A Study on Electron Acceptor of Carbonaceous Materials for Highly Efficient Hydrogen Uptakes

Seul-Yi Lee 1,2,3, Ji-Hye Park 1, Young-Jung Heo 1, Eun-Sang Lee 3,4 and Soo-Jin Park 1,*

1 Department of Chemistry, Inha University, Incheon 22212, Korea; leesy1019@inha.ac.kr (S.-Y.L.); pjhye9874@gmail.com (J.-H.P.); heoyj1211@naver.com (Y.-J.H.)
2 Department of Mechanical Engineering, Institute for Critical Technology and Applied Science, Virginia Tech, Blacksburg, VA 24061, USA
3 KIURI Center for Hydrogen Based Next Generation Mechanical System, Incheon 21999, Korea; lees@inha.ac.kr
4 Department of Mechanical Engineering, Inha University, Incheon 22212, Korea
* Correspondence: sjpark@inha.ac.kr; Tel.: +82-32-876-7234

Abstract: Significant efforts have been directed toward the identification of carbonaceous materials that can be utilized for hydrogen uptake in order to develop on-board automotive systems with a gravimetric capacity of 5.5 wt.%, thus meeting the U.S. Department of Energy technical targets. However, the capacity of hydrogen storage is limited by the weak interaction between hydrogen molecules and the carbon surface. Cigarette butts, which are the most abundant form of primary plastic waste, remain an intractable environmental pollution problem. To transform this source of waste into a valuable adsorbent for hydrogen uptake, we prepared several forms of oxygen-rich cigarette butt-derived porous carbon (CGB-AC, with the activation temperature range of 600 and 900 °C). Our experimental investigation revealed that the specific surface area increased from 600 to 700 °C and then decreased as the temperature rose to 900 °C. In contrast, the oxygen contents gradually decreased with increasing activation temperature. CGB-AC700 had the highest H2 excess uptake (Qexcess) of 8.54 wt.% at 77 K and 20 bar, which was much higher than that of porous carbon reported in the previous studies. We found that the dynamic interaction between the porosity and the oxygen content determined the hydrogen storage capacity. The underlying mechanisms proposed in the present study would be useful in the design of efficient hydrogen storage because they explain the interaction between positive carbonaceous materials and negative hydrogen molecules in quadrupole orbitals.

Keywords: hydrogen storage; oxygen-functional groups; porous carbons; pore size; 77 K

1. Introduction

For several decades, fossil fuels have been the primary energy source for industrial activity. However, the combustion of fossil fuels results in pollutant emissions and contributes to a wide variety of environmental problems including global warming and climate change. Therefore, clean and sustainable alternative energy sources such as wind, biomass, waves, and natural gas are required. In this respect, hydrogen (H2) has emerged as a promising renewable energy source for reducing the dependence on fossil fuels, thus leading to the development of a hydrogen economy [1–4].

One of the current drawbacks of utilizing H2 is the lack of safe and economical storage systems [5,6]. Existing H2 storage methods such as compressed gas and liquefied H2 are complex due to the fact that H2 has a low boiling point (20 K) and a low density (0.08988 g/L) at ambient pressure. Compressed gas requires very high pressures, meaning costly additional equipment is required to achieve the capacity required for practical use, while liquefied H2 requires cryogenic temperatures and additional refrigeration, which can lead to vaporization and the loss of H2. Due to these disadvantages, both storage methods have safety problems [7–9]. The U.S. Department of Energy (DOE) has established H2
storage technical targets for the gravimetric capacity (5.5 wt.%) and volumetric capacity (30 g/L) of on-board automotive systems to be achieved by 2025. In order to reach these targets, physisorption has attracted significant attention as a promising method for H2 storage because of its reversibility, fast kinetics, and high H2 uptake [10–13].

Storage materials have been extensively investigated for efficient H2 physisorption including carbon materials [14–16], metal organic frameworks (MOFs) [17–20], and zeolites [21–23]. Porous carbon materials including activated carbon (AC) have proven to be particularly promising adsorbents due to their high specific surface area (SSA), high porosity, and chemical and thermal stabilities [24,25]. It is also well-known that chemical activation using activating reagents such as potassium hydroxide (KOH), sodium hydroxide (NaOH), and zinc chloride (ZnCl2) for the preparation of AC can lead to additional advantages such as a higher SSA, improved microporosity, and low-temperature pyrolysis [26–29].

