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## Impact of $\text{NH}_4\text{OH}$ treatment on the ion-exchange and pore characteristics of metakaolin-based geopolymer

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This paper investigates the viability and influence of  $\text{NH}_4\text{OH}$  post-synthetic treatment on the pore characteristics of geopolymers. Geopolymers are a class of materials with amorphous aluminosilicate three-dimensional frameworks, regarded as amorphous analogues of zeolites. Similar to zeolites, when geopolymers are used in catalysis or adsorption applications, post-synthetic treatments such as ion-exchange with  $\text{NH}_4^+$  salts (e.g.,  $\text{NH}_4\text{Cl}$ ,  $\text{NH}_4\text{NO}_3$ ) and desilication (using strong bases such as  $\text{NaOH}$ ) are necessary to introduce active sites and modify their pore structure, respectively. Recently, it has been shown that treatment with  $\text{NH}_4\text{OH}$  combines these two steps, in which it introduces acidic sites and modifies the pore structures of zeolites simultaneously. Considering the increasing interests of geopolymers in catalysis and adsorption applications, understanding the impact of such treatment on the structure of geopolymers is needed. Our diffuse reflectance infrared fourier-transforms spectra show the  $\text{NH}_4^+$  exchange  $\text{Na}^+$  in geopolymer and both laser diffraction with scanning electron microscopy images show that the particle size of powdered geopolymer decreases after  $\text{NH}_4\text{OH}$  treatment.  $\text{N}_2$  sorption isotherms,  $^{129}\text{Xe}$  and  $^1\text{H}$  NMR measurements reveal information about the changes in interparticle pore structures: micropores enlarge to mesopores and inborn mesopores increase in diameter, thereby reducing the surface area to volume ratio. However, the pore accessibility and pore connectivity are not altered by  $\text{NH}_4\text{OH}$  treatment. Since solid-state NMR and X-ray fluorescence revealed the desilication, these changes in particles size and pore characteristics are considered to be due to desilication caused by  $\text{NH}_4\text{OH}$  treatment.

### 1. Introduction

Geopolymers are a class of amorphous aluminosilicate inorganic polymers synthesized by alkali-activation of aluminosilicate precursors (e.g., natural clays or low-Ca slags).<sup>1</sup> They could be described as the amorphous analogues of zeolites because of their disordered three-dimensional frameworks.<sup>2</sup> Compared with synthetic zeolites, geopolymers are cheaper and more easily synthesized at low temperatures (< 100 °C).<sup>3</sup> In our recent works, we showed that the pore structures of geopolymers include inborn and interconnected micro- and mesopores.<sup>4,5</sup> Geopolymers have shown good performance as catalysts and adsorbents in some processes, such as  $\text{NO}_x$  reduction,<sup>6</sup> oxidation of volatile organic compounds (VOCs)<sup>7</sup> and water purification.<sup>8,9</sup>

For catalysis applications, acidic sites within geopolymer framework have been generated by ion-exchange of the charge-balancing alkali cations (i.e.,  $\text{Na}^+$  or  $\text{K}^+$ ) with  $\text{NH}_4^+$  followed by thermal treatment which releases gaseous  $\text{NH}_3$  forming  $\text{H}^+$ -geopolymer.<sup>10</sup> This is typically done by the treatment of a pre-formed geopolymer with a solution of ammonium salt (e.g.,  $\text{NH}_4\text{Cl}$ ,  $\text{NH}_4\text{NO}_3$ ). In addition, ion-exchange procedures have also been used to incorporate catalytically reactive metals or metal oxides (e.g., Ni, Fe, Ce, Co, Cu, Pt etc.) within the geopolymer framework.<sup>2</sup> Such cations have been shown to be more efficiently incorporated into  $\text{NH}_4^+$  contained geopolymer compared to originally synthesised  $\text{Na}^+/\text{K}^+$ -geopolymer.<sup>2,11,12</sup> In such applications, the pore characteristics (i.e., surface area and pore volume) of geopolymer catalysts are essential. This has been shown to be significantly improved by applying post-synthetic treatments such as dealumination (treatment with a weak acid) and desilication (treatment with a strong base).<sup>13</sup> Such post-synthetic treatments are routinely carried out on zeolite catalysts, in which they generate additional interconnected and accessible mesopores.<sup>14</sup> Similar procedures have been shown to be applicable on geopolymer catalysts.<sup>13</sup> The effect of such treatments on the geopolymer properties have been

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studied to some extent by diffuse reflectance infrared fourier-transforms (DRIFT) spectroscopy for monitoring the success of the  $\text{NH}_4^+$  ion-exchange,<sup>15</sup> and  $^{27}\text{Al}$  and  $^{29}\text{Si}$  magic angle spinning nuclear magnetic resonance (MAS NMR)<sup>16</sup> which provide information about structural changes caused by the treatment. However, more information about the impact of such treatments on modifying the chemical structure, particle morphology, and pore properties, importantly pore-connectivity, is still needed.

