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# CO<sub>2</sub>

## PAPER

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# Amine-dependent CO<sub>2</sub> sorption on amine-impregnated Mg<sub>2</sub>(dobpdc) MOF under humid conditions†

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Amine-functionalized Mg<sub>2</sub>(dobpdc) sorbents are prepared and studied systematically using three amines of different sizes: *N,N'*-dimethylethylenediamine (m-2-m), tetraethylenepentamine (TEPA), and poly(ethyleneimine) (PEI), in order of increasing size. A prototypical amine-appended Mg-based metal-organic framework, m-2-m-Mg<sub>2</sub>(dobpdc), is tested under dry direct air capture (DAC) conditions at cold temperatures (<25 °C) with the objective of increasing the CO<sub>2</sub> capture fraction by shifting the step pressure in the isotherm to lower pressures. We observe that the theoretical amine efficiency (one CO<sub>2</sub> to one diamine) could not be achieved due to the failure of the established amine insertion mechanism. In contrast, TEPA-impregnated Mg<sub>2</sub>(dobpdc) shows a significant increase in its CO<sub>2</sub> adsorption capacity under humid conditions (3.9 mmol g<sup>-1</sup> and 0.33 amine efficiency at 25 °C) compared to dry conditions (0.54 mmol g<sup>-1</sup>), aided by hydration of amines by water at elevated relative humidities (≥50% RH), which frees some amine chains and alleviates diffusion resistances along the MOF pore. On the other hand, both branched and linear PEI-impregnated Mg<sub>2</sub>(dobpdc) samples undergo morphological degradation after humid adsorption/desorption cycles, likely due to the ineffective protection of the open metal sites in the MOF from water by the higher molecular weight amines. While degradation of PEI-impregnated Mg<sub>2</sub>(dobpdc) raises a concern about the overall stability of poly(amine)-impregnated Mg<sub>2</sub>(dobpdc) materials, the TEPA-impregnated sample shows stable performance over 20 humid sorption/desorption cycles with N<sub>2</sub> purge for desorption and over 8 humid cycles with vacuum desorption.

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## 1 Introduction

In the past decades, solid amine materials have been at the center of focus by researchers aiming to develop energy efficient CO<sub>2</sub> capture materials.<sup>1</sup> Among different amines, polymeric or oligomeric amines such as poly(ethyleneimine) (PEI) and tetraethylenepentamine (TEPA) have been intensively studied using various porous inorganic supports. For example, the concept of the molecular basket, *i.e.*, amine impregnation

in the pores of ordered porous materials, was first introduced by Xu *et al.* using mesoporous silica MCM-41, followed by expansion of the concept to amine impregnated mesoporous carbons and metal-organic frameworks (MOF) such as MIL-101(Cr), amongst other supports.<sup>2–4</sup> These amine impregnated sorbents typically show IUPAC type 1 isotherms, suggesting strong interaction between the amines and CO<sub>2</sub> even at ultra dilute CO<sub>2</sub> concentrations. While their adsorption mechanism is based on the direct interaction between amines and CO<sub>2</sub>, a novel CO<sub>2</sub> adsorption mechanism was discovered in amine-appended Mg<sub>2</sub>(dobpdc), where a CO<sub>2</sub> molecule is inserted between the metal in the framework and a pendant diamine bound to the open metal site of the framework.<sup>5</sup> The CO<sub>2</sub> insertion mechanism endowed amine-appended Mg<sub>2</sub>(dobpdc) with a unique step adsorption isotherm with record high amine efficiency (one CO<sub>2</sub> to one diamine). Later, Siegelman *et al.* reported that the step pressure of amine-appended Mg<sub>2</sub>(dobpdc) can be controlled by the choice of amines, which influences the strength of the interaction between the amine

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and Mg open metal site.<sup>6</sup> The resulting *N,N*-dimethylethylenediamine (m-2-m) functionalized Mg<sub>2</sub>(dobpdc) and *N,N*-diisopropylethylenediamine (ii-2) functionalized Mg<sub>2</sub>(dobpdc) have step pressures at <10 mbar and ~300 mbar in their 25 °C isotherms, respectively. In parallel, tetraamine-appended Mg<sub>2</sub>(dobpdc) showed outstanding stability under flue gas adsorption and steam regeneration conditions over 1000 cycles after optimizing the length of the amine to have two amine-open metal site bindings across the pore diameter of Mg<sub>2</sub>(dobpdc).<sup>7</sup>

Even though different combinations of amines with Mg<sub>2</sub>(dobpdc) demonstrated excellent CO<sub>2</sub> adsorption capacity and potential for energy efficient regeneration under flue gas CO<sub>2</sub> capture conditions (≥10 mbar CO<sub>2</sub>) by swinging across a narrow window of temperature or pressure between the adsorption onset temperature or pressure,<sup>6</sup> studies related to the DAC partial pressure region (~0.4 mbar CO<sub>2</sub>) remain rare. This is likely because of the disadvantages of amine-appended Mg<sub>2</sub>(dobpdc) materials for DAC conditions, such as their low CO<sub>2</sub> capture fraction (captured CO<sub>2</sub>/flowed CO<sub>2</sub>) in a dynamic adsorption system, as reported by Darunte *et al.*<sup>8</sup> As commercial scale DAC requires fast flow velocities, typically in excess of ~1 m s<sup>-1</sup>, the flow rate dependence of the carbon capture fraction limits the practicality of these particular amine-appended MOFs in DAC. Bose *et al.* did demonstrate 400 ppm CO<sub>2</sub> adsorption cycles using m-2-m-Mg<sub>2</sub>(dobpdc), but the thermogravimetric method deployed in the research did not provide a meaningful carbon capture fraction under DAC conditions due to its non-ideal gas flow path.<sup>9</sup>

In this study, we show how different amine sizes and structures influence the 400 ppm CO<sub>2</sub> adsorption capacity and sorbent stability under various DAC conditions, providing mechanistic insights into enhanced or compromised CO<sub>2</sub> adsorption behavior. We prepared amine-functionalized Mg<sub>2</sub>(dobpdc) materials with amines of three different sizes, m-2-m, TEPA, and PEI. A hypothesis was made that deploying amine-appended Mg<sub>2</sub>(dobpdc), specifically m-2-m-Mg<sub>2</sub>(dobpdc), in cold regions for DAC could enhance its carbon capture fraction due to the increased thermodynamic driving force for adsorption and potentially, increased rates thanks to its reportedly inverse Arrhenius kinetics (faster kinetics at lower temperatures) as communicated by Martell *et al.*<sup>10</sup> We studied the 400 ppm CO<sub>2</sub> capture behavior of amine appended Mg<sub>2</sub>(dobpdc) under a wide range of temperatures from -20 to 25 °C. As expected, lower temperatures shifted the adsorption onset pressure of the amine appended Mg<sub>2</sub>(dobpdc) adsorbents to lower values due to the exothermic nature of gas adsorption. However, breakthrough profiles for m-2-m-Mg<sub>2</sub>(dobpdc) from -20 to 25 °C showed similar adsorption capacities. In the literature, the slow adsorption kinetics of amine appended Mg<sub>2</sub>(dobpdc) has been previously reported.<sup>8,10,11</sup> Martell *et al.* observed a minimal CO<sub>2</sub> uptake for a certain time period at the beginning of 100 or 15 mol% CO<sub>2</sub> adsorption in a gravimetric adsorption system.<sup>10</sup> With thorough adsorption and spectroscopic studies, they suggested that this long induction

period of amine-appended Mg<sub>2</sub>(dobpdc) was due to the slow formation of metal-bound ammonium carbamate chains (CO<sub>2</sub> insertion mechanism) after relatively faster non-metal-bound ammonium carbamate formation as a first step.<sup>10</sup> Therefore, we attributed the insignificant adsorption capacity difference at different adsorption temperatures to the intrinsically slow kinetics or failure of initiating the CO<sub>2</sub> insertion mechanism of amine-appended Mg<sub>2</sub>(dobpdc) under our ultra dilute (400 ppm and dry) CO<sub>2</sub> concentration.<sup>8,10,11</sup> For the sake of conciseness, detailed results and discussion about amine-appended Mg<sub>2</sub>(dobpdc) for DAC are available in the ESI.†

