Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 13, No. 2, 2024

A Mechanical Robust, Self-Healable, Recyclable Elastomer for Damping Over A Broad Temperature Range

Jinlin Zhou*

Shanghai Starriver Bilingual School, No 2588 Jin Du Road, Minhang, Shanghai, 201100, China
* Corresponding author: Jinlin Zhou (Email: 59660981@qq.com)

Abstract: Polymers are able to suppress vibrations and noises in fields due to the high internal friction of molecular chains. Therefore, polymers are naturally fit to be damping material. However, currently available damping elastomers are not able to include robust mechanical properties and the temperature range for effective damping is not long enough. Here, the ion-dipole interactions which are able to adjust the relaxation behavior of supermolecular polymer network, are important for stable and enhance the network. Through introducing the ion-dipole interactions, the resulted elastomer shows excellent mechanical properties (fracture stress ~ 1.01 MPa, tensile strength ~ 2900%, toughness ~ 15.13 MJ m-3). Also, the elastomer demonstrate extraordinary damping properties. The damping capacity reaches 73.9% and the peak value of damping factor is 2.29. Because of the ion-dipole interactions which driven by entropy, make sure the elastomer is stable in a wide range of temperature (0-160 °C， tan δ＞0.3), which is difficult by traditional means. Furthermore, the elastomer is able to self-heal and the healing efficiency is about 95% in 2 hours. Moreover, this unique design concept will provide a general approach to developing advanced damping materials.

Keywords: Damping elastomers, ion-dipole interaction, self-healing, high strength, energy dissipation.

1. Introduction

Vibration and noises are harmful in the industrial field, which cause resonance, malfunctioning and harm human health [1]. The frequency range of the noise sources and vibrations mainly distribute between 0.01 and 300 Hz [2]. It is necessary to build damping material over a wide frequency to suppress these vibrations. Polymers are able to suppress vibrations and noises in fields due to the high internal friction of molecular chains and are naturally fit to be damping material [3]. Notably, most damping elastomers have low loss factors and do not provide excellent damping performance over a wide temperature range.

There are generally three major approaches to obtain high-performance damping elastomers. The first method is to shift the glass transition region to the room temperature or working temperature. This can be achieved by phase separation, mixing polymer, block-copolymerizaztion, interpenetrating polymer networks, and incorporating nanofillers [4]. Wu et al. designed a highly damping and self-healable ionic elastomer from dynamic phase separation of sticky fluorinated polymers for mimicking human skins [5]. However, materials at the glass transition region normally possess higher modulus in a narrow temperature range, which limits the usage of the scenarios requiring soft materials and weak phase-to-phase interactions result in materials unable to maintain stable properties when subjected to severe impacts or sustained vibrations [6]. In addition, dynamic bonds such as hydrogen bonds can also enhance frictions between the chains of polymers [7, 8]. However, the low strength nature of the bond will limit the mechanical properties of the materials. As temperatures raises, the bonds will dissociate and let the loss factors decrease [6]. This allows the temperature range to be limited. The third approach is that by introducing the relaxation components such as dangling or un-crosslinked free chains [9, 10]. These components create multiple relaxation modes and able to dissipate energy. For instance, Zeng et al. prepared a composite gel with dangling PDMS chains for effective heat dissipation in chips operating under vigorous vibrations [11]. However, free or dangling chains cause less entanglement between polymer chains, making them hardly afford large shocks.

Polymeric materials capable of spontaneously healing physical damages and restoring various functions have been attracting growing interest. In order to achieve the purpose of self-healing, there are usually two strategies which are extrinsic and intrinsic methods. [12]. Extrinsic self-healing materials are uniformly embedded with healing agents. These agents are released to seal any gaps when physical damage occurs. Intrinsic self-healing materials inherently contain dynamic covalent bonds, such as disulfide, transesterification, boroxines, Diels-Alder adducts, imine bonds, and dynamic non-covalent bonds (such as hydrogen, ionic bonding, π−π stacking, metal−ligand coordination, guest−host interactions) [13]. These materials depend on the interdiffusion of polymer chains at the crack interfaces, as well as the cleavage and recombination of molecular dynamic bonds to facilitate self-healing. [14]. As such, intrinsic self-healing materials, with their ability to undergo repeated healing processes, theoretically allow for multiple self-healing at the same location, a feat unachievable by extrinsic self-healing systems. [15]. For the purpose of balancing the mechanical properties and self-healing abilities, most of the crosslinking structure of polymers are built by using weak non-covalent bonds. If the damping-material is able to self-healing, this can largely increase the life of the material and reduce environmental wastes. To the best of our knowledge, none of the previous strategies can synergize high-damping, high-strength, self-healing ability in one elastomer.

