

FORMING POROUS SCAFFOLD FROM CELLULOSE DERIVATIVES

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. provisional application No. 61/006,090, filed December 18, 2007, the entire contents of which are incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The present invention relates to porous scaffolds and methods of forming such scaffolds.

BACKGROUND OF THE INVENTION

[0003] There are many different techniques for forming macroporous scaffolds, such as salt leaching, gas foaming, emulsion freeze drying, fibrous fabric processing, and 3D (three dimensional) printing. Macroporous scaffolds are useful for supporting cells as the large pores can facilitate migration and growth of the cells inside the pores and allow sufficient nutrient access and removal of metabolites. It has been reported that when hydroxypropylcellulose (HPC) is crosslinked at different temperatures, both non-porous and microporous HPC hydrogels can be formed. The average pore sizes in reported microporous HPC hydrogels are less than 10 microns. Generally, micropores refer to pores that have an average pore size in the range of 2 to 50 microns, and macropores refer to pores that have an average pore size of larger than 50 microns.

SUMMARY OF THE INVENTION

[0004] It has been recognized that in some applications it is desirable to

form macroporous scaffolds from cellulose derivatives such as HPC derivatives. It has also been surprisingly discovered that macroporous scaffolds can be formed from hydroxypropylcellulose partially substituted by a substituent, where the substituent comprises one or more self-crosslinkable groups. For example, the substituent can be allyl isocyanate. The macroporous scaffold formed from such partially substituted hydroxypropylcellulose can also have a relatively high interconnected porosity, such as about 50% or higher. The partially substituted hydroxypropylcellulose may be replaced by another thermo-sensitive polymer precursor, such as methylcellulose partially substituted by a substituent that comprises a self-linkable group, or a pH-sensitive polymer precursor partially substituted by a substituent that comprises a self-linkable group.

[0005] Therefore, in accordance with an aspect of the present invention, there is provided a scaffold comprising a polymer defining macropores and comprising hydroxypropylcellulose partially substituted by a substituent, the substituent comprising a self-crosslinkable group, the partially substituted hydroxypropylcellulose being crosslinked through the self-crosslinkable group, the macropores having an average pore size of larger than 50 microns and being at least partially interconnected. The polymer may have an interconnected porosity of about 50% or higher. The polymer may have a total porosity of about 80% or higher. The macropores may have a pore size distribution peaking at above 50 microns, such as at about 90 or about 100 microns. The polymer may have an equilibrium water content of about 85%. The polymer may have a Young's modulus of about 10 to about 20 kPa in a hydrated state. The self-crosslinkable group may comprise an unsaturated double carbon-carbon bond. The substituent may comprise allyl isocyanate, methacrylic acid, acrylic acid, or glycidyl methacrylate. The partially substituted hydroxypropylcellulose may have a degree of substitution of less than about 2.5, such as about 2.1. The polymer may be a gel, such as when in a hydrated state.

[0006] In accordance with another aspect of the present invention, there is provided a method of forming a scaffold, comprising forming a bicontinuous emulsion comprising a continuous aqueous phase and a continuous polymer phase, the polymer phase comprising hydroxypropylcellulose partially substituted

by a substituent, the substituent comprising a self-crosslinkable group; crosslinking the partially substituted hydroxypropylcellulose through the self-crosslinkable group to form a polymer defining at least partially interconnected pores. The substituent may comprise allyl isocyanate, methacrylic acid, acrylic acid, or glycidyl methacrylate. The pores may comprise macropores. The crosslinking may comprise irradiating the emulsion with γ -ray. The crosslinking may comprise crosslinking at least about 90 wt% of the partially substituted hydroxypropylcellulose in the emulsion. Water may be removed from the pores by freeze-drying the polymer. After the freeze-drying, the polymer may have an interconnected porosity of about 50% or higher, and the pores may have an average pore size of larger than 50 microns. The emulsion may comprise about 80 to about 90 wt% of the aqueous phase and about 10 to about 20 wt% of the polymer phase. The partially substituted hydroxypropylcellulose may have a degree of substitution of about 2.5 or less, such as about 2.1. The polymer may be a gel, such as when in a hydrated state. The emulsion may be formed by subjecting a solution comprising water and the partially substituted hydroxypropylcellulose to heat treatment. The heat treatment may comprise heat treatment at a temperature of about 313 K for about 5 minutes.

[0007] In accordance with a further aspect of the present invention, there is provided a method of forming a scaffold, comprising inducing phase separation in a solution comprising a polymer precursor and water, to form a bicontinuous emulsion comprising a continuous polymer phase and a continuous aqueous phase, the polymer precursor comprising a self-crosslinkable group; crosslinking the polymer precursor through the self-crosslinkable group in the emulsion to form a polymer defining at least partially interconnected macropores. The polymer precursor may be a cellulose derivative. The cellulose derivative may be a methylcellulose derivative, or a hydroxypropylcellulose derivative, such as hydroxypropylcellulose partially substituted by allyl isocyanate. The cellulose derivative may be partially substituted by a substituent that comprises a self-linkable group. The self-crosslinkable group may comprise an unsaturated double carbon-carbon bond. The substituent may comprise allyl isocyanate, methacrylic acid, acrylic acid, or glycidyl methacrylate. The polymer precursor may be thermo-sensitive, and the inducing phase separation may comprise heating the solution.

The polymer precursor may be pH-sensitive, and the inducing phase separation may comprise changing pH of the solution. The crosslinking may comprise irradiating the emulsion with γ -ray. The polymer may be a gel, such as when in a hydrated state.

