Supplementary Material

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1 Relaxation time constants

The single poroelastic time constant (τ_{PE}) and the single viscoelastic time constant (τ_{VE}) are estimated from 16 relaxation tests. Fig. S1 depicts a representative poroviscoelastic relaxation as a function of time. Initially, we

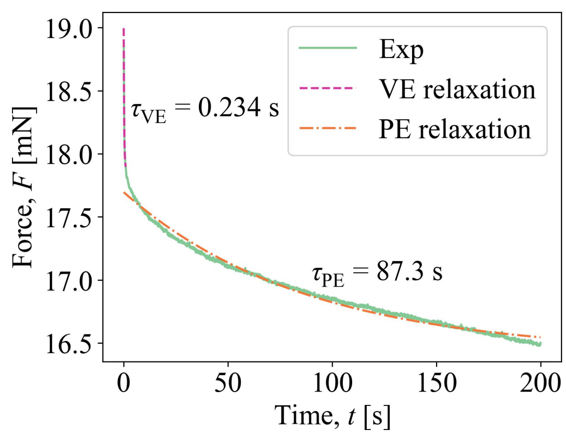

Figure S1: Representative relaxation curve from the adhesion experiments with a holding time of $t_{\mathrm{dwell}} = 200$ s. The curve illustrates two relaxation time constants:τ_{VE}, which covers the initial relaxation from 0 to 1 s, and τ_{PE}, which captures the broader range of relaxation from 0 to 200 s.

apply a Gaussian filter with $\sigma = 15$ to eliminate noise. Subsequently, we fit the filtered curve to Eq. (1), where τ denotes a relaxation time constant, and F_∞ and F_0 are constants.

$$F(t) = F_\infty + F_0 e^{-t/\tau} \tag{S.1}$$

Typically, poroelastic relaxation occurs much slower than viscoelastic relaxation. For a typical gelatin, τ_{VE} is less than 1 s. The poroelastic relaxation time constant can be expressed as $\tau_{\mathrm{PE}} \sim a^2/D_{\mathrm{eff}}$. For a hydrogel swollen with a water solvent, D_{eff} is on the order of 10^{-7} m^2/s to 10^{-10} m^2/s [1, 2, 3]. This results in $\tau_{\mathrm{PE}} \sim 84 - 84000s$ which is significantly larger than τ_{VE}. Here, the contact radius $a \approx 2.9$ mm, which is imaged by the imaging module (see §2.3 of the main text for details). The two relaxation time constants, τ_{PE} and τ_{VE}, are distinct. Therefore, we assume that the viscoelastic effect is dominant at the initial region of the relaxation curve. This assumption is supported by the observable sudden drop in the early stage of the curve, as shown in Fig. S1. We use this observation to estimate τ_{PE} and τ_{VE}. The entire relaxation curve relaxed for 200 s is fitted to Eq. S.1 to obtain τ_{PE}. We then fit the initial relaxation curve (being relaxed for 1 s) to Eq. S.1 and estimate τ_{VE}. The estimated poroelastic relaxation time constants, τ_{PE}, ranges from 73.2 to 111 s, with an average of 87.0 s. The estimated viscoelastic relaxation time constants,τ_{VE}, ranges from 0.186 to 0.239 s, with an average of 0.222 s.

2 Vertical extension

Soft materials, such as gelatin, due to their high compliance and strong adhesion, can form a pillar shape with a length h (referred to as vertical extension) when two interfaces are separated. If the unloading rate is sufficiently slow compared to the viscoelastic relaxation, the vertical extension h can be estimated using Eq. S.2.

$$h = \Delta t_u V_u - \delta_l \tag{S.2}$$

Here, Δt_u is the duration of unloading from the start to full separation, and $\delta_l = 0.5$ mm is the loading displacement in the adhesion experiments. However, if the interfaces are separated quickly, Eq. S.2 may no longer hold, as the interfaces can separate before the material fully recovers (viscoelastically). In such cases, we experimentally measure the vertical extension h and validate our estimation. Fig. S2(a) presents the duration of unloading Δt_u normalized by τ_{VE} as a function of V_u. The shaded area indicates the range of maximum and minimum values. $\Delta t_u/\tau_{\mathrm{VE}}$ provides a measure of how quickly we unload the indenter compared to the viscoelastic relaxation. For $V_u = \{0.01, 0.1, 1\}$ mm/s cases, the unloading is slow enough that the deformed material has sufficient time to recover while we unload the probe. On the other hand, for fast unloading cases such as $V_u = 10$ mm/s, the material

