**Phosphate recovery from water using cellulose enhanced magnesium carbonate pellets: Kinetics, isotherms, and desorption**

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**Abstract**

Phosphorus is an essential and limited nutrient that is supplied by a depleting resource, mineral phosphate rock. Eutrophication is occurring in many water bodies which provides an opportunity to recover this nutrient from water. One method of recovery is through adsorption; this study focused on fabricating a porous and granular adsorptive material for the removal and recovery of phosphate. Magnesium carbonate was combined with cellulose in varying weight ratios (0, 5, 10, 15, 20%) to synthesize pellets, which were then calcined to increase internal surface area. Physiochemical properties such as surface area, surface morphology, elemental composition, and crystal structure of the materials were characterized using Brunauer, Emmett and Teller (BET) surface area analysis, X-ray diffraction (XRD), scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS). The pellet proved to be uniform in composition and an increase in BET surface area correlated with an increase in cellulose content until pellet stability was lost. Phosphate adsorption using the pellets was studied via batch kinetics and sorption isotherms. The *pseudo*-second-order kinetics model fit best suggesting that the adsorption occurring was chemisorption. The isotherm model that fit best was the Langmuir isotherm, which showed that the maximum equilibrium adsorption capacity increased with an increase in cellulose content between 10% and 20%. The average adsorption capacity achieved in the triplicate isotherm study was 96.4 mg g-1 for pellets synthesized with 15% cellulose. Overall, using cellulose and subsequent calcination created additional internal surface area for adsorption of phosphate and suggests that granular materials can be modified for efficient removal and recovery of phosphate from water.

**Keywords:** Phosphorus; Magnesium carbonate; Cellulose; Adsorption; Kinetics and sorption isotherms; Recovery of phosphate from water

1. **Introduction**

As the limiting nutrient in most waterways, increased loads of phosphorus (P) can cause eutrophication, which leads to hypoxia and the proliferation of harmful algal blooms [1–5]. Additionally, while viewed as a pollutant at excessive concentrations (*i.e.*, > 20 µg L-1) [6], phosphate (PO43-), the main species of phosphorus in the environment, is necessary for a range of industrial purposes including the production of agricultural fertilizers, animal feeds, and chemical pesticides [7]. Yet phosphate reserves are quickly declining [8], making the recovery and reuse of PO43- an essential component of phosphate remediation. Adsorption is a technique which can both remove and recover PO43- from aqueous suspensions and has been extensively studied. Adsorbents ranging from modified iron oxide [9,10], to calcined waste egg shells [11], to magnesium modified corn biochar [12] have been investigated for phosphate adsorption. However, adsorption suffers from the problem of bottle-necking (i.e., after saturation, the adsorbent will no longer be applicable) [13]. While the use of highly adsorptive fine powders, which can desorb phosphate after remediation, is a growing area of study [14], their removal from solution after adsorption is difficult. Therefore, the synthesis of a highly adsorptive, inexpensive, and granular sized sorbents, which can recycle PO43- would be extremely beneficial to the problem of nutrient pollution.