[0008] There is also disclosed a scaffold which comprises a crosslinked polymer that defines macropores. The macropores are at least partially interconnected and have an average pore size of larger than 50 microns. The interconnected porosity may be about 50% or higher. The polymer is formed from a polymer precursor that is responsive to a phase separation stimuli to undergo phase separation in an aqueous solution. The stimuli may be heat or pH change in the solution. The polymer precursor also comprises a self-crosslinkable group so that the polymer molecules are crosslinked through the self-crosslinkable group. The crosslinkable group may be selected so that it will crosslink with each other when irradiated with γ -ray. The polymer precursor may be a cellulose derivative. The cellulose derivative may be a methylcellulose derivative, or a hydroxypropylcellulose derivative, such as hydroxypropylcellulose partially substituted by allyl isocyanate. The cellulose derivative may be partially substituted by a substituent that comprises a self-linkable group. The self-crosslinkable group may comprise an unsaturated double carbon-carbon bond. The substituent may comprise allyl isocyanate, methacrylic acid, acrylic acid, or glycidyl methacrylate. The polymer may have a total porosity of about 80% or higher. The macropores may have a pore size distribution peaking at above 50 microns, such as at about 90 or about 100 microns. The polymer may have an equilibrium water content of about 85%. The polymer may have a Young's modulus of about 10 to about 20 kPa in a hydrated state. The polymer may have a degree of substitution of less than about 2.5, such as about 2.1. The polymer may be a gel, such as when in a hydrated state.

[0009] Other aspects and features of the present invention will become apparent to those of ordinary skill in the art upon review of the following description of specific embodiments of the invention in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] In the figures, which illustrate, by way of example only, embodiments of the present invention,

[0011] **FIG. 1** is a data graph showing the dependence of UV absorbance on solution temperature for different sample solutions;

[0012] **FIG. 2** is a scanning electron microscopy (SEM) image of a cross-section of a sample scaffold;

[0013] **FIGS. 3 and 4** are SEM images of portions of the sample scaffold shown in **FIG. 2**, with increased magnification;

[0014] **FIG. 5** is a line graph showing the pore size distribution in two sample scaffolds;

[0015] **FIG. 6** is a confocal micrograph of a cross-section of a sample scaffold;

[0016] **FIG. 7** is a confocal micrograph of a cross-section of a comparison scaffold;

[0017] **FIG. 8** is a confocal micrograph of the sample scaffold of **FIG. 6** but stained with a different marker;

[0018] **FIG. 9** is a confocal micrograph of the sample scaffold of **FIG. 8** but with higher magnification;

[0019] **FIG. 10** is a data graph showing the dependence of cell numbers in a sample scaffold on culture time;

[0020] **FIGS. 11 and 12** are confocal micrographs of cells cultured in a sample scaffold stained with different markers;

[0021] **FIG. 13** is a superposition of **FIGS. 11 and 12**;

[0022] **FIGS. 14, 15, 16 and 17** are SEM images of cells cultured in a sample scaffold taken at different times with different magnification, respectively;

- [0023] FIG. 18 is a bar graph showing measured urea synthesis data;
- [0024] FIGS. 19 and 20 are bar graphs showing measured comparison data;
- [0025] FIGS. 21, 22, 23 and 24 are SEM images of cells cultured in a sample scaffold;
- [0026] FIG. 25 is a confocal micrograph (transmitted image) of cells cultured in a sample scaffold;
- [0027] FIG. 26 is a confocal micrograph of the cells cultured in the sample scaffold of FIG. 25;
- [0028] FIG. 27 is an SEM image of the cells cultured in the sample scaffold of FIG. 25 at an earlier time;
- [0029] FIG. 28 is a confocal micrograph (transmitted image) of the cells of FIG. 25 at a later time;
- [0030] FIG. 29 is a confocal micrograph of the cells of FIG. 28; and
- [0031] FIGS. 30, 31, 32 and 33 are confocal micrographs of different cells cultured in different sample scaffolds.

DETAILED DESCRIPTION

[0032] An exemplary embodiment of the present invention relates to a scaffold that is formed of crosslinked hydroxypropylcellulose partially substituted by allyl isocyanate (H-A). A scaffold is any porous material or structure that can be used to provide a supporting framework to support something else, such as cells or tissues. The pores of the H-A polymer are macropores of an average pore size of larger than 50 microns. The H-A polymer when hydrated may form a gel.

[0033] In one embodiment, the H-A polymer has an interconnected porosity of about 50 % or higher, and may have a total porosity of about 80% or higher. The

interconnected porosity refers to the extent of connection between adjacent pores, and can be determined by mercury intrusion porosimetry.

[0034] The macropores may have a pore size distribution peaking at above 50 microns, such as at about 90 or about 100 microns. The peak may be determined from the pore size distribution curves obtained by mercury intrusion porosimetry.

[0035] The pore sizes and their distribution in a scaffold may be determined using a porosimeter, such as a PASCAL 140 mercury porosimeter, available from Thermo Finnigan™.

[0036] The pore sizes may be measured when the H-A polymer is in a hydrated state or dehydrated state, depending on the technique used.

[0037] The H-A polymer may have an equilibrium water content (EWC) of about 85%, and a Young's modulus of about 10 to about 20 kPa in a hydrated state. The equilibrium water content (EWC) is calculated as $EWC = 100\% \times (W_h - W_d)/W_h$, where W_d is the dry weight of the gel and W_h is the fully hydrated weight of the H-A polymer.

[0038] The H-A molecules may have a degree of substitution (DS) of about 2.5 or less, such as about 2.1. The DS may be adjusted by varying the molar ratio of -OH in HPC to -NCO in allyl isocyanate. The DS may be determined using nuclear magnetic resonance (NMR) spectroscopy, as can be understood by persons skilled in the art.

