One-step soaking strategy toward mechanical double-network hydrogel

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Abstract. Double-network (DN) hydrogels, which comprise noncovalent interacting networks, are highly sought after due to their controlled compositions and environmental friendliness. However, the complex preparation methods hinder the application of these hydrogels. In this study, we present a simple and feasible approach for fabricating hybrid PAA-CS DN hydrogels by post-treating the PAA-CS composite hydrogels with $CuSO_4$ solutions to induce the formation of physical networks through CS chain entanglement. The composite hydrogel, composed of chitosan (CS) and polyacrylic acid (PAA), readily transforms into a DN hydrogel after soaking in a $CuSO_4$ solution, thanks to in situ formation of chain entanglements, hydrogen bonds, and ionic coordination. The resulting hybrid DN hydrogels exhibit porous networks, high tensile strength, and exceptional toughness. This facile but effective soaking method can be universally applied to fabricate mechanically robust hydrogels, modulate noncovalent interactions, and broaden their potential applications.

Keywords: Double-network hydrogel; one-step soaking strategy; Polyacrylic acid; Chitosan.

1. Introduction

Hydrogels, due to their three-dimensional cross-linking structures and tunable physicochemical attributes, occupy a pivotal position in various fields, notably enhancing agricultural drought tolerance, enabling precise drug delivery, facilitating pollution control, and advancing the realm of issue engineering [1-3]. Conversely, their applications were deeply influenced by poor mechanical strength particularly in load-bearing soft tissues that require stiffness, toughness, and impact resistance, like tendons, cartilage, and ligaments. To address this issue, it is essential to tailor the uniform structure of hydrogels and incorporate energy dissipation mechanisms to resist crack formation and expansion. Double-network (DN) comprising two distinct networks with contrasting characteristics, offer a promising avenue as they demonstrate exceptional and well-rounded mechanical attributes. Specifically, they possess notable stiffness, with an elastic modulus ranging from 0.05-1.0Mpa, along with remarkable breaking strength, characterized by a tensile stress between 0.2 and 10 MPa and an extensive strain capacity spanning 100% to 6000%. Furthermore, their toughness is exhibiting fracture energies as high as 100 to 15000 J m^{-2}. Such outstanding properties arise from the unique double network structure, in which the rigid and fragile network functions as energy- dissipating sacrificial bonds, while the pliable and ductile network ensures the structural integrity amidst deformation of hydrogels [4-7]. Compare to conventional chemically, cross-linked DN hydrogels, hybrid physically-chemically cross-linked DN (hybrid DN) hydrogels harness the disruption and recrosslinking dynamics of reversible physical networks, exhibit additional advantages including excellent fatigue resistance, self-recovery properties, and show great potential as substitutes for loading-bearing tissues [8].

The application of hybrid DN hydrogels is often constrained by the limited components and insufficient functionality. In contrast, composite hydrogels offer significant advantages such as abundant raw materials, diverse and easy preparation methods, and the ability to adjust functionality. Generally, chemically cross-linked hydrogels can be tailored into diversity composite hydrogels, each endowed with distinct functionalities, tailored for diverse applications spanning electron catalysis, instrument, and drug delivery systems. This versatility is attained through the strategic incorporation of nanoparticles, microspheres, and a myriad of physical interactions such as hydrogen bonding,

hydrophobic interaction, dipole-dipole interactions, and electrostatic attractions [9]. Hence, one of the most important significances in exploring diverse hybrid DN hydrogels and expanding their applications is that seamlessly integrating the compositional diversity and multifaceted functionalities of composite hydrogels within the DN hydrogel.

