Fly ash-derived MCM-41 as a low-cost silica support for polyethyleneimine in post-combustion CO₂ capture


1. Introduction

Anthropogenic carbon dioxide (CO₂) emissions from fossil fuel combustion are accepted as being major contributor to global warming, together with contributions from other greenhouse gases, methane, nitrous oxide (N₂O), water vapor, hydrofluoric acid, perfluorocarbons, and sulfur hexafluoride [1]. Power generation accounts for 30% of global CO₂ emissions and there is an urgent need to deploy carbon capture and storage (CCS) to both conventional pulverized fuel coal-fired and natural gas combined cycle power plants globally, as carbon capture and storage (CCS) to both conventional pulverized fuel coal-fired and natural gas combined cycle power plants globally, as well as for major industrial emitters, including iron & steel and cement production.

Currently, CO₂ absorption with aqueous amine solutions (mono-ethylenamine, MEA that can be used with secondary and tertiary amines) is the only mature capture technology to 90% of the equilibrium uptake had the largest mesopore volume of 1.13 cm³ g⁻¹. Given the PFA-derived MCM-41 uses a waste silicate solution for hydrothermal preparation and no prior preparation is needed, production costs are estimated to be considerably lower where silicate solutions need to be prepared by base treatment, even if ash is used, as for the RHA derived MCM-41 used here.

The mesoporous molecular sieve, MCM-41, has been synthesized from pulverized coal fly ash (PFA), where the silicate filtrate used is a by-product from hydrothermal zeolite production. Rice husk ash was also used for comparison but fusion with sodium hydroxide was used to prepare the silicate filtrate, along similar lines to earlier reports of using PFA as a precursor for MCM-41 synthesis. The MCM-41 samples are chemically and mineralogically similar to a commercially available sample, but with higher pore volumes dominated by mesopores (0.92–1.13 cf. 0.88 cm³ g⁻¹). After polyethyleneimine (PEI) impregnation for CO₂ capture, the ash derived MCM-41 samples displayed higher uptakes than the commercial sample with the maximum achievable PEI loading of 60 Wt.% PEI (dry basis) before particle agglomeration occurs, approximately 13 compared to 11 Wt.%, respectively, the latter being comparable to earlier reports in the literature. The PFA sample that displays the fastest kinetics to achieve 90% of the equilibrium uptake had the largest mesopore volume of 1.13 cm³ g⁻¹. Given the PFA-derived MCM-41 uses a waste silicate solution for hydrothermal preparation and no prior preparation is needed, production costs are estimated to be considerably lower where silicate solutions need to be prepared by base treatment, even if ash is used, as for the RHA derived MCM-41 used here.

The cost of CO₂ capture for amine solutions in CCS technology can constitute 75% of the total cost of CO₂ sequestration [3–5]. Therefore, the development of next generation capture technologies with significantly lower energy penalties than amine scrubbing has been identified as a high priority area in the recent CCS roadmaps, for example in the UK (APGTF) [6], USA (DOE/NETL) [7], U.S. Department of Energy [8] and by the International Energy Agency (IEA) [9].

An alternative to amine scrubbing for post combustion capture (PCC) is using solid adsorbents, numerous materials have been tested including activated carbons (ACs) (prepared and modified by using reagents such as, KOH, K₂CO₃, ZnCl₂) [10,11], metal organic frameworks [12,13], microporous polymers [14], covalent organic frameworks [15] and supported amines [16]. Amines grafted or impregnated on aluminosilicates have been extensively researched due to their high CO₂ uptakes in dry and moist flue gases with CO₂ at low partial pressures. More specifically, polyethyleneimine (PEI) has been the most widely investigated impregnated amine based adsorbent [17–24] with it displaying fast adsorption kinetics at temperatures of ca. 75 °C.
Previous work has shown that the stability of PEI is extremely high during circulating fluidised bed operation over long operating periods provided that there is moisture both in the flue gas and in the sweep gas to remove CO2 during regeneration at temperatures close to 130 °C [23]. However when considering scale-up, clearly the cost of mesoporous aluminosilicates used for PEI impregnation is a major consideration. Commercially available mesoporous silicas, MCM-41 and SBA-15 have all been found to be effective supports allowing PEI loadings of 50 wt.% or higher to be used [25,26]. Here we consider how the cost of MCM-41 can be reduced significantly by using a silicate solution which is a by-product from hydrothermal synthesis of zeolites using pulverized fly ash (PFA) from coal combustion.

