Kinetics of removing chromium complex dye from acidic aqueous solutions employing anion exchange resins

Danutė Kaušpėdienė*,

Eglė Kazlauskienė,

Aušra Selskienė,

Audronė Gefenienė

Institute of Chemistry of Center for Physical Sciences and Technology, A. Goštauto 9, LT-01108 Vilnius, Lithuania The kinetics of removing the chromium complex dye Lanasyn Navy M-DNL from model solutions, using the acrylic matrix gel type weak base anion exchanger Purolite A 845 and a polystyrene matrix, the macroporous type I strong base anion exchanger Purolite A 500P has been investigated in batch experiments with respect to solution concentration and temperature. The kinetics studies, combined with optical microscopy, were conducted to reveal the relation between the physical-chemical characteristics of the anion exchangers and their performance in the removal of the chromium complex dye. The chromium complex dye sorption mechanism onto both anion exchangers investigated consists of ion exchange, physical sorption and diffusion. Kinetic parameters such as the external mass transfer coefficient k_{i} , intraparticle diffusion coefficient k_{i} and the rate constants of chemical sorption k_2 for the dye – Purolite A 845 and dye – Purolite A 500P systems were studied using the Weber and Morris intraparticle diffusion model equations and the pseudo-second-order kinetic equation, respectively. The activation energies such as external mass transfer $E_{a,k,r}$ intraparticle diffusion E_{a-ki} and chemical sorption E_{a-k2} for dye–anion exchanger systems were calculated using the Arrhenius relationship. The intraparticle diffusion activation energy E_{a-ki} for the dye – Purolite A 845 system was 4.7-fold lower that for the dye – Purolite A 500P system, resulting in a deeper diffusion of the dye in the bead of the gel type weak base anion exchanger.

Key words: anion exchanger, chromium complex dye, sorption, kinetics, diffusion

INTRODUCTION

Adsorption is considered to be one of the most effective methods for removal of dyes and a proven technology that has applications for water reuse in industry. Its superiority over other techniques can be assessed in terms of initial costs, the flexibility and simplicity of design, ease of operation, intensity to toxic pollutants, and the advantage of not leading to harmful products [1]. Adsorption using ion exchangers is a common method for the removal of dyes from wastewaters. Its main advantages are the ion exchangers not being lost during regeneration, the recovery of water after use, and the removal of soluble dye. The removal of acid and reactive dyes using different anion exchangers (strong and weak basic) and a complete regeneration of anion exchangers saturated with the above dyes without loss of capacity using NaOH solutions or alkaline–methanol–water mixtures was described in [2–8].

The nature of sorption depends on both physical-chemical characteristics of the anion exchanger and on the conditions in the dye–anion exchanger system. Chemical kinetics explains the rate of chemical reactions, whereas mass transfer as a diffusion process for reaching sorption equilibrium is related to the processes such as chemisorption, physisorption, ion exchange, or complexation [9]. These processes can affect sorption kinetics as profoundly as they affect the equilibrium. Therefore, data concerning the rate of chemical reaction as well as mass transfer are required for the modelling of an ion exchange system from laboratory to practice, from calculating the necessary amount of ion exchanger to the time required for the taking-up processes.

The kinetics of organic compounds sorption onto natural sorbents and synthetic polymers has been described as a complex process in which the properties of the adsorbent and

^{*} Corresponding author: dana@ktl.mii.lt.

solutes play a crucial role [9–12]. All the design tools developed have been based on simple models, using the chemical interpretation of the adsorptive process; design equations are based on reaction rate constants [10]. A number of mechanisms are suggested to control the sorption rate of the dye– adsorbent systems. These include molecular diffusion from the bulk solution to a film layer surrounding the adsorbent particle; diffusion from the film to particle surface ("film diffusion"); migration inside the adsorbent particle by "surface diffusion" or diffusion within pores filled with a liquid ("pore diffusion"); and uptake, which includes several ways of interaction such as chemisorption, physisorption, ion exchange, or complexation [10].

Because there exist a large variety of dyes and their removal is based on dye-anion exchanger interaction depending on the number and type of functional groups or the chemical and physical structures of the matrix and on the structure of the dye, the performance of the corresponding anion exchangers should be thoroughly evaluated. The kinetic studies, as well as adsorption equilibrium studies, are important for determining the effectiveness of the adsorbent and identifying the type of adsorption. There is very little information in the literature on the removal kinetics of metal complex dyes, using anion exchangers.

