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A Facile Method for Synthesizing Free-Shaped and Tough Double Network Hydrogels via Physically Crosslinked Poly (Vinyl alcohol) as Internal Mold

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The creation of Double Network hydrogels (DN gels), which show the extremely high mechanical strength, enabled hydrogels to apply both in medical and industrial fields. However, one obstacle against various applications is the lack of formability of DN gels, owing to the brittleness of the first network PAMPS gels. In order to overcome this problem, we synthesized free-shaped DN gels (called PVA-DN gels) by using a physically cross-linked PVA gel as “internal mold”. PVA-DN gels can form any complex shapes and their mechanical properties were comparable to those of conventional DN gels. This study may expand the application of tough hydrogels.

Introduction

Polymer hydrogels, consisting of hydrophilic polymer network with large amount of water, are unique materials. They show many interesting functions, such as volume phase transition¹, low surface friction², and permeability, which cannot be implemented in solid materials. Thus, hydrogels have attracted much attention as novel functional materials from both medical and industrial fields. Although the strength of conventional hydrogels is typically too low to apply as any load-bearing materials, recent advance of synthesis enables to improve the strength of hydrogels, such as Slide-ring gels, Nanocomposite gels, Double Network gels, Click gels, and Tetra-PEG gels³⁻⁷. Among them, the Double Network gels (DN gels), which were created by our group, show the highest fracture stress and toughness. DN gels are interpenetrating network (IPN) hydrogels consisting of tightly cross-linked rigid poly(2-acrylamido-2-methylpropanesulfonic acid) (PAMPS) gels as the first network and loosely cross-linked flexible polyacrylamide (PAAm) as the second network (even if the cross-linker is not used, PAAm in common DN gels is actually cross-linked⁸).

Although the DN gels contain 90wt% of water (and only 10wt% of polymer chains), they show the excellent mechanical properties. The compressive fracture stress of the DN gels reaches to several dozen MPa^{5,9}, which is comparable to that of articular cartilage (36MPa)¹⁰, a common natural tough hydrogel. In addition, their fracture energy is up to 2200J/m²^{8,11-13}, which is approximately 200 times larger than the theoretical value¹¹. Some DN gels also exhibit suitability for regenerative medicine. Prof. Yasuda's group (Hokkaido University) has reported that the modified DN gels are excellently biocompatible and do not degrade in a body^{14,15}. Additionally, they first succeeded in regenerating articular cartilage in vivo by embedding the biocompatible DN gels¹⁶. Based on these excellent mechanical and medical properties, DN gels are supposed to become superior alternative materials for tough living organs, such as articular cartilages, blood

vessels, and tendons.

Nevertheless, DN gels still have a problem - lack of formability, which is crucial for being extensively used as a material. For example, it is required for an artificial cartilage to form any specific complex shape dependent on the body of each patient. However, conventional DN gels can be formed only in the limited shapes, such as a sheet or a disc. The shapes of DN gels are determined by the first network PAMPS gels as “skeleton” due to the two-step polymerization. Whereas PAMPS gels themselves can be formed any shapes by using molds, it is very difficult to eject convoluted PAMPS gels without crashing due to their extremely poor mechanical properties, such as 0.08MPa of tensile fracture stress, 0.36 of tensile fracture strain and 0.8J/m² of fracture energy¹¹. Incidentally, PAMPS gels or DN gels also cannot be cut or scraped into desired shape after the synthesis.

We have solved this problem by applying “Double Network” structure. As above-mentioned, shape of DN gels is determined by the first network. Based on this fact, it is imagined that if PAMPS gels are synthesized in another kind of hydrogels which are strong enough to eject from molds, the shape of them can be modified easily. We call these shape-deciding hydrogels “internal molds”, as the opposite concept of common “external” molds. This time, we chose physically cross-linked poly(vinyl alcohol) gels (PVA gels) as internal molds because they are so flexible and relatively strong that they can form any complicated shapes¹⁷⁻¹⁹. We performed the following experiments. Firstly, the PVA gels with complex shapes were synthesized. Secondly, the PAMPS network was polymerized in the PVA gels. Thirdly, the PAAm network was synthesized in the presence of the PVA/PAMPS double-network gels (PVA-PAMPS gels) and finally the free-shaped PVA/PAMPS/PAAm triple-network gels (PVA-DN gels) were obtained. These PVA-DN gels show the similar mechanical properties to the conventional DN gels.

