex, 2009; D. Wang et al., 2025). Accordingly, water content should be controlled carefully even though degree of compaction showed the stronger statistical association with the dynamic indices.

(3) DCPI was slightly more strongly correlated with degree of compaction ($R^2 = 0.98$) than E_{vd} ($R^2 = 0.93$), reflecting the different measurement scales of the two tests. DCP is governed mainly by local shear and compression resistance around the cone and is therefore sensitive to particle contacts, local voids, water content, and bonding integrity; this sensitivity supports its use for rapid field assessment of compacted fills (Du et al., 2016; Feng et al., 2022). PFWD, by contrast, represents the equivalent dynamic stiffness over a larger loaded volume and is influenced by stress distribution and interlayer contact (Fleming et al., 2007). For S-SR construction, DCPI can therefore be combined with rapid water-content measurements to identify local weak or overly wet areas, whereas E_{vd} is better suited to evaluating the overall stiffness of the compacted layer system.

4.2. Correlations of DCPI with field mechanical performance and leaching of characteristic anions

DCP is portable, rapid, and minimally disturbing. DCPI measured at 1, 3, 7, and 28 d was therefore correlated with CBR, M_R , rebound deflection, E_{vd} , and core-leached Cl^- and SO_4^{2-} to assess its value as a field indicator (Figs. S9–S11).

(1) As curing progressed, DCPI decreased from 1.20 to 0.10 mm/blow, while CBR, M_R , and E_{vd} increased and rebound deflection decreased. All four mechanical indices followed strong power-law relationships with DCPI ($R^2 = 0.94\text{--}0.99$; **Fig. S9**), demonstrating close synchronization between improved penetration resistance and the development of macroscopic bearing capacity and stiffness. CBR and E_{vd} showed larger absolute exponents than M_R and deflection, indicating different sensitivities related to their loading modes and measurement scales.

(2) **Figure S10** further shows that the DCP–CBR relationship for S-SR differs substantially from conventional empirical correlations. Using ordinary least-squares regression of the base-10-transformed variables, the best-fit relationship was $\log CBR = 1.67 - 0.59 \log DCPI$ ($n = 4$, $R^2 = 0.99$). The 95% confidence intervals of A and B were 1.542–1.793 and 0.380–0.809, respectively. Representative correlations for natural soils, granular materials, and conventional subgrades have A values of 2.465–2.62 and B values of 1.12–1.27 in the general form $\log CBR = A - B \log DCPI$ (Du et al., 2016; Harison, 1987; Kley, 1975; Webster et al., 1992). The field relationship reported by Du et al. (2016) for an industrial-solid-waste-stabilized subgrade, $A = 2.59$ and $B = 1.13$ also falls within this range. In contrast, both coefficients for S-SR were substantially lower ($A = 1.67$ and $B = 0.59$). The difference likely reflects the strongly cemented and age-dependent response of S-SR: DCP is highly sensitive to local hardening around the cone, whereas CBR averages load–deformation behavior over a larger stressed volume. Consequently, conventional DCP–CBR equations should not be applied directly to S-SR; the present relationship should be regarded as a preliminary material-specific calibration requiring independent validation across different sites, material batches, and service conditions.

(3) For leaching of the characteristic anions (**Fig. S11**), DCPI correlated positively and linearly with the leached Cl^- and SO_4^{2-} concentrations ($R^2 = 0.81$ and 0.91 , respectively). As DCPI decreased, both anion concentrations decreased, with the synchronization particularly evident for Cl^- . This correlation does not imply that DCPI directly controls ion release; rather, both reflect the common progression of curing and

stabilization. Continued structure development reduces DCPI through stronger particle bonding and lower pore connectivity, while the same evolving pore structure and solid-phase retention processes reduce the mobility of Cl^- and SO_4^{2-} (D. Wang et al., 2025; Zeng et al., 2026). DCPI may therefore serve as an auxiliary trend indicator of concurrent mechanical hardening and environmental stabilization, but cannot replace direct leaching measurements or serve as an independent predictor of pollutant release.