MCM-41 is synthesized from silicate solutions using hydrothermal synthesis as depicted in Fig. 1 via a liquid templating mechanism [27–32]. The conventional synthesis using commercially available sodium silicate and a cationic surfactant, such as hexadecyltrimethylammonium bromide (CTAB) and a pH regulator is depicted in Fig. 1 [33]. After the hydrothermal reaction, the resultant MCM-41 is separated by filtration, dried and then surfactants are removed by calcination at temperatures in the range of 500–550 °C. Given that the current cost of MCM-41 from commercial suppliers is prohibitively expensive for the purity required for CO2 capture, inexpensive sources of silicate are required to help reduce the overall production costs.

Inexpensive silica sources for base extraction that have received attention include fly ash from pulverised coal combustion (PFA) as well as rice husk ash (RHA) [34–38]. In the preparations of MCM-41 from PFA fly ash proposed by Majchrzak-Kuczęba et al. [35] and Zhou et al. [38], the extraction of silicate is clearly necessary. Majchrzak-Kuczęba et al. [35] used high temperature fusion of fly ash with NaOH, with the resulting sinter being mixed with water. In contrast, Zhou et al. [38] used the hydrothermal reaction of fly ash with NaOH solution, in an autoclave for 1 h at 100 °C. The second stage reported by Majchrzak-Kuczęba et al. [35] used an appropriate amount of the surfactant CTAB at a pH of 11. Zhou et al. [38] used the same surfactant but with the addition of ethyl acetate as a pH regulator. There was also a small difference in the reaction temperature (Majchrzak-Kuczęba et al. [35] used 100 °C and Zhou et al. [38] used 90 °C). Calcination in both cases was carried out 550 °C. The route proposed by Hui et al. [39] for PFA used NaOH solution at 100 °C for silicate extraction. The subsequent hydrothermal stage used CTAB as the surfactant, regulating pH with sulfuric acid but with the reaction being carried out at ambient temperature.

The aim of this study is to compare the structures of MCM-41 prepared from PFA and RHA and, then after PEI impregnation, compare their effectiveness for CO2 capture with a commercial sample that has been prepared conventionally. The PFA preparation used waste silicate solution from the hydrothermal synthesis of zeolites for the first time and the potential cost reductions are considered. The CO2 uptakes achieved are compared with those reported in other studies using conventional silicate sources for MCM-41 [25,26,35].

2. Materials and methods

To synthesise mesoporous MCM-41, RHA prepared by laboratory-scale combustion and a PFA from a Polish power plant were used (Kozienice Power Plant, Kozienice, Poland). The PEI used with a number average weight (Mn) of 800 was purchased from Sigma Aldrich (100 g) as was the commercial MCM-41 sample (25 g).

2.1. Chemical analysis

The chemical compositions of both starting material (PFA and RHA)
and the MCM-41 products were determined by X-ray energy dispersive fluorescence spectrometer (XRF, PANalytical Epsilon 3 spectrometer). The tests were carried out on the range of Na-Am (sodium to americium) and the instrument equipped with X-ray tube Rh 9kV, 50 kV, 1 mA, 4096-channel spectrum analyzer, 6 measurement filters (Cu500, Cu300, Ti, Al50, Al200, Ag), the high-solid state detector SDD (Be window, a thickness of 50 µm) cooled by a Peltier cell.