Experimental

Materials

Poly(vinyl alcohol) (PVA), polymerization degree: 2000 (Nakalai Tesque, Ltd.) was used as received. Dimethyl sulfoxide (DMSO, Junsei Chemical Co., Ltd.) was used as received. 2-Acrylamido-2-methylpropanesulfonic acid (AMPS, Toa Gosei Co., Ltd.) was recrystallized from methanol. *N,N'*-methylenebis(acrylamide) (MBAA, Wako Pure Chemical Industries, Ltd.) was recrystallized from ethanol. 2-oxoglutaric acid (Wako Pure Chemical Industries, Ltd.) was used as received. Acrylamide (AAM, Junsei Chemical Co., Ltd.) was recrystallized from chloroform.

Synthesis of PVA gels as internal mold

The physically cross-linked PVA gels were prepared by quenching method¹⁸. Firstly, the 10wt% PVA (DMSO:H₂O = 3:1, w/w) solution was prepared by heating a mixture of the PVA and the solvent for 1h at 90°C. Then, the PVA solution was poured into various shapes of molds made of silicone rubber or glass, and they were quenched for 24h at -40°C. After forming network structure, the gels were immersed in pure water more than 1 week to remove DMSO.

Synthesis of free-shaped Double Network gels

First, the AMPS aqueous solution was prepared from 1M of AMPS as monomer, 4mol% of MBAA as cross-linker, and 0.1 or 0.6mol% of 2-oxoglutaric acid as photoinitiator (the molar percentages are respective to the monomer). Then, the PVA gels with various shapes were immersed in this solution for at least 3 days. After immersing, the PVA gels containing AMPS were let in an argon blanket and sealed to prevent drying; then PAMPS network was synthesized in the presence of PVA gels by UV polymerization for 8h. These PVA/PAMPS double-network gels (called PVA-PAMPS gels) were then immersed in 2M of AAm and 0.01mol% of 2-oxoglutaric acid aqueous solution for at least 2 days. Then, PAAm was synthesized in the presence of PVA-PAMPS gels by the same method. After the synthesis, PVA/PAMPS/PAAm triple-network gels, called PVA-DN gels, were immersed in pure water more than 1 week in order to remove any un-reacted reagents. The swollen PVA-DN gels contained 90-92wt% of water. It is important to synthesis the PVA-DN gels under no oxygen atmosphere. If the synthesis proceeds with oxygen, the surface of the sample does not completely form gel state due to chain growth inhibition by oxygen²⁰.

We also synthesized the PAMPS/PAAm double-network gels (conventional DN gels), the PVA/PAMPS double-network gels, and the PVA/PAAm double-network gels as the positive/negative controls with the same composition and by the same method, except that the second network of the PVA/PAAm gel was loosely cross-linked (0.02mol% of MBAA was used). Table 1 shows the components of all the samples.

Mechanical Strength Measurements

The tensile-compressive tester (Tensilon RTC-1310A Orientic. Co.) was used for the measurement of mechanical properties. The compressive fracture stress σ and the Young's modulus E were measured by compressive test on cylindrical

Sample Name	Internal Mold	1 st network	2 nd network
PVA gel	-	PVA	-
PAMPS gel	-	PAMPS	-
PAAm gel	-	PAAm	-
PVA-PAMPS gel	PVA	PAMPS	-
PVA-PAAm gel	PVA	PAAm	-
DN gel	-	PAMPS	PAAm
PVA-DN gel	PVA	PAMPS	PAAm

Table 1 The components of the samples used in this paper.