Here, through introducing dynamic physical cross-linking points, they help to increase the mechanical strength and damping performance. The resulted elastomer exhibits remarkable damping and mechanical properties across a broad temperature range, thanks to the dynamic ion-dipole interactions that between polymers chains. Such an approach yields elastomer with standout mechanical attributes, such as a high stress of 1.01 MPa, and robust toughness of 15.13 MJ m−3. Furthermore, the introduction of multiple ion-dipole interactions into the polymer network results in diverse relaxation modes and effective internal friction, endowing the damping elastomer with a high tan of 2.29. Its effective damping temperature spans from 0 to 160 °C (tan δ > 0.3), surpassing the range offered by other materials. The excellent damping performance, mechanical properties, and temperature tolerance of the elastomer can not only effectively acquire (protect eggs from broken), but also resist external impacts or shocks to reduce the probability of damage and improve service life, which is of great significance for continuous monitoring of bioelectrical signals in complex environments.

2. Experimental section

2.1. Materials

Acrylonitrile (AN, 99%), n-butyl acrylate (nBA, 99%, stabilized with 10-60 ppm MEHQ), 2,2-azobis (2-methylpropionitrile) (AIBN, 99%), Lithium bis (trifluoromethanesulphonyl) imide (LiTFSI, 99%) and acetonitrile (ACN, 99.9%) were purchased from Aladdin Chemical. All chemicals were used as received without further purification.

Preparation of PAN-co-PBA and PAN-co-PBA-Li+ polymer

In a typical free radical copolymerization procedure, AN (5.0 g, 94.2 mmol), BA (12.08 g, 94.2 mmol), AIBN (0.309 g, 3.6 mmol) and 20 mL DMF in an eggplant-shaped bottle equipped with a magnetic stirrer. Then the solution was degassed with argon and stirred at 60 °C for 24 h. The mixture was then poured into a polytetrafluoroethylene mold, follow by solvents evaporation at room temperature for 4 h and 80 °C for 12 h to obtain the transparent yellow film. As for PAN-co-PBA-Li+ polymer, it was prepared following the same procedure as the PAN-co-PBA polymer, except for the addition of LiTFSI.

Preparation of polydimethylsiloxane (PDMS) elastomer.

Sylgard 184 and the curing agent were mixed in a volume ratio of 10:1, stirred thoroughly, and injected into a PE mold. The mixture was then defoamed in a vacuum dryer, and then cured in an oven at 80 °C for 2 h.

2.2. General Characterizations

Attenuated total reflectance-FT-IR (ATR-FT-IR) spectra were recorded on a Bruker Tensor27 FTIR spectrophotometer equipped with a Specac Golden Gate ATR heating cell in the range of 4000 to 600 cm−1. Thermogravimetric analysis (TGA) was carried out on a simultaneous SDT 2960 thermal analysis system from 30 to 600 °C with a heating rate of 10 °C min−1 under the nitrogen atmosphere. Differential scanning calorimetry (DSC) curves were performed using a Mettler-Toledo DSC1 STARe analyzer under dry N2 atmosphere with a scanning rate of 5 °C min−1. The measurements of each sample were performed with two cycles and the curves of the second cycle were used.

2.3. Uniaxial tensile experiments

Uniaxial tensile experiments were performed on the Instron 3343 instrument (load cell 500 N). All test samples were 30 mm (L) × 5 mm (W) × 0.5 mm (T) (stretch section length was 10 mm) and at least three samples were used for each test. And all the strain-stress curves were performed at the speed of 100 mm min−1. As for loading-unloading cycle tests, 100% strain was stretched at 25 °C at a strain rate of 100 mm min-1. Then, the stress was unloaded at the same rate.

The tensile toughness (τ) of the samples can be calculated by integrating the area under the stress (σ)-strain (ε) curves, using the following equation:

$$\tau = \sum_{i=0}^{i=\varepsilon_b} \sigma\varepsilon_i \quad (1)$$

Where ε_i is the tensile stress, ε_b is the elongation at break.

2.4. Rheological tests

The dynamic viscoelasticity of PAN-co-PBA was measured using a rheometer (DHR-2, TA) with parallel plates of 8 mm diameter. Frequency-sweeping tests were conducted with an angular frequency range from 0.1 to 100 rad s–1 and a shear strain of 1%. Temperature-sweeping measurements were performed with a frequency of 1 Hz and a shear strain of 1% while varying the temperature from 0 to 160 °C (3 °C min–1). The master curve was obtained according to the time-temperature superposition (TTS) principle at a reference temperature of 20 °C.

