Study of Hybrid Hydrogel Based on Polyvinyl Alcohol with Respect to Tailoring of the Internal Structure by Lecithin

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Research Article

Keywords: Hybrid network, hydrogel, lecithin, rheology, swelling, SEM, diffusion experiments, internal structure

Posted Date: June 16th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3034768/v1

Abstract

The presented paper is focused on preparation and subsequent characterization of structural and transport properties of hydrogels with double-network concerning their application potential. Hybrid hydrogels were prepared as a combination of synthetic polymer and natural polysaccharide, such as polyvinyl alcohol (PVA) and sodium alginate (SA), where mass ratio of those polymers was 1:1. In the preparation of the gel's hybrid network a freeze-thawing cycle technique for physical cross-linking of PVA was used, also calcium ions were used for ionic cross-linking of sodium alginate. Lecithin as a modification of the internal structure of hybrid hydrogels was also used in gel's system preparation. Physicochemical methods were used to characterise their viscoelastic, swelling and transport properties. Rheology measurements, specifically oscillation and amplitude tests, were used to study these mechanical properties. Morphology of the prepared hybrid hydrogels was confirmed by electron microscope scanning. Transport and release properties of gel systems were determined by diffusion experiments with the UV-VIS spectrometry detection method, in which an organic dye (methylene blue) was used as a model probe.

1 Introduction

Hydrogel is known as a hydrophilic polymer with three-dimensional chemically or/and physically cross-linked network [1], which is able to absorb and hold large amounts of water or biological fluids to a thousand times their own weight [2]. Hydrogels are able to be prepared by using natural or synthetic polymers, or their combination [3], which has the opposite yet complementary mechanical responses to each other. In this case, double networking has been demonstrated to be an effective approach to enhancing the strength and/or toughness of hydrogels [4]. One of the possibilities to form a double network is that the first network needs to be a strong polyelectrolyte, however this leads to limits in using different polymers. Then the second monomer is polymerised in the first network thereby the presence of initiators-activators is inevitable in these networks that adversely affect performance in the biological environment [5]. Thankfully their properties such as biocompatibility, biodegradability, great swelling capacity and microporous structure [6] make them the ideal candidate for various applications such as tissue engineering, wound healing, drug delivery systems, biosensors and bioelectronics, wastewater remediation, daily life products and many more [7]. Thanks to their softness, flexibility, and chemical composition they are able to simulate and mimic biological systems such as the extracellular matrix (ECM) [3]. Thus, this is a structural support network composed of diverse proteins, sugars, and other components that is why ECM regulates cellular processes including survival, growth, proliferation, migration and differentiation. However, in view of the fact that every single application has specific needs, it is necessary to take care of their properties and porous microstructure [2].

Polyvinyl alcohol (PVA) is a synthetic polymer, containing hydroxyl groups synthesised commonly from polyvinyl acetate. It shows excellent properties, such as non-toxicity, biocompatibility, good biodegradability, high hydrophilicity, fiber/film forming ability and convenient mechanical properties [1], also it is a water-soluble polymer, which is able to easily dissolve in the solution without using any

organic solvents [7]. Hydrogels based on PVA can be prepared by using chemical or physical methods, one of them is the freezing-thawing process [8], which is an advantageous method that does not require other crosslinking agents [3], that may cause toxicity [9]. Repeated freezing-thawing cycles of a polyvinyl alcohol aqueous solution lead to the formation of crystallites which act as cross-linking sites, and a hydrogel with a high swelling capacity is produced [3]. PVA-based hydrogels, are a well-known soft and elastic materials [7] with high degree of swelling in water and hydrophilicity [10], which makes them a promising biomaterial and candidate for biomedical area [1] and/or for polymer matrix in pharmaceutical fields [10].

Another widely employed polymer in the development of the polymer-based hydrogels is sodium alginate (SA) [1]. SA is a biopolymer with polyanionic linear polysaccharide comprising of 1,4-linked-α-L-guluronic acid and β-D-mannuronic acid which are able to be found in brown seaweeds [9]. Thanks to their biocompatibility, biodegradability, immunogenicity and non-toxicity, SA belongs among the promising materials for drug delivery systems [1]. The crosslinking reaction, ionic gelation, with the presence of divalent ions, such as calcium, barium and/or strontium ions, enable the formation of gels [8], which represent a group of materials, which found their application to the skin in case of difficult-healing wounds, including bedsores, venous ulcers, and diabetic wounds [11]. The ionic gelation is an effective and easy technique that enables the formation of spherical beads with regular shape, size and smooth surface as well as the preparation of ideal release retarding membrane [9]. However, limitations caused by poor mechanical properties and shortage of processing helped to find a combination of sodium alginate (SA) with a synthetic polymer, which could produce the optimal properties [12]. Thus, PVA is a perfect partner for biopolymers like sodium alginate [7], both components are non-toxic and biocompatible [11].

Incorporation of hydrophobic or micellar domains into the gel structure is one of the possibilities of how to modify, tailor or upgrade hydrogel's properties [2]. These self-assembled supramolecular assemblies are composed of reverse micellar structures as the basic building blocks, which are formed due to the weak van der Waals forces, hydrogen bonding and electrostatic interactions [13]. For example, Lecithin is a naturally occurring mixture of phospholipids, which generally consist of fatty acids and a polar or charged headgroup esterified to a glycerol backbone, with the key difference being the properties of the headgroup as well as the fatty acid type. Typical fatty acids associated with soy phospholipids are palmitic, stearic, oleic and linoleic acids [14]. With more water, spatial reorganisation from spheroidal to tubular reverse micelles takes place and at a critical water concentration. These tubular reverse micelles overlap and entangle thereby entrapping solvent molecules. The three-dimensional network of the tubular reverse micelles is held together by hydrogen bonds between the molecules of lecithin and water, and hydrophobic interactions between the organic and aqueous phases. Lecithin is extensively used in applications as a structuring agent in animal and human foods, pharmaceuticals, and cosmetics [2].

Hybrid hydrogel based on PVA and SA is not completely new, but still, nowadays the interest in their study is constantly growing. In this work, a series of experiments were performed in order to understand the properties of hybrid networks of hydrogels based on PVA and SA. Knowledge of the components used,

their behaviour and the possibility of cross-linking with other substances (e.g. drugs, organic dyes, internal structure modifiers, etc.) is essential here. The prepared hybrid hydrogel represents a hydrogel material that can not only protect the wound, but also support the healing process with the help of any built-in drugs, therefore such a material could potentially be used to cover wounds. Mechanical, transport and swelling capabilities were determined using physicochemical methods. Furthermore, the internal structure of the prepared hybrid hydrogels was characterised using scanning electron microscopy. The addition of a natural component during the preparation of gel systems is a simple way of changing the internal structure and modifying the properties, which is suitable for their biocompatibility and the possibility of biodegradation.

2 Materials and methods

2.1 Materials

Polyvinyl alcohol (PVA, M_w 130000 g/mol) with a hydrolysis degree 99%, sodium alginate (SA, M_w 100,4 ± 5,7 kDa), soy lecithin (LEC), dihydrate of calcium chloride (M_w 147,0146 g/mol), methylene blue was purchased from Sigma Aldrich, Saint Louis, Missouri, USA.

