

SYNTHESIS AND CHARACTERIZATION OF ELASTOMERIC SILICONE
URETHANE ACRYLATE HYDROGELS VIA ULTRAVIOLET
LIGHT-EMITTING DIODE PHOTOPOLYMERIZATION

NUR AMANINA ABDUL KHALID

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School of Chemical and Energy Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

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ABSTRACT

A new and simple method to develop highly stretchable and resilient hydrogels via ultraviolet light-emitting diode (UV LED) photopolymerization was carried out. Firstly, a single network (SN) polyacrylamide (PAAm) hydrogel was prepared. The SN hydrogel had achieved about > 98 % monomer conversion, 66 to 82 % gel fraction and 10.7 ± 0.1 to 4.1 ± 0.01 swelling degree. Differential scanning calorimetry result showed the existence of bound and free water in PAAm hydrogel which have interrelation with the swelling and tensile properties. Nevertheless, the SN hydrogels demonstrated poor tensile properties (tensile strength: ~ 0.06 MPa, Young's modulus: 0.26 ± 0.02 MPa, elongation at break: $\sim 32 \pm 3.4$ % and toughness: $\sim 1104 \pm 90.5$ J/m²) which severely limit their extensive uses for the advanced functional material. Thus, double network (DN) hydrogels were prepared and characterized by adding chitosan hyaluronic acid (ChiHA) to PAAm SN hydrogels at concentration ranging from 20-50 wt%. The optimized DN hydrogel with 30 wt% of ChiHA composition exhibited higher monomer conversion (up to 99 %), gel fraction (~ 73 to 98 %) and tensile properties (tensile strength: ~ 0.16 MPa, Young's modulus: ~ 0.47 MPa, elongation at break: $\sim 49 \pm 0.1$ % and toughness: $\sim 1785 \pm 58.4$ J/m²). However, the resilience property in DN hydrogels was low as indicated by large hysteresis upon loading-unloading cycle. To overcome this problem, the selected compositions of DN hydrogels with 40 and 50 wt% of overall monomer concentration (OMC) were modified to produce elastomeric hydrogels (EH). Silicone urethane acrylate (SUA), an elastomeric and resilient material, was integrated into DN hydrogels in a "sandwich-like" form via photopolymerization. EH was successfully polymerized by reaching up to 99 % of gel fraction. The peaks from Fourier transform infrared spectra at 1262, 1096, 1023 and 802 cm⁻¹ were attributed to Si-CH₃, Si-O-Si, -C-O and Si-C stretching mode for SUA network. EH possessed excellent tensile properties where its tensile strength, Young's modulus, toughness and elongation at break were ~ 2 -13 times larger than SN and DN hydrogels. EH also exhibited a remarkable compressive strength (~ 1.5 MPa), exceptional fracture toughness (~ 36851 J/m²) and highly resilient (~ 93 %). These exceptional properties were due to the reversible assembly of the strong and flexible SUA chain, which could be explained by the dissipation of the crack energy along the EH network. The temporarily molecular dissociation in EH network which could be instantly reconstructed during unloading process may also be responsible. These fascinating properties of the novel EH had offered an alternative candidate for biomaterial applications.

