Synthesis of Zeolite X/Activated Carbon Composites from Rice Hulls

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Abstract: Zeolite X/activated carbon composites were synthesized from rice hulls. The granules were made by mixing crushed rice hulls and sodium aluminate. The cellulose in the granules was converted to activated carbon by carbonization and activation processes. By a hydrothermal reaction, the activated granules were converted to zeolite X/activated carbon composites. The nitrogen adsorption and desorption isotherms of the zeolite X/activated carbon composites showed a combined shape isotherm of types I and IV. The specific surface area of the composite was 620 m² g⁻¹, the total pore volume was 0.39 cm³ g⁻¹, and the pore size was 3-4 nm.

Keywords: rice hull, zeolite X, activated carbon, composite, adsorbent

Introduction

While fossil resources are limited, biomass is a renewable and environmentally friendly resource, which can be found readily all over the world. Therefore, biomasses have attracted attention recently for the generation of energy and have become an important source of chemical industry [1].

One of biomass, the rice hull, comprises 20% of rice grains that are produced in many parts of the world; it is a major by-product of the rice industry. Annual rice hull production in the world has been estimated at ca. 50 million tons; 1.5 million tons is produced in the Republic of Korea. The rice hull is composed of 13 to 20% ash, which is mostly amorphous silica (95%) and cellulose depending on environmental conditions such as habitat and weather. Currently the usage of rice hull is very small; one example of its use is the generation of heat energy from its combustion. Hence, much development of efficient methods is required to make use of the high potential resource of rice hulls.

Because of the high silica content, the industrial applications of rice hull have been studied for use in SiC [2,3] and Si₃N₄ synthesis [4]. Also, the use of rice hull ash as an adsorbent in removing pigments, fatty acids, and phospholipids from vegetable oil has been investigated [5-7]. A method based on alkaline extraction after acid treatment has been developed to produce pure silica from the ash of rice hull [8,9]. Recently, production of activated carbon from char, which is a resultant product of the carbonization of rice hull cellulose, has been investigated actively [10,11]. However, since it has such a low activity, due to the extremely high content of silica, its commercialization is inferior to that of other activated carbons produced using other traditional methods. Also, the extraction of the silica from the rice hull using alkaline solutions is a complicated and low-yielding process. Ko and coworkers [12,13] prepared activated carbon from carbonized rice hull, after removal of silica using NaOH, and applied phosphoric acid to it as an active agent. Kim and coworkers [14,15] prepared the activated carbon having a high specific surface area from rice hull. After the carbonized rice hull was treated with alkaline solution, to remove the silica, it was impregnated with NaOH and finally activated. Rao and coworkers [16,17] have made granular activated carbons (GACs) from rice hull by adding coal tar or molasses as a binder, and they have applied GACs to decolorants.

There have been studies of the profitable gasification process in which gases are produced from the by-products of crops such as rice hulls and straws. These gases are modified to make raw materials for methanol and synthetic gas [18]. The rice hull ash, which is a residue from the synthetic gas production, contains 13-20% of amorphous silica. It also has been reported that amorphous
silica helps to improve the reinforcement of rubber [19].
In this study, zeolite X activated carbon composite adsorbents were synthesized from rice hull, which contains both silica and cellulose. The characteristics of the zeolite are as follows: uniform pore size, high hydrophilicity, and high adsorption of polar molecules. On the other hand, activated carbon is hydrophobic and efficient for the adsorption of non-polar molecules. Another major characteristic of the latter is the various sizes of its pores; micro pores adsorb molecules as well as macro pores. These two opposing characteristics are harmonized and enhance limiting factors, which arise when adsorbents are made using either zeolites or activated carbons, such as thermal stability and reusability. The zeolite/activated carbon composite adsorbents have the advantageous properties from both ingredients, which results in their optimized performance as adsorbents.

**Methods**

**Materials**
Rice hulls (RH) were obtained from a rice-polishing mill, Iksan, Korea. To remove the residue of the polished rice caused by pounding from rice hulls, the rice hulls were washed several times with distilled water and then dried at 110°C for 4 h. The dried rice hulls were crushed in a vibro rod mill (Yeongjin co., Chunan) for 20 min.