Several studies have reported that a high SSA is a key characteristic required to maximize the amount of H2 adsorbed onto AC [30,31]. However, the high H2 uptake of AC depends not only on the SSA, but also on its surface characteristics, which affect the interaction between H2 molecules and the carbon surface. The surface functionalization of AC can help to improve this interaction and promote the high storage performance of H2. However, it has been reported that surface functionalization alters the surface characteristics of AC and decreases the porosity due to the introduction of foreign functional groups [32]. The key to overcoming these issues is identifying appropriate precursors for the development of AC. For optimal use as a H2 storage material, AC should have a high SSA with well-developed micropores and precursors should have desirable surface properties that are retained in the resulting AC.

Many attempts have been made to understand the effect of oxygen-functional groups on the surface of carbonaceous materials for H2 uptake behaviors [33]. Some researchers have reported that oxygen functional groups on AC decrease its H2 storage capacity due to steric hindrance in the pores and an increase in the solid [34]. However, contradictory experimental results have shown that oxygen functional groups on AC can significantly increase H2 storage capacity, acting as active adsorption sites for H2 molecules. This outcome can also be explained by the influence of the acidic oxygen functional groups on the physisorption energy, which can be defined by the Dubinin–Astakhov model or electron acceptor–donor interactions at the carbon surface [35–37]. In order to resolve these conflicting observations, it is vital to explain the interaction between the oxygen functional groups and the textural properties of AC; this information could then be employed to maximize H2 storage capacity.

An estimated 5.7 trillion cigarette butts (CGBs) are disposed of globally as litter each year, and these contain contaminants that can be harmful to the environment and humans [36]. For this reason, CGBs need to be disposed of in an environmentally friendly manner, and their use as a precursor for value-added processes could be a useful strategy to achieve this. CGBs are mainly composed of cellulose acetate, which can be used as a carbon precursor with significant oxygen content [38,39]. Mokaya et al. investigated the potential of oxygen-rich activated carbons and reported that the H2 storage capacity exhibited excess hydrogen uptakes between 4.6 and 7.0 wt.% at 77 K and 20 bar due to the combined effects of high surface area, high microporosity, and an oxygen-rich nature [39,40].

Here, we investigated the use of CGBs as a carbon precursor for H2 storage capacities. The aim of this study was to investigate the relationship between the oxygen content and the textural properties of CGB-AC, and further the resulting effect on their H2 storage behaviors by the electron acceptor–donor interaction between oxygen moieties and hydrogen molecules. From the experimental results, CGB-AC700 (i.e., AC prepared at 700 °C), with a SSA of 2850 m2/g, had the highest H2 storage capacity (8.54 wt.% at 77 K and 20 bar). This can primarily be attributed to the porosity. We also found that the oxygen content of the CGB-AC provided effective adsorption sites, resulting in improvement of H2 uptake.
2. Results and Discussion

2.1. Synthesis and the Morphology

CGBs as a carbon precursor were initially carbonized using a hydrothermal reaction to obtain CGB-d-hydrochar. Chemical activation was then conducted using KOH to induce porosity in the CGB-d-hydrochar. The pore structure of the CGB-d-hydrochar was produced via KOH activation using an etching carbon framework and redox reactions with potassium compounds. The following reactions explain this mechanism [41]:

\[
4\text{KOH} + \text{C} \rightarrow \text{K}_2\text{CO}_3 + \text{K}_2\text{O} + 2\text{H}_2, \\
2\text{KOH} \rightarrow \text{K}_2\text{O} + \text{H}_2\text{O}, \\
\text{C} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}, \\
\text{CO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}_2, \\
\text{K}_2\text{O} + \text{CO}_2 \rightarrow \text{K}_2\text{CO}_3, \\
\text{H}_2\text{O} + \text{H}_2 \rightarrow 2\text{K} + \text{H}_2\text{O}, \\
\text{K}_2\text{O} + \text{C} \rightarrow 2\text{K} + \text{CO}, \\
\text{K}_2\text{CO}_3 + 2\text{C} \rightarrow 2\text{K} + 3\text{CO}.
\]

In these reactions, the porous structure was created by oxidizing the carbon atoms. Scanning electron microscopy (SEM) images of CGB-d-hydrochar and CGB-AC samples produced at different activation temperatures are presented in Figure 1a–e. In Figure 1a, the CGB-d-hydrochar exhibited a smooth, non-porous surface. After KOH activation, pores were observed on the carbon surface. With an increasing activation temperature, the pores became larger and larger craters appeared at temperatures above 800 °C (Figure 1b–e), which indicated the collapse of the porous structure.

