

Phosphate Adsorption from Aqueous Solutions by Syrian Zeolitic Ore: Kinetic Study

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Received: 11/09/2017

Accepted: 29/10/2017

Abstract:

Kinetic study aimed to describe the performance of natural Syrian zeolitic ore (NSZO) for Phosphate (P) adsorption from aqueous solutions, and the contribution of NSZO components on P- adsorption. Obtained results demonstrated that parameter derived from kinetic models predicted two accompanied mechanisms affected P- adsorption: Intraparticle diffusion mechanism in presence of film diffusion. Besides, carbonate removal promoted P- adsorption more than 40 % comparing with the sample removed carbonate and oxides, this led to fact that the efficiency of NSZO in P adsorption belongs to iron oxides coatings zeolite particles, and it explains the decrease of adsorbed P in samples removed from Fe oxides and carbonate components.

Keywords: Phosphate removal, Zeolite, Kinetics, Purification, Intraparticle diffusion.

Introduction:

Eutrophication, in the last decades, became a serious problem threats natural water in many countries (Leinweber *et al.*, 2002; Wang *et al.*, 2006; Huo *et al.*, 2011). Eutrophication occurs when phosphorus (P) concentrations exceeds 0.1 mg.L^{-1} as total phosphorus (TP) (Environmental protection Agency EPA, 1999). Therefore, many technologies have been developed to remove P from natural and waste waters by natural surfactants (Karaca *et al.*, 2006; Hrenovic *et al.*, 2008), precipitators and coagulators (Omoike and Vanloon 1999; Tanada *et al.*, 2003; Ebeling *et al.*, 2004; Yan *et al.*, 2010; El-shazley and Daous 2013), or by biological processes (Schroeder 1988; Mulkerrins *et al.*, 2004; Buda *et al.*, 2012). Zeolites are hydrated aluminosilicate minerals belongs to Tectosilicate. The cage-like framework structure of zeolites provides unique characteristics of high specific surface area, and high affinity to adsorb ions and organic compounds. Natural zeolites are good and cheap adsorbents, capable to remove cations like ammonium (Çelik *et al.*, 2001; Wen *et al.*, 2006; Li *et al.*, 2011), heavy metals (Payne and Abdel-Fattah 2004; Baker *et al.*, 2009), and organic compounds (Han *et al.*, 2009; Yousef *et al.*, 2011).

Phosphate removal by natural or modified zeolites from natural and waste waters is well studied (Karapinar 2009; Montalavo *et al.*, 2011; Capell 2015; Guaya *et al.*, 2016) as well as synthesized zeolites (Zhang *et al.*, 2007; Hamdi and Srasra 2012).

Natural Syrian zeolitic ore (NSZO) is a sedimentary volcanic tuff found basically within igneous rocks like basalt, or with sedimentary rocks corresponding with calcite and clay minerals and primary minerals like olivine and feldspar (Safarjalani *et al.*, 2010a; Safarjalani, 2010b).

Safarjalani, (2010) also illustrated that NSZO has three main components: calcite, oxides, and zeolite. This research hypothesizes that NSZO have the ability to remove phosphate, where no kinetic experiments were done to describe P adsorption behavior on NSZO and purified zeolite from oxides and/or calcite. This research will answer the questions: what is the effect of purification process on phosphate adsorption? and what is the contribution of NSZO components on phosphate adsorption? Hereby, this research will try to identify the kinetic characteristics of phosphate adsorption behavior on natural and purified Syrian zeolitic ore.

Materials and Methods:

Sampling material: NSZO obtained from 170 Km south eastern of Damascus, Syria. This area belongs to Tell Al-Sis, which locates 37° 15' to 37° 30' North 33° 15' to 33° 30' east (Al- Imadi *et al.*, 2003), which is petrographically consists of pyroclastic components, olivins, glass, as well as zeolites. Zeolites are found as secondary phases with calcite and smectites (Safarjalani, 2010b).

Raw material had the following chemical composition (on weight): 38.26 % SiO₂, 10.2% Al₂O₃, 10.86% Fe₂O₃, 0.14% MnO, 9.90% MgO, 11.94% CaO, 1.78% TiO₂, 0.56% P₂O₅, 2.44% Na₂O, 1.03% K₂O and 12.8% LOI (loss on ignition as CO₂ and H₂O content). (Safarjalani, 2010a).

