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Mathematical analysis of the linear increase in SiO_2 content during the activation of Navbakhor alkaline bentonite with hydrochloric acid

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ABSTRACT

In this study, the acid activation process of the bentonite clay, which was conducted for producing a bleaching sorbent for the oil and fat industry, was mathematically analyzed. Increase in SiO_2 content under different concentrations of HCl was analyzed using the different mathematical models. During acid activation, increasing the acid concentration from 5% to 20% resulted in an increase in the SiO_2 content from 61.94% to 65.12%. During the activation process, a moderate increase in HCl concentration caused the improvement of the sorption properties of the clay by dissolving some components and restructuring the active sites. An excessive increase in the concentration of HCl leads to degradation of the mineral structure and partial breakdown of the silica framework, which negatively influences sorption performance. Analysis of the obtained results using the different mathematical approaches showed that an increase in SiO_2 content during activation corresponds fully to a linear model. According to this, a linear model was described by the equation $y = 60.785 + 0.2088 \cdot X$. Accuracy of the results obtained from the linear equation was confirmed by a coefficient of determination, $R^2 = 0.9845$, indicating a high accordance with the experimental data. This model mathematically predicts the increase in SiO_2 content and proves that the activation process proceeds as a linear function. A mathematical approach to the activation process enables one to calculate in advance the properties of sorption of the clay, to reduce the consumption of acid and water, and to calculate the eventual demands of other reagents.

Keywords: bentonite clay, activation, sorption properties, mathematical modeling, linear model.

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Introduction

Natural mineralized clays (including both raw and activated forms) were characterized with high sorption capacity, among which are bentonite, kaolin, palygorskite, opoka-type clays, and others.

The structure of bentonite clays is based on the mineral montmorillonite, which represents the group of aluminosilicates. Their physicochemical properties depend on the structure of the crystal lattice of this mineral. The availability of ion-exchangeable components in bentonite clays provides possibilities to improve the sorption properties in the course of activation [1].

Depending on the mineralogical composition, structural characteristics, chemical properties, and intended field of application, natural clays' activation methods are carried out under different

conditions.

As a chemical modification process, acid activation replaces exchangeable metal cations, such as Na^+, Ca^{2+}, and Mg^{2+}, with H^+ ions. After the removal of the interlayer metal ions, a silica-rich framework is formed. In addition, new kinds of active sites within the clay structure will be generated in this process [1].

The specific surface area varies depending on the type of acid, its concentration, temperature, duration of treatment, and the hydromodule. A moderate acid concentration leads to an increase in

Due to acid activation, there is an increase in the specific surface area of the clay, its pore size, and pore volume [2].

The specific surface area depends on the kind of acid, the acid concentration, temperature, time of treatment, and the hydromodule. An increase in specific surface area due to a moderate acid concentration is accompanied by an increase in the SiO_2 content. A further increase in acid concentration reduces the ion-exchange capacity and provokes the degradation of the crystal structure of the mineral. As a result, the sorption properties of the clay decrease [3].

Of the different parameters, specific surface area and pH have been mainly considered in activated bleaching clays used for refining vegetable oils. The activation results in a manyfold increase of the specific surface area of the clay compared to its natural state, which increases its sorption capacity [[4], [5]].

However, at acid concentrations beyond the moderate values, deformation and blockage of pores occur; this would further reduce sorption performance. Controlling the type of acid and conditions of activation can yield selective sorbents suitable for different kinds of molecules, besides making a structure with varying proportions of micro, meso, and microporosity possible to obtain [[6], [7]].

Adsorption processes occurring between the sorbent and the sorbate generally proceed through physical and chemical mechanisms. Maximum sorption of dye compounds, oxidation products, cations, anions, and other components present in the sorbate is achieved when the pore size, pore volume, and pH of the adsorbent are optimal. In particular, harmful anionic substances can be effectively removed from industrial wastewater with polar sorbents [[8], [9], [10]].