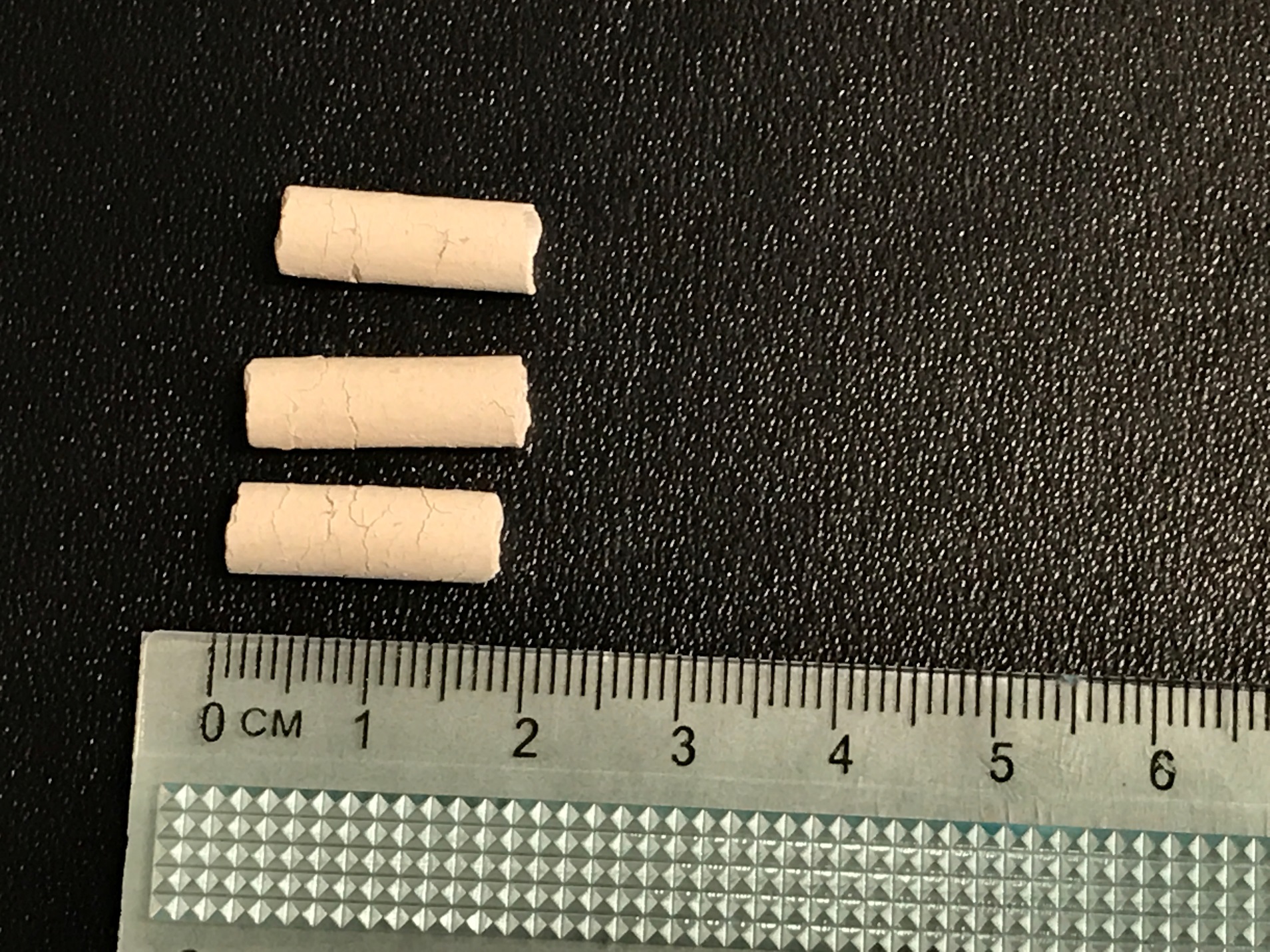
Magnesium (Mg) has been widely used in the medical field as a phosphate binder in dialysis patients as Mg can effectively bind PO43- without the adverse health effects demonstrated by aluminum and calcium [15–20]. Additionally, Mg salts have been used for environmental applications in drinking and wastewater [21,22]. For example, Mg has effectively been employed in enhanced biological phosphate removal (EBPR) processes, which allow phosphorus accumulating organisms (PAOs) to release P under anaerobic conditions and then excessively uptake P under aerobic conditions. The addition of Mg salts in EBPR processes under anaerobic conditions resulted in the formation of phosphate precipitates including newberyite (MgHPO4) and struvite (MgNH4PO4·6H2O) [23–25]. Newberyite and struvite can be used as slow-release fertilizers making their formation during phosphate remediation processes ideal for recycling PO43- [21,26–28].

For the above PO43- remediation processes, powdered, water-soluble Mg salts (e.g., magnesium chloride) were used [21,27]. Here, magnesium carbonate (MgCO3) was selected to prepare pellets (i.e., 6 mm x 17 mm) as phosphate adsorbents due to its very low water solubility (i.e., 0.11 g L-1 at 25 °C) [29]. Mechanically stable pellets were prepared by blending different ratios of MgCO3 and cellulose, which acted as a binder. After pellet stability in water was ensured, phosphate adsorption was evaluated.