The main elements in the filtrates were determined with Inductively Coupled Plasma Mass Spectrometry (ICP-MS, ELAN DRC-e Perkin Elmer instrument), the detection limits being below 0.01 mg/dm³ for the metals analysed.

2.2. Synthesis of MCM-41

MCM-41 samples PFA-1 and PFA-2 were synthesized from the silicate-rich filtrate by-product obtained after hydrothermal synthesis of zeolites (20 kg of fly ash, 12 kg NaOH, 90 dm³ of H₂O, temperature 80 °C, duration 36 h to prepare Na-P1 zeolite) using the apparatus described by Wdowin et al. [40] However, similar results should be obtained from waste silicate solution from synthesising other zeolites. For the RHA, the Si-rich filtrate was obtained by fusing 12.5 g of the RHA with 15 g NaOH (mass ratio of 1:2) at 550 °C for one hour, heating at 1 °C/min, as proposed by Majchrzak-Kucba et al. [35]. The resulting sinter was mixed with water using a mass ratio of 4:1. The chemical composition of the filtrates from the PFA and RHA are presented in Table 1 which indicates that Si and Sodium (Na) dominate in both cases. There is some potassium (K) present for the PFA but not the RHA. With the exception of S and P arising from dissolved sulphate and phosphates, the concentrations of the minor and trace metals present, including Al, are all below 0.5% of the Si concentrations.

The subsequent MCM-41 hydrothermal synthesis for both PFA and RHA was carried out by the method modified by Majchrzak-Kucba et al. [35] with CTAB as the surfactant. For PFA 1 and 2, 110 ml of filtrate was used with 5 g of CTAB, the reaction times differing being 96 and 72 h, respectively. This produced 2.5 and 2.6 g of MCM-41 respectively. From 34 ml of the RHA-derived silicate solution with 2.5 g of CTAB, 1.8 g of MCM-41 was obtained after a reaction time of 72 h.

### Table 2

<table>
<thead>
<tr>
<th>Compound</th>
<th>Concentration [Wt.%]</th>
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<tr>
<td>MgO</td>
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</tr>
<tr>
<td>Al₂O₃</td>
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<tr>
<td>SiO₂</td>
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<tr>
<td>P₂O₅</td>
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<tr>
<td>SO₃</td>
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<tr>
<td>K₂O</td>
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<tr>
<td>CaO</td>
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<tr>
<td>TiO₂</td>
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<tr>
<td>Cr₂O₃</td>
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<tr>
<td>MnO</td>
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<tr>
<td>Fe₂O₃</td>
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<tr>
<td>NiO</td>
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<td>CuO</td>
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<tr>
<td>ZnO</td>
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<td>As₂O₃</td>
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<td>Rb₂O</td>
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<tr>
<td>SrO</td>
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<tr>
<td>ZrO₂</td>
<td>0.001</td>
</tr>
<tr>
<td>Ag₂O</td>
<td>0.031</td>
</tr>
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</table>

2.3. PEI impregnation and measurement of loadings

The desirable amount of PEI from a 50% aqueous solution was dissolved in 10 ml water with vigorous stirring for 15 min. Next, the corresponding amount of calcined mesoporous silica was gradually poured into the solution. The mixture was stirred overnight at room temperature and then dried at 40 °C in a vacuum oven for 24 h.

The theoretical PEI loading on a dry basis is defined as:

\[
PEI\ loading\ (\text{Wt.\ %}) = \frac{W_{PEI}}{W_{PEI} + W_{Silica}} \times 100
\]  

(1)

where W refers to the mass fractions on a dry basis.