Various compositions developed through different approaches in adsorbent development have been studied, which showed that the process is kinetically described by the pseudo-second-order model. This indicates that, aside from physical adsorption, chemical bonding-i.e., chemisorption-adds to the active role of the sorption process. Thus, the mechanism of adsorption is not just a physical interaction of the molecules with the material but also involves chemical interactions.

The Langmuir and the Freundlich models are two of the most frequent models used in the study of the equilibrium state of adsorption processes. According to the assumptions of the Langmuir model, adsorption on the surface occurs as a monolayer-that is, as a single layer of adsorbate molecules. The Freundlich model characterizes sorption on a heterogeneous solid that is composed of sites with different energies and affinities [8].

As a result of acid treatment, the dissolution of soluble components in the octahedral layer increases or redistributes active sites surrounding the Si-O bonds. In this way, it increases the energetic activity of these sites and strengthens their interactions with organic compounds, pigments, peroxides, and other oxidation products. In bleaching clays applied in the oil and fat industry, activation with moderate acid concentrations is effective. High acid concentrations destroy the crystal structure of the mineral and subsequently its sorption properties. Washing the suspension in water after the process should be conducted at pH = 4-5, because, under such conditions, ion-forming substances present in oil bind effectively [4].

The pH of the sorbent, therefore, plays an important role in the efficient removal of contaminants in industrial wastewater. Its surface charge is one of the most important parameters for treating a variety of sorbates with differing pHs. Control of the surface charge of the sorbent properly orients the adsorption process and makes it highly feasible to achieve maximum efficiency in wastewater treatment applications [5].

Bentonite clays are considered to be abundant, low-cost materials that can be easily activated. At the same time, they offer the possibility to produce environmentally safe sorbents. They find wide application both as bleaching earths in the food industry and as sorbents for the removal of contaminants from industrial wastewater. Specific application of bleaching earths depends on their pore structure: mesopores effectively adsorb larger molecules such as phospholipids, while micropores are more suitable for the adsorption of smaller and more polar molecules. In the process of vegetable oils bleaching, the sorption properties and pH value of the sorbent directly influence the final result of

the process. The linear relationship between these parameters facilitates optimization of practical applications. Moreover, in the analysis of adsorption processes, it is recommended to evaluate the compatibility of kinetic and isotherm models, verify relative errors and statistical criteria, and assess the stability of the selected model [[4], [11], [12], [13], [14], [15], [16]].

Activated clays, due to their high specific surface area, tunable particle size distribution, and adjustable pH values, can be used as selective adsorbents that preferentially remove contaminants from multicomponent mixtures. In addition, in the study of physical and chemical properties of adsorbents obtained by activation of natural clays, adsorption isotherms and the kinetic characteristics of the adsorption processes have been described in detail [17].

In the detailed analysis of adsorbents, the study of adsorption–desorption isotherms is of great importance, as these curves characterize the equilibrium established between the sorbent and the sorbate. In this context, the Langmuir model is considered a classical approach, assuming that all active sites on the surface possess identical energies. Accordingly, molecules occupy the surface in a monolayer fashion. This model of monolayer adsorption applies to homogeneous surfaces with similar structural active sites and is based on assumptions of a finite number of adsorption sites. In contrast, the Freundlich model assumes that sorbent surfaces are inherently heterogeneous, possessing adsorption sites with dissimilar energetic characteristics. The arrangement of the molecules on such heterogeneous surfaces, according to this model, is not restricted to a monolayer; the adsorption may be a polylayer, reflecting a more complex nature of adsorption [18].

In the adsorption of different organic compounds using various modified bentonite clays, kinetic and isotherm properties of the process have been evaluated according to the pseudo-second-order kinetic model. This model is considered one of the most valuable mathematical models that describes the basic mechanisms of the adsorption rate. Usually, the use of a pseudo-second-order model indicates that the adsorption rate proceeds via a chemical mechanism, so that the active sites on the surface of the adsorbent interact with sorbate molecules through a direct covalent or strong chemical bonding. Therefore, the pseudo-second-order kinetic model can provide a theoretical basis for the study of the extent and rate at which the sorbate molecules are bound by the adsorbent [19].