![SEM images](image1.png)

**Figure 1.** SEM images of (a) CGB-d-hydrochar and (b–e) CGB-AC samples at different activation temperatures ((b): 600 °C, (c): 700 °C, (d): 800 °C, and (e): 900 °C), and (f) XRD patterns for the obtained samples.

2.2. Structural Properties

X-ray diffraction (XRD) patterns for the CGB-d-hydrochar and CGB-AC samples are presented in Figure 1f. Broad peaks at 2θ = 23.5° (1 0 1) and 44° (1 0 0, 1 0 1) were observed for the CGB-d-hydrochar, indicating an amorphous graphitic structure consisting of randomly distributed carbon [42]. The peaks at 2θ = 23.5° and 44° in the CGB-AC...
samples decreased with higher activation temperatures due to an increase in the irregularity of the graphitic structure and its eventual collapse, which was in agreement with the SEM results [43].

2.3. Elemental Compositions

The elemental composition of the prepared samples is displayed in Table 1. The O content of CGB-d-hydrochar was 41.8%, while that of the CGB-AC samples was 18.5–38.5%, higher than the typical range for AC derived from cellulose-derived polymeric precursors (~11%) [40,44,45]. This indicates that the CGB-AC samples had a high concentration of O, which may be attributable to the oxygen moieties produced from the CGB-d-hydrochar during the activation process. It was expected that the relative content of C in the hydrochar would increase gradually with an increasing KOH activation temperature while that of O would decrease [46]. However, the relative atomic content of H gradually declined while that of O decreased less dramatically. This might be because the aliphatic compounds in CGB-d-hydrochar were preferentially removed during the activation process. In particular, the CGB-AC600 and CGB-AC700 samples retained a high O content of 38.5% and 37.9%, respectively. The CGB-d-hydrochar and CGB-AC samples also contained low N content, which was attributable to the nicotine from smoking.

Table 1. Elemental analysis of the CGB-d-hydrochar and CGB-AC samples.

| Samples         | C (%) | H (%) | O (%) | N (%) | O/C | H/C |
|-----------------|-------|-------|-------|-------|-----|-----|
| CGB-d-hydrochar | 50.3  | 6.7   | 41.8  | 1.2   | 0.831 | 0.133 |
| CGB-AC600       | 59.7  | 0.8   | 38.5  | 1.0   | 0.645 | 0.013 |
| CGB-AC700       | 62.0  | 0.5   | 37.9  | 0.6   | 0.611 | 0.008 |
| CGB-AC800       | 74.6  | 0.6   | 24.3  | 0.5   | 0.326 | 0.008 |
| CGB-AC900       | 80.4  | 0.4   | 18.5  | 0.7   | 0.230 | 0.004 |

2.4. Surface Properties

To further explore the behaviors of the oxygen functional groups in the CGB-d-hydrochar and CGB-AC samples, we carried out Fourier transform infrared (FTIR) and X-ray photoelectron spectroscopy (XPS) measurements. The FTIR spectra of the prepared samples are presented in Figure S1, showing a broad peak at 3400 cm\(^{-1}\) corresponding to the O–H stretching vibrations from the hydroxyl or carboxyl groups, which decreased with an increase in the activation temperature [47]. The prepared samples exhibited a wide band at 2800–3000 cm\(^{-1}\) attributable to the C–H band for alkyl groups, which is generally found in all carbon materials at varying peak intensities [48]. Moreover, the prominent peak corresponding to C=O stretching vibrations at 1620 cm\(^{-1}\) indicated that the CGB-AC samples had various oxygen functional groups [47]. It is also important that the peaks for the oxygen functional groups in the CGB-d-hydrochar were higher than those for the CGB-AC samples, which corresponded with the elemental analysis results.