3. Results and Discussions

3.1. Design and fabrication of damping elastomers

The synthetic procedure consists only one step and involves mixing the two monomers into a homogenous precursor solution with or without the addition of LiTFSI. LiTFSI contributes positively charged Li+ that can establish ion-dipole interactions with the cynao group and carbonyl group. Subsequently, this enables us to regulate the relaxation behavior of the polymer network, thus achieving a controlled internal friction mechanism. Specifically speaking, these elastomers were prepared by a facile one-pot free-radical copolymerization of nBA, and AN in N,N-Dimethylformamide (DMF) with AIBN as the thermal initiator (Figure 1). The resulted polymer was named PAN-co-PBA. ATR-FTIR spectroscopy results were used to examine the chemical structure and successful copolymerization of the polymer. The characteristic ATR-FTIR vibration peaks of C=O signals from ester groups at 1724 cm-1, C≡N at 2241 cm-1 in the spectra confirm the successful polymerization of PAN-co-PBA.

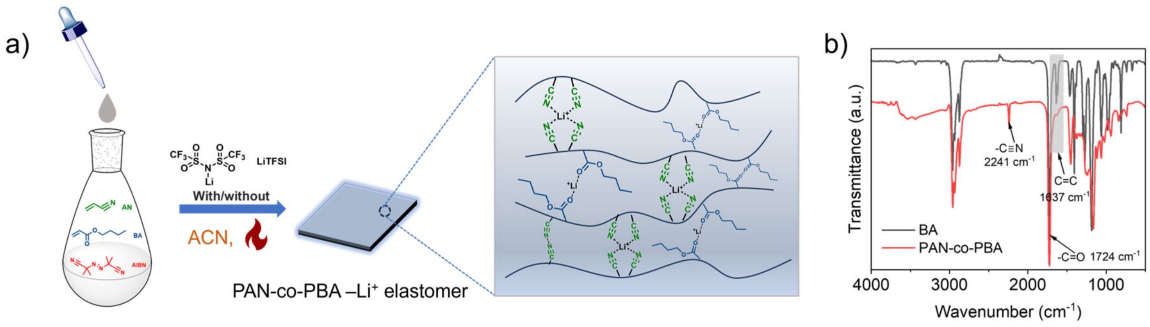

Figure 1. Synthesis and structural characterization of PAN-co-PBA and PAN-co-PBA-Li+ elastomer. a) Schematic route for the synthesis of PAN-co-PBA. b) ATR-FTIR spectra of BA and PAN-co-PBA.

As for the sample of adding LiTFSI, the characteristic peaks of S=O and S─N─S in LiTFSI appear at 1351 and 1056 cm−1, respectively. With the increase of LiTFSI content, the peaks of C=O and C≡N in PAN-co-PBA blueshift, indicating that Li+ ions will disrupt the dipole-dipole force between C=O and/or C≡N. Furthermore, the formation of ion-dipole interactions within the PAN-co-PBA-Li+ polymer network can also be easily approved by ATR-FTIR spectroscopy. The additional characteristic vibration peaks of C=O signals from ester groups at 1713 cm-1, C≡N at 2266 cm-1 in the spectra confirm the successful introduction of ion-dipole interaction between Li+ ions and the carbonyl group/cyano group.