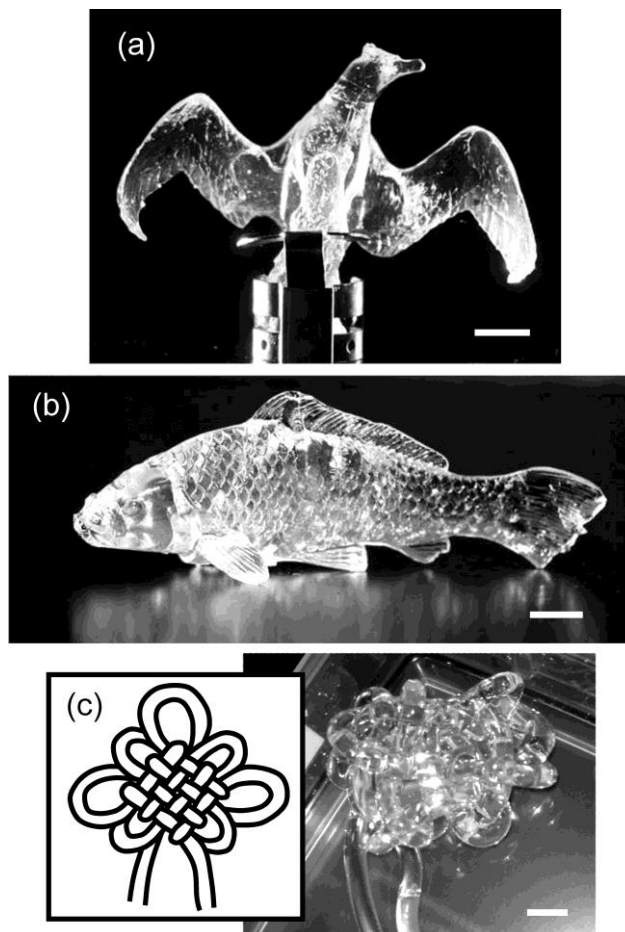


Fig. 1 The pictures of the PVA-DN gels with the shape of (a) the bird, (b) the fish, and (c) The Chinese knot. The conventional PAMPS gels and DN gels cannot form such complicated shapes. The scale bars: 1cm.

(5mm in thickness and 9mm in diameter) gels; the compression rate is 10%/min. The fracture energy G was measured by tearing test on trousers-shaped samples standardized as the JIS-K6252 1/2 size (5mm in thickness, 50mm in length (with 20mm initial legs) and 7.5mm in width). The tearing velocity was 250mm/min. G , defined as the energy required for creating a unit area of fracture surface in a sample, is calculated by $G = F_{ave}/w$, where F_{ave} is the average tearing resistance force, and w is the width of the gel¹¹. The loading curves were measured by tensile test on dumbbell-shaped gels standardized as the JIS-K6251-7 size (length:

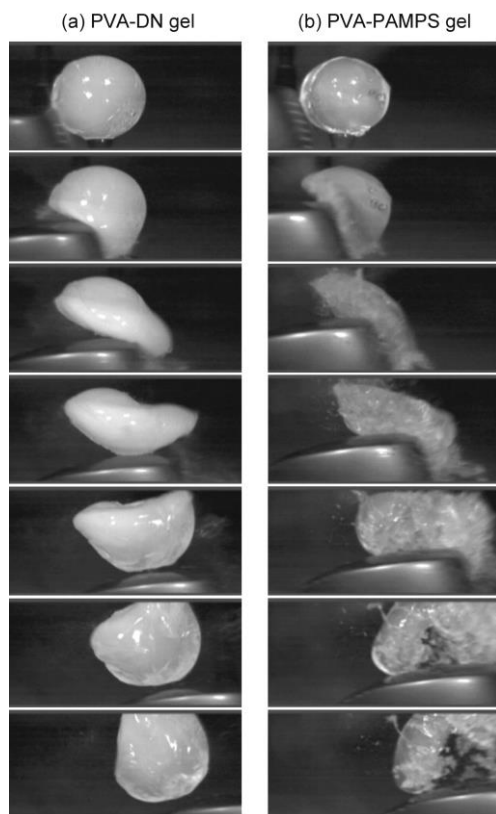


Fig. 2 High-speed camera images of the spherical (a) PVA-DN gel and (b) PVA-PAMPS gel hit by the golf club. Time interval between each picture is 3/4000 sec.

40mm; width: 10mm; thickness: 1.7-2.6mm; gauge length: 12mm; inner width: 2mm). The tensile velocity was 100mm/min.