A significant hindrance to the progression of hybrid DN hydrogels pertains to the limited diversity of their physical networks. Nowadays, a prevalent form of these physical networks within hybrid DN hydrogels comprises ionically cross-linked structures, primely constructed through intricate coordination interactions between acidic polysaccharides and multivalent cations. In order to augment the design space for innovative hybrid DN hydrogels, there is a pressing need to devise straightforward strategies for the creation of a wider array of physical networks. Among potential materials, Chitosan (CS), which can generate physical microcrystalline in alkaline and monovalent anionic saline solutions is the unique alkaline polysaccharide, stands out for its inherent biodegradability and biocompatibility. However, despite these favorable attributes, the long-chain nature of CS often leads to challenges in terms of low solubility and high viscosity, ultimately resulting in CS-based physical hydrogels that exhibit brittleness and inferior mechanical strength. Consequently, the direct application of CS physical networks as a component in hybrid DN hydrogels often falls short of being an optimal selection [10-13].

2. Experimental Section

Materials Acrylamide, 2-hydroxy-4’-(2-hydroxyethoxy)-2-methylpropiophenone (Irgacure 2959), N, N'-methylene-bis-acrylamide were purchased from Sigma-Aldrich. Short-chain chitosan (degree of deacetylation > 90%, viscosity: 45 mPa s for 1% (w/v) solution, molecular weight: ca. 10 kPa) was purchased from Shandong Jinhu Company, China. All the reagents were used as received. Highly purified water was used in all the experiments. Mechanical characterization all mechanical tests were performed with an Instron Model 5567 machine in air, at room temperature and 30% humidity. To avoid water volatilizing, silicone oil was coated on the hydrogel surface during the testing and storage time. In the present work, the samples were cut into rectangular shape (5 mm ×2 mm ×35 mm) to measure tensile properties. The rate of extension was fixed at 5 mm/min for tensile tests. The calculation of nominal stress (σ) entailed dividing the applied force (F) by the cross-sectional area, whereas the nominal tensile strain (ε) was derived by the ratio of the stretched length (Δl) to the initial length ($l0$). Subsequently, the elastic modulus was quantified based on the slope over 5-15% of strain ratio of stress-strain curves. For microstructural analysis, a JSM-6700F microscope facilitated the acquisition of field emission scanning electron microscopy (SEM) imagery. Prior to experimentation, freeze-dried specimens underwent sputter-coating technique with a thin Pt layer for 90 s, enhanceing their conductivity. The mechanical tests were executed at ambient temperature, utilizing an Instron 3365 apparatus.

3. Results and Discussion

To commence, short-chain chitosan (CS), known for its exceptional solubility in neutral aqueous media, is seamlessly integrated into a covalent polyacrylic acid (PAA) network via robust hydrogen bonding interactions, resulting in the synthesis of a composite hydrogel, henceforth referred to as the PAA-CS composite hydrogel. Subsequently, this composite undergoes a transition into mechanically robust double-network (DN) hydrogels, designated as PAA-CS-Cu DN hydrogels, by facilitating the intricate entanglement of CS chains within a newly formed network architecture, a process achieved through a straightforward immersion in $CuSO_4$ solutions. The PAA-CS-Cu DN hydrogels exhibit porous structures, coupled with high tensile strength (0.578 MPa), and exceptional toughness. The benefits of this strategy are as follow: 1) the swift and direct transition from a composite hydrogel into DN hydrogels is quickly realized as a simple one-step process; 2) it through adjusting soaking solutions that enabling the facile creation of diverse CS physical networks hybrid DN hydrogels; 3)

significantly toughens DN hydrogels are profit from the efficient dissipation of energy through the decrosslinking or dissociation of CS physical networks. This creative strategy significantly augments the mechanical properties of DN hydrogels, broadening their horizons for construction and diverse applications (Figure 1).