To address the obstacles originating from the CO<sub>2</sub>-amine insertion mechanism, oligomeric (TEPA) and polymeric amine (PEI) impregnated Mg<sub>2</sub>(dobpdc) materials were also synthesized, seeking to rectify the low CO<sub>2</sub> capture fraction of amine-appended Mg<sub>2</sub>(dobpdc) under DAC conditions. A high CO<sub>2</sub> capture fraction reported by Cao *et al.* using TEPA-appended Mg<sub>2</sub>(dobpdc) under 15 vol% CO<sub>2</sub> (fixed bed breakthrough) suggests a similarly high capture fraction might be realized in TEPA-impregnated Mg<sub>2</sub>(dobpdc) systems for DAC.<sup>12</sup> While focusing on flue gas CO<sub>2</sub> capture, isotherms presented by Choe *et al.* display increased CO<sub>2</sub> uptake at low partial pressure (isotherms) with higher TEPA loading in TEPA-appended Mg<sub>2</sub>(dobpdc) adsorbent, validating a high loading of amines in Mg<sub>2</sub>(dobpdc) as a suitable strategy for DAC application.<sup>13</sup> Here, we observe that TEPA-impregnated in Mg<sub>2</sub>(dobpdc) enabled a high carbon capture fraction and elimination of the flow rate dependency of 400 ppm CO<sub>2</sub> capture of the amine-appended materials. Although the TEPA-impregnated Mg<sub>2</sub>(dobpdc) showed diffusion-limited CO<sub>2</sub> adsorption behavior in its breakthrough curves under dry conditions, using a humidity above the stoichiometric amine hydration level (water/amine = 1.0 at ≥50% RH) alleviated much of the resistance to CO<sub>2</sub> diffusion. Moreover, *in situ* IR and desorption studies revealed that the hydration of the amines allows deeper penetration of CO<sub>2</sub> through the amine film, resulting in a delayed CO<sub>2</sub> desorption peak with increased humidity under temperature programmed desorption (TPD) conditions. Unexpectedly, branched or linear poly(ethyleneimine) (BPEI or LPEI, respectively) (~800 g mol<sup>-1</sup>) impregnated Mg<sub>2</sub>(dobpdc) materials showed substantial degradation in their CO<sub>2</sub> adsorption capacities and particle morphology after humid cycles, likely due to the ineffective protection of the Mg<sub>2</sub>(dobpdc) open metal sites using these large polyamines. In contrast, further investigation of TEPA-impregnated Mg<sub>2</sub>(dobpdc) demonstrated its stability under repeated humid DAC cycles under N<sub>2</sub> purge and more realistic vacuum desorption conditions. The structure of the amine plays a defining role in the utility, or lack thereof, of the Mg<sub>2</sub>(dobpdc) based adsorbents.

## 2 Results and discussion

In our initial study of amine-appended Mg<sub>2</sub>(dobpdc) under dry DAC conditions at low temperatures, we observed that



the CO<sub>2</sub> insertion mechanism did not proceed (data and discussion available in the ESI,† Section 2). To overcome the observed low adsorption capacity, low carbon capture fraction, and flow rate dependence of the amine appended Mg<sub>2</sub>(dobpdc) for DAC,<sup>8</sup> two different sizes of amines, tetraethylenepentamine (TEPA) and poly(ethyleneimine) (PEI), were used to functionalize Mg<sub>2</sub>(dobpdc) by a traditional impregnation method. Although both TEPA and PEI impregnated Mg<sub>2</sub>(dobpdc) showed improved CO<sub>2</sub> uptake under humid conditions compared to dry conditions (data available in ESI†), their adsorption behavior and stability under humid adsorption/desorption experiments were dissimilar. The presence of bulky amines in a narrow pore can cause significant CO<sub>2</sub> diffusion resistance and reduced amine availability.<sup>14</sup> Furthermore, some larger amines may not efficiently protect open metal sites in the Mg<sub>2</sub>(dobpdc) framework due to steric constraints and lead to the hydrolysis of the framework under humid conditions, as shown in Fig. 1. To this end, in the following section, we focus on the causes of their differing adsorption and degradation behaviors under humid conditions.

#### Increased CO<sub>2</sub> adsorption capacity of oligomeric amine impregnated-Mg<sub>2</sub>(dobpdc) under humid DAC conditions: hydration of amines enables amine availability

The CO<sub>2</sub> adsorption capacities of TEPA-impregnated Mg<sub>2</sub>(dobpdc) materials had a strong dependence on the relative humidity (RH) at 25 °C. In this section, this behavior was investigated by fixed bed breakthrough experiments under dry and humid conditions, measurement of single component H<sub>2</sub>O isotherms, both *via in situ* IR spectroscopy and *via* temperature programmed desorption (TPD) studies.

Cyclic TSA breakthrough experiments under various humidities at 25 °C were conducted to investigate the CO<sub>2</sub> adsorption behavior and the stability of the materials under

different humidities. The CO<sub>2</sub> adsorption capacity fractions, defined as CO<sub>2</sub> adsorption in each cycle divided by the initial CO<sub>2</sub> adsorption capacity, and the corresponding breakthrough profiles for each cycle, are shown in Fig. 2 and S16.† We note that the CO<sub>2</sub> adsorption behavior of PEI(30)-Mg<sub>2</sub>(dobpdc) will be discussed in the later section. For TEPA(50)-Mg<sub>2</sub>(dobpdc), a strong dependence of the CO<sub>2</sub> adsorption capacity on the relative humidity (RH) was observed (the CO<sub>2</sub> adsorption capacity decreases as humidity decreases at 25 °C) with relatively stable cycle performance (the decrease in CO<sub>2</sub> uptake of ~9% after the first cycle of humid DAC experiments in Fig. 2b is likely due to the evaporation of small molecular amines, as tetraethylenepentamine (TEPA) is a mixture of small aliphatic amines, as noted by the vendor). Two possible causes of this strong humidity dependence are changes in the adsorption chemistry with humidity and/or enhanced diffusion due to the freeing of amines originally constrained by amine–amine hydrogen bonds in dry conditions.<sup>15–17</sup>

To investigate changes in the chemical state(s) of the adsorbed CO<sub>2</sub>, *in situ* IR experiments were conducted, as shown in Fig. 3. IR peak assignments and references are tabulated in Table 1. Throughout the different humidity conditions ranging from 0% to 70% RH at 25 °C, ammonium carbamate formation (mainly two  $\delta_{\text{as}}\text{NH}^{3+}$  from ammonium ions,  $\nu\text{COO}^-$ , and  $\text{NCOO}^-$  skeletal vibrations from carbamate ions at 1650, 1546, 1490, and 1330 cm<sup>-1</sup>, respectively) were the dominant species detected, without emergence of new peaks, suggesting the same CO<sub>2</sub> adsorption mechanism occurred regardless of the humidity level at 25 °C.<sup>18–32</sup> This suggests that the role of water in enhancing CO<sub>2</sub> adsorption in TEPA(50)-Mg<sub>2</sub>(dobpdc) is mainly the improvement of the diffusion of CO<sub>2</sub> through the 1D pores of Mg<sub>2</sub>(dobpdc) in the presence of water vapor and the freeing of amine sites rather than changing the chemistry of the amine and CO<sub>2</sub> interactions.