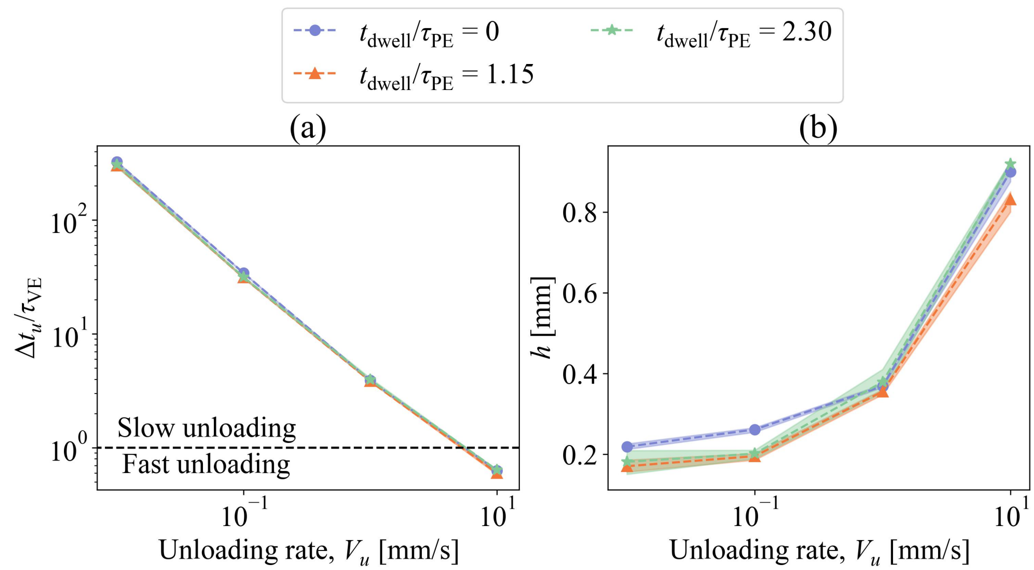

Figure S2: (a) The duration of unloading, from the start of unloading to full separation, normalized by the viscoelastic relaxation time $\Delta t_u/\tau_{VE}$. (b) The estimated vertical extension h. The shaded area in both figures represents the range between the maximum and minimum values.

may not have enough time to recover viscoelastically during unloading. If we estimate the vertical extension h using Eq. S.2 for $V_u = 10$ mm/s cases, the crack tip opening is likely to be underestimated. Therefore, for the fastest unloading case $V_u = 10$ mm/s, the vertical extension is estimated using Eq. S.2 and validated by experimental measurements using the imaging module. Fig. S2(b) displays the estimated vertical extension h. The vertical extension h at $t_{\text{dwell}}/\tau_{\text{PE}} = 0$ and $V_u = 10$ mm/s is estimated to be 0.900 mm. Fig. S3 illustrates the evolution of the vertical extension captured by the imaging module from the side view. Fig. S3(A) and (D) are the tilted side views of the contact at the instant of pull-off and immediately after full separation, respectively. Fig. S3(B) and (C) are the images right before the full separation with time interval of 1/240 s. The images are captured with a spatial resolution of 44 μm. The crack-tip radius of 0.85 mm can be fitted to the curved visible portion of the contact edge and that radius is close to the maximum vertical extension. Besides, the crack tip shape is maintained during unloading. Similar analysis for other unloading rate cases is not possible

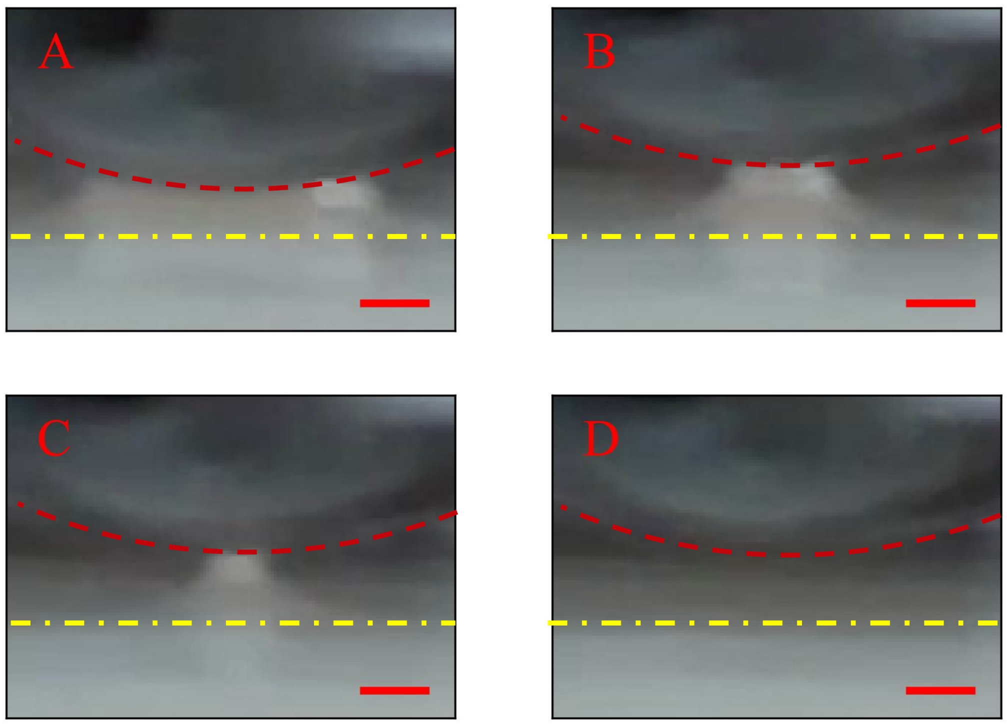

Figure S3: Evolution of the vertical extension viewed from the side for $V_u = 10$ mm/s and $t_{\mathrm{dwell}} = 0.5$ s case at the instant of (A) pull-off, (B) and (C) right before the full separation, and (D) right after the full separation. The red dashed lines denote the contour of the probe, while the yellow dashed lines represent the baseline of the vertical extension. (Scale bar: 1 mm) due to smaller vertical extensions ($h < 400\ \mu$m), 3 dimensional geometry of contact and tilted side view. The experimentally measured vertical extension is $h = 0.903$ mm, which closely matches the estimation. This suggests that the deformed material has either almost or fully recovered because the unloading duration at $V_u = 10$ mm/s is comparable to τ_{VE}.

References

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