1. **Experimental**

*2.1 Materials*

Analytical grade MgCO3 powder (Fisher Scientific) was made into pellets, 6 mm in diameter and 17 mm in length on average, using the MZL Flat Die Pellet Mill (Xuzhou Orient Industry) as seen in Figure 1. Varying amounts of a cellulose binder, average particle size of 20 µm (Sigma Aldrich), was used to optimize the pellet design. Pellets were made with a constant moisture content of 45% water to MgCO3 weight ratio. Cellulose was added in varying weight ratios from 0 – 20%. Conditions for use of the pellet mill were kept as consistent as possible, but the instrument did allow for variation as related to the length of pellets made. After synthesis, the pellets were calcined at 300 °C to remove cellulose for additional porosity without complete decomposition of the magnesium carbonate. Five specific pellet conditions were selected for further study with regard to cellulose ratio and calcination time: 0% cellulose calcined for 17 hours (0%17), 5% cellulose calcined for 1 hour (5%1), 10% cellulose calcined for 2 hours (10%2), 15% cellulose calcined for 1 hour (15%1) and 20% cellulose calcined for 2 hours (20%2). The phosphate stock solution was created using analytical grade sodium phosphate monobasic dihydrate (NaH2PO4 ·2H2O) (Fisher Scientific).



**Figure 1.** Pellets were synthesized with magnesium carbonate and cellulose for phosphate adsorption (photo by E. Martin).

*2.2 Sample Characterization*

Pellet composition was examined using SEM-EDS (EDAX JEOL 7401) performing both a line scan and cross section scan of the pellet from each batch. The uniformity was determined by comparing the percentage of carbon (C), oxygen (O) and Mg present across each scan. The BET surface area was determined using the NOVA 2000e Surface Area & Pore Size Analyzer (Quantachrome). Samples were first purged with nitrogen gas at 150 °C overnight before analysis. The surface morphology of the MgCO3 pellets was observed using SEM (Philips XL 30 ESEM-FEG), at an accelerating voltage of 30 kV. The crystal structure was determined using XRD (PANalytical X’Pert) with the 2-theta diffractometer under CuKα radiation and a wavelength of 1.54 µm and the XRD patterns were analyzed using JADE software (MDI, Inc., Livermore, CA).

*2.3 Adsorption studies*

*Kinetic studies.* Kinetic experiments were conducted to understand the adsorption reaction rates between adsorbate and adsorbent phosphate concentration. The initial conditions for the kinetic study were: (i) adsorbent amount: one pellet (~0.4 g), (ii) temperature: 22.7 °C ± 0.5, (iii) pH: 7.0 ± 0.1, (iv) target phosphate concentration: 160 mg L-1, and (v) mixing speed: 150 rpm. The study was conducted with 125 mL of the sodium phosphate monobasic dihydrate stock solution mixed with the five different MgCO3 pellet compositions in 125 mL Nalgene polypropylene bottles and placed on a G10 Gyrotary shaker (New Brunswick Scientific Co., Inc., USA). Samples were taken at various times (1, 2, 3, 4, 7, 9, 11, 14, 18 and 25 days) to analyze for phosphate concentration remaining in the solution. The samples were filtered using a 0.45 µm nylon syringe filter (Whatman) and analyzed for phosphate using a UV-Vis spectrophotometer (DR 2700, HACH) via the US EPA PhosVer 3® (Ascorbic Acid) method at 880 nm. The experiment was conducted once and the phosphate samples were analyzed in duplicate and averaged.

*Sorption studies.* Next, an isotherm experiment was completed with varying sorbent masses, from 1 (~0.4 g) to 6 (~2.4 g) pellets, to find the maximum equilibrium adsorption capacity of each material. The phosphate concentration in the stock solution was raised to 330 mg L-1 but, otherwise, the conditions were the same as for the kinetics studies. The various 125 mL Nalgene bottles were left on the shaker for 25 days to reach equilibration and then analyzed for phosphate concentration remaining in solution using the US EPA PhosVer 3® method. The isotherm with all five pellet compositions was conducted once. An additional isotherm experiment for the 15%1 pellet was conducted in triplicate. All of the phosphate analysis was conducted in duplicate and averaged.

