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Yolk-shell-type CaO-based sorbents for CO₂ capture: assessing the role of nanostructuring for the stabilization of the cyclic CO₂ uptake

Nanostructuring allows the elucidation of effective mechanisms for the stabilization of CaO-based solid sorbents for CO₂ capture. Combining wet-chemistry synthesis and an arsenal of characterization techniques, yolk-shell-type architectures are synthesized and studied in depth to challenge our current understanding of the engineering of CaO-based sorbents. Yolk-shell-type architectures stabilize CaO over many CO₂ capture and release cycles by mitigating deactivation routes such as sintering and the formation of inactive mixed oxides.

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Yolk–shell-type CaO-based sorbents for CO₂ capture: assessing the role of nanostructuring for the stabilization of the cyclic CO₂ uptake†

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Improving the cyclic CO₂ uptake stability of CaO-based solid sorbents can provide a means to lower CO₂ capture costs. Here, we develop nanostructured yolk(CaO)–shell(ZrO₂) sorbents with a high cyclic CO₂ uptake stability which outperform benchmark CaO nanoparticles after 20 cycles (0.17 g_{CO₂} g_{Sorbent}^{−1}) by more than 250% (0.61 g_{CO₂} g_{Sorbent}^{−1}), even under harsh calcination conditions (*i.e.* 80 vol% CO₂ at 900 °C). By comparing the yolk–shell sorbents to core–shell sorbents, *i.e.* structures with an intimate contact between the stabilizing phase and CaO, we are able to identify the main mechanisms behind the stabilization of the CO₂ uptake. While a yolk–shell architecture stabilizes the morphology of single CaO nanoparticles over repeated cycling and minimizes the contact between the yolk and shell materials, core–shell architectures lead to the formation of a thick CaZrO₃-shell around CaO particles, which limits CO₂ transport to unreacted CaO. Hence, yolk–shell architectures effectively delay CaZrO₃ formation which in turn increases the theoretically possible CO₂ uptake since CaZrO₃ is CO₂-capture-inert. In addition, we observe that yolk–shell architectures also improved the carbonation kinetics in both the kinetic- and diffusion-controlled regimes leading to a significantly higher cyclic CO₂ uptake for yolk–shell-type sorbents.

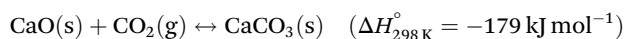
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1. Introduction

Climate change due to anthropogenic greenhouse gas emissions into the atmosphere is one of the most pressing challenges of our modern society.^{1,2} Net greenhouse gas emissions have to be reduced significantly in order to reach the IPCC's recommendation of limiting global warming to less than 2 °C compared to pre-industrial levels.³ Carbon dioxide capture and storage (CCS) technologies are a potential near- to mid-term solution to mitigate the emissions of carbon dioxide (CO₂), arguably the most prominent greenhouse gas.³ CaO-based sorbents are a viable class of materials to capture CO₂ emitted by large point sources.^{4–6} The associated cyclic CO₂ capture process is referred to as calcium looping (CaL) and is based on the reversible reaction of CaO and CO₂:



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CaO-based sorbents are non-toxic and cost-effective (estimated capture cost of <30 USD per t_{CO₂}) compared to the current benchmark technology for CO₂ capture, *i.e.* amine scrubbing (estimated capture costs of 40 to 55 USD per t_{CO₂}).^{7–9} However, CaO-based sorbents are prone to rapid deactivation, *i.e.* a reduction of their cyclic CO₂ uptake capacity from a theoretical maximum of 0.78 g_{CO₂} g_{CaO}^{−1} to typically <0.2 g_{CO₂} g_{CaO}^{−1}, largely due to sintering at the high operating temperatures (around 650–900 °C).^{10–12} Various approaches to mitigate sintering-induced deactivation have been reported, including (I) the addition of high Tammann-temperature stabilizers such as MgO, Al₂O₃ or ZrO₂,^{13–18} (II) the (re-)structuring of the morphology of sorbents,^{14,19} *e.g.* using steam treatment,²⁰ or (III) the manufacture of materials with a high surface area and pore volume.¹⁹

The stabilization of CaO-based sorbents using metal oxides such as MgO, Al₂O₃ and ZrO₂ has been widely applied and currently there are very few new sorbent formulations that do not contain either such structural stabilizers, promoters (*e.g.* alkali metal salts like Na₂CO₃) or other performance-enhancing precursors (*e.g.* Ca-precursors containing alcohol groups).^{5,14,16,17,21–25} The best reported materials exhibit cyclic CO₂ uptakes of up to 0.65 g_{CO₂} g_{Sorbent}^{−1} after 10 carbonation–



calcination cycles, which is six times higher compared to the benchmark limestone.²⁶ Here, the high Tammann-temperature stabilizer MgO is believed to act as a physical barrier (spacer) between the CaO grains, reducing in turn their sintering (or the sintering of the CaCO₃ formed).^{5,21,27,28} Hence, the size and distribution of these structural stabilizers within the CaO matrix must play an important role in mitigating sintering. It is important to note that the homogeneity of the distribution of the stabilizer might dynamically change with cycling (and indeed possibly even within one carbonation–calcination cycle). For example, Kim *et al.*¹⁵ observed that the stabilizer Ca₃Al₂O₆ migrates to the surface of CaO particles during cycling, reducing in turn the stabilizer's effectiveness in reducing sintering. Therefore, one of the proposed design criteria for effective CaO-based sorbents is a low mobility of the stabilizing phase to avoid the loss of its stabilizing functionality. In addition, many investigated stabilizers form mixed phases with CaO at CaL conditions (650–900 °C) that are inactive for CO₂ uptake, *e.g.* Ca₃Al₂O₆ or CaZrO₃.^{11,19,29,30} The formation of mixed phases that do not absorb CO₂ results in a reduced amount of reactive CaO, reducing the theoretically achievable CO₂ uptake of the sorbent. Hence, the synthesis of structures in which the interaction between CaO and the stabilizer is minimized to limit the formation of CO₂-capture-inactive mixed oxides is desirable.

Like many gas–solid reactions, the carbonation reaction of CaO proceeds in two principal reaction regimes: a kinetically-controlled, rapid CO₂ uptake regime that is followed by a much slower, diffusion-controlled CO₂ uptake regime.^{31–33} While the CO₂ uptake during the kinetically-controlled regime is largely controlled by the available pore volume and surface area, the apparent rate of reaction in the diffusion-controlled reaction regime is affected by morphological and structural parameters, *e.g.* the effective diffusivity of CO₂ in the material.²¹ In previous works, the transition between the two reaction regimes has been associated with the formation of a product layer of CaCO₃ on top of CaO, which causes the blockage of pores such that a certain fraction of the pore volume and surface area of the sorbent becomes inaccessible for CO₂ molecules.^{34–36} For a two-dimensional surface of a non-porous material it has been hypothesized that once the product layer reaches a critical thickness (estimated to be around 30–50 nm by various works^{34,37,38}), the reaction transitions from kinetic control to diffusion control.³⁹ To maximize the CO₂ uptake in the kinetically-controlled regime, the nanostructuring of CaO (*i.e.* particle size < 60–100 nm) is highly favorable. Previous works concerned with CaO (or CaCO₃) nanoparticles of size < 100 nm investigated uncoated nanoparticles or nanoparticles with coatings that have an intimate contact with the CaO nanoparticle core (core–shell structures), resulting in the formation of CO₂-capture-inactive mixed phases and hence comparatively low CO₂ uptake.^{40,41} For example, core–shell structures with CaCO₃ cores and shells of ZrO₂ or SiO₂ have been reported to yield materials with a significantly stabilized cyclic CO₂ uptake compared to bare CaCO₃.^{29,42,43} However, these materials deactivated over prolonged cyclic operation *via* the formation of

