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Preparation of sustained-release hydrogel for controlling dye release by liquid marbles

Shuai Han, Caixia Wang, Yongjun He*, Yaodong Liang & Lin Feng

Xi'an University of Science and Technology, Xi'an 710054, China
Email: yongjhe@sina.com.cn

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Liquid marbles with polyacrylamide as skeleton and eosin Y as core and hydrophobic silica as shell have been prepared to study the sustained release of eosin Y. The influences of the amount of crosslinker, the sustained-release medium, the volume of liquid marbles, the temperature, the adhesive powder and the addition of sodium bicarbonate on the sustained-release properties of eosin Y have been studied in detail. The results showed that with the increase of volume, the amount of eosin Y release increased but the release rate decreased. The release amount of eosin Y decreases as the amount of cross linking agent increase. The prepared liquid marbles have been hardly released in acidic conditions, but the release amount of eosin Y has been improved with the increase of pH. The amount of eosin Y release increased with the increase of temperature. The use of liquid marbles as a medium to preparation sustained-release hydrogel for dye release can not only control the dye loading by accurately controlling the volume of liquid marbles, but also the release rate of dyes can be controlled by tuning the sustained-release medium and other conditions. This method provides a new method for dye release.

Keywords: Liquid marbles, Polyacrylamide hydrogel, Sustained-release, Eosin Y

Liquid marbles are usually defined as typically micro/nano-sized liquid droplets wrapped by hydrophobic particles such as silica beads and lycopodium. Since liquid marbles were introduced by Aussillous and Quéré, research on the preparation and applications of liquid marbles has made considerable advances during the past decade[1-6]. Liquid marbles can be made by simply rolling liquid droplets over a bed of hydrophobic particles[7]. Due to the non-wetting property, liquid marbles have been proposed for various applications such as gas and pH sensing[8,9], biotechnology[10,11], microfluidics[12] and micro-reactors[13].

Hydrogels, which are soft matter consisting of a three-dimensional network of hydrophilic polymers held together through physical or chemical interaction[14]. Their primary structure is composed of hydrophilic groups such as hydroxyl groups, amide groups and carboxyl groups and hydrophobic group such as alkyl groups. The secondary structure is a three-dimensional network structure with low crosslinking density, and can maintain the hydrogel rapidly absorbing a large amount of water but insoluble[15]. Due to the excellent characteristics, hydrogels have valuable potential in drug delivery[16], tissue engineering scaffolds[17], biosensors[18] and dye release[19].

In this article, liquid marbles were used as the medium of micro-reactor to form hydrogel, and eosin Y was chosen as a model dye loaded into the hydrogels to study the sustained-release property. In the process of releasing, the accurate load of the initial dye is an important parameter to measure the release property. The volume of liquid marbles can be adjusted accurately by using liquid marbles as the medium of microreactor, thus the loading amount of eosin Y can be accurately controlled. To our knowledge, the preparation of sustained-release hydrogel using liquid marbles as a medium has not been reported for controlling the dye release till now. The preparation of sustained-release hydrogel by using liquid marbles can not only accurately control the volume of liquid marbles to determine the amount of dye loaded, but also decide the amount of dyes released by tuning the external conditions.

Materials and Methods

Super hydrophobic silica, a gift from Jiangxi Huiming Chemicals, was used to form liquid marbles. N,N-methylene-bis-acrylamide (MBA) and acrylamide (Am) monomers were obtained from Tianjin Fuchen Chemical Reagents Factory.

Ammonium persulfate (APS) was obtained from Guangdong Guanghua Sci-tech Co. Ltd. Sodium bicarbonate was obtained from Xi'an Chemical Reagents Factory. Deionized water was used throughout all the experiments.

Preparation of liquid marbles

0.1 g eosin Y was dissolved in 100 mL distilled water for later use. A 10 mg of ammonium persulfate as initiator and polymer monomer acrylamide with 1% mole ratio of N,N-methylene bis-acrylamide were completely dissolved in 10 mL of the eosin Y solution. In a typical procedure, aforementioned polyacrylamide with eosin Y solution was deposited onto the superhydrophobic silica particle powder bed using a micropipette. By gently rolling the dye aqueous solution on the powder bed to make the liquid fully coated by the powder, resulting in a liquid marble. The prepared liquid marbles were placed in a closed container and gelled after 4 h.