Laboratory procedures were done in 2016 in soil chemistry laboratory at the Faculty of Agriculture, Tishreen University. Total Organic Carbon (TOC) is determined according to Walkley-black method, total carbonate according to Loss method at 550 °C for 3 hours, Cation Exchange Capacity (CEC) by Cerri *et al.*, (2002), pH (suspension ratio 1:10 as w:v) for raw zeolite. Surface Area (SA) is determined by Sears method (1956) as follow: triplicate of 0.5 g NSZO is added to 40 mL distilled water and 10 g NaCl powder, stirred together for two hours, then 0.1 N of HCl is added to drop pH to 3.5, then volume is completed to 50 mL of distilled water. Then the sample is titrated by 0.1 N NaOH. (V) is the noted volume of alkali to raise the pH from 4 to 9. Surface area (SA) is calculated by the following formula: $SA (m^2.g^{-1}) = 32 \times V - 25$.

NSZO samples were subjected to XRD by STOE transmission diffractometer system STADI-P, and XRD patterns has been analyzed by X-Powder12 in order to identify the main minerals.

Purification treatments: Sample of NSZO underwent through sequential purification based on Kunze and Dixon (1986) with minor modifications as follow:

- **Carbonate removal:** An aliquot of NSZO is treated by adding sodium acetate (1N) acidified by acetic acid at (pH ~ 5.2) (~ 1: 2.5 w:v). Then, it is stirred overnight with saturated magnesium hydroxide solution, then filtered, and washed with distilled water to eliminate magnesium excess, this treatment is symbolized as carbonate removed zeolitic ore (C-ZO).
- **Al and Fe oxides removal:** An aliquot of (C-ZO) sample treated by Citrate Bicarbonate Dithionite extractant as ascribed by Mehra and Jackson (1960) (in water bath at 353 °K in presence of air flow for 15 min). This procedure considered efficient to extract amorphous and part of poor crystalline (Fe – Al) with less deformation of Zeolites structure. Sample stirred overnight with NaCl solution in order to get rid of soluble (Fe - Al) components. Finally, deep wash with distilled water to remove all soluble salts. This treatment symbolized as carbonate and oxides removed zeolitic ore (COX-ZO). Thereupon, all purified samples dried at 353 °C, and grinded (< 150 µm) for kinetic experiment.

Phosphorus kinetics:

Contact time: Phosphate solutions prepared in 0.01 M of CaCl₂, and initial pH adjusted at (8.2 ± 0.1) with 0.1 N of NaOH or HCl. Kinetic experiment is performed in 50 mL centrifuge tubes at ratio (1g: 20 mL) (W:V), using two initial phosphorus concentrations C_i (50 and 100 mg.L⁻¹). Samples were shaken for series of times (5, 15, 30,60, 120, 240, 480, 600, 960 and 1440) minutes. Phosphorus adsorbed quantity Q_t (mg.g⁻¹) at given time (t) was calculated as in Eq.(1):

$$Q_t = (C_i - C_t) \cdot V_t/W \quad (\text{Eq. 1})$$

Where C_i and C_t (mg.L⁻¹) are P concentration in equilibrium solution at initial and selected time, respectively. V_t (mL): is the volume of solution in batch.

Phosphorus concentration in solutions determined by the method of Murphy and Riley (1962).

Phosphorus Kinetics models: The pseudo-first-order (Lagergren's), pseudo-second-order, Elovich and Weber and Morris are common models used to describe phosphate kinetics on natural and purified zeolite samples. Lagergren's first-order rate equation is the earliest known one, it describes adsorption rate. It became widely used for the adsorption in solid-liquid systems such as metal ions, dyestuffs and several organic substances in aqueous systems onto various adsorbents (Ho, 2004, 2006). Eq. (2) gives a logarithmic straight line between log (q_e - q_t) vs. t of pseudo-first-order:

$$\log (q_e - q_t) = \log q_{e-cal} - \frac{k_{1th-ps}}{2.303} t \quad (\text{Eq. 2})$$

Where k_{1th-ps} is the rate constant of pseudo-first-order adsorption (min⁻¹), q_t is the quantity of phosphate at time t (mg. g⁻¹), and q_e is the theoretical amount of adsorbed-P at equilibria (mg. g⁻¹). k_{1th-ps}, and q_{e,cal} computed according to the slope and intercept of the Eq. (2)

Pseudo-second-order equation based on adsorption capacity, adsorption can be expressed in the form of Chowdhury and Saha (2010):

$$\frac{t}{q_t} = \frac{1}{k_{2th-ps}(q_{e-cal})^2} + \frac{1}{q_{e-cal}} \cdot t \quad \text{Eq. (3)}$$

Where k_{2th-ps} is the rate constant of pseudo-2nd order equation (g.mg⁻¹.min⁻¹). q_{e, cal} represent computed value of adsorbed amount of phosphate at equilibrium according to the contrary of slope of Eq. (3). Besides, the term 1/ k_{2th-ps}. (q_{e-cal})² is considered as (1/ h_{2th-ps}) where h_{2th-ps} is the initial adsorption rate (g.mg⁻¹.min⁻¹), it evaluates the affinity between phosphate and surfactant, through 1/h_{2th-ps} limits to (0) as t→ 0. h_{2th-ps} is calculated by reciprocal of the intercept related to the linear relationship (t/q_t vs. t).

