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Preparation of macroporous methacrylate monolithic material with convective flow properties for bioseparation: Investigating the kinetics of pore formation and hydrodynamic performance

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ABSTRACT

The preparation of macroporous methacrylate monolithic material with controlled pore structures can be carried out in an unstirred mould through careful and precise control of the polymerisation kinetics and parameters. Contemporary synthesis conditions of methacrylate monolithic polymers are based on existing polymerisation schemes without an in-depth understanding of the dynamics of pore structure and formation. This leads to poor performance in polymer usage thereby affecting final product recovery and purity, retention time, productivity and process economics. The unique porosity of methacrylate monolithic polymer which propels its usage in many industrial applications can be controlled easily during its preparation. Control of the kinetics of the overall process through changes in reaction time, temperature and overall composition such as cross-linker and initiator contents allow the fine tuning of the macroporous structure and provide an understanding of the mechanism of pore formation within the unstirred mould. The significant effect of temperature of the reaction kinetics serves as an effectual means to control and optimise the pore structure and allows the preparation of polymers with different pore size distributions from the same composition of the polymerisation mixture. Increasing the concentration of the cross-linking monomer affects the composition of the final monoliths and also decreases the average pore size as a result of pre-mature formation of highly cross-linked globules with a reduced propensity to coalesce. The choice and concentration of porogen solvent is also imperative. Different porogens and porogen mixtures present different pore structure output. Example, larger pores are obtained in a poor solvent due to early phase separation.

1. Introduction

Advances in the development of commercially viable techniques in bioseparation has birthed the option of employing continuous monolithic supports which are widely acknowledged to offer faster and better hydrodynamics and scalable feasibilities than the orthodox beaded or particle-oriented sorbents. The reason for this is ascribed to the presence of larger pores in monolithic sorbents which offer a convective transport system rather than the diffusion-based transport associated with particulate supports. It has been shown that polymer beads and monoliths prepared using the similar monomer mixture, porogen, initiator and temperature have vastly different pore structures [1,2]. The monoliths contained large pores that allowed liquid to flow through at a lower applied pressure. The process used to synthesize the monoliths and the beads differ only in the lack of interfacial tension between an aqueous and an organic phase and the absence of mechanical forces resulting from stirring in the case of the polymerisation in an unstirred mould. The kinetics of the overall process within the unstirred mould is one of the most critical variables that contributes to the formation of large pores and allows the control of the macroporous structure [2].

A typical polymer make-up commonly employed for biomolecule purification is the methacrylate resin which is an organic polymer with flexible surface and pore characteristics modification through precise alteration in synthesis conditions. Methacrylate monolithic polymer is synthesized via a free radical polymerisation process in an unstirred mould, thus resulting in a shape that conforms to that of the mould as well as a porous structure which allows direct flow of a liquid through it. The unimpeded flow fashion of the monolithic medium, as oppose to the flow around a classical bead has offered new opportunities in bioseparation targeting different biomolecules with distinct hydrodynamic sizes and nature. It is therefore imperative to control accurately the porous structure of the monoliths. The size distribution of the pores within the porous polymer may cover a wide

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range up to the second order of magnitude. Pores with a size of less than 2 nm are classified as micropores, pores ranging from 2 nm to 50 nm are mesopores, while pores over 50 nm are macropores. The larger the pores, the smaller the surface area. Therefore, porous polymers with very large pores sizes have relatively low specific surface areas [3]. The morphology of methacrylate polymers is rather complex. They consist of interconnected globules that are partly aggregated. The pores in the polymer actually consist of the irregular voids existing between clusters of the globules or between the globules of a given cluster or even within the globules themselves [4,5]. The pore size distribution reflects the internal organisation of both the globules and their clusters within the polymer and mainly depends on the composition of the polymerisation mixture and the reaction conditions. The most effective variables that control pore size distribution are the concentration of cross-linker, type and concentration of porogen, the concentration of initiator and the polymerisation temperature [3]. This work presents a detailed and resourceful experimental data that investigates and explains fundamentally the kinetics of pore structure formation of methacrylate monolithic materials and provides a platform to predict sufficiently the pore structure system of methacrylate monoliths based on polymerisation conditions and parameters. It encompasses the development of an optimum resource polymerisation “handbook” for poly(glycidyl methacrylate-*co*-ethylene glycol dimethacrylate) resin where the effects of porogen concentration, monomer ratio, initiator concentration and temperature are considered. The influences of a solid porogen and the use of a biporogen system are also investigated and discussed.

2. Experimental

2.1. Materials

Ethylene glycol dimethacrylate (MW 198.22, 98%), glycidyl methacrylate (MW 142.15, 97%), cyclohexanol (MW 100.16, 99%), 1-dodecanol (MW 186.33, 98%), azobisisobutyronitrile (MW 164.21, 98%), methanol (HPLC grade, MW 32.04, 99.93%), HCl (MW 36.46, 99.99%) and Na_2CO_3 (MW 105.99, 99.5%) were purchased from Sigma–Aldrich.