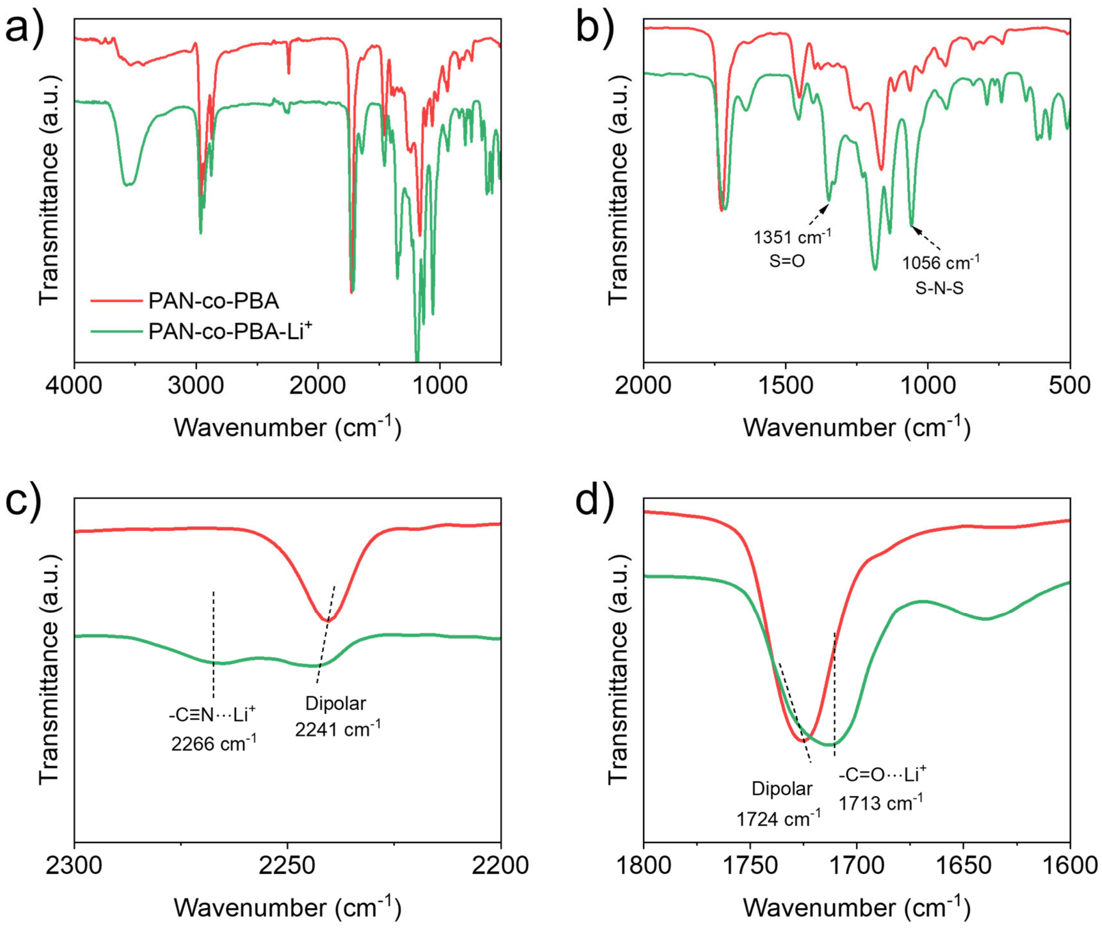

Figure 2. ATR-FTIR spectra of BA and PAN-co-PBA and PAN-co-PBA-Li+. a) Full spectrum and b)-d) localized magnified spectrum.

Additionally, the resulted polymers possess excellent thermal stability, with the decomposition temperature of PAN-co-PBA-Li higher than 330 °C (5% weight loss). Furthermore, the Tg of original material (PAN-co-PBA) is 0.5 °C. With the addition of LiTFSI, more crosslinkers resulted by ion-dipole interactions are formed. Therefore, it will restrict the movement of polymer chains and increase the Tg to 3.8 °C.

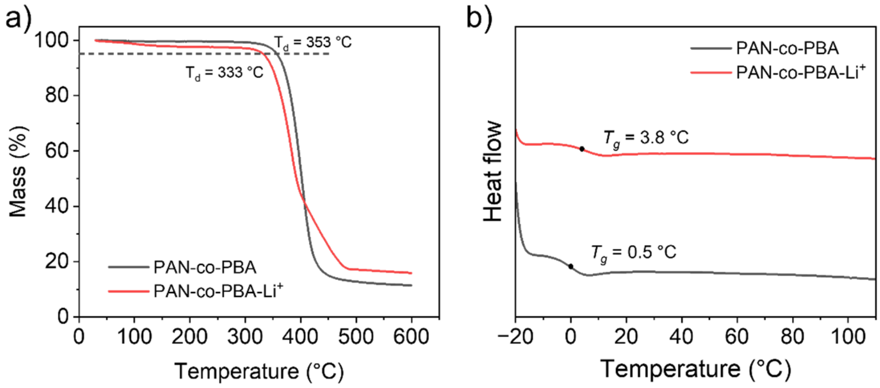

Figure 3. Thermal properties of PAN-co-PBA and PAN-co-PBA-Li+. a) TGA curves of PAN-co-PBA and PAN-co-PBA-Li+. b) DSC results of PAN-co-PBA and PAN-co-PBA-Li+.

3.2. Mechanical and damping properties of damping elastomers

Tensile tests were conducted on PAN-co-PBA to investigate their mechanical properties. The results of these tests are presented in Table 1. The SICE demonstrates good mechanical properties, with a maximum fracture strength of 1.1 MPa (Figure 4a). LiTFSI content leads to an increase in toughness from 4.5 to 15.13 MJ m−3 (Figure 4a), which is a two-fold increase. The reason is that by introducing Li+ ions, it will lead to more ion-dipole interactions and restrict more on the movement of polymer chains during stretching process, which are consistent with the rise of Tg. Furthermore, low-coordinated ion-dipole interactions are highly dynamic and will continuing reform themselves during the process of stretching, dissipating a large amount of energy. Eventually it will be more tough.

Next, cyclic tensile tests were conducted to evaluate the energy dissipation capacity of PAN-co-PBA-Li+ (Figure 4b). The mechanism for energy dissipation is that during stretching, the dynamic ion-dipole interaction would break and achieve the goal of energy dissipation. The dissipated energy can be calculated by integrating the area under the cyclic stress-strain curve, which defined as the ratio of dissipated energy to input energy, of above 70% can be achieved at 200% strain. High energy dissipation can assist PAN-co-PBA-Li+ elastomer to effectively resist external impacts.

Table 1. The mechanical properties of PAN-co-PBA and PAN-co-PBA-Li+ elastomers.