Elovich equation applied to predict the mechanism of phosphate release and adsorption in soils, and in aqueous solutions (Chien and Clayton 1980). Further, it became the most cited experimental application on adsorption in solution/solid systems, and heterogeneous surfaces (Limousin *et al.*, 2007, Wu *et al.*, 2009). It is summarized by the linear equation:

$$q_t = \frac{1}{K_{el}} \ln(t) - \frac{1}{K_{el}} \ln(h_{el} \cdot K_{el}) \quad \text{Eq. (4)}$$

Eq. (4) describes the relationship between qt (mg.g⁻¹) versus ln (t) and it should yield a straight line where K_{el} is the Elovich constant during any one experiment (g. mg⁻¹.min⁻¹), and (h_{el}) is defined as the initial adsorption rate (mg.g⁻¹.min⁻¹). t₀ is calculated value equals (h_{el} × K_{el}), it defines the initial adsorption time from which adsorption is started, calculated by the intercept of the linear Eq.(4).

Intraparticle diffusion equation: this model is proposed by Weber and Morris (1963). It is presented in this formula Eq. (5):

$$q_t = D_{id} \cdot \sqrt{t} + B_{id} \quad \text{Eq. (5)}$$

where: D_{id} is defined as intraparticle diffusion constant ($\text{mg.g}^{-1} \cdot \text{min}^{-1/2}$), calculated by slope of Eq. (5) when draw up a straight line between (q_t) and (\sqrt{t}), while B_{id} is a constant evaluates the effect of boundary layer on adsorption mechanism.

Validation test: SD_q (%) is a statistical parameter (normalized standard deviation) suggested to define the validity of using models (Wu *et al.*, 2001 and Karaca *et al.*, 2004). In accordance with linear equations (2,3), SD_q is given by formula:

$$SD_q(\%) = 100 \times \sqrt{\frac{\sum_{N=2}^{N=i} (Q_{t_{exp}} - Q_{t_{cal}} / Q_{t_{exp}})^2}{(N - 1)}} \quad \text{Eq. (6)}$$

where N: count of experimental data points. $Q_{t_{exp}}$, $Q_{t_{cal}}$: experimental and calculated adsorbed phosphate at equilibrium time respectively (mg.g^{-1}).

Results and Discussion:

Some NSZO characteristics are summarized in Table (1), results indicate that the NSZO sample classified as a material rich in carbonate where the dominant component is calcite (Safarjalani, 2010). Ca^{2+} and Mg^{2+} are the dominant extra table cations. Otherwise, the effect of Fe–OH sites in the oxide’s components of NSZO is suggested to be tributary on phosphate sorption, considering the Fe_2O_3 (%) content on the material of NSZO.

Table 1. chemical characteristics of natural Syrian Zeolite Ore (NSZO).

pH	$\text{CO}_3 \text{ Total}$	Fe Total	ex-Ca	ex-Mg	CEC	SA
	g.Kg^{-1}		mg.Kg^{-1}		cmol.Kg^{-1}	$\text{m}^2.\text{g}^{-1}$
9.7	197.8	181.4	24.02	9.99	113	183

XRD patterns for natural and purified zeolite ore samples presented in Fig (1). Calcite peaks is abundant in N-SZO sample (Fig 1.a) while it is absent in the carbonate removed sample (C-ZO) and in carbonate and oxides removed sample (COX-ZO) (Fig 1.b, c). In contrast, Forsterite (Mg-Olivine) is observed after the removal of carbonate and oxides (Fig 1.c). More intense peaks for Analcim and Phillipsite zeolite minerals observed in carbonate removed sample (C-ZO) (Fig 1.b). By means of XRD Patterns, we can extrapolate that Forsterite particles is probably the central core, coated with zeolite minerals side by side with carbonate and oxides. Despite the oxidation reaction (purification procedures) could partially damage zeolite framework, zeolite species appears in all figures.