[0039] Another exemplary embodiment of the present invention relates a process for preparing a scaffold, such as the scaffold described above. In this process, a bicontinuous emulsion is prepared, which contains a continuous aqueous phase and a continuous polymer phase. The polymer phase contains H-A molecules as a polymer precursor. The DS of H-A may be about 2.5 or less, such as about 2.1. The H-A molecules are crosslinked to form a polymer with at least partially interconnected macropores. The emulsion may be irradiated with γ -ray to induce crosslinking between the H-A molecules. The emulsion may be selected and irradiated such that at least about 90 wt% of the H-A molecules (polymer

precursor) are crosslinked (i.e. the degree of crosslink is 90 wt%). The H-A polymer will initially form a gel containing water or an aqueous phase in the macropores after crosslinking, which may be removed such as by freeze-drying the gel. The contents of the emulsion may be adjusted so that, after freeze-drying, the resulting polymer has an interconnected porosity of about 50% or higher, and the macropores have an average pore size of larger than 50 microns. The pore size distribution may peak at above about 50 microns, such as at about 90 or about 100 microns. For example, the emulsion may include about 80 to about 90 wt% of the aqueous phase and about 10 to about 20 wt% of the polymer phase (or H-A)

[0040] Several factors may affect the values of total porosity, interconnected porosity, and pore size distribution. These factors include polymer precursor concentration, the DS, crosslinking time, and the concentration of any crosslinker. These factors may be adjusted to control the porosity of the resulting scaffold. For example, increasing polymer precursor concentration or crosslinking time may reduce the pore sizes of the scaffolds.

[0041] In one embodiment, the bi-phase emulsion may be formed by subjecting an aqueous solution of H-A to heat treatment at a temperature of about 313 K for about 5 minutes to effect phase separation in the solution.

[0042] Conveniently, the scaffolds prepared as described herein can have certain benefits and advantages and can be used in various applications such as various medical or biological applications.

[0043] In some conventional techniques, macroporous hydrogels are prepared in complex procedures and their pores are not interconnected. The pores in these conventional hydrogels also lack depth distribution and tend to stay close to the surface. In contrast, embodiments of the present invention can provide 3D scaffolds where the interconnected macropores are distributed substantially uniformly in the entire 3D material. The scaffold disclosed herein can be prepared using relatively simple chemistry in a relatively simple fabrication procedure. In some embodiments, the process can be performed in a simple one step chemistry under mild temperature conditions, without using any organic solvent or additional agent (such as surfactant or crosslinking agent).

[0044] As can be appreciated, cellulose (poly (1,4'-anhydro- β -D-glucopyranose)) is a major ECM component of plant cells. It is naturally abundant, biocompatible, biodegradable, biorenewable and easily derivatizable. Cellulose-based materials can therefore be conveniently used in pharmaceutical and biomedical applications. The main raw materials used in embodiments of the present invention, such as HPC, can thus be obtained at a relatively low cost.

[0045] Hydroxypropylcellulose (HPC) is a derivative of cellulose and is readily available from commercial sources. It has been approved by the United State Food and Drug Administration (FDA) for use in drug delivery applications. HPC and H-A have high solubility in both water and a wide range of organic solvents. They are relatively easy to functionalize to meet various specific requirements in particular applications. An aqueous solution of HPC or H-A can undergo a unique low critical solution temperature (LCST) phase transition from an isotropic aqueous phase to a metastable bi-phase emulsion. This phase separation allows the formation of macroporous polymers and gels.

[0046] While microporous hydrogels and nanostructured hydrogels can be formed using other HPC derivatives, it has been recognized that a macroporous hydrogel would have certain benefits over hydrogels with smaller pores and it has been surprisingly discovered that a bi-phase emulsion containing a H-A phase can be conveniently utilized to form macroporous hydrogels.

[0047] HPC may be partially substituted with another suitable substituent, instead of ally isocyanate. For example, methacrylic acid, acrylic acid, glycidyl methacrylate, or the like may be a suitable substituent in some applications.

[0048] The inherent thermo-sensitive phase behavior of the H-A polymer precursor makes it convenient to form bicontinuous polymer-rich and water-rich phases in the solution by subjecting the solution to heat treatment. Conveniently, it is not necessary to add any chemical solvent or agent (e.g. surfactant) to form the bicontinuous emulsion.

[0049] The liquid biphasic structure can be stabilized (solidified) by crosslinking, which in turn may be efficiently effected with γ -ray irradiation. While

crosslinking of H-A may be effected using other techniques, γ -Ray irradiation may be advantageous in some applications. For instance, γ -ray can penetrate deeper into a target material than some other types of curing light. Thus, crosslinking in the solution can be activated uniformly at different depths with γ -ray. γ -ray irradiation does not give rise to many undesired side chemical effects and do not require any chemical initiator. Thus, it is a chemically "clean" technique.

[0050] It has been found that H-A with a degree of substitution of about 2.5 or less, such as about 2.1, may be advantageous in some applications. For example, H-A polymer precursors with a higher DS tend to have a lower solubility in water but crosslinked H-A polymer with a lower DS may have inferior mechanical properties as compared to H-A polymer with a higher DS. Thus, a balance between different desirable properties may be achieved with a DS of about 2.1 in some applications.

[0051] The mechanical properties such as mechanical strength of the H-A scaffolds may be controlled by varying the degree of crosslinking therein. The degree of crosslinking may be controlled by varying H-A concentration in the precursor solution and the crosslinking time. The ability to control mechanical properties of the H-A scaffolds can be advantageous in some applications. For example, it may be desirable to be able to adjust the mechanical properties to provide suitable mechanical stability and structural integrity for supporting cells.

[0052] Therefore, the H-A polymer described herein can form three-dimensional (3D) scaffolds for use as soft tissues. The scaffolds can be made to have various desirable physiochemical, mechanical and bio-interfacial properties. For example, the scaffold may have properties that are suitable for promoting cell adhesion. The scaffolds can be made relatively soft and are inherently hydrophilic. The interconnected macropores can facilitate cell growth into the scaffold with cell densities similar to biological tissues. Due to the 3D interconnected macropores, the scaffolds not only can have relatively high equilibrium water content (EWC), be biocompatible, and sustain gradual release of bioactive molecules, but can also support cell growth, migration, and ultimately, tissue formation. The scaffolds also allow ready incorporation of extracellular matrix (ECM) cues to regulate cell and

tissue functions. In embodiments of the present invention, the choices of material and the fabrication procedure can be flexible so that it is possible to introduce 3D ECM cues for regulation of cellular functions.

