

## Research article

### Optimization of CO<sub>2</sub> Adsorption and Physical Properties for Pelletization of Zeolite 5A

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#### Abstract

##### Keywords

zeolite 5A;  
zeolite pellet;  
CO<sub>2</sub> adsorption;  
pelletization;  
powder shaping process

This research investigated the effects of compression force, compression time, and addition of bentonite binder on zeolite 5A pelletization. Carbon dioxide (CO<sub>2</sub>) adsorption of zeolite 5A pellets was tested in a laboratory-scale packed-bed reactor at 298 K, atmospheric pressure and 2 l/h flow rate. Zeolite 5A pellets were prepared using a pelletization technique at 200-400 MPa compressive force, 5-15 min compression time, and with 0-15% wt. of bentonite binder. The specific surface area and density of zeolite 5A pellets increased with increase of compression force. Compression force led to increase in specific surface area and resulted in an agglomeration of zeolite pellets, making CO<sub>2</sub> molecules more difficult to become active sorbent. The addition of bentonite into zeolite 5A pellets with more compression time resulted in the reduction of specific surface area. The compression force and mass fraction of the binder were found to offer significant control over CO<sub>2</sub> adsorption capacity. No addition of binder, 200 MPa compression force and 5 min compression time resulted in a maximum CO<sub>2</sub> adsorption capacity of 3.64 mmol CO<sub>2</sub>/g. This research indicated that zeolite 5A pellets have a beneficial effect and high potential as an adsorbent, especially in terms of CO<sub>2</sub> adsorption and environmental applications.

## 1. Introduction

Current research indicates that within months of the novel coronavirus outbreak, a dramatic reduction in CO<sub>2</sub> emissions occurred. As a result, the world's energy demand has drastically reduced. The International Energy Agency (IEA) noted that global CO<sub>2</sub> emissions were 30.6 Gt for 2020, down nearly 8% from 2019 [1]. However, global land and ocean surface temperatures were the highest in 141 years.

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[2]. According to global carbon dioxide emission data in 2020, industrial plants had the highest levels of CO<sub>2</sub> emissions (22%), therefore, industrial plants have been seen as beneficial places to research, and to develop technology to be used in managing and reducing CO<sub>2</sub> in the future [3]. The most common adsorbents used for CO<sub>2</sub> emission reduction are activated carbon, metal organic frameworks (MOFs), polymers, and zeolite.

Zeolite is a highly stable solid that is more environmentally resistant than other materials. The most interesting thing about zeolite is its open, cage-like framework structures that can trap other molecules inside it. Generally, zeolite is in the form of powder, and this causes various restrictions on its use in industry such as loss as dust, high pressure drops through a reactor, changes in flow properties, and caking and lump formation [4, 5]. The shaping process of the zeolite into pellets can produce a uniform pack that allows an optimal use of the tank volume. The pellets have better mechanical properties, are hard and friction resistant, and can be handled easily. Production of adsorbent materials in industrial processes is a major challenge in facilitating the use of materials and making the process closer to commercialization.

Previous pelletization research has shown that the adsorbent material that incorporates PEI impregnated MCM-41, when pelletized has a CO<sub>2</sub> adsorption capacity that is approximately 10% lower than that of the powder adsorbent when the adsorbent is pelletized at 18-35 mesh [6]. The efficiency of SBA-15 supported PEI pellets were evaluated for their selective CO<sub>2</sub> capture. The powder material was pelletized under pressure of 7600 psig for 10 min. The pelletization results of the pelletized SBA-PEI material having the same adsorption kinetics as the powder sorbent slightly decreased the adsorption capacity of approximately 18% [7]. A recent study carried out by Peterson *et al.* [8] showed the effects of pelletization pressure on the physical and chemical properties of MOF, Cu<sub>3</sub>(BTC) and UiO-66. Both Cu<sub>3</sub>(BTC) and UiO-66 which had been pressed at 1,000 and 10,000 psig pressure into pellets; they were also partially degraded in porosity. Rezaei *et al.* [9] showed that surface area and pore volume were significantly reduced in amine-based pellet samples at 5,000 psig compared to the adsorbent powders due to pore blockage and collapse of pore structures under pressing. There were slow absorption kinetics and poor internal mass transfer for CO<sub>2</sub> adsorption at 1,000 psig, which were similar to those observed at 5,000 psig pressure. For pelleting under 1,000 psig pressure, the resulting pellets exhibited adsorption properties similar to adsorbent powder. Despite the preliminary investigations described above, there is no systematic study in the literature that shows to what extent pelletization pressure affects the physical properties of zeolite adsorbents. This research is therefore concerned with establishing the suitable factors and conditions for zeolite pelletization in order to promote optimum CO<sub>2</sub> adsorption efficiency.