The actual amount of PEI impregnated was determined by TGA (TA Instruments TGA Q5000). Approximately 20 mg of sample was placed onto a platinum pan, the temperature was raised from ambient to 115 °C at a heating rate of 30 °C/min in pure nitrogen (N₂) gas (1 bar, 100 ml/min) and held isothermally for 30 min to remove moisture. Then, the temperature was cooled to approximately 90 °C, the gas switched to air (atmospheric pressure, 100 ml/min) and the temperature was ramped at 30 °C/min to 800 °C and held isothermally for 30 min. Weight% (Wt.% PEI loadings) were calculated on a dry basis determining the weight change between 150 and 700 °C, the temperature range over which PEI decomposed with devolatilisation and subsequent combustion of the volatiles. Samples were run in duplicate with blank pan correction.

2.4. Mineralogical analysis of MCM 41 samples

Powder X-ray diffraction (XRD) (Panalytical X'pert APD diffractometer) was used with the data being processed by Philips X'Pert and ClayLab ver. 1.0 software. The identification of mineral phases was verified based on the PCPDFWIN ver. 1.30 database formalized by JCPDS-ICDD. The morphology and chemical composition of the main mineral components were investigated using an FEI Quanta 250 FEG scanning electron microscopy and energy dispersive spectroscopy (SEM/EDAX).
2.5. Textural characterisation

Textural properties were determined using a Micromeritics ASAP 2420 using N\textsubscript{2} as the adsorbate at \(-196^\circ\text{C}\). N\textsubscript{2} sorption isotherms were acquired from 0.01 to 0.99 relative pressure (P/P\textsubscript{0}). Approximately 0.2 g of sample was weighed into a sample tube and degassed at 250 °C for 24 h. The BET specific surface area was determined based on the SBET multilayer adsorption model, where P/P\textsubscript{0} was between 0.05 and 0.20 giving positive BET constants. The total pore volume (V\textsubscript{p}) was determined from the adsorbed nitrogen volume at P/P\textsubscript{0} = 0.99. Average pore diameters (D\textsubscript{p}) were calculated according to D\textsubscript{p} = 4 V\textsubscript{p}/SBET. Mesopore volumes were calculated by using BJH adsorption model (Harkins Jura thickness equation) between 2 and 50 nm.

2.6. CO\textsubscript{2} adsorption

The CO\textsubscript{2} uptakes of the PEI impregnated adsorbents were determined by TGA Q500. Approximately 20 mg was weighed on to a platinum pan and was preheated to 115 °C at a heating rate of 30 °C/min in pure N\textsubscript{2} gas (1 bar, 100 ml/min), and held isothermally for 30 min to remove moisture. After the moisture removal stage, the temperature was lowered to the adsorption temperature of 75 °C and the gas switched to 15% CO\textsubscript{2} balanced by N\textsubscript{2} (1 bar, 100 ml/min) and held for 60 min to achieve adsorption equilibrium. CO\textsubscript{2} uptake (Wt.%) was determined through the weight difference between initial dry mass and mass after adsorption as shown in Eq. (2). Samples were analysed in duplicate, with blank pan correction.

\[
\text{Wt. \%CO}_2 \text{ uptake} = \frac{W_{\text{final}} - W_{\text{initial}}}{W_{\text{initial}}} \times 100
\]  

Rates of adsorption (kinetics) were assessed from the CO\textsubscript{2} adsorption isotherms, by recording the times taken to reach 30, 60, 90 and 95% of the full equilibrium capacities at 60 min.

3. Results and discussion

3.1. Ash characteristics

The RHA is characterised by a very high content of Si (ca. 87 Wt.%, Table 2), the remaining oxides being mainly Calcium (Ca), K and P with small amounts of aluminium (Al), magnesium (Mg), iron (Fe) and sulphur (SO\textsubscript{3}). The PFA has a lower Si content than for RHA, approximately 53 Wt.%, with the Si to Al ratio being close to 2, with a significant amount Fe present (8 Wt.%). Oxides of K, Ca, Mg, Ti, together with SO\textsubscript{3}, account for the remainder.