mixed oxides with calcium that both reduce the amount of CaO available for reaction and also affect negatively the carbonation kinetics. Instead, the structure of an optimized model CaO-based sorbent should exhibit the following attributes: (I) the structure should be composed of CaO nanoparticles of size < 100 nm to reduce the effect of product layer diffusion limitation.^{5,34,37} (II) It should utilize a stabilizer to avoid physical contact (and hence sintering) between the individual CaO nanoparticles. Applying a stabilizer shell around the CaO nanoparticles would yield this physical separation, but the direct contact between the stabilizer and CaO might lead to the formation of CO₂-capture-inactive mixed phases. To prevent such direct contact, a sacrificial layer can be placed between the CaO nanoparticle and the stabilizer coating, creating upon its removal a space between the CaO nanoparticle and the stabilizing coating. (III) The stabilizer shell needs to be porous to allow for a fast transport of CO₂ to the surface of CaO. Overall, these requirements would demand a yolk–shell-type structure. Hence in this work, we report on the synthesis of such model, yolk–shell-structured sorbents to probe whether the aforementioned requirements concerning sorbent design are indeed correct and to understand better the deactivation and stabilization mechanisms of nanostructured sorbents. We note that such sorbents are very likely not to be directly usable in an industrial CO₂ sorption process in which mechanical stability of sorbent particles may be one of many additional constraints. However, the insights gained from this study will help to understand better the functioning of stabilizers, aiding the design of practically applicable, yet still superior sorbent systems.

To this end, we use CaCO₃ nanoparticles with an average particle size < 100 nm that are stabilized by a porous shell of ZrO₂ in a yolk(CaO)–shell(ZrO₂) architecture. The presence of a yolk–shell-type structure is shown to ensure a high sintering resistance and high rates of transport of CO₂ to CaO, while the formation of the CO₂-capture-inactive CaZrO₃ phase is avoided. The design approach is depicted in Fig. 1.

2. Experimental

2.1 Materials

2.1.1 Synthesis of a sacrificial carbonaceous shell. To minimize the contact area between CaO and the stabilizer, the CaCO₃ nanoparticles were first coated with a carbonaceous shell using a mixture of resorcinol and formaldehyde.⁴⁴ Here, 100 mg of the CaCO₃ nanoparticles (≥97.5%, SkySpring Nanomaterials) was dispersed in a mixture of 60 mL deionized water and 19.7 g ethanol by ultrasonating the suspension for 30 minutes. Subsequently, 150 mg of hexadecyltrimethylammonium bromide (CTAB, ≥99%, BioXtra, Sigma Aldrich) was added and the solution was stirred for 20 minutes. Next, 32 mg of resorcinol (≥98%, Sigma Aldrich) and 45 μL of a formaldehyde solution (37–41 wt% aqueous solution, Fisher Scientific) were added to the system. After the complete dissolution of the precursors, 0.4 mL of a 25 wt% aqueous



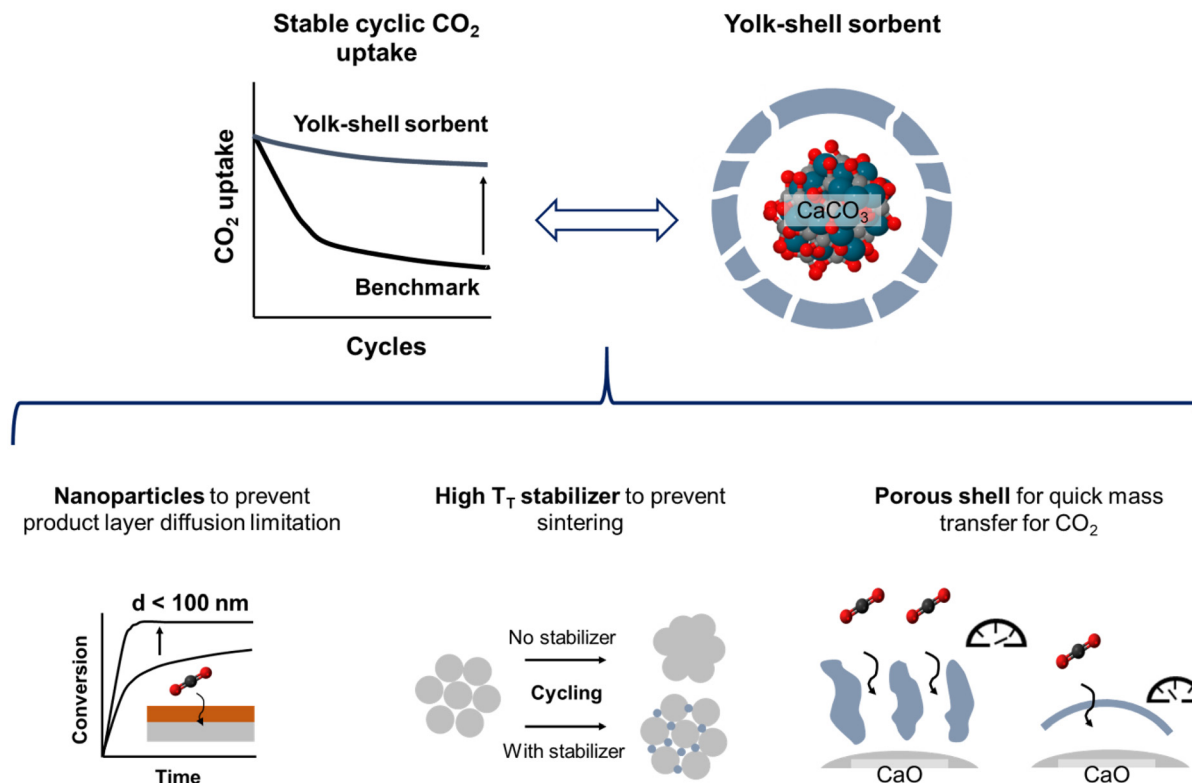


Fig. 1 Design approach for yolk-shell-type CaO-based sorbents. Using a nanoparticle core is expected to prevent diffusive limitations due to product layer formation, whereas a porous shell of a high T_T stabilizer shall mitigate sintering of the nanoparticles while at the same time allowing for a rapid transfer of CO_2 to unreacted CaO.

solution of ammonia (VWR International) was added and the reaction mixture was stirred for 5 hours at room temperature. The coated particles were collected by centrifugation, washed in deionized water, and dried at 60 °C overnight.

2.1.2 Deposition of a ZrO_2 -shell. To deposit a shell of ZrO_2 onto the carbonaceous shell-coated CaCO_3 nanoparticles the method reported by Arnal *et al.* was used.⁴⁵ Here, an aqueous solution of Lutensol AO 5 (BASF) was prepared by mixing 11 g of deionized water with 0.43 g of Lutensol AO 5. The aqueous Lutensol AO 5 solution was ultrasonicated for ~10 minutes to ensure a homogeneous mixture. Subsequently, 50 mg of the carbon-coated CaCO_3 nanoparticles were added to a mixture of 100 g of ethanol and 0.5 mL of the aqueous Lutensol AO 5 solution. The obtained suspension was ultrasonicated for 30 minutes to disperse the sorbent particles. The mixture was then stirred for 60 minutes at 350 rpm in order to homogenize the suspension. Subsequently, varying amounts (5–200 μL) of a zirconium(IV) butoxide solution (80 wt% in butanol, Sigma-Aldrich) were diluted in 0.5 mL of ethanol. The diluted zirconium(IV) butoxide solution was slowly added to the suspension under continuous stirring. The reaction proceeded under magnetic stirring in an oil bath at 35 °C for 16 hours. Afterwards, the particles were collected by centrifugation and washed in deionized water and ethanol. The obtained zirconia-coated particles were dried at 60 °C overnight. For the synthesis of core-shell sorbents, the same procedure was directly applied

to the CaCO_3 nanoparticles without the carbonaceous template coating. To yield the final core-shell and yolk-shell architectures, the sorbents were calcined at 900 °C (heating ramp of 50 °C min^{-1}) in synthetic air for 10 min.