Zeolite pellets are commercially prepared by mixing zeolite powder and inorganic binders such as bentonite clays, which provide structural mechanical stability during and after preparation [10]. Silicalite, ZSM-5 and zeolite A monoliths were also prepared using bentonite as a binder, and air separation efficiency was assessed [11-13]. However, the binder reduced the purity and degraded the effectiveness of the sorbent by blocking adsorbate access to zeolite crystals [11, 14-19]. Puccini *et al.* [20] studied the ratios of layered graphite binder and zeolite to provide good hardness and structure. The binder content in excess of 40 wt% reduced the good properties. In addition, zeolite NaY nanoparticles were shaped into spherical beads using bentonite clay. It is intended to improve the mechanical stability of the spherical beads. However, adding the binder reduces the N<sub>2</sub> adsorption capacity by 19.2% at 77 K and reduces the maximum Sr<sup>2+</sup> adsorption per granulation by 35% [21]. Pelletization is commonly compression or formation prior to size enlargement and applied mechanical forces [22-24]. However, mechanical forces and hold time will affect the properties of the pellet such as pore volume.

Therefore, it is worthwhile to investigate the adsorption characteristics of pelletized materials to explain how they compare with their powders. The motivation behind the current work is therefore to identify suitable pressures for pressing zeolite 5A adsorbents and making zeolite-binder pellets that can facilitate the utilization of such materials in practical CO<sub>2</sub> adsorption processes. This research

investigated key factors for physical properties and CO<sub>2</sub> adsorption capacity of the zeolite pellet, including 200-400 MPa compression forces, 5-15 min compression times and 0-15% wt. of bentonite.

## **2. Materials and Methods**

Commercially available zeolite 5A powder used for pelletization in this research was purchased from Thaisilicate Chemicals Co., Ltd., Thailand. The bentonite clay used as a binder of zeolite pellets was purchased from NIC Interchem Co., Ltd., Thailand. The pelletization processes were conducted in three parts: 1) shaping without binder and different compression forces, 2) shaping with optimum force and different wt.% of binder, and 3) shaping with optimum binder and different compression time.

### **2.1 Shaping without binder and different compression forces**

Shaping zeolite pellets without binder and different compression forces was used to find the optimum compression force of the pelletization process. Zeolite powder without binder was poured into each hole of the mold and then pressed by a hydraulic press at 200, 300 and 400 kPa for 10 min. The zeolite pellet was then dried to remove moisture at 378 K for 4 h. This was continued at 773 K for 3 h (Figure 1).

### **2.2 Shaping with optimum force and different wt.% of binder**

The zeolite powder was mixed with water and 5, 9 and 15 wt. % bentonite, respectively. The mixture was kneaded to obtain a paste mixture. The paste was pelletized into the form of pellets, using a hydraulic press at optimum compression force for 5 min. The zeolite pellet was then dried and calcined at 773 K for 3 h, as shown in Figure 1b.

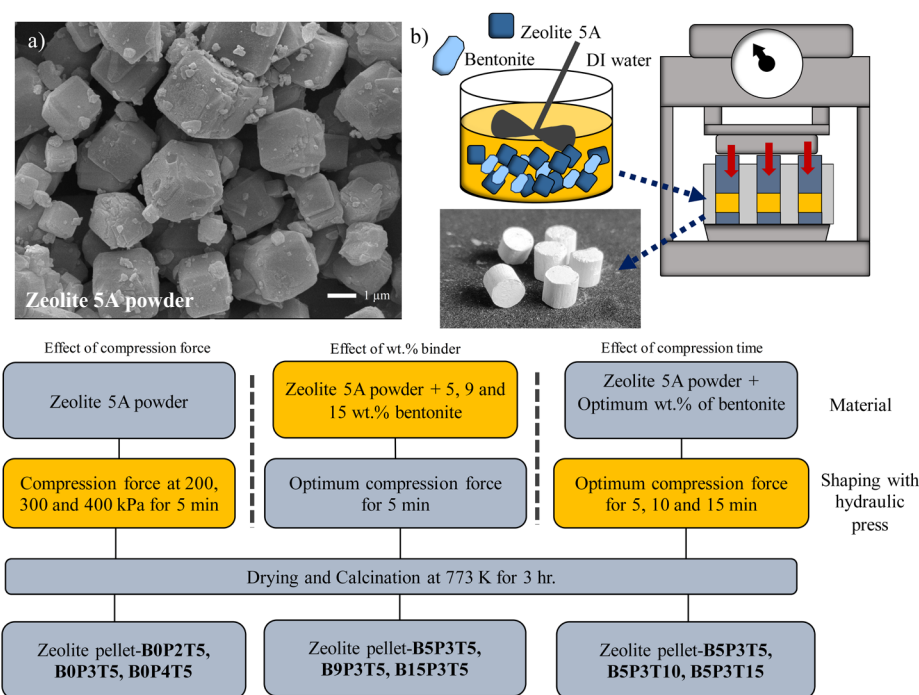
### **2.3 Shaping with optimum binder and different compression time**

The zeolite powder was mixed with optimum wt. % of bentonite binder and water. The pelletization with the hydraulic press machine was compressed at 300 kPa force for 5, 10 and 15 min. The zeolite pellet was dried and calcined as shown in Figure 1.

The resulting zeolite pellets were cylindrical shaped with 0.5 cm diameter and 0.5 cm height (Figure 1). The zeolite pellet samples were named according to their pelletizing condition; B0P2T5, B0P3T5, B0P4T5, B5P3T5, B9P3T5, B15P3T5, B5P3T10 and B5P3T15. The number after each letter B denoted wt.% of bentonite binder, after each P denoted compression force, and after each T represented the compression time.