2.2. Methods

2.2.1. Synthesis of methacrylate polymer resin

Methacrylate monolith was prepared by free radical co-polymerisation of ethylene glycol dimethacrylate (EDMA) and glycidyl methacrylate (GMA). Monolith synthesis was performed using P_1:P_2 (%, v/v) GMA as the functional monomer and EDMA as the cross-linker respectively. This solution was combined with alcohol-based porogen solvent or mixture in the ratio P_3:P_4 (%, v/v) making a solution with total volume V mL. AIBN (P_5 wt% with respect to monomer) was used to initiate polymerisation. The polymer mixture was sonicated for 10 min and sparged with N_2 gas to expel dissolved O_2 gas. The top end was sealed with a rubber bung and placed in a water bath for 20 h at T (°C). The polymer was washed to remove all porogen(s) and other soluble matters with methanol in a soxhlet extractor for 24 h and dried in an oven at 70 °C for characterisation (MEMMERT, Model 400, Germany).

2.2.2. Characterisation of polymer resin

The porous properties of the polymer in the dry state were studied by mercury intrusion porosimetry, using a micrometrics mercury intrusion porosimeter (Autopore III, USA). The specific surface areas were calculated from nitrogen adsorption/desorption isotherms at 77 K, obtained with a Micromeritics ASAP 2020 instrument, USA. A piece of the monolith was placed on a sticky carbon foil that was attached to standard aluminium specimen stub. The carbon foil was used to increase the conductivity of the sample. The sample was vapour deposited with gold using a sputter coater (Dynavac, model SC 150, Australia) and microscopic analysis was carried out using JEOL JSM-6300F high-resolution field emission scanning electron microscope, Japan at 15 kV.

2.2.3. Hydrodynamic measurements

BIORAD polypropylene column 120 mm × 15 mm containing V mL of poly(GMA-*co*-EDMA) monolithic resin was connected with a movable adaptor and configured to BIORAD HPLC system. Chromatographic and hydrodynamic measurements were carried out using distilled water as mobile phase.

3. Results and discussion

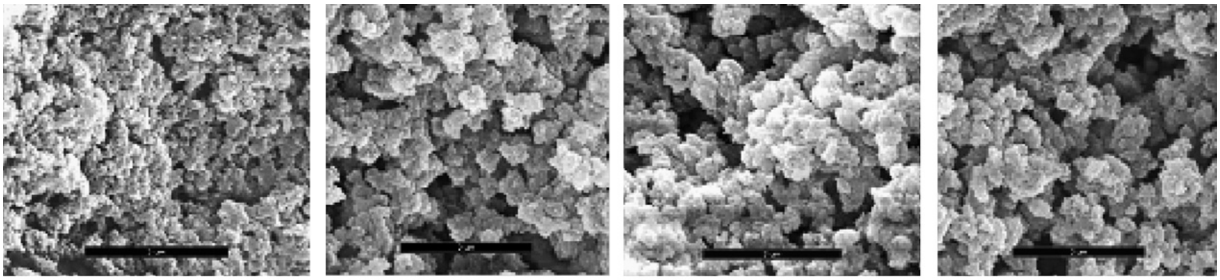
3.1. Effect of porogen content on polymer characteristics

The composition and concentration of the porogen, in this case cyclohexanol had a great effect on the properties of the polymer, especially on the pore size distribution within the polymer matrix. The existence of the porogen in the polymerisation mixture partly dictated the unique permeability and homogeneity of the pore structure as the creation of pore properties of the polymer is dependent on the physicochemical characteristics of the porogen by virtue of its dynamic molecules and inter-molecular rearrangement leading to phase separation of cross-linked nuclei. Phase separation of cross-linked nuclei is a prerequisite for the formation of the polymer morphology. The polymer phase separates from the solution during polymerisation because of its sparingly solubility in the polymerisation mixture that results from a molecular weight that exceeds the solubility limit of the polymer in the given solvent system or from insolubility associated with cross-linking. According to Table 1, increasing the amount (%, v/v) of porogen from 40% to 80% resulted in an increase in pore size from 116 nm to 876 nm with a final porosity of 87%. SEM pictures of the monoliths are shown in Fig. 1. As expected, the total surface area of the polymer decreased with increasing porogen content to a minimum of 2.3 m^2/g. In general, the more the cyclohexanol content in the polymerisation mixture, the higher the permeability and the lower the total surface area of poly(GMA-*co*-EDMA) monolithic

Table 1
Effect of cyclohexanol (porogen) concentration in the polymerisation mixture on the pore and surface characteristics of methacrylate monolith

