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Sustainable CO₂ Adsorbents Prepared by Coating Chitosan onto Mesoporous Silicas for Large-Scale Carbon Capture Technology

Gregor Sneddon,[a] Alexey Y. Ganin,[b] and Humphrey H. P. Yiu*[a]

In this article, we report a new sustainable synthesis procedure for manufacturing chitosan/silica CO₂ adsorbents. Chitosan is a naturally abundant material and contains amine functionality, which is essential for selective CO₂ adsorptions. It is, therefore, ideally suited for manufacturing CO₂ adsorbents on a large scale. By coating chitosan onto high-surface-area mesoporous silica supports, including commercial fumed silica (an economical and accessible reagent) and synthetic SBA-15 and MCF silicas, we have prepared a new family of CO₂ adsorbents, which have been fully characterised with nitrogen adsorption isotherms, thermogravimetric analysis/differential scanning calorimetry, TEM, FTIR spectroscopy and Raman spectroscopy. These adsorbents have achieved a significant CO₂ adsorption capacity of up to 0.98 mmolg⁻¹ at ambient conditions (P = 1 atm and T = 25 °C). The materials can also be fully regenerated/recycled on demand at temperatures as low as 75 °C with a > 85% retention of the adsorption capacity after 4 cycles, which makes them promising candidates for advanced CO₂ capture, storage and utilisation technology.

Introduction

Despite the impressive development of renewable energy sources for power generation, the progress is insufficient for tackling the worldwide problem of increasing “greenhouse gas” emissions from industry, in particular the energy sector.[1] With only a 4% growth predicted for the electricity generated from renewable sources over the next 30 years,[2] CO₂ carbon capture storage (CCS) remains the only viable solution. The world’s first commercial CCS plants are already in operation[3] and there has been a strong demand for the development of the current CCS technology to enable the additional step of utilisation of the CO₂. Current CCS technology in the power-generation industry employs amine solutions, such as 30% monoethanolamine in water, for eliminating CO₂ from the flue gas stream.[4] Despite the high recovery rate of CO₂ of up to 98% shown for these solutions,[5] there are numerous disadvantages associated with this technology. These include 1) the high energy consumption required for regenerating the aqueous amine absorbent; 2) degradation of the amine by other flue gas components, for example, SO₂, NO₂, HCl and oxygen; 3) corrosion of equipment; and 4) high toxicity.[6–9] Consequently, new solid-state adsorbents for CO₂ with high specificity and enhanced energy efficiency, handling and regeneration capabilities are needed for fully advancing the carbon capture storage utilisation (CCSU) technology.[10]

Several types of solid adsorbents have been proposed for CCSU, including nanoporous carbon materials, metal organic frameworks, aminated mesoporous silicas and microporous organic polymers.[11–13] With aminated mesoporous silica (NH₂-SBA-15 or NH₂-MCM-41) as an example, this adsorbent shows a good CO₂ capacity adsorption, typically of 1.0–3.6 mmolg⁻¹ at P = 1 atm and T = 25 °C.[14–16] However, the synthesis of aminated mesoporous silica involves grafting of toxic 3-aminopropyltriethoxysilicate, which is destructive to the mucous membranes and the upper respiratory tract of the human body, and the use of toluene as the solvent in an approximately 100-times quantity (1 g of silica in 100 mL of toluene).[17] For industrial-scale production of adsorbents, the excessive use of aromatic solvents and toxic reagents should be avoided.

Chitosan is a natural polysaccharide that contains randomly distributed D-glucosamine units (see Scheme 1) and has been widely used in various biomedical applications,[18] which indicates its benign nature to humans. Similar to other amine-based adsorbents, CO₂ adsorption can take place on the free amine groups of the D-glucosamine units by the cooperative adsorption of one CO₂ molecule with two adjacent amine groups.[19] Chitosan is a sustainable reagent because it occurs naturally as chitin, which is a major waste product of the seafood industry.[20] Such mass-scale availability presents...
and is widely used in industry,\textsuperscript{26} which implies that the chitosan/fumed silica composites developed herein would be suitable for large-scale applications including CO\(_2\) capture. The structural parameters, including the BET surface area, pore size distribution and pore volume, of all silica supports used in this work are summarised in Table 1. The fumed silica support was found to have a BET surface area of 186 m\(^2\) g\(^{-1}\) and a pore volume of 0.29 cm\(^3\) g\(^{-1}\). Table 1 also shows the structural parameters for two types of synthetic mesoporous silicas (SBA-15 and some MCFs), which were selected for the study of the effect of support’s mesoporous structure on the chitosan deposition. The nitrogen adsorption and desorption isotherms for the silica supports shown in Figure 1b–e exhibit type IV isotherm character with a hysteresis loop, typical for mesoporous materials, whereas fumed silica (Figure 1a) shows a transitional type II to type IV isotherm as a result of its large mesopores. The pore size distribution of SBA-15 (calculated from the adsorption data; Figure S1 in the Supporting Information) peaks at 8 nm in diameter, which is typical for an SBA-15 sample.