The morphology of the zeolite pellet was examined by SEM photographs taken with a FEI model QUANTA 450 SEM system. It was operated at an accelerating voltage of 15 kV. The obtained pellets with good shape were analyzed via SEM. The zeolite pellet samples for SEM analysis were prepared by immersing the pellets in liquid nitrogen and cutting them in half to examine the inside of the pellets. The specific surface area was evaluated from nitrogen adsorption isotherm measurements. The surface area and porosity analysis were done using a BELL model BELSORP-MINI apparatus. The surface area and porosity analyzer were measured on whole broken pellets.

Zeolite 5A pellets of 1 g were packed into the adsorption column. The adsorption column was heated in a furnace connected with a CO<sub>2</sub> analyzer (Handheld carbon dioxide meter, GM 70). The CO<sub>2</sub> adsorption of each zeolite pellet was tested at atmospheric pressure, 298 K and 2 l/h CO<sub>2</sub> flow rate. The CO<sub>2</sub> adsorption capacity was defined in equation (1).



**Figure 1.** Schematics of the pelletization process of zeolite 5A and bentonite binder by hydraulic press

$$q_e = \left( \frac{C_0 - C}{W} \right) * \frac{vt}{M_w} \quad (1)$$

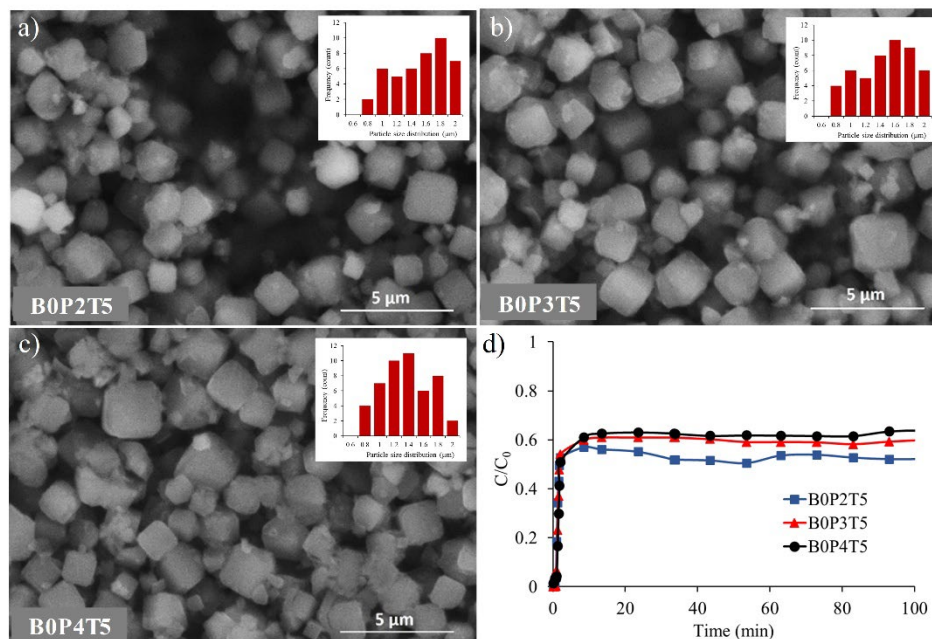
Where  $q_e$  is the equilibrium adsorption capacity,  $C_0$  and  $C$  are the concentrations initial and equilibrium of  $\text{CO}_2$  respectively;  $v$  is  $\text{CO}_2$  flow rate;  $M_w$  is the molecular weight of  $\text{CO}_2$ ;  $W$  is the weight of zeolite pellet and  $t$  is time.

### 3. Results and Discussion

#### 3.1 Effect of compression forces

Compression force is one of the main pelletization factors that affect the physical properties and  $\text{CO}_2$  adsorption capacity of zeolite 5A pellets. The characterization results from SEM photographs shown in Figure 2 indicate that increase in compression force made the zeolite 5A particles within the pellet come very close together. This resulted in  $\text{CO}_2$  adsorption capacity decreasing to 3.64, 3.37 and 1.89 mmol/g at compression force of 200, 300 and 400 kPa, respectively.

The inconsistent results suggested that the surface area of pellets was increased but the  $\text{CO}_2$  adsorption was reduced due to the increasing compression force. Because the zeolite 5A particles were compressed and broken into small pieces, the zeolite 5A particles were smaller than the original ones and the resultant density of the zeolite 5A pellets was increased from 1294 to 1593  $\text{kg/m}^3$ . Zeolites 5A



**Figure 2.** Scanning electron micrograph of zeolite pellets with different compression forces (a) 200, (b) 300 and (c) 400 kPa, (d) breakthrough curves of zeolite pellet with different compression forces

was inferred to be of 1.9  $\mu\text{m}$  average crystals size. When zeolite pellets were compressed at 400 kPa, the particle size was reduced to 1.3  $\mu\text{m}$  size approximately, as shown in Figure 2. When the zeolite particle size was reduced, the surface area increased; however, the zeolite particles were also closed up. Therefore, it was difficult for  $\text{CO}_2$  molecules to reach the zeolite particles. Lower mass transfer resulted in lower  $\text{CO}_2$  adsorption efficiency at 400 kPa compression force.