Porogen concentration (%, v/v)	Total intrusion volume (mL/g)	Modal pore diameter (nm)	Porosity (%)	BET surface area (m^2/g)
40	0.62 ± 0.09	115.7 ± 5.9	35.5 ± 1.5	26.2 ± 0.6
50	0.79 ± 0.07	235.6 ± 4.5	46.9 ± 1.3	22.4 ± 0.5
60	0.93 ± 0.06	346.5 ± 7.2	65.2 ± 0.9	11.8 ± 0.7
70	1.33 ± 0.08	532.6 ± 6.1	79.3 ± 1.4	7.1 ± 0.8
80	1.43 ± 0.05	875.6 ± 3.4	87.4 ± 1.2	2.3 ± 0.6

Polymerisations were carried out with a constant monomer ratio (EDMA/GMA) of 40/60 (%, v/v); polymerisation temperature of 60 °C; AIBN concentration of 1% (w/w) of monomers (n = 3).



40 % POR 60 % POR 70 % POR 80 % POR

Fig. 1. Effect of cyclohexanol (porogen) concentration in the polymerisation mixture on the surface morphology of methacrylate monolith. Polymerisations were carried out with a constant monomer ratio (EDMA/GMA) of 40/60; porogen concentrations of 40%, 60%, 70% and 80%; polymerisation temperature of 60 °C; AIBN concentration of 1% (w/w) of monomers. The SEM pictures show increasing pores size with increasing concentration of porogen in the polymerised feedstock. Microscopic analysis was performed at 15 kV. POR: porogen.

polymers. The mechanical strength of the polymer was also found to decrease with increasing porogen quantity.

3.2. *Effect of binary porogen system on polymer characteristics*

Addition of a co-porogen to the polymerisation mixture was found to influence the pore size distribution of the polymer matrix. Result from Fig. 2 shows that, the effect of altering 1-dodecnol concentration was found to be very significant especially within the polymerisation temperature range of 70–80 °C. However, the effect of 1-dodecanol is virtually insignificant for polymerisation performed at 55 °C since the polymerisation or nucleation rate at this temperature is so slow that the pore size is always large. A gradual removal of 1-dodecanol from 50% to 10% of the total porogen content results in the decrease of pore size from 2824 nm to 395 nm at 65 °C. 1-Dodoecanol is a poor solvent and as such presents no competition towards nucleation and precipitation in the polymerisation mixture. The addition of a poor solvent results in an earlier phase separation of the polymer. The resulting new phase swells with the monomers because it is thermodynamically a much better solvent for the polymer than the porogenic solvent. As a result of this preferential swelling, the concentration of monomers in the swollen gel nuclei is higher than that in the solution; hence the polymerisation reaction proceeds mainly in these swollen nuclei. Newly formed nuclei are adsorbed by the large preglobules formed earlier by coalescence of many nuclei and further increase their size. Overall, the globules that are formed in such a system are larger and consequently the voids between them are larger as well. The effect of adding a good solvent to move the distribution toward smaller pore sizes can be readily explained by considering that phase separation occurs in the later stages of polymerisation. In this case the cross-linking agent dominates the phase-separation process. As the pore-forming solvent quality improves, it competes with the monomers in the formation of nuclei; thereby reducing the local monomer concentration and this decreases the size of the globules.

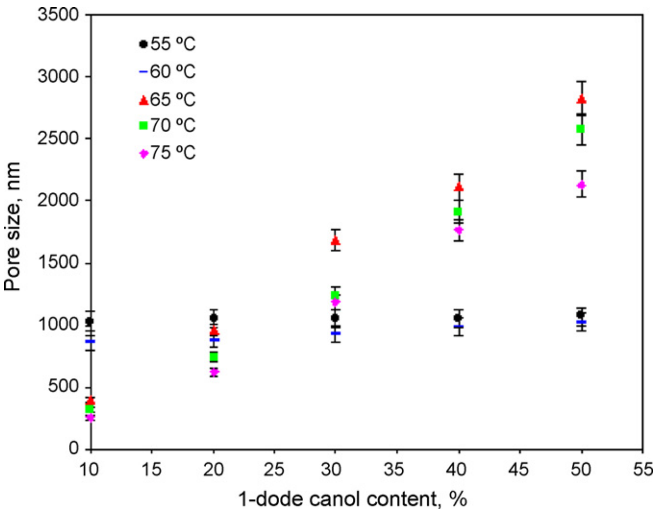


Fig. 2. Dependency of average pore size on the presence of 1-dodecanol as a co-porogen for polymers synthesised at different temperatures. Polymerisations were carried out with a constant monomer ratio (EDMA/GMA) of 40/60; polymerisation temperatures of 55 °C, 60 °C, 65 °C, 70 °C, 75 °C AIBN concentration of 1% (w/w) of monomers.

