

Supplementary Tables

Table S1 — Strength and Durability Under Wet-Dry Cycles

Cycles	UCS Retention (%)	CBR Retention (%)	Mass Loss (%)	Notes (AASHTO Standard)	Subgrade
0	100	100	0	Baseline	
4	92	95	2.5	Good	
8	88	90	4.8	Acceptable	
12	85	87	6.2	Meets CBR >7% for subbase (IRC)	

Table S2 — Residual Analysis for Gradient Boosting (Fused Data)

Metric	Value (UCS, kPa)	Interpretation
Mean Residual	1.2	Minimal bias
Std. Deviation Residual	8.5	Consistent
Max Positive Residual	18	High UCS cases
Max Negative Residual	-15.5	Low UCS cases

Table S3 — Multiscale Linkages (Macro to Micro, Optimal Mix)

Macro Property	Value	Linked Micro Change (SEM/XRD/Thermal)	Correlation Strength
UCS (250 kPa)	High	Dense C–S–H, reduced porosity (~10%)	Excellent
Swell Reduction (72%)	High	Flocculation + amorphous gel increase	Strong
Durability Retention (85% after 12 cycles)	Good	Stable polymeric bonds (thermal bound water high)	Good

Table S4 — Sustainability and Field Validation Summary

Aspect	Value/Outcome	Notes
CO ₂ Reduction vs. Lime	85–90%	Waste reuse
Cost Savings	35–50%	Low material cost
Field Trial (Simulated)	CBR 16–18% after 6 months	Durable under traffic

Table S5 — Material Unit Costs

Material	Price per Tonne (USD)	Price per Tonne (NGN)	Source Notes
Wood Ash	5–15	7,250–21,750	Byproduct
NaCl	50–80	72,500–116,000	Commercial
Lime	150–200	217,500–290,000	Geotech grade
Cement	120–160	174,000–232,000	Standard

Table S6 — Monetized Environmental and Societal Costs

Stabilizer System	Embodied CO ₂ (kg/tonne)	External Cost (USD/tonne)	Notes
Lime	90–100	17–19	High calcination
Cement	64–72	12–14	Process emissions

Optimal WA+NaCl	5–15	1–3	Near-zero for WA
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Table S7 — Salinity Mitigation Effectiveness

Strategy	Mechanism	Target Risk Reduction	Effectiveness (%)	Implementation Cost (Relative)	Applicability
Low NaCl Dosage ($\leq 10\%$)	Minimizes total soluble salts input	EC/SAR increase	70–90	Low	Core design
Co-add Ca ²⁺ -rich Binders	Displaces Na ⁺ , binds Cl ⁻ in C-S-H	Sodicity, leaching	>95	Low–Moderate	Essential
Controlled Post-Curing Leaching	Flushes excess salts below zone	Soluble Cl ⁻ /Na ⁺	60–80	Moderate	Drained sites
Deep Application ($>1\text{m}$) + Capping	Isolates from surface/ground water	Vegetation/groundwater contamination	80–90	Moderate	Roads/embankments
Substitute/Bond Salts (CaCl ₂ /MgCl ₂)	Better flocculation, lower Na ⁺	Sodicity	50–70	High	Alternative

Table S8 — Monitoring Parameters and Thresholds

Parameter	Safe Threshold (Geotech Subgrade)	Monitoring Method	Frequency
Electrical Conductivity (EC)	<4 dS/m	Soil paste extract	Annual
Sodium Adsorption Ratio (SAR)	<13	Exchangeable cations	Biennial
Chloride (Cl ⁻) Leachate	<500 mg/L	TCLP/leach test	Post-rainy season
pH	7–9	Soil pH meter	Annual