[0053] As a water soluble precursor can be used for preparing the scaffold, it may be possible to adjust the degradation profile of the scaffold by modifying the side chain chemistry of the polymer.

[0054] Embodiments of the present invention can also provide 3D scaffolds that have integrated interconnected macroporosity, nanofeatures (surface structures having a nanometer scale dimension, see Examples below), high water content and mechanical integrity suitable for soft tissue engineering. Such scaffolds can exhibit controllable, moderate elasticity, and hydrophilicity, which can be advantageous in providing mechanical stability and structural integrity to cells and tissues. The scaffolds can also have nano-features in the pores, which may play a role in the regulation of cell behavior. The nanofeatures may also be useful for loading of bioactive molecules such as adhesion proteins and growth factors *etc* to control cell behavior and functions.

[0055] With interconnected macroporosity and high equilibrium water content, biocompatibility and mechanical integrity, 3D H-A scaffolds as described herein may be suitable for a wide range of applications in soft tissue engineering and regenerative medicine.

[0056] Some embodiments of the present invention may also be suitable for application in *in vitro* substrates for cell culture and studies of cellular behavior in a 3D environment. 3D cell culture environments more closely mimic *in vivo* microenvironments than 2D culture environments. 3D scaffolds can therefore serve as ECM analogues to provide biomimicry 3D substrates for cell attachment, growth, migration, function and differentiation, or the like.

[0057] Some embodiments of the present invention may also be suitable for use in *in vitro* 3D tissue models that are based upon human cells for pathological study and drug testing.

[0058] Some embodiments of the present invention can be used for *in vitro*

cultivation of cells for the creation of external support organs. The highly interconnected macroporous architecture can provide temporary support to the cultivation of a sufficient cell mass with adequate cell-cell contact. Preliminary results have shown that the primary rat hepatocytes cultured in the scaffolds described herein can maintain their liver-specific functions over a period of one week (see Examples below). Other types of cells can also be cultivated in these scaffolds. Examples for relevant applications include inartificial liver assisted devices (BLAD) to provide essential liver functions for the patients with acute liver failure.

[0059] A soft, hydrophilic, and macroporous scaffold may be suitable for cell transplantation in soft tissue and organ repair or regeneration applications.

[0060] Some embodiments of the present invention can be used for high content screening for drug discovery and screening. A cellulosic scaffold can be easily fabricated into microplate configuration to provide uniform 3D microenvironments for various cellular assays.

[0061] Some embodiments of the present invention can be used for localized and sustained delivery of biologically or pharmaceutically active compounds. When the scaffolds are hydrophilic and have a high water retention ability, they can be conveniently used to incorporate and provide sustained release of bioactive molecules or other substances.

[0062] As now can be appreciated, in a different embodiment, HPC may be replaced with another thermo-sensitive polymer precursor that can form a stable bicontinuous emulsion in an aqueous solution in response to heat. For example, methylcellulose may be used to replace HPC. Further, a polymer precursor that can form a stable bicontinuous emulsion in an aqueous solution in response to another type of stimuli, such as a change in pH, may also be used to replace HPC. Thus, a suitable pH-sensitive polymer precursor may be used.

[0063] As can also be appreciated, in a different embodiment, allyl isocyanate may be replaced with another suitable substituent that includes a self-crosslinkable group. Self-crosslinkable groups refer to functional groups that can

be crosslinked between themselves. For example, a suitable substituent or the crosslinkable group may have an unsaturated C=C bond for providing a crosslinkable site. A suitable substituent should also have a functional group for bonding to HPC, so that the HPC can be partially substituted by the substituent. Suitable replacement for allyl isocyanate may include methacrylic acid, acrylic acid, glycidyl methacrylate, or the like. The substituent may include a multi-functional monomer.

[0064] Depending on the particular substituent used, the degree of substitution (DS) should be adjusted to retain sufficient thermo-sensitivity in the substituted HPC to allow convenient phase separation, and to allow sufficient crosslinking of the modified HPC during phase separation.

[0065] In view of the disclosure herein, it is possible to provide a scaffold which comprises a crosslinked polymer that defines macropores. The macropores are at least partially interconnected and have an average pore size of larger than 50 microns. The interconnected porosity may be about 50% or higher. The polymer is formed from a polymer precursor that is responsive to a phase separation stimuli to undergo phase separation in an aqueous solution. The stimuli may be heat or pH change in the solution. The polymer precursor also comprises a self-crosslinkable group so that the polymer are crosslinked through the self-crosslinkable group. The crosslinkable group may be selected so that it will crosslink with each other when irradiated with γ -ray. The polymer precursor may be a cellulose derivative. The cellulose derivative may be a methylcellulose derivative, or a hydroxypropylcellulose derivative, such as hydroxypropylcellulose partially substituted by allyl isocyanate. The cellulose derivative may be partially substituted by a substituent that comprises a self-linkable group. The self-crosslinkable group may comprise an unsaturated double carbon-carbon bond. The substituent may comprise allyl isocyanate, methacrylic acid, acrylic acid, or glycidyl methacrylate. The polymer may have a total porosity of about 80% or higher. The macropores may have a pore size distribution peaking at above 50 microns, such as at about 90 or about 100 microns. The polymer may have an equilibrium water content of about 85%. The polymer may have a Young's modulus of about 10 to about 20 kPa in a hydrated state. The polymer may have a

degree of substitution of less than about 2.5, such as about 2.1. The polymer may be a gel, such as when in a hydrated state.