2.2 Hybrid hydrogel samples preparation

2.2.1 Preparation of solution of sodium alginate and calcium chloride solution

Stock solution of sodium alginate (SA) was prepared according to the following procedure. Deionized water was added to a defined amount of sodium alginate to create a 2 wt.% solution and the mixture was then mixed on a magnetic stirrer for 24 hours at room temperature. The sodium alginate stock solution prepared in this way was then used immediately or stored in a laboratory refrigerator at a temperature of 7°C before use.

A calcium chloride solution with a concentration of 0,1 M was used as a cross-linking agent for SA. For its preparation, 0,72 g of anhydrous calcium chloride dihydrate was dissolved in 50 ml of deionized water. The prepared calcium chloride solution was then also used immediately or stored in a laboratory refrigerator.

2.2.2 Preparation of solution of polyvinyl alcohol

Stock solution of polyvinyl alcohol (PVA) was prepared by dissolving a synthetic polymer in deionized water to create a 10 wt.% solution under constant stirring on a magnetic stirrer with heating for 3 hours in a 90°C water bath. The prepared PVA stock solution was allowed to cool to room temperature for its subsequent use or was stored in a laboratory refrigerator for further use.

2.2.3 Preparation of hybrid hydrogel

The preparation of a hybrid hydrogel based on sodium alginate and polyvinyl alcohol is based on the procedure published by Xuefeng Li et all [4].

To prepare the PVA/ALG hybrid hydrogel, a solution of sodium alginate was added to PVA in the resulting mass ratio of 1:1. The solutions were then mixed in a homogenizer for 1 hour at 200 rpm. The resulting homogeneous solution was poured into a Petri dish and subsequently subjected to a different number of freezing and thawing cycles. For gelation, the freeze-thaw method was chosen, where the samples were kept in a laboratory freezer for 24 hours. Furthermore, after thawing the sample, the cross-linking method with calcium ions was performed, where a calcium chloride solution was added to the hybrid hydrogel so that the hydrogel was submerged. The prepared hybrid hydrogel system was left overnight in a laboratory refrigerator. The sample was then washed with deionized water, dried by wood pulp, and thus prepared for subsequent measurement.

2.2.4 Preparation of hybrid hydrogel with lecithin

In the preparation of PVA/SA hybrid hydrogels with the addition of lecithin, which serves as an internal structure modifier, sodium alginate solution was first mixed with lecithin so that the resulting concentration of lecithin in the gel system was 0,5 wt.%, 1 wt.% and 2 wt.%. In the case of 0,5 wt.% concentration of lecithin, 0,05 g of the mentioned substance was weighed, to which 10 g of sodium alginate solution was subsequently added. To thoroughly mix the lecithin in the alginate, the mixture was left overnight on a magnetic stirrer at 250 rpm. room temperature. After mixing, the mixture was added to 10 g of polyvinyl alcohol and mixed in a homogenizer for 1 hour at 200 rpm and room temperature. Subsequently, the samples were poured into Petri dishes and placed in a freezer for 24 hours for the freeze-thaw cycle cross-linking method.

A detailed description of the mixture compositions used for hydrogels preparation is shown in Table 1.

Table 1
Mixture compositions used for hybrid hydrogel's sample preparation

Sample symbol	PVA:SA mass ratio	Amount of lecithin [wt.%]
PVA	1:0	0
PVA/SA	1:1	0
1-LEC	1:1	0,5
2-LEC	1:1	1
3-LEC	1:1	2

2.3 Characterization of hybrid hydrogel network structure

2.3.1 Rheological measurements

A Discovery HR-2 rheometer (TA Instruments) was used to measure the mechanical properties of the hydrogel samples. The measurement geometry was designed in a plate-plate arrangement with a sensor diameter of 20 mm. The measurements were performed at least three times at constant temperatures of 25°C, which were ensured by a flow thermostat.

As part of the rheometer measurements, an amplitude test, the so-called "Strain sweep", was chosen, providing information on the area on which the viscoelastic moduli (elastic (G') and viscous (G")) amplitude of deformation of selected hydrogel systems, the so-called linear viscoelastic region (LVR) depend. The evaluation takes place on the basis of a comparison of the values of the viscoelastic modulus - specifically, if the modulus of elasticity prevails, the substance shows, on the other hand, the behaviour of a viscoelastic material with a predominance of the elastic component, if the viscous modulus predominates, the character of the substance corresponds to a viscous liquid [15].

Before starting the measurement, a relaxation step, the co-called “Conditioning step”, was performed, set to 120 s, during which the sensor in the measurement position was used on the sample in order to stabilise the measurement conditions and also temper the sample to the desired temperature of the experiment. The measurement took place at a constant frequency (1 Hz) and the deformation amplitude range was set to 0,01-1000%. The data obtained during the measurement of individual samples were dependence of viscoelastic moduli on the deformation amplitude, where for better orientation botch axes were set to a logarithmic scale.

All measurement parameters are listed in the following Table 2.

Table 2
Set parameters for rheological measurement

A relaxing step	Relaxation time	120 s
	Temperature	25 °C
Amplitude tests	Relaxation time	0 s
	Measuring temperature	25 °C
	Angular frequency	1 Hz
	Amplitude of deformation	0,01-1000%
	Points per decade	6

2.3.2 Scanning electron microscope analysis

Scanning electron microscopy (SEM) was chosen as a suitable method for obtaining information about the internal structure of hybrid hydrogels (with/without the addition of lecithin) and PVA hydrogel. Before the determination of the internal structure, the prepared samples of the gel systems were lyophilized. It differs from oven drying where the sample is flash-frozen under very low pressure. Next, a suitable part of the sample was cut out and plated with a conductive material in a vacuum sputtering device. The thus

prepared sample was observed using SEM with an accelerating voltage of 5 kV, an electron impact width of 100 pA and a working distance of around 10 mm. Each of the samples was measured at three different magnifications, i.e. 500, 1000 and 5000, in cross-section and on the surface.

2.3.3 Determination of swelling index and gel fraction

To determine the swelling properties of xerogels, the prepared samples of hybrid hydrogel and PVA hydrogel were cut into 3x3 cm pieces and dried in an oven at 50°C for 24 hours. The water absorption of the hydrogel sample was investigated in two ways, i.e., by measuring the weight of the hydrogels at certain times and by visual evaluation. The principle was to add enough deionized water to the xerogel and leave it at room temperature for 24 hours. Then, before changing the water, the swollen sample was carefully dried with wood pulp and weighed on an analytical scale. Swelling was monitored for 4 days, and water absorption percentage degree was determined from the measured values.

2.4 Characterization of hybrid hydrogel's transport properties

2.4.1 Diffusion cells

The diffusion experiment was performed using a PermeGear horizontal diffusion cell. At the beginning, the edges of the diffusion cuvettes were coated with silicone paste (Lukosan), then the prepared PVA/SA hybrid hydrogel was inserted between the cells and subsequently fixed using the diffusion cuvette holder. Since the gel itself did not hold its shape, it was decided to insert a sample of the gel system itself between the cells, which, after stabilisation with a holder, was additionally wrapped with parafilm so that the gel was not loose, the solution of the source and recipient cells would not mix or the cells would not drain their contents. Furthermore, a small magnetic stirrer was inserted into each chamber of the diffusion cell, which needed to be placed in a small space at the bottom of the cell. Using a funnel, 50 ml of methylene blue was simultaneously poured into the source cell and 50 ml of deionized water into the receiving cell, and the top holes were covered with parafilm. The cells were placed on a magnetic stirrer at 250 rpm (Fig. 1).