ABSTRAK

Satu kaedah baharu yang mudah untuk membangunkan hidrogel yang mempunyai kebolehgangan dan kebingkasan yang tinggi melalui fotopempolimeran diod pemancar cahaya ultraviolet telah dilakukan. Pada permulaannya, hidrogel jaringan tunggal (SN) poliakrilamida (PAAm) disediakan. Hidrogel SN mencapai > 98 % penukaran monomer, pecahan gel 66 hingga 82 % dan darjah pembengkakan 10.7 ± 0.1 hingga 4.1 ± 0.01 . Keputusan kalorimeter imbasan kebezaan (DSC) menunjukkan kewujudan air yang terikat dan bebas dalam hidrogel PAAm mempunyai hubung kait dengan sifat pembengkakan dan tegangan bagi hidrogel. Walau bagaimanapun, hidrogel SN menunjukkan sifat tegangan yang lemah (kekuatan tegangan: ~ 0.06 MPa, modulus Young: 0.26 ± 0.02 MPa, pemanjangan pada takat putus: $\sim 32 \pm 3.4$ % dan kekukuhan: $\sim 1104 \pm 90.5$ J/m²) sehingga menghadkan penggunaannya untuk bahan berfungsi termaju. Oleh itu, hidrogel jaringan berganda (DN) disediakan dan dicirikan dengan menambah asid hialuronik kitosan (ChiHA) ke dalam hidrogel SN PAAm dengan julat kepekatan 20-50 % berat. Komposisi hidrogel DN yang dioptimumkan dengan komposisi ChiHA 30 % berat menunjukkan penukaran monomer yang lebih tinggi (sehingga 99 %), pecahan gel (~ 73 hingga 98 %) dan sifat-sifat tegangan (kekuatan tegangan: ~ 0.16 MPa, modulus Young: ~ 0.47 MPa, pemanjangan pada takat putus: $\sim 49 \pm 0.1$ % dan kekukuhan: $\sim 1785 \pm 58.4$ J/m²). Namun, sifat kebingkasan dalam hidrogel DN adalah rendah seperti ditunjukkan oleh histerisis yang besar terhadap kitaran peletakan-pelepasan beban. Untuk mengatasi masalah ini, komposisi hidrogel DN yang terpilih dengan kepekatan monomer keseluruhan 40 dan 50 % berat telah diubahsuai untuk menghasilkan hidrogel elastomer (EH). Silikon uretana akrilat (SUA), bahan elastomer dan kenyal, telah diintegrasikan ke dalam hidrogel DN berbentuk seperti “sandwich” melalui fotopempolimeran. EH berjaya dipempolimerankan dengan mencapai pecahan gel sehingga 99 %. Puncak-puncak daripada spektrum inframerah transformasi Fourier disifatkan mod regangan Si-CH₃, Si-O-Si, -C-O dan Si-C bagi jaringan SUA. EH mempunyai ciri-ciri tegangan yang sangat baik dimana kekuatan tegangan, modulus Young, kekukuhan dan pemanjangan pada takat putusnya adalah ~ 2 - 13 kali ganda lebih besar berbanding hidrogel SN dan DN. EH juga mempamerkan kekuatan mampatan yang luar biasa (~ 1.5 MPa), kekukuhan patah yang hebat (~ 36851 J/m²) dan kebingkasan yang tinggi (~ 93 %). Ciri-ciri yang luar biasa ini disebabkan oleh rangkaian SUA yang kuat dan boleh dilentur, yang boleh dijelaskan oleh lesapan tenaga retak di sepanjang jaringan EH. Peleraian molekul sementara dalam jaringan EH yang boleh dibina semula dengan serta-merta semasa proses pelepasan beban juga bertanggungjawab untuk mendapatkan ciri-ciri ini. Sifat-sifat menarik yang dimiliki oleh EH yang novel ini menawarkan sebagai salah satu calon alternatif bagi aplikasi biomaterial.

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LIST OF ABBREVIATIONS

AAm	-	Acrylamide
Alg	-	Alginate
ChiHA	-	Chitosan hyaluronic acid
Chivacure 300	-	oligo[2-hydroxy-2-methyl-1-(4-morpholinophenyl)-1- butanone
CS	-	Chondroitin sulfate
DN	-	Double Network
DSC	-	Differential Scanning Calorimetry
EH	-	Elastomeric Hydrogels
FTIR	-	Fourier Transform Infrared
H-bond	-	Hydrogen bonding
HEA	-	Hydroxyethyl acrylate
LED	-	Light-emitting Diode
MBAAm	-	<i>N,N'</i> -methylenebisacrylamide
MCS	-	Methacrylated chondroitin sulphate
NMR	-	Nuclear Magnetic Resonance
OMC	-	Overall monomer concentration
PAA	-	Poly(acrylic acid)
PAAm	-	Polyacrylamide
PAMAA	-	Poly(acrylamide-co-acrylic acid)
PAMPS	-	Poly(2-acrylamido-2-methylpropanesulfonic acid)
PDGI	-	Poly(dodecyl glyceryl itaconate)
PDMAAm	-	Poly(<i>N,N'</i> - dimethylacrylamide)
PDMS	-	Polydimethylsiloxane
PEG	-	Poly(ethylene glycol)
PEGDA	-	Polyethylene glycol diacrylate
PHEA	-	Polyhydroxyethyl acrylate
HEMA	-	Poly(2-hydroxyethyl methacrylate)