Sustained-release performance

The liquid marbles containing eosin Y were placed in a certain sustained-release media. The amount of eosin Y release was measured by changing the different variables such as the volume of liquid marbles, temperature, dose of the crosslinker at the same sustained-release time. The concentration variations of the eosin Y released with time was utilized to investigate the sustained-release properties by UV spectrophotometer (TU-1810).

Results and Discussion

The liquid marbles were formed by rolling the dye aqueous solution over the powder bed. The prepared sustained-release hydrogel droplets lower their high surface energy by adsorbing on the low surface energy hydrophobic silica particles. During the process, the hydrophobic silica particles are spontaneously coated at the surface of the hydrogels droplets resulting in the minimization of the surface free energy[20]. Due to the fact that the liquid marbles were made of polyacrylamide hydrogels as the core, and there was little chemical interaction between polyacrylamide and eosin Y, therefore, eosin Y exists in the middle of the three-dimensional framework of hydrogel. Although, the hydrogels droplet was fully coated by the hydrophobic silica powder, the surface of the liquid marbles comprises solid particles and empty areas. The empty areas are larger than the powder size[21] , therefore, water molecules can enter the hydrogel from the empty areas and the middle of the three-dimensional skeleton of the hydrogel. Eosin Y was dissolved in water and then diffuses outward.

A photograph of a liquid marble with a volume of 20 μL after gelling is shown in Fig. 1a. The photograph results show that the liquid marble is approximately spherical. Existencing state of eosin Y in the hydrogel is shown in Fig. 1b.

The influence of volume

Eosin Y loaded on liquid marbles does not spontaneously diffuse outward into liquid marbles. When coated with hydrophobic silica, some hydrophobic silica particles were embedded in the gel, which increased the distance between hydrophobic silica particles. When the liquid marbles containing eosin Y were placed in the sustained-release media, the liquid marbles began to absorb the water molecules from the external media in a drier state. Firstly, the swelling surface of liquid marbles was wetted by water molecules and the water molecules moved inward into the hydrogel core[22]. The hydrophilic groups of amides in liquid marbles bind to water molecules by hydrogen bonding. When the hydrophilic group was united with water, the hydrogel system began to swell, the three-dimensional network

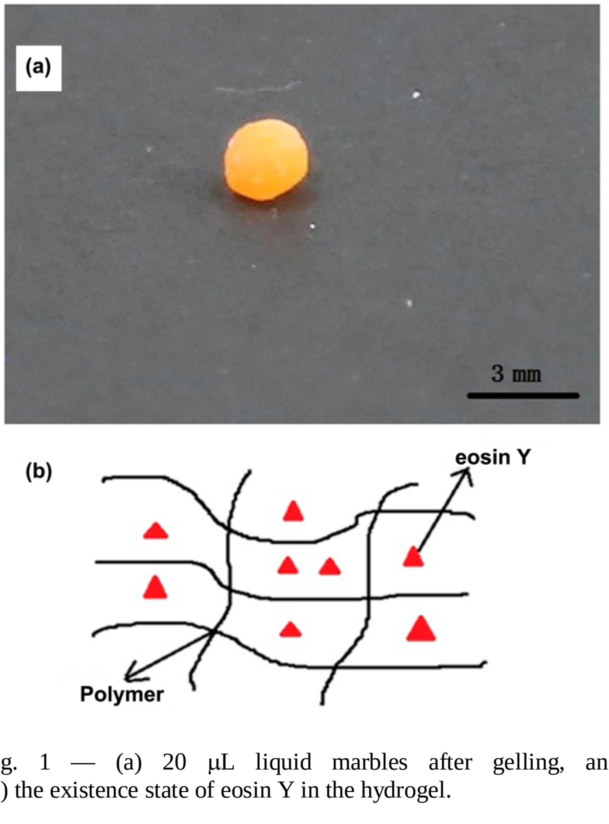

Fig. 1 — (a) 20 μL liquid marbles after gelling, and (b) the existence state of eosin Y in the hydrogel.

structure with low crosslinking density began to expand, the relaxation between the chains increased, and the hydrophobic groups were exposed to the water[23]. When the hydrogel is further swelled, the internal pressure of the hydrogel decreases and the osmotic pressure increases. With the increase of osmotic pressure, eosin Y in liquid marbles diffuses outwards because of the impelling force of osmotic pressure difference. When the internal and external osmotic pressure gradually decreased to zero, the system reached saturation state.

