Star-polymer-DNA gels showing predictable stress relaxation behavior

Xiang Li[1], Masashi Ohira[1,2], Takamasa Sakai[2] and Mitsuhiro Shibayama[3]

[1]Hokkaido University, Sapporo, Japan
[2]The University of Tokyo, Tokyo, Japan
[3]CROSS, Tokai, Japan

ABSTRACT

Dynamically crosslinked gels are attractive materials for applications requiring time-dependent mechanical responses. DNA duplexes with predictable binding energies are ideal crosslinkers for building such gels. However, the mechanical responses of most DNA gels are unpredictable due to the complications in the gel networks. Here, we designed a DNA gel with a highly homogeneous gel network and well predictable mechanical behaviour using star-polymer strategy. Stress-relaxation tests and dissociation kinetics measurements showed that the macroscopic relaxation time of the DNA gels was approximately equal to the lifetime of the DNA crosslinkers over 4 orders of magnitude from 0.1-2000 s. A series of durability tests show that the DNA gels are hysteresis-free and self-healing after the application of repeated temperature and mechanical stimuli. These results demonstrate the great potential of star-polymer-DNA precursors for building gels with predictable and tunable viscoelastic properties, suitable for applications such as stress-responsive extracellular matrices, injectable solids and soft robotics.

MAIN TEXT

We used a recently proved star polymer strategy [1,2] to improve the homogeneity of the gel network and designed a pair of DNA sequences showing a simple two-state transition as the dynamic crosslinkers[3]. The formed gels responded to multiple stimuli, such as temperature and forces, and were still self-healable and hysteresis-less. The contrast-matched small-angle neutron scattering (SANS) measurements confirmed the high spatial homogeneity of the gel network. UV spectroscopy determined that the two-state transition of the DNA duplexes occurred in the gels, the same as the simulated results from the DNA calculator. In addition, stress-relaxation tests and dissociation kinetics measurements revealed that the macroscopic relaxation time of our DNA gels agreed with the lifetime of the DNA crosslinkers over an extended time range from 0.1–2000 s, which was challenging for most other dynamically crosslinked gels. In combination with the demonstrated star-polymer–DNA gel scheme with the well-established database for DNA thermodynamics and kinetics, we will be able to

fabricate DNA gels with on-demand viscoelastic properties. We envision that highly predictable and tunable star-polymer–DNA gels can boost the fundamental understanding and applications of dynamically crosslinked gels.