The chemical mechanisms of adsorption are described by the pseudo–second-order kinetic model (1).

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

here:

q_t - amount of substance adsorbed at time *t*, *mg/g;*

q_e - amount of substance adsorbed at equilibrium, *mg/g;*

k_2 - rate constant, *g* mg^{-1} min^{-1}*;*

t - time, *min.*

According to the volumetric distribution of their pores, bentonite clays can serve as selective adsorbents, catalysts, or raw materials in the production of pharmaceutical preparations [20].

In scientific studies on the purification of wastewater from pharmaceutical manufacturing facilities, the sorption efficiency of natural bentonite clay and acid-activated samples has been comparatively evaluated for the removal of harmful antibiotics. The results indicate that the adsorption of antibiotic compounds from wastewater follows the pseudo-second-order kinetic model. Among the isotherm analyses based on the Langmuir and the Freundlich models, the Langmuir model yielded the highest coefficient of determination (R^2) [21].

Mathematical modeling of production processes enables the preliminary analysis of technological systems and the optimization of operational costs [[22], [23]]. A mathematical approach to industrial operations allows technological processes to be expressed in a digital framework and facilitates the examination of the relationship between theoretical predictions and practical outcomes. Such an approach significantly enhances production efficiency by reducing the consumption of raw materials and energy resources.

Although numerous studies have been devoted to the acid activation of bentonite clays, the majority of these works primarily focus on changes in adsorption properties and increases in specific surface area. In contrast, the quantitative relationship between hydrochloric acid concentration and the increase in silicon dioxide (SiO_2) content has not been systematically investigated. In particular, for alkali-earth bentonite

from the Navbahor deposit, the dependence of SiO_2 content on hydrochloric acid concentration has not yet been consistently described using a deterministic mathematical approach.

The scientific novelty of the present study lies in the fact that, for the first time, a statistically reliable and clearly defined linear relationship between hydrochloric acid concentration and the increase in SiO_2 content during the acid activation of Navbahor bentonite has been established. Unlike previous studies that relied mainly on empirical observations, this work proposes a simple yet highly reliable mathematical model that quantitatively characterizes the structural transformation of the silica framework during acid treatment.

The mathematical modeling of the HCl activation process of natural bentonite clay allows for an examination of the effect that increasing SiO_2 content has on the behavior of the specific surface area, as well as to predict the surface area that can be obtained. This makes it possible to maximize the quality parameters of the resulting adsorbent, control the process of activation digitally, and optimize the consumption of reagents.

Based on the experimental data, an empirical and deterministic mathematical model is developed to describe the relationship between SiO_2 content and hydrochloric acid concentration. An analysis of the proposed model was then made using a linear regression equation, as well as an evaluation of its reliability based on statistical indicators (R^2).

Materials and Methods

The material of the research is alkaline (calcium) bentonite of the Navbahor deposit, which is located in the Navoi region. The main component, according to the chemical composition of natural bentonite clay, is SiO_2-61.54%. That very fact testifies to the presence of a silica-based structural framework of this mineral. A high proportion of SiO_2 in its composition ensures stability of the mineral layers, and it acts as a non-degradable structural carcass during acid activation.

In addition, the bentonite clay contains 12.60% aluminum oxide (Al_2O_3), 6.23% iron oxide (Fe_2O_3), as well as other oxides, the respective amounts of which are presented in Table 1. This chemical composition was taken as the initial parameter for modeling the kinetics of SiO_2 increase during the activation of bentonite with hydrochloric acid.