MCFs are essentially pore-expanded SBA-15 with trimethylbenzene (TMB) as the swelling agent. Control of the pore size was achieved by varying the TMB/surfactant ratio; the higher the ratio, the larger the pores were found to be. However, the mesoscale structure becomes less ordered as the TMB/surfactant ratio increases. In contrast to the 2D hexagonal pore array structure of SBA-15, MCF silicas have a “foam-like” (or bubble-like) structure with interconnected cages. In Table 1, the pore volume data is presented as “small” mesopores (<4 nm in diameter), “medium” mesopores (4–10 nm) and “large” mesopores (>10 nm). As a result of the long-range order of tubular pores, the porous structure of SBA-15 is dominated by the medium mesopores (pore volume: 0.7 cm\(^3\) g\(^{-1}\)). With regard to MCF supports, although the BET surface area decreases as a result of the loss of long-range order, the pore volume of the large mesopores gradually increases from 0.04 cm\(^3\) g\(^{-1}\) for SBA-15 to 0.7 cm\(^3\) g\(^{-1}\) for MCF-10. Among all MCF samples, the medium mesoporous volume remains roughly unchanged. Such differences in pore volume provide us with a “structural tool” to study the effect of pore size on chitosan deposition and, consequently, CO\(_2\) adsorption capacity.

TEM analysis (Figure 2a) illustrates the 2D hexagonal mesoporous structure of SBA-15, with a mean pore size of

### Results and Discussion

#### Characterisation of silica supports

Fumed silica, a chosen support material for this study, is a commercial mesoporous silica (for example, Cab-O-Sil) with a high surface area (200 m\(^2\) g\(^{-1}\)) and is widely used in industry,\textsuperscript{26} which implies that the chitosan/fumed silica composites developed herein would be suitable for large-scale applications including CO\(_2\) capture. The structural parameters, including the BET surface area, pore size distribution and pore volume, of all silica supports used in this work are summarised in Table 1. The fumed silica support was found to have a BET surface area of 186 m\(^2\) g\(^{-1}\) and a pore volume of 0.29 cm\(^3\) g\(^{-1}\). Table 1 also shows the structural parameters for two types of synthetic mesoporous silicas (SBA-15 and some MCFs), which were selected for the study of the effect of support’s mesoporous structure on the chitosan deposition. The nitrogen adsorption and desorption isotherms for the silica supports shown in Figure 1b–e exhibit type IV isotherm character with a hysteresis loop, typical for mesoporous materials, whereas fumed silica (Figure 1a) shows a transitional type II to type IV isotherm as a result of its large mesopores. The pore size distribution of SBA-15 (calculated from the adsorption data; Figure S1 in the Supporting Information) peaks at 8 nm in diameter, which is typical for an SBA-15 sample.

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### Table 1. Surface area and pore volume data for all chitosan/mesoporous silicas, as well as fumed silica.

<table>
<thead>
<tr>
<th>Mesoporous silica</th>
<th>BET surface[^{a}] pore volume [^{c}]</th>
<th>Unmodified silica</th>
<th>Chitosan on mesoporous silicas</th>
</tr>
</thead>
<tbody>
<tr>
<td>support area [^{b}] pore volume</td>
<td>total [^{b}]</td>
<td>total [^{b}]</td>
<td>pore diameter range</td>
</tr>
<tr>
<td>(\leq 4) nm</td>
<td>(4-10) nm</td>
<td>(&gt;10) nm</td>
<td>(\leq 4) nm</td>
</tr>
<tr>
<td>Fumed silica</td>
<td>186</td>
<td>0.29</td>
<td>0.04</td>
</tr>
<tr>
<td>SBA-15</td>
<td>530</td>
<td>0.81</td>
<td>0.09</td>
</tr>
<tr>
<td>MCF-3</td>
<td>439</td>
<td>0.75</td>
<td>0.10</td>
</tr>
<tr>
<td>MCF-6</td>
<td>387</td>
<td>0.83</td>
<td>0.08</td>
</tr>
<tr>
<td>MCF-10</td>
<td>375</td>
<td>1.01</td>
<td>0.06</td>
</tr>
</tbody>
</table>

\[^{a}\] Error in samples: ±4 m\(^2\) g\(^{-1}\).

