cbecimat26
26° Congresso Brasileiro de Engenharia e Ciência dos Materiais
22 a 26 de novembro de 2026
Costão do Santinho
Florianópolis-SC

Thermal treatment of end-of-life solar panels: effects on the glass component

Pedro Cerqueira[1]; Daniel Majuste[1]; Luiz Pereira[2]

1. Department of Metallurgical and Materials Engineering, Federal University of Minas Gerais, Belo Horizonte, Brazil;
2. GEOLAB, Hangzhou International Innovation Institute, Beihang University, Hangzhou, China

Introduction & Background

Global photovoltaic (PV) waste reached 0.6 Mt in 2022, with only 17% formally recycled, and is projected to quadruple to 2.4 Mt/year by 2030. Because soda-lime glass represents over 70 wt% of an end-of-life PV module; thus, closing its material loop is vital for environmental sustainability, circular economy, and resource preservation. Thermal delamination successfully degrades the ethyl-vinyl acetate (EVA) encapsulant, but the recovered substrate must retain its high optical transmittance and mechanical integrity without network degradation.

Objective

Investigate the effects of isothermal EVA thermal delamination at 400°C in air (1 to 128 h) on the optical, structural, and mechanical response of the recovered solar glass.

Methodology

Module Pre-treatment: Removal of aluminum frame, junction box, and polymeric backsheet.

↧

Muffle furnace: 400 °C in air (1 to 128 h) to pyrolyze EVA, detaching solar cells from glass

↧

Recovered Glass Characterization: Evaluation of optical, structural, and mechanical integrity of the separated glass substrate

Substrates: Pristine (NHTSG) and isothermal series HTSG-0 to HTSG-7 (400 °C, 1–128 h).
Composition (ICP-OES): 72.3% SiO_2–14.5% Na_2O–9.1% CaO–2.8% MgO–1.0% Al_2O_3–0.07% Fe_2O_3.
Protocols: Gravimetry, 3D profilometry, UV-Vis (3.2 mm), Raman, Vickers (300 gf), and GlassNet models.

Results & Discussion

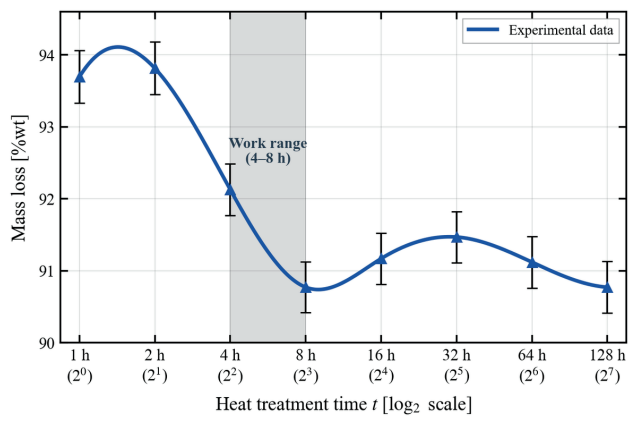


Figure 1. Normalized mass versus heat-treatment time at 400 °C. The ≈ 9 wt% loss (EVA removal) is complete by 4–8 h; the mass remains constant afterwards.

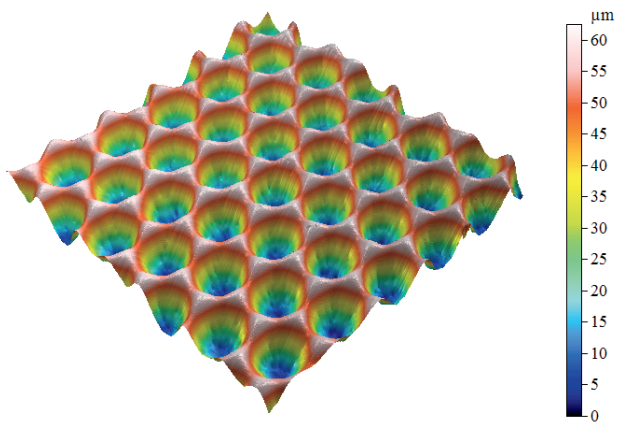


Figure 2: Profilometry 3D height map of the textured glass surface.

