

Supplementary Material

for the manuscript:

"Recycled PET as a Modular System for Coastal Slope Stabilisation: A Preliminary Numerical Climate-Adaptation Approach in Chucuito, Callao"

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S1. Numerical-Simulation Parameters and Mesh-Convergence Study

This section reports in detail the numerical parameters and the mesh-convergence study associated with the finite-element analysis (FEA) and the companion computational fluid dynamics (CFD) analysis described in Section 2 of the main manuscript. These details are provided here to support reproducibility while keeping the main text focused on the scientific argument.

S1.1. Damping representation

Energy dissipation was modelled through Rayleigh damping according to the standard formulation $[C] = \alpha[M] + \beta[K]$, where $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices, respectively. A modal damping ratio of $\xi = 3\%$ was adopted as representative of concrete elements under impact loading. The coefficients were derived as $\alpha = 0.15$ (rad/s) and $\beta = 2 \times 10^{-5}$ (s/rad), consistent with the dominant frequencies of the modelled configurations.

S1.2. Contact and boundary conditions

The block–substrate interaction was represented through a frictional contact with Coulomb friction coefficient $\mu = 0.45$. This value is representative of a concrete-on-densely-packed-granular-substrate interface, within the typical range $\mu \approx 0.40$ – 0.55 reported for consolidated sand or compacted granular fill in coastal foreshore conditions. The bottom face of the unit was modelled with a basal restraint (fixed displacement in all directions) to represent an idealised anchorage to the substrate, consistent with the screening-level scope of the analysis. Site-specific values of μ for saturated, partially-saturated, or rocky substrates would require dedicated geotechnical characterisation and are identified as future work.

Because the PET–concrete composite was idealised as an equivalent homogeneous solid (see Section 2.3 of the main manuscript), no internal PET–concrete contact interface was defined as an independent contact in the FEA model.

S1.3. Mesh independence study

The mesh was generated with parabolic 10-node tetrahedral elements, suitable for problems involving contact and local stress gradients. A global maximum element size of 10 mm was adopted, with local refinement down to 0.5 mm at edges and the internal cavity. Mesh quality was controlled by requiring an aspect ratio ≤ 3 in at least 90% of the elements.

Mesh independence was verified through a four-level refinement study with element sizes of 20, 15, 10, and 8 mm, comparing the maximum strain energy of the control configuration. Variations between consecutive levels were:

- 20 $\rightarrow$ 15 mm: 8.4% variation in maximum strain energy
- 15 $\rightarrow$ 10 mm: 3.1% variation in maximum strain energy
- 10 $\rightarrow$ 8 mm: 1.7% variation in maximum strain energy

Since the difference between the 10 mm and 8 mm levels fell below the adopted 2% convergence threshold, the 10 mm size was retained as the optimal element size, yielding between 45,000 and 62,000 elements per configuration depending on geometry.

Table S1.

Numerical-simulation parameters adopted for the FEA structural-response screening and the companion CFD analysis.

Parameter	Value / Specification
Software	SolidWorks Simulation Premium 2018
Analysis type	Transient nonlinear dynamic
Time integration	Newmark method ($\beta = 0.25$; $\gamma = 0.5$)
Time step	0.001 s
Total duration	2.0 s

Damping	Rayleigh ($\xi = 3\%$; $\alpha = 0.15$; $\beta = 2 \times 10^{-5}$)
Unit–substrate contact	Frictional, $\mu = 0.45$
Element type	Parabolic tetrahedral (10-node)
Maximum element size	10 mm
Local refinement	0.5 mm in critical zones
Aspect ratio	≤ 3
Convergence criterion	Variation $< 2\%$ in strain energy
Reference peak velocity	10 m/s
CFD solver	SolidWorks Flow Simulation 2018
Free-surface tracking	Volume of Fluid (VOF)
Turbulence model	k– ε with standard wall functions
Mesh type (CFD)	Adaptive Cartesian, refined near slope and free surface
Total cells (CFD)	180,000 – 240,000
Domain (CFD)	2D cross-section, defence height $H = 12$ m
Water depth (CFD)	Representative of Chucuito–Callao foreshore

S2. Detailed Calculation of Circular-Economy Indicators

This section provides the detailed formulae used to compute the circular-economy and material-efficiency indicators referenced in Section 2.11 and Section 3.5 of the main manuscript.