The diffusion experiment was carried out for 5 days. After the start of the experiment, samples were taken from the receiving cell into a quartz cuvette in three repetitions every 2 hours for subsequent absorbance measurements on a UV-VIS spectrometer, then at 24-hour intervals. To maintain a constant volume in the receiving cell, after spectrophotometric analysis, the collected samples were returned to the diffusion cell.

2.4.2 Determination of the diffusion coefficient

In view of the study by Sedlacek et al. [16] the effective diffusion coefficient was determined, which could include also the effective structural parameters of hydrogels, i.e., effective porosity, tortuosity factor, and some standard diffusion and interaction parameters, i.e. diffusion and partition coefficients and apparent equilibrium constants, were calculated. Determination of the diffusion coefficient is one of the

possibilities of the formulation of the diffusion process. The value of the effective diffusion coefficient D_{eff} [$m^2 \cdot s^{-1}$] was determined at the stage when all particles have already passed through the gel from the following equation:

$$\varepsilon \cdot D_{eff} = \left(\frac{\mathrm{d}n}{\mathrm{d}t}\right) \cdot \left(\frac{l}{\Delta C_{10}}\right)$$

where dn/dt [$mol \cdot m^{-2} \cdot s^{-1}$] is the slope of the linear part of the time dependence of the total diffusion flux into the receiving cell, l is the length of the gel [m] and ΔC_{10} is the constant value of the concentration difference of the diffusing substance between the cells [$mol \cdot m^{-3}$], ε is the value of the equilibrium coefficient [-], representing the concentration jump at the interface.

2.4.3 Release of methylene blue from gel's network

In order to monitor the release kinetics of methylene blue (MB), the following experiment was performed. According to Chap. 5.4, samples of hybrid hydrogel and PVA hydrogel were prepared, but for the preparation of PVA, instead of deionized water, a MB solution with a mass concentration of 25 mg/l was used. Furthermore, the samples were submerged in beakers with a defined amount of deionized water, so that subsequently it was possible to visually and with the help of UV-VIS spectrometer observe the release of MB from the gel matrix. After spectrophotometric analysis, the collected samples were returned to the beaker to maintain a constant volume. This experiment also lasted 5 days and, as with the diffusion cell method, sampling into quartz cuvettes was carried out after the start of the experiment in three repetitions every 2 hours, then only after 24 hours.

3 Results and Discussion

3.1 Mechanical and structural properties

In this chapter, the results of the measurements summarize the characterization of the properties of the prepared gel systems, i.e. the PVA/SA hybrid hydrogel with or without 0,5 wt.%, 1 wt.% and 2 wt.% lecithin, and PVA hydrogel, in order to also determine the effect of SA on the properties and thus on the structure of the PVA gel. The addition of natural lecithin was expected to modify the properties of the gel materials. All samples had the same method of preparation, which is presented in Chap. 2.2

3.1.1 Rheology measurement

Rheological measurements were performed in order to characterise the mechanical and viscoelastic properties of the prepared gel systems using the amplitude test method, which deals with the determination of the linear viscoelastic region (LVR) and was sufficient to compare the properties of the studied gels. Viscoelasticity is one of the important mechanical properties including the viscous behaviour of a fluid and the elastic behaviour of a solid. All samples were measured in triplicate on a TA

Instruments HR 2 Discovery rheometer and the settings for individual tests are listed in Table 1 in Chap. 2.3.1.

Figure 2 and Fig. 3 show graphs of the dependence of viscoelastic moduli on the deformation amplitude for hybrid hydrogel samples with/without the addition of lecithin and PVA hydrogel. In all cases, it is evident that in the linear viscoelastic region the elastic modulus prevails over the viscous one which confirms the fully cross-linked gel structure and the behavior of the samples as materials with a predominance of the elastic component. Then they decrease and cross over, however, for the PVA hydrogel sample, this will occur at higher values of the deformation amplitude (around 1000%) which means that it is a solid sample with the ability to withstand the action of external stress. Hybrid hydrogels have higher elastic moduli compared to PVA hydrogel which proves a double hybrid network, i.e. a higher density of cross-linking is present in a unit volume, i.e. a larger number of nodes, since PVA is physically cross-linked by hydrogen bridges while SA has ionic cross-linking by calcium ions. However, the presence of ionic bonding which is weaker in terms of strength compared to hydrogen bonds in PVA leads to an earlier deformation of the sample, i.e. an earlier decrease in the elastic modulus. Considering the range of LVR, the results of the amplitude test also indicate a minimal effect of lecithin on the properties of the hybrid hydrogel, although they shift the crossover point to lower values of the amplitude deformation.

Comparisons of viscoelastic moduli for all gel system samples are shown in Table 4 (see in Supplementary data).

3.1.2 Scanning electron microscope

Scanning electron microscopy (SEM) was used to investigate the morphological properties of the samples, the internal structure and the surface of the gel system samples. Thanks to this technique, it was possible to determine how much the structure is different between samples, helping to determine the changes caused by mixing PVA with alginate, or adding lecithin. PVA hydrogel was selected as the first set of samples, followed by PVA/SA hybrid hydrogel and finally PVA/SA with the addition of lecithin.

The images as a result of SEM are shown in Fig. 4 and Fig. 9 (see in Supplementary data), from which it is evident how the samples look in cross-section and on the surface and also how much they differ from each other. At maximum zoom, the PVA xerogel has a clearly visible porous structure with different pore sizes, yet its structure is irregular and damaged in places which may have been caused by lyophilization. The xerogel of the hybrid hydrogel in cross-section has a layered arrangement due to the good cross-linking of PVA and SA, however, with the addition of lecithin, it changes to a porous spongy structure. The overall compact structure of both samples explains the smooth surface without visible pores.

3.1.3 Swell experiment

The swelling of the gel systems was determined by drying the prepared samples in an oven with a set temperature of 50°C for 24 hours and then leaving them in deionized water to investigate their ability to absorb a certain amount of liquid. The experiment ran for 4 days, with results recorded every 24 hours.

Determining the swelling behaviour of the hybrid hydrogel provides very valuable information that can be used in other methods, especially in the explanation of their transport properties

Figure 5 shows a graphic representation of sample rehydration. Due to the compact structure with high cross-linking density, low swelling of the hybrid hydrogel is evident when PVA binds more water, as its structure has different pore sizes. However, as lecithin has a greater affinity for water, the hybrid hydrogel sample with 2 wt.% addition of lecithin bound the most water.

Figure 10 (see in Supplementary data) shows the gradual swelling of individual samples. It can be seen from the photos that after certain time intervals the volume of the sample increased which explains the absorption of water by the gel systems.

3.2 Transport properties

The final part of this work was the monitoring of the transport of a model hydrophilic probe, i.e. methylene blue (MB), through individual prepared gel systems, the course of which was examined both visually and analytically using UV-VIS spectrometry. Diffusion experiments make it possible to get a relatively accurate idea of transport processes, so they were performed in two ways. The first was the use of horizontal diffusion cells using MB as an active target substance, the transport of which was observed during the experiment. Another way was the observation of the release of MB from the gel matrix into water.