**Fig. 1** Schematic illustration of the differing water effects in amine-impregnated Mg<sub>2</sub>(dobpdc). Water increases CO<sub>2</sub> uptake in oligomeric amine (TEPA) impregnated Mg<sub>2</sub>(dobpdc) by increasing CO<sub>2</sub> diffusion into the amine films, whereas water decreases CO<sub>2</sub> uptake in polymeric amine (PEI) analogue by Mg<sub>2</sub>(dobpdc) particle/pore collapse.





**Fig. 2** Results of breakthrough experiments for BPEI(30)-Mg<sub>2</sub>(dobpdc) and TEPA(50)-Mg<sub>2</sub>(dobpdc) under (a) different humidities (30–70% RH) with 400 ppm CO<sub>2</sub>/N<sub>2</sub> at 25 °C and (b) cycles at 70% RH. The samples were desorbed at 80 °C for 3 h under 40 sccm of N<sub>2</sub>. The flow rate of 400 ppm CO<sub>2</sub> was 22 sccm and particles between 125 and 425 μm were sieved and used for the experiments (data correspond with Fig. S16†). At 70% RH and for the first cycle, CO<sub>2</sub> capacities of PEI(30)-Mg<sub>2</sub>(dobpdc) and TEPA(50)-Mg<sub>2</sub>(dobpdc) were 2.5 and 3.9 mmol g<sup>-1</sup>, respectively (Table S4†).

To further investigate the role of water in the amine-impregnated Mg<sub>2</sub>(dobpdc) materials, water isotherms (30 °C) and water uptakes (25 °C) during fixed bed experiments were measured, as shown in Fig. 4a. The water uptake increased in both the isotherm and the fixed bed adsorption experiments (25 °C) over the range of humidities studied (0 to 80%). At higher RH, the water uptake from the fixed bed experiment starts to asymptote near 15 mmol g<sup>-1</sup>. In Fig. 4b, the y-axis in Fig. 4a is replotted as the ratio of adsorbed water to amines in TEPA(50)-Mg<sub>2</sub>(dobpdc). At 50% RH, the adsorbed water and amine ratio becomes ~1.0, indicating equimolar levels of amines in TEPA and water. Given that the TEPA(50)-Mg<sub>2</sub>(dobpdc) breakthrough profile at 30% RH (Fig. S16†) showed a short breakthrough time with a long mass transfer zone compared to breakthrough profiles for the same material at higher RH, we hypothesize that the hydration of TEPA significantly improves the access of CO<sub>2</sub> to free amine chains, and that this increase in uptake coincides with the amount of adsorbed water approaching and matching the amine loading on the adsorbent.

To separate CO<sub>2</sub> and water co-adsorption from the adsorption breakthrough profiles, humid 400 ppm CO<sub>2</sub> breakthrough profiles were measured after water presaturation, as shown in Fig. S18.† Although the breakthrough profile at 30% RH with presaturation became sharper than the co-adsorption breakthrough profile (Fig. S16b†), the pseudo equilibrium CO<sub>2</sub> capacity (0.74 mmol g<sup>-1</sup>) decreased by 31% compared to the co-adsorption mode (1.07 mmol g<sup>-1</sup>), probably due to the water molecules from the presaturation stage occupying or blocking adsorption sites for CO<sub>2</sub>, but having overall insufficient humidity to effectively free the hydrogen-bonded amine chains. However, breakthrough profiles at higher RH (≥50%) showed pseudo equilibrium CO<sub>2</sub> adsorption capacities comparable to their capacities measured in co-adsorption mode (2.66 and 2.48 mmol g<sup>-1</sup> at 50% RH, respectively for presaturation and co-adsorption) as well as sharp breakthrough slopes, suggesting

the hydration of TEPA enabled additional CO<sub>2</sub>-amine interactions that were not accessible at lower humidities, presumably by untangling amine-amine bonds and enhancing CO<sub>2</sub> access to amines deeper inside the Mg<sub>2</sub>(dobpdc) pore.<sup>16</sup>

TPD results also corroborate that amines that are not accessible without hydration become accessible as humidity increases, showing a larger amount of CO<sub>2</sub> desorbed and concomitant delayed desorption time with increased humidity (Fig. 5). In both the water and CO<sub>2</sub> desorption profiles, physisorbed species desorb during the N<sub>2</sub> purge at 25 °C (denoted as stage I). Upon temperature ramping in stage II, the rest of the water and weakly bound CO<sub>2</sub> leave the system, rendering the sorbent nearly fully dried after stage II. Provided that water completely desorbs in this stage, and the amount of CO<sub>2</sub> desorbed is proportional to the humidity level during the adsorption stage, the CO<sub>2</sub> desorption peak from stage II is attributed to the water-involved CO<sub>2</sub> adsorbed species, such as bicarbonate<sup>‡</sup> and hydronium carbamate (carbamic acid is excluded due to the absence of the relevant IR peaks from Fig. 3).<sup>16,33</sup> Surprisingly, in Fig. 5b stage III, the CO<sub>2</sub> desorption peak displays a delayed desorption trend as the humidity increases. Two hypotheses to explain this unexpected phenomenon are (1) an increase in the concentration of strongly bound adsorbed species and/or (2) deeper penetration of CO<sub>2</sub> inside the amine film with increased humidity, resulting in a longer desorption path for CO<sub>2</sub>. The first hypothesis is not favored due to the weaker binding energy of water-involved CO<sub>2</sub> adsorption species such as bicarbonate and hydronium carbamate.<sup>33</sup> Disappearance of the later desorption

‡ While carbamic acids are readily observed in dry (primarily) and humid (occasionally) supported amine/CO<sub>2</sub> systems *via* IR spectroscopy, bicarbonate species are rarely observed by IR, even when the conditions are ripe for their formation. This may be associated with differing extinction coefficients for the various species. Given the large increase in CO<sub>2</sub> uptake under humid conditions observed here, we cannot fully rule out bicarbonate formation, despite no evidence for its formation by vibrational spectroscopy.