The influences of varying the liquid marbles volume at a constant dosage of crosslinker on the sustained-release properties are shown in Fig. 2. It can be seen from the figure that the amount of dye released out increases with the increase of volume, which is because the dye loaded inside increases with the increase of the volume of liquid marbles, so the amount of released increases. However, the sustained-release rate decreases with increase of the liquid marble volume. It needs to be emphasized that the amount of release is the concentration released from the substance to the medium in the system, and the rate of release is the ratio of the concentration of the dye to medium and the initial concentration. The larger the volume, lower the sustained-release rate. It can be attributed to a decrease of specific area and an increase of diffusion path of dye with increasing the volume of liquid marbles[24], resulting in a lower dye release rate than those smaller ones. So, the sustained-release rate shows a downward trend. It is also suggested that the sustained-release performance of the liquid marbles can be modulated simply by changing the marble volume.

The influence of sustained- release media

The influences of varying the sustained-release media at a constant dosage of crosslinker on the sustained-release properties of eosin Y are shown in Fig. 3. It can be seen from the figure that when the liquid marbles were put into the acidic solution, there was almost no sustained-release influence, and the release in water reaches equilibrium at about 20 h, while in alkaline condition the system reaches equilibrium at about 8 h. The principle is that the eosin Y has poor solubility in the acidic conditions, and the degree of ionization of the dissociating group (the carboxylic acid after hydrolysis of amide group) in the polymer chain forming the network of polyacrylamide hydrogels is very small. The ionized association of protonated polyacrylamide and eosin Y occurs under acidic conditions, resulting in little or no release of eosin Y. With the increase of pH, the degree of ionization of carboxylic groups will be significantly increased, resulting in a large difference in ion concentration inside and outside the hydrogel, and the osmotic pressure of the internal solution will

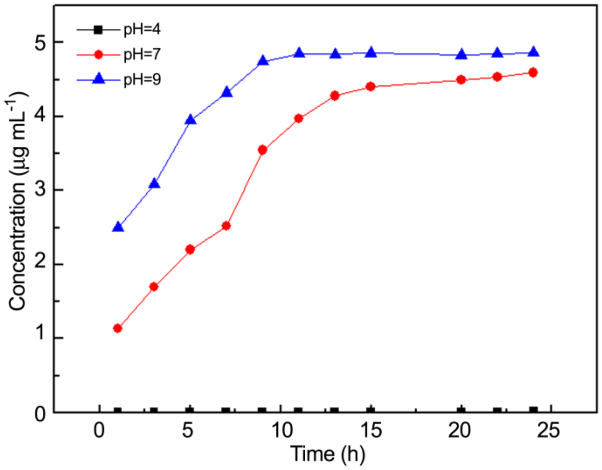

Fig. 3 — Variation of the concentration of eosin Y dye released from 50 μL liquid marbles with sustained-release media at same dosage of crosslinker (0.01 g).

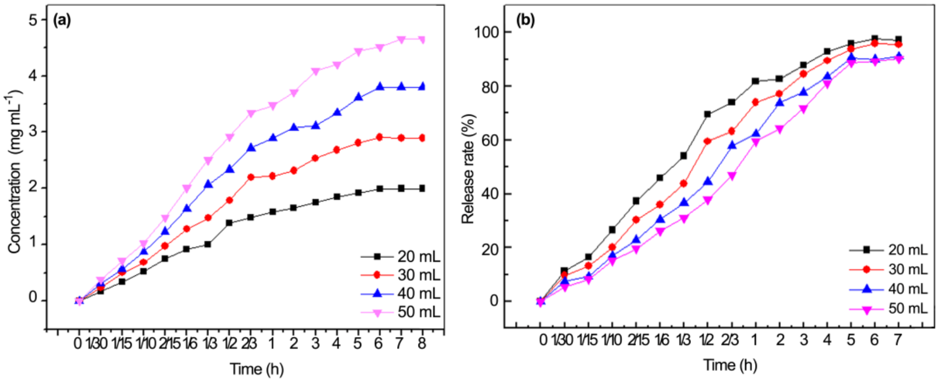

Fig. 2 — (a) Variation of the concentration and (b) release rate of eosin Y dye released from liquid marbles with time at same dosage of crosslinker (0.01 g) in alkali solution.