3.2.1 Diffusion cells

The calibration curve for methylene blue was constructed for the purpose of quantitative evaluation of the measured data. The principle of its construction was the preparation of series of calibration solutions with different concentrations of methylene blue and measurement on a UV-VIS spectrometer. Furthermore, the wavelength of 664 nm was selected from the obtained absorption spectrum, where the absorption maximum of MB was found. The obtained calibration curve was used to calculate the concentration of the model organic dye in diffusion experiments, i.e. in diffusion cells and in the release of MB from the gel matrix. Figure 11 (see in Supplementary data) shows the calibration curve.

For this diffusion experiment, PVA hydrogel, PVA/SA hybrid hydrogel with/without the addition of lecithin at a concentration of 0,5 wt.%, 1 wt.% and 2 wt.% were used where individual samples were inserted between the source and receiver cells, making sure that the samples were placed over the entire surface of the opening of the diffusion cells in order to avoid tearing after their fixation and fixing. MB solution with a mass concentration of 25 mg/l was poured into the source cell and deionized water into the receiving cell. A detailed description of the assembly of diffusion cells and sample preparation is given in Chaps. 2.4.1 and 2.2. Subsequently, the permeation of the model organic dye through the gel samples was monitored which was quantified using UV-VIS spectrophotometry in the range of 400–800 nm. Absorption spectra were subsequently constructed in MS Excel.

To determine the content of MB in the receiving cell, the absorbance values at the wavelength of 664 nm where their absorption maximum is located, were subtracted from the prepared absorption spectra and the concentration of MB was calculated using the linear regression equation of the calibration curve which was subsequently used to create a graph of the dependence of the mass concentration of the passed organic dyes across individual samples over time. After the start of the experiment, the absorbance of the solution from the receiving cell was measured at certain time intervals for 5 days after which the absorbance did not change any further. On the last day of measurement, the absorbance of the dye from the source cell was measured to calculate the absorbed amount of MB. It was assumed that the measurement would take 2 weeks which is the usual time for the implementation of the given experiment.

After pulling out the samples from the space between the cells, an obvious difference in the colour of the gel system after diffusion was seen, this is shown in Fig. 6. The PVA hydrogel had a light blue colour which corresponds to the MB partly remaining attached. The dark blue colour of the hybrid hydrogel is caused by the alginate contained in the structure, it has the opposite charge to MB, and therefore it absorbs the largest amount of dye into its structure. Hybrid hydrogels with the addition of lecithin have different shades of dye depending on the concentration, precisely according to the opening of the diffusion cells which was caused by the reaction of lecithin with the dye. Also, from a visual point of view, there was no swelling and disintegration of the structure of the gels.

The dependence of MB concentration on time for samples of gel systems is shown in Fig. 7. For all samples, a linear increase in concentration can be seen with increasing time in the beginning, when MB diffused into the environment of the receiving cell with deionized water, but certain differences are visible. Compared to the other samples, the PVA hydrogel released MB faster where after 5 hours there was a sharp increase in MB concentration with time. The rapid course of diffusion can be explained by the porous structure of the gel which was determined in subsection 3.1.2. The PVA/SA hybrid hydrogel had a slow diffusion process which was due to both the electrostatic interaction of alginate (negative charge) and MB (positive charge) and the layered arrangement of the structure without pores. The samples with the addition of lecithin had the slowest rate of diffusion. The difference in speed could be caused not only by the electrostatic interaction and structure, but also by the fact that MB was first attached to the structure of the gel systems by lecithin, and then to the subsequent penetration of the probe into the receiving cell.

3.2.2 Determination of the diffusion coefficient

Table 3 shows the results of the calculation of the effective diffusion coefficient, the transit time and the concentration of the organic dye in the gel at the end of the experiment. It can be seen from the table that the obtained values of the effective diffusion coefficient also indicate a faster course of diffusion in the case of PVA gel than in the other samples which is also confirmed by the values of the transit times. The presence of lecithin and alginate cross-linked by calcium ions leads to a change in the internal structure of PVA hydrogel or hybrid hydrogel and thus slows down the diffusion process. However, this is still due

to the reaction of lecithin and the electrostatic interaction of alginate with MB, due to which the data for PVA/SA hybrid hydrogel with/without lecithin addition may be inaccurate.

Table 3
Summary results of effective diffusion coefficient, transit time and concentration of methylene blue in the gel for samples

Sample	Effective diffusion coefficient [$m^2 \cdot s^{-1}$]	Transit time [h]	Concentration of MB in the gel [$mol \cdot m^{-3}$]
PVA	$9{,}52 \cdot 10^{-11}$	1,47	0,15
PVA/SA	$5{,}59 \cdot 10^{-11}$	4,26	0,21
1-LEC	$3{,}31 \cdot 10^{-11}$	4,78	0,23
2-LEC	$1{,}90 \cdot 10^{-12}$	3,95	0,45
3-LEC	$2{,}77 \cdot 10^{-13}$	2,16	0,53

A follow-up work and research on deeper investigation and a more accurate mathematical description of MB transport through gel systems with/without lecithin addition in which the reaction between oppositely charged functional groups also takes place is needed

3.2.3 Release of MB from gel's network

For the diffusion experiment, PVA/SA and PVA gel systems with MB with a mass concentration of 25 mg/l were prepared and a detailed description of sample preparation is given in subsection 2.4.3. The transport properties were determined based on the release sequence of MB from individual gel matrices. The task was to find out if MB with a concentration of 25 mg/l will be released from the structure of PVA/SA and PVA gel systems and to determine the kinetics of this release.

From Fig. 8, it can be seen that in both samples, after 2 hours, MB was released from the gel matrix into the deionized water environment, but after 9 hours, the release stabilized which can also be seen in the absorption spectra (see Fig. 12 and Fig. 13 in Supplementary data). In this case, MB was also bound into the structure of the gels, although clear differences in MB concentration can also be seen here. Here too the structure of the gels played a big role, i.e. the layered structure of the PVA/SA hybrid hydrogel which led to slow release of MB and the porous structure of the PVA hydrogel which led to fast release. The slow progress of the PVA/SA gel here is also caused by the opposite charges of alginate and MB which leads to their electrostatic interaction.

4 Conclusion and the future possibilities

Hybrid hydrogels are complex systems, where their complexity may lie in their preparation, as well as in their characterization, as there are many variants. The aim of the work was to carry out a study of structural and transport, or release properties of hybrid hydrogels based on polyvinyl alcohol and sodium alginate materials. The goal was to also modify their internal support structure with suitable agents and repeatedly study their properties.

Viscoelastic, swelling and transport properties were determined using physicochemical methods. Oscillation and amplitude tests were performed in order to study the mechanical properties where the structural properties of the hydrogels, respectively xerogels, were determined using a scanning electron microscope. Diffusion experiments with the UV-VIS spectrometry detection method were used to identify the transport (release) properties in which the organic dye methylene blue was used as a model probe. The measurement results indicate that the presence of alginate in the PVA structure increases the modification of cross-linking density and the presence of lecithin in their internal structure. Due to the achieved results, it is possible to correct the properties of hybrid gel systems according to the required applications.