### 3.2 Effect of bentonite binder

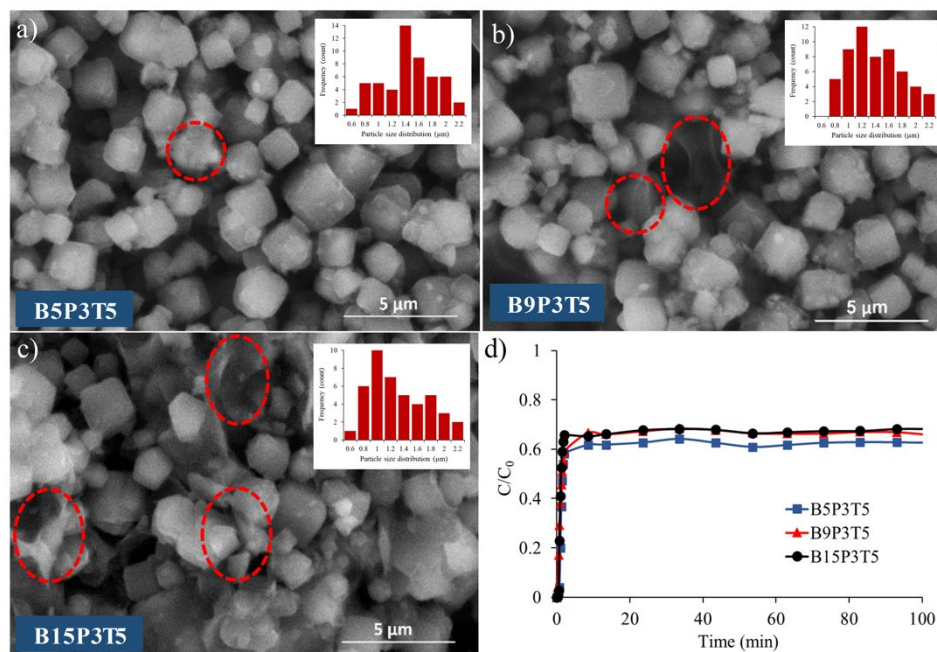
The adsorbent material is very important in the adsorption process. Fluid flow through the adsorbent during operating may break or degrade the adsorbent material chemically. Moreover, attrition/abrasion occurs between the adsorbent materials and also between the adsorbent material and reactor wall. As mentioned above, dust problems such as blocking of valves have occurred while running an adsorption process. In order to avoid dust formation, binders must be used appropriately. However, an excess amount of binder may affect the  $\text{CO}_2$  adsorption efficiency, physical properties, pore volume and surface area, and also compressive strength of zeolite pellets. Therefore, the optimum conditions for adding binder to zeolite 5A powder to form zeolite 5A pellets were carried out. The pelletization of zeolite pellets was done at 300 kPa compressive force since the results in section 3.1 had shown that there was a large gap between the zeolite crystals in the pellets at 200 kPa (Figure 2a), and zeolite crystals were broken into smaller pieces at 400 kPa (Figure 2c). Figure 3 showed the results of adding bentonite binder. In fact, the pore size must be appropriate to allow the adsorbed molecules to penetrate within. Increasing the bentonite binder at 5, 9, 15 wt.% decreased pore volume of pure zeolite 5A starting from the variant with no added binder from 0.2208  $\text{cm}^3/\text{g}$  to 0.1606, 0.1601 and 0.1869  $\text{cm}^3/\text{g}$ , respectively. The characteristics of the zeolite 5A powder were cubic shaped crystals of smooth surface, as shown in Figure 1a. When the bentonite binder was added, the bentonite adhered to the external surface of zeolite



5A particle, which then appeared as fibers bound between zeolite particles, as SEM micrographs shown in Figures 3a, 3b and 3c. The red dotted circles indicate the formation of “bentonite-bridges” on the zeolite interface that formed after the calcination resulted in pore volume reduction with an increase of bentonite content.

In addition, previous research on bentonite and CO<sub>2</sub> adsorption found that the CO<sub>2</sub> adsorption capacity varied from 0.11 to 0.32 mmol/g at 298-318 K and 1 atm [25-27]. It was seen that there was very low adsorption capacity due to the structure of bentonite, which was composed of H<sub>2</sub>O and cations. These molecules that were involved in high relative humidity hindered the access of CO<sub>2</sub> molecules within the interlayer spacing. Furthermore, the CO<sub>2</sub> adsorption capacity on zeolite 5A powder in this research was 3.8 mmol/g at 298 K, 1 atm. When shaping zeolite powder into the pellets with bentonite, there was a pressure drop in the column, and the product could be easily regenerated and stored. However, zeolites with binder showed a slight decrease in CO<sub>2</sub> adsorption efficiency compared to those without binder.

The percentage of bentonite was varied and ranged from 5 to 15 wt.%. This was done in order to identify the optimal amount needed to produce good hardness and ensure the porous structure of the pellets. However, when the bentonite binder was increased, there was a drop in CO<sub>2</sub> adsorption, as shown in Figure 3d. In any case, the zeolite pellets require a suitable mixing of zeolite powder and binder to provide sufficient mechanical strength to resist attrition loss for most commercial applications. The optimum binder content was at 5 wt.%, which produced enough compressive strength when compared with 9 wt.% binder additions because the increased binder at 9 wt.% increased the compressive strength by 60 kPa. Moreover, increases in binder result in higher production costs and lower adsorption capacity.