The aim of this study was, therefore, to investigate the removal kinetics of a chromium complex dye using the commercially available anion exchangers Purolite A 845 and Purolite A 500P. The effect of phase contact time and temperature on external mass transfer, intraparticle diffusion and on the rate of chemical reaction for the chromium complex dyeanion exchanger systems was determined in batch studies.

EXPERIMENTAL

Materials

The chromium complex dye tested was the commercial textile anionic dye Lanasyn Navy M-DNL obtained from Clariant (Switzerland). Chemically, it is a 1 : 2 chromium monoazo complex dye (trisodium bis [3-hydroxy-4 [(2-hydroxy-1-naphthyl) azo] naphthalene-1-sulphonato (3-)] chromate (3-)) with the molecular mass of 834 g/mol. The chemical structure of the dye is presented elsewhere [13].

An accurately weighed quantity of the dye (0.1 mmol/L) was dissolved in deionized water to prepare the stock solution. Experimental solutions of the desired concentrations were obtained by successive dilutions.

Two types of anion exchangers, obtained from Purolite International Ltd, were used: the gel. polyacrylic–divinylbenzene weakly basic (functional groups $HN^+(CH_3)_2$) Purolite A 845 and the macroporous, styrene-divinylbenzene, strongly basic, type I (functional groups $N^+(CH_3)_3$) Purolite A 500P. Purolite A 845 is recommended for demineralization of water high in organic matter, whereas Purolite A 500P is used as an organics scavenger from industrial and domestic water supplies. They were obtained in Cl⁻ form. Their conversion into OH⁻ form was carried out by treating the resins with 5 bed volume (*BV*) of 4% NaOH at a flow rate 4 mL/min (*BV* = volume of the treated solution / volume of resins). After rinsing with distilled water for excess alkalinity elution, the resin samples were sieved in the range of 0.315–1.000 mm.

Batch studies

The removal kinetics of chromium complex dye using Purolite A 845 and Purolite A 500P was studied in batch experiments under stirring at 300 ppm 0.5 g of anion exchanger in the OH⁻ form with 25 mL of 83.4 mg/L aqueous dye solution at different time intervals (5–360 min) at a range of temperature 293–333 K. Considering that in our previous studies the dye sorption on both anion exchangers was maximum in acidic media, the experiments were performed at pH 2. The pH value of the initial solution was adjusted to pH 2 with 1 M HCl.

At the end of the predetermined time interval, the anion exchanger was removed by centrifugation. The residual concentrations of the dye were determined using a UV-Vis Cintra 101 spectrometer (GBS Scientific Equipment (USA) LLS) at the respective λ_{max} value which is 616 nm for this dye. The dye concentration was calculated from a calibration curve. The residual colour, *Res* (%), was calculated by comparing the absorption (A) of the treated sample with the reference treated identically, but without a sorbent:

$$Res (\%) = A \text{ (sample)} \cdot 100\% / A \text{ (reference)}.$$
(1)

This was necessary because the molar extinction coefficient of the dyes changes with pH.

Residual concentrations were calculated by multiplying the residual colour by the initial concentration:

$$C = Res \cdot C_0, \tag{2}$$

where C_0 (mg/L) is the initial concentration and *C* (mg/L) is the residual concentration of the dye.

Data obtained from sorption experiments were used to calculate the sorption capacity of the anion exchanger q_t and q_e (mg/g) at the phase contact time *t* and for attaining the equilibrium time:

$$q_{t(q)} = \frac{\left(C_0 - C_{t(q)}\right)V}{m},$$
(3)

here C_0 , and C_t (or C_e) are the concentrations (mg/L) of the dye in the solution before and after sorption, respectively, V is the volume of the solution (L), and m is the mass of the dry anion exchanger (g).

The kinetics of dye sorption onto anion exchange resins was analysed using the intraparticle diffusion and pseudosecond rate models.

Optical microscopy images of the anion exchanger bead cross-section were obtained using the MBC-9 optical microscope (Russia) with the Nikon Coolpix 4 500 digital camera at \times 25 magnification.

