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Dynamics of phase transitions in Na₂TiO₃ and its possible utilization as a CO₂ sorbent: a critical analysis

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Na-Based materials are emerging as promising high-temperature CO₂ sorbents. In this work, we provide a detailed study on the synthesis of Na₂TiO₃ via a solid-state route using NaOH and TiO₂ as starting reactants. The CO₂ sorption properties of the synthesized Na₂TiO₃ were evaluated by thermogravimetric analysis. A subsequent comprehensive study on the complex reaction mechanism of Na₂TiO₃ at high temperatures under carbonation conditions was performed via real time *in situ* synchrotron X-ray diffraction analysis. *In situ* experiments performed under different conditions revealed the occurrence of thermally-driven phase transitions derived from the structural instability of the material at high temperatures. These reactions could be differentiated from carbonation processes, allowing the proposal of a reaction mechanism of the material as a CO₂ sorbent. The obtained results can explain the abnormal dynamic thermogram displayed by Na₂TiO₃ in the presence of CO₂ within a temperature range that is of interest for practical applications and serve as a basis for evaluating the feasibility of using this material in CO₂ capture schemes.

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1 Introduction

Global CO₂ emissions have increased by about 90% in the last 50 years, with industrial processes and fossil fuel combustion being the two major contributors, and about 78% of the total increment having occurred in the period from 1970 to 2011.¹ Since CO₂ has been pointed out as mainly responsible for the greenhouse effect that drives global climate change, the development of strategies for mitigating its release to the atmosphere constitutes an essential prerequisite to prevent further global warming. A closer look into anthropogenic CO₂ emissions shows that approximately 40% of them are generated by power plants.² Hence, the design and engineering of materials and processes to capture and retain the CO₂ before its release to the atmosphere appear as a

viable alternative to tackle climate change, while transitioning to more sustainable and renewable power schemes.

Solid sorbents have been proven to efficiently remove CO₂ from high-temperature industrial gas streams,^{3–5} with promising results when implemented at a pilot scale in different coal-fired and cement plants.^{6,7} Indeed, these materials with the ability to react with CO₂ at high temperatures have shown great potential for the separation of CO₂ in sorption enhanced reaction processes (SERPs) for hydrogen production, CH₄ + 2H₂O → CO₂ + 4H₂,^{8,9} where the *in situ* CO₂ removal shifts the equilibrium towards high-purity hydrogen production and increased hydrocarbon conversion. In the case of steam reforming processes (SESRs), continuous capture of CO₂ can dramatically enhance H₂ selectivity and avoid cooling processes.^{10,11} Therefore, solid sorbents can be applied in either pre-combustion or post-combustion CO₂ capture schemes. Ideally, these materials should exhibit high sorption capacities, good regeneration capabilities and long-term stability, together with a low price.

Among proposed high-temperature solid CO₂ sorbents,¹² alkali and alkaline-earth oxides containing lithium, sodium, potassium, calcium and/or magnesium have shown promising properties towards CO₂ capture. When reacting with CO₂, these sorbents usually exhibit a temperature-dependent behaviour in which CO₂ is first chemisorbed,

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producing an external shell composed of either Li_2CO_3 , Na_2CO_3 , K_2CO_3 , CaCO_3 or MgCO_3 . Once the temperature is high enough to activate diffusion processes, the reaction proceeds through the bulk of the particles.

Li-Based materials, such as Li_4SiO_4 , Li_2ZrO_3 , Li_5AlO_4 and Li_2CuO_2 , have been widely studied as CO_2 sorbents,¹³ displaying high sorption capacities within the temperature range of 400–700 °C.^{14–17} However, from a large-scale application perspective, low cost Na-based captors, such as Na_2TiO_3 , Na_2ZrO_3 , Na_2SiO_3 and Na_4SiO_4 , are more attractive.^{18–21} The lower cost is usually associated with the manufacture process since, as a general rule, lithium oxides are more expensive than their sodium counterparts. Given that Na-based sorbents, such as Na_2ZrO_3 , can reach CO_2 sorption capacities very close to those of Li-based systems,^{22,23} it is important to further explore their properties and capabilities towards CO_2 capture.

Na_2TiO_3 is a promising material for positive electrodes in Na-ion batteries^{24–26} and has also been proposed as a possible CO_2 sorbent.^{22,27} Interestingly, the thermogram displayed by Na_2TiO_3 when subjected to a CO_2 flow differs from those exhibited by other CO_2 sorbents. The Na_2TiO_3 thermogram shows two weight increments, which are then followed by sequential weight decrements. This experimental evidence questions the stability Na_2TiO_3 at high temperatures and its ability to trap CO_2 . In addition to this, *ex situ* XRD characterization of Na_2TiO_3 – CO_2 reaction products showed the formation of Na_2CO_3 , Na_2O , m- $\text{Na}_4\text{Ti}_5\text{O}_{12}$, h- $\text{Na}_4\text{Ti}_5\text{O}_{12}$ and $\text{Na}_{16}\text{Ti}_{10}\text{O}_{28}$ phases.²⁷ The observation of these chemical species, together with the absence of TiO_2 , is indicative of the partial reaction of Na_2TiO_3 with CO_2 , and also suggests a complex temperature-dependent reaction mechanism. Despite the great effort to understand the reaction pathway of Na_2TiO_3 – CO_2 at high temperatures,²⁷ the great likelihood of disproportionation of this material and its thermal instability makes standard characterization methods inaccurate. Instead, more sophisticated analysis tools that allow tracking in real time the structural changes occurring at high temperatures in the presence of CO_2 need to be employed in order to describe the reaction path and better understand the behavior of the system under operative conditions.

In this work, we present thermodynamic calculations and experimental data on the synthesis of Na_2TiO_3 *via* a solid-state route. Then, we show the benefits of using high temperature *in situ* synchrotron X-ray diffraction analysis to gain valuable insights on phase transformations that are difficult to detect by standard *ex situ* characterization techniques. *In situ* X-ray diffraction experiments revealed the occurrence of thermally driven structural changes of the material. These phase transformations could be differentiated from carbonation processes, allowing the proposal of a reaction mechanism of Na_2TiO_3 as a CO_2 sorbent. The influence of the surrounding atmosphere on the carbonation kinetics and reaction path of Na_2TiO_3 at high temperatures is discussed.

2 Experimental

2.1 Material synthesis

Sodium hydroxide (millimeter spheres of NaOH, Biopack, purity 98%) and titanium dioxide (nanopowder of TiO_2 , Sigma, purity 99%, anatase ≈ 75 wt% and rutile ≈ 25 wt%) were used as starting materials. The synthesis of $\beta\text{-Na}_2\text{TiO}_3$ was performed as follows. A mixture of NaOH– TiO_2 with a 2.1:1 molar ratio was handled in an Ar-filled glove box and introduced into a milling chamber. The powder mixture was then milled in a planetary ball mill (Fritsch Pulverisette P6) for 15 min in an Ar atmosphere. The selected milling conditions included a ball to powder ratio of 40:1 and 400 rpm. After milling, the powders were pressed and heated in air at 800 °C for 5 h.