2.2 Characterization

2.2.1 Electron microscopy. A JEOL JEM-1400 Plus transmission electron microscope (TEM) with an operating voltage of 120 kV was used to image the sorbent nanoparticles. The samples were prepared by ultrasonication in ethanol for 15–20 min and subsequently deposited onto a carbon coated Cu grid. To visualize the textural properties of the sorbents, a FEI Talos F200X was used, operating in scanning transmission electron microscopy (STEM) mode at an operating voltage of 200 kV. The instrument was equipped with a high-brightness field-emission gun, a high-angle annular dark-field (HAADF) detector, and a large collection-angle energy-dispersive X-ray (EDX) detector, which was used for the compositional analysis of the samples.

A FEI Magellan 400 FEG high resolution scanning electron microscope (SEM) was used for the textural and morphological analysis of the synthesized sorbents. The instrument was operated at an acceleration voltage of 10 kV and a beam current of 25 pA. To minimize charging effects during imaging, the samples were sputtered with a 4 nm thick film of Pt/Pd (80 : 20) prior to SEM analysis.



2.2.2 X-ray powder diffraction (XRD). XRD analysis was carried out on a PANalytical Empyrean diffractometer using Cu K α radiation with a wavelength of $\lambda \approx 1.5418 \text{ \AA}$ in a reflection geometry. In a typical *ex situ* XRD experiment, the measurement was carried out for 65 min from 5–90° at a step size of 0.0167°. In order to quantify the weight fractions of the individual crystal phases, Rietveld refinement was carried out using the FullProf Suite software. More details on the Rietveld method and the refinement data can be found in the ESI.†

2.2.3 Raman spectroscopy. Raman spectroscopy was performed on a DXR 2 Raman spectrometer (Thermo Fisher) equipped with a 532 nm excitation laser with a spot size of 2.1 μm . All *ex situ* measurements were performed in air at atmospheric pressure using a laser power in the range 2–5 mW. Four to six measurements at different locations of the sample with a measurement time ranging between 5–20 s were acquired and averaged. For *in situ* Raman measurements, a high-temperature Linkam CCR1000 cell was used. For the carbonaceous template removal, the sample was heated to 600 °C (heating rate of 10 °C min⁻¹) under 50 ml min⁻¹ of synthetic air. The temperature was held every 25 °C to collect Raman spectra.

2.2.4 Thermogravimetric analysis (TGA). Cyclic CO₂ capture–release experiments were conducted in a thermogravimetric analyzer (Mettler Toledo TGA/DSC 3+) with a reaction chamber volume of 45 mL. Under harsh regeneration conditions, calcination was performed at 900 °C for 5 min in 80 vol% CO₂. The carbonation reaction was performed at 650 °C for 20 minutes in 15 vol% CO₂. The heating and cooling ramps between the carbonation and calcination temperatures were set to 50 °C min⁻¹ (in N₂). Prior to the first carbonation reaction, each sample was calcined at 900 °C in synthetic air for 10 min. The total volumetric gas flow was set to 200 mL min⁻¹ throughout the entire experiment. The CO₂ uptake, $C_{\text{CO}_2,i}$, was determined *via*:

$$C_{\text{CO}_2,i} = \frac{m_{\text{carb},i} - m_{\text{calc}}}{m_{\text{calc}}} \quad (1)$$

where $m_{\text{carb},i}$ is the mass of the sorbent at the end of the carbonation step of cycle number i and m_{calc} is the mass of the calcined sorbent after the first calcination.

3. Results and discussion

3.1 Synthesis of the yolk–shell sorbents

To yield CaO–ZrO₂-based yolk–shell-structured sorbents, a two-step synthesis approach was performed (Fig. 2a). First, commercial CaCO₃ nanoparticles (Ca-NP, $d_{\text{avg,CaCO}_3} = 67 \text{ nm}$, Fig. 2b) were coated with a carbonaceous shell (Ca@C, Fig. 2c).⁴⁴ The thickness of the coating was about 40 nm, an optimized value to ensure a homogeneous carbonaceous layer, while avoiding the formation of separate carbonaceous spheres (Fig. S1†). The homogeneity of the carbonaceous coating was confirmed by EDX-TEM (Fig. 2c).

In the second step of the synthesis, the Ca@C particles were coated with a layer of Zr(OH)₄ utilizing a wet-chemistry-based approach (see Materials section for details).⁴⁵ A homogeneous coating with Zr(OH)₄ (see below) was confirmed *via* EDX-TEM, see Fig. 2d. The resulting yolk–shell structure after calcination (synthetic air, 900 °C) is shown in Fig. 2e and will be discussed in more detail further below. Throughout this work, the nomenclature for yolk–shell sorbents will be Ca@xZr, where x is the experimentally determined amount of ZrO₂ (in wt%) in the sorbent. As a reference material, CaCO₃ NPs (Ca-NP) were also directly coated with zirconia using the same coating procedure but without addition of the carbonaceous shell, yielding core–shell sorbents. Throughout the manuscript, the core–shell sorbents will be referred to as Ca-xZr.

The structure of the as-synthesized (*i.e.* before the first calcination) sorbents was assessed by XRD and Raman spectroscopy. The XRD patterns of the reference material and the zirconia-stabilized yolk–shell and core–shell-type sorbents are shown in Fig. 2f. The diffractogram of Ca-NP (as received) showed only the characteristic diffraction peaks of CaCO₃ (calcite polymorph). Also all of the yolk–shell and core–shell sorbents showed the diffraction peaks due to CaCO₃. An amorphous halo with a maximum around approximately $2\theta = 30^\circ$, relating to amorphous Zr(OH)₄, was observed in the sorbents prior to their calcination.⁴⁶ The ZrO₂ content in the sorbents was estimated using Rietveld analysis of XRD data acquired of sorbents that have undergone 20 cycles and are listed in Table 1 (see Fig. S2 and Table S1† for details on the Rietveld refinement). The Raman spectra of the as-synthesized sorbents are shown in Fig. 2g. All yolk–shell sorbents (prior to calcination) showed features due to the D-band (1350 cm⁻¹) and G-band (1574 cm⁻¹) of carbon confirming the presence of a carbonaceous coating. These sorbents also show a weak band related to amorphous Zr(OH)₄ between 590 and 670 cm⁻¹, confirming the Zr phase observed in XRD.⁴⁷ Additional features related to CaCO₃ (158 cm⁻¹, 284 cm⁻¹, 713 cm⁻¹, 1087 cm⁻¹) were observed as well.

3.2 Characterization of as-prepared sorbents after template removal

The as-synthesized sorbents were calcined in synthetic air (80 vol% N₂, 20 vol% O₂, 10 min at 900 °C, heating ramp of 25 °C min⁻¹) to remove the carbonaceous template as well as to decompose CaCO₃ into CaO, yielding as-prepared yolk–shell sorbents. The normalized weight (solid line) of Ca@C and the temperature ramp recorded during a TGA measurement (synthetic air, 175 ml min⁻¹, heating ramp of 25 °C min⁻¹) are shown in Fig. 3a. The initial mass loss (I) ($T < 150 \text{ }^\circ\text{C}$) is related to the release of residual solvent (water and ethanol) from the synthesis. The subsequent weight losses (II) and (III) are related to the removal of the carbonaceous template layer, resulting in a total weight loss of 35 wt% at 550 °C.^{48,49} At temperatures >600 °C, an additional weight loss (approximately 30% of the initial weight or 78% of the weight after full decomposition) is observed. This weight loss is due to the decomposition of CaCO₃ to CaO through the release of CO₂ (CaO has a theoretical CO₂ uptake capacity of 0.78 g_{CO₂} g_{Sorbent}⁻¹).