Results and Discussion

Fig. 1 shows the pictures of PVA-DN gels with various shapes. By this method, any complicated shapes can be formed, such as the bird, the fish, and the Chinese knot shape depending on the shape of the PVA gels as the internal mold. In contrast, conventional PAMPS gels (and DN gels) cannot form even the simple ball-like shape. PAMPS gels were so fragile that they crashed whenever they were removed from the external molds. Even though the PVA-DN gels have obtained the formability, their strength and toughness were still extremely high. Fig. 2 shows the pictures of the sphere-shaped PVA-DN gel hit by a golf club (wood), recorded by a high-speed camera. In spite of the strong impact and the large deformation, the PVA-DN gel recovered its original shape without breaking. On the contrary, the PVA-PAMPS gel was catastrophically broken by the impact. The full movies are available as the supporting informations. It is noted that the PVA-DN gels look a little bit opaque in contrast with completely transparent common DN gels. This decrease of transparency is derived from the crystalline domain of PVA gels.

Here, we express the toughness of the PVA-DN gels by numeral values. Fig. 3 (filled bars) shows the fracture energy G of the PVA-DN, conventional DN, and PVA/PAAm DN

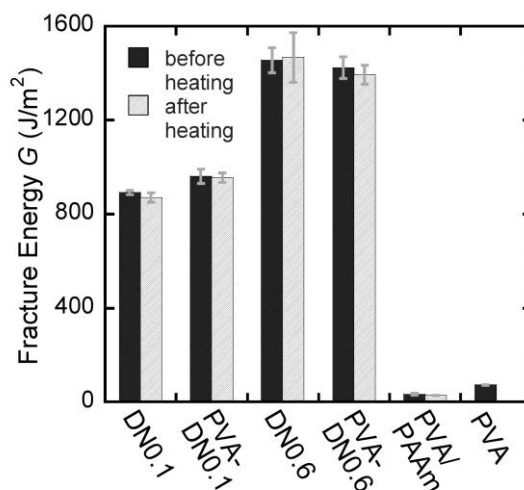


Fig. 3 The fracture energy G of the PVA-DN gels, the conventional DN gels, the PVA-PAAm gel, and the PVA gel. The filled bars represent the G of the DN gels before heating and the mesh bars represent the G after heating. As the PVA gel was dissolved by immersing in hot water, the G of the PVA gel after heating could not be measured. The tearing velocity was 250mm/min. PVA-DN denotes the PVA-DN gels, DN denotes the conventional DN gels, PVA/PAAm denotes the PVA/PAAm DN gels. The PAMPS gels and the PVA-PAMPS gels are too weak to be measured. The following number denotes the initiator concentration for the PAMPS network (mol%).

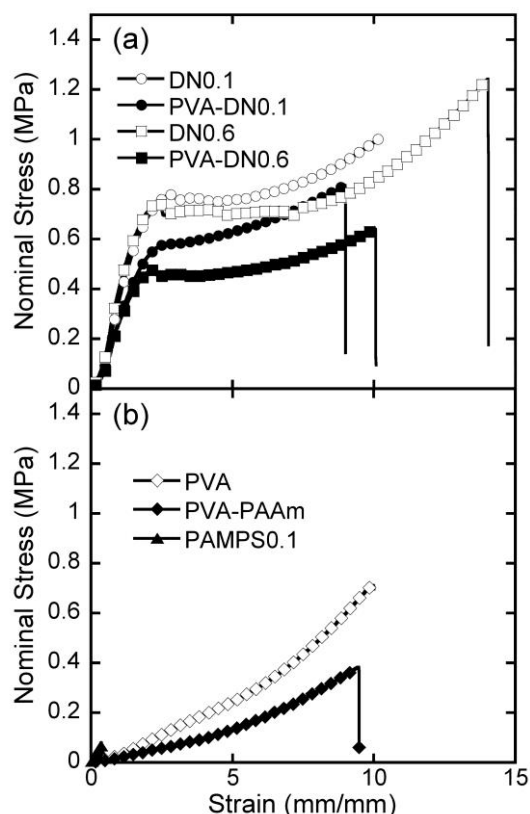


Fig. 4 The tensile stress-strain curves of (a) the PVA-DN gels, the conventional DN gels (b) the PVA-PAAm gel, the PVA gel, and the PAMPS gel measured by the tensile test. The PVA-PAMPS gels are too weak to be measured. The tensile velocity was 100mm/min.