When probing the pore structures of geopolymers,  $\text{N}_2$  sorption is a widely used method to provide information about mesopores.<sup>17</sup> Previously,  $^{129}\text{Xe}$  and  $^1\text{H}$  NMR have been shown to be efficient methods to investigate the pore structures of geopolymers<sup>4,5</sup> as well as zeolites, silica gels and cementitious materials.<sup>18–21</sup> By introducing Xe and  $\text{H}_2\text{O}$  as probe fluids into pores, three of the most relevant porous characteristics, pore accessibility, pore connectivity and pore sizes, can be determined.  $^{129}\text{Xe}$  NMR spectra give information about the pore size and accessibility, as  $^{129}\text{Xe}$  chemical shift ( $\delta$ ) is inversely proportional to the pore size<sup>22</sup> and variable temperature  $^{129}\text{Xe}$  spectra enable the determination of the mesopore sizes.<sup>23</sup>  $^{129}\text{Xe}$  spin–spin relaxation time ( $T_2$ ), spin–lattice relaxation time ( $T_1$ ) and exchange rates of Xe gas between different pores ( $k$ )<sup>24</sup> reflect the pore connectivity.<sup>5</sup>  $^1\text{H}$   $T_1$  and  $T_2$  relaxation times of  $\text{H}_2\text{O}$  also reveal information about the pore structure, such as pore size, pore connectivity, and information about the pore surface characteristics.<sup>4,19</sup> Two-dimensional (2D) relaxation experiments, such as  $T_2$ – $T_2$ <sup>25</sup> and  $T_1$ – $T_2$ <sup>26,27</sup> experiments, provide higher resolution and more detailed exchange information than 1D measurements.<sup>4</sup> Pore size distributions can be measured by  $^1\text{H}$  NMR cryoporometry,<sup>28,29</sup> which relies on the fact that the melting point of water in a small pore is inversely proportional to the pore size. The amount of unfrozen water is detected as a function of temperature by  $^1\text{H}$  spin echo or Carr–Purcell–Meiboom–Gill (CPMG) experiments. The derivative of the signal intensity is converted to pore size distributions using the Gibbs–Thompson equation.<sup>30,31</sup>

In this work, we report, for the first time, the impact of mild  $\text{NH}_4\text{OH}$  treatment on the chemical and physical properties of geopolymers. We investigate the dual role of  $\text{NH}_4\text{OH}$ ; the ion-exchange of  $\text{Na}^+$  with  $\text{NH}_4^+$  simultaneously with modifying the pore structure of geopolymer by desilication (due to the basicity of  $\text{NH}_4\text{OH}$ ). The impact of  $\text{NH}_4\text{OH}$  treatment on zeolite catalysts have been reported,<sup>32</sup> but as far as we are aware it has not been reported on geopolymers previously. Modified geopolymer catalysts with post-synthetic treatments have been previously produced via multistep synthesis procedures involving initial  $\text{NH}_4^+$  ion-exchange step, followed by dealumination, desilication and then an additional  $\text{NH}_4^+$  ion-exchange step. Using  $\text{NH}_4\text{OH}$  produces desilicated geopolymer in its  $\text{NH}_4^+$  form in an one-pot process without the need for an additional ion-exchange step. Herein, the  $\text{NH}_4\text{OH}$  (0.02 M) treatment was done on a metakaolin based geopolymer,

previously treated with acetic acid (0.1 M). The chemical structure and particle morphology of the modified geopolymer were thoroughly investigated with different  $\text{NH}_4\text{OH}$  treatment durations. Special attention was paid on studying the impact of  $\text{NH}_4\text{OH}$  treatment on the intraparticle pore structure of geopolymer via  $\text{N}_2$  physisorption combined with  $^{129}\text{Xe}$  and  $^1\text{H}$  relaxometry NMR techniques.