RESULTS AND DISCUSSION

Kinetics studies

The chromium complex dye molecule (a salt consisting of a medium strong acid and a strong base) in aqueous solutions was dissolved, and the medium strong sulfonate groups of the chromium complex dye were dissociated and converted to anionic dye ions [20]:

$$\mathbf{R}^{\prime}(\mathrm{SO}_{3})_{2}\mathrm{Na}_{2} \to \mathbf{R}^{\prime}(\mathrm{SO}_{3})_{2}^{2-} + 2\mathrm{Na}^{+}.$$
(4)

The acidic medium is favorable for the dye dissociation through the neutralization of hydroxide ions released from the strong base with the hydrogen group released from HCl (R-SO₃Na \rightarrow RSO₃⁻ + Na⁺;RSO₃⁻ + H₂O \rightarrow RSO₃⁻H⁺ + OH⁻; OH⁻ + HCl \rightarrow H₂O + Cl⁻).

The sorption proceeded due to the interaction between the anionic dye $(R'(SO_3)_2^{2-})$ and the functional groups of the anion exchanger in the OH⁻ form (ROH):

$$2ROH + R'(SO_2)^{2-} + 2H^+ \Leftrightarrow R_2(SO_2)_2R' + 2H_2O.$$
(5)

The system pH changed from 2.7 to 3.2 during sorption at the initial solution pH 2. As follows from the above, the chromium complex dye forms a stable ion pair R_2 (SO₃)₂ R' in the weak base and strong base anion exchangers. Moreover, the aromatic rings (styrene, divinylbenzene) in Purolite A 500P, aromatic ring (divinylbenzene) and -C = O groups in Purolite A 845 and groups $-SO_3Na, -N = N-$, aromatic rings in the dye structure can participate in covalent, columbic, hydrogen or weak interaction of van der Waals forces [1, 14]. The amount of the sorbed dye is the summation of sorption on all sites. The adsorption of chromium complex dye on both anion exchangers follows the pseudo-second-order kinetic model, which is expressed as follows [15, 16]:

$$\frac{dq_t}{dt} = k_2 \left(q_e - q_t\right)^2,\tag{6}$$

where k_2 (g/(mg min) is the pseudo-second-order rate constant; q_t mg/g) and q_e (mg/g) is the amount of dye adsorbed at time *t* and at equilibrium, respectively. The integration of Eq. 6 and the application of the conditions $q_t = 0$ at t = 0 and $q_t = q_t$ at t = t, give

$$\frac{1}{q_e - q_t} = \frac{1}{q_e} + k_2 t.$$
(7)

The following equation can be obtained by rearranging Eq. 7 into a linear form:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t,$$
(8)

here k_2 and q_e can be calculated from the intercept and slope.

The plot of $t/q_t vs t$ shows a linear relationship for Purolite A 845 and Purolite A 500P (Fig. 1). The calculated q_e and k_2 values are given in Table 1. The correlation coefficients R^2 are high (0.9862–0.9984), confirming a good agreement with the experimental data.

The pseudo-second-order rate constants k_2 for chromium complex dye sorption on Purolite A 845 with an increase in the solution temperature from 293 K to 313 K indicate a slight decreasing trend – from 0.1113 to 0.0840 g/(mg min) – and an increase from 0.0840 to 0.1386 g/(mg min) with increasing the temperature from 313 K to 333 K. The k_2 values obtained for Purolite A 500P indicate a decrease from 0.1516



Fig. 1. Pseudo-second-order plots for chromium complex dye sorption on anion exchangers Purolite A 845 (A) and Purolite A 500P (B)

Anion ovehongov	Terrer eventure V	Pseudo-second-order rate constants		
Anion exchanger	Temperature, K	K2r g/mg min 0.1113 0.0840 0.1386 0.1516 0.1516	<i>q_{e'}</i> mg∕g	R ²
Purolite A 845	293	0.1113	1.69	0.9959
	313	0.0840	2.12	0.9950
	333	0.1386	2.27	0.9984
Purolite A 500P	293	0.1516	1.84	0.9862
	313	0.1490	2.11	0.9915
	333	0.1860	2.43	0.9933

Table 1. Pseudo-second-order rate constants and equilibrium sorption values for chromium complex dye sorption on Purolite A 845 and Purolite A 500P at various temperatures

to 0.1490 g/(mg min) with increasing the temperature from 293 K to 313 K and an increase from 0.1490 to 0.1860 g/ (mg min) with increasing the temperature from 313 K to 333 K. The equilibrium adsorption capacity q_e increases with temperature for dye adsorption both on Purolite A 845 and on Purolite A 500P (Table 1). This effect of temperature is called activated chemical adsorption. Different trend variations of the pseudo-second-order kinetic rate constant k_2 for both anion exchangers indicates that the adsorption mechanism at a higher temperature differs from that at lower temperatures.

