Electronic Supplementary Information (ESI) for

A sustainable L-serine-induced hydrogel with ultrafast gelation, mechanical resilience, and environmental robustness for efficient sand stabilization

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1. Characterization of hydrogels

1.1 Gelation time testing

The gelation time of the hydrogels was determined using the Fishell method, which is commonly used to evaluate gelation in epoxy resin systems. Specifically, 35 mL of the initiator-containing precursor solution was poured into a 9 cm-diameter glass dish. A glass rod was used to periodically probe the mixture, and the time taken for the solution to reach the stringing state was recorded as the gelation time. All tests were conducted at 25 °C under ambient conditions. For visual demonstration, the vial inversion method was also utilized.

1.2 FTIR spectroscopy testing

The chemical structures of the hydrogels were analyzed using a Nicolet iS50 Fourier transform infrared spectrometer (Thermo Scientific, USA) in attenuated total reflectance (ATR) mode. Spectra were collected in the 4000–500 cm^{-1} range to identify functional group compositions and changes.

1.3 Rheological testing

The rheological behavior of the hydrogels was evaluated using an MCR 302 rheometer (Anton Paar, Austria) in frequency sweep mode. Hydrogel samples were prepared as disks (25 mm diameter, 2 mm thickness). Measurements were conducted at a fixed strain of 0.01% over 0.1–10 Hz, at 25 °C, –20 °C, and 45 °C to assess temperature-dependent viscoelastic properties.

1.4 Water retention testing

Water retention capacity was determined gravimetrically. Each sample's initial mass (W_0) was recorded, then placed at 25 °C and 60% relative humidity. Mass (W_t) was monitored every 12 hours using an electronic balance. All tests were performed in triplicate, and average values were used. The water retention rate was calculated using the following equation: Water retention rate (%) = (W_t / W_0) × 100%.

1.5 Differential scanning calorimetry (DSC) testing

Hydrogel samples (5–10 mg) were sealed in aluminum pans and analyzed using a PE 8500 differential scanning calorimeter (PerkinElmer, USA). Tests were conducted under nitrogen from –40 °C to 20 °C at a 5 °C/min heating rate.

1.6 Antifreeze performance testing

Hydrogel samples were cut into cylindrical shapes (12.5 mm diameter, 2 mm thickness), frozen at –20 °C for one week, and their post-freezing appearance was documented photographically.

1.7 Thermogravimetric analysis (TGA)

Thermal stability was assessed using a TGA Q500 (TA Instruments, USA). Samples (~10 mg) were heated from 25 °C to 600 °C at 10 °C/min under 50 mL/min nitrogen flow.

1.8 Swelling behavior testing

Freshly prepared $PGL_{0.25}$ hydrogel samples were molded into uniform disks (diameter: 10 mm, thickness: 2 mm) and immediately immersed in aqueous solutions with different pH values (3, 5, 7, and 9) at 25 °C. At predetermined time points (days 1−10), the swollen hydrogels were removed, surface water was gently blotted with filter paper, and the swollen weight (W_t) was recorded. Each condition was tested in triplicate to ensure data reliability. The initial weight (W_0) was measured before immersion. The swelling ratio (SR) was calculated as: Swelling ratio (%) = $(W_t - W_0) / W_0 \times 100\%$.

1.9 Degradation behavior testing

Hydrogel samples of the same dimensions were immersed in aqueous solutions with varying pH (3, 5, 7, and 9) at 25 °C. At selected time points over 15 days, the samples were removed, rinsed with deionized water, vacuum-dried at 45 °C to constant weight

(W_t), and compared to their initial dry weight (W_0). All experiments were conducted in triplicate. The mass retention was calculated as: Mass retention (%) = $W_t / W_0 \times 100\%$.

2. Environmental stability and compatibility evaluation

2.1 Thermal aging resistance testing

PGL0.25 hydrogel-stabilized sand samples were aged at 45 °C, with samples collected on days 0, 2, 4, 8, 16, and 32 for mass and compressive strength evaluation. SEM was used to analyze surface morphology at each time point. Mass loss (%) was calculated as: $(W_0 - W_n) / W_0 \times 100\%$, where W_0 was initial mass and W_n was mass after n days.