### Scheme 1. (a) Structure of chitosan, with the N-acetyl-\(\beta\)-D-glucosamine and \(\beta\)-glucosamine units shown. (b) The cooperative adsorption of one CO\(_2\) molecule by two \(\beta\)-glucosamine units of chitosan.
around 7–9 nm; this is consistent with the pore size distribution data obtained from the N₂ adsorption isotherms. In Figure 2c, the MCF-3 sample shows the effect of the pore expander on the structure of these materials. The hexagonal mesoporous structure of SBA-15 has been completely transformed into a foam-like porous structure. MCF-6 and MCF-10 (Figure 2d and e) showed a similar structure to MCF-3 but the increase in pore size was difficult to depict. The N₂ adsorption isotherm data shown in Table 1 are, therefore, used to confirm the increase in the total pore volume of large mesopores.

**Characterisation of chitosan on fumed silica**

Initially, chitosan was supported on fumed silica in a range of compositions (7.4, 14, 19, 24, 29 and 32 wt%) to determine the optimal chitosan-to-support ratio. Vibrational spectroscopic analyses (FTIR and Raman spectroscopy) were carried out on chitosan and used as tools to identify the chitosan component on all chitosan/silica samples. The FTIR spectrum for chitosan and the assignment for the peaks are shown in Figure S2 in the Supporting Information. The twin peaks at ̅v = 3355 and 3290 cm⁻¹ correspond to the R–NH₂ and R–OH groups. The C–H stretches of the chitosan backbone are shown at ̅v = 2910 and 2870 cm⁻¹. The C=O stretch of the residual N-acetyl-β-D-glucosamine units of chitin appears at ̅v = 1645 cm⁻¹, whereas the NH₂ bending vibration appears at ̅v = 1590 cm⁻¹. The C–H bending vibrations are shown at ̅v = 1420, 1375 and 1320 cm⁻¹. FTIR studies were also performed on all of the samples of chitosan deposited on fumed silica (Figure 3a), with the increasing intensity of the peaks corresponding to increasing chitosan content. No peak was observed within the range of 1690–1760 cm⁻¹, which corresponds to carboxylic acid or carboxylate species. Hence, the results suggest that most of the acidic solvent had been removed during drying under vacuum. Also, it is indicated that most of the NH₂ groups on chitosan are not bound to carboxylate ions. Thermogravimetric analysis (TGA) and elemental analysis data were used to verify the composition of each of the samples as accurate (see Table S1 in the Supporting Information).

Raman spectroscopy was used to probe on a microscopic scale the distribution of the chitosan within the sample. It is, therefore, a complementary technique to the FTIR spectroscopy, which is a bulk technique and probes the presence of chitosan in the sample without giving a distinct answer about the distribution of the chitosan in the silica matrix. Whereas the control sample of pristine fumed silica did not show any significant Raman activity, even a small amount of chitosan (7.4 wt%) was sufficient for observing the characteristic signals of the chitosan molecule, as indicated in the Figure 3b. In contrast, the same sample showed very low peak intensity on its FTIR spectrum (Figure 3a). Furthermore, the intensity of the Raman signals also increases with the amount of the chitosan present in the sample. The most distinct peaks in the spectra are at ̅v = 2900/2933 and 3311 cm⁻¹ and are associated with the R₃–CH₂ and R–NH₂ groups stretching fre-
The clear split of the $R_2/\text{CH}_2$ group signal is a result of out-of-phase and in-phase bond stretching vibrations. Indeed, characterisation with Raman spectroscopy instead of FTIR spectroscopy avoids the interference from the silica support, a distinct advantage for characterising samples with a low organic content. Figure 3c shows the Raman map of a 19 wt% chitosan/fumed silica particle and the chitosan is shown to be evenly distributed at a μm scale. Chitosan has a large amount of hydroxy groups, so it is likely that the chitosan interacts with the silica support through strong hydrogen bonds between these OH groups and the Si-OH groups on the silica surface.

From the analysis with $N_2$ adsorption isotherms, pure chitosan has been shown to have a very low BET surface area (0.31 m$^2\cdot$g$^{-1}$) and a pore volume of 0.0016 cm$^3\cdot$g$^{-1}$, which suggests that it is virtually non-porous; these results lead to a negligible CO$_2$ adsorption capacity, consistent with the findings of Yoshida et al. [21]. This illustrates the need for the deposition of chitosan on a suitable support and for maximising the CO$_2$ adsorption capacity of a natural amine material. The thermal stability of chitosan was studied by simultaneous TGA/differential scanning calorimetry (DSC) analysis (Figure 4a). There is an initial endothermic weight loss at approximately $T=100^\circ C$, which corresponds to removal of water from the sample. Thermal decomposition, associated with a large exothermic peak, starts at about $T=230^\circ C$, which indicates that chitosan can be used at an elevated temperature range. There is no recordable change (for example, glass transition) for chitosan between $T=100$–$200^\circ C$.