[0066] While some variation and modification of the exemplary embodiments and their applications are discussed herein, they are for illustration purposes and are not exhaustive. Other applications of the embodiments of the present invention are also possible.

[0067] Examples

[0068] All raw chemical materials used in these examples were obtained from Sigma-Aldrich Pte Ltd.™, Singapore, unless otherwise specified.

[0069] Example I (Synthesis of allyl carbamate of HPC (H-A))

[0070] HPC ($M_n \approx 10,000$; degree of etherification was about 3.4, as determined by ^1H NMR) was dehydrated by azeotropic distillation in toluene.

[0071] The dehydrated HPC (2.0 g, 6.0 mmol [OH]) was dissolved in chloroform (100 ml), to which a solution of allyl isocyanate (1.83 ml, 3.5 molar equivalents) in chloroform (10 ml) was added dropwise. After one drop of dibutyltin dilaurate was added as a catalyst, the reaction mixture was stirred at room temperature for about 48 hours, then concentrated using a rotatory evaporator and precipitated into diethyl ether.

[0072] The reaction product was collected by vacuum filtration, and purified by re-dissolution in chloroform and precipitation into diethyl ether. The residual impurities were removed by Soxhlet extraction from diethyl ether.

[0073] The product contained, according to ^1H NMR analysis (CDCl_3 , δ ppm): 0.5-1.5 ($-\text{CH}_3$), 5.7-6.1 ($-\text{CH}=\text{CH}_2$), 2.5-5.3 (all other protons).

[0074] The degree of substitution was 2.1, as calculated by ^1H NMR recorded in CDCl_3 .

[0075] The temperature-mediated phase behavior of the sample H-A solutions at 10 wt% and 20 wt% (weight percentage of H-A in the solution) was

investigated on a UV/VIS/NIR spectrophotometer (Jasco™, V-570, Japan), by measuring the optical densities at 480 nm as a function of temperature. The temperatures of sample holders were controlled using a Jasco PSC-498 temperature controller. The samples were allowed to reach equilibrium at each temperature for 10 min before the readings were taken. Representative measurement results are shown in **FIG. 1**. The occurrence of phase separation was indicated by reduction in optical density. The temperature at which the reduced optical density reached a plateau was selected as the operating temperature for inducing phase separation of H-A solutions and subsequent crosslinking.

[0076] **FIG. 1** shows representative measured data indicating the temperature-dependences of normalized (normalized to the absorption intensity at 298 K) UV absorption of sample solutions containing different concentrations of HPC (diamonds: 10wt% - solid, 20wt% - hollow) and H-A (triangles: 10 wt% - solid, 20 wt% - hollow). The phase transition is manifested by a precipitous decrease in the transmittance upon increasing temperature. The temperature at which the sample transmittance decreased by 50% is denoted herein as LCST. Compared to HPC, the phase separation in H-A solutions of both 10 wt% and 20 wt% took place at a lower temperature range, with LCST being about 307 K, resulting from hydrophobic substitution with allyl groups.

[0077] Like the HPC samples, the H-A samples became white and opaque when the temperature was increased, but without any noticeable sedimentation over the temperature range studied, indicating the formation of stable colloidal systems in the H-A solutions.

[0078] Stable colloidal formation can be advantageous for subsequent generation of 3D open porous structures.

[0079] Based on the experimental data, 313 K was selected as a suitable temperature for induction of phase separation and crosslinking of H-A solutions.

[0080] Example II (Preparation of 3D H-A scaffolds)

[0081] Sample solutions of H-A and water were prepared. The solutions

contained about 10 or about 20 wt% of H-A respectively. The water was degassed and deionised before mixed with H-A.

[0082] In a representative procedure, a glass vials (10 mm in diameter × 50 mm height) containing a sample H-A solution was placed in a water bath at 313 K for 5 min to induce phase separation in the solution to form a bicontinuous emulsion.

[0083] The emulsion was transferred, in a beaker containing water at 313 K, to a gamma irradiator (Gammacell 220, MDS Nordion™, Canada), and subjected to γ -ray irradiation at a dose rate of 10 kGy h⁻¹ for 30 min, to crosslink the polymeric phase in the emulsion to form a gel.

[0084] The crosslinked gel was freeze-dried, washed with deionised water for one week with daily water change, and lyophilized for storage.

[0085] The sample polymer (scaffold) formed with 10 wt% H-A is referred to as Sample I, and the sample polymer (scaffold) formed with 20 wt% H-A is referred to as Sample II.

[0086] Example III (Comparison samples)

[0087] For comparison purposes, H-A solutions as prepared in Example II were also crosslinked at temperatures from about 273 to about 277 K, without phase separation, by irradiation as described in Example II. The resulting products were homogenous gels and were subjected to similar post-irradiation treatment as described in Example II. These gels were referred to as Sample IC (for 10 wt% H-A) and Sample IIC (for 20wt% H-A).

[0088] Example IV (characterization of Sample Scaffolds)

[0089] The degree of crosslink in the samples was expressed as the weight percentage of the crosslinked fraction of the scaffold.

[0090] Residual soluble polymers were removed by Soxhlet extraction with acetone for 4 h.

[0091] The lyophilized scaffolds were allowed to swell in water at room temperature for 48 h. The samples were weighed before and after this hydration process. The EWC of the sample scaffolds were determined based on their dry and hydrated weights, according to the equation discussed above.

[0092] The Mechanical properties of hydrated scaffolds were evaluated by compression tests on an Instron™ Micro-Tester 5848 (Instron Co., Canton, MA, U.S.A.), at a speed of 0.5 mm/min and a temperature of 25 ± 2 °C. The compression moduli were calculated from the slopes of the initial linear portion of the stress-strain curves.

[0093] The pore size distribution in the sample scaffolds was determined using a PASCAL 140 mercury porosimeter (Thermo Finnigan, Italy, S.p.A.) with S-CD6 dilatometer.