gels. The G , which represents the toughness, of the PVA-DN gels was anomalously high and similar to that of the conventional DN gels. On the other hand, even though the PVA/PAAm DN gels also show formability, their fracture energy G was quite lower than the other DN gels. Fig. 4 shows the tensile stress-strain curves of the DN gels. The tensile fracture stress of the PVA-DN gels was less than that of DN gels; on the other hand, the fracture strain of those gels was similar to each other. This phenomenon might be caused by a lower PAMPS concentration in the PVA-DN or PVA-PAMPS gels than conventional PAMPS gels and DN gels. As the PVA gels contained 10wt% of polymer, concentration of AMPS in the PVA-PAMPS gels did not reach to 1M in spite of the gel immersion in 1M AMPS solution. Using slightly higher concentration of AMPS solution may be useful to overcome the effect of PVA chains.

Next, we try to clarify the effect of the PVA chains to the toughness of the PVA-DN gels. Physical PVA gels are cross-linked by the formation of hydrogen bonds¹⁸ and these bonds were easily destroyed by applying heat. Thus, the effect of PVA network to the mechanical properties of PVA-DN gels can be removed by heating the samples. So we investigated the effect of PVA network by measuring the fracture energy G of the PVA-DN gels before and after heating. The DN gels, the PVA-DN gels, and the PVA gel were immersed in hot water at 70°C for 8h. Fig. 3 shows the fracture energy G of the DN gels before and after heating. The G of the conventional DN gels and the PVA-DN gels did not change by this operation. This result implies that PVA network of PVA-DN gels has no effect to the mechanical strength of DN gels. The PVA network works only as “internal mold”.

In order to explain why PVA-DN gels have both formability and toughness, we discuss the mechanical properties of the first network gels. First, we investigated the mechanical properties of as-prepared gels in order to discuss formability. Fig. 5 shows the tensile loading curves of the PVA gel, which consists of neutral polymer and show formability, and the as-prepared PAMPS gels and PVA-PAMPS gels, consisting of polyelectrolyte. The PVA gel showed high flexibility, indeed it did not break even if the strain reached to 10. In addition, its tensile fracture stress is relatively high. Therefore, PVA gels are not broken when they were ejected from complex molds. In contrast, the conventional PAMPS gels showed the completely different behavior, rigid and brittle. They were broken when the stress attained only 0.08MPa; thus, they cannot be removed from the mold without being broken. These data imply that the flexibility is so important for the formability.

Second, we take notice of the mechanical properties of swollen first network gels. Our first paper about DN gels reports experimentally that the rigidity of the swollen first network PAMPS is enormously important for the strength of the DN gels⁷. This point is also indicated theoretically by some other papers²¹⁻²⁵. As the index parameter of rigidity, we use modulus for simplification. Fig. 6 shows the compressive stress-strain curves and the modulus of the PVA/PAMPS gels, the conventional PAMPS gels and PVA gel in swollen state. The conventional PAMPS gels showed

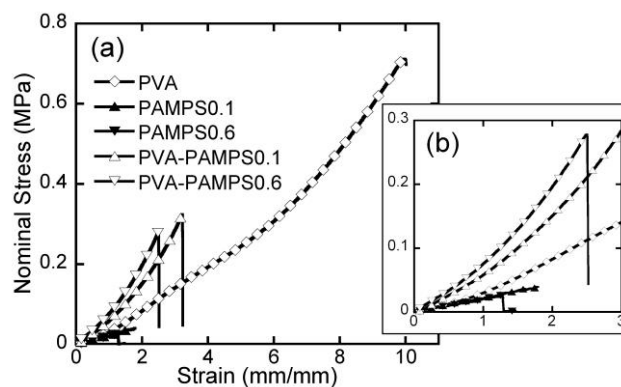


Fig. 5 (a) The tensile stress-strain curves of the PVA gel, the as-prepared PAMPS gels, and the as-prepared PVA-PAMPS gels. (b) The enlarged figure of the low-strain region.