From the $N_2$ adsorption isotherm analysis, there was a gradual decrease in the BET surface area as the chitosan content of the composite samples increased (Table 2). The chitosan can fill up the mesopores of the fumed silica support, so the available surface area decreases. If the pore volume data of the chitosan/silica composites was examined in detail according to the small (≪4 nm), medium (4–10 nm) and large (>10 nm) mesopore classification (see Table 1), the chitosan/fumed silica samples showed a decrease in both the small (pore volume changes from 0.04 to 0.02 cm$^3\cdot$g$^{-1}$) and medium (pore volume changes from 0.07 to 0.05 cm$^3\cdot$g$^{-1}$) mesopore regions as a result of pore blockage. Interestingly, the pore volume of the large mesopore range (>10 nm) increased from 0.18 to 0.26 cm$^3\cdot$g$^{-1}$ after coating with chitosan. This may be caused by large pores created from interconnecting the fumed silica particles with chitosan. Overall, this leads to an increase in the total pore volume upon deposition of chitosan from 0.29 to 0.33 cm$^3\cdot$g$^{-1}$. This phenomenon becomes more transparent from Figure S3 in the Supporting Information, in which the pore size distributions of samples with various chitosan contents are presented. Upon incorporation of 7.4 wt% chitosan into the pore network of fumed silica, there was a decrease in the pore volume with pore sizes below 8 nm relative to the results with the fumed silica support. However, an increase in the pore volume was observed at pore sizes of >10 nm. Notably, pure, unsupported chitosan is non-porous with a low BET surface area and pore volume (0.13 m$^2\cdot$g$^{-1}$ and 0.0016 m$^3\cdot$g$^{-1}$, respectively) and the coating process is unlikely to break up the porous structure of fumed silica to form new larger pores of >10 nm. Hence, the assumption of large pores created by interconnecting fumed silica particles offers a reasonable explanation for this observation. For samples with a higher percentage of chitosan (> 19 wt% on fumed silica (1 g))

<table>
<thead>
<tr>
<th>Chitosan content [wt %] on fumed silica (1 g)</th>
<th>Mass of chitosan added in synthesis [g]</th>
<th>Measured BET surface area[a] [m$^2\cdot$g$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (control) [b]</td>
<td>0</td>
<td>186</td>
</tr>
<tr>
<td>7.4</td>
<td>0.08</td>
<td>153</td>
</tr>
<tr>
<td>14</td>
<td>0.16</td>
<td>136</td>
</tr>
<tr>
<td>19</td>
<td>0.24</td>
<td>123</td>
</tr>
<tr>
<td>24</td>
<td>0.32</td>
<td>109</td>
</tr>
<tr>
<td>29</td>
<td>0.40</td>
<td>80</td>
</tr>
<tr>
<td>32</td>
<td>0.48</td>
<td>65</td>
</tr>
</tbody>
</table>

[a] Error in BET surface area: ±3 m$^2\cdot$g$^{-1}$. [b] Fumed silica sample treated with acetic acid.
The surface areas and pore volumes of the samples decrease significantly and are likely to reduce the CO₂ adsorption capacity. The 19 wt% chitosan sample still retains a high surface area (123 m² g⁻¹) and pore volume (0.33 cm³ g⁻¹), yet has a significant chitosan loading. Therefore, 19 wt% chitosan was chosen as a benchmark loading for this work.

Characterisation of chitosan on mesoporous silicas

Chitosan (19 wt%) was coated on SBA-15 (chitosan/SBA-15), MCF-3 (chitosan/MCF-3), MCF-6 (chitosan/MCF-6) and MCF-10 (chitosan/MCF-10) in order to study the effect of the porosity of the support on the chitosan deposition and on the CO₂ adsorption capacity. These composite materials showed no significant difference in the FTIR analysis in comparison to pure chitosan, with all samples showing peaks associated with both chitosan and silica (Figure S2b in the Supporting Information). The organic content from TGA analysis of the composite materials was found to be consistent across all chitosan/mesoporous silica samples (see TGA data in Figure S4 and Table S1 in the Supporting Information). The surface area and pore size distribution data in Table 1 show a decrease of 30–50% in the pore volume in both the medium (4–10 nm) and large mesopore ranges (>10 nm), which suggests that chitosan has been coated evenly across all pore ranges. Hence, there was no apparent preference for deposition/blockage to one particular pore range, which would have led to an overall decrease in the total pore volume and the BET surface area. If the chitosan was only deposited on the exterior of the support without entering the mesopores, such a high amount (19 wt%) would have led to a large decrease in both pore volume and BET surface area. Our results suggested that chitosan entered the pores, aided by sonication during deposition. These samples retained a high BET surface area (187–376 m² g⁻¹), which was adequate for use as gas adsorbents.
Volumetric and gravimetric CO₂ adsorption analysis