## 2. Experimental methods

### 2.1. Sample preparation

An alkali activating solution was first prepared by mixing 37.4 g sodium silicate solution (27%  $\text{SiO}_2$ , 8%  $\text{Na}_2\text{O}$  and 65%  $\text{H}_2\text{O}$ ) (VWR, BDH, Frankenwald, South Africa) with 5.6 g NaOH pellets (VWR, BDH, Frankenwald, South Africa). The mixing procedure was done by a shear mixer (IKA, T 25 digital ULTRA–TURRAX, Staufen, Germany) using 3000 rpm speed for 5 min. Then 31.55 g metakaolin (MetaMax, BASF, Ludwigshafen, Germany) was dissolved into the alkali activating solution, with 3.85 mL  $\text{H}_2\text{O}$ . The mixture was placed into silicone molds and sealed into a plastic bag for curing at room temperature. After 24 h of curing, the solid samples were ground into powders by a vibratory disc mill (Retsch RS200, RETSCH GmbH, Haan, Germany). The oxide molar ratio of this geopolymer were:  $\text{Na}_2\text{O}:\text{Al}_2\text{O}_3:\text{SiO}_2:\text{H}_2\text{O} = 1.0:1.1:3.8:13.6$ .

Before the  $\text{NH}_4\text{OH}$  treatment, a low concentration acetic acid treatment was performed. 12.5 g of the geopolymer powder were added into 100 mL of 0.1 M acetic acid (VWR, Merck, Radnor, United States) and shaken on an orbital shaker (Advanced d3500 Orbital Shaker, VWR, Radnor, United States) for 10 mins. The powders were then filtered out, while the pH of the filtered liquid was measured (Accumet model 20, Fisher scientific, Vantaa, Finland). The geopolymer powders were then shaken with 0.1 M acetic acid and filtered repeatedly until the pH value of filtered liquid became 7 to 8.

The four sets of 12.5 g of geopolymer powders were subjected to 500 mL of 0.02 M  $\text{NH}_4\text{OH}$  (Sigma–Aldrich, Munich, Germany) solution treatment in a beaker, and stirred using a magnetic stirrer (Mixdrive 6, 2mag AG, Muenchen, Germany) with 600 rpm for 0 min, 15 min, 3 h and 24 h, respectively. These four geopolymers treated samples were named N1, N2, N3 and N4, respectively. Before four samples were sent for characterization, they were dried overnight at 100°C.

Here we would like to note that we used the low concentration (0.02 M)  $\text{NH}_4\text{OH}$  solution in the in order to avoid spoiling the pore structure, which is expected to happen at higher concentration. However, the 0.02 M concentration was too low to replace efficiently  $\text{Na}^+$  ions by  $\text{NH}_4^+$  ions and thus it was hard to observe the effect of the  $\text{NH}_4^+$  treatment. Therefore, an acetic acid treatment was applied before the  $\text{NH}_4^+$  treatment in order to help to exchange some original  $\text{Na}^+$

ions in geopolymer by  $H^+$  ions, thus facilitating the introduction of  $NH_4^+$  ions into pores.

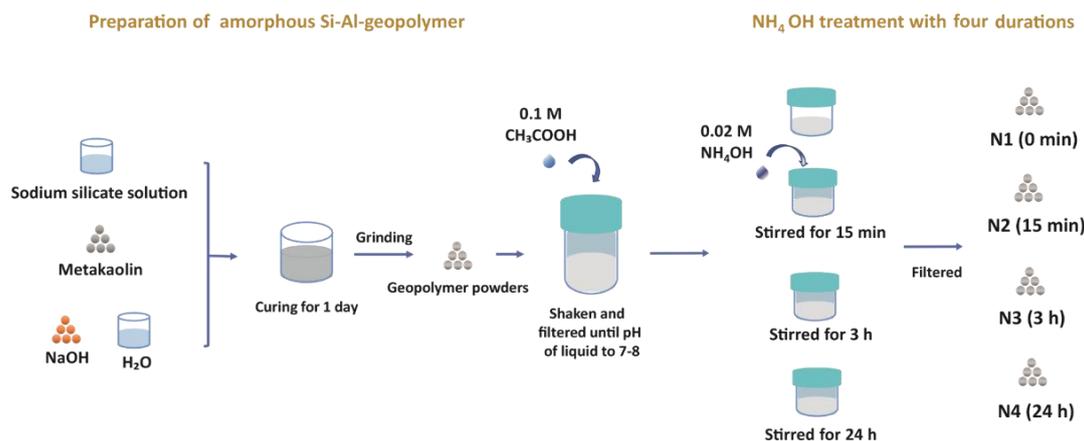


Figure 1. The procedure of the sample preparation.