**Fig. 3** *In situ* IR spectra for TEPA(50)-Mg<sub>2</sub>(dobpdc) during 400 ppm CO<sub>2</sub> adsorption at 25 °C under (a) dry (b) 30, and (c) 70% RH (H<sub>2</sub>O/CO<sub>2</sub> co-adsorption after H<sub>2</sub>O presaturation) conditions.

peak at slower ramping rates (0.1 and 0.3 °C min<sup>-1</sup> compared to 0.5 °C min<sup>-1</sup>) during TPD experiments, as shown in Fig. S19,<sup>†</sup> corroborates that the seemingly two separate desorption peaks displayed in Fig. 5b are a result of kinetic and/or diffusion limitations rather than species with different heats of desorption. Further delayed and lengthened desorption peaks shown in Fig. S20<sup>†</sup> at a larger particle size (125–425 vs. 425–825 μm) at the same ramping rate (0.5 °C min<sup>-1</sup>) during TPD

**Table 1** *In situ* IR peak assignments during 400 ppm CO<sub>2</sub> adsorption at different humidities

Wave number (cm <sup>-1</sup> )	Assignment	Ref.
1650	$\delta_{as}NH_3^{3+}$	18–23
1539–46	$\delta_{as}NH_3^{3+}$	18, 22, 24–27
1490–1506	$\nu COO^-$	19, 22, 28
1450	$\delta_s NH_3^{3+}$	25
1372, 1389	$\nu_s COO^-$	18, 22, 25, 27, 29
1330–40	NCOO <sup>-</sup> skeletal vibrations	19–21, 23, 24, 30–32, 30–32

experiments clearly indicate that the desorption kinetics of the system are limited by intraparticle mass transfer resistance, derived from the resistance in the amine film in the Mg<sub>2</sub>(dobpdc) pores. Therefore, we propose that the last desorption peak is from carbamate species and the desorption was slowed due to the formation of carbamate species deeper inside the amine film under humid conditions. We further suggest that the desorption of water during stage II contributes to this delayed desorption by closing the water-facilitated diffusion path and rigidifying the amine film, akin to the diffusion limited adsorption under dry conditions, as schematically explained in Fig. 6. The schematic illustration summarizes our hypothesis that CO<sub>2</sub> cannot diffuse deeply inside of the amine film at dry or low humidity (30% RH) conditions, but the hydration of TEPA at higher humidities (≥50% RH) enables CO<sub>2</sub> diffusion deeper into the amine film followed by adsorption. Then, during desorption, the high CO<sub>2</sub> loading, including occupation of sites deep within the amine film, causes a longer desorption diffusion time due to the carbamate formation deep inside amine film along with the removal of the facilitated diffusion path for CO<sub>2</sub> during desorption by water.

In the last decade, studies with different types of support materials and amines suggested the observed improvement of CO<sub>2</sub> uptake in the presence of water can be attributed to the enhancement in CO<sub>2</sub> diffusion, increased amine availability, and sometimes, altered adsorption chemistry, as summarized in Sayari's review paper.<sup>17</sup> With additional focus on DAC, we tabulated the dry and humid CO<sub>2</sub> adsorption performance of different solid supported amines under DAC conditions in Table S5.<sup>†</sup> Importantly, a recent study by Hoffman *et al.* clearly reported that humidity improves the 400 ppm CO<sub>2</sub> uptake of PEI films by reducing their diffusion resistance as shown using their customized tandem QCM/PM-IRRAM apparatus.<sup>34</sup> This observation, combined with our findings, suggests that DAC adsorbents previously excluded from consideration for practical deployment due to their low CO<sub>2</sub> uptake under relatively dry conditions (<50% RH) may require reevaluation at higher humidity conditions. We expect that this enhancement in the CO<sub>2</sub> uptake kinetics in the presence of humidity will be more prominent in support materials with one dimensional pores due to their long diffusional path, as reported by Heydari-Gorji *et al.*, compared to those supports with multidimensional connections.<sup>35</sup>





Fig. 4 TEPA(50)-Mg<sub>2</sub>(dobpdc) (a) water uptake by gravimetric sorption (30 °C) and fixed bed experiments (25 °C); the water uptake was converted into (b) the ratio of water and amine.



Fig. 5 Temperature programmed desorption profiles of (a) H<sub>2</sub>O and (b) CO<sub>2</sub> after adsorption (400 ppm CO<sub>2</sub>/N<sub>2</sub>) at different humidities from dry to 70% RH for TEPA(50)-Mg<sub>2</sub>(dobpdc). Ramping rate was 0.5 °C min<sup>-1</sup> and 60 sccm of dry N<sub>2</sub> was used to purge desorbed gases. I: Purging stage at 25 °C under N<sub>2</sub>; II: drying stage during temperature ramping under N<sub>2</sub>; III: CO<sub>2</sub> desorption stage after water desorption.



Fig. 6 Schematic illustration of CO<sub>2</sub> adsorption/desorption of TEPA-impregnated Mg<sub>2</sub>(dobpdc) under different humidities during adsorption. The annotations  $t_{d1}$  and  $t_{d2}$  represent desorption time for CO<sub>2</sub> desorbed from surface and buried amines, respectively. CO<sub>2</sub> desorption time from the surface amines should be faster than that from amines buried under surface amines.



### Decreased CO<sub>2</sub> adsorption capacity of polymeric amine-impregnated Mg<sub>2</sub>(dobpdc) under humid DAC conditions: water-induced structural disorder

Branched PEI (BPEI)-impregnated Mg<sub>2</sub>(dobpdc) was prepared and tested under humid DAC conditions as well. In contrast to the TEPA case discussed above (Fig. 1 and S16†), a decrease in the CO<sub>2</sub> capture capacity for BPEI(30)-Mg<sub>2</sub>(dobpdc) was observed after humid cycling at 25 °C and 70% RH, as shown in Fig. 2b and S16.† Two hypotheses were put forth to explain this performance degradation. The first hypothesis was a loss of amines needed to adsorb CO<sub>2</sub> due to the evaporation of amines during regeneration. Recently, Mahajan *et al.* reported the degradation of the CO<sub>2</sub> adsorption capacity of ethylenediamine functionalized Mg<sub>2</sub>(dobpdc) (MOF-74) due to the loss of ethylenediamine over humid (65% RH humidity at 25 °C) DAC cycles.<sup>36</sup> However, in our case, similar combustion TGA profiles (Fig. S21a†) before and after humid cycling do not support an extensive loss of the low volatility BPEI amines. The second hypothesis was MOF framework degradation due to the extensive interaction with water during humid cycles. In Fig. S21b,† *in situ* IR spectra of the freshly activated sample subtracted from the activated BPEI(30)-Mg<sub>2</sub>(dobpdc) after each humid 400 ppm CO<sub>2</sub> adsorption (30 °C, 50% RH) and desorption (80 °C and N<sub>2</sub> for 2 h) cycle are shown. Interestingly, the subtracted spectra displayed two distinct peaks, positive at 1682 cm<sup>-1</sup> and negative at 1021 cm<sup>-1</sup>. The bending mode of the water molecules [ $\beta(\text{H}_2\text{O})$ ] corresponding to an 18 cm<sup>-1</sup> blue shift from that of water molecules adsorbed in the Mg-MOF-74 (1663 cm<sup>-1</sup> at 24 °C) suggests liquid-like water formation rather than gas phase water (~1590 cm<sup>-1</sup>) in the BPEI impregnated Mg<sub>2</sub>(dobpdc) channels, even after activation.<sup>37,38</sup> The red shift (1682 to 1680 cm<sup>-1</sup>) of this  $\beta(\text{H}_2\text{O})$  peak as the cycling evolved represents a decrease in water hydrogen bonding and redistribution of water either in the Mg<sub>2</sub>(dobpdc) framework or amine domains.<sup>39,40</sup> While several possibilities (C-C, C-O, and C-N) for the negative peak at 1020 cm<sup>-1</sup> exist due to the highly overlapping nature of various bands in this wave number range (the fingerprint region, 600–1400 cm<sup>-1</sup>), we suggest that large BPEI polymer coils, whose radii of gyration (~1.4 nm) are larger than the pore radius of Mg<sub>2</sub>(dobpdc) (1.05 nm), could not stabilize the open metal sites of Mg<sub>2</sub>(dobpdc) effectively and this led to the occurrence of metal-linker hydrolysis reactions upon exposure to the humid conditions.<sup>6,40–42</sup> From powder X-ray diffraction (PXRD) patterns shown in Fig. S22,† a slight decrease in the peak intensity at  $2\theta = 4.9^\circ$  was observed for both BPEI(30) and TEPA(50)-Mg<sub>2</sub>(dobpdc), representing disorder in the translational symmetry of the hexagonal Mg<sub>2</sub>(dobpdc) (210) plane upon exposure to ambient air.<sup>40</sup> A significant decrease in the BET surface area for both materials was also measured (Fig. S23†), attributed to either pore blockage by pore/particle collapse or amine redistribution.