This assumption is similar to results obtained by (Al- Imadi *et al.*, 2003; Safarjalani, 2011) who mentioned that Forsterite is the abundant mineral with extrusions of magnetite (Fe_3O_4), limonite ($\text{FeO(OH).nH}_2\text{O}$) and hematite (Fe_2O_3) beneath and around Mg- Olivine aggregates side by side with zeolite particles which are sedimentary components with carbonate and oxides.

Contact time effect:

NSZO has heterogeneous surfaces, Fig (.2) illustrates the relationship between adsorbed phosphate (q_t) vs. time (t). It is found that (q_t) increased at first contact time (0-240 min) in both initial

concentrations (50 and 100 mg. L⁻¹), then slow increase is observed. Table (2.) illustrates four model constants computed by linear equations (3, 4, 5, 6). Correlation factor value (R²) is used to evaluate the fitness of using model to obtained data, where (R²→1) means that model is sui table for predicting phosphate sorption from solution.

data varies between models, and from initial concentration to another. Pseudo second order model gives extremely high correlation R² (>0.98) for the two initial concentration, secondly Elovich and Intraparticle diffusion models. Pseudo first order model was unsuiTable to predict phosphate sorption kinetic (R²<0.9) at range (5-1440 min) (Table 2).

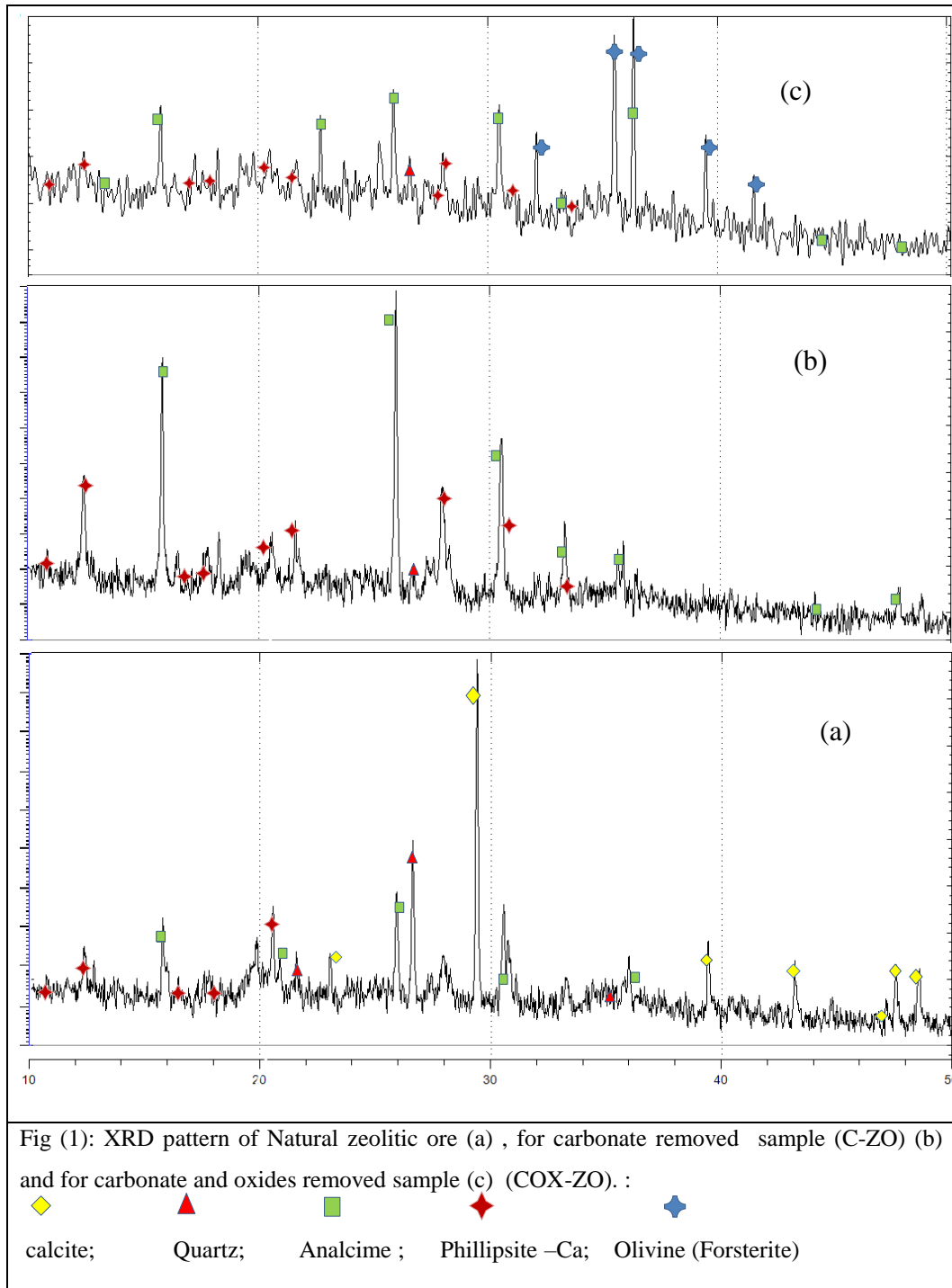