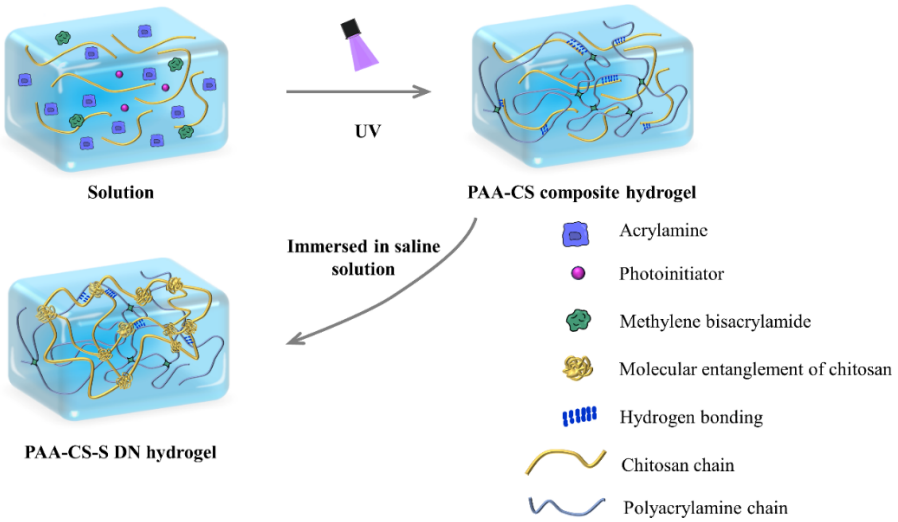


Fig 1. Mechanisms of converting the composite hydrogel into hybrid DN hydrogels.

As shown in Figure 2, the synthesis of composite hydrogels was achieved through a one-step UV-induced free-radical polymerization process involving aqueous solutions. These solutions encompassed short-chain CS, acrylic acid (AA), Irgacure 2959 as the photoinitiator, and N, N′-methylene-bis-acrylamide (MBA), as the cross-linker. Then, the composite hydrogels PAA-CS is obtained which exhibited superior mechanical properties compared to the single-network (SN) PAA hydrogel, which is likely attributable to the hydrogen bonding interactions established between CS and PAA network that are hypothesized to contribute to an increase in both ductility and toughness.

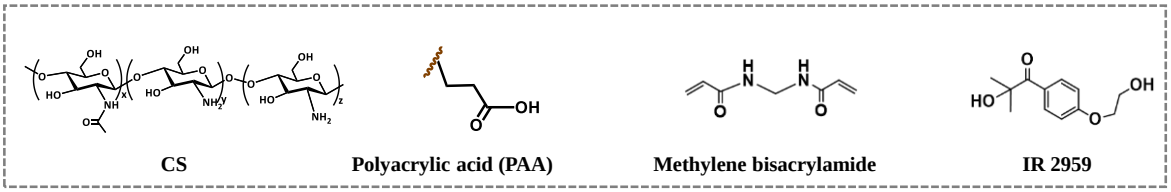


Fig 2. Chemical structural formula of the CS, PAA, MBA and IR 2959.

Upon immersion in a 0.1 mol·L-1 $CuSO_4$ solution for a duration of 20 min, the initially transparent PAA-CS hydrogel underwent transformation, evolving into opaque PAA-CS-Cu DN hydrogels, concomitant with the establishment of CS physical networks. The PAA-CS-A DN hydrogel still withstood various deformations that similar to the PAA-CS hydrogel, such as elongation, knotting, compression, and twisting. But despite its remarkable toughness, the DN hydrogel conspicuously demonstrated superior stiffness, underscoring its unique mechanical properties (Figure 3).