In future studies of the transport properties of these gel systems, common diffusion cells with synthetic and skin membranes can be evaluated, in which a solution simulating physiological properties and regulating osmotic pressure could be used. Also in these solutions, swelling of the xerogels could be performed and the samples analysed by other methods providing information on the degree of cross-linking and pore size.

Declarations

Acknowledgements

Author Contributions

D.Z., J.S. and M.P. conceived of the presented idea. D.Z. developed the theory and performed the computations. D.Z. and J.S. conceived and planned the experiments. D.Z. carried out the experiments. M.T. conducted an electron microscope experiment. D.Z., M.P., M.T. and J.S. contributed to the interpretation of the results. D.Z. wrote the manuscript with support from J.S. and M.P. All authors provided critical feedback and helped shape the research, analysis, and manuscript.

Funding

This research project was supported by the project BUT – internal BUT projects, Reg. No. FCH-S-23-8303 and was supported by Faculty of Chemistry (BUT).

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data used in this study are available on request from the corresponding author.

Conflicts of Interest

The authors declare no conflict of interest.

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Figures

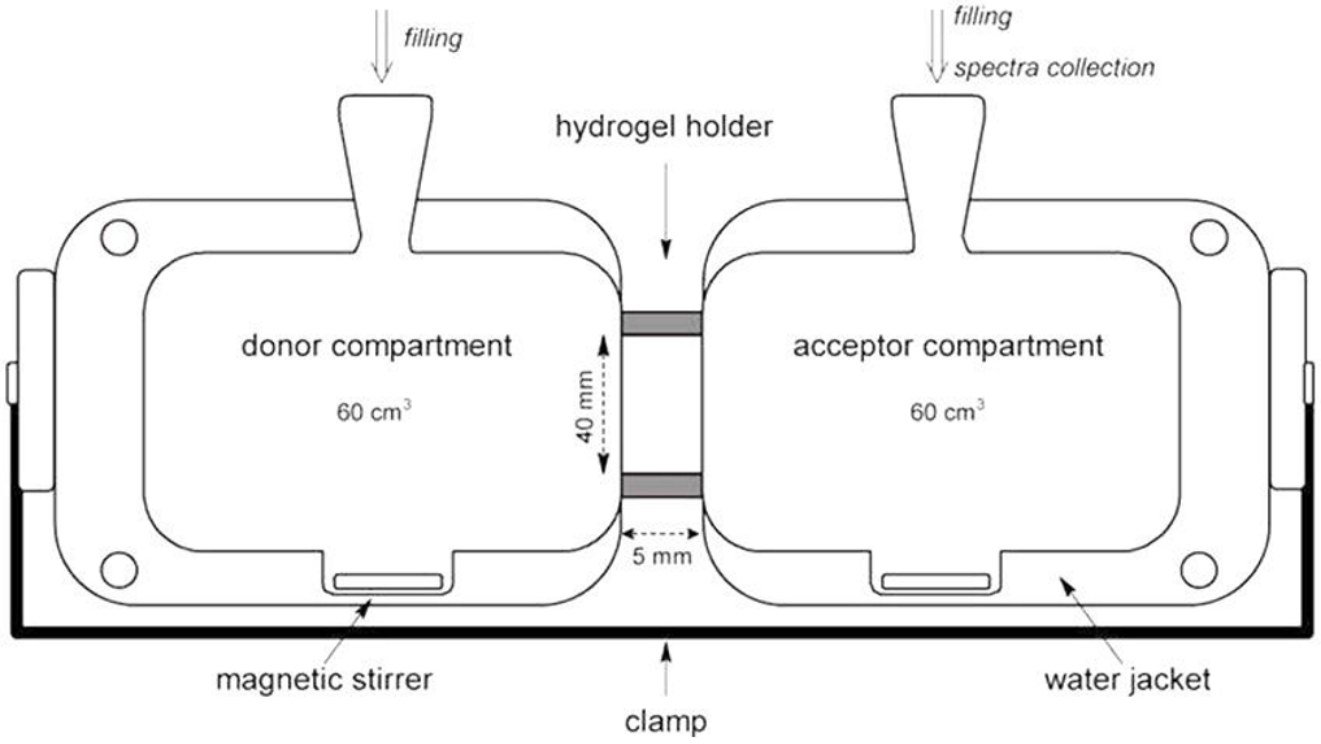

Figure 1

Schematic illustration of applied diffusion cell apparatus [16]

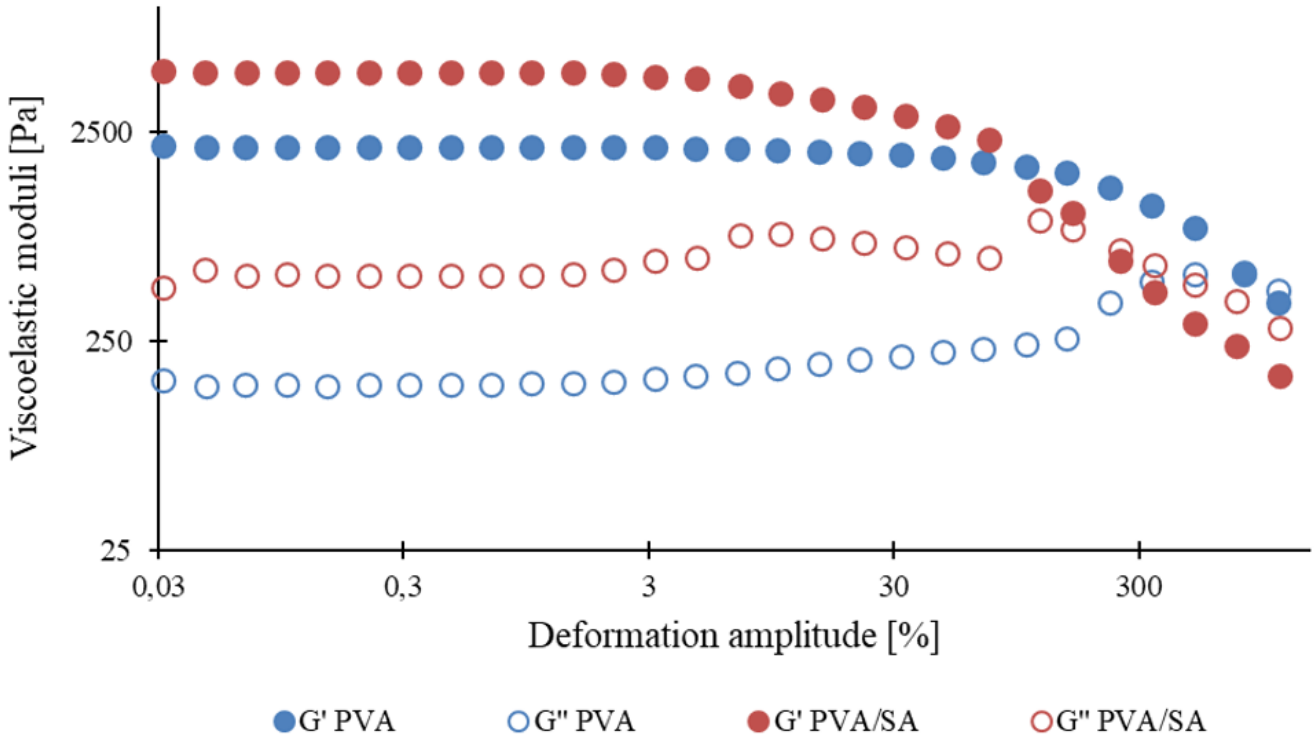

Figure 2

Dependence of viscoelastic moduli on strain amplitude for PVA hydrogel and PVA/SA hybrid hydrogel