From XRD analysis both ash samples observed a very high background level of XRD diffraction curves (Figs. 2 and 3), indicating a high proportion of amorphous Si phases as well as quartz. For PFA (fly ash), a large degree of Fe components are observed, such as magnetite, hematite and mullite. For RHA the main mineral phase is abundantly Si related, such as silica glass, quartz and a polymorphic form coesite, this coincides with the data from XRF showing that RHA is predominately SiO\textsubscript{2}.

Further, the ashes have very different morphological forms (Fig. 4). PFA comprises uniform spherical grains (pleospheres) with some agglomeration evident (Fig. 4a) on the surface, ranging from approximately 2–30 μm. For RHA (Fig. 4b), grains of non-uniform irregular shapes, larger than for PFA are evident, with a large amount of shapeless agglomeration of Si on the surface.
3.2. Characteristics of the MCM-41 samples

Table 3 indicates that the MCM-41 samples PFA-1 and PFA-2 approximately 97 Wt.% as SiO₂. Considerable amounts of Na₂O and Al₂O₃ are evident (ca. 1 to Wt.%). Other components were all less than 1 Wt. %. The RHA sample (RHA-1) has similar SiO₂ and Na₂O contents. The commercial MCM-41 has a lower measured content of silica (90 Wt.%), but this is likely to be experimental error since there is less Na₂O and no

![Fig. 4. SEM microphotographs of (a) PFA – mag. 2000× (left) and 4000× (right), (b) EDS analysis of PFA surface (c) RHA mag. 500× (left) and 1000× (right) and (d) EDS analysis of RHA surface.](image)
Al2O3 compared to the PFA samples.

Fig. 5 shows that all the MCM-41 samples have very similar XRD profiles. The identification of the MCM-41 phase is based on the main d-spacing dH1 = 40.71, 23.56, 20.31, 15.26 Å. Some very small shifts of peaks in the PFA and RHA-derived samples are evident, arising from the slightly higher levels of impurities.

Fig. 6 shows SEM microphotographs and accompanying EDS analysis for MCM-41 sample PFA-1. All three samples display very similar morphology approaching spherical and partially elongated shapes about size of 0.2 μm. Since all cases, EDS confirms the high silica contents. The high content of carbon arises from the coating to achieve better conductivity of electrons and reduce charging.

N2 sorption isotherms of the MCM-41 samples are all type IVb, indicative of adsorbents with narrow mesopores. A steep rise in the amount of N2 adsorbed can be observed between 0.3–0.4 P/P0 that is common in MCM-41. On closer inspection, a slight hysteresis is observed in this region for the ash derived MCM-41 samples that is close to H1 hysteresis [41] which has been reported in templated mesoporous silicas such as MCM-41 and 48. However, all the MCM-41 samples have excellent pore uniformity due to little hysteresis, indicating little or no ink bottle pores.

Table 4 indicates that all MCM-41 samples are predominantly mesoporous, with mesopores accounting for over 90% of the total pore volume. PFA-1 has the highest BET specific area and pore volume, although the overall range of values for BET specific surface areas, total pore volume and mesopore volumes is relatively small. This might be explained by the longer reaction time of 96 h used in the hydrothermal synthesis for PFA-1 compared to 72 h for PFA-2 and RHA-1. Overall, RHA-1 is very similar to the commercial MCM-41 sample, with the proportion of mesopores accounting for slightly less of the total pore volume (91–92%) than for the two PFA samples (95–98%, Table 4).

3.3. PEI loadings

The TGA profiles of the impregnated MCM-41 samples displayed sharp weight decreases up to 115 °C due to moisture (Fig. 7 for the commercial and PFA-1 derived samples). Although the samples were pre-dried for 24 h in a vacuum oven at 40 °C, this was not a high enough temperature to remove all the moisture due to association with the PEI and surface silanol groups, coupled with the fact the samples re-equilibrate with moisture on exposure to the atmosphere. Another noticeable drop in mass occurs around 150 °C attributed to the volatilisation of low molecular mass PEI oligers. Thermal decomposition and combustion of the remaining PEI occurs and this continues up to 700 °C where only the silica substrate remains.