**Extruding and Drying**
Powdered rice hulls were mixed with sodium aluminate (NaAlO₂) by injecting NaAlO₂ regularly through spray nozzles for 20 min to ensure that they were combined well. The molar ratios of the reactants were controlled at SiO₂/Al₂O₃ = 3.0 and Na₂O/SiO₂ = 0.98. The mixture was molded into a cylindrical shape (2-mm diameter) and cut into 5-mm long pieces using an extruder (Xtruder, Fuji Paudal, model EXDFS-60). The molded granules were finally dried in a convection oven at 110°C for 4 h.

**Carbonization and Activation**
Carbonization of the molded granules was carried out in a continuous rotary tube kiln (Lindberg, A unit of General Signal, max. temp. 1500°C, 100-mm diameter) and kept inside the heating zone at 500 ~ 800°C for 30 min amount of a continuous stream of nitrogen gas (20 L min⁻¹) to prevent granules from experiencing burn-off. The carbonized granules were activated in the same rotary tube kiln at 700 ~ 900°C for 0.5 ~ 4 h in the presence of steam as an oxidizing gas. The ratio of the amount of steam to granules was kept in the range 0.25 ~ 0.70. During the carbonization and activation process, the yield was calculated by the following equation.

**Figure 1.** Block diagram of the experimental process.

Yield (%) = Effluent/Influent × 100

**Zeolite Synthesis and Ion Exchange**
To form zeolite X types in the granules, the activated granules (125 g) were added into sodium hydroxide solution (1 ~ 2 N, 175 g) and aged for 12 h at room temperature while bubbling with air. The reactants had the following molar ratios:

\[
\text{Na}_2\text{O} / \text{Al}_2\text{O}_3 / \text{SiO}_2 / \text{H}_2\text{O} = 3.75 ~ 4.56 / 1.00 / 3.00 / 95.36 ~ 143.64
\]

The aged reactants (300 g) were treated hydrothermally in a round bottom flask (500 mL) at 100°C for 8 h. After the reaction, the synthesized granules were filtered to separate the treated granules from the mother liquid. They were washed with distilled water several times. After these granules were added into a 21 wt% calcium chloride solution for 1 h to ion-exchange the zeolite from zeolite Na-X to zeolite Ca-X, they were washed with an abundant distilled water.

**Drying and Calcination**
The ion-exchanged granules were dried for 4 h and their water content was < 5%. Then, they were calcined in a rotary tube kiln at 600°C for 20 min under a continuous stream of nitrogen gas (20 L min⁻¹). A flow diagram of the experimental procedure is shown in Figure 1.
**Determination of Physical and Chemical Properties**

**Sample Characterization**
To examine the crystalline phases and their crystallinity, X-ray diffraction measurements were performed using a dual goniometer X'pert XRD system (Rigaku, model D/ MAX-3B) using monochromated Cu Kα radiation.

The samples (0.2 g) were dispersed in 100 mL of ethyl alcohol for 15 min. After coating them on a Cu specimen plate, they were dried in the air plate at room temperature for 15 min. Then, the plate was coated with Au for 3 min in the ion coater under vacuum. SEM (model JSM-840A) was used to observe the microstructure of the samples.

The chemical compositions of the samples were determined using an energy dispersive X-ray spectrometer (Phoenix, model EDS), which contains an ultra-thin window X-ray detector using working distance of 0.5 m and an acceleration voltage of 20 kV.

**Porous Properties**
Samples (100-200 mg) were dried at 330°C for 3 h under vacuum. Samples were placed in a surface area analyzer (Micrometrics, model ASAP 2010) and nitrogen adsorption isotherms were run at 77 K. From these isotherms, micropore volumes, pore size distributions, and pore surface areas were calculated by using the Dubinin-Radushkevich (DR) method, the Balalett-Joynar-Hahenda (BJH) method, and the Brunauer-Emmet-Teller (BET) method, respectively [20].

**Adsorption Properties**
The amount of iodine adsorbed by the granule was determined from a modification of the method of Hessler (1963). A stock solution of iodine was prepared by dissolving 2.7 g of I₂ and 4.1 g of KI in 1 L of deionized water. A granule (0.5 g) and 10 mL of 5% hydrochloric acid were placed in a 250 mL flask. The flask was swirled until the granule was wetted, and then 100 mL of the stock iodine solution was added and the mixture was shaken for 5 min. A blank was prepared without adding the granule. All samples were titrated with 0.1 M sodium thiosulfate using starch as an indicator.