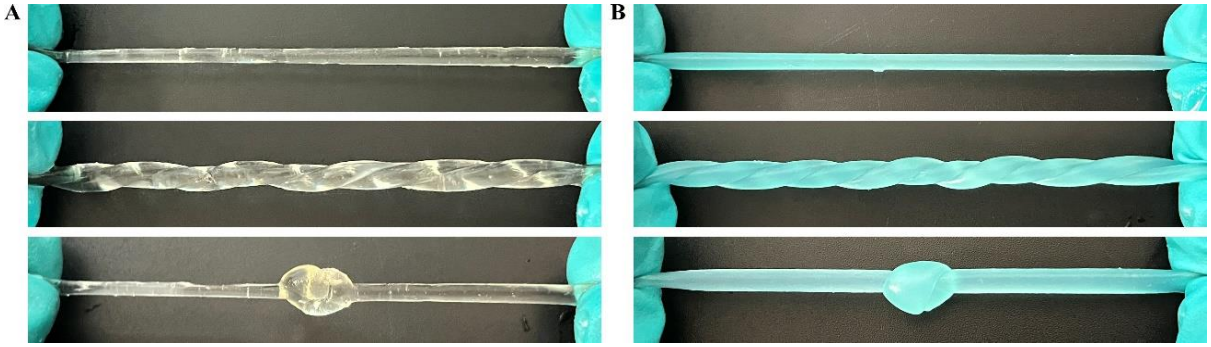


Fig 3. Mechanical properties of the (A) PAA-CS composite hydrogel and (B) PAA-CS-Cu DN hydrogel with stretching, twisting and knotting behaviors.

The function of the newly formed CS physical networks lies in the construct of hybrid DN hydrogels, facilitated by the facile mobility and reorganization of short-chain CS within the composite hydrogel under alkaline and saline conditions. As illustrated in Figure 3, the mitigation of electrostatic repulsions, the concerted action of salting-out phenomena, and the augmentation of hydrophobic interchain interactions facilitated the formation of intermolecular assemblies upon immersion in CuSO4 solution. These assemblies acted as nodal points within the chain-entanglement network, ultimately resulting in the generation of CS microcrystalline and chain-entanglement physical networks upon exposure to saline solution which transformed the initially transparent composite hydrogel into an opaque PAA-CS-A hybrid DN hydrogel.

The integration of inherently elastic covalent PAA network with the rigid CS physical networks, arising from a dense concentration of short-chain CS, imparts remarkable mechanical prowess to the PAA-CS DN hydrogel. As depicted in Figure 4A, the PAA-CS-A DN hydrogel can reach high tensile strengths to be 0.578 MPa, surpassing that of the PAA-CS hydrogel by a factor of four (0.146 MPa). Figure 4B showed that the PAA-CS-A DN hydrogel exhibited stronger elastic modulus compared to weak elastic modulus of the PAA-CS hydrogel (38.5 ± 3.1 kPa) which to be 68.6 ± 2.4 kPa.

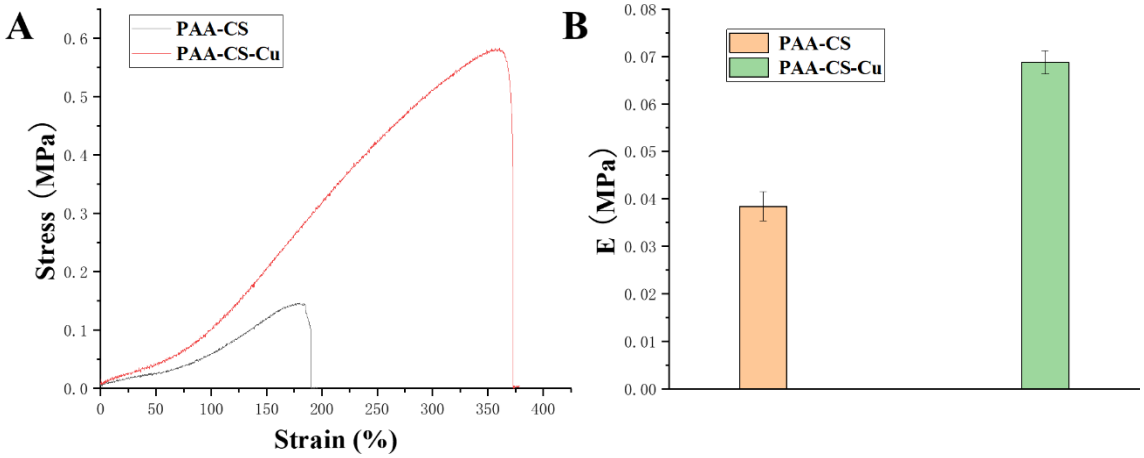


Fig 4. (A) Tensile curves and (B) elastic modulus of the PAA-CS composite hydrogel and PAA-CS-Cu DN hydrogel.