PFICC	-	Polyfunctional initiating and cross-linking centers
PNIPAAm	-	Poly(<i>N</i> -isopropylacrylamide)
PRU	-	Polymer repeating unit
PU	-	Polyurethane
PVA	-	Poly(vinyl alcohol)
PVP	-	Poly(<i>N</i> -vinylpyrrolidone)
SN	-	Single Network
SNP	-	Silica nanoparticles
SUA	-	Silicone Urethane Acrylate
TN	-	Triple Network
TOC	-	Total Organic Carbon
UV	-	Ultraviolet
UV Hg	-	Mercury-based ultraviolet lamps
WSPI	-	Water soluble photoinitiator
XG	-	Xanthan gum

LIST OF SYMBOLS

MPa	-	Mega Pascal
J/m ²	-	Joules per metre square
MJ/m ³	-	Mega Joules per metre cubic
wt%	-	Weight percent
kPa	-	kilo Pascal
nm	-	Nanometre
cm ² /s	-	centimetre square per second
cP	-	centipoise
mL/min	-	millilitre per minute
°C/min	-	degree Celcius per minute
mm/s	-	millimetre per second
W _{fw}	-	Free water
W _f	-	Freezable bound water
W _{nf}	-	Non-freezable bound water
λ	-	Wavelength

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Three dimensional crosslinked networks of hydrophilic polymer known as hydrogels have attractive properties due to their tunable chemical and physical performances and inherent resemblances to biological materials. Hydrogels possess a great potential of applications ranging from biomedical fields, tissue engineering, nano-reactor design and separation systems. In the presence of hydrophilic groups, hydrogels tend to swell and retain water in their structure due to the crosslinking network¹. Also, hydrogels are soft and wet materials owing to high water content with their stiffness comparable to body tissues and 10-100 times lower than latex².

In addition, hydrogels that can change their shape and physical properties in response to pH, temperature and light are being explored for applications such as biosensors, controlled drug delivery and artificial muscle tissues^{1,3,4}. Hydrogels are also completely transparent and biocompatible with surrounding biological tissues. Thus, hydrogels are safe for human and already established for manufacturing of contact lenses, diapers, toothpaste and shower gel⁵.

The conventional hydrogels which are also known as single network (SN) hydrogels can either be chemically or physically crosslinked. Polyacrylamide (PAAm) hydrogel is one of the most widely explored hydrogels, which is typically synthesized by chemically initiated free-radical copolymerization or ultraviolet (UV) initiated of

acrylamide (AAm) in the presence of crosslinker such as *N,N'*-methylenebisacrylamide (MBAAm). Hydrogels based on AAm/MBAAm have been studied for tissue engineering⁶, controlled release⁷, DNA electrophoresis⁸ and microfluidic devices⁹. They also have sufficient hydrophilicity but low in hydrolytic stability and tensile strength^{10,11}.

Double network (DN) hydrogels had been proposed as substitutes to improve the mechanical properties of the SN hydrogels¹²⁻¹⁶. Fundamentally, DN hydrogels are formed from combination of brittle polyelectrolyte and ductile neutral polymer network which contribute to the improvement of tensile strength^{17,18}, compressive strength^{18,19} and toughness^{12,16,18}. The remarkable enhancement in mechanical properties of DN hydrogels could be explained by the understanding of their network structures. Almost all DN hydrogels are particularly synthesized as covalent-covalent, ionic-covalent and physical-physical crosslinked networks. In 2003, Gong and her co-workers have developed the first covalently linked poly(2-acrylamido-2-methylpropanesulfonic acid)/polyacrylamide (PAMPS/PAAm) DN hydrogels. The PAMPS/PAAm gels exhibited fracture tensile stress of 1-10 MPa, fracture tensile strain of 1000-2000 % and fracture toughness of 10^2 - 10^3 J/m²⁰. The ionic-covalently crosslinked of Ca²⁺ alginate/polyacrylamide (Ca²⁺-Alg/PAAm) DN hydrogel exhibited only 0.16 MPa of tensile strength with 74 % of recoverability due to the introduction of reversible noncovalent bonds²¹. Meanwhile, the physically crosslinked of poly(dodecyl glyceryl itaconate)-polyacrylamide (PDGI-PAAm) bilayer exhibited excellent flexibility and high toughness²².