The PEI loadings determined form TGA are listed in Table 5. All the measured PEI loadings are comparable to the theoretical values. All of the MCM-41 impregnated samples are free flowing powders up to 60 Wt.%, but above this point, samples become heavily agglomerated and adhesive, as PEI starts to cover the surface of particles.

3.4. CO2 adsorption and kinetics

CO2 uptakes were determined by TGA in 15% CO2 balanced by N2 at 75 °C simulating PCC conditions from coal-fired power plant, within the temperature range found to be optimum for PEI by other researchers [18–23,35,42]. Fig. 8 presents the uptake profiles for the commercial and PFA-1 derived samples. CO2 uptakes and with the times taken to reach 30 with 60 and 90% of the final uptakes after an hour are listed in Table 6.

The CO2 uptake profiles are dominated by the rapid initial uptake that occurs in less than 4 min, followed by a much slower uptake that typically accounts for less than 20% of the final uptake reached after an hour. At the higher PEI loadings (50 and 60 Wt.%) for the commercial MCM-41, it is noticeable that the slower component tails more and does not appear to quite reach the limiting or equilibrium capacity within one hour (Fig. 8).

As is well established [24,25,35], CO2 uptake increases with PEI loading, as can be seen for the commercial MCM-41 going from 6.4 to 11.2 Wt.% as the PEI loading increases from 40 to 60 Wt.% (Fig. 8 and Table 6).
However, the results clearly indicate that the ash derived MCM-41 samples have considerably higher maximum CO$_2$ adsorption capacities at both 50 and 60 Wt.% PEI loading, probably attributable to the larger mesopore volumes (Table 4), 1.13, 0.96 and 0.92 cm$^3$ g$^{-1}$ for PFA-1 and 2, RHA-1, respectively compared to 0.88 cm$^3$ g$^{-1}$ for the commercial sample. As already indicated, increasing the loading further to 65 and 70 Wt.% gave samples that were adhesive and largely agglomerated with CO$_2$ uptakes falling to well below 10 Wt.%.

As well as giving higher CO$_2$ uptake, all three ash derived MCM-41 samples have superior kinetics compared to their commercial equivalent at 50 and 60 Wt.% PEI loading, probably attributable to the larger mesopore volumes (Table 4), 1.13, 0.96 and 0.92 cm$^3$ g$^{-1}$ for PFA-1 and 2, RHA-1, respectively compared to 0.88 cm$^3$ g$^{-1}$ for the commercial sample. As already indicated, increasing the loading further to 65 and 70 Wt.% gave samples that were adhesive and largely agglomerated with CO$_2$ uptakes falling to well below 10 Wt.%.

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3.6. Economic assessment

The PFA derived MCM-41 samples prepared from waste silicate solution offer considerable potential for reducing the overall cost of synthesis of this material. Indeed, the commercial fabrication of sodium silicate from quartz sand and sodium carbonate at 1300 °C requires a large input of energy [43,44]. The synthesis costs are even higher if organic silicon reagents are used for preparing mesoporous silicates [45,46]. In order to reduce the cost, a number of low-cost silica sources have been identified including natural zeolites [47], clay [48,49], ore tailoring [50,51], agriculture slag waste [52], E-waste [53], wheat husk [54], rice husk [37,55], as well as coal fly ash [38,56]. However, either fusion or autoclave treatment step with NaOH is still required with energy costs still being considerable.

Regarding the direct use of waste silicate solutions as used here for PFA, Shah et al. [57] used siliceous sugar industry waste but they employed a multistep extraction procedure to obtain a solution with the silicate content being similar to that used here.