## 2.2. DRIFT spectra

DRIFT spectra in the range of 500 – 4000  $\text{cm}^{-1}$  were collected for powder samples by a Bruker Vertex v80 spectrometer (Bruker, Rheinstetten, Germany).

## 2.3. X-ray fluorescence

X-ray fluorescence (XRF) measurements were used to determine the chemical composition of the samples. Scans were performed on a XRF spectrometer, PANalytical AXIOSmAX fitted with a Rh X-ray tube, which has a maximum power of 4 kW (Malvern PANalytical, Malvern, UK).

## 2.4. Solid-state magic angle spinning (MAS) NMR

$^{27}\text{Al}$  and  $^{29}\text{Si}$  MAS NMR spectra were measured with Bruker Avance III 7.05 T spectrometer (Bruker, Billerica, MA, USA). Samples were packed into 7 mm zirconia rotors and a 7 kHz spinning frequency was applied. For collecting  $^{27}\text{Al}$  MAS spectra, a single pulse sequence was used. The length of the excitation pulse was 1  $\mu\text{s}$ . The number of scans was 1024 with the relaxation delay of 2 s. The experiment time was about 0.5 h. The  $^{27}\text{Al}$  spectra were collected for all four samples and referenced to external reference of  $\text{Al}(\text{NO}_3)_3$  at 0 ppm. The  $^{29}\text{Si}$  MAS spectra were also collected with the single pulse sequence. The pulse length was 4  $\mu\text{s}$ . The spectra were accumulated for 8192 scans. The relaxation delay was 3 s and the experiment time was about 7 h. The  $^{29}\text{Si}$  spectra were referenced to tetramethylsilane (TMS) at 0 ppm.

## 2.5. Particle sizes

Particle size distributions were measured when geopolymer samples were dispersed into  $\text{NH}_4\text{OH}$  treatment solution by using a laser diffraction particle-size analyser (LS 13320, Beckman Coulter, Inc., Brea, CA, USA). The induced optical model was 'Fraunhofer. rfd'.

## 2.6. SEM images

The SEM images were recorded by using a Zeiss Ultra Plus field emission scanning electron microscope (FESEM) (Zeiss, Jena, Germany). The powder geopolymers were carbon coated before scanning.

## 2.7. $\text{N}_2$ sorption

The  $\text{N}_2$  sorption measurements were performed at  $-196\text{ }^\circ\text{C}$  with Micromeritics ASAP 2020 (Micromeritics, Norcross, US). The four samples were degassed under vacuum at  $100\text{ }^\circ\text{C}$  for overnight. The pore size distributions of mesopores were obtained using the Barret–Joyner–Halenda (BJH) method<sup>33</sup> and the pore volumes of micropores were obtained using the t–plot method.<sup>34</sup> The surface areas were analysed by Brunauer–Emmett–Teller (BET) method.<sup>35</sup>

## 2.8. $^{129}\text{Xe}$ NMR

To control for the particle size effect on the  $^{129}\text{Xe}$  NMR results, the samples were sieved with an air jet sieve (HOSOKAWA ALPINE 200LS, Hosokawa Alpine AG, Augsburg, Germany) before the experiments. The particles in the range of 90 – 250  $\mu\text{m}$  were selected. However, this is not the actual particle size as this sieve cannot separate the aggregated small particles. The actual particle size distributions were measured while dispersed into iso-propanol by using a laser diffraction particle-size analyser (see Section 2.4).

The sample powders were loaded into 5 mm NMR tube and 5–6 atm of  $^{129}\text{Xe}$  gas was then condensed into each sample using liquid nitrogen and a vacuum system. After 5–6 atm of  $^{129}\text{Xe}$  gas was condensed into each sample using liquid nitrogen and a vacuum system,  $^{129}\text{Xe}$  NMR spectra were collected on Bruker Avance III 7.1 T spectrometer (Bruker, Billerica, MA, USA) with a 10 mm BBO probe. The  $^{129}\text{Xe}$  dynamic experiments, including measurements of exchange rates and relaxation times ( $T_2$  and  $T_1$ ), were performed for samples N1, N2 and N3 on Bruker Avance III 14.1 T spectrometer (Bruker, Billerica, MA, USA) with a 5 mm BBO probe.