In addition, the biomedical applications of tough hydrogels demanded them to have outstanding deformation recoverability or resilience. For instance, the mechanical parts or artificial organs (*e.g.* artificial muscles) made of hydrogels ought to endure repeated deformation for a longer time. Accordingly, Spinks and Wallace proposed the fabrication of tough hydrogels on the basis of the DN formulations with good tensile strength (0.7 to 1.3 MPa), Young's modulus (0.6 to 0.9 MPa), strain at break (~ 350 %) and instant recovery (75 to 85 % at first loading cycle)²³. Meanwhile, polyethylene glycol/polydimethylsiloxane (PEG/PDMS) hydrogel demonstrated

resilience over 97 %, fractured toughness 80 J/m² and measured strain up to 300 %²⁴. Progress towards robust hydrogels was further explored by a group of researchers which successfully synthesized skin-inspired hydrogel-elastomer hybrids with excellent interfacial toughness (> 1000 J/m²) and functional microstructures²⁵. All those studies have revealed that the development of elastomeric hydrogels (EH) could be a possible approach to enhance the mechanical properties of tough hydrogels including resiliency. Meanwhile, difunctional silicone urethane acrylate (SUA) oligomer has been identified as a component that possesses elastomeric property and is predominant for enhancing the elasticity and resiliency of EH^{26,27}. In addition, the excellent flexibility and toughness of SUA cured film are crucial for development of biomaterials requiring high mechanical properties such as cartilage and tissue engineering²⁶.

Herein, PAAm-chitosan hyaluronic acid (ChiHA) DN hydrogel was selected to represent the covalently crosslinked and ionically crosslinked networks. PAAm has long chain length, sufficient hydrophilicity and convenient for mechanical adjustability. Meanwhile, ChiHA has strong polar and ionic interactions between amine and hydroxyl group, responsible for the enhanced mechanical properties due to physical crosslinking²⁸. In this study, PAAm-ChiHA/SUA EH was synthesized via ultraviolet light-emitting diode (UV LED) photopolymerization. UV LED system offers a fast curing rate, low maintenance cost and emits no ozone extraction or harmful toxic chemicals²⁹ as compared to conventional UV mercury system. Since SUA possesses good photosensitivity and compatibility with the acrylate monomers, EH could rapidly photopolymerize under UV photopolymerization^{26,27}. Similar to SN and DN hydrogels, EH possesses high water content and has outstanding moisture absorbing. EH is also an innovative thin material that is extensively tougher than SN hydrogels. Additionally, EH exhibits good recoverability with very minimum hysteresis after loading-unloading cycle without permanent damage which can address the disadvantages of DN hydrogels. On top of that, EH are potential advanced biomaterials which could offer a new vision into the design of the tough and highly resilient hydrogels.

1.2 Problem Statement

Hydrogels are promising biomaterials due to their good compatibility and low friction with surroundings biological tissues³⁰⁻³². However, classical SN gels are mechanically weak and notoriously brittle with low stretchability, poor toughness and no recoverability^{16,33,34}. They generally fail at a stress less than 1 MPa and strain less than 100 %³⁵. SN hydrogels also have low resistance against crack propagation with fracture energy within a range of 0.1-10 J/m² when compared to usual cartilages (~ 1000 J/m²) and natural rubber (~ 10,000 J/m²)³⁵. The use of SN hydrogels also is limited to the applications requiring low mechanical properties only such as water absorber and drug delivery devices³⁶.

In order to improve the characteristics of SN hydrogels, DN hydrogels which composed of stiff and brittle first network as well as soft and ductile second network have been introduced^{14,37,38}. DN hydrogels based on PAAm and PAMPS were found to have high tensile (~ 2 MPa) and compression strengths (~ 17 MPa)^{3,39,40}. In other study, the methacrylated chondroitin sulphate/polyacrylamide (MCS/PAAm) DN hydrogel demonstrated remarkably high toughness (~ 1.16 MJ/m³) and fracture properties (> 1.5 MPa) as compared to SN hydrogels⁴⁰. Besides that, DN hydrogels are capable to exhibit high mechanical strength and fracture energies due to strain energy dissipation of the second network^{13,16}. Even though they have significant improvement in toughness as compared to SN hydrogels, yet they suffered a large hysteresis^{13,22,41}. This also proved that DN hydrogels are susceptible to the permanent damage caused by load-induced scission of the network strands and subsequently leading to poor recoverability^{13,41}. Due to these facts, they are still not the best material to substitute hydrogel-like bio-tissues such as skin, cartilage, tendon, muscle and blood vessel which are commonly highly strong and resilient.