Profilometry reveals a hexagonal, honeycomb-like array of concave cavities (peak-to-valley ~50 µm). This texture promotes light trapping [2], so the measured transmittance depends strongly on surface reflection and scattering.

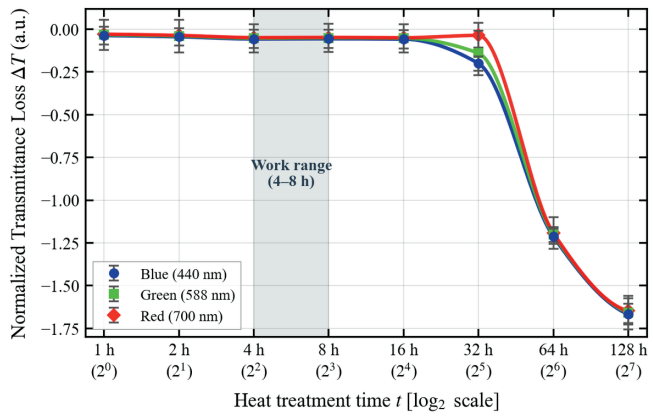


Figure 3. Normalized transmittance loss ΔT across RGB wavelengths (Blue 440 nm, Green 588 nm, Red 700 nm). Optical loss is negligible within the optimal EVA removal window (4–8 h, ΔT < 0.06). The identical decay profile across all RGB channels confirms an achromatic response and rules out bulk Fe3+ → Fe2+ reduction, indicating that accelerated decay for t ≥ 32 h stems from sub-T_g surface hazing rather than glass network alteration

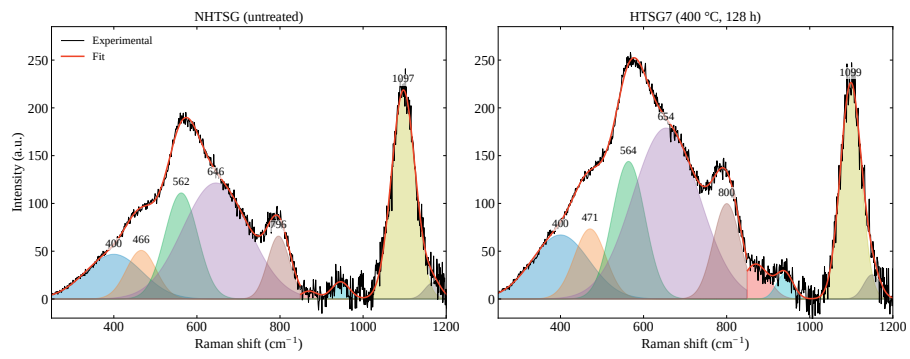


Figure 4. Raman spectra and Gaussian deconvolution of untreated (NHTSG) and 128 h treated (HTSG-7) solar glass. Deconvolution reveals strict structural preservation: dominant Q3 units (~1095 cm^{-1}) and bending modes (~560 cm^{-1}) exhibit rigid wavenumber shifts ≤ 1.6 cm^{-1} (within instrumental precision, ± 2 cm^{-1}, with zero devitrification peaks or iron vibrational changes.