3.3. *Effect of solid porogen on the pore characteristics of the polymer*

The fundamental reaction of a carbonate and a dilute acid which results in the formation of carbon dioxide was expedited as a technique to increase the pore size of poly(GMA-*co*-EDMA) resin. The effect of the solid porogen, in this case a carbonate (used as a porosigen) was found to affect tremendously the pore properties of the polymer matrix. According to Fig. 3, the average pore size of different methacrylate monolithic resins was increased after the addition of a carbonate as a solid porogen. Gradual increase in the concentration of carbonate in the polymerisation mixture corresponded with increasing pore size at different temperature (Fig. 4). The removal of the added carbonate after the polymerisation was achieved by pumping and washing the resin severally with dilute hydrochloric

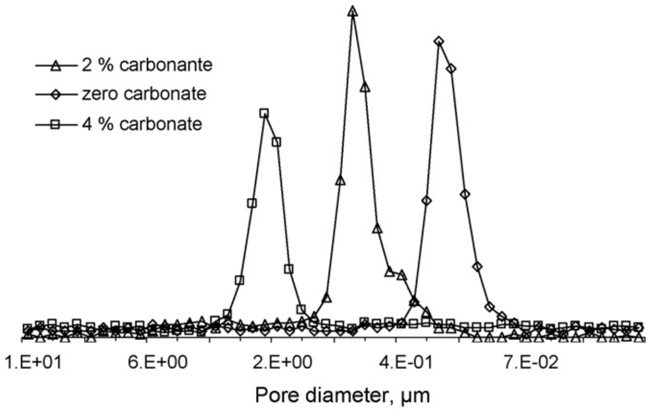


Fig. 3. Dependency of pore size distribution on the presence of a carbonate as a solid porogen. Polymerisations were carried out with a constant monomer ratio (EDMA/GMA) of 40/60; polymerisation temperature of 60 °C; AIBN concentration of 1% (w/w) of monomers; carbonate concentrations of 0%, 2% and 4%.

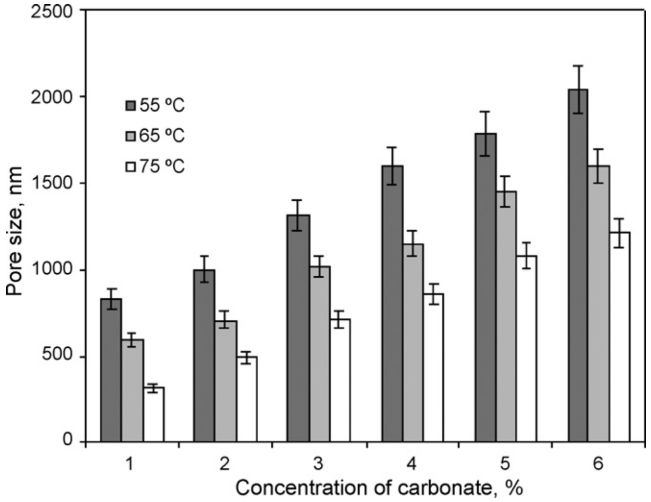


Fig. 4. The effect of the presence of a carbonate as solid porogen on the average pore size of poly(EDMA-*co*-GMA) monolith for different polymerisation temperature. Polymerisations were carried out with a constant monomer ratio (EDMA/GMA) of 40/60; polymerisation temperatures of 55 °C, 65 °C, 75 °C; AIBN concentration of 1% (w/w) of monomers.

acid which resulted in the occurrence of effervescence leading to the evolution of carbon dioxide gas. This washing step is halted until effervescence ceases which is an indication of total removal carbonate. The escape of embedded carbonate as carbon dioxide from the polymer matrix results in the creation of extra pores or pore enlargement right from inter-globule to inter-cluster level. Incorporation of large quantities of the carbonate results in large pore sizes but puts extra stress on the polymer washing step.

3.4. *Dependency of pore and surface properties of the monolith on EDMA/GMA ratio*