Fig 1. XRD pattern of Natural zeolitic ore (a), for carbonate removed sample (C-ZO) (b) and for carbonate and oxides removed sample (c) (COX-ZO). Symbols of minerals are: calcite; Quartz; Analcime; Phillipsite -Ca; Olivine (Forsterite).

These data suggest that sorption of phosphate on NSZO is quietly slow and irreversible. It may point out the chemisorption with respect to good correlation estimated for pseudo second order model estimation and less for Elovich model. (Ho and McKay 1999; Chowdhury and Saha, 2010) Initial adsorption rate (h_{2th-ps}) (calculated from Pseudo second order) and intraparticle diffusion constant (D_{id}) increased as initial concentration of phosphate solution increased; whereas, initial adsorption rate (h_{el}) of Elovich's decreased (Table 2).

Kinetic study search for the rate controlling mechanism by using the validation test (SDq%). Results show that calculated parameter of equilibrium concentration (q_{e-cal}) deviated from experimental (q_{e-exp}), where the correspond experimental data (SDq %) is high (>10 %) at the initial concentration 50 mg. L⁻¹ (PO₄ – P), and (>20 %) at the initial concentration 100 mg.L⁻¹ (PO₄ – P) (Table.2) this leads to fact that film diffusion is not rate controlling for P sorption.

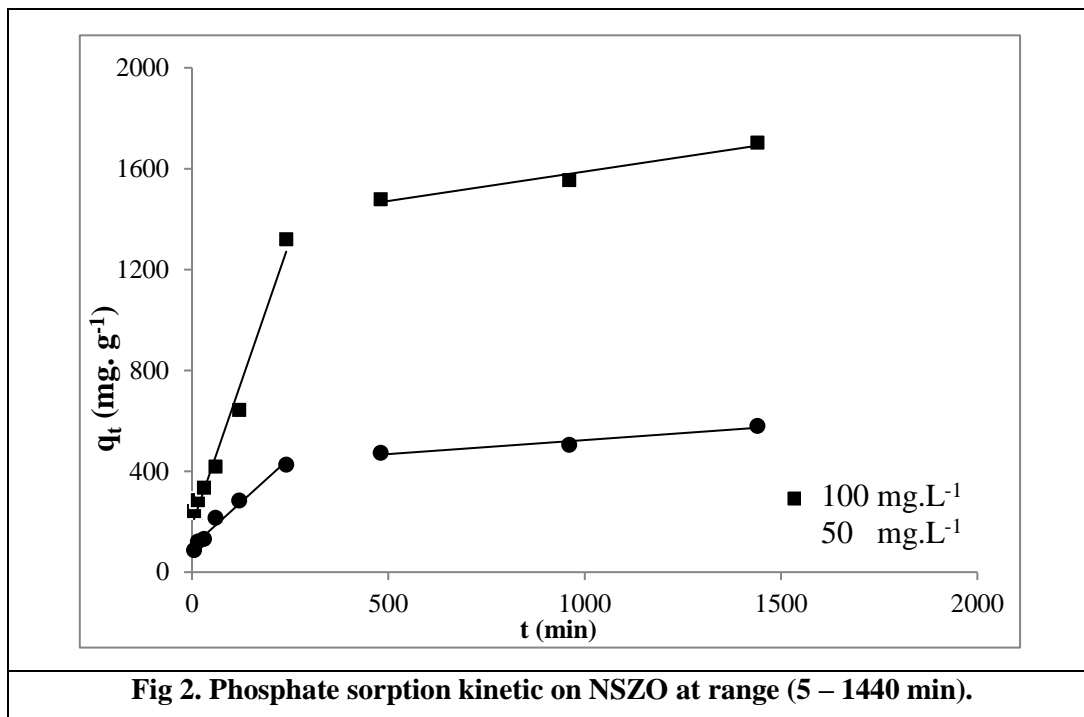
Table 2. Parameters of phosphate adsorption kinetics on NSZO at range (5 - 1440) min.