To address the above problem, several efforts on designing both tough and highly resilient hydrogels have drawn extensive interest among scientists recently^{23,25,42}. For instance, it is stated that the hydrogel based elastomer achieved

high toughness ($\sim 1900 \text{ J/m}^2$) and extremely high resilient (~ 95 to 98%) at high strain (300 to 400%)⁴³⁻⁴⁵. Thin and tough hydrogel reveals $\sim 350 \%$ of extensibilities, 580 – 910 kPa of Young's modulus, 715 – 1320 kPa of tensile strength and immediate recovery up to 75 – 85% ²³. In 2016, a group of researchers proposed a method to develop hydrogel-elastomer hybrids with robust interfacial toughness (1000 J/m^2)²⁵. Therefore, innovation of hydrogels with extraordinary mechanical properties such as high stretchability, excellent toughness and super resilient, is crucially important and provides a new biomimetic route to engineered hydrogels.

Since the study on EH is still limited, a new hydrogel material that possess elastomeric properties with additionally high toughness and high resilient was developed in this study via UV LED photopolymerization. This hydrogel is devoted to PAAm-ChiHA/SUA EH. EH is thin material and extensively tougher than conventional SN and DN hydrogels. SUA bilayer was assembled onto PAAm-ChiHA hydrogel in “sandwich-like” form to engineer a novel PAAm-ChiHA/SUA EH with elevated stretchability, toughness and resiliency. SUA oligomer was selected due to its chain flexibility and good compatibility with a number of acrylate monomers^{26,27}. Furthermore, SUA which represents as elastomeric part is responsible to improve gel flexibility and resiliency of EH. This is primarily ascribed to the huge quantity of flexible polysiloxane chains, which were enhanced by the branching degree of SUA in EH network. Therefore, this makes them suitable candidates to replace the conventional hydrogels and may provide a resourceful platform for developing tough and highly resilient hydrogels.

1.3 Objectives of the Study

This study revolves on the synthesis and characterization of PAAm-ChiHA/SUA EH using UV LED curing system. Specifically, the aims were:

- a) To synthesize various formulations of EH in the form of “sandwich-like” between SUA and PAAm-ChiHA DN hydrogel via UV LED photopolymerization.
- b) To optimize the formulations of PAAm SN and PAAm-ChiHA DN hydrogels in terms of tensile properties for further developing of PAAm-ChiHA/SUA EH.
- c) To characterize the properties of PAAm-ChiHA/SUA EH in terms of tensile, compression, thermal and physicochemical properties.

1.4 Scopes of the Study

The first network pre-gel solution was prepared first with 0 to 40 wt% of total monomer concentration in this study. Briefly, PAAm SN pre-gel solution consisting of main monomer AAm, crosslinker MBAAm and photoinitiator Chivacure 300. In the second task, ChiHA pre-gel solution in the range of 0 to 40 wt% was incorporated into PAAm SN pre-gel solution to prepare PAAm-ChiHA DN pre-gel solution. Both composition of SN and DN hydrogels were optimized from the characterization of tensile test, which then were used for synthesizing of EH.

At the same time, SUA was dissolved in a mixture of 10 wt% of benzophenone and ethanol and stirred until homogenous solution. The SUA solution was poured into two different glass moulds and placed in a fume hood for 24 h at room temperature to allow the solvent to evaporate. Thereafter, PAAm-ChiHA DN pre-gel solution was assembled between bilayers of SUA in the form of “sandwich-like” to prepare PAAm-ChiHA/SUA EH. For further characterization, the pre-gel solution was cured using UV LED photopolymerization. Optimization of formulations has to be achieved in order to produce biomaterials based on EH. Properties of EH obtained such as extensibility, recoverability, firmness, toughness and swellability were evaluated and compared with various polymer materials.

The scope of the work also includes characterization of physical and structural properties of resulting PAAm-ChiHA/SUA EH. After polymerization, monomer conversion, crosslinking percentage and functional groups of EH were characterized using total organic carbon (TOC), gel fraction, swelling test and Fourier transform Infrared (FTIR), respectively. Besides, the photopolymerized EH was characterized by conducting tensile, compression and thermal tests.

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