While these observations do not give clear insight into the differing stability of BPEI(30)-Mg<sub>2</sub>(dobpdc) and TEPA(50)-Mg<sub>2</sub>(dobpdc), SEM images before and after humid cycles provided a clear contrast between these samples, as shown in

Fig. 7. Damage on the surface of bare Mg<sub>2</sub>(dobpdc) and BPEI(30)-Mg<sub>2</sub>(dobpdc) after 5 humid fixed bed adsorption and desorption cycles was observed, unlike in the TEPA(50)-Mg<sub>2</sub>(dobpdc) case, which had a clean particle surface. This pore/particle collapse can lead to pore blockage, as reported by Vitillo *et al.*, and this can be detrimental to gas adsorption in one-dimensional pore materials.<sup>38,43,44</sup> Indeed, Forse *et al.* found the diffusion coefficient of CO<sub>2</sub> through the wall of Mg<sub>2</sub>(dobpdc) at 625 mbar was 30 times slower than the diffusion coefficient along the pore channel.<sup>43</sup> Further comparison of humid breakthrough cycles with BPEI(40)-Mg<sub>2</sub>(dobpdc), and LPEI(40)-Mg<sub>2</sub>(dobpdc), as shown in Fig. S24,† revealed a similar degradation in adsorption capacity, manifesting as fast CO<sub>2</sub> breakthroughs (low adsorption capacity) after multiple cycles. Low molecular weight (MW: 800), lab-synthesized LPEI material was used for control experiments here because we hypothesized it can better access the pores of Mg<sub>2</sub>(dobpdc) than commercial 800 MW BPEI or 2500 MW LPEI. The similar degradation behavior observed here for these samples implies that PEI may be

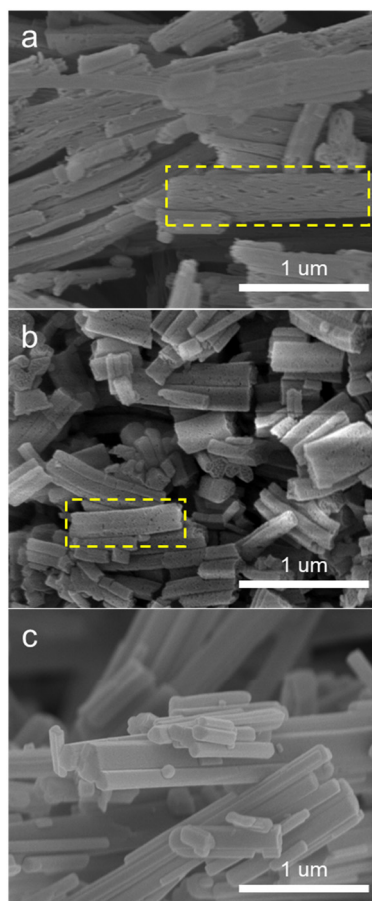


Fig. 7 SEM images of (a) bare Mg<sub>2</sub>(dobpdc), (b) BPEI(30)-Mg<sub>2</sub>(dobpdc), and (c) TEPA(50)-Mg<sub>2</sub>(dobpdc) after 5 humid adsorption/desorption cycles. Adsorption and desorption conditions were 30 °C and 50% RH for 2 h with 400 ppm CO<sub>2</sub>/N<sub>2</sub> and 80 °C and dry N<sub>2</sub> for 2 h, respectively. Perforation (yellow box) on the crystal surfaces of the (a) bare Mg<sub>2</sub>(dobpdc) and (b) BPEI(30)-Mg<sub>2</sub>(dobpdc) is notable.



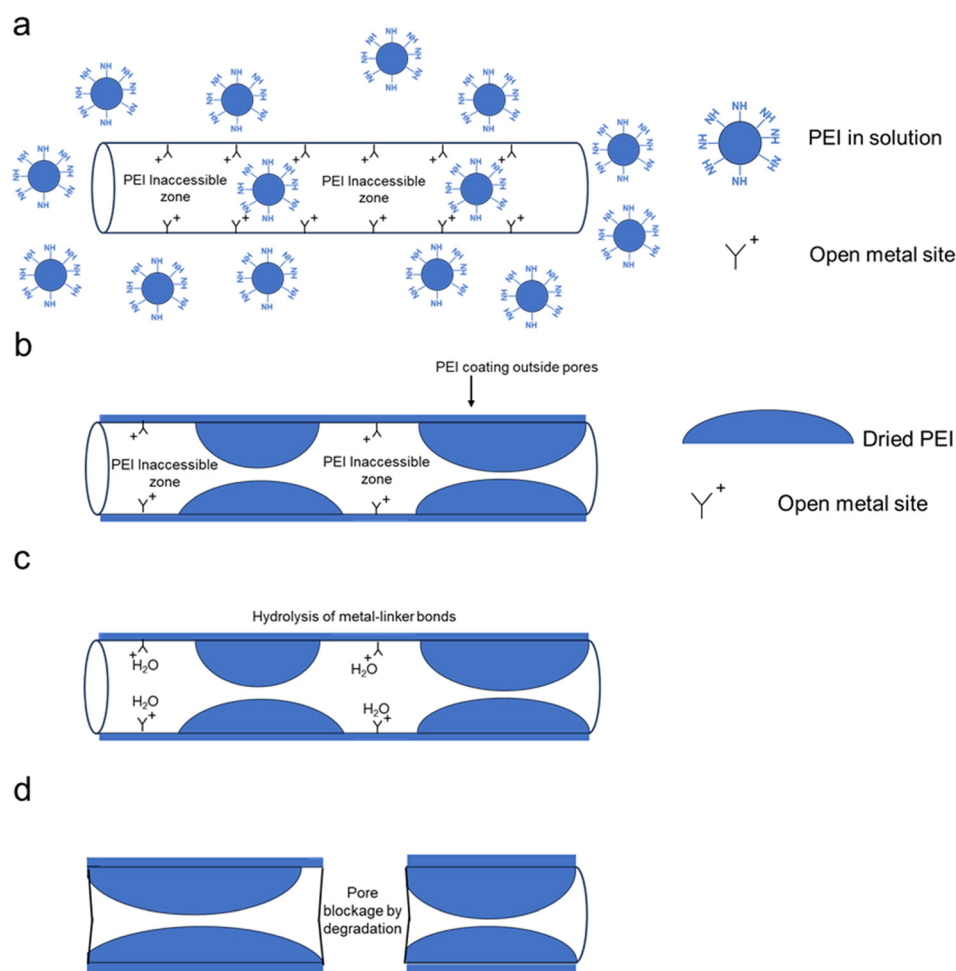
stuck in the middle of the one-dimensional pores due to multiple interactions between amines and open metal sites within a single, (relatively) long organic chain. Based on the above observations, we conclude that the larger number of interaction points in BPEI or LPEI with  $\text{Mg}_2(\text{dobpdc})$  open metal sites hindered the diffusion of PEI along the pore and limited the filling of amines in the pores and the coverage of open metal sites with amines. Consequently, this leads to free open metal sites and instability under humid conditions (hydrolysis of the linker and metal node),<sup>6,40–42</sup> leading to pore/particle collapse that causes a decrease in  $\text{CO}_2$  adsorption capacity during cycling, as schematically illustrated in Fig. 8.