2.2 Thermodynamic calculations

The equilibrium composition of the 2NaOH– TiO_2 mixture as a function of temperature was calculated by a Gibbs free energy minimization method using HSC software (6.1 version).²⁸ This method determines the equilibrium products at different temperatures and pressures for a heterogeneous system based on an extensive thermochemical database which contains enthalpy, entropy and heat capacity data of chemical compounds. The reaction system was specified in terms of the number of phases, species and the initial amount of reactants. The starting reaction system was composed of 2 kmol NaOH and 1 kmol TiO_2 (75% anatase and 25% rutile) in the solid phase, and air ($\text{N}_2 = 78$ kmol and $\text{O}_2 = 21$ kmol O_2) in the gas phase. The presence of $\text{H}_2\text{O}(\text{l},\text{g})$ was also contemplated. Several species were considered as possible in the solid phase: NaOH– H_2O ; Na_2O ; Na; NaH; Ti_3O_2 ; Ti_2O_3 ; Na_2O_2 ; Na_2TiO_3 (beta phase); $\text{Na}_2\text{Ti}_2\text{O}_5$; $\text{Na}_2\text{Ti}_3\text{O}_7$; $\text{Na}_2\text{Ti}_6\text{O}_{13}$. Some sodium titanates ($\text{Na}_4\text{Ti}_5\text{O}_{12}$, $\text{Na}_{16}\text{Ti}_{10}\text{O}_{28}$) previously reported were not included in the equilibrium composition calculations because of the lack of thermodynamic properties reported in the literature. Calculations were carried out in the temperature range of 0–800 °C and at 1 atm.

2.3 Characterization techniques

The structural and thermal properties of the samples were studied using X-ray powder diffraction (XRPD, Bruker D8 Advance) and simultaneous thermogravimetry and differential scanning calorimetry (TG-DSC, Linseis STA PT1600) coupled with mass spectroscopy (MS, ThermoStar Pfeiffer). *Ex situ* XRPD patterns were collected in the 2θ range of 10–80° with $\text{CuK}\alpha$ radiation, a voltage of 40 kV and an electric current of 40 mA. The thermal behaviour of the as-milled 2NaOH– TiO_2 mixture was measured with a heating rate of 5 °C min^{-1} from room temperature to 800 °C under a synthetic air flow (50 cm^3 min^{-1} STP). Dynamic CO_2 capture measurements were carried out with a thermogravimetric instrument (TG-HP50, TA Instruments). The as-synthesized $\beta\text{-Na}_2\text{TiO}_3$ was heated from room temperature to 800 °C at a



heating rate of 5 °C min⁻¹ using a CO₂ flow rate of 50 cm³ min⁻¹ (STP).

In situ synchrotron X-ray diffraction (XRD) measurements were performed at the beamline ID31 of the European Synchrotron Radiation Facility (ESRF). For this, β-Na₂TiO₃ samples were loaded into 1 mm outer diameter quartz capillaries and then subjected to different treatments: 1) dynamic heating under a N₂ gas flow up to a final temperature of 615 °C, and then switching the gas to CO₂ and maintaining isothermal conditions for 1 h; 2) heating under a N₂ gas flow up to 770 °C and then switching the gas to CO₂ and maintaining isothermal conditions for 1 h; 3) heating under a CO₂ gas flow up to 770 °C and maintaining isothermal conditions. In all cases, the heating ramp was 5 °C min⁻¹. A sketch of the experimental setup can be found elsewhere.²⁹ *In situ* synchrotron X-ray diffraction data were collected using a PerkinElmer detector, at a wavelength of 0.1771 Å and with a beamsize of 0.6 mm × 0.6 mm (*V* × *H*). Each frame was collected with an exposure time of 1 s. Data were processed using the pyFAI package.³⁰ The analysis of selected diffraction peaks representative of different crystallographic phases was performed by curve fitting with the Gaussian function, using Fityk software.³¹ Rietveld refinements were performed using GSAS II software.³²

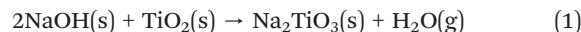
3 Results and discussion

3.1 Synthesis and CO₂ properties of the β-Na₂TiO₃ system

3.1.1 Study of the thermal behaviour of 2NaOH–TiO₂ mixtures. The equilibrium composition of the 2NaOH–TiO₂ system was estimated based on the Gibbs energy minimization method.²⁸ The thermodynamic calculations displayed in Fig. 1 predict the complete consumption of TiO₂ at 0 °C, simultaneous with the formation of β-Na₂TiO₃ and H₂O(l,g) as the main reaction products.

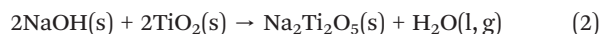
The hydration of NaOH to NaOH·H₂O at temperatures lower than 100 °C is promoted by the H₂O formation. A progressive temperature rise to 300 °C increases the amounts

of both β-Na₂TiO₃ and H₂O(g), reaching for each phase a maximum amount that remains constant for higher temperatures. From the previous interpretations, it is possible to infer that the formation of β-Na₂TiO₃ is favored thermodynamically by heating of the starting mixture in air. The expected reaction at room temperature can be expressed as:



where ΔG° (293 K) = -44.75 kJ mol⁻¹ which is thermodynamically favorable.

From the thermodynamic calculations, it is expected that the both formation of Na₂Ti₂O₅ and β-Na₂TiO₃ will occur simultaneously from 0 °C; however, the Na₂Ti₂O₅ amount decreases to a minimum value with the temperature rising to 200 °C. A possible formation reaction is:



As the temperature increases from 0 °C, Na₂Ti₂O₅ is the only titanium source to induce the production of an extra amount of β-Na₂TiO₃, consuming NaOH:



Reactions (2) and (3) are also thermodynamically favorable above 0 °C and 100 °C, respectively.

Previous thermodynamic analysis determined the on-going reactions in the absence of any restrictions caused by kinetics and/or transport phenomena and can serve as a benchmark to compare with the experimental results. In order to evaluate the reactivity of the 2NaOH–TiO₂ mixture for the synthesis of β-Na₂TiO₃, TG-DSC measurements were combined with MS analysis (Fig. 2). The TG curve of the as-milled 2NaOH–TiO₂ powder shows a sharp weight loss of 13% between 50 and 200 °C, which correlates with an endothermic peak in the DSC curve. According to MS analysis, this sharp weight loss can be

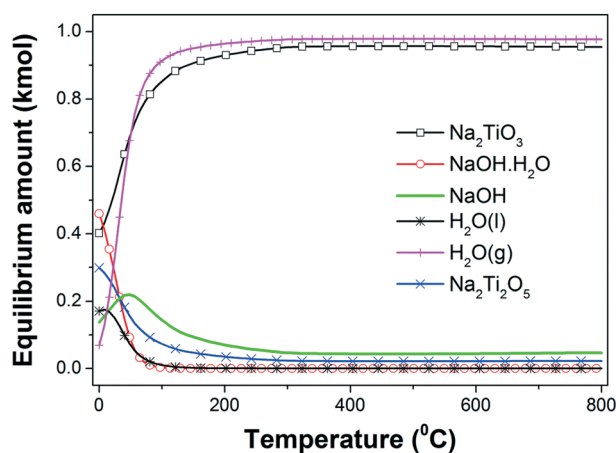


Fig. 1 Equilibrium amount (kmol) of different species in the 2NaOH–TiO₂ system as a function of temperature at 1 atm.