[0094] Cross-sectional surfaces of sample lyophilized H-A scaffolds were sputter coated with gold and examined on a field-emission scanning electron microscope (FESEM) (JEOL™, JSM-7400M, Japan) at an accelerating voltage of 20 kV. The morphology of the hydrated H-A scaffolds was investigated by laser confocal fluorescence microscopy. The freeze-dried scaffolds were stained overnight with fluorescein isothiocyanate conjugated dextran (FITC-dextran) (1.0 mg ml^{-1}) or propidium iodide (PI) ($50 \text{ } \mu\text{g ml}^{-1}$) in the phosphate-buffered saline (PBS), respectively. They were then washed with PBS for 5 times and examined using a laser confocal fluorescence microscope (Olympus™, Fluoview 300, Japan). Optical sectioning with a Z resolution of $2 \text{ } \mu\text{m}$ was used to obtain a 3D image stack of scaffolds.

[0095] Some representative results of the above tests are summarized in **Table I** and shown in the figures.

Table I Properties of Sample H-A Scaffolds

	Sample I	Sample II
Porosity (%)	83	92
Interconnected porosity (%)	52	56
Peak pore size (micron)	103	88
EWC (wt%)	91	89
Young's modulus in hydrated state (kPa)	9.5	20.5
Degree of crosslink (wt%)	90	92

[0096] In **Table I**, peak pore size refers to the location of the highest peak in the pore distribution, and is the pore size that occurs most frequently in a porous material.

[0097] There was no significant observed change in sample dimension due to dehydration or re-hydration. This stability is expected to be due to the extensive (about 90 wt%) crosslinking in the H-A polymer.

[0098] The presence of interconnected macroporous structures in Samples I and II was observed by mercury intrusion porosimetry and scanning electron microscopy (SEM). **FIG. 2** is a representative SEM image of Sample II at a magnification factor of 90. Further magnified SEM images of a portion of the image of **FIG. 2** are shown in **FIGS. 3** (500 magnification) and **4** (15000 magnification). Similar interior morphology of interconnected macroporosity were also observed in Sample I. Nano-scale features and structures on the pore surfaces, such as edges, spikes in the regions connecting the macropores, were also visible in the images.

[0099] In contrast to some conventional techniques in which only micropores were formed in HPC scaffolds, the sample scaffolds formed of hydrophobically modified H-A had interconnected macropores. The H-A samples also retained the phase behavior characteristics of HPC, as indicated by the formation of stable, opaque colloidal system over the temperature range studied.

[00100] Both samples had a broad and bimodal distribution of pore sizes, as

shown in **FIG. 5** (Sample I – solid; Sample II – hollow), with 50% to 60% interconnected porosity respectively. As can be seen, for both samples, the pore size distribution had two peaks, a taller and sharper peak at a smaller pore size and a shorter and broader peak at a larger pore size. When the H-A concentration was increased, from about 10 wt% to about 20 wt%, the taller peak in the pore size distribution curve was shifted to the left (smaller pore size) and the higher peak was shifted to the right (larger pore size); and the taller peak became taller and the shorter peak became shorter.

[00101] The porous structures of Samples II and IIC were also characterized and compared in their hydrated state.

[00102] Both Samples II and IIC were stained with FITC-dextran in PBS for 24 hours. A highly porous network was observed in hydrated Sample I in laser confocal microscopy images of the sample. See a representative image in **FIG. 6**. In comparison, **FIG. 7** shows a similar image for Sample IIC, which revealed a nonporous, homogenous structure. This result indicates that phase separation facilitated the formation of interconnected macropores.

[00103] The highly macroporous architecture in hydrated Sample II was also confirmed in another staining study using propidium iodide (PI). Representative images of PI-stained Sample II are shown in **FIGS. 8 and 9**. The sizes of water-filled pores varied broadly from tens to hundreds microns and the thickness of water-swollen struts ranged from about 5 to about 20 microns.

[00104] Example V (Cell culture and seeding in Sample Scaffolds)

[00105] For cell culture, Samples I and II were cut into discs of about 10 mm in diameter and about 2 mm in thickness.

[00106] NIH 3T3, HepG-2 and MCF-7 cells (ATCC, USA) were cultured according to the standard procedure in high glucose Dulbecco's modified Eagle's medium (DMEM) (Invitrogen™, Singapore) supplemented with 10% fetal bovine serum, 100 unit/ml penicillin and 100 µg/ml streptomycin in a humid incubator at 37 °C and 5% CO₂, respectively.

[00107] Hepatocytes were harvested from male Wistar rats weighing 250-300 g by a two-step in situ collagenase perfusion method, as described in P. O. Seglen, *Methods Cell Biol.*, 1976, vol. 13, p. 29. Viability of the hepatocytes was $\geq 90\%$, as determined by Trypan Blue Exclusion assay. Hepatocytes cultured in the scaffolds were maintained in William's E supplemented with 1 mg/ml bovine serum albumin (BSA), 10 ng/ml epidermal growth factor (EGF), 0.5 $\mu\text{g/ml}$ insulin, 5 nM dexamethasone, 50 ng/ml linoleic acid, 100 unit/ml penicillin and 100 $\mu\text{g/ml}$ streptomycin.

[00108] The sample scaffold discs were sterilized in a 12 well plate by gamma irradiation at a dose rate of 10 kGy/h for 4 h. Cell seeding was conducted at a density of $0.5 \sim 1.0 \times 10^6$ cells per scaffold, by adding 20 μl of concentrated cell suspension into each scaffold followed by 200 μl of cell medium. Cell-free scaffold was used as control for all the following work. The scaffolds were incubated for 3 h, after which time 1 ml of cell medium was added, respectively. The viability of cells cultivated in the scaffolds was assessed by fluorescence live/dead staining. The scaffolds were incubated for 30 min with 5 μM Calcein AM (Molecular probe, USA) and 25 $\mu\text{g/ml}$ of propidium iodide in Dulbecco's modified essential medium (DMEM) at 37 °C, 5% CO₂. Images of live (green) and dead (red) cells were then acquired by laser confocal fluorescence microscopy. Optical sectioning with a Z-resolution of 2 μm was used to obtain a 3D image stack of scaffolds.