It may be concluded that the chromium complex dye adsorption mechanism onto both anion exchangers investigated consists of ion exchange, physical sorption and diffusion. On the one hand, the sorption does not follow exclusively the physical sorption mechanism, when generally the rate of approaching the equilibrium increases with increasing the temperature, and the equilibrium adsorption capacity decreases; on the other hand, the fact that the dye sorption capacity increases with temperature indicates the presence of other processes including diffusion [17, 18]. Therefore, the influence of the diffusion process on dye removal was also considered.

Diffusion studies

Two steps appear to control the sorption rate. These are mass transfer in either the bead (intraparticle diffusion) or the liquid (film diffusion), whichever is slower [19, 20]. The pseudo-second-order kinetic model cannot identify the diffusion mechanism, and the kinetic results were analysed using the intraparticle diffusion model. Since the experiments were carried out in a rapidly stirred batch reactor, the possibility of intraparticle diffusion could not be ruled out. The initial rate of intraparticle diffusion is given by the equation [19, 21–23]

$$q_t = k_t t^{0.5} + A,$$
 (9)

where q_t is the amount of dye on the surface of the sorbent at time t (mg/g), k_i is the intraparticle diffusion rate constant (mg/g min^{0.5}), t is the time (min), and A is the intercept (mg/g). According to this model, the plot of q_t versus the square root of time ($t^{0.5}$) should be linear if intraparticle diffusion is involved in adsorption and if these lines pass through the origin; then the intraparticle diffusion is the rate-controlling step. The plots of q_t against $t^{0.5}$ for dye sorption on Purolite A 845 and Purolite A 500P (Figs. 2A, 2B)



Fig. 2. Intraparticle diffusion plots for diffusion in the Purolite A 845-dye (A) and Purolite A 500P-dye (B) systems



Fig. 3. Intraparticle diffusion plots for calculating the intraparticle diffusion coefficient k_i in the Purolite A 845-dye (*A*) and Purolite A 500P-dye (*B*) systems. Plots of *C* / C_0 vs time for calculating the external mass transfer coefficients at the initial time intervals in the Purolite A 845-dye (*C*) and Purolite A 500P-dye (*D*) systems

are multi-linear, indicating that the sorption process consists of two or more steps. The first, sharper portion (about 5 min) is external surface adsorption or an instantaneous adsorption stage. The second portion for Purolite A 845 (at a temperature range of 293–313 K from 5 to 45 min, at a temperature of 333 K from 5 to 30 min) and for Purolite A 500P (at temperatures of 293 K and 333 K from 5 to 30 min, at 313 K from 5 to 60 min) is a gradual adsorption stage in which the intraparticle diffusion is rate-controlling. The third portion is the final equilibrium stage in which the intraparticle diffusion starts to slow down due to the extremely low solute concentration in the solution. The slope of the second linear portion for both anion exchangers was used to derive the values of the intraparticle diffusion rate parameter k_i (Figs. 3A, 3B) presented in Table 2. The values of the intercept *A* represent the boundary layer thickness;

Table 2. Intraparticle diffusion and external mass transfer parameters for chromium complex sorption on Purolite A 845 and Purolite A 500 at various temperatures

Anion ovehongor	Т, К	Intraparticle diffusion			External diffusion
Amon exchanger		k _r mg/g min⁰.⁵	A (boundary layer thickness, mg/g)	R ²	k_{r} min ⁻¹
Purolite A 845	293	0.112	0.759	0.9842	0.288
	313	0.134	0.964	0.9417	0.256
	333	0.139	1.284	0.8952	0.232
Purolite A 500P	293	0.066	0.439	0.9621	0.296
	313	0.110	0.548	0.9326	0.240
	333	0.186	0.430	0.9983	0.224

thus, the larger the intercept the greater the boundary layer effect is.