*2.4 Desorption experiment*

Desorption experiments were conducted using 4 – 6 pellets from the isotherm adsorption experiment in various solutions to analyze the recovery of phosphate. Two solutions varied pH in an attempt to achieve desorption: 0.1 M HCl and 0.1 M NaOH. Pellets were also placed into deionized water just to measure leaching without changing pH. The spent adsorbents were placed in 125 mL Nalgene bottles with 125 mL of each various solution and left on the shaker at a mixing speed of 150 rpm for 25 days, as with the isotherm experiments. The concentration of phosphate that returned to the solution was measured using the US EPA PhosVer 3® Method mentioned in Section 2.3 and the desorption percentage of phosphate was calculated. This experiment provided insight into the ability of the pellets to release phosphate as a potential slow release fertilizer.

1. **Results** 
   1. *Sample characterization*
      1. *Physical characteristics*

The first step for pellet characterization was to ensure that the pellets were uniform in composition. This was accomplished by investigating two separate batches of a pellet from the same recipe, namely the 15%1 pellet. One pellet from each batch was analyzed using SEM via a line scan as well as a cross section scan. The elemental composition of these pellets prior to adsorption was determined using EDS for Mg, O, and C. Figure 2 shows the percentage range of each element across the particular scan of the pellet.

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**Figure 2.** Line scan and cross section scans of two 15% cellulose samples for carbon, oxygen and magnesium;(a) line scan of sample 1, (b) cross section scan of sample 1, (c) line scan of sample 2, (d) cross section scan of sample 2.

The two cross section scans have the same distance scanned because the diameters of the pellets were limited to the diameter of the die hole on the pelletizer, which was about 6 mm. The line scans show the variety in length of the two pellets. Overall, the range of percentages of each element were consistent for the two pellets in both the line scan and the cross section scan. The carbon and magnesium percentages ranged from 15 – 35% and the oxygen ranged from 45 – 55%. This showed uniform composition between the two batches and demonstrated the random distribution of each element within the pellet.

Physical properties of the pellets are summarized in Table 1. The BET surface areas for the 0%17, 5%1, 10%2, 15%1, and 20%2 pellets were 27.5, 33.2, 36.9, 43.1, and 37.6 m2 g-1, respectively. As the ratio of cellulose increased, the BET surface area increased until the 20%2 sample. At this point, the stability of the pellet began to be lost which could account for the decrease in surface area. The 20%2 sample had more visual char that was clogging the pores and decreasing the surface area. As expected, the addition of cellulose provided additional internal surface area.

**Table 1.** Physical characteristics for the 5 various pellet recipes (n = 100).

|  |  |
| --- | --- |
| General Characteristics |  |
| **Diameter** | 6.0 mm ± 0.05 |
| **Length** | 17.0 mm ± 2.13 |
| **Surface area** | 377.0 mm2 ± 40.63 |
| **Volume** | 480.8 mm3 ± 61.56 |
| **Weight** | 0.4 g ± 0.05 |

|  |  |  |
| --- | --- | --- |
| Pellet specific characteristics | Weight change from calcination (%) | BET Surface Area (m2 g-1) |
| **0%17** | -64 ± 2 | 27.5 |
| **5%1** | -49 ± 2 | 33.2 |
| **10%2** | -46 ± 2 | 36.9 |
| **15%1** | -51 ± 2 | 43.1 |
| **20%2** | -59 ± 4 | 37.6 |

* + 1. *Surface morphology of the pellets*

Figure 3 shows SEM images of the surface of the 0% cellulose baseline pellet and the 10% cellulose pellet before and after phosphate adsorption. Many particulate aggregates were observed on the surface of the MgCO3 pellets before phosphate exposure. To confirm phosphate adsorption on the surface of the pellet, the elemental composition was checked with EDS. A clear peak was seen for phosphorus on the 10%2 pellet while the 0%17 pellet did not have such a clear peak. This illustrated that increased cellulose content resulted in an increase in phosphate adsorption, as expected.



**Figure 3.** SEM images of (a) 0%17 pellet before adsorption, (b) 0%17 pellet after adsorption, (c) 10%2 pellet before adsorption and (d) 10%2 pellet after adsorption (all scale bars represent 1 µm).