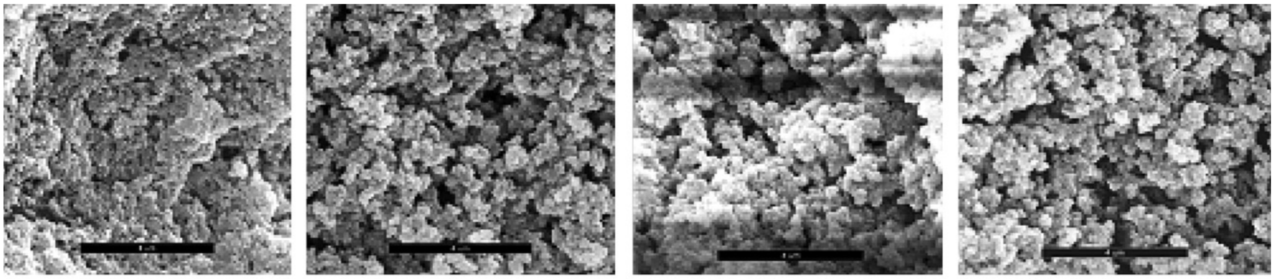
The monomer ratio was found to affect strongly the permeability, surface area and mechanical strength of poly(GMA-*co*-EDMA) monolith as well as its composition. Changes in EDMA/GMA ratio were achieved by varying proportionally the amount of EDMA in the polymerisation mixture. As obtained according to Table 2, the presence of more EDMA in the polymerisation mixture decreases the pore size of the resulting polymer, hence decreasing permeability and pore volume. EDMA is the cross-linking monomer and as a result propagates and forms extensive polymer networks via the formation of covalent bonds linking the different polymer chains to achieve properties, such as higher tensile strength, impact modification and large surface area. Although variables such as temperature and porogenic system affect the polymer porosity without changes in composition, the concentration of the cross-linking agent affects the porous properties and composition of polymer network. This behaviour is due to the fact that an increase in the EDMA concentration leads to the formation of more cross-linked nuclei. The higher cross-linking density of the nuclei limits their swelling so monomer diffusion into the nuclei and the real coalescence of formed nuclei in the later stage of the reaction do not occur. Therefore the micro-globule formed is small and consequently the voids between them are smaller as shown in Fig. 5.

3.5. *Effect of polymerisation temperature on the pore characteristics of the polymer*

Table 3 and Fig. 6 illustrate the effect of temperature on the pore size of poly(GMA-*co*-EDMA) monolith. The higher the polymerisation temperature, the smaller the pore size. This can be explained in terms of the initiator decomposition rate because at a higher reaction temperature, more free radicals are generated per unit time and these overwhelm the remaining monomers in the polymerisation feedstock so more nuclei and micro-globules are formed. Since the monomer concentration is the same for each polymerisation reaction, the formation of a larger number of nuclei and micro-globules at high temperatures is balanced by a decrease in their size. As a result, smaller pore sizes exist between them. The shift in pore size distribution induced by changes in the polymerisation temperature can be accounted for by the difference in the number of nuclei that result from such changes. Therefore, temperature constitutes an essential tool for obtaining poly(GMA-*co*-EDMA) monoliths with different pore sizes from the same composition of feedstock.

3.6. *Dependency of the pore structure of the polymer on initiator concentration*

A thermal free radical initiator is moderately stable at room temperature but decomposes rapidly enough at the polymerisation temperature to ensure an appreciable reaction rate. Apart from temperature, the decomposition rate of a free radical initiator depends on the porogen solvent and/or monomers used. The confining effect of the porogen molecules causes unwanted reactions including recombination of radicals to regenerate the initiator. The confining effect becomes more significant as viscosity increases [6]. The decomposition of 1% (w/v) AIBN (Fig. 7) in 5 mL cyclohexanol at a maximum set temperature of 100 °C was studied. Mass loss due to AIBN decomposition was determined as the difference between the mass of AIBN/cyclohexanol mixture and only cyclohexanol at different time intervals. The results show that the decomposition of AIBN in the cyclohexanol commenced at a temperature of 40–50 °C



70 % CRSL 60 % CRSL 50 % CRSL 40 % CRSL

Fig. 5. Effect of the ratio of monomers (EDMA/GMA) in the polymerisation mixture on the pore and surface morphology of methacrylate monolith. Polymerisations were carried out with monomer ratios of 70/30, 60/40, 50/50 and 40/60; polymerisation temperature of 55 °C; AIBN concentration of 1% (w/w) of monomers; porogen concentration of 70% (v/v) feedstock. The SEM pictures show increasing pores size with decreasing monomer ratio in the polymerised feedstock. Microscopic analysis was performed at 15 kV. CRSL: cross-linker.

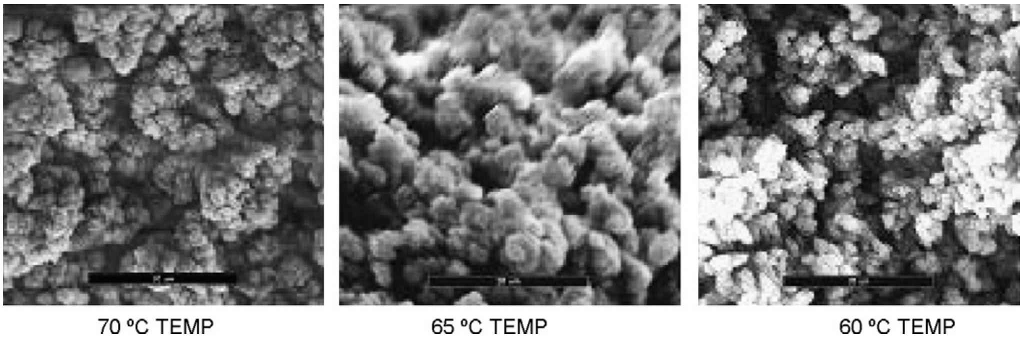


Fig. 6. Effect of polymerisation temperature on the pore and surface morphology of methacrylate monolith. Polymerisations were carried out with monomer ratio of 40/60; polymerisation temperatures of 60 °C, 65 °C, 70 °C; AIBN concentration of 1% (w/w) of monomers; porogen concentration of 75% (v/v) feedstock. The SEM pictures show increasing pores size with decreasing polymerisation temperature. Microscopic analysis was performed at 15 kV.