Sample	Stress (MPa)	Strain (mm/mm)	Toughness (MJ m^{-3})
PAN-co-PBA	0.0027	50	4.5
PAN-co-PBA-Li^+	1.12	29.8	15.13

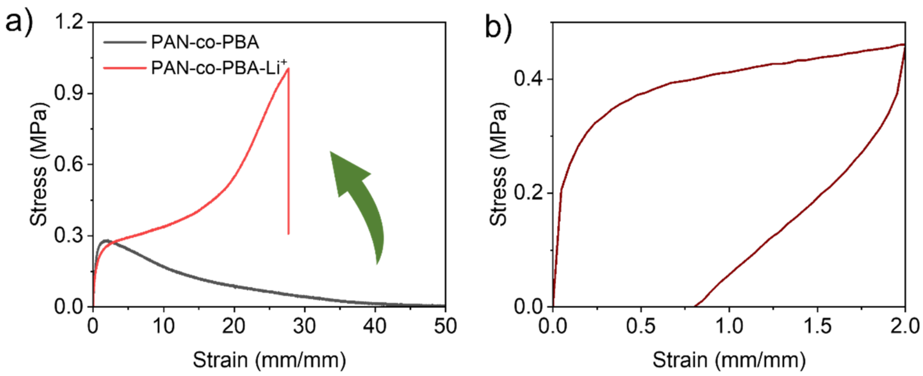

Figure 4. Mechanical and Damping Properties of PAN-co-PBA-Li+ elastomer. a) Stress-strain curves of PAN-co-PBA-Li+ and PAN-co-PBA-Li+ elastomer. b) Cyclic tensile stress–strain curves of PAN-co-PBA-Li+elastomer at a strain of 200% with a tensile rate of 100 mm min−1.

Furthermore, temperature-sweeping rheological tests were conducted on PAN-co-PBA-Li+ elastomer to investigate the influence of temperature variation on the damping properties. Benefit from the entropy-driven rearrangement phenomenon of Li+-O/Li+-N ion-dipole interactions, PAN-co-PBA-Li+ elastomer exhibits high-temperature stability, resulting in a wide effective damping temperature range (tan $\delta > 0.3$, 0-160 °C) of 160 °C (Figure 5a). Such high-temperature stability surpasses the usable range of commercially available damping materials (e.g., Alphagel and Sorbothane) and outperforms almost reported damping materials. The reason that the modulus will decrease is that, the weak ion-dipole force would break during high temperature. Meanwhile, PAN-co-PBA-Li+ elastomer has a wide plateau modulus region (60-160 °C) because of high-coordinated ion-dipole interactions, only with a slight modulus decrease. Also, it can be seen that by introducing ion-dipole interactions, the storage modulus of the material is enhanced and the internal friction between the polymer chains is strengthened, resulting in excellent damping ability over a wide temperature range.

Moreover, the master curves of PAN-co-PBA-Li+ elastomer was obtained using the time-temperature superposition (TTS) principle to investigate the vibration-related dynamic behavior at different time scales. The peak value of the damping factor of PAN-co-PBA-Li+ was 2.1 (Figure 5b), indicating a more powerful energy dissipation capability.

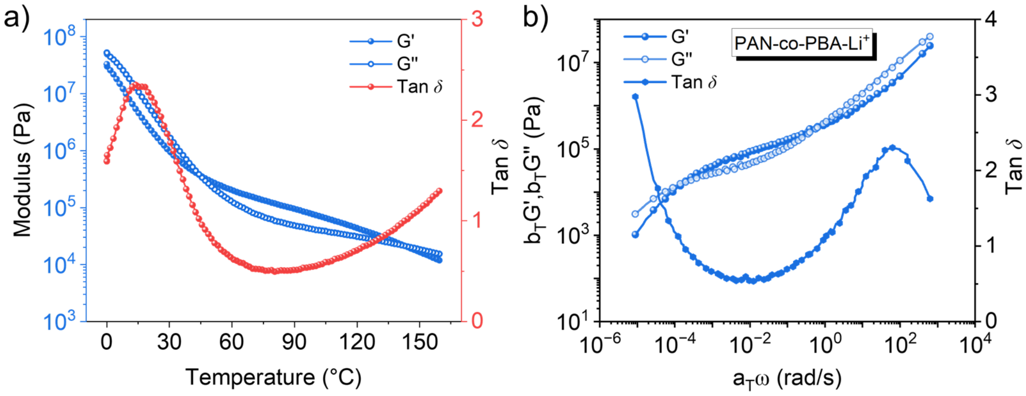

Figure 5. Characterization of rheological behavior. a) Temperature-sweeping rheological results of PAN-co-PBA-Li+ elastomer. b) Master curve of PAN-co-PBA-Li+ elastomer at 20°C.