The XPS spectra were recorded at a range of 200–700 eV, as shown in Figure S2. The spectra exhibited two prominent peaks at a binding energy of 531 and 284.5 eV, corresponding to O1s and C1s, respectively [49]. The prominent peaks for O1s in all samples indicated that abundant oxygen functional groups remained at the CGB-AC surfaces during the thermal activation process [50]. It was clearly observed that the peak intensity of O1s decreased while that of C1s increased with an increase in the activation temperature.

2.5. Textural Properties

The textural properties of the CGB-AC samples were verified using their nitrogen adsorption–desorption isotherms at 77 K, as presented in Figure 2a and Table 2. The CGB-AC samples exhibited typical Type I isotherms, in accordance with the IUPAC classification, which is characteristic of microporous materials based on a sharp increase in the amount of N\(_2\) adsorbed at very low relative pressures below 0.1 [51]. We found that the SSA and total
pore volume increased following KOH activation at increasing activation temperatures up to 700 °C and then decreased abruptly. It was expected that the KOH activation would promote the development of a porous structure, especially micropores, resulting in more advantageous textural properties [52]. The porosity was the highest for the CGB-AC700 sample, which exhibited the highest SSA and \( V_{\text{total}} \) (2850 m\(^2\)/g and 1.734 cm\(^3\)/g, respectively).

![Figure 2](image)

**Figure 2.** (a) \( N_2 \) adsorption–desorption isotherms of CGB-AC samples recorded at 77 K and (b) pore size distributions of the prepared samples as determined using the NLDFT method.

| Samples    | a SSA (m\(^2\)/g) | b \( V_{\text{total}} \) (cm\(^3\)/g) | c \( V_{\text{micropore}} \) (cm\(^3\)/g) | d \( V_{\text{mesopore}} \) (cm\(^3\)/g) | e \( F_{\text{micropore}} \) (%) | f \( Q_{\text{total}} \) (H\(_2\) uptake at 77 K and 20 bar) | g \( Q_{\text{excess}} \) (H\(_2\) excess uptake at 77 K and 20 bar) |
|------------|-------------------|--------------------------------------|----------------------------------------|---------------------------------------|---------------------------|---------------------------------|-------------------------------|
| CGB-AC600  | 1412              | 0.858                                | 0.834                                  | 0.023                                 | 97.20                     | 5.79                            | 5.85                          |
| CGB-AC700  | 2850              | 1.734                                | 1.559                                  | 0.175                                 | 89.91                     | 8.54                            | 9.67                          |
| CGB-AC800  | 1520              | 1.156                                | 1.028                                  | 0.128                                 | 88.93                     | 3.27                            | 4.05                          |
| CGB-AC900  | 987               | 0.516                                | 0.490                                  | 0.026                                 | 94.96                     | 2.40                            | 2.74                          |

\( \text{a SSA: specific surface area computed using BET equation at a relative pressure range of 0.00001-0.01;} \)
\( \text{b \( V_{\text{total}} \): total pore (0–50 nm) volume determined from the NLDFT method; ;} \)
\( \text{c \( V_{\text{micropore}} \): micropore (0–2 nm) volume determined from the NLDFT method; ;} \)
\( \text{d \( V_{\text{mesopore}} \): mesopore (2–50 nm) volume determined from the NLDFT method; ;} \)
\( \text{e \( F_{\text{micropore}} \): fraction of micropore volume = (micropore volume/total pore volume) \times 100; ;} \)
\( \text{f \( Q_{\text{excess}} \): H\(_2\) excess uptake at 77 K and 20 bar; ;} \)
\( \text{g \( Q_{\text{total}} \): H\(_2\) total uptake at 77 K and 20 bar.} \)

The decrease in the \( N_2/77 \text{ K} \) adsorption–desorption isotherms for the CGB-AC800 and CGB-AC900 samples indicated that a KOH activation temperature above 800 °C caused the porous structure to collapse. This is linked to the results for the pore size distribution (PSD) results (Figure 2b). The PSD for the CGB-AC samples had a broad peak at a pore size range of 0.5–3.0 nm, with the CGB-AC700 sample exhibiting a more dominant peak at 1 nm compared to the other samples, which is indicative of the presence of a well-developed microporous structure. For the CGB-AC800 and CGB-AC900 samples, the peak intensity decreased dramatically with an increase in the activation temperature, with CGB-AC900 exhibiting a broad peak at a comparably larger pore size range of 0.5–4.0 nm. This represents clear evidence that the porous structure was destroyed as the pores merged into wider pores at a higher activation temperature above 800 °C.