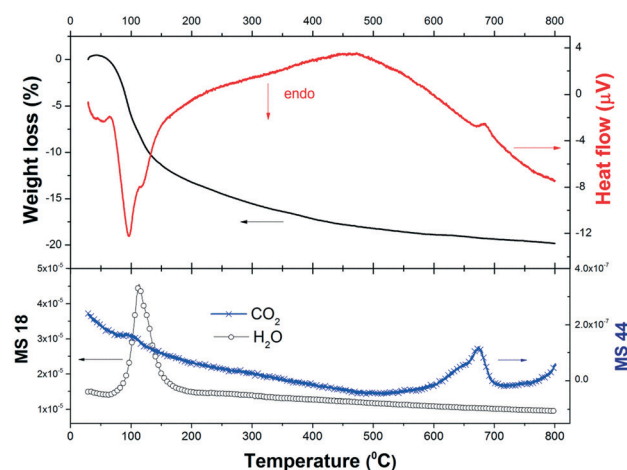


Fig. 2 Weight loss (in%), heat flow (µV) and gas evolved (H₂O and CO₂) during heating of as-milled 2NaOH–TiO₂ in synthetic air.



ascribed mainly to water evolution due to the formation of $\text{Na}_2\text{-TiO}_3$ (reaction (1), theoretical value of 11.3%) and also attributable to dehydration from pre-adsorbed water on NaOH. As the temperature increases up to 800 °C, the weight loss progresses to 20% and MS analysis evidences gradual water and CO_2 evolution. In the DSC curve, no melting of pure NaOH or melting of the NaOH- Na_2CO_3 eutectic mixture³³ was observed. These events are expected at about 320 °C and 282 °C, respectively. Their absence indicates that NaOH was completely consumed at temperatures lower than 282 °C and/or NaOH partially reacted with CO_2 present in the air during handling, forming Na_2CO_3 .³⁴ CO_2 detection by MS reveals CO_2 release, evidenced by the occurrence of: a small bump at 100 °C, a gradual decline observed in the curve starting from low temperatures, and a peak between 600 and 700 °C. These events indicate that slight CO_2 adsorption occurred prior to the thermal analysis run. Additionally, an exothermic peak at 685 °C was identified and is analyzed in the following paragraph.

The *ex situ* XRPD patterns of the products obtained at different reaction temperatures are displayed in Fig. 3. As reference, the XRPD patterns of nano- TiO_2 and as-milled 2NaOH-TiO_2 powders are also included (Fig. 3a and b). After milling, the anatase and rutile phases of TiO_2 remain, while Na_2CO_3 is formed due to carbonation of NaOH during the XRD measurement in air (Fig. 3b). Thus, milling processes promote a high degree of mixing of the starting reactants, independent of the starting size of the powders. Heating at 650 °C induces the formation of $\alpha\text{-Na}_2\text{TiO}_3$ (Fig. 3c) simultaneous with minor CO_2 release, as inferred from the TG curve. The most intense diffraction peaks of Na_2CO_3 are still detected, with very low intensity. At 800 °C, the main phase obtained is $\beta\text{-Na}_2\text{TiO}_3$ with $\text{Na}_{16}\text{Ti}_{10}\text{O}_{28}$ (Fig. 3d). Prolonged heating at 800 °C favors the complete crystallization of $\beta\text{-Na}_2\text{TiO}_3$ (Fig. 3e). From the XRD and TG-DSC results, it can be speculated that at 685 °C, transformation between α - and

$\beta\text{-Na}_2\text{TiO}_3$ occurred during heating, in agreement with previous studies using fine rutile- TiO_2 .³⁴

Some correlations can be made by comparison of the TG-DSC-MS results, XRPD studies and thermodynamic calculations. TG-DSC-MS measurements show the high reactivity between NaOH and TiO_2 at temperatures lower than 200 °C, with H_2O evolution due to reaction (1) and, as a consequence, NaOH dehydration. This reaction continues as the temperature increases, showing progressive H_2O release. Similar predictions were obtained from the thermodynamic calculations up to 200 °C. However, equilibrium calculations anticipate that the reaction between NaOH and TiO_2 is almost completed at 300 °C, with the difference from experimental results being ascribed to kinetic factors. The tests show the formation of metastable $\alpha\text{-Na}_2\text{TiO}_3$ at 650 °C, which transforms to $\beta\text{-Na}_2\text{TiO}_3$ upon heating. The phase transformation towards the formation of $\beta\text{-Na}_2\text{TiO}_3$ progresses during the temperature ramp up to 800 °C, however upon reaching this temperature the reaction is still incomplete and requires additional time at this temperature to achieve completion. Although $\alpha\text{-Na}_2\text{TiO}_3$ and $\text{Na}_{16}\text{Ti}_{10}\text{O}_{28}$ were identified at different temperatures, their formation could not be derived from thermodynamic calculations due to the lack of thermochemical data. Heating for 5 h produces $\beta\text{-Na}_2\text{TiO}_3$ as a single phase. Therefore, nano- TiO_2 reacts with NaOH at the beginning of heating, producing water, forming $\alpha\text{-Na}_2\text{TiO}_3$ as an intermediate phase and finally producing $\beta\text{-Na}_2\text{TiO}_3$ at 800 °C after prolonged heating.

3.1.2 Thermogravimetric characterization of the reaction of $\beta\text{-Na}_2\text{TiO}_3$ with CO_2 . To study the CO_2 sorption behaviour of as-synthesized $\beta\text{-Na}_2\text{TiO}_3$, dynamic CO_2 measurements were performed. The results displayed in Fig. 4 show a continuous CO_2 capture up to 3.5 wt% from room temperature to 400 °C, followed by a progressive weight loss of 1.5 wt% until 600 °C. After that, a sharp CO_2 absorption peak was registered from 620 °C to 800 °C, with 8.0 wt% CO_2 captured.