Bentonite clay samples weighing 100 g each were activated in HCl solutions of varying concentrations (5, 10, 15, and 20%) at a hydromodule of 1:2.5 and a temperature of 373 K for 2 hours under continuous stirring in a water bath. The activated suspension was washed with distilled water until reaching pH 4, followed by drying at 473 K, grinding, and sieving through a 56 µm mesh. The SiO_2 content in the clay was determined using the colorimetric method [7].

Three parallel experiments were conducted simultaneously, and their average values were used for analysis. Based on the obtained experimental results, the relationship between the increase in hydrochloric acid concentration and the change in SiO_2 content was examined. Accordingly, a mathematical model was developed that describes this process. The analytical results were processed by mathematical-statistical methods, and the reliability of the data was checked.

Accordingly, it has been determined that the increase in SiO_2 content as a function of hydrochloric acid concentration can be given by the linear regression Equation (2), from which the mathematical treatment clearly shows the level of accuracy of the experimental results.

$$y = a + b \cdot X \quad (2)$$

here:
y - *SiO_2* content, %
a - Value of *y* when *X = 0*
b – Regression coefficient, %
X – hydrochloric acid concentration, %

In the model, hydrochloric acid concentration was an independent variable, while SiO_2 content was the dependent variable. The value of the coefficient of determination (R^2) was used to determine the exactitude of the results from the model. Mathematically, R^2 is given by expression 3.

$$R^2 = 1 - \frac{SST}{SSE} \quad (3)$$

here:
R^2 - coefficient of determination
SST - deviation of experimental values from the mean
SSE - difference between the model and experimental values.

Table 1 - Chemical composition of natural Navbahor alkali-earth bentonite

Sample	Content, %							
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O
Natural bentonitic clay	61.54	12.60	6.23	0.56	0.75	3.98	0.82	2.11

A high value of the coefficient obtained, R^2, means that the increase in the concentration of hydrochloric acid translates into a rise in the rate of disruption of the silicon-oxygen bonds within the silica framework; that is, it reflects structural changes corresponding to increasing the acid concentration. For example, usually, when $R^2 \geq 0.95$, the model is considered highly accurate; however, with $R^2 < 0.80$, the model has failed to effectively describe the process at hand. In this context, the results of the correlation analysis also support the findings above. The value of r = 0.992 further confirms the linear relationship between acid concentration and SiO_2 content. That is to say, it demonstrates the stability of the model and its physical soundness 4.

$$r = \frac{(u_i - \hat{u}) \cdot (y_i - \acute{y}}{\sqrt{(u_i - \hat{u})^2 \cdot (y_i - \acute{y})^2}} \quad (4)$$

here:
r - correlation coefficient
u_i - independent variable
y_i - dependent variable
û ȳ - mean value of the variables

A larger value of the correlation implies that the model is strongly accurate and that random scattering in the experimental data is practically absent. The closeness of the r value to 1 indicates that with an increase in SiO_2 content, this proceeds in a well-defined and deterministic linear pattern.

$$\mathrm{MRE} = \frac{1}{n} \sum_{i=1}^{n} \left[\frac{y_i - \acute{y}_i}{y_i}\right] \cdot 100 \quad (5)$$

here:
y_i - experimental value
$\acute{y}_i$ - model value
n - number of experiments
$(y_i - \acute{y}_i)$ - relative error for each experiment

MRE gives the estimation of the average deviation of the model results from the experimental values. The standard deviation (SD) and the root mean square error (RMS) are used to further judge the reliability of the model results. These kinds of analyses confirm the accuracy and stability of the empirical model describing the dependence of SiO_2 content in the clay on the acid concentration.

The coefficient of determination obtained from the modeling was $R^2 = 0.9845$, which reveals an excellent fit of the model to the experimental data. Origin 2021 Pro software was used to build the graphical analyses shown in Figure 1 below. These plots are a visual representation of the agreement between the model predictions and the experimental values.