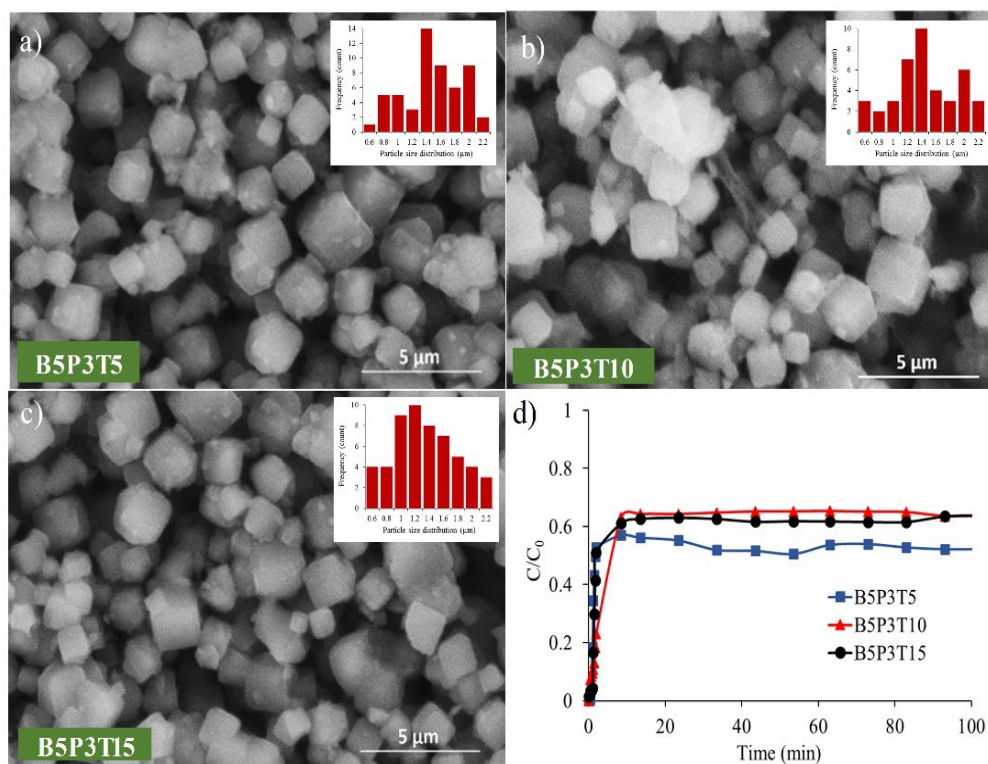


**Figure 3.** Scanning electron micrograph of zeolite pellet with different wt.% bentonite binder (a) 5, (b) 9 and (c) 15 wt.% bentonite, (d) breakthrough curves of zeolite pellet with different wt.% bentonite binder

### 3.3 Effect of compression time

Compression time is another factor that affects the physical properties of zeolite pellets. When compression time was too low, the zeolite powder pelletized had a low density that led to easy cracking. Figure 4 shows the morphology of zeolite pellets made with different compression times. From the SEM photographs in Figures 4a, 4b and 4c, there was no different size for pellets made with different compression times of 5, 10 and 15 min. However, when the compression time was increased to 15 min, the CO<sub>2</sub> adsorption capacity decreased, as shown in Figure 4d. This was due to the restriction of movement of molecules permanently from long-compression time. It could be one reason for the lower adsorption efficiency compared to zeolite powder.

Figures 2d, 3d and 4d show the breakthrough curves with different conditions of compressive forces, bentonite binder, and compressive time, respectively. Interestingly, at low compression force, a low amount of bentonite binder content and short compression time, the breakthrough curve might not have reached equilibrium, but these conditions still provided good CO<sub>2</sub> adsorption. This was due to the density of zeolite pellet, as shown in Table 1. With less bulk density, the pore size within the pellet was larger than the effective pore size in high density pellet. The immediate breakthrough curves at high compression force, high amount of bentonite binder content and long compression time suggested that CO<sub>2</sub> molecules were not able to access the pores of the zeolite 5A pellets.