### 2.6. Hydrogen Adsorption Behaviors

The overall adsorption isotherms are presented in Figure 3. The excess adsorption \( (Q_{\text{excess}}) \) and the absolute amount of gas adsorbed \( (Q_{\text{total}}) \) for H\(_2\) at 77 K and 20 bar are also summarized in Table 2. \( Q_{\text{total}} \) was determined while experiments measured \( Q_{\text{excess}} \). These values were obtained using Equation (1) [53]:

\[
Q_{\text{excess}} = Q_{\text{total}} - V_{\text{pore}} \rho_{\text{bulk}} (P, T)
\]

where \( V_{\text{pore}} \) is the total pore volume for the adsorbent and \( \rho_{\text{bulk}} \) is the density of the bulk gas (i.e., H\(_2\)) at the given adsorption pressure and temperature. The bulk H\(_2\) density at
different pressures was obtained from the National Institute of Standards and Technology (NIST) [54].

![Figure 3. Total H\textsubscript{2} storage capacity of CGB-AC samples at 77 K and 20 bar.](image)

Based on Equation (1), CGB-AC700 had the highest \( Q_{\text{total}} \) (9.67 wt.\%) at 77 K and 20 bar. The high SSA and microporosity of the CGB-AC700 sample increased its \( Q_{\text{total}} \) storage capacity because of the higher number of \( \text{H}_2 \) adsorption sites. Similarly, the hydrogen uptake was lowest for CGB-AC900 (2.40 wt.\%) because of its low porosity.

Normally, the hydrogen adsorption capacity of activated carbons with high SSA tends to be in line with Chahine’s rule. Chahine’s rule is a typical trend obtained empirically where approximately 1 wt.\% of gravimetric \( \text{H}_2 \) uptake is obtained for every 500 m\textsuperscript{2} g\textsuperscript{−1} of SSA at 77 K and elevated pressure up to ~350 bar [55,56]. Figure 4a displays Chahine’s line (solid) and the relationship between \( Q_{\text{excess}} \) and SSA for CGB-AC samples. We found that CGB-AC800 and CGB-AC900 samples were closely related to the SSA while the others (CGB-AC600 and CGB-AC700) greatly outperformed at the trend. This exceptionally high \( \text{H}_2 \) uptake of CGB-AC600 and CGB-AC700 might be attributed to the high oxygen contents of 38.5\% and 37.9\%, respectively, on the carbon surfaces [40].

![Figure 4. (a) Relationship between \( \text{H}_2 \) uptake capacity and specific surface area for CGB-AC samples and (b) schematic illustration of the oxygen-rich porous carbon surface of CGB-AC and the adsorption mechanism of partially quadrupole-induced \( \text{H}_2 \) molecules.](image)

The \( \text{H}_2 \) uptake of CGB-AC700 was much higher than that reported for other experimental results in the literature when using carbon materials with a similar range of textural properties under the same conditions (6.5–7 wt.\%) [44,57–62]. The CGB-AC samples in the present study had a higher oxygen content, suggesting that the oxygen levels of carbon materials may influence their \( \text{H}_2 \) storage behaviors. It was also found that the \( Q_{\text{total}} \) for CGB-AC800 was lower than that of CGB-AC600 (4.06 wt.\% and 5.85 wt.\%, respectively) even though they had similar textural properties. The oxygen content of CGB-AC600 was higher than that of CGB-AC800, providing more evidence that oxygen functional play a
key role in improving the electron acceptor characteristics ($\delta^+$) of the material, resulting in increasing the H$_2$ ($\delta^-$) uptake (Figure 4b).