2.2 Freeze–thaw durability testing

To evaluate freeze–thaw durability, PGL0.25 hydrogel-stabilized sand samples were subjected to cyclic freezing at −20 °C for 12 hours, followed by thawing at 25 °C for 12 hours. Each cycle consisted of one freezing and one thawing phase. Samples were collected after 0, 2, 4, 8, 16, and 32 cycles for mass measurement and compressive property testing. SEM was employed to examine surface morphology and assess microstructural changes induced by repeated freeze–thaw stress. For comparison, control samples were prepared by adding an equivalent amount of water to the sand without hydrogel. After undergoing the same freeze–thaw protocol, these samples were subjected to compression testing to demonstrate the structural instability in the absence of hydrogel reinforcement. The mass loss rate after n freeze–thaw cycles was calculated using the following equation: Mass loss rate (%) = $(W_0 - W_n) / W_0 \times 100\%$, where W_0 is the initial mass of the sample, and W_n is the mass after n freeze–thaw cycles.

2.3 Water and pH resistance testing

$PGL_{0.25}$ hydrogel-stabilized sand samples were first weighed and measured to record the initial mass (W_0) and volume (V_0). The samples were then immersed in aqueous solutions with pH values of 3, 5, 7, and 9. At 12-hour intervals, the samples were removed to measure their mass (W_n) and volume (V) to evaluate the swelling behavior and volume change under different pH conditions. SEM was employed to observe the

surface morphology of the samples under each condition, providing insight into microstructural changes. The swelling ratio and volume ratio were calculated using the following formulas: Swelling ratio (%) = $(W_n - W_0) / W_0 \times 100\%$.

2.4 Environmental compatibility evaluation

To evaluate the environmental compatibility of the hydrogel-stabilized sand, a plant cultivation experiment was conducted using mung bean and wheat as indicator species. In the experimental group, $PGL_{0.25}$ hydrogel-stabilized quartz sand was used as the planting medium, while the control group consisted of the same amount of quartz sand moistened with distilled water. An equal number of seeds were sown on the surface of each medium and cultured under identical conditions of light, temperature, and humidity. Germination rate, seedling height, and root development were regularly recorded and compared between the two groups. This assessment aimed to determine the suitability of the hydrogel-stabilized sand for supporting plant growth and its overall environmental compatibility.

Supplementary Figures

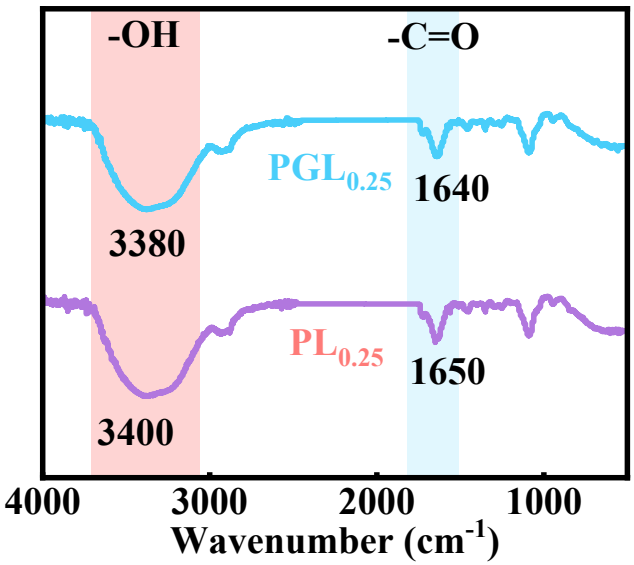

Fig. S1. FTIR spectra of the $PGL_{0.25}$ and $PL_{0.25}$ hydrogels.