Results and Discussions

The results of experiments carried out in this research demonstrate the processes of structure transformations during the hydrochloric acid activation of Navbahor alkaline earth bentonites. In contrast with previous observations made on certain qualitative criteria, in this research, the linear relationship between hydrochloric acid concentration and content of SiO_2 has been revealed.

Table 2 shows the variations in SiO_2 content in samples activated with HCl solutions of different concentrations (5%, 10%, 15%, and 20%) at hydromodule 1:2.5.

Table 2 – SiO_2 content (%) for the clay samples activated at different concentrations of hydrochloric acid

HCL concentration, %	SiO_2 content, %
5	61.95
10	62.79
15	63.72
20	65.12

Experimental results indicated that whereas the specific surface area for the natural clay was 43.52 m^2/g, that of the sample activated with 15% HCl had a specific surface area of 134.43 m^2/g as obtained by BET analysis. This value reduced to 95.34 m^2/g at an HCl concentration of 20%. In other words, with increasing acid concentration beyond 20%, the specific surface area of the clay decreased. Such findings suggest that when the acid concentration exceeds the optimum, both

exchangeable ions are removed from the clay structure, and structural degradation of the mineral occurs.

As observed from the table, SiO_2 content in the bentonite increases steadily with an increase in the hydrochloric acid concentration. While the value of SiO_2 content for the natural clay was 61.54%, this reached up to 65.12%, increasing the acid concentration to 20%.

The SiO_2 increase caused by acid activation can be explained by the forced leaching of alkaline and alkaline-earth metals, magnesium, aluminum, and iron from the clay structure. In this procedure, the removal of a large proportion of bonded hydroxyl ions from the silicate lattice, together with the release of Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, and other cations, formed unsatisfied valences with a net increase in surface area. This implies that structural rearrangement occurred in the montmorillonite crystal lattice during the process of acid activation. Thus, more extensive voids were created, and atoms or ions located in these areas were transformed into an unsaturated state, increasing their potential to bind other atoms or ions; in other words, enhancing adsorption capacity.

Furthermore, sorption properties depend not only on the specific surface area but also on the pH of the medium. Thus, the increase in the specific surface area of the clay during the activation process can be predicted based on changes in SiO_2 content and by mathematical modeling. This, in turn, helps reduce the number of expensive analyses such as BET measurements.

The model yielded a coefficient of determination $R^2 = 0.9845$, indicating a high degree of accuracy and strong agreement with the experimental data.

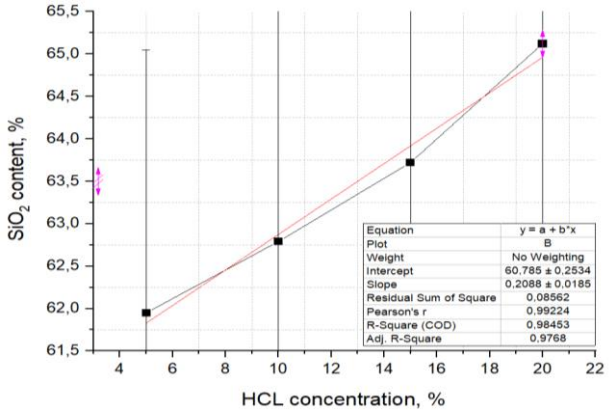

Figure 1 - Linear increase in SiO_2 content as a function of hydrochloric acid concentration

Based on the results obtained during the activation process, the dependence of SiO_2 content on hydrochloric acid concentration was established and graphically illustrated (Figure 1).

According to the graph, the linear increase in SiO_2 content is confirmed by the model, and the value $R^2 = 0.9845$ indicates an excellent agreement between the model and the experimental data. This relationship is expressed by the following equation:

$$SiO_2 = 60.785 + 0.2088 \cdot X$$

According to the above equation, each 1% increase in hydrochloric acid concentration results in a 0.2088% increase in SiO_2 content.