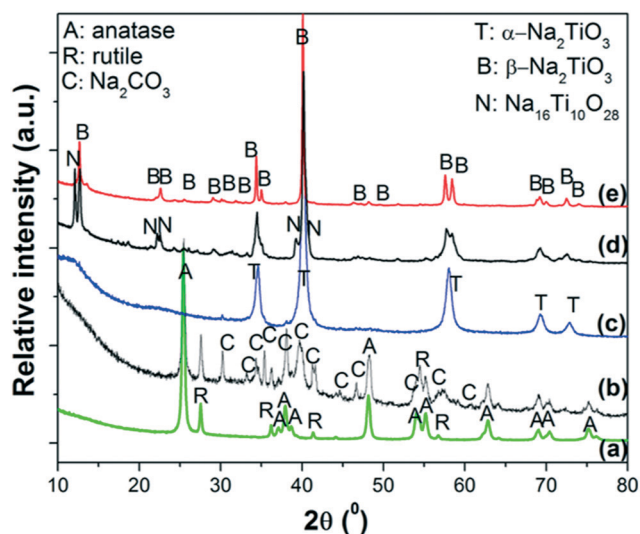


Fig. 3 XRPD patterns of: a) starting powders of nano- TiO_2 ; b) as-milled 2NaOH-TiO_2 mixture; heating up to c) 650 °C, d) 800 °C and e) 800 °C, 5 h. Heating ramp: 5 °C min^{-1} in synthetic air.

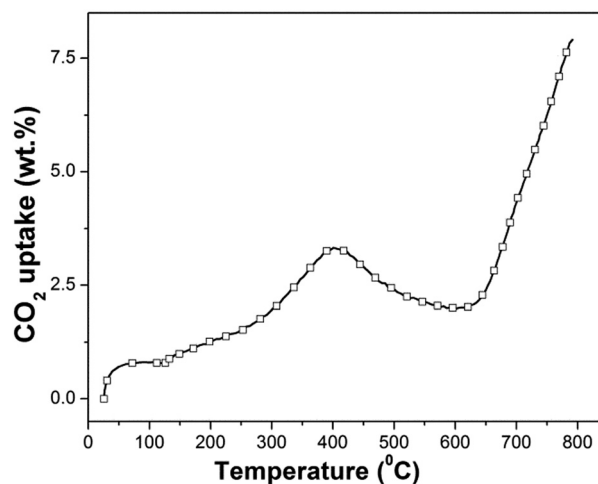


Fig. 4 Dynamic thermogravimetric analysis of synthesized $\beta\text{-Na}_2\text{TiO}_3$. Heating ramp: 5 °C min^{-1} ; 50 $\text{cm}^3 \text{min}^{-1}$ STP of CO_2 .



The dynamic thermogram showing a weight increment followed by a weight decrement, and a subsequent weight increment, is not in line with previous results reported for other CO₂ sorbents, which typically exhibit two consecutive weight increments as a function of increasing temperature (the first one is associated with CO₂ chemisorption and the second one is associated with CO₂ absorption). However, our results show similarities to the only non-isothermal previous study on Na₂TiO₃,²⁷ although there are differences in the temperature ranges where the CO₂ capture and weight loss were observed. In the above-mentioned report, the authors attribute the abnormal dynamic thermogram of Na₂TiO₃ to a different temperature-dependent CO₂ capture reaction mechanism, and to the poor thermal stability of the ceramic.

3.2 *In situ* synchrotron X-ray diffraction analysis

Three *in situ* XRD experiments were carried out with the aim of understanding: 1) the reaction mechanism of Na₂TiO₃ during high temperature carbonation, and 2) the effect of the initial atmosphere on the reaction path and kinetics.

The experiments involved dynamic heating under either a N₂ or CO₂ flow followed by isothermal conditions at selected temperatures under a CO₂ gas flow. The proposed measurements allowed distinguishing structural changes derived from the reaction of Na₂TiO₃ with CO₂ from thermally driven changes that may occur due to the instability of the material. Furthermore, the preheating of the samples under a N₂ flow allowed mimicking the procedure commonly used to characterize carbonation reaction products by *ex situ* methods. In this procedure, samples are first heated to a selected temperature under an inert gas atmosphere and then exposed to CO₂ for 1 or 2 hours. Therefore, the obtained results also will serve to visualize the limitations that these procedures might present for obtaining

an accurate description of high temperature carbonation reactions. This is essential to relate chemical processes to dynamic TG CO₂ sorption curves.

3.2.1 Na₂TiO₃ heated under N₂ followed by isothermal heating at 615 °C under CO₂. Na₂TiO₃ was subjected to continuous heating at a ramp of 5 °C min⁻¹ under an inert gas flow up to 615 °C. Once this temperature was reached, the gas was switched to CO₂ and the sample was kept under isothermal conditions for 1 h. Fig. 5a displays the evolution of the X-ray diffraction patterns upon heating, and Fig. 5b shows the corresponding phase composition and temperature evolution. Interestingly, it is possible to notice that at 40 °C (initial temperature of the experiment), β-Na₂TiO₃ already has suffered a partial transition and the resulting material is a mixture of β-Na₂TiO₃, a secondary phase and a very small fraction of Na₂CO₃ that could be formed due to CO₂ chemisorption derived from air exposure. It is important to remark that the initial composition of the system is different from the one observed right after the synthesis process. The secondary phase was indexed using DICVOL06 (ref. 35) and the results showed good agreement with a monoclinic lattice having the following parameters: *a* = 6.6651 Å, *b* = 4.6488 Å, *c* = 3.4209 Å and β = 110.1°. This phase is indicated within the figures as m-Na₂TiO₃, and to the best of our knowledge, it has not been previously reported. The presence of the β-Na₂TiO₃ phase accompanying the monoclinic one hinders any attempt to determine other structural parameters of this phase, such as atomic positions. The monoclinic phase reverts to β-Na₂TiO₃ after reaching 300 °C, as can be seen in the patterns presented in Fig. 5a, where the characteristic reflections of the monoclinic phase, such as the peak at 2θ = 5.22°, disappear. Simultaneously, the small percentage of Na₂CO₃ also decreases, indicating the release of CO₂. This is accompanied by the subtle appearance of reflections corresponding to the Na₂O phase. According to