* + 1. *XRD analysis*

The XRD patterns for each sample before and after an adsorption isotherm showed that cellulose, periclase (MgO) and brucite (MgOH) were present for the pellets before adsorption. As shown in Figure 4a, the pellets had both variations of magnesium present due to mixing magnesium carbonate with water and then calcining the pellets. After adsorption experiments were conducted, magnesium variations were detected mostly as hydromagnesite (Mg5(CO3)4(OH)2·4H2O) with some remaining brucite and magnesium phosphate (as cattiite) as shown in Figure 4b. The pellet with the most phosphate present was the 15%1 pellet as seen with the highest peak of cattiite. Finding magnesium phosphate after the adsorption experiments further confirmed that adsorption occurred and that the increased surface area from cellulose addition was providing additional adsorption capacity.



**Figure 4.** XRD patterns of the various pellets (a) before and (b) after adsorption isotherms were conducted.

*3.2 Adsorption studies*

*3.2.1 Kinetic studies*

An adsorption experiment was conducted to determine the equilibrium time for the phosphate concentration remaining in the solution after pellets had reached adsorption capacity. Figure 5 shows how the phosphate concentration in solution changed with respect to time and suggested an apparent equilibrium time of 600 hours or 25 days. Each recipe removed a different overall percentage of phosphate; 0%17 removed 34%, 5%1 removed 80%, 10%2 removed 72%, 15%1 removed 95% and 20%2 removed 81%.



**Figure 5.** Phosphate concentration remaining in solution over time as the various pellet recipes reached adsorption capacity.

Batch experiments, with one pellet in 125 mL of a solution with target phosphate concentration of 160 mg L-1, were conducted to determine the rate of phosphate adsorption, specifically to find the order of the rate constant. The kinetics of each of the five pellet recipes were studied and compared with the *pseudo*-first-order (Figure 6a) and *pseudo*-second-order (Figure 6b) kinetics models to find the best fit using a linear regression analysis.



**Figure 6.** Linearized (a) *pseudo* first-order kinetics model and (b) *pseudo* second-order model applied on the four various pellet recipes.

The *pseudo*-first-order model and *pseudo*-second-order model are, respectively, as follows:

(1)

(2)

where qe is the amount of adsorbate adsorbed per unit mass of adsorbent (mg g-1) at equilibrium, qt is the amount of adsorbate adsorbed per unit mass of adsorbent (mg g-1) at time t, k1 (hr-1) and k2 (g mg-1 hr-1) are the rate constants for the *pseudo*-first-order model and *pseudo*-second-order model, respectively. The linear forms of the models, the parameters, and how the parameters correlate with each model (R2) are listed in Table 2. The pellet recipe without cellulose is not included since it is the baseline.

**Table 2.** Adsorption kinetic models, the corresponding linear forms and parameters of MgCO3 pellets with various amounts of cellulose for 4 different synthesis conditions (percent cellulose and calcination time) with initial pH 7 at 23 °C.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Sorbent | *Pseudo*-first-order | | |  | *Pseudo*-second-order | | |
|  | qe (mg g-1) | k1 (hr-1) | R2 |  | qe (mg g-1) | k2 (g mg-1 hr-1) | R2 |
| 5%1 | 33.34 | 0.0095 | 0.9824 |  | 36.22 | 0.0004 | 0.9880 |
| 10%2 | 36.91 | 0.0084 | 0.9497 |  | 40.50 | 0.0003 | 0.9979 |
| 15%1 | 56.49 | 0.0118 | 0.9959 |  | 52.25 | 0.0003 | 0.9959 |
| 20%2 | 27.48 | 0.0071 | 0.9312 |  | 43.54 | 0.0005 | 0.9988 |

Overall the best fit model was the *pseudo*-second-order model with R2 > 0.98 for all pellet recipes, but the *pseudo*-first-order model fit all recipes with R2 > 0.93 so both models had strong correlation, which has been found in other phosphate adsorption experiments[12,30–36]. The *pseudo*-second-order model indicates that the adsorption that occurred was chemisorption, which assumes monolayer adsorption. The highest model adsorption capacity for both models occurred for the 15%1 pellet; qe was 56.49 mg g-1 for *pseudo*-first-order and 52.25 mg g-1 for *pseudo*-second-order. In the *pseudo*-second-order model, k2qe2 represents the initial adsorption rate. The rate for the 5%1, 10%2, 15%1 and 20%2 pellets were as follows: 0.492, 0.449, 0.823 and 1.021 mg g-1 hr-1, respectively. This means that although the 15%1 pellet has the highest adsorption capacity, the 20%2 recipe had the fastest initial adsorption rate with 15%1 as a close second.