due to the sharp decrease in the concentration of AIBN resulting from mass loss by the evolution of N_2 gas according to Fig. 8. The corresponding sharp increase in temperature confirms this observation as the decomposition of AIBN is an exothermic reaction, thereby increasing the overall system temperature. Increasing the concentration of AIBN in the polymerisation mixture was also studied according to Fig. 9. It was observed that increasing initiator concentration increases the rate of polymerisation which results in late phase separation; a phenomenon which leads to small-size nuclei and hence globules formation resulting in decrease in pore size. Increasing initiator content from 0.5% (w/w of monomers) to 1.5% (w/w of monomers) results in the decrease in pore size from 980 nm to 410 nm.

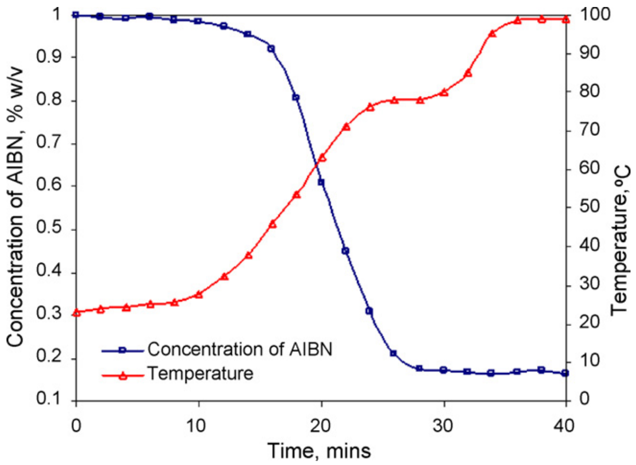


Fig. 7. Decomposition of 1% (w/v) of AIBN in cyclohexanol at a maximum set temperature of 100 °C. Data show AIBN decomposition temperature of 40–50 °C with a corresponding decrease in the concentration of AIBN owing to the evolution of N_2 gas.

3.7. *Flow rate and pressure drop analysis*

An ideal stationary phase for the purification of biomolecules either on semi-preparative or preparative scale of separation must allow the use of variable flow rates under tolerable pressure drops. Since the designed methacrylate monolithic resin is intended as such, especially high flow rates are expected to be used. To examine its suitability, different volumes of the methacrylate resin with average pore size 570 nm were analysed in a polypropylene column with diameter 15 mm. The volume of the resin in the column was varied simply by adding known volume discs of the methacrylate

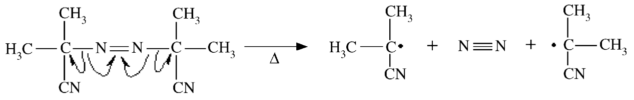


Fig. 8. Reaction scheme for the decomposition of azobisisobutyronitrile (AIBN). Reaction shows the formations of free radicals with the evolution of N_2 gas.

Table 2
Effect of the ratio of monomers (EDMA/GMA) in the polymerisation mixture on the pore and surface characteristics of methacrylate monolith

EDMA/GMA (%, v/v)	Total intrusion volume (mL/g)	Modal pore diameter (nm)	Porosity (%)	BET surface area (m^2/g)
30/70	1.41 ± 0.08	1072.7 ± 8.2	93.4 ± 1.3	1.2 ± 0.8
40/60	1.05 ± 0.06	825.5 ± 5.6	85.1 ± 1.5	5.3 ± 0.6
50/50	0.86 ± 0.05	652.1 ± 7.5	66.3 ± 1.2	10.4 ± 0.8
60/40	0.69 ± 0.04	426.8 ± 4.8	59.2 ± 1.6	16.3 ± 0.5
70/30	0.42 ± 0.07	312.7 ± 6.4	41.2 ± 1.7	21.6 ± 0.7

Polymerisations were carried out with monomer ratios of 30/70, 40/60, 50/50, 60/40 and 70/30 (%, v/v); polymerisation temperature of 55 °C; AIBN concentration of 1% (w/w) of monomers; porogen concentration of 70% (v/v) feedstock (n = 3).