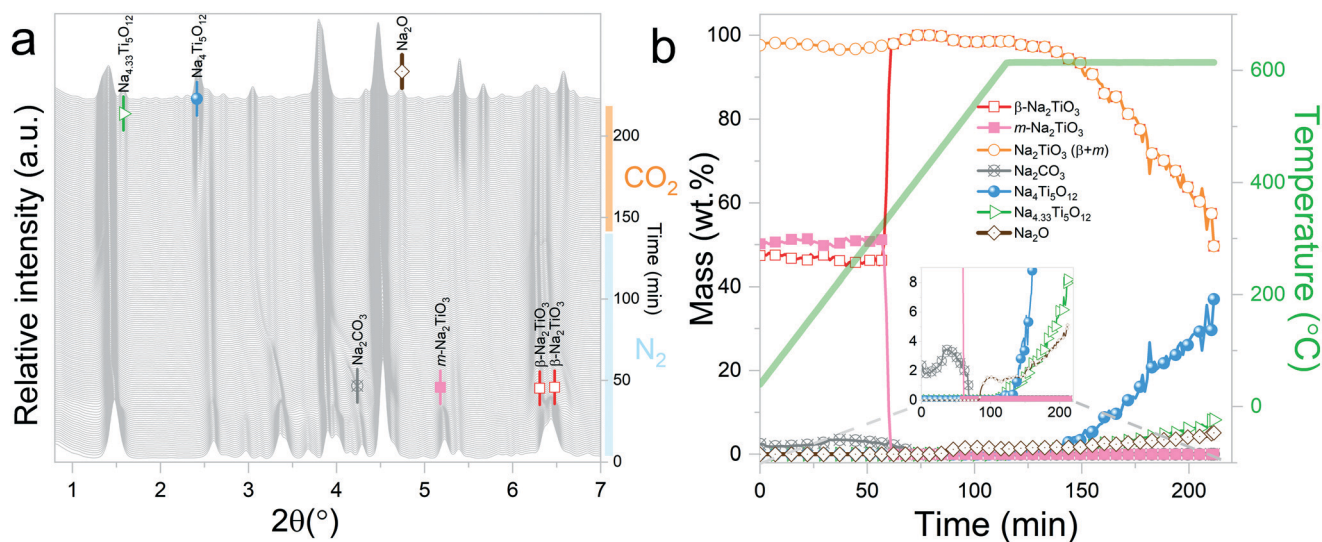
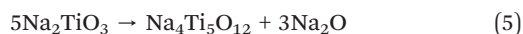
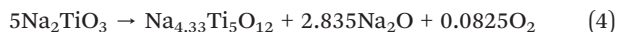


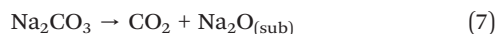
Fig. 5 Na₂TiO₃ heating under a N₂ flow until 615 °C, followed by isothermal conditions under a CO₂ gas flow: a) evolution of X-ray diffraction patterns upon heating; b) phase evolution (wt%) as a function of time and temperature.



Sánchez-Camacho *et al.*,²⁷ these results can be explained by CO₂ chemisorption followed by CO₂ release, caused by the heating, which would lead to the formation of an external shell of Na₂O. From the figure, it can be noticed that β-Na₂TiO₃ remains stable up to 600 °C under an inert atmosphere. Once the gas flow is switched to CO₂, β-Na₂TiO₃ undergoes partial decomposition into Na_{4.33}Ti₅O₁₂ (01-084-8819 PDF file) and Na₄Ti₅O₁₂ (00-052-1814 PDF file). The disproportionation follows reactions (4) and (5), respectively.

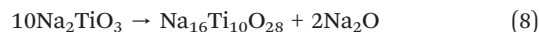


Sánchez-Camacho *et al.*²⁷ propose reaction (6) as an intermediary step for reaction (5), suggesting that Na₂CO₃ is not observed because it immediately decomposes following reaction (7).

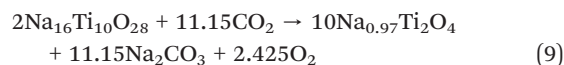


3.2.2 Na₂TiO₃ heated under N₂ followed by isothermal heating at 770 °C under CO₂. Na₂TiO₃ was heated to 770 °C at a ramp of 5 °C min⁻¹ under an inert gas flow. At 770 °C, the gas was switched to CO₂ and the sample was kept under isothermal conditions for 1 h. The initial diffractograms for this measurement (Fig. 6a) display a similar phase mixture to the previous one (Fig. 6b) with a difference in composition of 2%, which is well within the margin of error. As expected, the sample follows the same path as the previous one until around 630 °C. At this temperature, β-Na₂TiO₃ decomposes showing the appearance of a new phase, which is similar to the Na₁₆Ti₁₀O₂₈ structure previously reported by Mayer and Perez³⁶ (01-076-0686 PDF file). This phase was also observed

by Sánchez-Camacho *et al.*²⁷ However, the intensity ratios between some reflections do not match the expected values. This could be an indication of an isostructural phase with a slightly different composition. Unfortunately, the presence of secondary phases makes it difficult to determine the exact difference in the stoichiometry. A proposed reaction mechanism is presented in eqn (8).



Interestingly, it should be noticed that in the previously mentioned work, the proposed reaction pathway considers β-Na₂TiO₃ carbonation as an intermediary step for reaction (8). However, our results show that reaction (8) occurs even in the absence of CO₂. The results from these measurements also confirm the proposition of Sánchez-Camacho²⁷ regarding eqn (6) being a required intermediary step for reaction (5), since this decomposition to Na₄Ti₅O₁₂ is not observed under a N₂ flow. Peaks belonging to Na₂O can also be observed up to 770 °C, the temperature at which the sample atmosphere is changed to CO₂. At this stage, new reflections emerge, indicating the formation of an additional phase. The new peaks were indexed to the Na_{0.97}Ti₂O₄ phase (04-014-7035 PDF file). Since this transition only occurs in the presence of a CO₂ gas flow, it is possible to assume that Na₂CO₃ plays a role as an intermediate product of this decomposition. A possible reaction path is presented in eqn (9).



3.2.3 Na₂TiO₃ heated under CO₂ followed by isothermal heating at 770 °C. β-Na₂TiO₃ was heated at a ramp of 5 °C min⁻¹ under a CO₂ gas flow, until reaching a temperature of 770 °C. Once this temperature was reached, the sample was

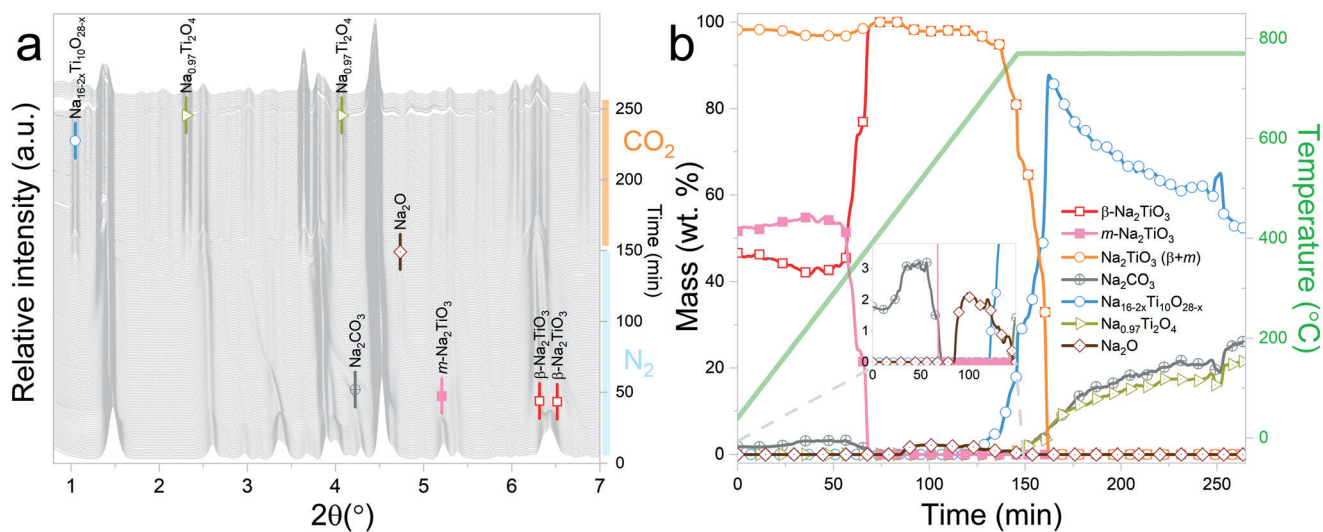


Fig. 6 Na₂TiO₃ heating under a N₂ flow until 770 °C, followed by isothermal conditions under a CO₂ gas flow: a) evolution of X-ray diffraction patterns upon heating; b) phase evolution (wt%) as a function of time and temperature.