*3.2.2 Sorption isotherms*

Sorption isotherms describe the relationship between the equilibrium adsorbate concentration in the solution and the amount of phosphate adsorbed on the adsorbent. Batch experiments, with one to six pellets in 125 mL of a solution with target phosphate concentration of 330 mg L-1, were conducted to determine the maximum adsorption capacity of the pellets. Isotherm data was fitted to both the Langmuir and Freundlich models to determine the best fit using a regression analysis as shown in Figure 7a and 7b, respectively.



**Figure 7.** Linearized (a) Langmuir model and (b) Freundlich model applied on the four various pellet recipes.

The linearized Langmuir equation is as follows:

(3)

where qe is the amount of adsorbate adsorbed per unit mass of adsorbent (mg g-1), Ce is the amount of unadsorbed adsorbate concentration in solution at equilibrium (mg L-1), qmax is the maximum amount of adsorbate per unit mass of adsorbent to form a complete monolayer on the surface (mg g-1), and KL is a constant related to the affinity of the binding sites (L mg-1). Similarly, the linearized Freundlich equation is as follows:

(4)

where KF is the adsorption capacity of the adsorbent (mg g-1 (L mg-1)1/n) and n indicates sorption favorability. The parameters found via plotting these linearized equations are shown in Table 3, excluding the 0% cellulose baseline pellet.

**Table 3.** Adsorption isotherm models, the corresponding linear forms and parameters of MgCO3 pellets with various amounts of cellulose for 4 different synthesis conditions with initial pH 7 at 23 °C.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Sorbent | Langmuir isotherm | | |  | Freundlich isotherm | | |
|  | qmax (mg g-1) | KL (L mg-1) | R2 |  | KF (mg g-1 (L mg-1)1/n) | n-1 | R2 |
| 5%1 | 18.69 | -0.1264 | 0.9761 |  | 17.47 | 0.0683 | 0.8257 |
| 10%2 | 14.47 | -0.1247 | 0.9381 |  | 20.61 | 0.1900 | 0.9513 |
| 15%1 | 28.17 | -0.4517 | 0.9917 |  | 19.57 | 0.2126 | 0.7094 |
| 20%2 | 44.25 | 0.9741 | 0.9995 |  | 16.06 | 0.4031 | 0.9124 |

Based on this analysis, the best fit for the isotherm studies was the Langmuir model revealing that the adsorption occurred in a monolayer fashion. This confirms the findings that the *pseudo*-second-order kinetics model fit best, which also assumes monolayer adsorption. The maximum theoretical adsorption capacities found using the Langmuir model were: 18.7, 14.5, 28.2, and 44.3 mg g-1 for 5%1, 10%2, 15%1 and 20%1 pellets, respectively. Here the 20%2 pellet had the highest capacity, but this is the least stable pellet.

The final isotherm conducted was completed for the 15%1 pellet in triplicate with the 330 mg L-1 solution to find the reproducibility of the adsorption capacity. The results were modeled with the linearized Langmuir and Freundlich models as shown in Figure 8a and b, respectively. The parameters determined from these models are listed in Table 4.



**Figure 8.** Linearized (a) Langmuir model and (b) Freundlich model applied on the triplicate isotherm experiment with 15%1 pellets.

**Table 4.** Adsorption isotherm models, the corresponding linear forms and parameters of MgCO3 pellets with 15% cellulose with initial pH 7 at 23°C. Data from triplicate experimental runs.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Sorbent | Langmuir isotherm | | |  | Freundlich isotherm | | |
|  | qmax (mg g-1) | KL (L mg-1) | R2 |  | KF (mg g-1 (L mg-1)1/n) | n-1 | R2 |
| 15%1 | 91.74 | 0.3586 | 0.9657 |  | 28.95 | 0.2825 | 0.9457 |
| 15%1 | 116.28 | 0.5478 | 0.9785 |  | 36.46 | 0.4531 | 0.7824 |
| 15%1 | 81.30 | 0.4786 | 0.9944 |  | 29.89 | 0.2333 | 0.7358 |
| Average | 96.44 ± 18.0 | 0.46 ± 0.1 |  |  | 31.76 ± 4.1 | 0.32 ± 0.1 |  |