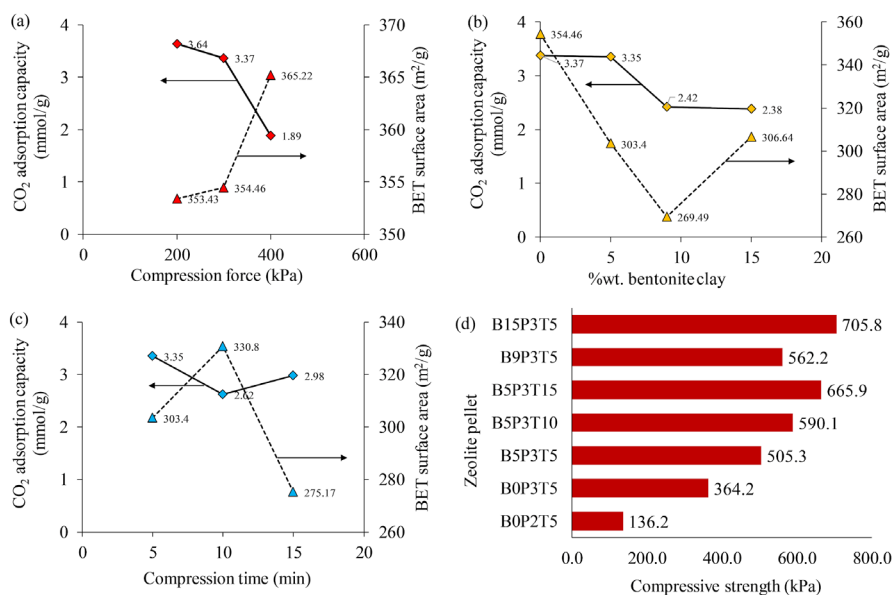


**Figure 4.** Scanning electron micrograph of zeolite pellet with different compression times (a) 5, (b) 10 and (c) 15 min, (d) breakthrough curves of zeolite pellet with different compression times

**Table 1.** Bulk density of zeolite 5A pellet

Zeolite 5A pellet	Bulk density (kg/m <sup>3</sup> )
B0P2T5	1294
B0P3T5	1324
B0P4T5	1593
B5P3T5	1630
B5P3T10	1640
B5P3T15	1898
B9P3T5	1719
B15P3T5	1823

Interestingly, the CO<sub>2</sub> adsorption capacity on the zeolite pellets decreased when the compressive force was increased from 200 to 400 kPa. Meanwhile, the surface area slightly increased from 353.43 to and 365.22 m<sup>2</sup>/g (Figure 5a) as discussed in section 3.1. From Figure 5d, the increase of bentonite binder content at 5, 9 and 15 wt.% bentonite resulted in increased pellet compressive strength of 505.3, 562.2 and 705.8 kPa, respectively, while the surface area and CO<sub>2</sub> adsorption capacity decreased (Figure 5b). For compression times of 5, 10 and 15 min, the density of the zeolite pellet increased by 1630, 1640 and 1898 kg/m<sup>3</sup>, respectively. Additionally, the BET surface area and CO<sub>2</sub> adsorption capacity values did not follow the theoretical trend. This suggested that at 15 min compression time, the BET surface area was greatly reduced and the CO<sub>2</sub> adsorption capacity had decreased when compared to the result at 5 min, as shown in Figure 5c. It was owing to the reduction of the amount of active sorbent and blocked pores [20, 21].



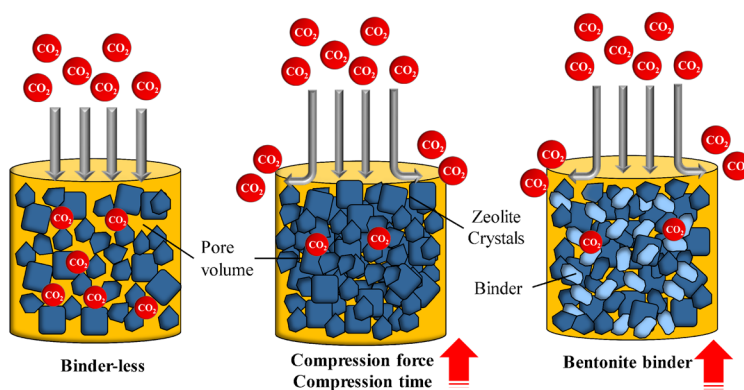
**Figure 5.** CO<sub>2</sub> adsorption capacity and BET surface area with different pelletized conditions, (a) different compression forces (b) different wt.% bentonite binder (c) different compression times and (d) compressive strength of zeolite pellets



However, excess amounts of binder, compression times and compression forces may have affected the CO<sub>2</sub> adsorption efficiency and physical properties including pore volume, surface area and the compressive strength of zeolite pellets, as shown in Figure 5d.

The CO<sub>2</sub> adsorption capacity of the obtained zeolite 5A pellet in this research reached a maximum at 3.64 mmol CO<sub>2</sub>/g. It is considered that CO<sub>2</sub> adsorption efficiency of zeolite 5A pellets was higher than commercial zeolite CaA pellet [28] but it was little lower than the CO<sub>2</sub> adsorption efficiency of zeolites CaA bead [29].

In addition, the structural diversity of the zeolite structure produces a wide range of properties, including geometric characteristics (dimensions of channels, connections and pore space), which are directly related to adsorption applications and physical properties such as mechanical behavior. Indeed, many three-dimensional porous structures have been found in zeolites that display elastic anisotropy properties. Zeolites have elastic properties, and when compression force is applied; the molecules are arranged in a disorganized way due to the slight displacement of the molecules in the zeolite structure. Conversely, when a compression force is removed, these molecules will return to their original position. If the compression force has been applied too long, it can affect the movement of molecules permanently. This could be one reason for getting low adsorption efficiency compared to zeolite powder. Mechanisms of CO<sub>2</sub> adsorption include e physical adsorption and chemical adsorption. This research dealt primarily with physisorption; the target molecules are attracted to the surface of pore walls within a high surface-area sorbent by Van der Waals forces. Therefore, the density of pellets increased (less pore volume) with increasing compression force, amount of binder, and compression time, making it more difficult for CO<sub>2</sub> molecules to reach active sorbents. As a result, the internal mass transfer of CO<sub>2</sub> in zeolite pellet is lower [30, 31]. A schematic illustration of the CO<sub>2</sub> sensing mechanism for the interior of the zeolite pellet ash is shown in Figure 6. Therefore, the optimum conditions for pelletization highlighted in this research can be beneficial for expansion to industrial-scale adsorption processes.