Fig. 2 (a) Illustration of the two-step synthesis approach to yield yolk-shell-type structures containing a CaO yolk and a ZrO₂ shell. (b) Particle size distribution of commercial CaCO₃ nanoparticles determined by TEM, (c) TEM micrograph and EDX elemental map of CaCO₃ nanoparticles coated with a homogeneous carbonaceous shell with an average thickness of 40 nm, (d) TEM micrograph and EDX elemental map of a sorbent containing both the carbonaceous template coating and the ZrO₂ coating, (e) TEM micrograph of the calcined yolk-shell sorbent after template removal in synthetic air at 900 °C, (f) XRD patterns of Ca-NP and as-synthesized (prior to calcination) zirconia-stabilized sorbents, and (g) Raman spectra of as-synthesized sorbents.

To assure that the carbonaceous template was removed completely during calcination in synthetic air, we studied the decomposition and removal of the template by *in situ* Raman

spectroscopy. Fig. S3† shows the Raman spectra of Ca@C during heat treatment in synthetic air (up to 550 °C). We observe the disappearance of hydroxyl groups $\nu(\text{OH})$, at



approximately 2800 cm^{-1} , in the temperature range 50 to $100\text{ }^{\circ}\text{C}$, corresponding to mass release (I) as observed in the TGA measurement. The modes relating to the G-band and D-band of carbon decrease in intensity between 100 and $500\text{ }^{\circ}\text{C}$. At $550\text{ }^{\circ}\text{C}$, no features related to the D- and G-band were observed, confirming the complete removal of the car-

bonaceous template at $550\text{ }^{\circ}\text{C}$. The characteristic mode for CO_3^{2-} ($\sim 1087\text{ cm}^{-1}$) in CaCO_3 is present at all temperatures (*i.e.* up to $550\text{ }^{\circ}\text{C}$). EDX-TEM analysis of the particles before and after calcination confirms the carbon removal; the respective images are shown in Fig. S3b and c.†

The structure of the as-prepared (*i.e.* calcined), zirconia-stabilized sorbents was assessed by XRD (Fig. 3b). The calcined core-shell particles show the characteristic diffraction peaks of both CaO ($Fm\bar{3}m$ space group, cubic) and CaZrO_3 ($Pcmn$ space group, orthorhombic). Unexpectedly, the intensity of the peaks related to CaZrO_3 increased from Ca-15Zr to Ca-26Zr, indicating the formation of larger amounts of the mixed phase with increasing ZrO_2 contents. Using Rietveld analysis (see Fig. S2 and Table S1†), we estimated the fraction of the CaZrO_3 mixed phase in the core-shell sorbents Ca-15Zr and Ca-26Zr as 15 and 37 wt%, respectively. The XRD patterns of the yolk-shell sorbents Ca@16Zr and Ca@12Zr showed peaks due to CaO

Table 1 ZrO_2 content in yolk-shell and core-shell sorbents based on Rietveld analysis (sorbent exposed to 20 carbonation-calcination cycles)

Type	Sorbent	ZrO_2 content [wt%]
Core-shell	Ca-15Zr	15
Core-shell	Ca-26Zr	26
Yolk-shell	Ca@16Zr	16
Yolk-shell	Ca@12Zr	12
Yolk-shell	Ca@55Zr	55



Fig. 3 (a) Weight loss of CaCO_3 nanoparticles containing a carbonaceous template coating during calcination in air (heating ramp of $25\text{ }^{\circ}\text{C min}^{-1}$ up to $900\text{ }^{\circ}\text{C}$), (b) XRD patterns of calcined zirconia-stabilized sorbents after template removal; TEM micrographs and EDX-TEM elemental maps for Ca and Zr for (c) a zirconia-stabilized, yolk-shell structured sorbent (Ca@12Zr) and (d) a zirconia-stabilized, core-shell structured sorbent (Ca-26Zr).



and very low intensity peaks possibly due to CaZrO_3 , which we were not able to quantify using Rietveld refinement (due to their small intensity). This suggests, considering the detection limit of the XRD setup, that in such sorbents the weight fraction of CaZrO_3 is <1 wt%. In addition, no peaks due to ZrO_2 were observed. Hence, in the yolk-shell sorbents Ca@12Zr and Ca@16Zr Zr is very likely present in an amorphous phase. However, for Ca@55Zr , tetragonal zirconia ($t\text{-ZrO}_2$) was observed in addition to both CaO and CaZrO_3 . Rietveld refinement showed that this sorbent contained about 11 wt% CaZrO_3 and 52 wt% $t\text{-ZrO}_2$. In conclusion, compared to the core-shell particles, CaZrO_3 formation was reduced in the yolk-shell-type sorbents (at similar ZrO_2 contents), in particular when comparing Ca@16Zr and Ca-15Zr .

The morphologies of the calcined yolk-shell sorbents and core-shell sorbents were imaged using (EDX)-TEM, see Fig. 3c and d. The yolk-shell-structured sorbents Ca@12Zr (Fig. 3c) and Ca@16Zr (Fig. S4a†) exhibit individual CaO nanoparticles encapsulated by a Zr-containing shell with an occasionally dendritic appearance. The void space between the yolk and the shell, characteristic for the yolk-shell architecture, is clearly visible for Ca@12Zr . Ca@55Zr (Fig. S4b†) showed both larger agglomerates coated with a Zr-containing shell as well as some yolk-shell structures similar to the ones observed for Ca@16Zr and Ca@12Zr . For the larger agglomerates, the distribution of Ca and Zr, based on EDX-TEM, overlapped in intensity, indicating the formation of large CaZrO_3 particles or CaZrO_3 -coated CaO particles, in line with our XRD observations (Fig. 3b). For high Zr contents (Ca@55Zr), TEM also shows the presence of ZrO_2 particles, which are, taking into account the XRD results, related to $t\text{-ZrO}_2$. The core-shell sorbent Ca-26Zr (Fig. 3d) exhibited a Zr-containing coating covering the whole surface of the CaO particles. Based on our XRD analysis, this coating is composed of a thick layer of CaZrO_3 . On the other hand, the calcined core-shell sorbent Ca-15Zr (Fig. S4c†) showed an inhomogeneous Zr-containing coating on the CaO particles, indicating that the added amount of ZrO_2 was insufficient to completely coat the CaO nanoparticles with a Zr-containing phase. Based on our XRD analysis, we also expect the Zr-containing coating of Ca-15Zr to be CaZrO_3 .

3.3 Cyclic CO_2 uptake of the nanostructured zirconia-stabilized sorbents

The cyclic CO_2 uptake of the zirconia-stabilized yolk-shell sorbents and the references Ca-NP as well as the core-shell particles were assessed over 20 carbonation-calcination cycles (Fig. 4a). Sorbents with ZrO_2 contents <10 wt% were not investigated in more detail because they did not form well-defined yolk-shell structures and hence exhibited a lower CO_2 uptake than Ca-NP .