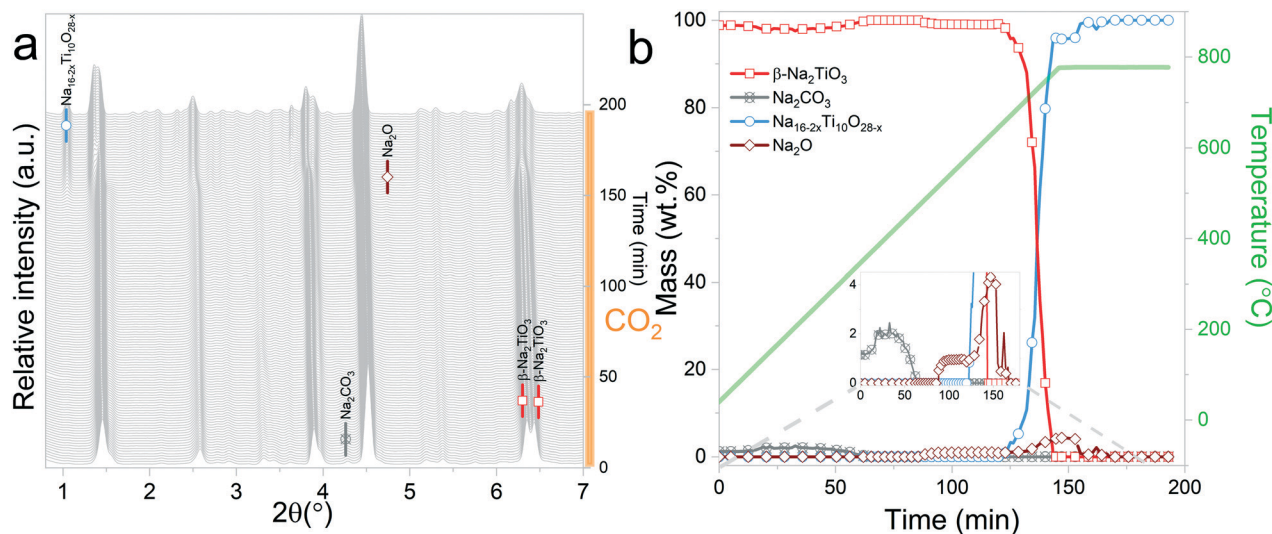
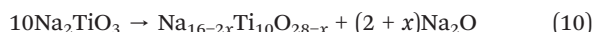


Fig. 7 Na_2TiO_3 heating under a CO_2 gas flow, followed by isothermal conditions at 770°C : a) evolution of X-ray diffraction patterns during heating; b) phase evolution (wt%) as a function of time and temperature.

kept under isothermal conditions. As it can be observed from Fig. 7a and b, the phase composition of the starting material differs from the ones observed in the previous measurements, in which the heating process was performed under an inert gas flow. In this case, the sample exhibits almost pure $\beta\text{-Na}_2\text{TiO}_3$. Although the reason for this is not clear, it could be speculated that the presence of CO_2 inhibits the growth of the monoclinic phase.

At the initial stages of heating, the XRD patterns display an almost negligible amount of Na_2CO_3 , which is evidenced by the presence of the two main peaks corresponding to this phase at $2\theta = 3.989^\circ$ (overlapping with a secondary peak of Na_2TiO_3) and $2\theta = 4.289^\circ$. During the first stage of the heating process, a slight increment in the amount of

carbonate can be observed, but after reaching 300°C , it starts to diminish. At 350°C , no trace of Na_2CO_3 can be detected. Between 350°C and 660°C , $\beta\text{-Na}_2\text{TiO}_3$ is the only phase remaining. This is consistent with the TG results shown in Fig. 4, and also with previously reported curves,²⁷ in which the absorption of CO_2 into similar samples is only observed at temperatures starting from 675°C . At this temperature, a phase change occurs, evidenced by the subtle appearance of new peaks. Some of these new peaks match the ones observed in the previous measurement, indicating the presence of a $\text{Na}_{16}\text{Ti}_{10}\text{O}_{28-x}$ -like structure. In this case, due to the higher abundance of this phase, it was possible to perform a deeper analysis of the XRD data. A refinement of the final diffractogram (Fig. 8) showed a higher number of sodium and oxygen vacancies compared to the one observed by Sánchez-Camacho *et al.*,²⁷ indicating a composition more in line with a $\text{Na}_{16-2x}\text{Ti}_{10}\text{O}_{28-x}$ formula, with x in the range 0.1–0.25. This leads to a slightly modified eqn (8) as follows:



By observing Fig. 7, it is clear that a second reaction resulting in the formation of $\text{Na}_{0.97}\text{Ti}_2\text{O}_4$ does not occur. This is difficult to understand since at this stage, the temperature and gas flow conditions are comparable to those in the previous experiment. A possible explanation is that the CO_2 gas flow generates a change in the morphology of Na_2TiO_3 by preventing the first transition towards the monoclinic phase. These changes then are transferred to $\text{Na}_{16-2x}\text{Ti}_{10}\text{O}_{28-x}$, inhibiting the further decomposition of the titanate. As it can be observed from Fig. 5, reaction (9) is very slow, so it may be possible that an unfavorable particle morphology, such as larger crystallite sizes³³ or larger diffusion paths, could make this reaction impossible to see in the time frame of the experiment. A closer inspection toward the last XRD pattern

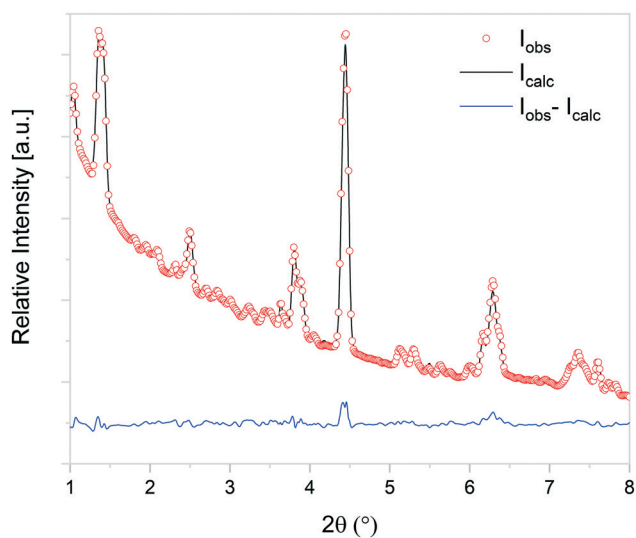


Fig. 8 Observed (open circles) and calculated (line) X-ray diffraction patterns of $\text{Na}_{16-2x}\text{Ti}_{10}\text{O}_{28-x}$, with x in the range 0.1–0.25.