We note that TEPA-impregnated  $\text{Mg}_2(\text{dobpdc})$  was the most resistant toward degradation from humidity among all samples, including the open metal site functionalized m-2-m- $\text{Mg}_2(\text{dobpdc})$ , even after 40 TGA humid cycles, as judged by their SEM images (Fig. S25†). We hypothesize this is because this sample has several layers of TEPA protecting the  $\text{Mg}_2(\text{dobpdc})$  framework. The degradation of  $\text{Mg}_2(\text{dobpdc})$  framework may explain the compromised  $\text{CO}_2$  adsorption

capacity of m-2-m- $\text{Mg}_2(\text{dobpdc})$  by 30% after 5 cycles of 10%  $\text{CO}_2/\text{N}_2$  under humid condition (73% RH) at 25 °C from the work of Adil *et al.*<sup>45</sup>

#### Practical aspects of TEPA(50)-impregnated $\text{Mg}_2(\text{dobpdc})$ : sorption at 70% RH at 25 °C demonstrates stability over the tested cycles

The stability of TEPA(50)- $\text{Mg}_2(\text{dobpdc})$  over multiple humid adsorption–desorption cycles was investigated next, as shown in Fig. 9. Compared to the first cycle, the pseudo equilibrium capacities of subsequent cycles decreased modestly, by 18% (from 3.78 to 3.11  $\text{mmol g}^{-1}$  or 0.28 to 0.23  $\text{CO}_2/\text{amine}$ ). The evaporation of low molecular weight amine species in TEPA may cause a decrease in the  $\text{CO}_2$  adsorption capacity, as commercial TEPA is a mixture of small amines. After the first cycles, however, the TEPA(50)- $\text{Mg}_2(\text{dobpdc})$  showed reproducible breakthrough profiles over the period of the tests (20 cycles, roughly a month of lab scale breakthrough experiments), demonstrating its stability under practical DAC adsorption conditions, unlike the PEI analogue. For fast



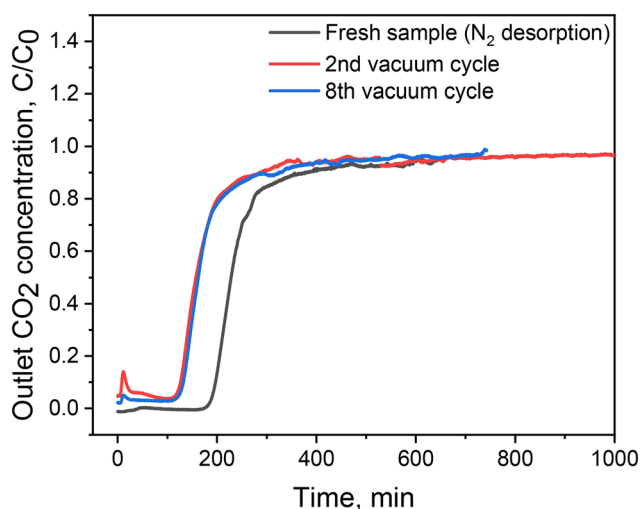
**Fig. 8** Schematic illustration of the degradation of PEI-impregnated  $\text{Mg}_2(\text{dobpdc})$  under humid adsorption conditions. (a) and (b) represent PEI distribution in the  $\text{Mg}_2(\text{dobpdc})$  pore during the amine impregnation and after the drying step, respectively; (c) and (d) display water molecule adsorption on the  $\text{Mg}_2(\text{dobpdc})$  open metal site and consequential pore blockage after hydrolysis, respectively.





**Fig. 9** Cyclic breakthrough profiles for TEPA(50)-Mg<sub>2</sub>(dobpdc) under 70% RH with 400 ppm CO<sub>2</sub>/N<sub>2</sub> at 25 °C. The sample was desorbed at 80 °C for 3 h under 40 sccm of N<sub>2</sub>. The flow rate of 400 ppm CO<sub>2</sub> was 22 sccm.

cycling and scalability, steam and/or vacuum regeneration is the preferred desorption mode. In Fig. 10, vacuum desorption was chosen over steam regeneration due to the possible hydrolysis of the Mg<sub>2</sub>(dobpdc) framework by steam.<sup>40</sup> Vacuum regeneration was tested using a separate vacuum oven at 0.1 bar (static) and 80 °C. Like the cyclic breakthrough experiments where a N<sub>2</sub> purge was used for degassing, the adsorption profiles became stable after a drop in the first cycle. On the 8th cycle, the pseudo equilibrium



**Fig. 10** Breakthrough profiles for TEPA(50)-Mg<sub>2</sub>(dobpdc) under 70% RH and 400 ppm CO<sub>2</sub>/N<sub>2</sub> flow (co-adsorption) after vacuum desorption cycles. The adsorption and vacuum desorption experiment cycles consisted of exposing samples to ambient air (22 °C and 50% RH) for 20 h and desorbing adsorbates at 80 °C for 4 h under 0.1 bar static vacuum, followed by transferring the samples after certain cycles (2nd and 8th) to the fixed bed without further desorption. The flow rate was 44 sccm (400 ppm CO<sub>2</sub>/N<sub>2</sub>).

CO<sub>2</sub> capacity was recorded as 3.23 mmol g<sup>-1</sup> (0.24 CO<sub>2</sub>/amine), suggesting the potential use of the TEPA(50)-Mg<sub>2</sub>(dobpdc) for DAC under warm and humid conditions using a temperature vacuum swing adsorption process.