The reference sorbent Ca-NP (without Zr) has a high CO_2 uptake of $0.63 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$ in the first cycle. However, the CO_2 uptake decreases rapidly with cycle number, reaching $0.21 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$ (decrease of 66% compared to the 1st cycle) and $0.17 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$ (decrease of 73% compared to the 1st cycle) after 10 and 20 cycles, respectively. The CO_2 uptake of

the yolk-shell-structured sorbents varied substantially with the content of Zr. Compared to Ca-NP ($0.17 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$), Ca@16Zr and Ca@12Zr show significantly higher CO_2 uptakes after 20 cycles, reaching, respectively, $0.38 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$ (maximum theoretical CO_2 uptake of $0.65 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$) and $0.61 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$ (maximum theoretical CO_2 uptake of $0.69 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$). In particular, the CO_2 uptake performance of Ca@12Zr is promising, as it showed a relatively stable CO_2 uptake over 20 cycles with only a small decrease from $0.66 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$ in the 1st cycle to $0.61 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$ (decrease of 8%) in the 20th cycle. For the sorbent with the highest zirconia content investigated (Ca@55Zr), very low CO_2 uptakes of, respectively, $0.17 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$ and $0.04 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$ in the 1st and 20th cycle were observed. The low CO_2 uptake of Ca-NP@55Zr was due to the large fraction of CO_2 -capture-inactive $t\text{-ZrO}_2$ and CaZrO_3 in this material as evidenced by XRD measurements (Fig. 3b). Turning to the core-shell structured sorbents, the most promising core-shell sorbent Ca-26Zr showed a significantly lower CO_2 uptake in the 20th cycle ($0.29 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$) compared to Ca@12Zr ($0.61 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$). Further, the core-shell sorbent Ca-15Zr had a CO_2 uptake of $0.27 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$ after 20 cycles, which is significantly lower than the CO_2 uptake of its yolk-shell analogue with a similar ZrO_2 content, *i.e.* Ca@16Zr ($0.38 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$). Hence, a yolk-shell architecture yielded significantly better performing sorbents compared to the core-shell architecture (and the Ca-NP reference). This observation will be rationalized in the following sections.

3.4 The effect of nanostructuring on the carbonation kinetics

The carbonation kinetics in the 1st and 10th cycle of the most promising yolk-shell sorbents (Ca@16Zr and Ca@12Zr) and the core-shell analogues (Ca-15Zr and Ca-26Zr), as well as the reference Ca-NP are plotted in Fig. 4b and c. Independent of the material and the cycle number, the carbonation reaction can be divided into two reaction regimes, *i.e.* a fast, kinetically-controlled regime followed by a slower, diffusion-controlled regime. The effect of the yolk-shell and core-shell architectures on these regimes will be discussed below.

First, we analyzed the effect of the yolk-shell and core-shell architectures on the kinetically-controlled regime. Based on the normalized CO_2 uptake rate reaching a plateau, see Fig. 4d, we defined the end of the kinetically-controlled regime at $t = 150$ s for all sorbents. Within the kinetically-controlled regime in the 1st cycle, the yolk-shell sorbents reached significantly higher CO_2 uptakes of $0.56 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$ (Ca@12Zr) and $0.51 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$ (Ca@16Zr) compared to the core-shell sorbents ($0.3 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$ for Ca-15Zr and $0.28 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$ for Ca-26Zr) and Ca-NP ($0.35 \text{ g}_{\text{CO}_2} \text{ g}_{\text{Sorbent}}^{-1}$). Also, the maximum normalized CO_2 uptake rate (Fig. 4d) achieved for the yolk-shell sorbents was significantly higher than for Ca-15Zr , Ca-26Zr and Ca-NP . In the 10th cycle, the CO_2 uptake at the end of the kinetically-controlled regime was comparable for Ca@12Zr and Ca-26Zr , whereas Ca@16Zr , Ca-15Zr and Ca-NP showed a lower CO_2 uptake. The maximum achieved CO_2 uptake rate was also slightly higher for the yolk-shell sorbents





Fig. 4 (a) Cyclic CO₂ uptake over 20 carbonation–calcination cycles of zirconia-stabilized, yolk–shell-structured sorbents as well as core–shell-type sorbents and the CaCO₃ NP reference; carbonation at 650 °C in 15 vol% CO₂ and calcination at 900 °C in 80 vol% CO₂, (b) CO₂ uptake as a function of time in the 1st cycle and (c) 10th cycle of zirconia-stabilized sorbents and the CaCO₃ NP reference, and (d) normalized CO₂ uptake rate during the first 200 s of the 1st (—) and 10th (---) carbonation for zirconia-stabilized sorbents and the CaCO₃ NP reference.

than for the core–shell sorbents and the Ca-NP reference. In the kinetically-controlled regime in which the CO₂ mass transfer resistance to reach the reaction surface is negligible, the reaction proceeds as a surface reaction. Hence, the CO₂ uptake rate (dm_{CO_2}/dt) is proportional to the reaction surface area S_0 and the reaction rate k_s :

$$\frac{dm_{\text{CO}_2}}{dt} \sim S_0 \cdot k_s \quad (2)$$

As the reaction itself (*i.e.* the carbonation of CaO) has an intrinsic reaction rate k_s ,^{33,50,51} a higher maximum CO₂ uptake

rate implies a higher reaction surface area of CaO. Hence, we can conclude that a yolk–shell architecture improved the accessibility of CaO for reaction with CO₂, *i.e.* provided sorbents with a higher reaction surface area compared to the core–shell sorbents and the Ca-NP reference. N₂ physisorption measurements to further confirm this conclusion could not be conducted due to the small amount (<20 mg) of sorbent retained from a single synthesis.

The analysis of the kinetics in the diffusion-controlled regime, *i.e.* $t > 150$ s, will be discussed next. All sorbents exhibited a comparable CO₂ uptake in the diffusion-controlled



regime in the 1st cycle, see Fig. 4b. In the 10th cycle (Fig. 4c), the yolk-shell sorbents achieved a large part of their total CO₂ uptake after 20 minutes of carbonation in the diffusion-controlled regime with an average normalized CO₂ uptake rate (for 150 s < t < 1200 s) for Ca@12Zr and Ca@16Zr of 2.5 and 1.5 × 10⁻⁴ s⁻¹, respectively. The CO₂ uptake of the core-shell sorbents in this regime was significantly smaller, reaching an average CO₂ uptake rate of 1.04 × 10⁻⁴ s⁻¹ and 6.73 × 10⁻⁵ s⁻¹ for Ca-15Zr and Ca-26Zr, respectively. The Ca-NP reference exhibited a CO₂ uptake rate of 8.0 × 10⁻⁵ s⁻¹ and its overall CO₂ uptake in the 10th cycle was comparably low. The average CO₂ uptake rates in the 20th cycle were consistent with those observed in the 10th cycle and scaled in the following order: Ca@12Zr (2.2 × 10⁻⁴ s⁻¹) > Ca@16Zr (1.3 × 10⁻⁴ s⁻¹) > Ca-15Zr (9.3 × 10⁻⁵ s⁻¹) > Ca-26Zr (7.3 × 10⁻⁵ s⁻¹) ≈ Ca-NP (6.7 × 10⁻⁵ s⁻¹). Hence, for yolk-shell-structured materials also the CO₂ uptake rates in the diffusion-controlled regime were improved compared to the core-shell sorbents and the Ca-NP reference. In particular, the yolk-shell-structured material Ca@16Zr compared favorably with the core-shell sorbent Ca-15Zr which possesses a very similar Zr content. According to the random pore model (RPM), which is widely used to describe the carbonation reaction of CaO, a higher CO₂ uptake rate in the diffusion-controlled regime is indicative of a higher effective

diffusivity of CO₂.⁵² Hence, there is a strong indication that the yolk-shell structure improves the effective diffusivity of CO₂ compared to core-shell architectures. It is worth noting that the accessibility and availability of CaO for reaction with CO₂ may be affected by several factors, including the morphology of the sorbent as well as the structural properties, which will be discussed below.