**Results and Discussion**

**Rice Hull Crushing**
Since rice hull has a hard silica surface layer, milling is extremely inefficient by normal milling methods such as turbo or jet milling and the hard silica causes abrasion of the cutter. Therefore, vibro rod milling, which uses friction and percussion to soften the hard silica, is most suitable for producing the best results of milling. The distribution on milled rice hull particles was largely dependant on the retention time. In this experiment, the vibro rod mill was used for 20 min. The particle size distribution of the rice hull powder showed that > 95% of the particle sizes were < 250 μm.

**Carbonization and Activation**
The compositions of the raw rice hulls and the molded granules are shown in Table 1. Figure 2 illustrates the carbonization yield curves of the raw rice hulls and the molded granules as a function of the carbonization temperature under a continuous stream of nitrogen gas. These two samples showed different ranges of their yields depending on the carbonization temperature.

The yield of the raw rice hull decreases steeply with an increase in the carbonization temperature. Then it remains almost constant at 42% when the carbonization occurs at 550~700°C. The carbonization yield of the molded granules, however, was different from the previous one. As the carbonization temperature increases, the yield of granules containing alkaline tends to decrease. This could be explained by chemical activation in the presence of alkaline, which acts as an activating agent, above 600°C, resulting in burn-off of the fixed carbon. Therefore, it is
desirable to remove water and volatile compounds in the molded granule during the carbonization process and to control the carbonization temperature so that high content of fixed carbon is obtained. Thereby, temperatures between 500 and 600°C are found to be suitable for the carbonization of the molded granules. However, the temperatures higher than 700°C resulted in serious cracks on the surfaces.

The objective of the activation process is to enlarge the volume and the size of the pores that are formed during the carbonization process.

In this study, a common manufacturing method for granules used as a gas adsorbent, the gas activation method, was applied in the presence of steam as an oxidizing gas.

The factors affecting the activation process are temperature, retention time, and the amount of steam feed, and they influence the product characteristics, such as their adsorption properties, surface areas, and ash contents. Therefore it was necessary to minimize burn-off of the carbon and the activation occurred under conditions that enhanced the adsorption ability.

The influence of activation temperature on the carbonized granules at 500°C was examined to evaluate the yield and adsorption capacity of the granules. Figure 3 shows the yield and the amount of iodine adsorbed (mg g⁻¹) for different activation temperatures (from 700 to 900°C). Other factors, such as the retention time (1 h) and the ratio of the amount of granules to the amount of steam (0.4), were kept constant during this experiment. We observed that an increase in activation temperature caused a linear increase in the amount of iodine adsorbed by the fixed carbon (excluding ash content). The yield, however, decreased because the amount of carbon burn-off increased at the high temperature. The required temperature for the activation is ca. 900°C because steam acts as an oxidizing agent at > 850°C and the amount of iodine adsorbed should be 900 mg g⁻¹. It is difficult, however, to control and prevent carbon from burn-off at temperatures higher than 900°C.

Subsequently, as shown in Figure 4, the activation process was examined as a function of activation time at 900°C. Carbon with high adsorption could be obtained by increasing the activation time because more micropores were formed from the increased amount of burn-off. Nevertheless, this process was not the best method for obtaining carbon with high adsorption because the yield decreased as the activation time increased.

The time taken for activation is closely related to the length of the rotary tube kiln. On that account, it was more appropriate in this study to control the temperature of activation and the steam feeding rate at retention times within 1 h in the case of the carbonized granules. Lastly, the experiment was carried out under the same given conditions except for changing the ratio of injected steam to the amount of carbonized granules. As shown in Figure 5, the amount of iodine adsorbed tended to increase with increasing the amount of injected steam, but the yield decreased as in the two previous experimental results presented in Figures 3 and 4.

The amount of iodine adsorbed by the fixed carbon grew to over 1000 mg g⁻¹ - A.C. when steam was injected into the carbonized granules having 43–45% fixed carbon at a ratio of 0.5 and, finally, the yield was kept constant at ca. 80%.