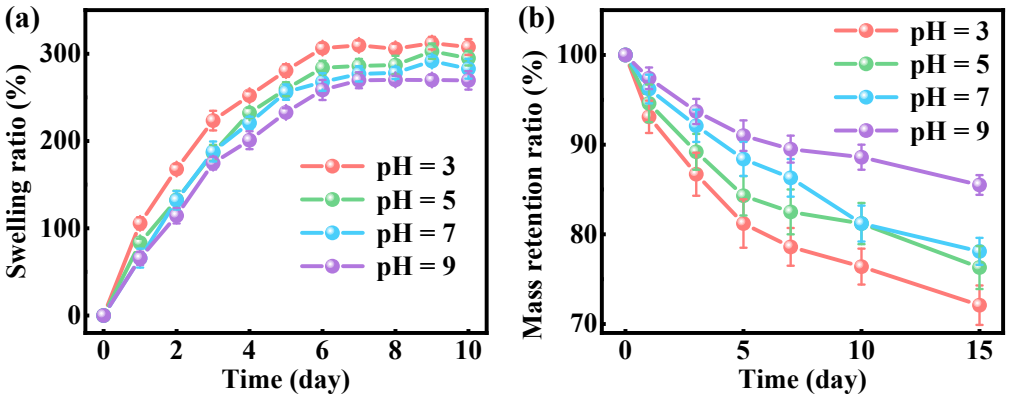

Fig. S2. Swelling and degradation behavior of the $PGL_{0.25}$ hydrogel under different pH conditions.

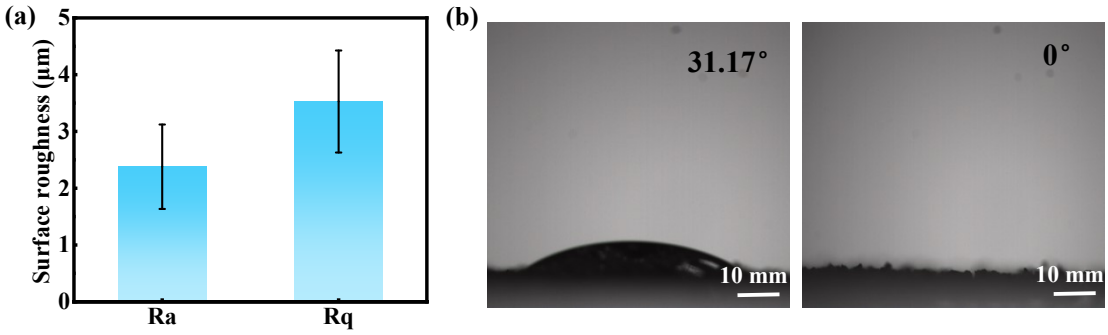

Fig. S3. (a) Surface roughness profile of the quartz sand surface measured using white-light

interferometry. (b) Static contact angle image of the hydrogel precursor droplet deposited on the quartz sand surface.

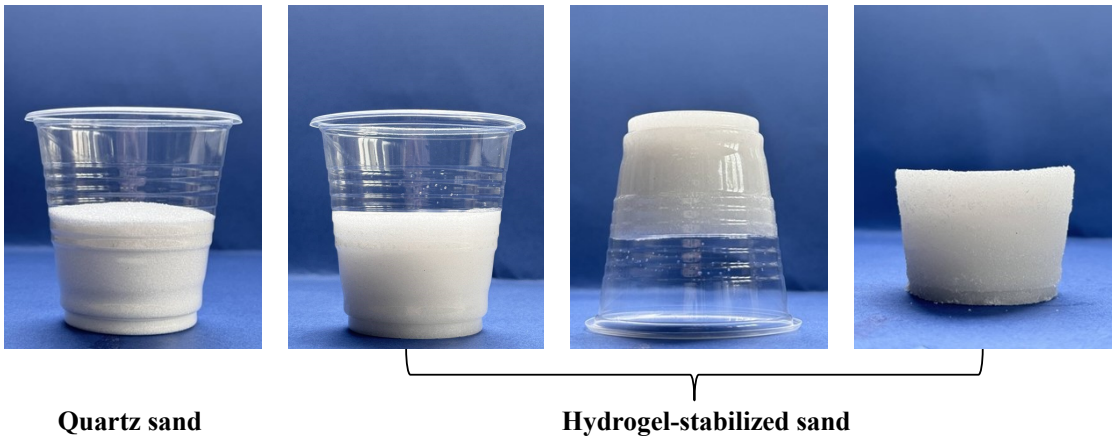

Fig. S4. Representative images of the sand matrix following precursor infiltration and in situ gelation.