3.5 Stabilization of the morphology during cycling probed by electron microscopy

The analysis of the carbonation kinetics revealed that (i) the maximum CO₂ uptake rate in the kinetically-controlled regime is higher for the zirconia-stabilized, yolk-shell-structured sorbents (Ca@12Zr and Ca@16Zr) compared to Ca-NP and the core-shell-structured sorbents, and also (ii) that the CO₂ uptake in the diffusion-controlled regime is higher for the yolk-shell-structured sorbents compared to Ca-NP and the core-shell-structured sorbents, implying a higher effective CO₂ diffusivity in such materials. In the following, we probe the structural stability of the different sorbent architectures using electron microscopy.

After 10 cycles, the yolk-shell-structured sorbents Ca@12Zr (Fig. 5a) and Ca@16Zr (Fig. S5a†) exhibit Zr-containing shells with a skeletal appearance that encapsulate individual CaO



Fig. 5 (a) (EDX)-TEM analysis of the most effective yolk-shell-structured sorbent Ca@12Zr after 10 carbonation–calcination cycles, (b) (EDX)-TEM analysis of the core-shell-structured sorbent Ca-26Zr, (c) high-resolution TEM micrograph and EDX mapping of the dendritic structures observed for all zirconia-stabilized sorbents (here: Ca@16Zr) and XRD patterns of the zirconia-stabilized sorbents after (d) 10 carbonation–calcination cycles as well as (e) 20 carbonation–calcination cycles.



nanoparticles. Compared to the unreacted sorbents, the shells have to some degree lost their shape and integrity, in particular for Ca@16Zr (see Fig. S4a† for comparison). The yolk-shell structure of the as-prepared sorbents is lost to some degree over cycling, resulting in shell structures with higher porosity. Nonetheless, SEM micrographs of Ca@12Zr (Fig. S5b†) confirm that after cycling the sorbent is still composed of individual CaO nanoparticles that are surrounded by a protective shell of dendritic appearance. Based on EDX-TEM analysis, the shells of the yolk-shell sorbents are Zr-containing. After 20 cycles (see Fig. S5d-h†), large agglomerates of yolk-shell particles (in this case Ca@12Zr) are observed. The morphology of the individual particles is therefore difficult to assess. Some of the larger dendritic structures observed for the cycled yolk-shell sorbents consist of smaller crystallites as shown in Fig. 5c. The high-resolution TEM micrograph of these smaller crystallites reveal plane distances that resemble the spacings of the [0 0 2] and [0 1 1] planes of CaZrO₃.

On the other hand, electron microscopy-based analysis of the core-shell sorbent Ca-26Zr after 10 cycles shows large CaO agglomerates surrounded by a Zr-containing layer (Fig. 5b). These particles also exhibited Zr-containing dendritic structures covering the surface of the CaO particles. EDX-TEM shows that the Zr coating is in intimate contact with the CaO surface, indicative of the formation of the Ca-Zr mixed phase. In addition, Ca-15Zr (Fig. S5c†) showed enlarged (*i.e.* sintered) CaO particles with dendritic coating structures at the surface. Indeed, cycled Ca-15Zr does not feature a homogeneous coating around CaO particles anymore. To conclude, a yolk-shell-structured architecture protected the single CaO nanoparticles from sintering more effectively than a core-shell-structured morphology. We expect the ZrO₂- (or CaZrO₃-) shell to act as a physical barrier against sintering between single CaO nanoparticles, reducing in turn sintering,^{6,29,53} whereby the yolk-shell architecture seems to be more effective in reducing the interfacial area between the individual CaO nanoparticles. Further, the high porosity of the yolk-shell-structured morphology allowed for a fast transport of CO₂ to the surface of the CaO particles. In contrast, for core-shell-type particles the intimate contact between zirconia and CaO led to the formation of a thick Zr-containing shell (likely CaZrO₃, see below) that reduced the rate of CO₂ uptake by creating diffusional resistance for CO₂. The formation of CaZrO₃ over cycling will be discussed below.

3.6 Delay in CaZrO₃ formation during cycling in yolk-shell-structured sorbents

XRD measurements of the as-prepared sorbents showed that the yolk-shell architecture reduces the degree of CaZrO₃ formation compared to the core-shell morphologies. In the following we track the formation of CaZrO₃ over repeated carbonation-calcination cycling and its correlation with sorbent deactivation.

The XRD patterns of zirconia-stabilized yolk-shell and core-shell sorbents after 10 and 20 cycles are shown in Fig. 5d and e, respectively. Using Rietveld analysis (Table S1†), we esti-

mate the fraction of CaZrO₃ in the different materials and define the parameter α , *i.e.* the molar ratio of CaZrO₃ to the total molar amount of CaO in the as-synthesized sorbent (see Table 2):

$$\alpha = \frac{n_{\text{CaZrO}_3}}{n_{\text{CaO}}} \quad (3)$$

In the core-shell sorbent Ca-15Zr the ratio α increased slightly from 0.07 (as-prepared) to 0.08 after 20 cycles. This small increase is however within the accuracy of the experiment. Therefore, we conclude that in Ca-15Zr most, if not all, of the CaZrO₃ phase already formed after the initial calcination step. For Ca-26Zr, α was 0.21 (as-prepared), 0.20 (10 cycles) and 0.24 (20 cycles). Hence, also for Ca-26Zr most of the Zr is in the form of CaZrO₃ after the initial calcination step. The intimate contact between Ca and Zr-containing phases in the core-shell-based architectures leads to the rapid formation of a CO₂-capture-inactive CaZrO₃ layer around CaO particles (as also evidenced by TEM analysis). Hence, the deactivation of the core-shell sorbents over repeated carbonation-calcination cycles is not driven by the additional formation of CaZrO₃. Instead, it is very likely that deactivation is due to the sintering of the individual CaO particles and an increase in the density (and thickness) of the CaZrO₃ layer itself (as a result of sintering). This reduces the size of the active surface area and decreases the effective diffusivity of CO₂.

The XRD patterns of the yolk-shell sorbents after 10 and 20 cycles (Fig. 5d and e) show the presence of CaZrO₃. The values of α after 10 cycles are 0.03 and 0.04 for Ca@16Zr and Ca@12Zr, respectively. Hence, for yolk-shell-structured sorbents the fraction of CaZrO₃ increased significantly with cycle number (the as-prepared materials have $\alpha < 0.01$). After 20 cycles, α increased further to 0.09 for Ca@16Zr and 0.07 for Ca@12Zr, indicating a continuing formation of CaZrO₃ during cycling. In addition, a small peak due to t-ZrO₂ (approximately 1 wt%) was observed for Ca@16Zr (20 cycles). This continuing formation of CO₂-capture-inactive CaZrO₃ for the yolk-shell-structured materials, in particular for Ca@12Zr, is one explanation for their decreasing CO₂ uptake with cycle number (~40% decrease from the 1st to 20th cycle for Ca@16Zr), yet sintering of CaO nanoparticles must also contribute to the decay in the CO₂ uptake for Ca@16Zr. For Ca@12Zr on the other hand, the formation of CaZrO₃ would result in a theoretical loss of approximately 6 wt% of the initially available CaO. At the same time, Ca@12Zr shows a drop in the cyclic CO₂ uptake from the 1st to the 20th cycle of ~8%, *i.e.* for Ca@12Zr

Table 2 Molar ratio of CaZrO₃ to CaO derived from Rietveld analysis

Sorbent	Ratio as-prepared	Ratio after 10 cycles	Ratio after 20 cycles
Ca-15Zr	0.07	0.08	0.08
Ca-26Zr	0.21	0.20	0.24
Ca@16Zr	<0.01	0.03	0.09
Ca@12Zr	<0.01	0.04	0.07



the loss of reactive CaO due to CaZrO₃ formation accounts to ~75% of the decay in CO₂ uptake. Hence, the yolk-shell-structured architecture of Ca@12Zr largely prevented sintering of the CaO nanoparticles, making the loss of reactive CaO through the formation of CaZrO₃ the dominating deactivation mechanism. The formation of CaZrO₃ is likely a result of the partial loss of the yolk-shell-type structure during cycling, as evidenced in our TEM analysis (Fig. 5a). Hence, the sacrificial template can reduce the amount of CaZrO₃ formation during the first cycles, but cannot prevent entirely the contact between CaO and ZrO₂.