(4) It should be noted that the above field mechanical-performance evolution and correlation analyses were based on measurements obtained within 28 d after construction and therefore primarily represent the early-age bearing capacity and stiffness development of S-SR rather than its long-term mechanical durability under traffic loading and seasonal environmental actions. Although the field curing period experienced low temperatures, rainfall, and rain-snow events, these natural exposures cannot substitute for standardized long-term wet-dry, freeze-thaw, or traffic cyclic-loading tests. Therefore, the long-term mechanical performance of S-SR under multi-year service, repeated wetting, and freeze-thaw conditions requires further verification through longer-term field monitoring and dedicated durability testing.

4.3. Coupled evolution of the all-solid-waste subgrade hydrothermal state and leachate chemistry

Because the VWC channel was not specifically calibrated for high-salinity S-SR, no quantitative VWC–EC regression was performed. The analysis was therefore limited to the temperature relationships, the leachate EC–pH relationship, and the relationships of leachate pH and EC with cumulative rainfall (Figs. 10 and S12).

(1) Lysimeter leachate temperature correlated positively with air temperature and with subgrade temperatures at depths of 0.3 and 0.7 m (Fig. 10a). The fitted slopes were 0.18, 0.21, and 0.23, with R^2 values of 0.71, 0.84, and 0.83, respectively. Because all slopes were much smaller than 1 and the correlations with subgrade temperature were stronger than that with air temperature, atmospheric thermal fluctuations were evidently

attenuated and smoothed by heat transfer through the subgrade before affecting the lysimeter leachate. The leachate temperature therefore represents a longer-term integrated thermal state rather than instantaneous air temperature, suggesting that its long-term hydrochemical evolution is governed more strongly by sustained infiltration and stabilization than by short-duration temperature excursions.

(2) Lysimeter leachate EC correlated strongly with pH ($R^2 = 0.93$; **Fig. 10b**), and both decreased with cumulative rainfall according to power-law relationships (**Fig. S12**). The absolute rainfall exponent for EC was approximately 4.4 times that for pH, indicating greater sensitivity of leachate EC to rainfall flushing. EC responds directly to the total concentration of mobile ions, whereas pH remains buffered by residual alkaline solids and reaction products. For the high-chloride S-SR, readily mobile Cl^- can be exported rapidly during infiltration, while a less mobile fraction may be retained by solid-phase interactions. The long-term hydrochemical response therefore cannot be attributed to simple dilution alone; rainfall-driven flushing and continued stabilization act concurrently to reduce soluble-salt release and progressively shift the lysimeter leachate from a high-alkalinity, high-EC state toward a more stable weakly alkaline and lower-EC condition. Similar long-term attenuation of leachate chemistry has been reported for other solid-waste road materials ([Chen et al., 2013](#)).

(3) Because the field lysimeter had a closed HDPE hydraulic boundary and monitoring began approximately two months after construction, its results represent middle-to-late-stage leachate evolution rather than the complete field seepage process or early Cl^- release. Early anion release was therefore assessed by core leaching, whereas groundwater response was evaluated independently using paired upstream and downstream monitoring wells. Longer-term migration under extreme rainfall and service conditions still requires further monitoring. The test road contained no reinforced components; for coastal transport infrastructure containing reinforcement, residual Cl^- migration and corrosion risk require further assessment.