**Figure 6.** Schematic illustration of CO<sub>2</sub> adsorption mechanism for interior zeolite pellet

#### 4. Conclusions

Zeolite 5A pellets were formed by pelletization with a hydraulic press. The impact of pelletization on the physical properties and CO<sub>2</sub> adsorption of the zeolite pellets were evaluated by comparing zeolite pellets pelletized under 200, 300 and 400 kPa pressure, with compression times of 5, 10 and 15 min and 0, 5, 9 and 15 wt.% of bentonite binders. The BOP2T5, without the binder, gave the highest CO<sub>2</sub>

adsorption capacity of 3.64 mmol/g under 200 kPa pressure and 5 min of compression time with 353.43 m<sup>2</sup>/g surface area. The binder could increase the mechanical strength of the zeolite pellets but it may block the pores, resulting in reduction of the BET surface area and CO<sub>2</sub> adsorption capacity. The addition of 15 wt.% bentonite binder gave the highest compressive strength of 705.8 kPa. Increased compression force at 400 kPa compression force resulted in the zeolite particle size decreasing from 1.9 µm in zeolite powder size to 1.3 µm in zeolite pellet, and creating a large BET surface area of 365.22 m<sup>2</sup>/g. On the other hand, the large surface area did not increase the CO<sub>2</sub> adsorption capacity. For the reason, the zeolite particles were closer together which reduced the gaps and made it difficult for the CO<sub>2</sub> molecules to reach and enter the zeolite pores.

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## References

- [1] Stevens, P., 2020. *Energy Demand, Hit by Coronavirus Crisis, Is Set to See Record Drop This Year, IEA Says*. [online] Available at: <https://www.cnbc.com/2020/04/30/energy-demand-set-to-fall-the-most-on-record-this-year-amid-coronavirus-pandemic-iea-says.html>.
- [2] National Centers for Environmental Information, 2020. *State of the Climate: Global Climate Report for October 2020*. [online] Available at: <https://www.ncdc.noaa.gov/sotc/global/202010>.
- [3] Bradshaw, J., Chen, Z., Garg, A., Gomez, D., Rogner, H. H., Simbeck, D. and Williams, R., 2005. Sources of CO<sub>2</sub>. In: B. Metz, O. Davidson, H. de Coninck, M. Loos and L. Meyer, eds. *IPCC Special Report on Carbon Dioxide Capture and Storage*. Cambridge: Cambridge University Press, pp. 75-104.
- [4] Akhtar, F., Andersson, L., Ogunwumi, S., Hedin, N. and Bergström, L., 2014. Structuring adsorbents and catalysts by processing of porous powders. *Journal of the European Ceramic Society*, 34, 1643-1666.
- [5] Mosca, A., Hedlund, J., Ridha, F.N. and Webley, P., 2008. Optimization of synthesis procedures for structured PSA adsorbents. *Adsorption*, 14, 687-693.
- [6] Xu, X., Song, C., Wincek, R., Andresen, J.M., Miller, B.G. and Scaroni, A.W., 2003. Separation of CO<sub>2</sub> from power plant flue gas using a novel CO<sub>2</sub>" molecular basket" adsorbent. *Fuel Chemistry Division Preprints*, 48, 162-163.
- [7] Knowles, G.P., Webley, P.A., Liang, Z. and Chaffee, A.L., 2012. Silica/polyethyleneimine composite adsorbent S-PEI for CO<sub>2</sub> capture by vacuum swing adsorption (VSA). In: M.I. Attalla, ed. *Recent Advances in Post-Combustion CO<sub>2</sub> Capture Chemistry*. Washington DC: American Chemical Society, pp. 177-205.
- [8] Peterson, G.W., DeCoste, J.B., Glover, T.G., Huang, Y., Jasuja, H. and Walton, K.S., 2013. Effects of pelletization pressure on the physical and chemical properties of the metal-organic frameworks Cu<sub>3</sub>(BTC)<sub>2</sub> and UiO-66. *Microporous and Mesoporous Materials*, 179, 48-53.
- [9] Rezaei, F., Sakwa-Novak, M.A., Bali, S., Duncanson, D.M. and Jones, C.W., 2014. Shaping amine based solid CO<sub>2</sub> adsorbents: effects of pelletization pressure on the physical and chemical properties. *Microporous and Mesoporous Materials*, 204, 34-42.
- [10] Breck, D.W., 1974. *Zeolites, Molecular Sieves, Structure, Chemistry and Use*. New York: Wiley.