4. Conclusion

In this work, we designed and synthesized yolk(CaO)-shell (ZrO₂)-structured sorbents for CO₂ capture. The nano-structured materials developed here exceeded the CO₂ uptake of the bare CaO nanoparticle benchmark by more than 250% after 20 carbonation-calcination cycles. Comparing the performance of yolk-shell-structured sorbents with that of core-shell structures for which there is an intimate contact between the stabilizer (ZrO₂) and CaO, we demonstrate that the yolk-shell-structured materials have a significantly reduced rate of deactivation. The void space between the stabilizer shell and CaO nanoparticle, introduced by a sacrificial carbonaceous template, is crucial to increase the effective diffusivity of CO₂, delay the formation of CaZrO₃ and stabilize the individual CaO nanoparticles against sintering. The yolk-shell-structured sorbent with a ZrO₂ content of 12 wt% performs best and in this material the gradual formation of CaZrO₃ with cycle number is the main deactivation mechanism, accounting for 75% of the overall decay in the cyclic CO₂ uptake over 20 cycles. Hence, yolk-shell architectures can successfully mitigate sintering, but need to be optimized further to reduce the loss of active CaO. Another important aspect for future work is to develop strategies to maintain the initial yolk-shell-type structure during high-temperature pretreatment and cycling. Furthermore, the use of stabilizers that do not form a mixed phase with CaO under calcium looping conditions, *e.g.* magnesium oxide, may help to provide a yolk-shell architecture with even higher CO₂ uptakes and prolonged stability.

Author contributions

M. K. and C. R. M. conceived and planned the project. M. K. performed the material synthesis, performance characterization, structural characterization as well as SEM analysis. A. O. performed the material synthesis, performance characterization and structural characterization. J. N. performed the material synthesis and structural characterization. A. L. and A. K. performed (EDX)-TEM characterization. M. K. wrote the manuscript with input from all authors. F. D. and A. H. B. revised the manuscript. C. R. M. supervised the project, wrote and revised the manuscript.

Conflicts of interest

The authors have no conflicts of interest to declare.

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References

- 1 R. K. Pachauri and L. A. Meyer, *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 2014.
- 2 NASA, *Local CO₂ concentration at Mauna Loa Observatory*, Hawaii, USA, 2020.
- 3 G. Krinner, *et al.*, Long-term climate change: Projections, commitments and irreversibility. *Climate Change 2013 the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 2013, vol. **9781107057**.
- 4 D. P. Hanak, E. J. Anthony and V. Manovic, A review of developments in pilot-plant testing and modelling of calcium looping process for CO₂ capture from power generation systems, *Energy Environ. Sci.*, 2015, **8**, 2199–2249.
- 5 A. M. Kierzkowska, R. Pacciani and C. R. Müller, CaO-based CO₂ sorbents: From fundamentals to the development of new, highly effective materials, *ChemSusChem*, 2013, **6**, 1130–1148.
- 6 M. T. Dunstan, F. Donat, A. H. Bork, C. P. Grey and C. R. Müller, CO₂ Capture at Medium to High Temperature Using Solid Oxide-Based Sorbents: Fundamental Aspects, Mechanistic Insights, and Recent Advances, *Chem. Rev.*, 2021, **121**, 12681–12745.
- 7 C. H. Yu, C. H. Huang and C. S. Tan, A review of CO₂ capture by absorption and adsorption, *Aerosol Air Qual. Res.*, 2012, **12**, 745–769.
- 8 G. Manzolini, *et al.*, Economic assessment of novel amine based CO₂ capture technologies integrated in power plants based on European Benchmarking Task Force methodology, *Appl. Energy*, 2015, **138**, 546–558.
- 9 I. M. Bernhardsen and H. K. Knuutila, A review of potential amine solvents for CO₂ absorption process: Absorption capacity, cyclic capacity and pK_a, *Int. J. Greenhouse Gas Control*, 2017, **61**, 27–48.