Table 3
Effect of polymerisation temperature on the pore and surface characteristics of methacrylate monolith

Temperature (°C)	Total intrusion volume (mL/g)	Modal pore diameter (nm)	Porosity (%)	BET surface area (m^2/g)
55	0.98 ± 0.05	828.7 ± 6.3	75.3 ± 1.8	7.3 ± 0.8
60	0.72 ± 0.07	702.3 ± 4.5	66.4 ± 1.4	13.4 ± 0.6
65	0.64 ± 0.06	593.1 ± 7.7	52.3 ± 1.6	18.2 ± 0.7
70	0.56 ± 0.04	416.2 ± 3.2	45.6 ± 1.2	23.9 ± 0.5

Polymerisations were carried out with monomer ratio of 40/60 (%, v/v); polymerisation temperatures of 55 °C, 60 °C, 65 °C, 70 °C; AIBN concentration of 1% (w/w) of monomers; porogen concentration of 75% (v/v) feedstock (n = 3).

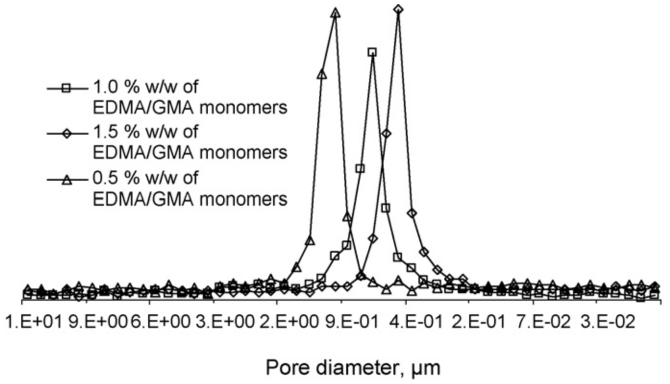


Fig. 9. Dependency of pore size distribution on AIBN concentration. Polymerisations were carried out with monomer ratio of 40/60; polymerisation temperature of 60 °C; AIBN concentration of 0.5% (w/w), 1.0% (w/w) and 1.5% (w/w) of monomers; porogen concentration of 75% (v/v) feedstock.

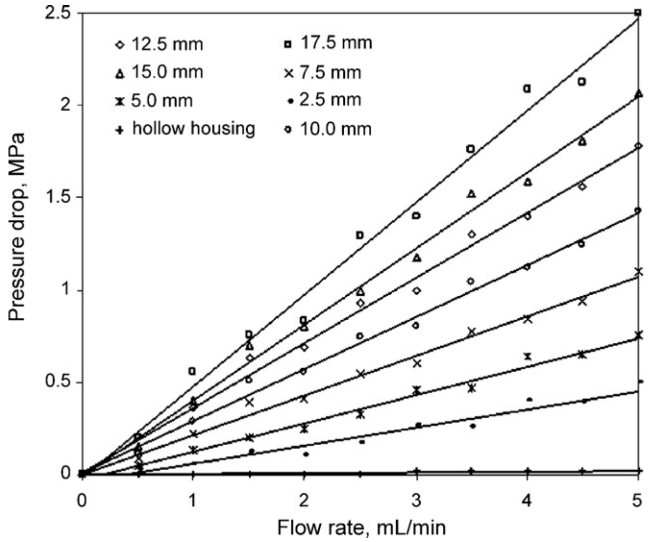


Fig. 10. The dependence of the measured pressure drop on flow rate and length (volume at constant diameter) of the monolithic layer having an average pore diameter of 570 nm. Pressure drop increases with increasing flow rate and increasing length of the monolithic layer.

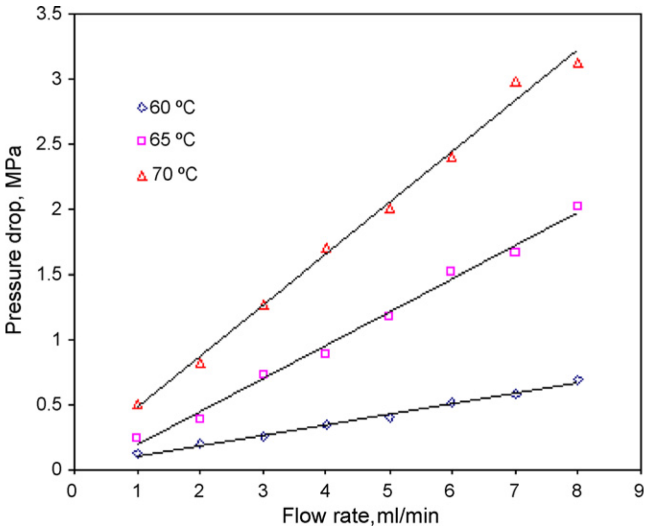


Fig. 11. Dependency of measured pressure drop on flow rate for different monoliths polymerised at different temperatures 60 °C, 65 °C and 70 °C. Polymerisations were carried out with monomer ratio of 40/60; AIBN concentration of 1.0% (w/w) of monomers; porogen concentration of 65% (v/v) feedstock. Generally, an increase in pressure drop was observed with increasing polymerisation temperature.

monolith into the polypropylene housing. Generally, a linear relationship was observed between the pressure drop and the flow rate for the different volumes of methacrylate resin as shown in Fig. 10 and this depicts that the porous structure of the resin is stable and does not contract at higher flow rates. However, the pressure drop was found to increase with increasing volume of the methacrylate resin due to the increase in length of travel and this is in agreement with Hagen-Poisseuille equation under laminar conditions. A maximum pressure of 2.5 MPa was recorded at a flow rate of 5 mL/min for 17 mm length of column which is generally on the low side. The possibility to run the monolithic column at high flow rates under low pressure drops indicates that separation and purification of biomolecules can be achieved within a very short time.