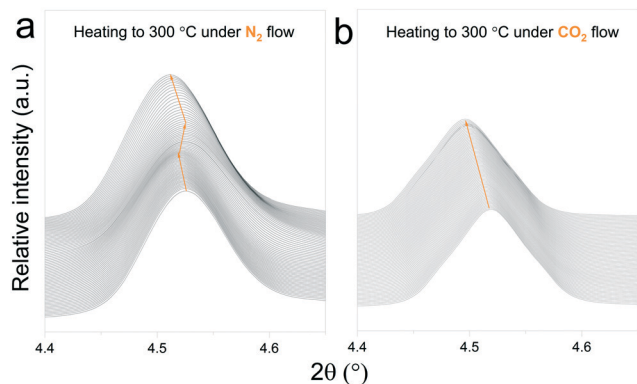


Fig. 9 Structural changes of Na_2TiO_3 under dynamic heating at a ramp of $5\text{ }^\circ\text{C min}^{-1}$ under a N_2 flow (a) and CO_2 flow (b).

from these measurements showed a faint hint of the characteristic peak of $\text{Na}_{0.97}\text{Ti}_2\text{O}_4$ at $2\theta = 1.9^\circ$. This different morphology could also be an explanation about why the decomposition into $\text{Na}_4\text{Ti}_5\text{O}_{12}$ and $\text{Na}_{4.33}\text{Ti}_5\text{O}_{12}$ is not observed here, since those two reactions are much slower than the decomposition to $\text{Na}_{16-2x}\text{Ti}_{10}\text{O}_{28-x}$, as can be seen by comparing Fig. 5b and 6b.

3.3 Effect of the initial atmosphere on the $\text{Na}_2\text{TiO}_3\text{-CO}_2$ reaction pathway

In situ X-ray diffraction analysis for real-time monitoring of chemical reactions on CO_2 capture materials^{15,37-40} has been proven to be a useful tool to understand the behaviour of CO_2 sorbents at temperatures that are relevant for real applications, allowing the identification of structural changes, to reveal intermediate phases and re-conversion processes occurring during operational conditions^{29,41} and to investigate the impact of the presence of H_2O in the gas stream.⁴² However, due to the limited access to powerful X-ray probes, many reports have proposed carbonation mechanisms of these materials based on *ex situ* X-ray diffraction data.^{27,43} Typically, *ex situ* samples are obtained after heating different samples under an inert atmosphere, switching the gas flow to CO_2 once the desired temperature is reached and then maintaining isothermal conditions for a couple of hours. The results obtained by these procedures can provide valuable insights into the reaction mechanism of CO_2 sorbents. However, the results presented in this work indicate that thermal preheating under an inert atmosphere can severely affect the structure of the sorbent prior to its exposure to CO_2 . In Fig. 9ab and , a selected 2θ region in which Na_2TiO_3 is heated under a N_2 and CO_2 gas flow, respectively, is displayed. From Fig. 9a, it can be observed that there is a transition from monoclinic Na_2TiO_3 to $\beta\text{-Na}_2\text{TiO}_3$ when the sample is subjected to a N_2 flow. As shown in the previous subsection, these structural changes can influence the further dynamic evolution of the material by either slowing or speeding up the next reaction steps. Although these transitions are difficult to observe with

traditional methods, they are critical to explain the dynamic CO_2 capture thermograms. This further emphasizes the need for *in situ* tools to obtain an accurate description of the CO_2 capture performance of sorbent materials.

4 Conclusions

Na_2TiO_3 was successfully synthesized from NaOH and TiO_2 via a solid state route, where the powder mixture was heat treated at $800\text{ }^\circ\text{C}$ for 5 h. The CO_2 sorption properties of synthesized Na_2TiO_3 were analyzed by dynamic thermogravimetric analysis.

In situ synchrotron XRD analysis, performed to study the reaction mechanism of Na_2TiO_3 at high temperatures in the presence of CO_2 , revealed the complex behaviour of the Na-Ti-O system. With the aim of differentiating phase transformations driven by carbonation processes from those occurring as a consequence of the thermal stability of the ceramic, the high temperature behavior of Na_2TiO_3 under different gas flows was studied. A careful analysis of Na_2TiO_3 phase transitions showed that its structure can be strongly influenced by the surrounding atmosphere.

At $40\text{ }^\circ\text{C}$, samples subjected to a N_2 flow show the presence of $\beta\text{-Na}_2\text{TiO}_3$ and monoclinic Na_2TiO_3 phases, while the sample subjected to a CO_2 flow showed no evidence of the latter. This difference in composition disappears upon heating, when the monoclinic phase reverts to $\beta\text{-Na}_2\text{TiO}_3$. Further heating at temperatures above $650\text{ }^\circ\text{C}$ causes $\beta\text{-Na}_2\text{TiO}_3$ to transition to $\text{Na}_{16-2x}\text{Ti}_{10}\text{O}_{28-x}$. This transition occurs under either a pure N_2 or CO_2 gas flow. However, at this point, while the samples have reached a similar situation in terms of phase composition and environmental conditions, the previous history of the sample seems to play a role in the kinetic behaviour of the system. In both cases, when subjected to a CO_2 flow, $\text{Na}_{16-2x}\text{Ti}_{10}\text{O}_{28-x}$ undergoes a carbonation process. However, although both samples showed similar reaction paths, considerable differences in the reaction kinetics between both have been observed. The retardation effect observed for the sample preheated under CO_2 is evident in the results, and it can be attributed to morphological differences related to the lack of transition from the monoclinic phase, which could influence the diffusion processes required for the carbonation of $\text{Na}_{16-2x}\text{Ti}_{10}\text{O}_{28-x}$.

The differences found when subjecting Na_2TiO_3 to different atmospheres upon heating demonstrate that *in situ* XRD characterization is essential to monitor in real time the structural changes that occur to the system and to correlate them to dynamic TG observations, providing a much reliable insight on the chemical processes that take place during sorption reactions.

Conflicts of interest

“There are no conflicts to declare”.