[00109] Proliferation of NIH 3T3 seeded in sample scaffolds were assessed by monitoring their metabolic activities using almarBlue™ assay. The cell-seeded and cell-free scaffolds were incubated for 4 hours with 10% (v/v) almarBlue(Biosource) in phenol-red free, supplemented DMEM medium. 200 μl of the media from each sample was transferred to a 96-well plate, and the absorbance at 570 nm and 600 nm were measured using a Sunrise™ microplate reader (Tecan, Switzerland). The reduction of almarBlue of each sample was calculated, and converted to cell numbers based upon a standard curve constructed from 2D cell culture with known cell numbers.

[00110] Sample II was selected for cellular compatibility tests. A detailed cell

viability and proliferation test was conducted on the mouse fibroblast NIH 3T3 cultivated in the scaffold, by measuring the metabolic activity using Alamar Blue assay. The cells were found to be not only viable but also to proliferate well over prolonged culture. The number of cells over time in Sample II was plotted in the graph of **FIG. 10**.

[00111] **FIG. 11** is a fluorescence microscopy image of NIH 3T3 cells cultured in Sample II after 4 weeks of cultivation. The cells were stained with Calcein AM (shown as bright regions in **FIG. 11**) for live cells. **FIG. 12** is a similar image but for cells stained with PI (shown as lighter spots in **FIG. 12**) for dead cells. **FIG. 13** is a superposition of the images of **FIGS. 11** and **12**.

[00112] **FIGS. 14** and **15** show SEM images of NIH 3T3 cultured in Sample II for one day at different magnifications. **FIGS. 16** and **17** show SEM images of NIH 3T3 cultured in Sample II for five days at different magnifications. The scale bars represent 100 microns in **FIGS. 14** and **16**, and 10 microns in **FIGS. 15** and **17**.

[00113] To investigate the urea synthesis of hepatocytes, the cells cultured in the sample scaffolds were incubated in a culture medium containing 1.0 mM NH_4Cl for 90 min; the medium was analyzed by the Urea Nitrogen Kit (Sigma Diagnostics), as described in S. Ng et al., *Biomaterials*, 2005, vol. 26, p. 3163. The data was normalized by the number of cells seeded in the scaffolds that was quantified using Quan-iTTM PicoGreen dsDNA Assay Kit (Invitrogen, Singapore).

[00114] Primary hepatocyte has been a major cell source for liver tissue engineering; it tends to lose its hepatic function rapidly *in vitro*. The present data showed that primary rat hepatocytes cultured in the sample scaffolds could maintain their urea secretion, a liver-specific function, over a period of one week. **FIG. 18** shows the measured result.

[00115] **FIGS. 19** and **20** show albumin secretion and urea synthesis of the primary rat hepatocytes cultured in Sample II, in comparison to 2D collagen monolayer culture. 2D collagen monolayer has been conventionally used for hepatocyte culture. The sustained liver-specific functions of primary rat hepatocytes cultured in the scaffolds were different in the two tested scaffolds. The

albumin secretion and urea products of the hepatocytes cultivated in the 3D Sample II were higher than those cultured in the 2D collagen monolayer.

[00116] **FIGS. 21, 22, 23 and 24** show SEM images of primary rat hepatocytes cultured in Sample II, taken over a period of 7 days, and the morphologies of these cells in Sample II, . The cells appeared round and tended to form cellular aggregates in the scaffold, well supported by cell-cell and cell-matrix interactions.

[00117] Fluorescence viability staining was also carried out on human MCF-7 breast cancer cells (MCF-7), human hepatoblastoma cells (C3A), showing good cellular biocompatibility.

[00118] **FIG. 25** is a transmitted image of C3A cells cultured in sample 3D scaffolds for two days. The C3A cells formed spheroids in the scaffolds. **FIG. 26** is a fluorescence image of live/dead staining of the C3A spheroids at day 2. **FIG. 27** is an SEM image of the C3A spheroids at day 1 and **FIG. 28** is a transmitted image of the C3A spheroids at day 7. **FIG. 29** is a fluorescent image of live/dead staining of C3A spheroids at day 7.

[00119] It is expected that the presence of –OH groups in Sample scaffolds can also allow facile incorporation of ECM proteins to improve cell adhesion. This method is also applicable to other types of ECM proteins. Collagen type I was used to verify this expectation. Under sterile condition, scaffolds were rinsed with acetone for three times, then treated with 20 mM 1,1'-carbonyl diimidazole (CDI) overnight at room temperature. It is expected this method is also applicable to other types of ECM proteins. The scaffolds were washed with acetone for 5 times before being immersed into collagen I solution (0.29 mg/ml, pH10.0). The conjugation was conducted on an orbital shaker at 4 °C overnight. The modified scaffolds were then washed with PBS and deionised water before freeze dry. Cell attachment has been significantly improved in the modified scaffolds as demonstrated in Fig 31 and 33. in **FIG. 30** shows an image of live/dead staining of human foreskin fibroblasts cultured in an unmodified sample scaffold at day 1; **FIG. 31** shows an image of live/dead staining of human foreskin fibroblasts cultured in an collagen conjugated sample scaffold at day 1; **FIG. 32** shows an image of

live/dead staining of human umbilical vein endothelial cells cultured in the unmodified scaffold at day 1; and **FIG. 33** shows an image of live/dead staining of human umbilical vein endothelial cells cultured in the collagen conjugated sample scaffold at day 1.

[00120] Other features, benefits and advantages of the embodiments described herein not expressly mentioned above can be understood from this description and the drawings by those skilled in the art.