As a result, the most suitable conditions for the carbonization and the activation were as follows: carbonization for 30 min at 500°C, activation for 1 h at 900°C, steam injection at half the amount of carbonized granules.
Table 2. Synthetic Zeolite NaO-Al2O3-SiO2-H2O Systems

<table>
<thead>
<tr>
<th>Zeolite type</th>
<th>Typical reactant comp. (moles/Al2O3)</th>
<th>Typical conditions temp. (°C)</th>
<th>Zeolite comp. (moles/Al2O3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NaO</td>
<td>SiO2</td>
<td>H2O</td>
</tr>
<tr>
<td>A</td>
<td>2</td>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td>P_e</td>
<td>2</td>
<td>3.8</td>
<td>94</td>
</tr>
<tr>
<td>P_e*</td>
<td>6</td>
<td>8</td>
<td>a*</td>
</tr>
<tr>
<td>R</td>
<td>3.2</td>
<td>4</td>
<td>260</td>
</tr>
<tr>
<td>S</td>
<td>2.4</td>
<td>6</td>
<td>80</td>
</tr>
<tr>
<td>X</td>
<td>3.6</td>
<td>3</td>
<td>144</td>
</tr>
<tr>
<td>Y</td>
<td>8</td>
<td>20</td>
<td>320</td>
</tr>
</tbody>
</table>


Figure 5. Variation of the yield and amount of iodine adsorbed according to the ratio of steam feeding.

Lastly, the amount of iodine adsorbed on the fixed carbon was ca. 1050 mg g⁻¹.A.C. and the ash content was ca. 70%.

Zeolite Synthesis

The granules activated with sodium aluminosilicate were soaked into alkali solution and reacted hydrothermally. It has been reported that the dominant factors that affect the zeolite synthesis are the aging temperature and time [21]. It was noted that for aging temperatures above 60°C, other phases, such as sodalite and analcime, were formed. Therefore, the appropriate temperature to obtain X-type zeolites from the activated granule was chosen to be 40°C. Also, these conditions required a minimum aging time of 10 h, otherwise the final crystallinity of the synthesized granules decreased because of feeble seed formation.

The important factors that influence crystallization during the hydrothermal synthesis are the concentration and the quantity of alkali in the reactants, reaction temperature, and time taken for the X-type zeolite crystallization. Typical gels are prepared from aqueous solutions of various compositions of starting reactants. From studies of many aluminosilicate gel compositions, relationships between the synthetic zeolite product and the starting reactant mixture composition have been established [22,23]. Table 2 demonstrates that the conventional explanation for the range overlap is inadequate and merely suggests recipes for preparing a given zeolite. Table 2 shows the compositional ranges that can be used to prepare synthetic zeolites. These ranges not only overlap but they also extend into areas previously designated for preparing other zeolites [24]. As shown in Table 2, zeolite X crystallizes at temperatures ranging from 20 – 120°C with corresponding variations in the time required. Zeolite A has been crystallized at temperatures ranging from 20 – 175°C with the crystallization time varying from 14 days to 2.5 h. Zeolite P is stable at higher temperatures and has been formed over a temperature range from 60 to 250°C. Hence, with our crystallization conditions, we can expect that the possibility that various zeolite types are formed is high.

It has also been reported that the zeolite X crystallization reaction temperature are suitable between 90 and 105°C [25]. To decrease the reaction time, it is necessary to raise the reaction temperature as high as possible. In spite of that necessity, the crystallinity of X-type zeolite decreases if the reaction proceeds above 100°C because of the rapid increase in the crystallinity of sodalite.

The concentration of alkali in reactants is an important factor for the nucleation and crystal growth of zeolites. In this study, it is impossible to get a sufficient concentration of alkali from the activated granule; therefore, it had to be adjusted by adding an extra amount of NaOH. At that time, the crystallization of analcime or sodalite occurred when the concentration of alkali was too high. On the other hand, P-type or A-type zeolites were produced partially.