The CO₂ capacity of the chitosan/silica composites was measured with two different methods: volumetric and gravimetric adsorptions. The volumetric CO₂ adsorption capacity of the 19 wt% chitosan/fumed silica sample was found to be 0.29 mmol g⁻¹ and that measured gravimetrically was 0.09 mmol g⁻¹ (Table 3). No uptake of CO₂ was recorded from the gravimetric measurement for a pure fumed silica sample (see Figure S5 in the Supporting Information), which indicates that the CO₂ uptake from these samples is attributed to the coated chitosan. With consideration that pure chitosan has a CO₂ adsorption capacity of approximately 0.02 mmol g⁻¹,[21] our results show a remarkable 23-fold increase in capacity per unit mass of chitosan (0.47 mmol g⁻¹ chitosan), a unique property of these chitosan/silica composites. The higher capacity measured from the volumetric analysis than from the gravimetric measurement is consistent with other works in the literature.[26] The difference between these two measuring systems is that the gravimetric analysis was carried out in a dynamic flow system, whereas a static closed system was used for the volumetric measurement. Moreover, a 50% CO₂ in N₂ purge stream was used for the gravimetric measurements, instead of 100% CO₂ for the latter. In the next section, we will discuss the effect of CO₂ concentration in the gas adsorbate on the CO₂ adsorption capacity.

The results of the volumetric CO₂ adsorption analysis for the chitosan on mesoporous silica supports (SBA-15 and MCFs) are shown in Figure 5 and Table 3. The chitosan/MCF-3 sample has the highest adsorption capacity at 0.98 mmol g⁻¹, whereas other samples vary from 0.75–0.80 mmol g⁻¹. These recorded capacities are comparable with other high-surface-area nanomaterials designed for CO₂ adsorption, such as metal organic frameworks (for example, MOF-5 with a capacity of approximately 2 mmol g⁻¹, measured with a volumetric method).[27] Indeed, we can compare this result in terms of adsorption efficiency (that is, CO₂/NH₂ ratio) with an adsorbent of similar structure, NH₂-MCM-41, which gives a CO₂ adsorption capacity of 1.0 mmol g⁻¹ at P = 1 atm and T = 20°C.[15] NH₂-MCM-41 has a concentration of 2.48 mmol g⁻¹ of NH₂ groups, which results in a CO₂/NH₂ ratio of 0.4. The chitosan/MCF-3 sample has a concentration of approximately 0.76 mmol g⁻¹ of NH₂ groups (based on the elemental analysis) and a CO₂/NH₂ ratio of 1.3, which can be viewed as a 3-fold increase in efficiency compared with that of NH₂-MCM-41. In theory, the adsorbent with the highest BET surface area should adsorb the highest amount of CO₂ as a result of physisorption. However, this was not observed in this case because chitosan/MCF-3 had the lowest BET surface area among all of the samples except chitosan/fumed silica (Table 1). There is also no clear correlation between the pore volume of the adsorbents and their CO₂ adsorption.

Table 3. Volumetric and gravimetric CO₂ adsorption capacities measured for chitosan/mesoporous silica adsorbents.

<table>
<thead>
<tr>
<th>CO₂ adsorbent</th>
<th>Volumetric capacity (100% CO₂) [mmol g⁻¹]</th>
<th>Gravimetric capacity (50% CO₂ in N₂) [mmol g⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>chitosan/fumed silica  (19 wt %)</td>
<td>0.29</td>
<td>0.09</td>
</tr>
<tr>
<td>chitosan/SBA-15</td>
<td>0.80</td>
<td>0.32</td>
</tr>
<tr>
<td>chitosan/MCF-3</td>
<td>0.98</td>
<td>0.34</td>
</tr>
<tr>
<td>chitosan/MCF-6</td>
<td>0.75</td>
<td>0.29</td>
</tr>
<tr>
<td>chitosan/MCF-10</td>
<td>0.79</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Figure 4. (a) TGA/DSC traces of pure chitosan from T = 20–800 °C with air as the carrier gas to show thermal decomposition of the chitosan. Thermal decomposition begins at approximately T ≈ 200 °C. (b) TGA/DSC traces for the 19 wt% chitosan/fumed silica sample with air as the carrier gas. Thermal decomposition starts at T ≈ 200 °C, which is similar to the pure chitosan sample in (a).