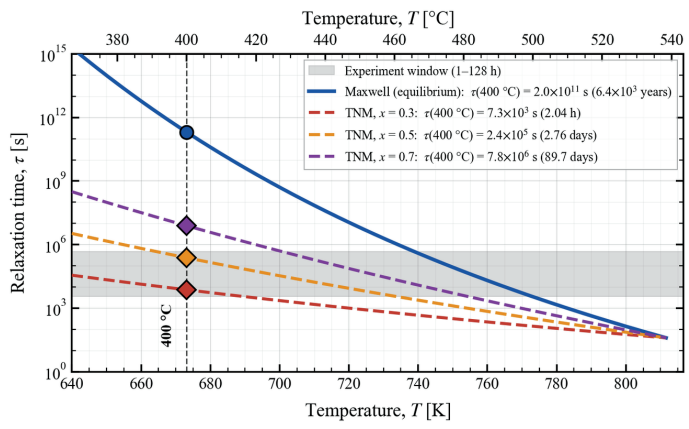


Figure 5. Structural relaxation time of the glass versus temperature. Maxwell time τ = η/G∞ (MYEGA viscosity from GlassNet [4,5]) gives τ ≈ $3.8×10^{11}$ s at 400 °C, an upper bound for the process. Non-equilibrium (TNM) relaxation [7,8] gives τ ≈ 2.3 h (x = 0.3) to 115 days (x = 0.7), overlapping the 1–128 h experimental window (shaded). Glass transition: Tg = 542 °C (τ ≈ 40 s).The Maxwell time at 400 °C (≫ 128 h) bounds the equilibrium relaxation; the non-equilibrium (TNM) times match the 1–128 h window, in line with the small Raman shifts.

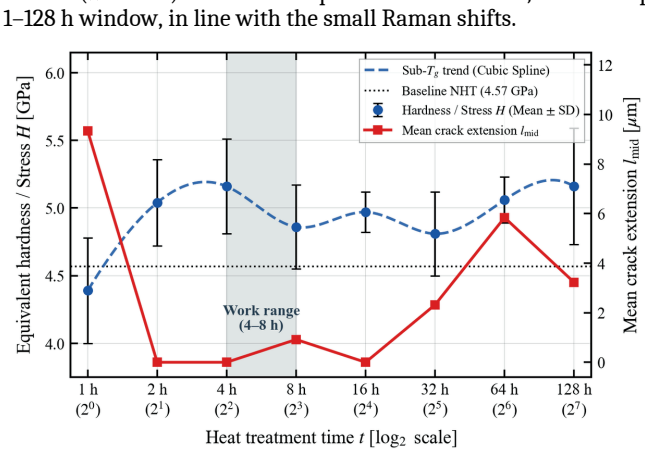


Figure 6. Equivalent hardness H (mean ± SD) and mean crack extension l_mean = c - a versus isothermal treatment time at 400 °C. In the pristine state (NHTSG), high residual compressive stress suppresses crack growth (l_mean = 0). Within the optimal 4–8 h window, hardness stabilizes in a plateau (~5.0 GPa) with negligible crack extension (l_mean < 1 µm), confirming beneficial relief of internal stress gradients. For t ≥ 32 h, progressive relaxation of the compressive surface layer alongside sub-Tg structural densification lowers damage tolerance, re-initiating lateral chipping and crack propagation (l_mean ≈ 2.3–5.8 µm).

Conclusion

Thermal treatment at 400 °C completely removes the EVA (~9 wt%) within 4–8 h. In this window, optical loss is negligible (ΔT < 0.06) without Fe^{3+} reduction, the silicate network remains intact (Raman shifts ≤ 1.6 cm^{-1}), and microhardness shows beneficial stress relief (l_mid < 1 µm). Extended heating (t ≥ 32 h) induces surface weathering and relaxes protective compressive tempering, validating 4–8 h as the optimal window for high-value glass recovery.

References & Acknowledgments

1. BALDÉ, Cornelis P. et al. The Global E-waste Monitor 2024: electronic waste rising faster than recycling. 2. ed. [S. l.]: UNITAR, ITU, ISWA, 2024.
2. DINGWELL, Donald B. Relaxation in silicate melts. Reviews in Mineralogy and Geochemistry, v. 32, n. 1, p. 21–66, 1995.
3. LE LOSQ, Charles et al. Determination of the oxidation state of iron in Mid-Ocean Ridge basalt glasses by Raman spectroscopy. Geochimica et Cosmochimica Acta, v. 126, p. 495–517, 2014.
4. TAN, Yangping et al. Designs for photovoltaic glass surface texturing to improve transmittance and minimize glare. AIP Advances, v. 14, n. 12, p. 125028, 2024.

The authors thank FINEP, CNPq, INCT-ACQUA, DEMET-UFMG and Beihang University.