3.3. Self-healing and recyclability of PAN-co-PBA-Li+ elastomer

Due to the highly reversible dissociation and reorganization of dynamic bonds and good mobility of the polymer chains, the PAN-co-PBA-Li+ elastomer can also be self-healable and recyclable at room temperature. As shown in Figure 6a, the sample was first cut into two halves, one of which was stained with Prussian blue. The cut samples can then be repaired after being left at room temperature for 120 minutes. Furthermore, the two healed samples can be stretched to 4 times its original length and bear a load of 300 g, demonstrating the excellent properties of self-healing (Figure 6b). We also quantitatively evaluated the self-healing efficiency of the elastomer by tensile stress–strain curves (Figure 6c), which is defined as the ratio of the fracture stress of the sample before and after healing. As demonstrated in Figure 6d, the healing efficiency increased with increasing healing time, and after healing at room temperature for 120 min, the healing efficiency can reach as high as 95%. At the same time, the cracks generated by the cuts can almost completely disappear after healing, which can be observed by the optical microscopy (Figure 6e). Thanks to the dynamic physical cross-linking of the polymer chains, the PAN-co-PBA-Li+ elastomer can also be re-dissolved in solvent and re-formed after solvent evaporation, allowing solvent-assisted recovery at room temperature (Figure 6f).

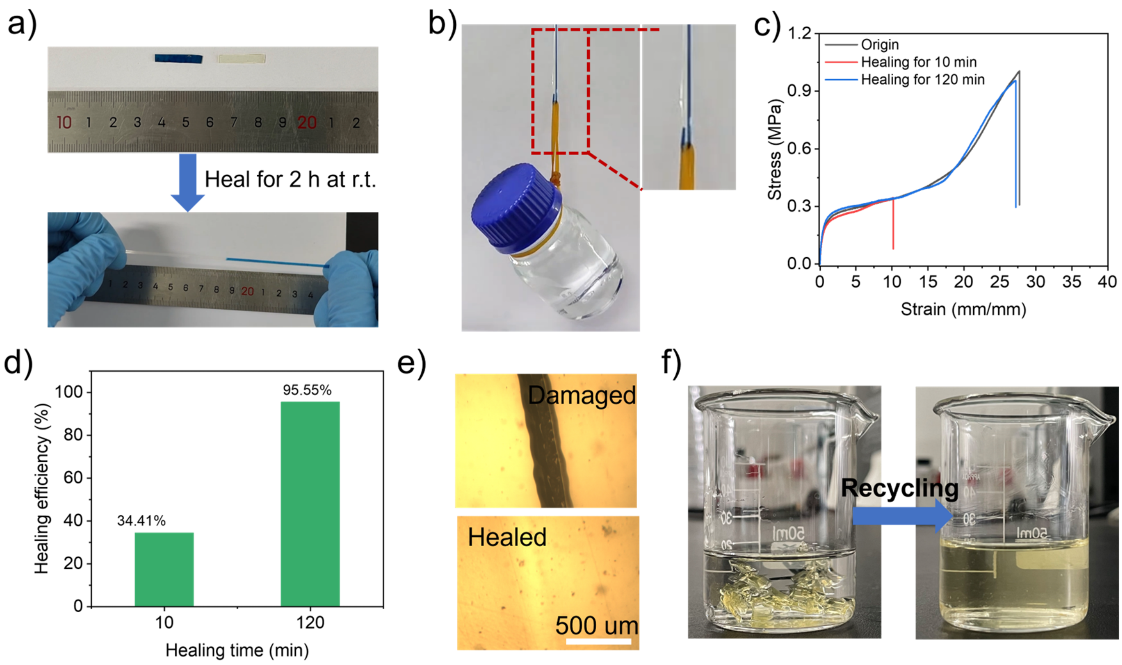

Figure 6. Self-healing and recyclability properties of PAN-co-PBA-Li+ elastomer. a) Two separated samples can be repaired as a whole and can be stretched. b) The repaired samples can bear a load of 300 g. c) The stress-strain curves of the samples before and after self-healing for different time at room temperature. d) The corresponding self-healing efficiency. e) The optical images of PAN-co-PBA-Li+ elastomer before and after self-healing at room temperature. f) The recycling process of PAN-co-PBA-Li+ elastomer.

3.4. Anti-impact performance of PAN-co-PBA-Li+ elastomer

With excellent energy dissipation and force attenuation capabilities, PAN-co-PBA-Li+ elastomers can largely reduce vibration and have anti-impact in multiple aspects. To confirm this point, PDMS (Polydimethylsiloxane) with a size of 30 mm × 30 mm × 0.5 mm and PAN-co-PBA-Li+ elastomer with a size of 30 mm × 30 mm × 0.5 mm were used as safe guards to protect glasses from collision (Figure 7a). Glass with a size of 76 mm × 26 mm × 1.2 mm was covered with these two materials and a metal ball which has a diameter of 20 mm falls from a height of 100 cm (Figure 7a). The glass, that was protected by PDMS, was broke and the glass, that was protected by PAN-co-PBA-Li+ elastomer, maintained integrity (Figure 7b). In addition, dropping a quail egg from a height of 100 cm on the PAN-co-PBA-Li+ elastomer, which has a size of 30 mm × 30 mm × 0.5 mm, was also maintained integrity (Figure 7c).