As shown in Table 3, when the H2O/Na2O molar ratio was above 29 after the hydrothermal reaction, the conversion rate to zeolite X was only 25%. The conversion rates increased until the H2O/Na2O molar ratio reached 28. The maximum conversion rate to zeolite X, 78.8%, was observed when the H2O/Na2O molar ratio was 28.13.
Table 3. Molar Ratio in the Filtrate after Hydrothermal Reaction

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>SiO$_2$/Al$_2$O</th>
<th>Na$_2$O/SiO$_2$</th>
<th>H$_2$O/Na$_2$O</th>
<th>Conversion rate (%)$^{(1)}$</th>
<th>Concentration (wt%)$^{(2)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZC-01</td>
<td>3.00</td>
<td>1.25</td>
<td>31.50</td>
<td>25.0</td>
<td>9.40</td>
</tr>
<tr>
<td>ZC-02</td>
<td>3.00</td>
<td>1.34</td>
<td>29.17</td>
<td>71.2</td>
<td>11.0</td>
</tr>
<tr>
<td>ZC-03</td>
<td>3.00</td>
<td>1.39</td>
<td>28.13</td>
<td>78.8</td>
<td>11.4</td>
</tr>
<tr>
<td>ZC-04</td>
<td>3.00</td>
<td>1.43</td>
<td>27.13</td>
<td>67.4</td>
<td>12.6</td>
</tr>
<tr>
<td>ZC-05</td>
<td>3.00</td>
<td>1.47</td>
<td>26.21</td>
<td>59.5</td>
<td>12.8</td>
</tr>
<tr>
<td>ZC-06</td>
<td>3.00</td>
<td>1.52</td>
<td>25.34</td>
<td>56.8</td>
<td>13.0</td>
</tr>
</tbody>
</table>

$^{(1)}$ Conversion rate (%) is the rate of conversion from ash content, excluding the fixed carbon, to zeolite 13X and was calculated using a comparison of the XRD data of the synthesis granule with that of reference zeolite 13X.

$^{(2)}$ NaOH concentration (wt%) of filtrate after hydrothermal reaction.

Figure 6. Variation of conversion rate according to crystallization time at 100°C; H$_2$O/Na$_2$O molar ratio of 28.13.

At that condition, the concentration of alkali filtrate after the hydrothermal reaction was about 11.4 wt%. When the molar ratio was < 28, the conversion rate tended to decrease, but the concentration of the alkali filtrate still slightly increased.

As shown in Figure 6, the zeolite X crystallization process depends on the synthesis time at 100°C at a H$_2$O/Na$_2$O molar ratio of 28.13. The conversion rate was observed to increase dramatically until the reaction time reached 5 h. After that time, it remained relatively constant until 7 h had elapsed. However, it started to decrease gradually after a reaction time of 8 h.

In Figure 7, the X-ray diffraction patterns of the activated granule and the hydrothermal synthesized granule are compared with that of zeolite X as a reference. The sodium aluminosilicate, which exists in the activated granule, has an amorphous phase. The synthesized granule is composed of impurities of zeolite A and zeolite P, even though most of it has converted to zeolite X in the alkaline solution.

Figure 7. X-ray diffraction patterns of various samples.

Figure 8. Adsorption and desorption isotherms of nitrogen on the synthesized granule and the carbonized/activated sample at 77 K.

of nitrogen on the synthesized granule (A) and the carbonized/activated sample (B) at liquid nitrogen temperature (77 K). We note that the isotherms are a combined shape of types I and IV in BDDT’s classification [20]. The sharp increase of adsorption at low relative pressure (0.00 ~ 0.02 p$_0$) was mainly due to the adsorption in the micropore, which can be found in zeolite X and some parts of the activated carbon. The other region of in-
Table 4. Pore Properties of Representative Samples

<table>
<thead>
<tr>
<th></th>
<th>Specific Surface Area (m²/g)</th>
<th>Micropore Volume (cm³/g)</th>
<th>Total Pore Volume (cm³/g)</th>
<th>Iodine Value (mg/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>620</td>
<td>0.17</td>
<td>0.38</td>
<td>350</td>
</tr>
<tr>
<td>B</td>
<td>483</td>
<td>0.16</td>
<td>0.32</td>
<td>425</td>
</tr>
</tbody>
</table>

A: Synthesized granule sample; B: Carbonized/activated rice hull sample.