- 10 C. Luo, *et al.*, Morphological Changes of Pure Micro- and Nano-Sized CaCO₃ during a Calcium Looping Cycle for CO₂ Capture, *Chem. Eng. Technol.*, 2012, **35**, 547–554.
- 11 Z. S. Li, N. S. Cai and Y. Y. Huang, Effect of preparation temperature on cyclic CO₂ capture and multiple carbonation-calcination cycles for a new Ca-based CO₂ sorbent, *Ind. Eng. Chem. Res.*, 2006, **45**, 1911–1917.
- 12 R. Barker, The reversibility of the reaction CaCO₃ ⇌ CaO + CO₂, *J. Appl. Chem. Biotechnol.*, 2007, **23**, 733–742.
- 13 K. Wang, P. T. Clough, P. Zhao and E. J. Anthony, Synthesis of highly effective stabilized CaO sorbents via a sacrificial N-doped carbon nanosheet template, *J. Mater. Chem. A*, 2019, **7**, 9173–9182.
- 14 A. Kurlov, *et al.*, Mechanochemically Activated, Calcium Oxide-Based, Magnesium Oxide-Stabilized Carbon Dioxide Sorbents, *ChemSusChem*, 2016, **9**, 2380–2390.
- 15 S. M. Kim, *et al.*, In Situ XRD and Dynamic Nuclear Polarization Surface Enhanced NMR Spectroscopy Unravel the Deactivation Mechanism of CaO-Based, Ca₃Al₂O₆-Stabilized CO₂ Sorbents, *Chem. Mater.*, 2018, **30**(4), 1344–1352.
- 16 C. Chi, Y. Li, W. Zhang and Z. Wang, Synthesis of a hollow microtubular Ca/Al sorbent with high CO₂ uptake by hard templating, *Appl. Energy*, 2019, **251**, 113382.
- 17 Y. Xu, *et al.*, Characteristics and performance of CaO-based high temperature CO₂ sorbents derived from a sol-gel process with different supports, *RSC Adv.*, 2016, **6**, 79285–79296.
- 18 M. Broda and C. R. Müller, Sol-gel-derived, CaO-based, ZrO₂-stabilized CO₂ sorbents, *Fuel*, 2014, **127**, 94–100.
- 19 S. M. Kim, A. Armutlulu, A. M. Kierzkowska and C. R. Müller, Inverse Opal-Like, Ca₃Al₂O₆-Stabilized, CaO-Based CO₂ Sorbent: Stabilization of a Highly Porous Structure To Improve Its Cyclic CO₂ Uptake, *ACS Appl. Energy Mater.*, 2019, **2**, 6461–6471.
- 20 J. Blamey, V. Manovic, E. J. Anthony, D. R. Dugwell and P. S. Fennell, On steam hydration of CaO-based sorbent cycled for CO₂ capture, *Fuel*, 2015, **150**, 269–277.
- 21 M. Krödel, A. Landuyt, P. M. Abdala and C. R. Müller, Mechanistic Understanding of CaO-Based Sorbents for High-Temperature CO₂ Capture: Advanced Characterization and Prospects, *ChemSusChem*, 2020, **13**, 6259–6272.
- 22 A. Kurlov, A. M. Kierzkowska, T. Huthwelker, P. M. Abdala and C. R. Müller, Na₂CO₃-modified CaO-based CO₂ sorbents: The effects of structure and morphology on CO₂ uptake, *Phys. Chem. Chem. Phys.*, 2020, **22**, 24697–24703.
- 23 Y. Xu, *et al.*, Structure and surface insight into a temperature-sensitive CaO-based CO₂ sorbent, *Chem. Eng. J.*, 2022, **435**, 134960.
- 24 M. Broda, A. M. Kierzkowska and C. R. Müller, Application of the sol-gel technique to develop synthetic calcium-based sorbents with excellent carbon dioxide capture characteristics, *ChemSusChem*, 2012, **5**, 411–418.
- 25 H. Lu, A. Khan and P. G. Smirniotis, Relationship between structural properties and CO₂ capture performance of CaO-based sorbents obtained from different organometallic precursors, *Ind. Eng. Chem. Res.*, 2008, **47**, 6216–6220.
- 26 M. A. Naeem, *et al.*, Optimization of the structural characteristics of CaO and its effective stabilization yield high-capacity CO₂ sorbents, *Nat. Commun.*, 2018, **9**, 1–11.
- 27 W. Liu, *et al.*, Synthesis of sintering-resistant sorbents for CO₂ capture, *Environ. Sci. Technol.*, 2010, **44**, 3093–3097.
- 28 L. Zhang, Y. Lu and M. Rostam-Abadi, Sintering of calcium oxide (CaO) during CO₂ chemisorption: A reactive molecular dynamics study, *Phys. Chem. Chem. Phys.*, 2012, **14**, 16633–16643.
- 29 K. S. Sultana, D. T. Tran, J. C. Walmsley, M. Rønning and D. Chen, CaO Nanoparticles Coated by ZrO₂ Layers for Enhanced CO₂ Capture Stability, *Ind. Eng. Chem. Res.*, 2015, **54**, 8929–8939.
- 30 M. Zhao, *et al.*, Durability of CaO-CaZrO₃ sorbents for high-temperature CO₂ capture prepared by a wet chemical method, *Energy Fuels*, 2014, **28**, 1275–1283.
- 31 J. Cai, S. Wang and C. Kuang, ScienceDirect A Modified Random Pore Model for Carbonation Reaction of CaO-based limestone with CO₂ in Different Calcination-carbonation Cycles, *Energy Procedia*, 2017, **105**, 1924–1931.
- 32 A. Di Giuliano, K. Gallucci and P. U. Foscolo, Determination of Kinetic and Diffusion Parameters Needed to Predict the Behavior of CaO-Based CO₂ Sorbent and Sorbent-Catalyst Materials, *Ind. Eng. Chem. Res.*, 2020, **59**, 6840–6854.
- 33 Y. Li, Z. Li, H. Wang and N. Cai, CaO carbonation kinetics determined using micro-fluidized bed thermogravimetric analysis, *Fuel*, 2020, **264**, 116823.
- 34 H. Sun, *et al.*, Fundamental studies of carbon capture using CaO-based materials, *J. Mater. Chem. A*, 2019, **7**, 9977–9987.
- 35 D. Alvarez and J. C. Abanades, Pore-size and shape effects on the recarbonation performance of calcium oxide submitted to repeated calcination/recarbonation cycles, *Energy Fuels*, 2005, **19**, 270–278.
- 36 S. K. Bhatia and D. D. Perlmutter, Effect of the product layer on the kinetics of the CO₂-lime reaction, *AIChE J.*, 1983, **29**, 79–86.
- 37 Z. S. Li, F. Fang, X. Y. Tang and N. S. Cai, Effect of temperature on the carbonation reaction of CaO with CO₂, *Energy Fuels*, 2012, **26**, 2473–2482.
- 38 G. Grasa, R. Murillo, M. Alonso and J. C. Abanades, Application of the random pore model to the carbonation cyclic reaction, *AIChE J.*, 2009, **55**(5), 1246–1255.
- 39 D. Alvarez and J. Carlos Abanades, Determination of the critical product layer thickness in the reaction of CaO with CO₂, *Ind. Eng. Chem. Res.*, 2005, **44**, 5608–5615.
- 40 N. Mahinpey, M. H. Sedghkerdar, A. Aqsha and A. H. Soleimanisalim, CO₂ Capture Performance of Core/Shell CaO-Based Sorbent Using Mesoporous Silica and Titania in a Multicycle CO₂ Capture Process, *Ind. Eng. Chem. Res.*, 2016, **55**, 4532–4538.
- 41 W. Peng, Z. Xu, C. Luo and H. Zhao, Tailor-Made Core-Shell CaO/TiO₂-Al₂O₃ Architecture as a High-Capacity and



- Long-Life CO₂ Sorbent, *Environ. Sci. Technol.*, 2015, **49**, 8237–8245.
- 42 S. Zhang and X. Li, Synthesis and characterization of CaCO₃@SiO₂ core-shell nanoparticles, *Powder Technol.*, 2004, **141**, 75–79.
- 43 C. Huang, M. Xu, X. Huai and Z. Liu, Template-Free Synthesis of Hollow CaO/Ca₂SiO₄ Nanoparticle as a Cyclically Stable High-Capacity CO₂ Sorbent, *ACS Sustainable Chem. Eng.*, 2021, **9**, 2171–2179.
- 44 X. Fang, *et al.*, Precisely controlled resorcinol-formaldehyde resin coating for fabricating core-shell, hollow, and yolk-shell carbon nanostructures, *Nanoscale*, 2013, **5**, 6908–6916.
- 45 P. M. Arnal, C. Weidenthaler and F. Schüth, Highly monodisperse zirconia-coated silica spheres and zirconia/silica hollow spheres with remarkable textural properties, *Chem. Mater.*, 2006, **18**, 2733–2739.
- 46 X. Zhang, *et al.*, Methane decomposition and carbon deposition over Ni/ZrO₂ catalysts: Comparison of amorphous, tetragonal, and monoclinic zirconia phase, *Int. J. Hydrogen Energy*, 2019, **44**, 17887–17899.
- 47 D. S. S. Padovini, D. S. L. Pontes, C. J. Dalmaschio, F. M. Pontes and E. Longo, Facile synthesis and characterization of ZrO₂ nanoparticles prepared by the AOP/hydrothermal route, *RSC Adv.*, 2014, **4**, 38484–38490.
- 48 C. Dwivedi, *et al.*, Resorcinol-formaldehyde coated XAD resin beads for removal of cesium ions from radioactive waste: Synthesis, sorption and kinetic studies, *RSC Adv.*, 2012, **2**, 5557–5564.
- 49 D. F. Molina-Campos, R. A. Fonseca-Correa, D. P. Vargas-Delgado, L. Giraldo and J. C. Moreno-Piraján, Data for the synthesis of resorcinol-formaldehyde aerogels in acidic and basic media, *Data Brief*, 2017, **12**, 409–417.
- 50 Z. Zhou, P. Xu, M. Xie, Z. Cheng and W. Yuan, Modeling of the carbonation kinetics of a synthetic CaO-based sorbent, *Chem. Eng. Sci.*, 2013, **95**, 283–290.
- 51 H. Wang, Z. Li, Y. Li and N. Cai, Reduced-order model for CaO carbonation kinetics measured using micro-fluidized bed thermogravimetric analysis, *Chem. Eng. Sci.*, 2021, **229**, 116039.
- 52 R. H. Borgwardt, K. R. Bruce and J. Blake, An Investigation of Product-Layer Diffusivity for CaO Sulfation, *Ind. Eng. Chem. Res.*, 1987, **26**(10), 1993–1998.
- 53 P. Sun, J. R. Grace, C. J. Lim and E. J. Anthony, The effect of CaO sintering on cyclic CO₂ capture in energy systems, *AIChE J.*, 2007, **53**, 2432–2442.