The correlation coefficients (R^2) for the intraparticle diffusion model range between 0.8952-0.9842 for the Purolite A 845 - dye system and between 0.9326-0.9983 for the Purolite A 500P – dye system. This indicates that chromium complex dye adsorption on both anion exchangers proceeds according to the intraparticle diffusion model. The rate of dye diffusion into a bead of the anion exchanger depends on the anion exchanger structure, the functional groups present and the sorption temperature (Table 2). The intraparticle diffusion coefficient k, values obtained at 293 K and 313 K for the gel structure anion exchanger Purolite A 845 are higher (0.112 and 0.134 mg/g min^{0.5}) than those obtained for the macroporous Purolite A 500P (0.066 and 0.110 mg/g min^{0.5}) (Table 2). The boundary layer thickness effect is greater for dye sorption on the weak basic anion exchanger than on the strong basic anion exchanger (Table 2).

As the multi-nature of the intraparticle diffusion plot suggested the external mass transfer of the dye at initial periods, the rate constant k_s corresponding to the external mass transfer at these initial time intervals was calculated using the plot of C / C_0 vs. time *t*, where *C* and C_0 represent the concentration mg / L at any time and at the initial concentration, respectively. Figures 3C and 3D show the plots of C / C_0 vs. time up to 5 min at various temperatures. The k_s values calculated using the data for linear regression are given in Table 2.

Figure 4 quantitatively compares the sorption of the dye onto anion exchanger beads. The bead of Purolite A 845 is clearly turning blue, while in the case of Purolite A 500P only the edges of the beads turned blue after 60 min of contact with the chromium dye solution. The prediction of the rate-limiting step is an important factor to be considered for proper design purposes. In order to determine the actual rate-controlling step involved in the dye sorption process, the sorption data were further analysed using the kinetic expression given by Boyd et al. and successfully adapted to various adsorption systems [18, 20, 24]:

$$F = \frac{q_t}{q_e} = 1 - \frac{6}{\pi^2} \exp(-Bt),$$
 (10)

where *F* is the fraction of solute adsorbed at different times *t*, and *Bt* is a mathematical function of F, q_t and q_e represent the amount of the adsorbed dye (mg/g) at any time *t* and infinite time.

$$Bt = -0.4977 - \ln\left(1 - \frac{q_t}{q_e}\right).$$
(11)

The value of *Bt* can be calculated for each value of q_t / q_e using Eq. (11). The q_e value was calculated using the pseudosecond-order kinetic model. The linearity of the Boyd plot will provide information needed to distinguish between external-transport and intraparticle-transport-controlled rates of adsorption [24]. Figure 5 shows that the plots are not linear for both anion exchanger – dye systems, indicating that the external mass transport governs the rate-limiting process, especially for Purolite A 500P.

Effect of temperature

The temperature exerts two major effects on the adsorption. An increase in temperature leads to an increase in the rate of diffusion of the adsorbed molecules across the external boundary layer and the internal pores of the adsorbent particles, owing to a decrease in the viscosity of the solution. In addition, the changing temperature will change the equilibrium



Fig. 4. Optical microscopy images of bead cross-section (\varnothing 1.000 mm) at \times 25 magnification comparing the sorption of chromium complex dye (834 mg/L, 293 K) onto Purolite A 845 and Purolite A 500P



Fig. 5. The boyd plots characterising the actual rate-controlling step involved in dye sorption onto the Purolite A 845 and Purolite A 500P anion exchangers

Table 3. Activa	tion energies of a	lye sorption on	Purolite A 845	and Purolite A 500P
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Anion exchanger	<i>E_{a−k2},</i> kJ/mol	E _{a-ki} , kJ/mol	E _{a-ks} kJ/mol
Purolite A 845	10.8	4.44	-4.39
Purolite A 500P	9.3	20.98	-5.71

capacity of the adsorbent for a particular adsorbate [25, 26]. With an increase in the temperature, the rate of intraparticle diffusion and the boundary layer effect shows a tendency of increase, while the external diffusion shows a tendency of a decrease for both systems (Purolite A 845 – dye at 293–333 K, Purolite A 500P – dye at 293–313 K).

From the kinetic parameters k_2 , k_i and k_s at different temperatures, the activation energies representing the minimum energy that the dye–anion exchanger system should have for adsorption to proceed were estimated using the Arrhenius relationship [20, 25]:

$$\ln k = \ln A - \frac{E_a}{PT} \,, \tag{12}$$

RT where E_a is the Arrhenius activation energy of adsorption, A is the Arrhenius factor, R is the gas constant equal to 8.314 J/mol K, and T is the solution temperature, K. When $ln k_2$, lnk_i and lnk_s are plotted against 1 / T, straight lines with a slope $-E_a$ / R are obtained (not shown). The values of activation energies are presented in Table 3.