Figure 5. Volumetric CO₂ adsorption isotherms of chitosan/fumed silica (○), chitosan/SBA-15 (□), chitosan/MCF-3 (●), chitosan/MCF-6 (■) and chitosan/MCF-10 (△). The CO₂ adsorption capacity recorded is in the order: chitosan/MCF-3 > chitosan/SBA-15 > chitosan/MCF-10 > chitosan/MCF-6 > chitosan/fumed silica.
capacity (Table 1 and 3), which suggests a complex relationship between adsorption and the structural parameters (surface area and pore volume). Notably, these structural parameters were measured for the whole composite, with no distinction between the gas adsorption (N₂ or CO₂) from the silica surface or from the chitosan coating. It would be difficult to pinpoint the critical structural factor influencing the overall CO₂ adsorption capacity.

Similar to that for chitosan/fumed silica, the adsorption results from the gravimetric analysis show a lower capacity for all chitosan on mesoporous silica samples relative to the adsorption capacity from the volumetric method (Table 3). Nonetheless, the CO₂ adsorption capacity of all chitosan/silica composite samples follows the same trend; the gravimetric adsorption is approximately one third of the volumetric adsorption capacity. On comparison between these two techniques, the CO₂ adsorption capacity measured with the gravimetric method is more representative of the real adsorption from a flowing flue gas, in contrast to the volumetric measurement from a closed system. Therefore, many recent research works in the literature have adopted the gravimetric method for measuring the CO₂ adsorption capacity for adsorbents.[28–30]

Gas composition analysis

In order to examine the effect of the CO₂ content in a gas stream on the adsorption capacity, gravimetric analysis with four CO₂ in N₂ gas compositions (100, 50, 13 and 8%) was also carried out with chitosan/MCF-3, which had shown the highest capacity, as the adsorbent (Figure S6 in the Supporting Information). With a 100% CO₂ stream, a maximum adsorption capacity of 0.42 mmol g⁻¹ was achieved quickly, within T=30 min, which was faster than with a 50% CO₂ stream (T=90 min). Gas streams containing 13 and 8% CO₂ were used to simulate the CO₂ content in the flue gas from coal-fired and gas-fired power stations, respectively. In both cases, the same adsorption capacity (0.10 mmol g⁻¹) was recorded after T=90 min. This suggested that chitosan/MCF-3 has the potential to be used as a CO₂ adsorbent for power stations, with a reasonable capacity achieved by utilising a waste polymer material as the major component for adsorption.

Water is another flue gas component (around 6–15%) to influence the efficiency of CO₂ adsorbents during carbon capture. Many solid-state adsorbents, such as zeolites and metal organic frameworks, can be deactivated by high moisture content. On the other hand, aminated silicas have not shown deactivation and, in some instances (for example, SBA-15 grafted with ethylenediamine groups), have shown an improved CO₂ adsorption capacity and adsorption efficiency in presence of water.[30] The chitosan/silica composites also utilise surface amine groups for interaction with CO₂; hence, deactivation by water is unlikely. Indeed, these composites were prepared in an aqueous medium and so water should have little negative effect on their adsorption behaviour.

Regeneration study

In addition to the adsorption capacities, the study of the regeneration of the materials at a low temperature is also important. A high energy requirement for regenerating the liquid amine absorbent (for example, 10–30% monoethanolamine in water is regenerated at T=140°C) in conventional carbon capture systems presents a major obstacle for a wider application. During the regeneration of these liquid-phase systems, much of the energy was spent on the evaporation of water, which is the “non-adsorptive” component of the adsorbent. To circumvent this obstacle, water-free solid-state adsorbents with a low regeneration temperature (T<100°C) are preferred.

In our regeneration study, four adsorption–regeneration cycles were carried out with the chitosan/MCF-3 sample, as shown in Figure 6. The overall adsorption for each cycle re-
desorbed at $T=75^\circ$C. Nonetheless, this feature has no impact on the overall performance of the adsorbent.

**Conclusions**

A family of chitosan/mesoporous silica composite materials were prepared with a simple deposition method. Unlike many other solid-state adsorbents, including aminated mesoporous silicas, metal organic frameworks and carbon nanotubes, the procedure for preparing these materials follows closely the green chemistry principles (room temperature and pressure conditions, avoidance of the use of toxic solvents, with 0.2 M acetic acid as the only solvent, and minimum waste emissions). These adsorbents, with a maximum volumetric CO$_2$ adsorption capacity of 0.98 mmol g$^{-1}$ at $T=25^\circ$C, are also chemically and thermally stable (up to $T=200^\circ$C). More importantly, they can be regenerated at a low temperature of $T=75^\circ$C and retained 85% capacity after 4 cycles. Such low energy consumption is advantageous for industrial applications, particularly in comparison with liquid-phase monoethanolamine solutions, which require an energy-intensive regeneration regime.