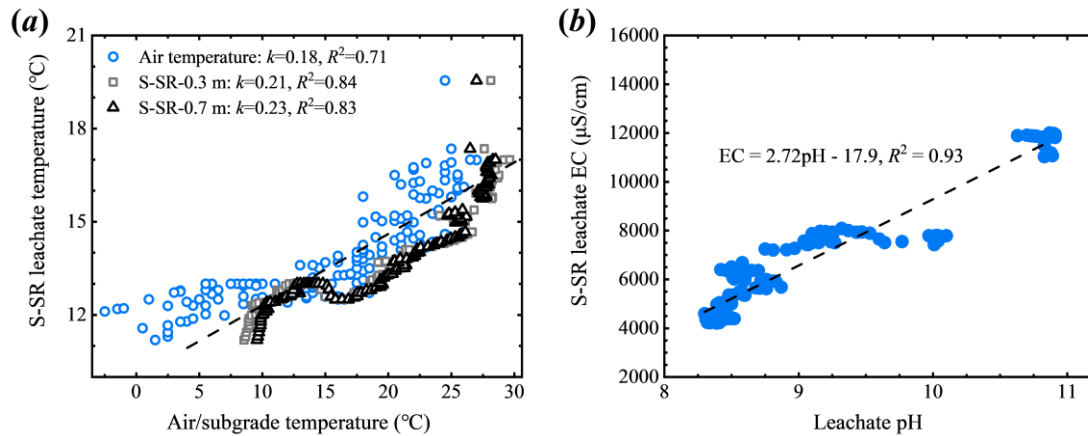


Fig. 10. Relationships between field-monitored hydrothermal and hydrochemical parameters: (a) leachate temperature versus air and subgrade temperatures; and (b) leachate EC versus pH.

4.4. Comparative performance of S-SR and reported soda-residue-based subgrade materials

To compare the engineering performance of S-SR with reported soda-residue-based subgrade materials, four representative systems were selected and compared in terms of SR utilization, 7-d field CBR, reported environmental/leaching data, material-related cost, and production-stage carbon emissions (**Table 4** and **Fig. 11**).

(1) SR consumption (**Fig. 11a**). S-SR contained 70% raw SR versus 30% raw SR in the four literature systems. Unlike systems in which soda residue is an amendment to soil with lime or cement, S-SR used raw SR as the principal constituent and only locally available GGBS, FA, and IT as stabilizers. For a 0.8-m-thick, 6-m-wide subgrade, this corresponds to approximately 7,000 m³ of raw SR per kilometer of roadway.

(2) Mechanical performance (**Fig. 11b**). The 7-d mean field CBR of S-SR was 100.8%, exceeding the reported values for LSRSS (65%), SRS (71.1%), PRS (79.6%), and A-LS (27.6%). Thus, the highest residue content among the compared systems was achieved without sacrificing early field bearing capacity.

(3) Environmental/leaching data (**Table 4**). This study provides standardized multi-age leaching results for Cl⁻, SO₄²⁻, and heavy metals over 1–60 d, together with

approximately five months of field lysimeter pH/EC monitoring and short-term groundwater monitoring before and after construction, providing a relatively complete dataset on age-dependent behavior and field response. In contrast, the compared literature systems report limited information on long-term leaching of characteristic anions or field water-environment responses.

(4) Material cost and carbon emissions (methods and parameters are provided in **SI Text S2** and **Tables S4–S6; Figs. 11c and 11d**). Based on a design degree of compaction of 95%, the material cost of S-SR was 41.8 CNY/m³, approximately 54%–60% of those of the lime-based systems (70.0–76.9 CNY/m³) and 28% of that of the cement-based A-LS (149.5 CNY/m³). Its production-stage carbon emissions were 9.0 kg CO₂e/m³, approximately one-seventh of those of the lime-based LSRSS, SRS, and PRS systems (63–67 kg CO₂e/m³) and one-twelfth of that of A-LS (108.4 kg CO₂e/m³). Sensitivity analysis confirmed that the comparative conclusions remained stable under variations in compaction, emission factors, and material prices (**Table S6**). These comparisons are limited to the material-production stage and do not constitute a full life-cycle assessment.

Table 4. Composition and reported environmental/leaching data for typical soda-residue-based subgrade materials.