### 3 Conclusions

The theoretical maximum amine efficiency (one CO<sub>2</sub> per one diamine) for chemisorption using amine-appended Mg<sub>2</sub>(dobpdc) could not be achieved under DAC conditions, even at cold temperatures. Therefore, the amine impregnation method was used to enhance the DAC performance of sorbents based on the Mg<sub>2</sub>(dobpdc) framework as an alternative solution. Oligomeric amine-impregnated TEPA(50)-Mg<sub>2</sub>(dobpdc) showed a strong dependence of its adsorption and desorption performance on the humidities during adsorption. At low humidity (30% RH), the breakthrough profile of TEPA(50)-Mg<sub>2</sub>(dobpdc) showed a long tail, indicative of diffusion-limited CO<sub>2</sub> adsorption behavior. However, humidities at or above equimolar TEPA hydration (water/amine = 1) conditions (≥50% RH) could facilitate CO<sub>2</sub> diffusion and enhance the CO<sub>2</sub> capture capacity of TEPA-impregnated Mg<sub>2</sub>(dobpdc). We propose that the hydration of TEPA increases CO<sub>2</sub> diffusion through the amine domain, leading to more TEPA available for CO<sub>2</sub> as the humidity increases. Deep penetration of CO<sub>2</sub> into the amine domains, as evidenced by the observed delayed CO<sub>2</sub> desorption peak during TPD with increased humidity supports our hypothesis. On the other hand, small molecular weight (MW: 800) polymeric amine-impregnated PEI(30)-Mg<sub>2</sub>(dobpdc) showed structural degradation (particle collapse by SEM) after exposure to the humid DAC conditions, resulting in a significant decrease in CO<sub>2</sub> adsorption capacity in comparison to the fresh sample (25 °C and 70% RH). Partial size exclusion of BPEI and ineffective protection of all the open metal sites in the Mg<sub>2</sub>(dobpdc) framework were attributed as the causes of the degradation. Additional cyclic adsorption experiments with LPEI-functionalized Mg<sub>2</sub>(dobpdc) resulted in a similar CO<sub>2</sub> uptake decrease, further suggesting that multiple interaction points in the PEI chain hinder PEI diffusion through the Mg<sub>2</sub>(dobpdc) pore during synthesis, causing exposed open metal sites to exist. In contrast, 50% wt TEPA-impregnated Mg<sub>2</sub>(dobpdc) showed outstanding CO<sub>2</sub> adsorption capacity and intact morphology after humid (70% RH, 25 °C) adsorption/desorption cycles. Furthermore, this TEPA-impregnated Mg<sub>2</sub>(dobpdc) showed stable and high CO<sub>2</sub> capture capacity (3.2 mmol g<sup>-1</sup>) over multiple cycles in a fixed bed and in vacuum desorption experiments.

Although the TEPA-impregnated Mg<sub>2</sub>(dobpdc) showed high and reproducible CO<sub>2</sub> adsorption capacities under multiple humid DAC experiments, there are a few practical limitations to its potential use. First, the best-performing sample tested in this study, TEPA(50)-Mg<sub>2</sub>(dobpdc), showed a strong dependence on the humidity of the DAC stream. The best performance was achieved at 25 °C and 70% RH among



the tested conditions. If the temperature and humidity window of effective operation cannot be extended, the locations where this adsorbent would be favorable for DAC deployment would be limited.<sup>46,47</sup> Furthermore, a demonstration of true long-term stability (thousands of cycles) under humidity is also needed before commercial deployment could be considered. Given that the bonds between Mg and the carboxylic acid ligand can be hydrolyzed under humid conditions, particle collapse may be unavoidable, even for the most stable TEPA(50)-Mg<sub>2</sub>(dobpdc), under such extended cycling over long operation times (>6 months), and further testing is warranted.<sup>48</sup> Finally, the scalability of the Mg<sub>2</sub>(dobpdc) is still uncertain given the instability (hydrolysis) of bare Mg<sub>2</sub>(dobpdc) under humid conditions and limited commercial supply chains.

## 4 Experimental

### 4.1 Materials and chemicals

Solvents for material synthesis such as methanol, *N,N*-dimethylformamide (DMF), hexane, and anhydrous toluene were purchased from Sigma Aldrich. Mg(NO<sub>3</sub>)<sub>2</sub>·6H<sub>2</sub>O from Sigma Aldrich and H<sub>4</sub>dobpdc from Trylead Chemical Technology Co., Ltd. were used for Mg<sub>2</sub>(dobpdc) synthesis. For amine functionalization, *N*-methylethylenediamine (m-2), *N,N*-dimethylethylenediamine (m-2-m), *N,N*-diethylethylenediamine (ee-2), *N,N*-diisopropylethylenediamine (ii-2), tetraethylenepentamine (TEPA), branched poly(ethyleneimine) (BPEI) (800 Da) were acquired from Sigma Aldrich. All chemicals were used without further purification. Gases for adsorption experiments were provided by Airgas, LLC. The synthesis of linear PEI (LPEI) is described in the ESI.†

### 4.2 Mg<sub>2</sub>(dobpdc) synthesis

The bare Mg<sub>2</sub>(dobpdc) was synthesized by a gram-scale solvothermal method as previously reported.<sup>6</sup> The metal source Mg(NO<sub>3</sub>)<sub>2</sub>·6H<sub>2</sub>O (9.89 g, 36.1 mmol) and ligand H<sub>4</sub>-dobpdc (11.5 g, 44.9 mmol) were first dissolved in the mixture of methanol and DMF solution (55:45 volume fraction) *via* bath type sonication until the solution to be clear without any particulates. Subsequently, the reaction solution was transferred to a 350 mL glass pressure vessel with a Teflon screw cap and stirring bar. The reaction was conducted for 20 h at 120 °C using silicon oil bath. After naturally cooling down the reactor, the product was washed three times with 250 mL of DMF and methanol. In each step, the product was soaked by solvents for at least 3 h at 60 °C and separated by centrifugation (12 000 rpm, 15 min).

### 4.3 Amine-appended Mg<sub>2</sub>(dobpdc)

Open metal site functionalization with amines was conducted as reported by Siegelman *et al.*<sup>6</sup> Roughly 450 mg of the methanol solvated Mg<sub>2</sub>(dobpdc) was solvent exchanged by three times of anhydrous toluene (30 mL each) using centrifugation (12 000 rpm, 15 min). After redispersing

Mg<sub>2</sub>(dobpdc) in 120 mL of the anhydrous toluene using bath sonication for 20 min, the dispersion was transferred to 250 mL Erlenmeyer flask with Ar purge. Subsequently, amines for open metal functionalization (30 mL) such as m-2, m-2-m, ee-2, and ii-2 were added to the Mg<sub>2</sub>(dobpdc) dispersion and sonicated for another 20 min. Without any disturbance, the reaction solution was left for 24 h at room temperature. Finally, as synthesized amine-appended Mg<sub>2</sub>(dobpdc) was washed with 150 mL of toluene and hexane three times each.

### 4.4 Amine-impregnated Mg<sub>2</sub>(dobpdc)

Roughly 450 mg of methanol-solvated Mg<sub>2</sub>(dobpdc) was dispersed in a round bottom flask using bath type sonication for 20 min. In parallel, a targeted amount of TEPA, LPEI800, or BPEI800 was dissolved in 10 mL of methanol under the bath sonication for 20 min. Subsequently the amine solution was added to the Mg<sub>2</sub>(dobpdc) dispersion and the mixture of the solution was stirred for 24 h at room temperature. The solid powder of amine-impregnated Mg<sub>2</sub>(dobpdc) was obtained by evaporating methanol at 50 °C and 200 mbar using rotary evaporator.

### 4.5 Material characterizations

The weight fraction of amines in Mg<sub>2</sub>(dobpdc) was determined by thermogravimetric analysis (TGA, TGA 550 TA instruments). Samples were degassed under N<sub>2</sub> for 2 h at 110 °C before ramping up to 800 °C. The weight fraction of amines was calculated based on the ratio of the residual weight fraction of bare Mg<sub>2</sub>(dobpdc) and amine-functionalized Mg<sub>2</sub>(dobpdc). X-ray diffraction (XRD) patterns for samples were measured using X'Pert PRO Alpha-1 using Cu K $\alpha$  radiation. Micrographs of Mg<sub>2</sub>(dobpdc) particles were obtained by scanning electronic microscopy (SEM) (Hitachi SU8230).