Chitosan is a major food waste product and to make use of it for tackling another environmental problem is an attractive approach. Large-scale use of the chitosan/fumed silica composite can be easily adapted because both chitosan and fumed silica are already commonly used in industries. To further enhance the CO$_2$ adsorption capacity, mesoporous silicas with high surface areas (for example, SBA-15 and MCF-3) can be used as the support material. These mesoporous silicas synthesised from surfactant templates have yet to be widely used in industry, but room-temperature synthesis methods and continuous preparation processes have already been reported.[35] Surfactant-free preparation routes have also been reported in the literature.[19] Therefore, large-scale use of these high-surface-area silicas could be possible in the near future. Alternatively, if there is a new non-silica material with a high surface area and a similar porous structure to those chitosan/MCF-3, coating chitosan onto it could give similar adsorptive properties to those chitosan/MCF-3.

Currently, the high running cost associated with carbon capture technology is one major obstacle for carbon capture storage (CCS) to become popular and the energy required for adsorbent regeneration contributes significantly to this cost. To fully realise the potential of carbon capture technologies, a lowering of the running costs is fundamental. The low-cost sustainable preparation of adsorbents in a large quantity, together with the low-temperature regeneration, presented herein can reduce the overall operational cost for CCS. Furthermore, green CO$_2$ adsorbents, such as the chitosan/mesoporous silica composites from this work, will have to be considered in order to achieve a net reduction of the carbon footprint.

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**Experimental Section**

**Materials**

Low-molecular-weight chitosan (75–85% deacetylated), fumed silica with a BET surface area of approximately 200 m$^2$g$^{-1}$ (data provided by supplier), glacial acetic acid (99.7%), tetraethyl orthosilicate (TEOS, 98%) and 1,3,5-trimethylbenzene (TMB or mesitylene, 98%) were all purchased from Sigma–Aldrich. Concentrated hydrochloric acid (37%) was supplied by Fisher Scientific. Pluronic P123 surfactant (EO$_3$PO$_7$EO$_3$, EO: ethylene oxide, PO: propylene oxide, $M_w=5800$) was kindly donated by BASF. Deionised water was used in all experimental procedures. All chemicals were used as received without further purification. All gases used (N$_2$, He, and CO$_2$, all >99.99%,) were supplied by BOC.

**Synthesis and characterisations for SBA-15 and MCF mesoporous silicas**

The procedure for preparing SBA-15 was selected because of its high reproducibility.[36] In a typical synthesis, Pluronic P123 surfactant (4 g) was first dissolved in an acidic solution containing concentrated hydrochloric acid (10 mL) and deionised water (139 mL) at $T=30^\circ$C. After the surfactant was fully dissolved, TEOS (8.3 g) was added dropwise and the reaction mixture was allowed to stir for $t=24$ h at $T=30^\circ$C. The solution was then transferred to a polytetrafluoroethylene bottle and heated in an oven to $T=100^\circ$C for $t=72$ h. The white precipitates were then filtered off with a Büchner flask and funnel and allowed to dry overnight. The white solid was then calcined in air at $T=550^\circ$C for $t=6$ h to remove the surfactant template. For MCF support materials, the same procedure as that for the SBA-15 synthesis was carried out but the pore-expanding agent TMB (1.2, 2.4 and 4.0 g) was added to the surfactant solution and allowed to dissolve completely prior to the addition of TEOS.[37] The samples were then calcined at $T=550^\circ$C for $t=6$ h. These materials were denoted as MCF-$n$, in which $n$ indicates the TMB/P123 weight-to-weight ratio; hence, MCF-3 has a TMB/P123 ratio of 0.3 (that is, 1.2 g of TMB and 4.0 g of P123).