Figure 9. Pore size distribution of the synthesized granule and the carbonized/activated sample.

decreasing slope after 0.8 p p₀⁻¹ was due to the multilayer adsorption on the external surfaces. The clearly distinguishable hysteresis loop implies that the structure of the pore in the synthesized granule were A-type-cylindrical or ink-bottle-shape-from 5 types of the pore by de Boer’s classification [26]. The silica ingredient of the synthesized granule exists in zeolite crystal form on the activated carbon inside because of a crystallization reaction. Therefore, new pores formed on contact of the surface of the zeolite crystal with the activated carbon. The hysteresis of the synthesized granule that passed through crystallization is larger than that of the carbonized/activated sample. The surface area calculated by using the BET method, the micropore volume obtained from the DR method, the single point total pore volume, and the iodine value are listed in Table 4.

As shown in Figure 9, the pore size distribution of the synthesized granule (A) and carbonized/activated sample (B) was calculated by the BJH method. The graph shows well-developed mesopores in the range of 3 ~ 4 nm. Usually, activated carbon has a wide distribution, such as micro, meso, and macropores, but, most zeolite of the composite in this research exists inside the macropore. Therefore, the composite had a distribution of the mesopore size. As a result, the pore size distribution is quite narrow. The presence of these pores indicates a favorable pore distribution for the adsorption of organic molecules. It also implies that the synthesized granule is a candidate for adsorption and separation processes for VOCs.

In Figure 10(a), the SEM micrograph indicates the growth of composite zeolite X crystals on the surface of activated carbon as a cluster type. This image might be suggesting that the soluble silica, which is attached on the surface of the rice hull, reacts with sodium aluminate and forms a hydrogel. It then adheres to the granule during the processes of drying, carbonization, activation, and, finally, the synthesis of the zeolite crystals.

Table 5 shows a comparison between two different parts [marked (A) and (B) in Figure 10(a)] of the synthesized granule based on an elemental analysis using EDS. There are differences in the amount of each component when the two different parts of the synthesized granules were imaged by SEM. However, the components, which made up the granules, were the same despite the location where the SEM image was taken [refer to positions (A) and (B) in Figure 10(a)]. This finding suggests that the synthesized
Table 5. Elemental Analysis of Synthesized Granules  

<table>
<thead>
<tr>
<th>Element</th>
<th>(A) part in Figure 10(a)</th>
<th>(B) part in Figure 10(a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>77.40</td>
<td>53.49</td>
</tr>
<tr>
<td>O</td>
<td>17.98</td>
<td>37.44</td>
</tr>
<tr>
<td>Na</td>
<td>0.31</td>
<td>0.82</td>
</tr>
<tr>
<td>Ca</td>
<td>0.70</td>
<td>1.73</td>
</tr>
<tr>
<td>Al</td>
<td>2.72</td>
<td>3.30</td>
</tr>
<tr>
<td>Si</td>
<td>1.20</td>
<td>3.16</td>
</tr>
</tbody>
</table>

granules were not a mixture of zeolite X-type crystals and activated carbon, but a composite of both ingredients.
Figure 10(b) is an SEM micrograph showing a cross section of the synthesized granules. Many zeolite X crystals are observed inside the macropores of the granules. This observation can be explained by considering that the absorbed sodium aluminate and the silica that exist inside the rice hull cytoplasm are combined and remain inside the pores during the carbonization and activation processes, and are converted to zeolite X during the hydrothermal process.

Conclusions

In this study, rice hull was granulized by adding sodium aluminate and the carbonization was optimized at temperatures between 500 and 600°C. The activation of the carbonized granule was carried out at 900°C for 1 h and the best results were obtained when the ratio of steam to granules was 0.5. The iodine value of the fixed carbon was 1050 mg g⁻¹-AC and the content of the ash was 70 wt%.
To synthesize the zeolite from amorphous sodium aluminosilicate in the activated granule, it was aged for 12 h after mixing with alkali solution at 40°C and crystallized at 100°C for 8 h.
The adsorption and desorption isotherms of nitrogen for the synthesized granule were a combination of types I and IV with well-developed mesopores of 3–4 nm. The specific surface area and the total pore volume of the synthesized granule were 620 m² g⁻¹, and 0.39 cm³ g⁻¹, respectively.
From the results of SEM and EDS analyses, we confirmed that the synthesized granule had a composite form with well-distributed zeolite X-type crystals in the activated carbon pores.
From these results, we deduce that this newly developed material will be useful in industrial fields such as deodorization, elimination of air pollution, water treatment, and other environmentally related industries.

References