Pseudo first order model					
Ci mg.L ⁻¹	R ²	k _{1th-ps} min ⁻¹	q _{e-cal} mg.g ⁻¹	SDq %	
100	0.880	8.86 × 10 ⁻⁰⁴	1783.14	24.69	
50	0.780	1.19 × 10 ⁻⁰³	786.32	18.95	
Pseudo second order model					
Ci mg.L ⁻¹	R ²	k _{2th-ps} g.mg ⁻¹ min ⁻¹	h _{2th-ps} mg.g ⁻¹ min ⁻¹	q _{e-cal} mg.g ⁻¹	SDq %
100	0.983	4.09 × 10 ⁻⁰⁶	13.67	1828.001	24.76
50	0.992	1.81 × 10 ⁻⁰³	6.36	592.429	12.86
Elovich model					
Ci mg.L ⁻¹	R ²	K _{el} mg.g ⁻¹	h _{El} g.mg ⁻¹ min ⁻¹		
100	0.909	0.149	0.133		
50	0.857	0.042	0.422		
Intraparticle diffusion model					
Ci mg.L ⁻¹	R ²	D _{id} mg.g ⁻¹ .min ^{-1/2}	B _{id}		
100	0.884	5.894	193.910		
50	0.906	1.810	101.306		

On the other hand, intraparticle diffusion correlation factor is satisfying for phosphate initial concentration 100, 50 mg.L⁻¹ (PO₄ – P) where R² =0.88 and 0.9 respectively. Besides, the absolute value of B_{id-100} =193.9 , B_{id-50} = 101.3 are high indicating the effect of film diffusion on Phosphate sorption on NSZO (Hameed et al., 2008).

Kinetic models are simple and capable to predict one mechanism to explain phosphate sorption on natural zeolite ore. Results obtained from these simple models show how it is confusing to describe phosphate sorption on Zeolite ore by using one model alone. Therefore, phosphate sorption on NSZO could be controlled by more than one mechanism of mass transfer just as a complex sorption kinetic system (Ho and Mckay, 1999).

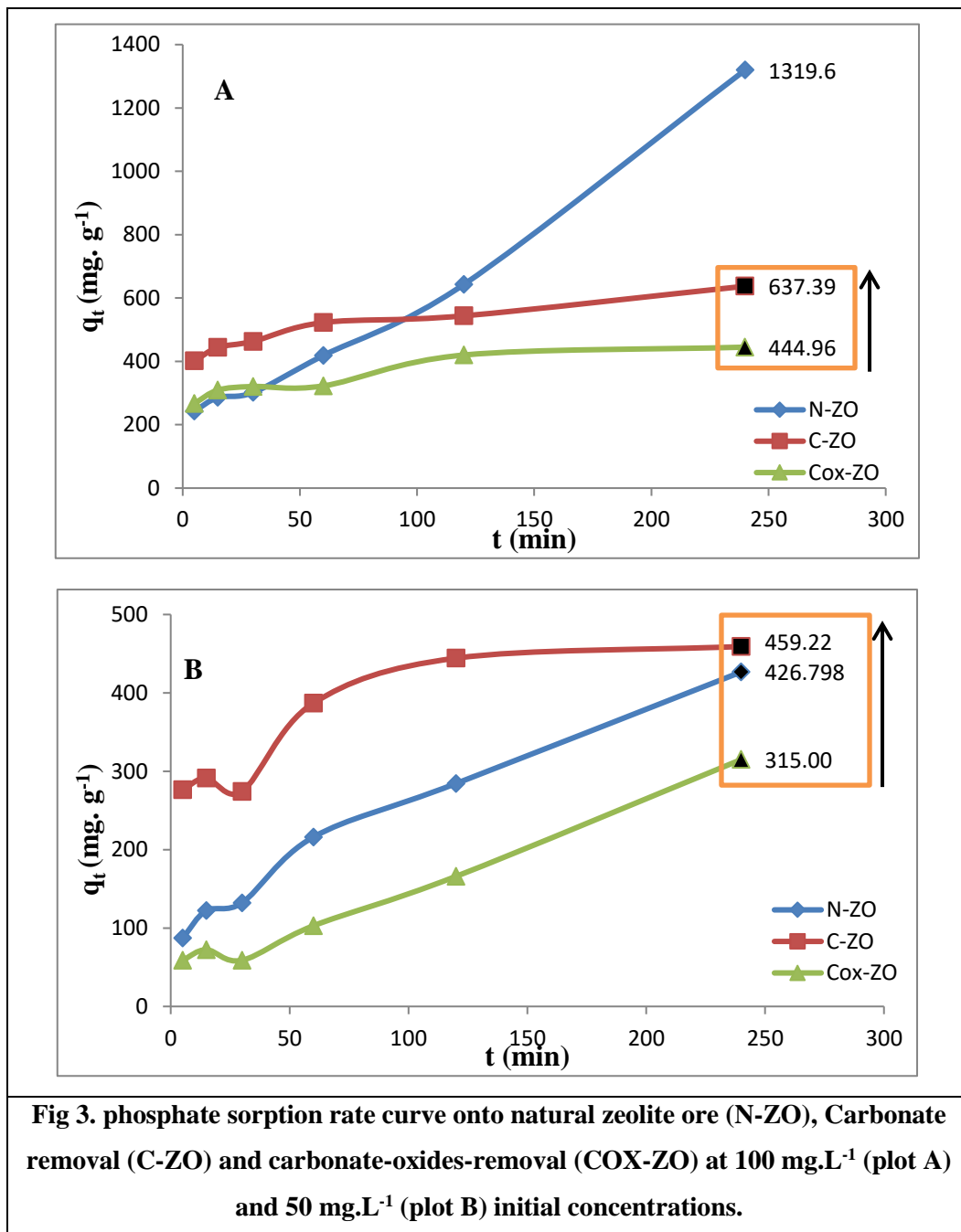
In accordance with this assumption, phosphate kinetics on NSZO surfaces were undertaken in two ranges of contact time (Fig.2). The first stage where sorption rate is high, the other is quite slow. The predominant mechanism in the first stage may has physical nature with both kinds of diffusion mechanisms, both may contribute in P- adsorption on NSZO (intraparticle and film diffusion). Whereas, chemisorption interfered by intraparticle diffusion control in the second stage.