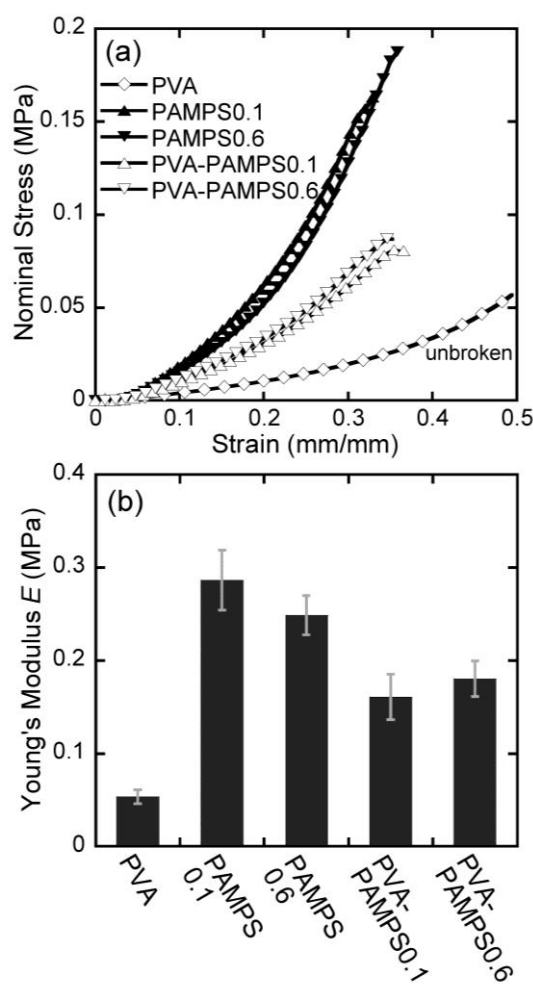


Fig. 6 (a) The compressive stress-strain curves and (b) the Young's modulus of the PVA gel, the swollen PAMPS gels, and the swollen PVA-PAMPS gels.

the highest moduli (~0.25MPa). The PVA-PAMPS gels also showed the high moduli (~0.15MPa), while the values were less than those of PAMPS gels. It is suggested that despite of the presence of PVA network, the properties of the swollen PVA/PAMPS gels are mainly dominated by rigid PAMPS network, caused by fully stretching of polyelectrolyte chains.

This rigidity leads to the toughening of DN gels; thus, both the PVA-DN gels and the DN gels showed the toughness. In contrast, the modulus of the swollen PVA gel is quite low (~0.05MPa) even though its polymer concentration is higher than that of the swollen PAMPS gels. Thus, the PVA/PAAm DN gels do not show the toughness.

The essential points of this study are the following. Formability of (DN) gels is introduced by flexibility of as-prepared first network gels. On the other hand, the extremely high strength of DN gels is derived from the rigidity of swollen first network⁴. Until now, there has been no rigid and flexible gel in accordance with our best knowledge; thus, tough DN gels with formability have not been synthesized. For example, PAMPS/PAAm DN gels are strong but not formable due to the rigid and “brittle” first network; on the other hand, PVA/PAAm DN gels show formability but weak due to the flexible and “soft” first network. This problem can be solved by using PVA/PAMPS gels as the first network. They are enough flexible (and soft) to form any shapes in as-prepared PVA single network state; in contrast, after synthesizing PAMPS network and swelling, their property changes to rigid (and brittle), which enables to toughen (PVA-)DN gels. This is the reason why PVA/PAMPS/PAAm (PVA-DN) gels have both formability and toughness.

Conclusions

Free-shaped Double Network hydrogels (PVA-DN gels) were synthesized by using PVA gels as internal molds. They could form any complicated shapes, such as the fish and the bird. Additionally, the mechanical properties of PVA-DN gels were almost the same as those of the conventional DN gels. These formability and the strength are provided via the difference of the mechanical properties between the flexible as-prepared PVA gels and the rigid swollen PVA/PAMPS gels. This study will enable DN gels to apply to biological and industrial fields, such as artificial cartilages adopted into individual patient, artificial blood-vessels with complicated shapes, and nano-gel machines based on chemomechanical systems²⁶.

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