The triplicate analysis of the 15%1 pellet resulted in an average qmax of 96.4 mg g-1 with a standard deviation of 18 mg g-1 and relative standard deviation of 18.6% for the experiments. The variation in predicted adsorption capacity from the kinetics and isotherm experiments can be explained by the variation in diffusion and surface area of pellets exposed to the solution. The bottles in the kinetics experiment were moved from the shaker for each sample throughout the experiment whereas the bottles in the isotherm experiment were kept on the table until the full 25 days had passed. During the movement for the kinetics experiment, the pellet may have shifted in the solution and exposed additional surface area for adsorption.

*3.3 Desorption experiment*

Since the adsorption of phosphate was proven reasonably successful, pellets from the isotherm were studied for the ability to recover phosphate through desorption. Three different solutions were used to try to achieve this: deionized water (pH ~ 6.6), 0.1 M HCl (pH < 2) and 0.1 M NaOH (pH ~ 12.4). Table 5 shows the percentage of desorption seen after 25 days. This desorbability parameter is defined by the ratio of phosphate desorbed over phosphate adsorbed and provides an indicator for phosphate recovery potential.

**Table 5.** Desorption of adsorbed phosphate using three different solutions.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sorbent | 0.1 M HCl | | | 0.1 M NaOH | | | DI Water | | |
|  | Adsorbed PO43- (mg g-1) | Desorbed PO43- (mg g-1) | Desorption Percentage | Adsorbed PO43- (mg g-1) | Desorbed PO43- (mg g-1) | Desorption Percentage | Adsorbed PO43- (mg g-1) | Desorbed PO43- (mg g-1) | Desorption Percentage |
| 5%1 | 7.29 | 0.26 | 3.6 % | 10.69 | 0.14 | 1.3 % | 8.93 | 0.01 | 0.1 % |
| 10%2 | 7.65 | 0.06 | 0.7 % | 11.98 | 0.23 | 1.9 % | 9.43 | 0.01 | 0.1 % |
| 15%1 | 8.32 | 0.08 | 1.0 % | 12.69 | 0.56 | **4.4 %** | 10.44 | 0.01 | 0.1 % |
| 20%2 | 9.25 | 0.07 | 0.8 % | 13.91 | 0.35 | 2.5 % | 11.07 | 0.01 | 0.1 % |

Based on the results, leaching into water without a desorption aid was negligible. Even with the change in pH, only as much as 4% of phosphate was desorbing. To further investigate what was occurring on the surface of the pellet, XRD analysis was conducted on each pellet after desorption in the acidic and basic solutions (Figure 9a and 9b, respectively).



**Figure 9.** XRD patterns of the various pellets after (a) 0.1M HCl solution and (b) 0.1M NaOH solution desorption experiments were conducted.

From the figure, magnesium phosphate was no longer detected on the pellets after the desorption period (25 days). On closer inspection for the experiment with the acidic solution, phosphorus was detected via EDS but may have been amorphous and not detectable by XRD. For the basic solution desorption experiment, the XRD pattern was shifted slightly such that the phosphate compound and hydromagnesite peaks were not differentiable.

1. **Conclusions**

MgCO3 pellets prepared with varying amounts of cellulose were found to be effective adsorbents for removing phosphate from aqueous suspensions. The calcination of the pellets with higher cellulose ratios proved to result in increased BET surface area until the pellet with 20% cellulose. The highest surface area achieved was 43.1 m2 g-1 for the 15%1 pellet. The increased surface area corresponded to an increased adsorption capacity as seen through the Langmuir models. Although the highest theoretical adsorption capacity was 44.3 mg g-1 for the 20%2 pellet from the isotherm, the 15%1 pellet showed the most promise from kinetics experiments and surface area analysis. The 20%2 pellet was the least stable after calcination so the 15%1 pellet would provide adsorption without the stability being lost. From the isotherm experiments conducted for the 15%1 pellet, the adsorption capacity had an average of 96.4 mg g-1. The surface of the pellets changed as phosphate was adsorbed as shown by the SEM and XRD analysis. While enhanced P availability might occur when exposed to the real world, the simple dissolution/desorption experiment suggested quite minimal release. It, of course, says nothing about very slow release.

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