Purification treatment effect: In order to justify the role of NSZO main components in phosphate kinetic sorption. Kinetic study is proceeded to identify kinetics for (5 – 240) min illustrated in Fig (3.). It shows the (q_t vs. t) curves for each sample (N-ZO), (C-ZO) and (COX- ZO) at (100 mg.L^{-1} and 50 mg.L^{-1}) initial phosphate concentration ($\text{PO}_4 - \text{P}$), respectively. Sorption rate between zeolite sample treatments gives the following order (N-ZO > C-ZO > COX- ZO) for 100 mg.L^{-1} ($\text{PO}_4\text{-P}$) and (C-ZO > N-ZO > COX- ZO) for 50 mg.L^{-1} ($\text{PO}_4\text{-P}$).

Purification procedure pointed the importance of Fe- oxides as P- surfactant; Fig (3) showed that P – adsorption increased from 315.00 to 459.22 mg.g^{-1} , and from 444.96 to 637.39 mg.g^{-1} , as initial concentration increased from $50 - 100 \text{ mg.L}^{-1}$ at 240 min contact time, it means that Fe- oxides promoted zeolites more than 40% in P- adsorption. In contrary of that, carbonate inhibited P- adsorption at initial contact time (< 240 min) and (< 120 min) at initial concentration $50 - 100 \text{ mg P.L}^{-1}$ respectively.

Regardless of initial phosphate solution, it suggests that carbonate coating zeolite ore may inhibit phosphate sorption rate at short time range. Therefore, phosphate sorption behavior can be confirmed regarding to value of ($k_{2\text{th-ps}}$), where it gives 1.63×10^{-4} and $2.21 \times 10^{-4} \text{ g. mg}^{-1} \cdot \text{min}^{-1}$ for C-ZO treatment at 100 mg.L^{-1} and $50 \text{ mg.L}^{-1} \text{ PO}_4\text{-P}$ initial concentration respectively (Table 4.), it is about ten times higher than the corresponding values of N-ZO and COX-ZO treatments. Similar results observed for Elovich constant k_{EI} . On the other hand, R^2 of intraparticle diffusion model gives a good estimation for all zeolite samples regardless purification status (Table 4).



Besides, Absolute value of B_{id} is quietly high and deviated from the for all zeolite samples, through which gives an idea about the dominant rule of film diffusion on phosphate sorption.