Our experimental results revealed that the synergetic effect between the textural properties and the oxygen content is a significant factor in improving H$_2$ uptake. The $Q_{\text{excess}}$ of the CGB-AC samples was between 2.40 wt.% and 8.54 wt.%, leading to a $Q_{\text{total}}$ of between 2.74 wt.% and 9.67 wt.% . It was also remarkable that a $Q_{\text{total}}$ greater than 7.67 wt.% was observed above 20 bar of $Q_{\text{total}}$ for any of the samples. These results can be explained in relation to the surface interactions of polar and nonpolar adsorbates. With a polar adsorbate, the electron acceptor–donor interaction plays a dominant role in hydrogen adsorption. Figure 4b presents the effect of oxygen functional groups on the carbon surface for H$_2$ adsorption, suggesting that oxygen functional groups provide H$_2$-affiliated sites. These acidic sites are charged, thus polarizing the H$_2$ molecules [63]. Although a direct charge transfer does not occur between H$_2$ molecules and the oxygen functional groups, the charge-induced dipole interaction offers adsorption-friendly sites in accordance with a partial loss of positively charged electrons, which is associated with the strong electron-acceptor characteristics [63]. In contrast, for a nonpolar adsorbate, the effect of pore size is dominant. Thus, an optimized pore size would be important for efficient H$_2$ physisorption. The efficiency factor ($\phi$) for pore size in an effective H$_2$ physisorption process can be estimated using experimental and theoretical calculations, as described in Equation (2):

$$\phi = \frac{\text{Effective pore size}}{\text{Kinetic diameter of H}_2\text{ molecule}}$$

where the kinetic diameter of H$_2$ molecules is 0.289 nm and the effective pore size represents a variable optimum pore size.

In a previous study, we experimentally determined that the $\phi$ of activated multi-walled carbon nanotubes (A-MWCNTs) prepared using KOH activation was approximately 2.5 at 77 K and 1 bar [64]. It can be assumed that much effective hydrogen uptake can be observed in the efficiency factor of 2.5. In the present study, the efficiency factor ($\phi$) fits roughly within a larger range, and it is clearly presented that the factors in the range of 2.0 to 3.1 showed quite a high value of $Q_{\text{total}}$ in the CGB-AC600, 700, and 800 samples, while CGB-AC900 showed the lowest $Q_{\text{total}}$ because it was far off the factor of 5.1.

Detailed information on the surface characteristics of the CGB-AC samples is critical to understanding their observed H$_2$ storage behavior. As listed in Table 3, the $\phi$ for CGB-AC600 and CGB-AC800 was 2.0 and 2.1, respectively, but they exhibited a different $Q_{\text{total}}$, possibly due to the much higher oxygen content in CGB-AC600. In addition, for CGB-AC700, which had the highest $Q_{\text{total}}$, the estimated $\phi$ was ~3, which was a result of its highest peak intensity in the PSD analysis, occurring at approximately 0.9 nm. It is important to note that $\phi$ can be affected by variation in the pressure and temperature. The closer $\phi$ is to 3, the more efficient it is for H$_2$ adsorption using carbonaceous materials at 77 K and 20 bar in the presence of higher oxygen content. Thus, CGB-AC700 exhibited an exceptional $Q_{\text{Excess}}$ of 8.54 wt.% at 77 K and 20 bar when compared to previous studies. Consequently, we suggest that the interaction between the adsorbate based on its electron-donor polarity ($\delta^-$) and the adsorbent based on its electron-acceptor polarity ($\delta^+$) should be considered in the design of a highly efficient H$_2$ adsorption system.

Table 3. Peak centers from pore size distribution analysis and the efficiency factor ($\phi$) for hydrogen uptake for the CGB-AC samples.

| Samples   | Peak Center (nm) | Efficiency Factor ($\phi$) |
|-----------|------------------|---------------------------|
| CGB-AC600 | 0.59             | 2.0                       |
| CGB-AC700 | 0.90             | 3.1                       |
| CGB-AC800 | 0.63             | 2.1                       |
| CGB-AC900 | 1.49             | 5.1                       |
3. Experimental Section

3.1. Sample Preparation

Littered cigarette butts (CGB) were collected to use as a precursor. Prior to the experiment, the paper wrapped around the CGB was removed, and then the CGBs were ground using a mortar. Hydrothermal carbonization was then performed to obtain CGB-derived hydrochar (CGB-d-hydrochar). The synthetic route for the CGB-d-AC (hereafter CGB-AC) is presented in Scheme 1. The ground CGBs were heated in a stainless-steel autoclave at 250 °C at a heating rate of 5 °C/min, followed by cooling to room temperature. The synthesized CGB-d-hydrochar was mixed with KOH (at a KOH/CGB-d-hydrochar weight ratio of 5 for chemical activation. A tubular furnace was heated to the target temperature at a heating rate of 5 °C/min and maintained for 1 h in a nitrogen atmosphere. The obtained CGB-AC was then washed with distilled water until a neutral pH was observed, followed by drying in an oven at 80 °C for 24 h. The prepared CGB-AC samples were labelled CGB-AC'T', where T indicates the activation temperature.