- [11] Li, Y.Y., Perera, S.P. and Crittenden, B.D., 1998. Zeolite monoliths for air separation: Part 1. Manufacture and characterization. *Chemical Engineering Research and Design*, 76, 921-930.
- [12] Li, Y.Y., Perera, S.P. and Crittenden, B.D., 1998. Zeolite monoliths for air separation: Part 2. Oxygen enrichment, pressure drop and pressurization. *Chemical Engineering Research and Design*, 76, 931-941.
- [13] Li, Y.Y., Perera, S.P., Crittenden, B.D. and Kolaczowski, S.T., 2000. Manufacture and characterization of silicalite monoliths. *Adsorption Science and Technology*, 18, 147-170.
- [14] Li, Y.Y., Perera, S.P. and Crittenden, B.D., 2001. The effect of the binder on the manufacture of a 5A zeolite monolith. *Powder Technology*, 116, 85-96.
- [15] Madhusoodana, C.D., Das, R.N., Kameshima, Y. and Okada, K., 2005. Preparation of ZSM-5 zeolite honeycomb monoliths using microporous silica obtained from Metakaolinite. *Journal of Porous Materials*, 12, 273-280.
- [16] Jasra, R.V., Tyagi, B., Badheka, Y.M., Choudary, V.N. and Bhat, T.S.G., 2003. Effect of clay binder on sorption and catalytic properties of zeolite pellets. *Industrial and Engineering Chemistry Research*, 42, 3263-3272.
- [17] Grande, C.A., Gigola, C. and Rodrigues, A.E., 2002. Adsorption of propane and propylene in pellets and crystals of 5A zeolite. *Industrial and Engineering Chemistry Research*, 41, 85-92.
- [18] Dorado, F., Romero, R. and Canizares, P., 2001. Influence of clay binders on the performance of Pd/HZSM-5 catalysts for the hydroisomerization of n-butane. *Industrial and Engineering Chemistry Research*, 40, 3428-3434.
- [19] Carizares, P., Duran, A., Dorado, F. and Carmona, M., 2000. The role of sodium montmorillonite on bounded zeolite type catalysts. *Applied Clay Science*, 16, 273-287.
- [20] Puccini, M., Stefanelli, E., Seggiani, M. and Vitolo, S., 2016. Removal of CO<sub>2</sub> from flue gas at high temperature using novel porous solids. *Chemical Engineering Transactions*, 47, 139-144.
- [21] Charkhi, A., Kazemeini, M., Ahmadi, S.J. and Kazemian, H., 2012. Fabrication of granulated NaY zeolite nanoparticles using a new method and study the adsorption properties. *Powder Technology*, 231, 1-6.
- [22] Li, Y.Y., Perera, S.P., Crittenden, B.D. and Bridgwater, J., 2001. The effect of the binder on the manufacture of a 5A zeolite monolith. *Powder Technology*, 116, 85-96.
- [23] Rongsayamanont, C. and Sopajaree, K., 2007. *Modification of Synthetic Zeolite Pellets from Lignite Fly Ash A: The Pelletization*. [online] Available at: [https://www.academia.edu/7412437/Modification\\_of\\_Synthetic\\_Zeolite\\_Pellets\\_from\\_Lignite\\_Fly\\_Ash\\_A\\_The\\_Pelletization](https://www.academia.edu/7412437/Modification_of_Synthetic_Zeolite_Pellets_from_Lignite_Fly_Ash_A_The_Pelletization).
- [24] Czuma, N., Panek, R., Baran, P. and Zarębska, K., 2020. The Influence of binder for pelletization of fly ash zeolites on sorption properties in relation to SO<sub>2</sub>. *Clay Minerals*, 55, 40-47.
- [25] Chen, C., Park, D.W. and Ahn, W.S., 2013. Surface modification of a low cost bentonite for post-combustion CO<sub>2</sub> capture. *Applied Surface Science*, 283, 699-704.
- [26] Vilarrasa-García, E., Cecilia, J.A., Azevedo, D.C.S., Cavalcante, C.L. and Rodríguez-Castellón, E., 2017. Evaluation of porous clay heterostructures modified with amine species as adsorbent for the CO<sub>2</sub> capture. *Microporous Mesoporous Materials*, 249, 25-33.
- [27] Gómez-Pozuelo, G., Sanz-Pérez, E.S., Arencibia, A., Pizarro, P., Sanz, R. and Serrano, D.P., 2019. CO<sub>2</sub> adsorption on amine-functionalized clays. *Microporous Mesoporous Materials*, 282, 38-47.
- [28] Liu, Z., Grande, C.A., Li, P., Yu, J. and Rodrigues, A.E., 2011. Adsorption and desorption of carbon dioxide and nitrogen on zeolite 5A. *Separation Science and Technology*, 46(3), 434-451.
- [29] Narang, K., Fodor, K., Kaiser, A. and Akhtar, F., 2018. Optimized cesium and potassium ion-exchanged zeolites A and X granules for biogas upgrading. *RSC Advances*, 8(65), 37277-37285.
- [30] Thakkar, H., Eastman, S., Hajari, A., Rownaghi, A.A., Knox, J.C. and Rezaei, F., 2016. 3D-printed zeolite monoliths for CO<sub>2</sub> removal from enclosed environments. *ACS Applied Materials & Interfaces*, 8(41), 27753-27761.
- [31] Narang, K. and Akhtar, F., 2020. Freeze granulated zeolites X and A for biogas upgrading. *Molecules*, 25, 1378, <https://doi.org/10.3390/molecules25061378>.