be much higher than that of the external solution, thus improving the release performance of eosin Y[25].

The influence of crosslinker

The influences of varying the dosage of crosslinker at a constant volume of liquid marbles on the sustained-release properties are shown in Fig. 4. It can be seen from figure, with the increase of the amount of crosslinker, the concentration of dye release shows a downward trend. The reason is that the inside of liquid marbles is a hydrogel system. As the amount of crosslinker increased, the cross density of the molecular chain increased. Only less water molecules diffused to the highly cross-linked network, resulting in a decreasing swelling capacity, which affected the diffusion of dyes and slowed down the sustained-release[26].

The influence of temperature

The influence of varying the temperature at a constant volume of liquid marbles on the sustained-release properties of eosin Y is shown in Fig. 5. It can be seen from the figure, the sustained-release property of dye is increased with the increase of temperature. The diffusion coefficient plays an important role in the dye release. With the increase of temperature, the diffusion coefficient and the velocity with which the small molecules diffuses outward in the hydrogel are increase, which accelerates the release rate of eosin Y, and then affects the sustained-release performance.

The influence of sodium bicarbonate

The influence of adding sodium bicarbonate on the sustained-release properties of eosin Y is shown in Fig. 6. It can be seen from the figure that the sustained-release performance with the addition of sodium bicarbonate is improved to some extent. The amide group of the polyacrylamide is hydrolyzed to generate carboxylic acid groups. When H^+ was replaced from Na^+ in the system, the ionization degree of carboxyl group in the gel network was increased and the swelling degree of polyacrylamide increased. At the same time, the alkalinity of sodium bicarbonate solution is weak, which will promote the dissociation of carboxylic groups and affect the swelling property[27].

The influence of adhesive powder

The part of the liquid marbles surface hydrophobic silica brush and unbrushed powder was compared and

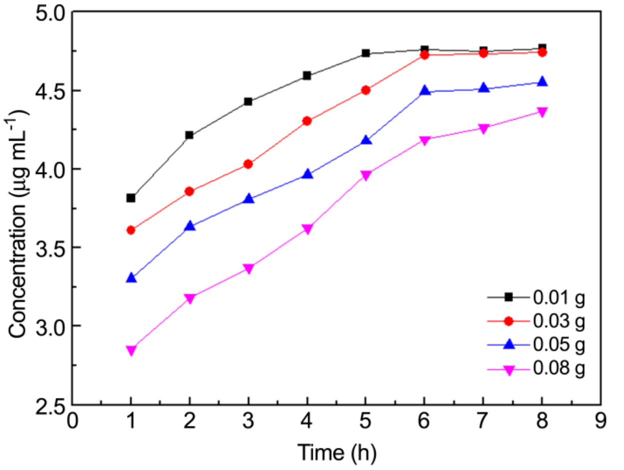

Fig. 4 — Variation of the concentration of eosin Y dye released from 50 μL liquid marbles with dosage of crosslinker.

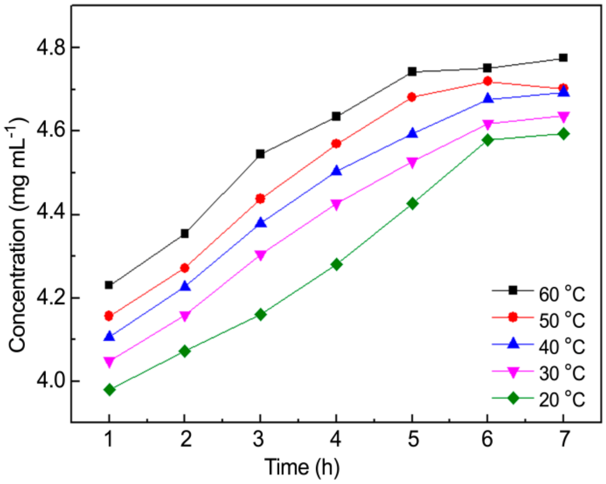

Fig. 5 — Variation of the concentration of eosin Y dye released from 50 μL liquid marbles with temperature.