### 4.6 Adsorption experiments

N<sub>2</sub> and CO<sub>2</sub> adsorption isotherms were measured by a surface area and porosity (SAP) system (Autosorb IQ/Quantachrome). To degas, about 60 mg of the amine appended samples (m-2, m-2-m, ii-2, ee-2) were activated at 120 °C under vacuum (<0.1 mbar) for 12 h. For amine-impregnated (BPEI and TEPA) Mg<sub>2</sub>(dobpdc), samples were activated at 80 °C for 4 h under the same vacuum level. The BET surface area was calculated from the N<sub>2</sub> physisorption data in the *P/P*<sub>0</sub> range of 0.05–0.2.<sup>49</sup> For CO<sub>2</sub> isotherms, an equilibration interval of 15 min was used throughout the whole pressure range after optimization of the equilibration time using ii-2-Mg<sub>2</sub>(dobpdc). For the amine-impregnated samples, PEI-Mg<sub>2</sub>(dobpdc) or TEPA-Mg<sub>2</sub>(dobpdc), 7 min of equilibration time was allowed, resulting in at least 5 days to complete the entire measurement. Different *P/P*<sub>0</sub> tolerance was applied over the following pressure ranges: (i) +2.5 × 10<sup>-6</sup> and -8.3 × 10<sup>-7</sup> for a relative pressure range from 10<sup>-5</sup> to 10<sup>-2</sup>, (ii) +3.0 × 10<sup>-5</sup> and -1.0 × 10<sup>-5</sup> for a relative pressure range from 1.0 ×



$10^{-2}$  to  $2.5 \times 10^{-2}$  and (iii)  $+3.0 \times 10^{-3}$  and  $-1.0 \times 10^{-3}$  for a relative pressure range from  $2.5 \times 10^{-3}$  to 1.

Water isotherms were obtained on a vapor sorption analyzer (VTI-SA+, TA instrument). To begin with, 30 mg of wet samples were loaded in a quartz pan and degassed at 80 or 110 °C for 4 h with dry N<sub>2</sub> flow. During isotherm measurements, the maximum equilibration time and tolerance were set to be 400 min and 0.0005 wt% weight change in 5 min, respectively.

Breakthrough profiles were obtained using a custom-built fixed bed system as described in our previous studies.<sup>50,51</sup> Briefly, adsorbent materials (60 mg, wet weight) were loaded in 1/4 inch diameter stainless tube with both ends blocked by glass wool after obtaining particles between 125 and 425 μm using sieves. The dry weight of the samples was measured in parallel by running a TGA degassing procedure on the sample from the same container right after loading the materials in the fixed bed. To start breakthrough experiments, the loaded samples were activated at 110 °C (heating tape) or 80 °C (chiller, Julabo CD-600F) until the outlet CO<sub>2</sub> concentration was lower than 5 ppm (typically  $\leq 4$  h) for amine appended and impregnated Mg<sub>2</sub>(dobpdc), respectively. Before adsorption started, the fixed bed was immersed in a chiller (Julabo CD-600F) at the adsorption temperature and 10 min of thermal equilibration time was allowed. During adsorption, dry or humid 400 ppm CO<sub>2</sub>/N<sub>2</sub> gas was introduced to the adsorbent bed for dry and CO<sub>2</sub>/H<sub>2</sub>O co-adsorption experiments. Flow rates for 400 ppm CO<sub>2</sub>/N<sub>2</sub> were 22 or 44 sccm (specified in the figure captions). For presaturation experiments, wet N<sub>2</sub> gas (60 sccm) with specified relative humidity flowed to the bed until the inlet and outlet concentration of H<sub>2</sub>O became equal, before passing humid 400 ppm CO<sub>2</sub>/N<sub>2</sub> through the bed. Pseudo equilibrium and breakthrough capacities are defined as the captured CO<sub>2</sub> amount when the ratio of the outlet CO<sub>2</sub> concentration to inlet CO<sub>2</sub> concentration ( $C/C_0$ ) reached 95% and 5%, respectively. The CO<sub>2</sub> or H<sub>2</sub>O capacities were calculated by the integration of the area between the CO<sub>2</sub> or H<sub>2</sub>O concentration profiles with and without adsorbents. The outlet CO<sub>2</sub> concentration was monitored by an infrared gas analyzer (LI-850/LI-COR). During 20 cyclic experiments, various humid conditions were tested in between periodic 70% RH adsorption cycles. For the cyclic experiments with vacuum desorption, several samples were stored in a vacuum oven and alternatively exposed to the ambient lab air (22 °C, 50% RH on average) for 20 h and vacuum for 4 h (80 °C, 0.1 bar static). To perform a breakthrough adsorption experiment with these vacuum-desorbed samples, one of the stored samples, after the vacuum desorption step, was transferred to the fixed bed, and wet 400 ppm CO<sub>2</sub>/N<sub>2</sub> gas was introduced without additional desorption.

#### 4.7 Spectroscopy

*In situ* infrared spectra of the samples under different DAC adsorption and desorption conditions were measured using a

Nicolet iS10 IR spectrometer with a low-temperature diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) cell (CHC-CHA-4, Harrick Scientific Products Inc.), as shown our previous report.<sup>52</sup> About 50 mg of the sample was loaded in a sample holder inside the DRIFTS cell and then was activated at 80 °C under 60 sccm of N<sub>2</sub> flow for 4 h. Then, once the sample temperature reached the desirable adsorption temperature (−20 °C or 25 °C), the inlet gas flow was switched from N<sub>2</sub> to dry or wet (30% or 70% RH) 400 ppm CO<sub>2</sub>/N<sub>2</sub> (40 sccm). During the adsorption and desorption steps, IR spectra were collected every 5 min with 64 scans per spectra at a resolution of 4 cm<sup>−1</sup>. The humidity for the wet gas was introduced by a humidifier (WETSYS/SETARAM). For presaturation experiments, wet N<sub>2</sub> gas (60 sccm) was flowed first until the outlet water concentration had the same concentration as the inlet concentration using an IR CO<sub>2</sub>/H<sub>2</sub>O analyzer (LI-COR 850, Bioscience). After the sample was saturated with H<sub>2</sub>O, the wet N<sub>2</sub> gas was switched to wet 400 ppm CO<sub>2</sub>/N<sub>2</sub> gas (40 sccm). Proton T<sub>1</sub>–T<sub>2</sub> correlation NMR measurements were conducted under a static N<sub>2</sub> environment without spinning as described in our previous publications.<sup>53,54</sup> Detailed experimental parameters and the data processing method for proton T<sub>1</sub>–T<sub>2</sub> correlation measurements are available in the ESI.†

#### Data availability

The data supporting this article have been included as part of the ESI.† Raw data are available from the corresponding author upon reasonable request.

#### Conflicts of interest

The authors declare the following competing financial interest(s): C. W. J. has a financial interest in several DAC companies that seek to commercialize CO<sub>2</sub> capture from air. C. W. J. has a conflict-of-interest management plan in place at Georgia Tech.

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