[00121] Of course, the above described embodiments are intended to be illustrative only and in no way limiting. The described embodiments are susceptible to many modifications of form, arrangement of parts, details and order of operation. The invention, rather, is intended to encompass all such modification within its scope, as defined by the claims.

WHAT IS CLAIMED IS:

1. A scaffold comprising:

a polymer defining macropores and comprising hydroxypropylcellulose partially substituted by a substituent, said substituent comprising a self-crosslinkable group, said partially substituted hydroxypropylcellulose being crosslinked through said self-crosslinkable group, said macropores having an average pore size of larger than 50 microns and being at least partially interconnected.
2. The scaffold of claim 1, wherein said polymer has an interconnected porosity of about 50% or higher.
3. The scaffold of claim 1 or claim 2, wherein said polymer has a total porosity of about 80% or higher.
4. The scaffold of any one of claims 1 to 3, wherein said macropores have a pore size distribution peaking at above 50 microns.
5. The scaffold of any one of claims 1 to 3, wherein said macropores have a pore size distribution peaking at about 90 microns.
6. The scaffold of any one of claims 1 to 3, wherein said macropores have a pore size distribution peaking at about 100 microns.
7. The scaffold of any one of claims 1 to 6, wherein said polymer has an equilibrium water content of about 85%.
8. The scaffold of any one of claims 1 to 7, wherein said polymer has a Young's modulus of about 10 to about 20 kPa in a hydrated state.
9. The scaffold of any one of claims 1 to 8, wherein said self-crosslinkable group comprises an unsaturated double carbon-carbon bond.
10. The scaffold of any one of claims 1 to 9, wherein said substituent comprises allyl isocyanate.

11. The scaffold of any one of claims 1 to 9, wherein said substituent comprises methacrylic acid, acrylic acid, or glycidyl methacrylate.
12. The scaffold of any one of claims 1 to 11, wherein said partially substituted hydroxypropylcellulose has a degree of substitution of less than about 2.5.
13. The scaffold of any one of claims 1 to 11, wherein said partially substituted hydroxypropylcellulose has a degree of substitution of about 2.1.
14. The scaffold of any one of claims 1 to 13, wherein said polymer is a gel.
15. A method of forming a scaffold, comprising:

forming a bicontinuous emulsion comprising a continuous aqueous phase and a continuous polymer phase, said polymer phase comprising hydroxypropylcellulose partially substituted by a substituent, said substituent comprising a self-crosslinkable group;

crosslinking said partially substituted hydroxypropylcellulose through said self-crosslinkable group to form a polymer defining at least partially interconnected pores.
16. The method of claim 15, wherein said substituent comprises allyl isocyanate.
17. The method of claim 15, wherein said substituent comprises methacrylic acid, acrylic acid, or glycidyl methacrylate.
18. The method of any one of claims 15 to 17, wherein said pores comprise macropores.
19. The method of any one of claims 15 to 18, wherein said crosslinking comprises irradiating said emulsion with γ -ray.
20. The method of any one of claims 15 to 19, wherein said crosslinking comprises crosslinking at least about 90 wt% of said partially substituted hydroxypropylcellulose in said emulsion.

21. The method of any one of claims 15 to 20, comprising removing water from said pores by freeze-drying said polymer.
22. The method of claim 21, wherein, after said freeze-drying, said polymer has an interconnected porosity of about 50% or higher, and said pores have an average pore size of larger than 50 microns.
23. The method of any one of claims 15 to 22, wherein said emulsion comprises about 80 to about 90 wt% of said aqueous phase and about 10 to about 20 wt% of said polymer phase.
24. The method of any one of claims 15 to 23, wherein said partially substituted hydroxypropylcellulose has a degree of substitution of about 2.5 or less.
25. The method of any one of claims 15 to 24, wherein said partially substituted hydroxypropylcellulose has a degree of substitution of about 2.1.
26. The method of any one of claims 15 to 25, wherein said polymer is a gel.
27. The method of any one of claims 15 to 26, wherein said emulsion is formed by subjecting a solution comprising water and said partially substituted hydroxypropylcellulose to heat treatment.
28. The method of any one of claims 15 to 27, wherein said heat treatment comprises heat treatment at a temperature of about 313 K for about 5 minutes.
29. A method of forming a scaffold, comprising:
 - inducing phase separation in a solution comprising a polymer precursor and water, to form a bicontinuous emulsion comprising a continuous polymer phase and a continuous aqueous phase, said polymer precursor comprising a self-crosslinkable group;
 - crosslinking said polymer precursor through said self-crosslinkable group in said emulsion to form a polymer defining at least partially interconnected macropores.
30. The method of 29, wherein said polymer precursor is a cellulose derivative.

31. The method of claim 30, wherein said cellulose derivative is methylcellulose derivative.
32. The method of claim 30, wherein said cellulose derivative is a hydroxypropylcellulose derivative.
33. The method of claim 32, wherein said hydroxypropylcellulose derivative is hydroxypropylcellulose partially substituted by allyl isocyanate.
34. The method of any one of claims 30 to 32, wherein said cellulose derivative is partially substituted by a substituent that comprises a self-linkable group.
35. The method of claim 34, wherein said self-crosslinkable group comprises an unsaturated double carbon-carbon bond.
36. The method of claim 34, wherein said substituent comprises allyl isocyanate, methacrylic acid, acrylic acid, or glycidyl methacrylate.
37. The method of any one of claims 29 to 36, wherein said polymer precursor is thermo-sensitive, and said inducing phase separation comprises heating said solution.
38. The method of claim 29, wherein said polymer precursor is pH-sensitive, and said inducing phase separation comprises changing pH of said solution.
39. The method of any one of claims 29 to 38, wherein said crosslinking comprises irradiating said emulsion with γ -ray.
40. The method of any one of claims 29 to 39, wherein said polymer is a gel.