Scheme 1. Schematic illustration of the preparation process for CGB-AC samples.

3.2. Characterization and Hydrogen Adsorption Measurement

The morphology of the samples was investigated using scanning electron microscopy (SEM, Model SU 8010, Hitachi Co., Japan). The surface characteristics of the prepared samples were examined by X-ray photoelectron spectroscopy (XPS, K-Alpha, Thermo Scientific Co., USA), and the functional groups on the prepared samples were observed with a Fourier transform-infrared vacuum spectrometer (FT-IR, VERTEX 80V, Bruker Co., Germany). An elemental analyzer (EA, EA1112, Thermo Scientific Co.) was used to investigate the chemical elemental composition of the prepared samples. The textural properties of the samples were obtained from nitrogen adsorption–desorption isotherms at 77 K with a volumetric adsorption analyzer (Belsorp Max, BEL Japan Inc., Japan). The SSA was calculated using the Brunauer–Emmett–Teller (BET) equation, and the non-local density functional theory (NLDFT) was used to determine the pore size distribution (PSD). The \( \text{H}_2 \) adsorption isotherm was obtained using the volumetric analysis method using a gas adsorption analyzer (Model BEL-HP, BEL Japan, Inc., Japan) at 77 K and 20 bar. All of the samples were degassed before analysis at 473 K for 12 h in a vacuum. For the adsorption analysis, ultrahigh-purity \( \text{H}_2 \) (99.9999%) was used to eliminate the influence of impurities.
4. Conclusions

We prepared hydrothermally carbonized CGB-d-hydrochar with a high oxygen content. The CGB-d-hydrochar was chemically activated using KOH to obtain a highly porous carbon material. The resulting samples had varying oxygen levels and different textural properties, which resulted in a \( Q_{\text{total}} \) range of 2.74–9.67 wt.%. Our experimental data confirmed that the textural properties of the CGB-AC samples influenced their \( \text{H}_2 \) storage behavior. In particular, we found that the efficiency factor (\( \varphi \)) for \( \text{H}_2 \) molecules plays a key role in enhancing the \( \text{H}_2 \) uptake at 77 K and 20 bar. It was demonstrated that high oxygen levels in a carbon material play an important role in improving the electron acceptor–donor intermolecular interaction between the oxygen functional groups and \( \text{H}_2 \) molecules. Therefore, our experimental results for \( \text{H}_2 \) adsorption based on the \( \varphi \) of the pore size of the material should help in the design of more efficient \( \text{H}_2 \) uptake systems.

**Supplementary Materials:** The following are available online at https://www.mdpi.com/article/10.3390/catal11121524/s1, Figure S1: FTIR spectra of CGB-d-hydrochar and CGB-AC samples; Figure S2: The XPS survey scans of CGB-d-hydrochar and CGB-AC samples. Figure S3: Total \( \text{H}_2 \) uptakes of CGB-AC samples at 77 K and 20 bar.

**Author Contributions:** Conceptualization, S.-Y.L. and J.-H.P.; Data curation, J.-H.P. and Y.-J.H.; Investigation, Y.-J.H.; Project administration, and S.-J.P.; Writing—original draft, S.-Y.L. and S.-J.P.; Writing—review & editing, S.-Y.L., E.-S.L. and S.-J.P. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the Technology Innovation Program (or Industrial Strategic Technology Development Program), Innovative technology for \( \text{CO}_2 \) free hydrogen production using molten catalysts (20012373) funded by the Ministry of Trade, Industry & Energy(MOTIE, Korea), the Korea Electric Power Corporation (Grant number: R21X001-5), and the Korea Initiative for Fostering University of Research and Innovation (KIURI) Program of the National Research Foundation (NRF) funded by the Korean government (MSIT) (No. NRF-2021M3H1A106413511).

**Conflicts of Interest:** The authors declare no conflict of interest.

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