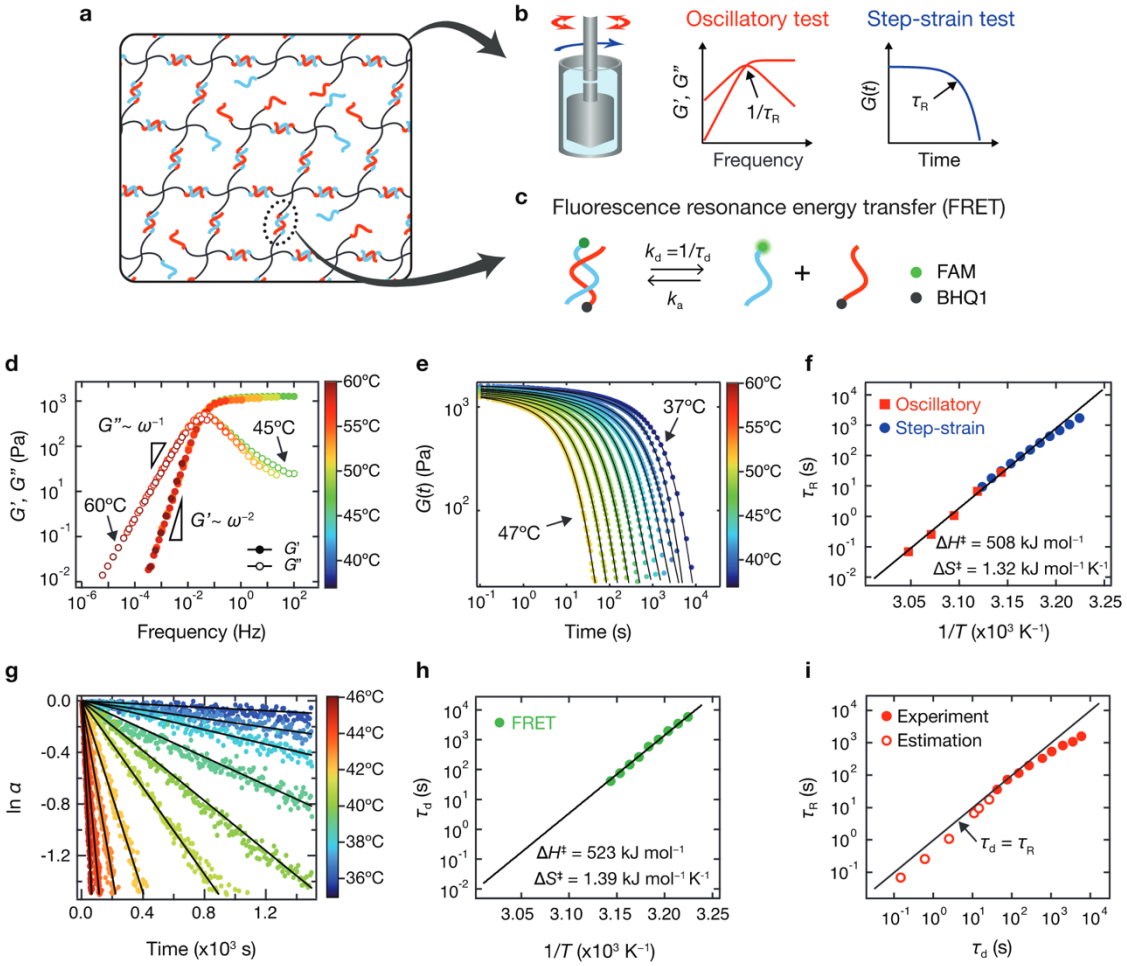

Figure 1: Relationship between gel stress relaxation and DNA duplex dissociation. a) An illustration of the deformed star-polymer–DNA network. b) The viscoelastic properties of the gels were characterized with a rheometer using two different methods: an oscillatory test for fast relaxation at high temperatures and a step-strain test for slow relaxation at low temperatures. c) The duplex dissociation kinetics were evaluated for DNA-only solutions using fluorescence resonance energy transfer (FRET). d) Master curves of G′ and G″ obtained from the oscillatory test for star-polymer–DNA gels over the range of 45–60 °C at intervals of 2.5 °C. The master curves were prepared by the time–temperature superposition treatment, using the curves at 45 °C as reference. e) Stress-relaxation curves of star-polymer–DNA gel obtained from the step-strain tests over the range of 37–47 °C at 1 °C intervals. f) Temperature dependence of the stress-relaxation time of the gels (τR). g) Time variation of the normalized molar concentration of DNA duplexes (α) obtained from FRET measurements over the temperature range of 36–45 °C at 1 °C intervals. h) Temperature dependence of the lifetime of the DNA duplexes (τd). i) Correlation plot of τR with respect to τd. The τd values in the experimentally inaccessible time range were estimated using the Eyring equation and displayed as open circles to distinguish them from the experimentally measured τd values (filled circles). All τR values were obtained experimentally. The solid line denotes a guide for the one-to-one correspondence limit (τR = τd), where the macroscopic stress relaxation is directly linked with the microscopic dissociation of the DNA duplexes. Reproduced from Ref. 3 with permission from the Royal Society of Chemistry.

ACKNOWLEDGEMENTS

This study was supported by Japan Society for the Promotion of Science (JSPS) KAKENHI grants to X.L. (JP17K14536, JP19K15628), M.O. (JP20J22044)). This study was also supported by Japan Science and Technology Agency (JST) grants to X.L. (FOREST Program JPMJFR201Z) and T.S. (CRESTJPMJCR199).

REFERENCES

(1) Sakai, T.; Matsunaga, T.; Yamamoto, Y.; Ito, C.; Yoshida, R.; Suzuki, S.; Sasaki, N.; Shibayama, M.; Chung, U. Design and Fabrication of a High-Strength Hydrogel with Ideally Homogeneous Network Structure from Tetrahedron-like Macromonomers. *Macromolecules* 2008, *41* (14), 5379–5384. https://doi.org/10.1021/ma800476x.

(2) Li, X.; Nakagawa, S.; Tsuji, Y.; Watanabe, N.; Shibayama, M. Polymer Gel with a Flexible and Highly Ordered Three-Dimensional Network Synthesized via Bond Percolation. *Sci Adv* 2019, *5* (12), eaax8647. https://doi.org/10.1126/sciadv.aax8647.

(3) Ohira, M.; Katashima, T.; Naito, M.; Aoki, D.; Yoshikawa, Y.; Iwase, H.; Takata, S.; Miyata, K.; Chung, U.; Sakai, T.; Shibayama, M.; Li, X. Star-Polymer-DNA Gels Showing Highly Predictable and Tunable Mechanical Responses. *Adv Mater* 2022, 2108818. https://doi.org/10.1002/adma.202108818.