Table 3. Parameters of Pseudo first order model and intraparticle diffusion model on NSZO and purified samples during (5- 240) min of contact time, at initial concentration 50 -100 mg P. L⁻¹.

sample	C_i $Mg.L^{-1}$	pseudo first order		Intraparticle diffusion		
		R^2	k_{1th-ps} min^{-1}	R^2	D $mg.g^{-1}min^{-0.5}$	B_{id}
N-ZO	100	0.827	6.08×10^{-3}	0.923	89.81	- 107.92
C-ZO		0.917	3.64×10^{-3}	0.981	16.98	251.67
COX-ZO		0.916	6.89×10^{-3}	0.927	37.66	- 16.67
N-ZO	50	0.827	5.74×10^{-3}	0.976	25.77	- 44.69
C-ZO		0.713	3.16×10^{-4}	0.814	15.08	237.85
COX-ZO		0.842	1.21×10^{-3}	0.942	39.597	185.50

(Hameed et al., 2008). Elovich initial rate constant h_{EI} did not correspond with the pseudo –second order 's, this indicates that Elovich is not appropriate to describe the behavior of phosphate sorption. Elovich gives the best results when adsorption is applied in wide period > 40 hours (Chien and Clayton, 1980), ~ 25 hours (Ye et al., 2006) and 60 – 240 hours (Liu et al., 2012).

Table 4. Parameters of Pseudo second order model and Elovich model on NSZO and purified samples during (5- 240) min of contact time, at initial concentration 50 -100 mg P. L⁻¹.

sample	C _i mg.L ⁻¹	Elovich			pseudo 2 nd order		
		R ²	k _{EI}	h _{EI}	R ²	k _{2th-ps}	h _{2th-ps}
			mg.g ⁻¹	g.mg ⁻¹ min ⁻¹		g.mg ⁻¹ min ⁻¹	mg.g ⁻¹ min ⁻¹
N-ZO	100	0.832	0.87 × 10 ⁻³	239.87	0.798	0.56 × 10 ⁻⁵	14.12
C-ZO		0.966	32.3 × 10 ⁻²	57.70	0.994	1.63 × 10 ⁻⁴	37.88
COX-ZO		0.934	1.66 × 10 ⁻³	127.26	0.996	1.02 × 10 ⁻⁵	75.68
N-ZO	50	0.929	1.83 × 10 ⁻³	84.04	0.813	0.59 × 10 ⁻⁵	15.34
C-ZO		0.893	43.1 × 10 ⁻²	51.98	0.997	2.21 × 10 ⁻⁴	46.98
COX-ZO		0.877	1.01 × 10 ⁻²	124.66	0.921	0.64 × 10 ⁻⁵	75.68

Conclusions:

Results of current research demonstrated that it is not sufficient to describe P- adsorption mechanisms by one model alone. It suggested that parameters derived from kinetic models predicted two accompanied mechanisms affected P- adsorption: Intraparticle diffusion mechanism in presence of film diffusion.

Purification procedures gave a good estimation to explore the performance of NSZO in P- adsorption. Results showed that carbonate inhibits P- adsorption and deviates the rate of P – adsorption comparing with carbonate - removal- samples; it is shown that carbonate removal modification promoted P- adsorption more than 40 % comparing with the sample removed carbonate and oxide, this led to fact that the efficiency of NSZO in P adsorption belongs to iron oxides coatings on zeolite particles, and it explains the decrease of adsorbed -P in Fe oxides – carbonate- removal samples.

Obtained results is primary for further applications on NSZO, when it will be used as a surfactant for environmental purposes or for fertilizer industries.

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ادمصاص الفوسفات من المحاليل المائية باستخدام الخام الزيوليتي السوري: دراسة حركية

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تاريخ القبول: 2017/10/29

تاريخ الاستلام: 2017/09/11

الملخص

هدفت الدراسة الحركية إلى وصف أداء الخام الزيوليتي السوري الطبيعي، في ادمصاص الفوسفات من المحاليل المائية، ومدى مساهمة مكونات هذا الخام في ادمصاص الفوسفات. لقد أوضحت النتائج أنّ الثوابت الرياضية المشتقة من الموديلات الحركية، تنبأت عن ميكانيكيتين متلازمتين تؤثران في ادمصاص الفوسفات وهي: الانتشارية البينية داخل المسام بوجود الانتشار السطحي العشوائي. فضلاً عن ذلك، سببت عملية إزالة الكربونات زيادة في ادمصاص الفوسفات بمقدار 40% عن العينة التي أزيلت فيها الكربونات والأكاسيد، وهذا يفضي إلى حقيقة أنّ فعالية الخام الطبيعي الزيوليتي السوري، تعود إلى طليات أكاسيد الحديد على حبيبات الزيوليت، وهذا ما يفسّر انخفاض ادمصاص الفوسفور في العينات التي أزيلت مكوناتها الكربوناتية وأكاسيد الحديد منها.

الكلمات المفتاحية: إزالة الفوسفات، الزيوليت، الحركية، التنقية، الانتشارية البينية.