The estimated cost for production at a laboratory scale of the PFA-derived MCM-41 is approximately 1200 euro per kg. This includes some equipment cost, but the largest operating costs are for reactants (approx. 1000 euro per kg), mainly for the surfactant, as well as energy, at approx. 2.5 euro/kWh, and labour costs. There is some savings on reagent costs because the synthesis does not require ethyl acetate as co-solvent as in case of Meléndez-Ortiz et al. [33]. As reported by Lawrence et al. [58], costs can be reduced by shortening time for MCM-41 synthesis but it was found here and in earlier work, that relatively long times are needed to obtain high purity MCM-41.

Compared to the cost of the waste-silicate solution-derived here, the cost of the commercial sample used here purchased on a small-scale runs to several tens of thousands of euros per kg, although clearly not produced on a kg scale. The only such sample we could identify (ACS Material LLC) is currently available at a cost of approximately 2000 euro per 1 kg [59] but this has lower purity than the commercial sample used here.

Regarding the potential application to PCC, it should be remembered that after prolonged usage in circulating fluidized-bed systems, provided that MCM-41-PEI has good attritional resistance as found for other mesoporous silicas [23], then it should be possible to recycle the silica where degraded PEI can be removed by controlled combustion. Therefore, provided the cost of recycling is low, the silica preparation costs can be considered largely as an initial cost whilst the cost of replenishing PEI will be a significant operating cost.

4. Conclusions

Fly and rice husk ash as low-cost silica sources have successfully been used for the synthesis of high purity MCM-41. Chemical and mineralogical analysis shows that the ash derived MCM-41 samples have similar chemistry to that of a commercial sample, with SEM showing identical morphologies between samples. However, the ash-derived samples have higher mesopore volumes than the commercial sample used (0.92–1.13 cf. 0.88 cm³ g⁻¹).

After PEI impregnation for CO₂ capture, the ash derived MCM-41 samples displayed higher uptakes and faster kinetics at the maximum loading of 60 Wt.% PEI than the commercial sample, approximately 13 wt.% for PFA-1, PFA-2 and RHA-1 compared to 11 Wt.%.

Table 5

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>Theoretical Loading (Wt.%)</th>
<th>Actual PEI loading (Wt.%)</th>
</tr>
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<tbody>
<tr>
<td>MCM-41 Com 40%</td>
<td>40</td>
<td>38.04 ± 0.56</td>
</tr>
<tr>
<td>MCM-41 Com 50%</td>
<td>50</td>
<td>50.01 ± 0.93</td>
</tr>
<tr>
<td>MCM-41 Com 55%</td>
<td>55</td>
<td>55.42 ± 0.07</td>
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<tr>
<td>MCM-41 Com 60%</td>
<td>60</td>
<td>60.81 ± 0.24</td>
</tr>
<tr>
<td>MCM-41 PFA-1 50%</td>
<td>50</td>
<td>51.39 ± 0.96</td>
</tr>
<tr>
<td>MCM-41 PFA-1 60%</td>
<td>60</td>
<td>57.46 ± 0.24</td>
</tr>
<tr>
<td>MCM-41 PFA-2 50%</td>
<td>50</td>
<td>47.75 ± 0.33</td>
</tr>
<tr>
<td>MCM-41 PFA-2 60%</td>
<td>60</td>
<td>60.87 ± 0.36</td>
</tr>
<tr>
<td>MCM-41 RHA-1 50%</td>
<td>50</td>
<td>48.02 ± 1.86</td>
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<tr>
<td>MCM-41 RHA-1 60%</td>
<td>60</td>
<td>61.71 ± 0.22</td>
</tr>
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</table>

Com = commercial.
respectively. At the maximum 60 Wt.% PEI loading, PFA-1 sample has the fastest adsorption kinetics to achieve 90% of the equilibrium uptake, attributed to it having the largest mesopore volume of 1.13 cm$^3$ g$^{-1}$.

The use of PFA-derived waste silicate solution from synthesizing other zeolites has the potential to reduce production costs considerably for MCM-41 which are estimated to approximately 1200 euro per kg for the scale of the facility used here.

Conflict of interest

There are no conflict of interest to declare.

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References