During the activation process, H^{+} ions leach out the exchangeable cations Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Al^{3+} , and Fe^{3+} from the interlayer spaces of the bentonite clay. At the same time, when the acid concentration reaches 20% and above, it leads to degradation of the mineral structure, as illustrated in the figure (Figure 2).

As shown in the figure, the ion-exchange process leads to the expansion of interlayer spaces in the clay structure, resulting in an increase in specific surface area and an improvement in adsorption properties.

The experimental results and the model-calculated values were compared.

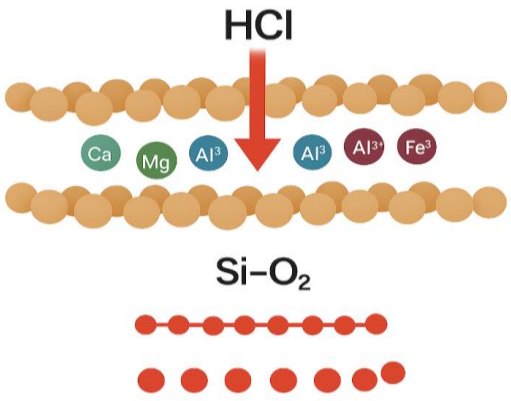

Figure 2 - Ion-exchange mechanism during acid activation

The differences between these values, along with evaluation parameters such as relative error (RE), standard deviation (SD), and root mean square error (RMSE), are presented in Table 3.

Table 3 - Experimental and modeled values of SiO_2 content increase in the clay

HCl, %	SiO_2 (Experimental), %	SiO_2 (model), %	Difference ($\Delta = y-\hat{y}$)	Relative error, (RE), %	Standard deviation (SD), %	Root mean square error (RMSE)
5	61.95	62.36	-0.41	0.65	0.289914	62.155
10	62.79	63.29	-0.50	0.80	0.353553	63.04
15	63.72	64.23	-0.51	0.79	0.360624	63.97
20	65.12	65.16	-0.04	0.06	0.028284	65.14

The table presents the absolute difference and relative error between the experimental and model-derived SiO_2 values for each trial. Relative error values below 5% indicate a high degree of accuracy of the model.

Conclusion

The results of the study indicate that the SiO_2 content increases consistently with rising hydrochloric acid concentration. This relationship is given by the equation $SiO_2 = 60.78 + 0.187 \cdot X$, and the coefficient $R^2 = 0.9845$ testifies to an excellent fit of the model to the experimental data. The rate of the SiO_2 increase in the silica framework rises linearly with acid concentration, confirming that the process proceeds according to a linear mechanism.

The destructive change in the structure during acid activation with HCl results in fragmentation of montmorillonite particles. This way, the dispersity of the clay increases. During the first stage of activation, the exchangeable cations Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+} are leached out and replaced by H^{+} and Al^{3+} ions acting as active sites afterward. In the second stage, each particle was further divided into thinner units-down to a single elementary layer-while each fragment retains the internal structure of the original crystal packet.

Based on the above findings, it can be concluded that treating Navbahor alkaline-earth bentonite with HCl solutions up to 15% increases the adsorption properties of the clay, while treatment at 20% or higher concentrations results in degradation of the mineral crystal structure and a reduction in specific surface area.

The importance of this approach is that, based on the increase in SiO_2 content, one might predict increases in the specific surface area of the clay during activation and through mathematical modeling. This reduces the number of analyses involving such expensive analytical techniques as BET measurements.

This mathematical model of the acid activation process allows for a digital approach to enhance the specific surface area of bentonite, optimizes the concentration of hydrochloric acid, and minimizes the consumption of water during the neutralization of acidic effluents.