Material system	Composition	Reported environmental/leaching data	Reference
LSRSS	6% lime + 30% SR+ 70% clay	NR	Zhao et al. (2024)
SRS	6% lime + 30% SR + 70% WFS (waste fishpond soil)	Only total Cl ⁻ and heavy metals were measured at 7 d	Zhang et al. (2025)
PRS	6% lime + 30% SR + 35% PT (phosphate tailings) + 35% WFS	Only total Cl ⁻ and heavy metals were measured at 7 d	Zhang et al. (2025)
A-LS	30% OPC + 40% GGBS + 30% SR	NR	Wang et al. (2026)
S-SR	17% GGBS + 3% FA + 10% IT + 70% SR	Age-dependent Cl ⁻ /SO ₄ ²⁻ leaching (1–60 d), field lysimeter pH/EC, and 3-month groundwater monitoring	This study

Note: NR = not reported. For the lime-based systems, lime is added externally at 6% of the dry mass of the soil–SR mixture. For S-SR, the Class IV groundwater values of [GB/T 14848-2017 \(2017\)](#) are used only as screening references for standardized leaching results; environmental information for

the literature systems is reported as available in the cited studies. Reference materials are abbreviated as follows: LSRSS, lime-soda-residue-stabilized soil (Zhao et al., 2024); SRS, soda residue modified fishpond soil (Zhang et al., 2025); PRS, phosphate tailings-soda residue modified fishpond soil (Zhang et al., 2025); and A-LS, alkali residue-based lightweight soil (Wang et al., 2026).