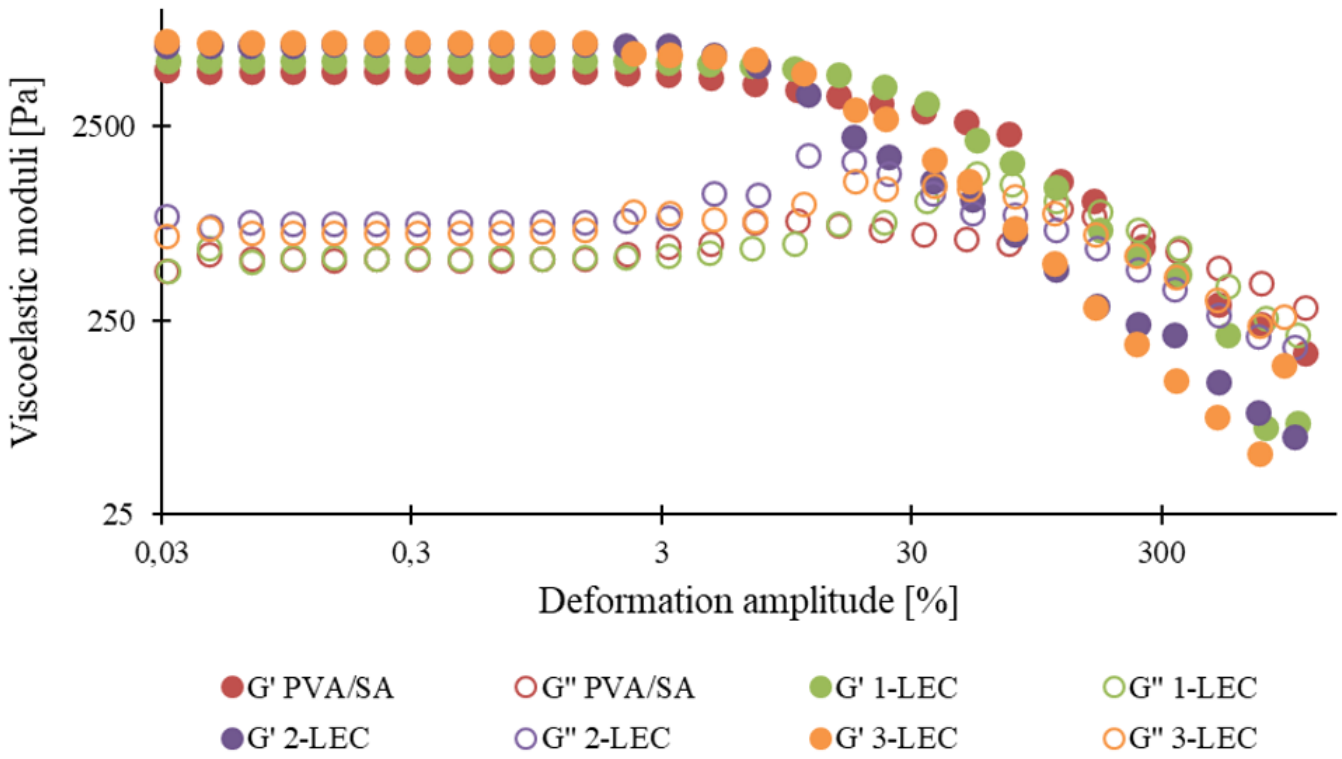

Figure 3

Dependence of viscoelastic moduli on strain amplitude for PVA/SA hybrid hydrogel and hybrid hydrogel samples with the addition of lecithin