Conflicts of interest. On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Навабахор сілтілі бентонитін тұз қышқылымен белсендендіру кезінде SiO_2 мөлшерінің сызықтық артуын математикалық талдау

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ТҮЙІНДЕМЕ

Бұл зерттеуде май-тоң май өнеркәсібіне арналған ағартқыш сорбент алу мақсатында жүргізілген бентонит сазын қышқылдық активация процесіне математикалық талдау жүргізілді Әртүрлі концентрациядағы HCl әсерінде SiO_2 мөлшерінің артуы түрлі математикалық модельдер қолдану арқылы талданды. Қышқылдық активтендіру барысында қышқыл концентрациясының 5%-дан 20%-ға дейін жоғарылауы SiO_2 құрамының 61,94%-дан 65,12%-ға дейін өсуіне алып келді. Активтендіру кезінде HCl концентрациясының орташа деңгейде артуы кейбір компоненттердің еруі және белсенді орталықтардың қайта құрылуы есебінен саздың сорбциялық қасиеттерін жақсартады. HCl концентрациясының шамадан тыс жоғарылауы минералдық құрылымның бұзылуына және кремнезем қаңқасының ішінара ыдырауына алып келеді, бұл сорбциялық сипаттамаларға теріс әсер етеді. Әртүрлі математикалық әдістерді қолдану арқылы алынған мәліметтерді талдау белсендіру процесі кезіндегі SiO_2 құрамының жоғарылауы сызықтық модельге толық сәйкес келетінін көрсетті. Осыған сәйкес, сызықтық модель мына теңдеумен сипатталады: $y = 60.785 + 0.2088 \cdot X$. Сызықтық теңдеу арқылы алынған нәтижелердің дәлдігі детерминация коэффициенті $R^2 = 0.9845$ мәнімен расталды, бұл эксперименттік мәліметтермен жоғары сәйкестігін көрсетеді. Ұсынылған модель SiO_2 құрамының артуын математикалық түрде болжайды және активтендіру процесі сызықтық функция ретінде жүретінін дәлелдейді. Активтендіру процесін математикалық тәсілмен сипаттау саздың сорбциялық қасиеттерін алдын ала болжауға, қышқыл мен судың шығынын азайтуға, сонымен қатар басқа реагенттерге деген қажеттілікті есептеуге мүмкіндік береді.

Түйін сөздер: бентонит сазы, ативация, сорбциялық қасиеттер, математикалық модельдеу, сызықтық модель.

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Математический анализ линейного увеличения содержания SiO_2 при активации навбахорского щелочного бентонита соляной кислотой

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АННОТАЦИЯ

В данном исследовании был проведён математический анализ процесса кислотной активации бентонитовой глины, осуществляемой для получения отбеливающего сорбента для масложировой промышленности. Повышение содержания SiO_2 при различных концентрациях HCl было проанализировано с использованием разных математических моделей. В ходе кислотной активации увеличение концентрации кислоты с 5% до 20% привело к росту содержания SiO_2 с 61,94% до 65,12%. При активации умеренное повышение концентрации HCl улучшает сорбционные свойства глины за счёт растворения отдельных компонентов и перестройки активных центров. Чрезмерное увеличение концентрации HCl вызывает деградацию минеральной структуры и частичное разрушение кремнезёмного каркаса, что отрицательно сказывается на сорбционных характеристиках. Анализ полученных данных различными математическими методами показал, что повышение содержания SiO_2 в процессе активации полностью соответствует линейной модели. Согласно этому, линейная зависимость описывается уравнением: $y = 60.785 + 0.2088 \cdot X$. Точность результатов, полученных по линейному уравнению, подтверждена коэффициентом детерминации $R^2 = 0.9845$, что указывает на высокую согласованность с экспериментальными данными. Данная модель математически предсказывает увеличение содержания SiO_2 и доказывает, что процесс активации протекает как линейная функция. Математический подход к описанию процесса активации позволяет заранее рассчитывать сорбционные свойства глины, снижать расход кислоты и воды, а также определять потребность в других реагентах.

Ключевые слова: бентонитовая глина, активация, сорбционные свойства, математическое моделирование, линейная модель.

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