Remarkably, when compared to the composite hydrogel, the PAA-CS-A DN hydrogel possesses superior modulus and toughness, attributes that can be due to the integration of novel CS physical networks that formed denser network structures with enhanced cross-linking densities and finer pores, leading to cleared performance. The smaller pores can facilitate crack propagation, enhance the toughness and mitigating stress concentrations of the hydrogels, and avoid stress concentration. Additionally, the DN hydrogel also stiffer than the original PAA-CS hydrogel because of the increased cross-linked density (Figure 5). During the process of deformation, the CS chain-entanglement physical networks undergo dissociation, effectively dissipating energy and contributing to the exceptionally high fracture energy exhibited by the PAA-CS DN hydrogel.

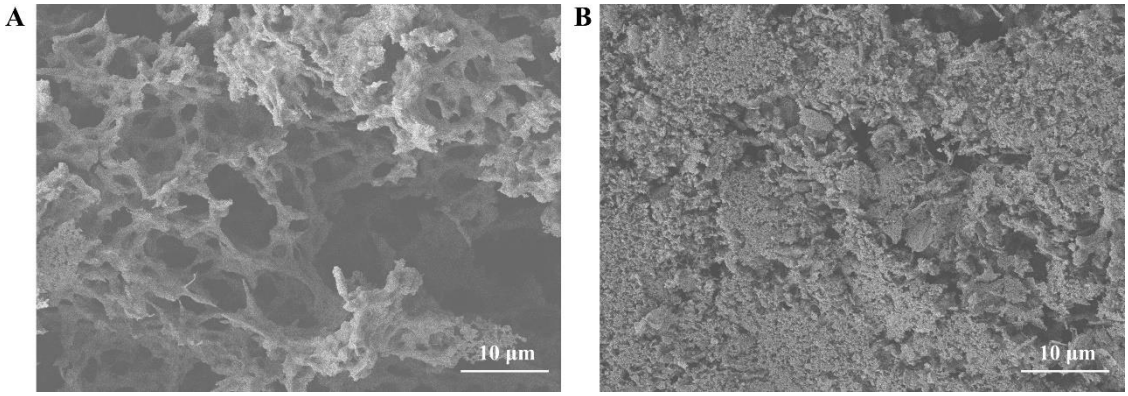


Fig 5. SEM images of (A) PAA-CS composite hydrogel and (B) PAA-CS-Cu DN hydrogel.

4. Conclusion

In essence, we presented a facile and practical approach for constructing hybrid PAA-CS-Cu DN hydrogel by transformation of the CS chain-entangled physical networks via a simple $CuSO_4$ solutions treatment of the PAA-CS composite hydrogels. The hybrid DN hydrogels exhibit remarkable toughness and unparalleled tensile strength. The synergetic interplay between the CS physical networks and PAA covalent network imparts exceptional mechanical properties to the hybrid DN hydrogels. Notably the PAA network preserves hydrogel integrity during deformation, while the disruption and reversible reconfiguration of CS physical networks efficiently dissipate energy, resulting in superior toughness, modulus, and fatigue resistance. Employing diverse solutions such as KCl, $MgCl_2$, and $CaCl_2$ effectively yields various outstanding mechanical characteristics in hybrid DN hydrogels. Consequently, the soaking methodology constitutes a versatile approach for transforming CS composite hydrogels into robust and resilient DN hydrogels. This strategy adeptly integrates CS physical networks with diverse covalent networks, enabling the fabrication of a plethora of CS-based hybrid DN hydrogels. Particularly, immersing CS composite hydrogels in saline solutions containing functional molecules, including drugs and fluorescent probes, yields functionalized hybrid DN hydrogels that retain their exceptional mechanical properties. This ubiquitous technique holds promising prospects for crafting diverse and multifaceted DN hydrogels with applications spanning antifouling materials, biological imaging, drug delivery systems, and tissue engineering.

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