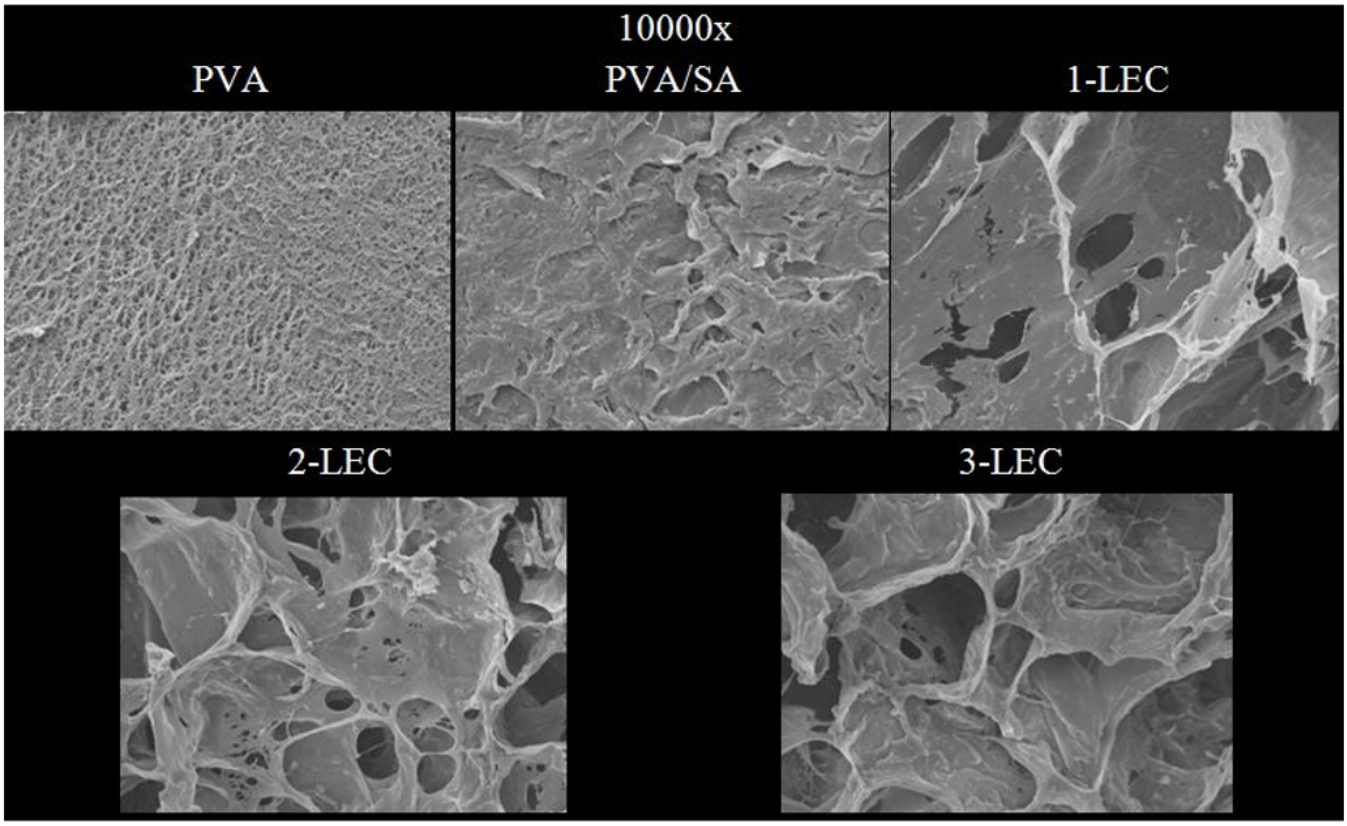

Figure 4

Scanning electron microscope images with zoom for sample's surface

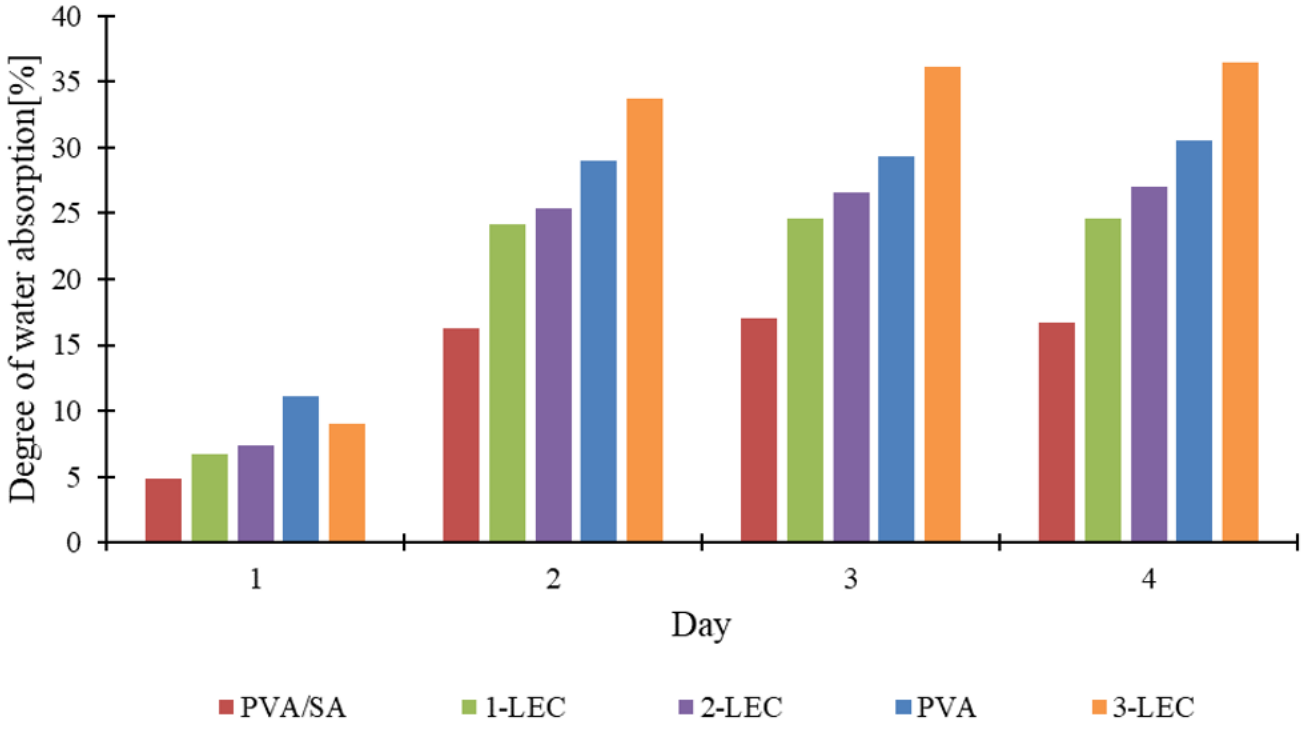

Figure 5

Graphic representation of sample rehydration

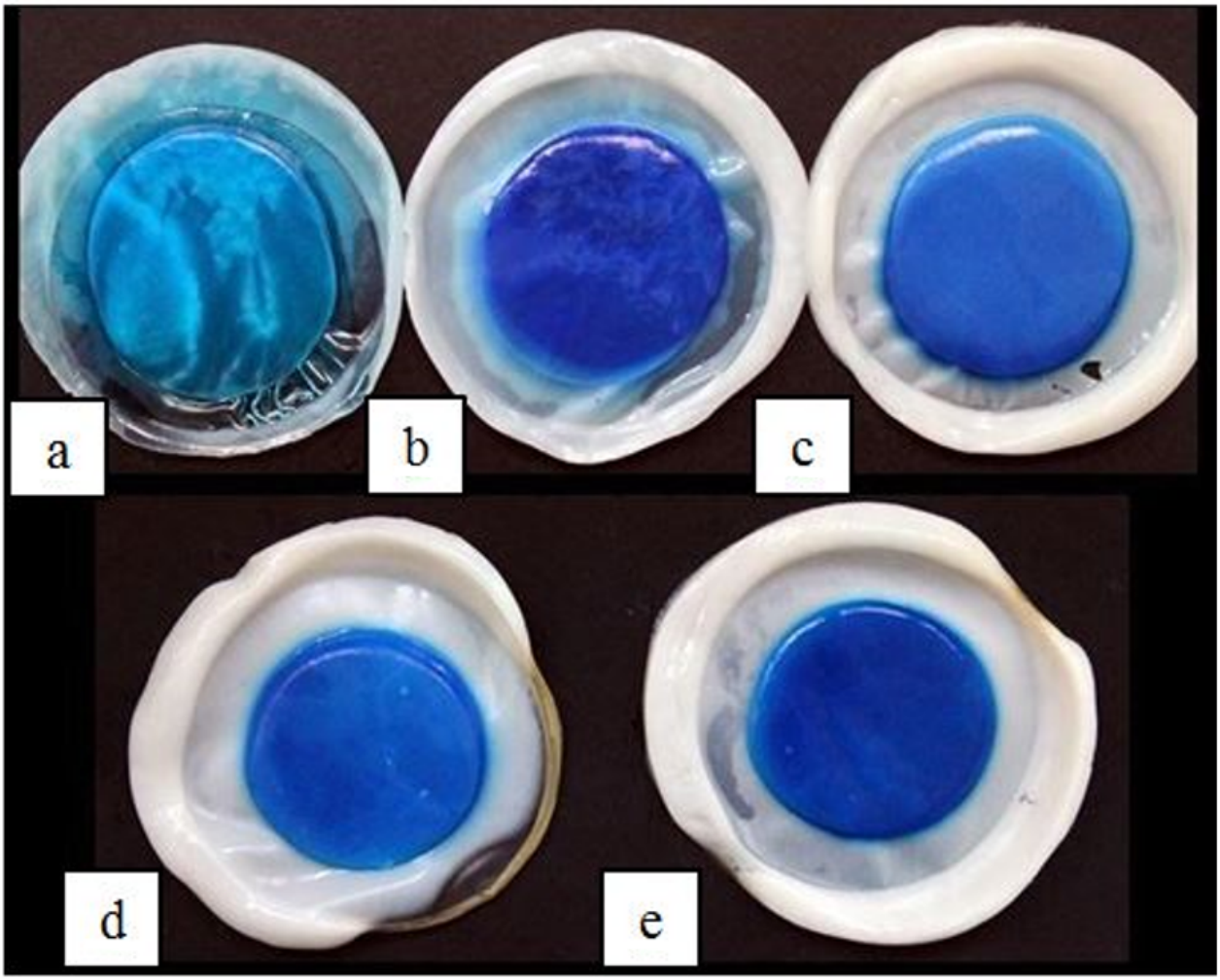

Figure 6

PVA hydrogel (a), PVA/SA hybrid hydrogel (b), PVA/SA hybrid hydrogel with 0,5 wt.% (c), 1 wt.% (d) and 2 wt.% (e) of lecithin after diffusion