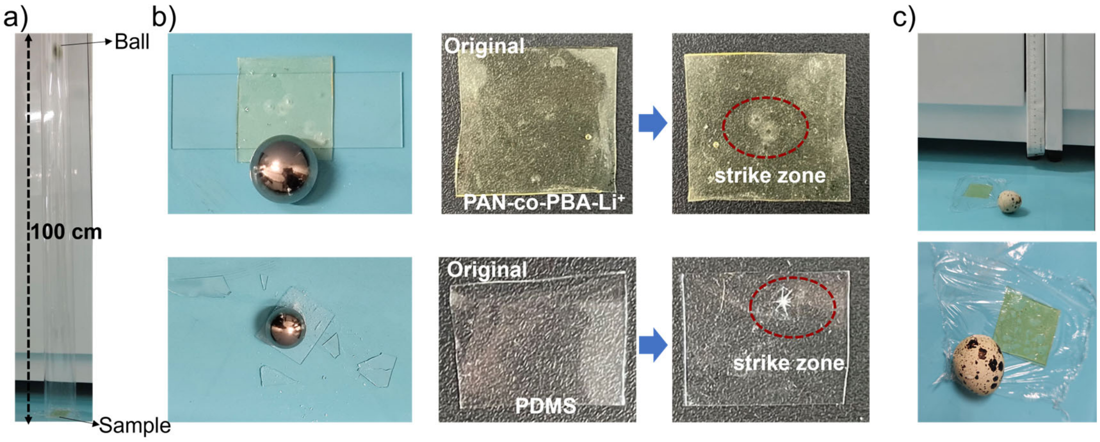

Figure 7. Demonstration of anti-impact performance. a) Photos of a steel ball (30 g) dropped from a height of 100 cm. b) Photographs of PAN-co-PBA-Li+ elastomer and PDMS elastomer used as glass protection materials when subjected to impact. c) Photo of a quail egg dropped onto PAN-co-PBA-Li+ elastomer from a height of 100 cm.

4. Conclusion

In conclusion, we develop a robust damping elastomer with excellent damping performance over a wide temperature range by introducing dynamic physical cross-linking points. The introduction of ion-dipole interactions allows us to achieve simultaneous enhancement of both mechanical toughness and damping properties. In addition, the damped elastomers we obtained can also act as cushioning as well as prevent quail eggs from breaking when dropped from a height. As I move forward, this unique design concept will provide a general approach to developing advanced damping materials.

Acknowledgement

The research topic selection and background of this paper is about to solve the problem that the damping-materials do not usually include robust mechanical properties and have short temperature range for effective damping. By introducing the ion-dipole forces, it allows the damping material to self-repair and expand its temperature range.

Developing damping material has significant implications across various industries and applications. Damping materials are substances designed to reduce or control vibrations, oscillations, and noise in systems. Their development involves extensive research and innovation to create materials with specific properties that efficiently dampen vibrations. One of the primary purposes of developing damping materials is to enhance the performance and lifespan of mechanical systems. Vibration can cause wear and tear, leading to premature failure of components. By incorporating damping materials into these systems, engineers can mitigate the adverse effects of vibrations, reducing the likelihood of breakdowns and extending the overall durability of the system. In the automotive industry, damping materials play a crucial role in improving ride comfort and reducing noise levels in vehicles. They help to minimize the vibrations transmitted from the engine, road, or other sources, leading to a smoother and quieter driving experience. By developing damping materials with optimal properties, manufacturers can create more comfortable and enjoyable vehicles for consumers. Another significant application of damping materials is in the field of structural engineering. Structures such as buildings, bridges, and aircraft are subject to various forms of vibrations, including wind-induced vibrations, seismic vibrations, and machinery-induced vibrations. These vibrations can cause structural fatigue and decrease the overall stability of the structure. Damping materials can be used to reduce these vibrations, enhancing the structural integrity and safety of these systems. Developing damping materials also has implications in the field of electronics and telecommunications. Electronic devices, such as smartphones, tablets, and laptops, often generate vibrations that can affect their performance and reliability. Damping materials can be incorporated into the design of these devices to absorb and dissipate vibrations, minimizing the risk of damage and improving their overall functionality. Furthermore, damping materials find applications in aeroacoustics, where they are used to reduce noise levels in aircraft, machinery, and other equipment. By developing materials with tailored acoustic properties, engineers can effectively attenuate noise, creating quieter environments and reducing the impact of noise pollution on human health. In summary, the development of damping materials holds immense significance in various industries and applications. These materials help to reduce vibrations, oscillations, and noise, leading to improved performance, durability, and comfort. From automotive and structural engineering to electronics and aeroacoustics, damping materials play a vital role in enhancing the efficiency and safety of systems. Continued research and innovation in this field are essential to create advanced damping materials that address specific needs and challenges across different industries.