**Coating chitosan on silica supports**

To determine the optimum chitosan/silica ratio, a series of samples were prepared with fumed silica as a model support material. In a typical experiment, the fumed silica support (1.0 g) was mixed with a chitosan solution (0.08, 0.16, 0.24, 0.32, 0.40 and 0.48 g of chitosan to give 7.4, 14, 19, 24, 29 and 32 wt% samples, respectively) in acetic acid (20 mL, 0.48 g of chitosan to give 7.4, 14, 19, 24, 29 and 32 wt% samples, respectively) in acetic acid (20 mL). Once mixed, the fumed silica/chitosan solutions were sonicated in an ultrasonic bath for 1 h to degas the samples and encourage pore filling with the chitosan solution. After degassing, the sample suspensions were transferred to petri dishes to dry at room temperature in a fume cupboard. Petri dishes were used to increase the evaporation rate of the acetic acid. After 48 h of drying, the samples were then dried in a vacuum oven at $T=50^\circ$C with a reduced pressure of $P=20$ mbar overnight to remove residual acetic acid. The dried samples were finally ground with a mortar and pestle. The supported chitosans are notated as chitosan/support with the designated chitosan content in wt%. For example, chitosan/fumed silica (19 wt%) refers to 19 wt% of chitosan on fumed silica, which was prepared with 0.24 g of chitosan and 1 g of support.

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port. Chitosan supported on other mesoporous silica samples (19 wt%) were similarly prepared by using silica support (1 g; SBA-15, MCF-3, MCF-6 or MCF-10) with a chitosan solution containing chitosan (0.24 g, based on the results from chitosan/fumed silica samples) and acetic acid (20 mL, 0.2 M).

Sample characterisation

The structural characters of SBA-15 and the MCFs were studied with nitrogen adsorption-desorption isotherms and TEM. The N_2 adsorption-desorption isotherms were measured with a Micromeritics Gemini VII 2390p unit. All samples were outgassed at T = 80°C under flowing nitrogen for t = 2 h by using a Flowprep unit (Micromeritics). Nitrogen adsorption-desorption isotherms were recorded at T = -196°C. The BET surface area, pore size distribution and Barrett-Joyner–Halenda pore volume were calculated by using Micromeritics software V1.03A. TEM analysis was carried out with a Tecnai T20 microscope (200 kV).

The chitosan/mesoporous silica samples were characterised with nitrogen adsorption isotherms, TGA, elemental analysis and vibration spectroscopies (FTIR and Raman). BET surface area and pore volume analysis was carried out with a Micromeritics Gemini VII 2390p unit with the same procedure as that described above. Thermal analysis (simultaneous TGA and DSC) was performed with a TA Instruments Q600 thermobalance. TGA and DSC data were collected between T = 20 and 800°C at a heating rate of 1°C min^{-1} with air as the carrier gas. Elemental analysis was carried out with a CE 440 elemental analyser. Carbon, hydrogen and nitrogen contents (as percentages) in samples were determined to an error of ±0.15%. The FTIR spectra were recorded with a Perkin-Elmer Spectrum 100 spectrophotometer. Spectra were collected in the wavenumber range between 650–4000 cm^{-1} with 16 scans at a resolution of 4 cm^{-1}. Raman spectroscopy was carried out on a powdered sample on a Horriba LabRam-HR spectrometer operated in back-scattered geometry with a 532 nm laser at ambient temperature over a sample area of 100 μm². Calibration was performed by referencing the spectrometer to the 520.1 cm^{-1} silicon line. The typical acquisition times were 6×30 s. Several spectra recorded at different points for each probe sample indicated consistently that the peaks were associated with the spectra of chitosan. The Raman imaging technique was also employed over a wider area of 50×60 μm on a selected sample to probe the bulk character of the coated materials and to test the distribution of the chitosan within the composite materials.

Volumetric and gravimetric CO_2 uptake and regeneration study by using adsorption isotherms and TGA

The volumetric adsorption study (P/P_0 = 0–760 mm Hg) was carried out by using a Micromeritics Gemini VII 2390p unit fitted with a chiller bath set at T = 25°C. The samples were outgassed at T = 80°C under flowing N_2 prior to CO_2 adsorption measurement. For the gravimetric adsorption measurements, the SDT Q600 unit was used with a cyclic custom programme. Samples were activated at T = 75°C overnight prior to adsorption studies. After activation, the samples were cooled down to T = 25°C and a 50:50 gas mixture of CO_2:N_2 was purged through the sample for 90 min once the weight stabilised. After 90 min of exposure, the temperature was raised to T = 75°C at a rate of 5°C min^{-1} and held at T = 75°C for a further 30 min to allow CO_2 desorption and, hence, regeneration of the samples to be complete. The temperature was then decreased to T = 25°C for the second adsorption loop. This procedure was repeated for four cycles to test the regeneration of the chitosan/MCF-3 sample. CO_2 adsorption tests were also carried out at varying CO_2:N_2 volume ratios (100, 13 and 8% CO_2) with the chitosan/MCF-3 sample. These experiments were carried out to mimic the flue gas environment of coal-fired (13% CO_2) and gas-fired (8% CO_2) power stations.

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