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Notes and references

- O. US EPA, *Global Non-CO2 GHG Emissions: 1990–2030*, 2016, <https://www.epa.gov/global-mitigation-non-co2-greenhouse-gases/global-non-co2-ghg-emissions-1990-2030>.
- A. Alonso, J. Moral-Vico, A. Abo Markeb, M. Busquets-Fité, D. Komilis, V. Puentes, A. Sánchez and X. Font, *Sci. Total Environ.*, 2017, **595**, 51–62.
- Q. Wang, J. Luo, Z. Zhong and A. Borgna, *Energy Environ. Sci.*, 2011, **4**, 42–55.
- A. Samanta, A. Zhao, G. K. H. Shimizu, P. Sarkar and R. Gupta, *Ind. Eng. Chem. Res.*, 2012, **51**, 1438–1463.
- J. Wang, L. Huang, R. Yang, Z. Zhang, J. Wu, Y. Gao, Q. Wang, D. O'Hare and Z. Zhong, *Energy Environ. Sci.*, 2014, **7**, 3478–3518.
- M. G. Plaza, S. Martínez and F. Rubiera, *Energies*, 2020, **13**, 5692.
- T. O. Nelson, A. Kataria, P. Mobley, M. Soukri and J. Tanthana, *Energy Procedia*, 2017, **114**, 2506–2524.
- E. R. van Selow, P. D. Cobden, P. A. Verbraeken, J. R. Hufton and R. W. van den Brink, *Ind. Eng. Chem. Res.*, 2009, **48**, 4184–4193.
- P. Pecharaumporn, S. Wongsakulphasatch, T. Glinrun, A. Maneedaeng, Z. Hassan and S. Assabumrungrat, *Int. J. Hydrogen Energy*, 2019, **44**, 20663–20677.
- B. Dou, C. Wang, Y. Song, H. Chen, B. Jiang, M. Yang and Y. Xu, *Renewable Sustainable Energy Rev.*, 2016, **53**, 536–546.
- C. S. Martavaltzi, E. P. Pampaka, E. S. Korkakaki and A. A. Lemonidou, *Energy Fuels*, 2010, **24**, 2589–2595.
- D. M. D'Alessandro, B. Smit and J. R. Long, *Angew. Chem., Int. Ed.*, 2010, **49**, 6058–6082.
- Y. Zhang, Y. Gao, H. Pfeiffer, B. Louis, L. Sun, D. O'Hare and Q. Wang, *J. Mater. Chem. A*, 2019, **7**, 7962–8005.
- Y. Hu, W. Liu, Y. Yang, M. Qu and H. Li, *Chem. Eng. J.*, 2019, **359**, 604–625.
- M. L. Grasso, M. V. Blanco, F. Cova, J. A. González, P. A. Larochette and F. C. Gennari, *Phys. Chem. Chem. Phys.*, 2018, **20**, 26570–26579.
- C. Wang, B. Dou, Y. Song, H. Chen, Y. Xu and B. Xie, *Ind. Eng. Chem. Res.*, 2014, **53**, 12744–12752.
- T. Ávalos Rendón, J. Casa-Madrid and H. Pfeiffer, *J. Phys. Chem. A*, 2009, **113**, 6919–6923.
- Q. Zheng, L. Huang, Z. Zhong, B. Louis and Q. Wang, *Chem. Eng. J.*, 2020, **380**, 122444.
- G. Ji, M. Z. Memon, H. Zhuo and M. Zhao, *Chem. Eng. J.*, 2017, **313**, 646–654.
- R. Rodríguez-Mosqueda and H. Pfeiffer, *J. Phys. Chem. C*, 2013, **117**, 13452–13461.
- J. Liu, Z. Wang, Z. Wang, J. Song, G. Li, Q. Xu, J. You, H. Cheng and X. Lu, *Phys. Chem. Chem. Phys.*, 2019, **21**, 13135–13143.
- A. López-Ortiz, N. G. P. Rivera, A. R. Rojas and D. L. Gutierrez, *Sep. Sci. Technol.*, 2005, **39**, 3559–3572.
- G. Ji, H. Yang, M. Z. Memon, Y. Gao, B. Qu, W. Fu, G. Olguin, M. Zhao and A. Li, *Appl. Energy*, 2020, **267**, 114874.
- S. Song, M. Kotobuki, Y. Chen, S. Manzhos, C. Xu, N. Hu and L. Lu, *Sci. Rep.*, 2017, **7**, 373.
- T. Kobayashi, W. Zhao, H. B. Rajendra, K. Yamanaka, T. Ohta and N. Yabuuchi, *Small*, 2020, **16**, 1902462.
- Q. Liu, Z. Hu, W. Li, C. Zou, H. Jin, S. Wang, S. Chou and S.-X. Dou, *Energy Environ. Sci.*, 2021, **14**, 158–179.
- P. Sánchez-Camacho, I. C. Romero-Ibarra, Y. Duan and H. Pfeiffer, *J. Phys. Chem. C*, 2014, **118**, 19822–19832.
- H. Outokumpu, *HSC Chemistry For Windows Version 6.1*, 2009.
- F. Cova, G. Amica, K. Kohopää and M. V. Blanco, *Inorg. Chem.*, 2019, **58**, 1040–1047.
- J. Kieffer and D. Karkoulis, *J. Phys.: Conf. Ser.*, 2013, **425**, 202012.
- M. Wojdyr, *J. Appl. Crystallogr.*, 2010, **43**, 1126–1128.
- B. H. Toby and R. B. Von Dreele, *J. Appl. Crystallogr.*, 2013, **46**, 544–549.
- F. Meng, Y. Liu, T. Xue, Q. Su, W. Wang and T. Qi, *RSC Adv.*, 2016, **6**, 112625–112633.
- M. L. Grasso, P. Arneodo Larochette and F. C. Gennari, *J. CO2 Util.*, 2020, **38**, 232–240.
- A. Boultif and D. Louër, *J. Appl. Crystallogr.*, 2004, **37**, 724–731.
- M. Mayer and G. Perez, *Rev. Chim. Miner.*, 1976, **13**, 237–242.
- R. Molinder, T. P. Comyn, N. Hondow, J. E. Parker and V. Dupont, *Energy Environ. Sci.*, 2012, **5**, 8958–8969.
- M. T. Dunstan, S. A. Maugeri, W. Liu, M. G. Tucker, O. O. Taiwo, B. Gonzalez, P. K. Allan, M. W. Gaultois, P. R. Shearing, D. A. Keen, A. E. Phillips, M. T. Dove, S. A. Scott, J. S. Dennis and C. P. Grey, *Faraday Discuss.*, 2016, **192**, 217–240.
- A. Biasin, C. U. Segre and M. Strumendo, *Cryst. Growth Des.*, 2015, **15**, 5188–5201.
- J. Manuel Valverde, A. Perejon, S. Medina and L. A. Perez-Maqueda, *Phys. Chem. Chem. Phys.*, 2015, **17**, 30162–30176.
- M. V. Blanco, K. Kohopää, I. Snigireva and F. Cova, *Chem. Eng. J.*, 2018, **354**, 370–377.
- J. M. Valverde and S. Medina, *Phys. Chem. Chem. Phys.*, 2017, **19**, 7587–7596.
- F. Durán-Muñoz, I. C. Romero-Ibarra and H. Pfeiffer, *J. Mater. Chem. A*, 2013, **1**, 3919–3925.