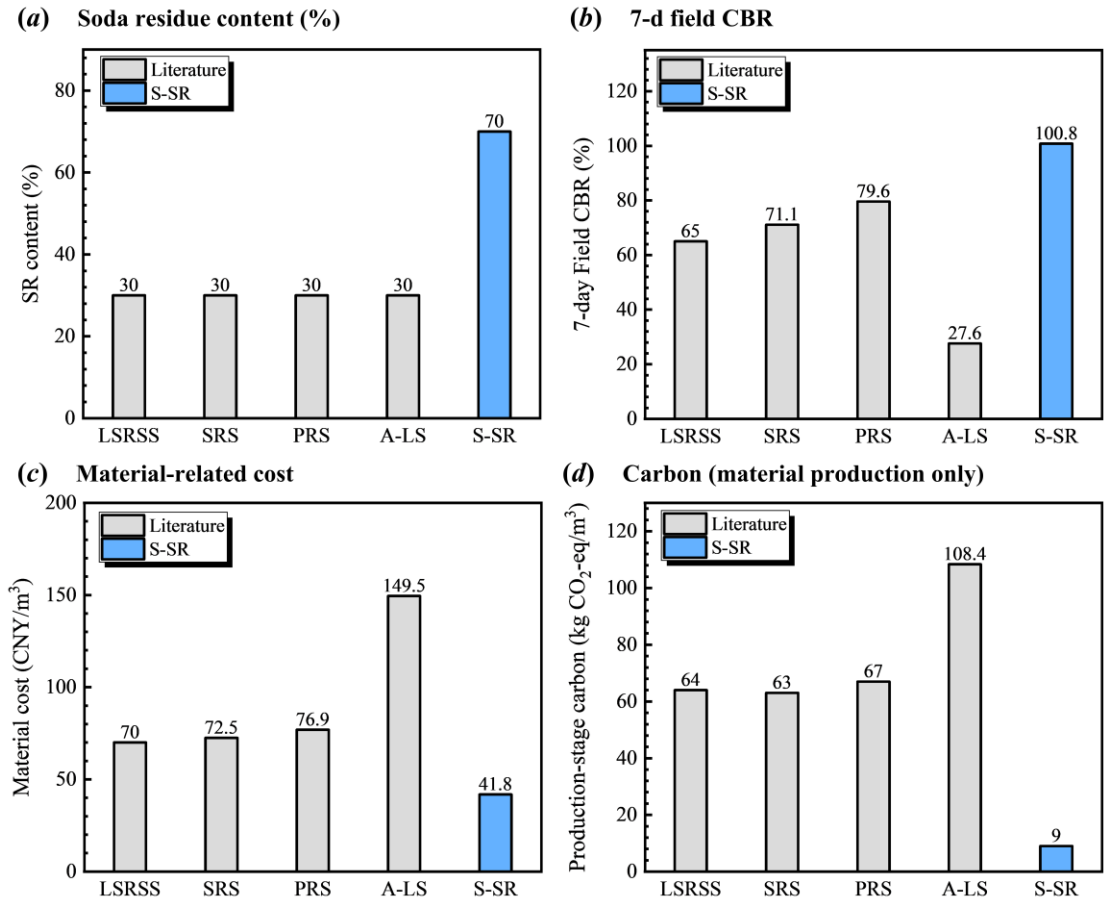


Fig. 11. Comparison of typical soda-residue-based subgrade materials in terms of (a) soda-residue content, (b) 7-d field CBR, (c) material cost, and (d) material-production-stage carbon emissions. Light-grey bars denote literature materials.

5. Conclusions

Based on the full-scale field trial, this study investigated the construction, early-age mechanical performance, leaching behavior, and in situ environmental response of the all-solid-waste stabilized soda residue (S-SR) subgrade. The main conclusions are as follows:

(1) A practical construction procedure was established for high-SR-content S-SR using layered placement, multi-pass in situ mixing, staged water-content conditioning, and graded compaction. The optimum water content and maximum dry density were 28.4% and 1.26 g/cm³, respectively. The poorer compaction of wetter Layer III relative to Layer IV confirmed the importance of controlling water content and its uniformity.

(2) S-SR developed high bearing capacity under low-temperature natural curing. From 1 to 28 d, mean CBR increased from 38.6% to 164.6%, M_R from 260.8 to 388.6 MPa, and Layer IV E_{vd} increased from 65.6 to 199.9 MPa, while rebound deflection decreased from 0.374 to 0.190 mm. Interlayer differences in E_{vd} and DCPI were jointly influenced by degree of compaction and construction water content.

(3) Multi-age core leaching showed that Cl⁻ dominated early-stage leaching, with its concentration decreasing from 3028 to 268 mg/L and SO₄²⁻ from 286 to 15 mg/L between 1 and 60 d. Five months of field lysimeter monitoring, initiated about two months after construction, showed decreases in leachate pH from 10.87 to 8.32 and EC from 15,469 to 4,236 μ S/cm, reflecting lower middle-to-late-stage alkalinity and overall dissolved-ion levels. Groundwater monitoring showed no sustained increase in Cl⁻, SO₄²⁻, or heavy metals during the first three months after construction, although longer-term effects require further field monitoring.

(4) DCPI showed strong relationships with field mechanical indices and age-dependent anion leaching. The material-specific DCP–CBR relationship, $\log CBR = 1.67 - 0.59 \log DCPI$, differed markedly from conventional correlations. DCPI can therefore serve as an auxiliary trend indicator of S-SR hardening and environmental response, but not as an independent predictor of pollutant release; the preliminary DCP–CBR calibration requires independent field validation.

(5) Compared with representative literature systems, S-SR achieved higher SR utilization (70% vs. 30%) and 7-d field CBR (100.8% vs. 27.6%–79.6%), together with lower material cost (41.8 vs. 70–149.5 CNY/m³) and production-stage carbon emissions (9.0 vs. 63–108.4 kg CO₂e/m³). The cost and carbon comparison is limited to the material-production stage and does not constitute a full life-cycle assessment.

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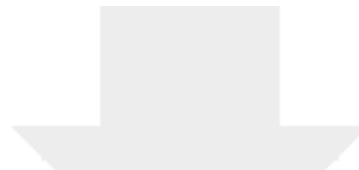
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Supplementary material

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