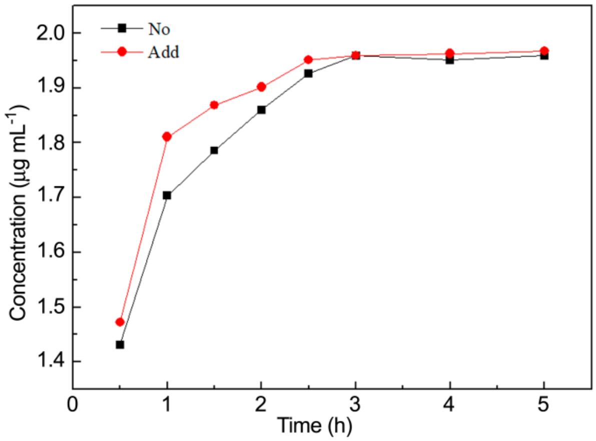

Fig. 6 — Variation of the concentration of eosin Y dye released with adding sodium bicarbonate.

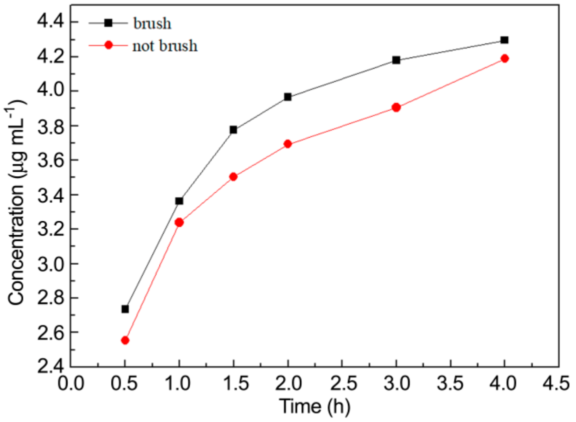

Fig. 7 — Variation of the concentration of eosin Y dye released with adhesive powder.

the results shown in Fig. 7. It can be seen from the figure that the dye sustained release performance of brushing powder is better than the not brush. The surface of liquid marbles is coated with 90% hydrophobic silica[28], the hydrophobic particles may hindered in the release of dye. Brushing will reduce the adhesion of hydrophobic silica concentration on the surface of liquid marbles. With the decrease of surface hydrophobic silica concentration, the barrier of eosin Y diffusion inside the hydrogel decreases, which accelerate the release rate of eosin Y and improves the sustained-release performance.

Conclusions

Liquid marbles with polyacrylamide as skeleton, eosin Y as core and hydrophobic silica as shell were prepared to study the sustained release of eosin Y. The results show that as the increase of volume, the amount of eosin Y loaded on liquid marbles increases, and the amount of eosin Y released out of the system also increases. Compare with the sustained-release rate, the volume increases and the sustained-release rate decreases, which is related to the volume of liquid marbles. In different sustained-release media, eosin Y was almost not released influence occurs in acid solution, and the concentration of eosin Y released out increased with the increase of pH. With increase the amount of crosslinking agent, the concentration of eosin Y released out decreases, which is related to the crosslinking density of the system. The bigger the crosslinking agent is, the greater the crosslinking density of the system is, and only a small amount of water molecules can enter the liquid marbles, thus affecting the sustained release performance. The sustained-release properties of eosin Y improved with the increase of temperature. Adding a small amount of sodium bicarbonate can improve the release performance of eosin Y. Compared with the effect of adhesive powder, it is found that the amount of eosin Y release from the brush powder of liquid marbles is faster than that without brush the powder. Preparation of sustained-release dyes by liquid marbles provides a new controlled release method for dyes.

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