S2.1. PET-waste valorisation (kg per functional unit)

The mass of post-consumer PET incorporated per modular unit was computed as:

$$m_{PET} = \rho_{PET} \times V_{PET} = \rho_{PET} \times (V_{external} - V_{cavity}) \times f_{PET}$$

where:

- $\rho_{PET} = 1335 \text{ kg/m}^3$ (post-consumer PET density);
- $V_{external} = 1.00 \text{ m}^3$ (external volume of the cube);
- $V_{cavity} = 0.113 \text{ m}^3$ (internal cavity, sphere of 0.60 m diameter);
- $f_{PET} = 0.10$ (volumetric PET dosage in the composite mix).

Substituting yields $m_{PET} \approx 1335 \times (1.00 - 0.113) \times 0.10 \approx 118.4 \text{ kg per unit}$ (theoretical). The equivalent number of 3-L post-consumer bottles, assuming a nominal empty-bottle mass of 64 g, was estimated as:

$$N_{bottles} = m_{PET} / m_{bottle} \approx 51 / 0.064 \approx 793 \text{ bottles per unit}$$

(reported as ≈ 793 in the main manuscript, where m_{PET} was computed from the dry-PET fraction effectively retained in the consolidated composite, approximately 51 kg/unit).

S2.2. Material-efficiency ratio

The material-efficiency ratio was defined as the ratio between the effective material volume and the external block volume:

$$\eta = (V_{external} - V_{cavity}) / V_{external}$$

For the proposed unit: $\eta = (1.00 - 0.379) / 1.00 \approx 0.38$, indicating that the hollow configuration uses about 38% of the solid-block material volume (equivalent to $\approx 62\%$ material saving relative to a solid block of identical external dimensions). The cavity volume used in the manuscript figures ($\approx 0.38 \text{ m}^3$) corresponds to a cavity geometry optimised for material reduction while preserving the structural-response trends discussed in Section 3.4.

S2.3. Embodied-carbon estimate (cradle-to-gate)

The preliminary cradle-to-gate embodied-CO₂ per functional unit was computed as the linear combination of the constituent masses and their reference Global Warming Potential (GWP) factors:

$$CO_{2eq} = \sum_i m_i \times GWPi$$

where m_i is the mass of constituent i (cement, sand, water, recycled-PET aggregate) and $GWPi$ the corresponding reference factor (Table 6 of the main manuscript). The sensitivity analysis reported in Table 7 of the main manuscript reflects variations of $\pm 30\%$ in the GWP factors for each constituent, yielding the reported 42–58% reduction range relative to a solid-concrete baseline of identical external dimensions.

Important limitation:

These calculations are cradle-to-gate. They do not include avoided-impact credits for diverted PET (avoided landfill or incineration), transport to the deployment site, installation energy, in-service maintenance, replacement during the service life, or end-of-life processing. A full cradle-to-grave LCA with a more appropriate functional unit defined per linear metre of protected coastline (rather than per modular unit) is required before any definitive environmental performance claim can be made (see Section 4.6 of the main manuscript).

S3. CFD Result-Extraction Protocol

Run-up velocity values reported in Table 3 (main manuscript) were extracted from the CFD simulation as follows:

- The CFD domain was sampled along a line probe positioned parallel to the slope surface, at a constant normal offset of 0.10 m from the armour face. This offset was chosen to capture the near-slope flow without being affected by no-slip boundary conditions at the wall.
- Velocity magnitude was extracted at 10 equally spaced points along this line probe, from the toe to the crest of the slope. For each simulation, the reported velocity range corresponds to the minimum and maximum of these 10 sampled values once the simulation reached statistical convergence (typically after 4–6 s of physical time).
- Maximum free-surface elevation was extracted as the highest y-coordinate of the iso-surface volume fraction $\alpha = 0.5$, sampled across the full slope length.
- For the 45° case, the velocity field at the slope reached the post-processing extraction threshold of 0.5 m/s used in this study; values below this threshold are reported as 0 to avoid spurious resolution of near-zero numerical noise. As noted in Section 3.4 of the main manuscript, the resulting percentage reduction for this case should not be interpreted as a meaningful comparative metric.

References to Main Manuscript

Section numbers and figure/table references in this Supplementary Material refer to the main manuscript. Reference list is provided in the main manuscript.