The positive values of activation energies E_{a-k2} and E_{a-k2i} obtained for both Purolite A 845 – dye and Purolite A 500 – dye systems indicate that the adsorption process is a combination of ion exchange, physical sorption and diffusion processes [23]. The data in Table 3 also show that the activation energy for the intraparticle diffusion of the dye – Purolite A 845 system is 4.7-fold lower than for the dye – Purolite A 500P system, resulting in a deeper diffusion of the dye in the beads of the gel type weak base anion exchanger (Fig. 4).

Because of the better sorption and kinetic characteristics obtained in batch studies, the weak basic anion exchanger Purolite A 845 was examined in the column experiment because the batch experiment cannot give accurate scale-up data in a fixed bed system. These results were published in a separate paper [17]. The controlled technological parameters (effluent pH and conductivity) indicating the performance of the column loaded with the anion exchanger obtained for Purolite A 845 satisfy the recommendations for the discharge of treated wastewater (pH \approx 7, conductivity <5 µS/cm⁻). It also has a possibility to regenerate the anion exchanger with a mixture of 4% NaOH and ethanol (1 : 1).

CONCLUSIONS

The sorption kinetics and diffusion for the chromium complex dye–anion exchanger systems (Lanasyn Navy M-DNLweak basic Purolite A 845 anion exchanger and the strong basic Purolite A 500P anion exchanger) were studied in a batch experiment by considering the rate constants of the chemical reaction and the mass transfer (intraparticle diffusion and external diffusion) process. The actual rate-controlling step was elucidated.

The chromium complex dye sorption mechanism onto both anion exchangers studied consisted of ion exchange, physical sorption and diffusion.

The adsorption of chromium complex dye onto both anion exchangers follows the pseudo-second-order rate kinetic model. Different trend variations in the pseudo-second-order kinetic rate constants k_2 for Purolite A 845 with an increase in temperature indicates that the adsorption mechanism at higher temperatures differs from that at lower temperatures.

The adsorption of chromium complex dye onto both anion exchangers proceeds according to the intraparticle diffusion model. The effect of the intraparticle diffusion coefficient k_i values and boundary layer thickness for the Purolite A 845 anion exchanger are higher than those obtained for Purolite A 500P. According to the kinetic expression given by Boyd, the external mass transport governs the rate-limiting process, especially for Purolite A 500P.

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Danutė Kaušpėdienė, Eglė Kazlauskienė, Aušra Selskienė, Audronė Gefenienė

CHROMO KOMPLEKSINIO DAŽIKLIO PAŠALINIMO IŠ RŪGŠČIŲJŲ TIRPALŲ ANIJONITAIS KINETIKA

Santrauka

Tirta chromo kompleksinio dažiklio šalinimo iš modelinių tirpalų akriliniu geliniu, silpnai baziniu anijonitu Purolite A 845 ir polistireniniu, makroporiniu, I tipo stipriai baziniu anijonitu Purolite A 500P kinetika, atsižvelgus į dažiklio tirpalo koncentraciją ir temperatūrą. Kinetiniais ir optinės mikroskopijos tyrimais įvertinti anijonito fizikinių cheminių charakteristikų pokyčiai dažiklio šalinimo anijonitais metu. Dažiklio šalinimo anijonitais mechanizmą sudaro jonų mainai, fizinė sorbcija ir difuzija. Sistemų dažiklis - Purolite A 845 ir dažiklis - Purolite A 500 kinetiniai parametrai, tokie kaip dažiklio difuzijos per tirpalo plėvelę koeficientas (k,), vidinės difuzijos koeficientas (k,) ir cheminės sorbcijos greičio konstanta (k_{2}) , įvertinti atitinkamai pagal Weberio ir Moriso vidinės difuzijos modelio lygtį ir pseudoantrojo laipsnio kinetikos lygtį. Apskaičiuotos išorinės difuzijos (E_{a-ks}) , vidinės difuzijos (E_{a-ki}) ir cheminės reakcijos (E_{a-k2}) aktyvacijos energijos. Sistemai Purolite A 845–dažiklis E_{a-ki} vertės 4,7 karto mažesnės už vertes sistemai Purolite A 500P liudija apie tai, kad dažiklis ženkliai giliau prasiskverbia į gelinio anijonito grūdelį.