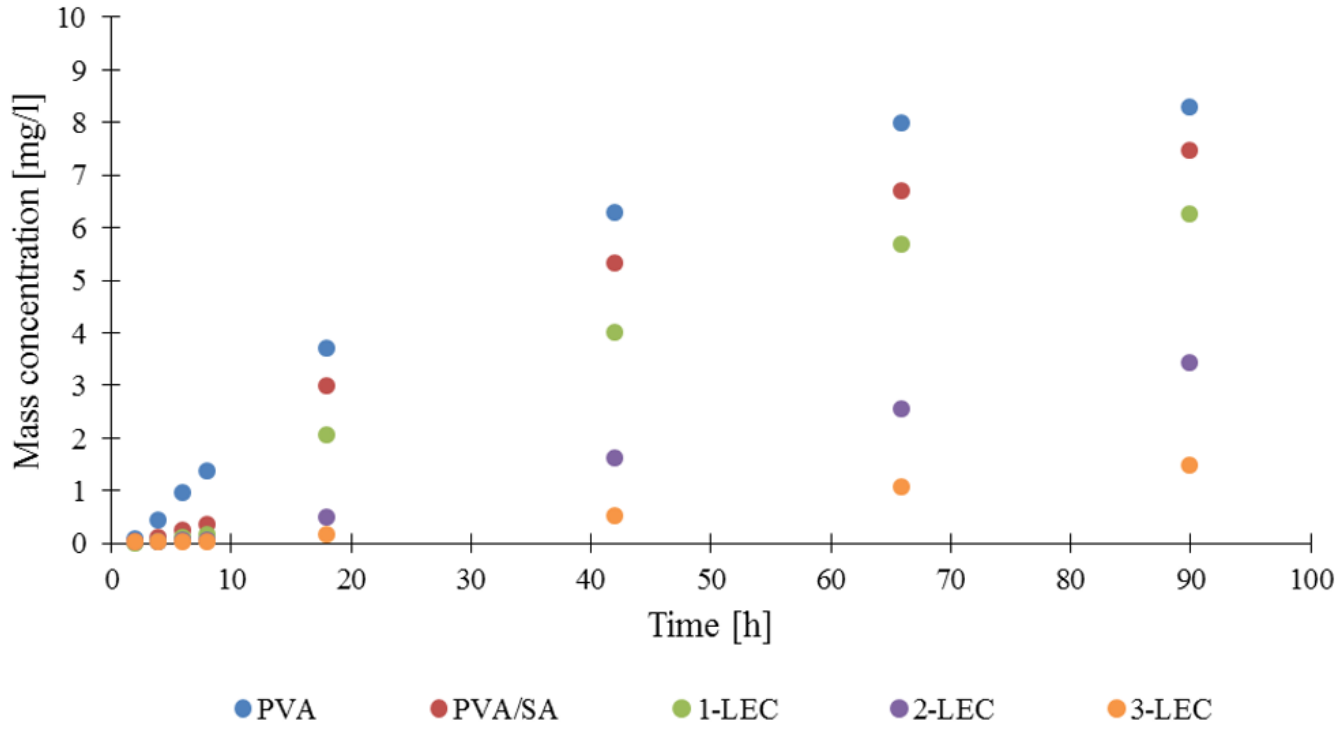

Figure 7

Dependence of methylene blue mass concentration over time for gel systems samples

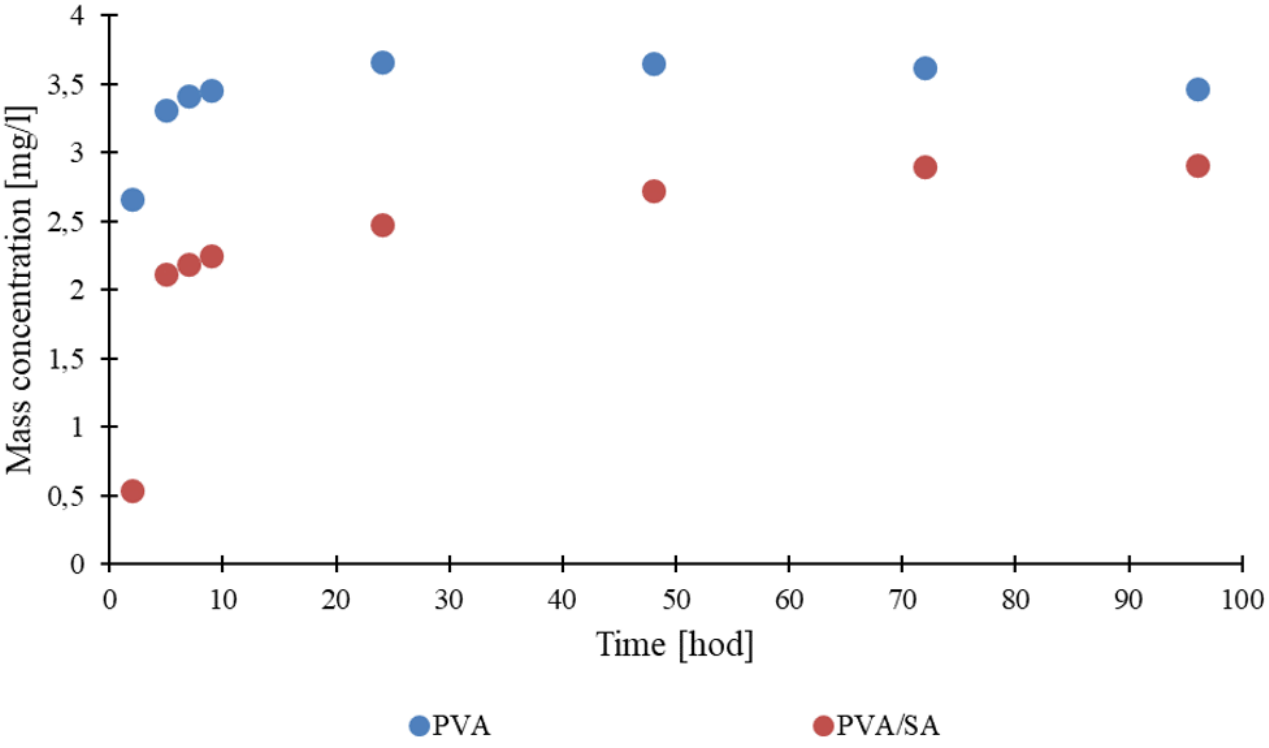

Figure 8

Time dependence of the concentration of methylene blue released from the PVA/SA gel matrix and PVA gels

Supplementary Files

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- Supplementarydata.docx
- Graphicalabstract.png