Under the guidance of the instructors, I (Jinlin Zhou) conducted all experimental work, data processing, and the composition of the paper. The relationship to the guiding instructor is devoid of any financial interests, characterized by uncompensated guidance and assistance throughout the process of paper composition. The instructor plays a supportive role by providing academic mentorship, addressing queries, and offering assistance as needed, with no pecuniary interests involved.

References

[1] Cheng, L.; Zhao, J.; Xiong, Z.; Liu, S.; Yan, X.; Yu, W. Hyperbranched vitrimer for ultrahigh energy dissipation. Angewandte Chemie International Edition 2024, 63 (28), e202406937.

[2] Qatu, M. S.; Abdelhamid, M. K.; Pang, J.; Sheng, G. Overview of automotive noise and vibration. International Journal of Vehicle Noise and Vibration 2009, 5 (1-2), 1-35.

[3] Yamazaki, H.; Takeda, M.; Kohno, Y.; Ando, H.; Urayama, K.; Takigawa, T. Dynamic viscoelasticity of poly(butyl acrylate) elastomers containing dangling chains with controlled lengths. Macromolecules 2011, 44 (22), 8829-8834.

[4] Huang, J.; Xu, Y.; Qi, S.; Zhou, J.; Shi, W.; Zhao, T.; Liu, M. Ultrahigh energy-dissipation elastomers by precisely tailoring the relaxation of confined polymer fluids. Nature Communications 2021, 12 (1), 3610.

[5] Xiang, H.; Li, X.; Wu, B.; Sun, S.; Wu, P. Highly damping and self-healable ionic elastomer from dynamic phase separation of sticky fluorinated polymers. Advanced Materials 2023, 35 (10), 2209581.

[6] Shen, S.; Du, Z.; Zhou, P.; Zou, Z.; Lyu, X. A mechanically robust, damping, and high-temperature tolerant ion-conductive elastomer for noise-free flexible electronics. Advanced Functional Materials 2024, 2408017.

[7] Shi, Y.; Wu, B.; Sun, S.; Wu, P. Aqueous spinning of robust, self-healable, and crack-resistant hydrogel microfibers enabled by hydrogen bond nanoconfinement. Nature Communications 2023, 14 (1), 1370.

[8] Yuan, F.; Zhang, X.-X.; Wu, K.; Li, Z.; Lin, Y.; Liang, X.; Yang, Q.; Liu, T. Damping chitin hydrogels by harnessing insect-cuticle-inspired hierarchical structures. Cell Reports Physical Science 2023, 4 (11), 101644.

[9] Li, Y.; Lian, Q.; Lin, Z.; Cheng, J.; Zhang, J. Epoxy/polysiloxane intimate intermixing networks driven by intrinsic motive force to achieve ultralow-temperature damping properties. Journal of Materials Chemistry A 2017, 5 (33), 17549-17562.

[10] Faghihi, F.; Mohammadi, N.; Hazendonk, P. Effect of restricted phase segregation and resultant nanostructural heterogeneity on glass transition of nonuniform acrylic random copolymers. Macromolecules 2011, 44 (7), 2154-2160.

[11] Ding, S.-C.; Fan, J.-F.; He, D.-Y.; Cai, L.-F.; Zeng, X.-L.; Ren, L.-L.; Du, G.-P.; Zeng, X.-L.; Sun, R. High thermal conductivity and remarkable damping composite gels as thermal interface materials for heat dissipation of chip. Chip 2022, 1 (2), 100013.

[12] Yao, H.; Liu, T.; Jia, Y.; Du, Y.; Yao, B.; Xu, J.; Fu, J. Water-insensitive self-healing materials: from network structure design to advanced soft electronics. Advanced Functional Materials 2023, 33 (48), 2307455.

[13] Li, B.; Cao, P.-F.; Saito, T.; Sokolov, A. P. Intrinsically self-healing polymers: from mechanistic insight to current challenges. Chemical Reviews 2023, 123 (2), 701-735.

[14] Webber, M. J.; Tibbitt, M. W. Dynamic and reconfigurable materials from reversible network interactions. Nature Reviews Materials 2022, 7 (7), 541-556.

[15] Yang, Y.; Urban, M. W. Self-Healing of Polymers via supramolecular chemistry. Advanced Materials Interfaces 2018, 5 (17), 1800384.