Resistance to flow is a vital issue in chromatographic separation as the pressure needed to drive the liquid through the monolithic resin should be as low as possible. This can be achieved by employing material with a high percentage of large pores. However, binding of biomolecules to the stationary phase also requires a large surface area and therefore a balance must be set between the requirements of low flow resistance and high surface area. This compromise can easily be drawn by knowing the hydrodynamic dimension and the nature of the target molecule and tailoring the structural characteristics of the methacrylate monolithic resin using the parameters outlined earlier to suit its binding, retention, elution and general flow dynamics. Fig. 11 demonstrates the effect of flow rate through cylindrical rods of methacrylate monolith synthesized under different temperature conditions. A general trend in pressure drop increase was observed with increasing flow rate and temperature since increasing polymerisation temperature was found to decrease the pore size of the methacrylate resin.

3.8. Preparation of large methacrylate monoliths; bottlenecks and technological way-forwards

Methacrylate-based monoliths synthesized from the polymerisation of ethylene glycol dimethacrylate and glycidyl methacrylate in the presence of a porogen and an initiator were introduced a decade ago. Many papers have described the numerous applications of methacrylate monoliths but most of them are on the analytical scale. Only a few have really considered the scale-up of methacrylate monoliths for large-scale applications [7,8]. The synthesis of large-volume homogeneous methacrylate monolithic polymer is a very difficult process mainly because of the large amount of exothermic heat associated with the polymerisation process causing pronounced temperature non-homogeneity that significantly affects the structure [9]. Polymerisation temperature control and heat transfer mechanisms within the monolith are key parameters required for the preparation of large monoliths with reproducible and homogenous pore and surface structure. In order to control the temperature, usually polymerisation is performed in a thermostated water bath with a uniform temperature distribution. However, the polymerisation is highly exothermic and therefore the occurrence of significant temperature gradients in large moulds is unavoidable. This is the main reason for non-uniform structure of large monolithic support. The possibilities of controlling the temperature differences inside large moulds are very limited during polymerisation and therefore the temperature gradient is determined by experimental conditions, mould dimension and geometry. Peters et al. [9] proposed that during the preparation of large-volume monoliths, gradual addition of the feedstock could control the polymerisation rates so as to decrease the temperature gradient in the system. This method only minimizes the extent of the reaction exotherm, but it does not improve the heat transfer in the reaction system. This could possibly result in a monolith with pore structure gradient in the radial direction. Podgornik et al. [10] prepared several annular monoliths with different outer diameters and then embed one into another. By this technique, the reactant mixture in a single preparation is reduced and consequently the temperature distribution is effectively controlled. Nevertheless, it can be quite complicated to prepare large volume monoliths because there is a high probability of damaging the pieces during the embedding process. There is also the likelihood occurrence of large nesting dead volumes in the final resin. For a successful synthesis of large columns, experimental conditions have to be optimally selected with minimum exothermicity. In order to accomplish this, detailed understanding of the kinetics of the polymer formation and heat transfer mechanism is essential. To ensure the desired performance of monoliths, it is essential to remove the heat so that the temperature distributes uniformly in the preparation of monoliths.

4. Conclusion

Experimental results obtained for polymerisation of the monomers glycidyl methacrylate-ethylene dimethacrylate show that it is possible to control accurately the porous properties of moulded macroporous materials within a very broad range. This is achieved by changing the reaction temperature, the composition of pore-forming solvent, or the content of monomers in the polymerisation mixture and the concentration of initiator. The polymerisation temperature is the most convenient variable to adjust the pore size distribution because it does not require any change in the composition of the reaction mixture. Increasing the concentration of a poor solvent such as 1-dodecanol in a biporogen system leads to the formation of polymers with larger pore sizes. An increase in the content of cross-linking monomer results in a decrease in pore size. All of these variables represent very important tools for the optimisation of methacrylate materials that contain large pores and are therefore easily permeable. Consideration of methacrylate scale-up options shows possibility though detailed understanding of heat transferred mechanisms with in the unstirred mould and extensive temperature control is necessary to circumvent the pore structure heterogeneity caused by outstanding temperature gradient in large monoliths.

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