The  $^{129}\text{Xe}$  NMR spectra were measured using a single pulse sequence. The data was collected using 64 scans and a 60 s relaxation delay between each scan. The experiment time of one  $^{129}\text{Xe}$  spectrum was about 1 hour. The variable temperature  $^{129}\text{Xe}$  spectra were collected for 11 temperature points in the range of 212 – 324 K. For 1 K of temperature

increase, the sample was left for 5 min for temperature stabilization.

The exchange rates ( $k$ ) were measured with  $^{129}\text{Xe}$  selective inversion recovery (IR) experiments<sup>24</sup> at 298 K.<sup>5</sup> The recovery time was varied from 10  $\mu\text{s}$  to 1 s by 36 log spaced steps. The length of the selective sinc pulse was 436  $\mu\text{s}$  with 7 W power and the pulse was centred on the peak at 42 – 53 ppm (labelled with IP in Fig. 6). The number of scans was 128 and the relaxation delay was 10 s. The experiment time was about 15 h.

$T_1$  of  $^{129}\text{Xe}$  was measured by the IR pulse sequence<sup>36</sup> at 298 K. The recovery time increased from 100  $\mu\text{s}$  to 1 s with 25 log spaced steps. The number of scans was 64 and the relaxation delay was 10 s. The experiment time was about 6 h.

$T_2$  of  $^{129}\text{Xe}$  was measured by the CPMG pulse sequence<sup>37</sup> at 298 K. The echo time ( $2\tau$ ) was 160  $\mu\text{s}$ . The number of echoes varied from 2 to 50 with 14 log spaced steps. The number of scans was 256 and the relaxation delay was 10 s. The experiment time was about 10 h.

The  $k$ ,  $T_1$  and  $T_2$  data fits were shown in Section. S2.

### 2.9. $^1\text{H}$ NMR experiments

Before the  $^1\text{H}$  NMR experiments, the geopolymer samples were water saturated for 14 days. The  $^1\text{H}$   $T_2$  and  $T_1$  measurements, as well as 2D  $^1\text{H}$   $T_2$ – $T_2$  and  $T_1$ – $T_2$  experiments were performed on Magritek Spinsolve 43 MHz NMR spectrometer (Magritek, Aachen, Germany) at 298 K.

The spectrally resolved CPMG experiments were conducted to acquire  $T_2$  distributions. The echo time was 150  $\mu\text{s}$  and 1000 echoes were collected in a single scan. The number of scans was 4 and the relaxation delay was 14 s. The experiment time was about 16 h.

The  $T_1$  distributions were acquired with the saturation recovery (SR) pulse sequence.<sup>38</sup> The recovery time was varied from 1 ms to 2 s with 64 log spaced steps. The number of scans was 4 and the repetition time was 14 s. The experiment time was about 1 h.

The  $T_2$ – $T_2$  experiments<sup>26</sup> were performed with an echo time equal to 150  $\mu\text{s}$  and 1000 echoes were acquired in the direct dimension. In the indirect dimension, echo number was varied from 2 to 2000 in 64 log spaced steps. The number of scans was 128 and the relaxation delay was 6 s. The experiment time was about 14 h. The experiments were repeated with four different mixing times of 0.01, 0.02, 0.2 and 1 ms.

The  $T_1$  SR– $T_2$  pulse sequence<sup>26,27</sup> was used for collecting  $T_1$ – $T_2$  data. The echo time was 150  $\mu\text{s}$  and 1000 echoes were collected in a single scan. The recovery time varied from 1 ms

to 5 s with 64 log spaced steps. The number of scans was 128 and the relaxation delay was 6 s. The experiment time was about 14 h.

The  $^1\text{H}$  NMR cryoporometry experiments<sup>30</sup> were performed on Bruker Avance III 11.7 T spectrometer (Bruker, Billerica, MA, USA) with a 10 mm BBO probe. The cryoporometry experiments contained 56 variable temperature CPMG experiments over a temperature range of 170 to 276 K. A temperature stabilization delay of 5 min/K was used between experiments. The CPMG echo time was 200  $\mu\text{s}$  and the number of echoes was 1000. The relaxation delay was 5 s and the number scans was 64. The total experiment time for each sample was about 16 h. The data fits were shown in Section. S3.

1D  $T_2$  and  $T_1$  as well as 2D  $T_2$ – $T_2$  and  $T_1$ – $T_2$  distributions were obtained using the Laplace inversion implemented in MATLAB R2017b (Mathworks, Natick, Massachusetts, United States of America), provided by the research group of late prof. P. Callaghan.<sup>30,39,40</sup>

## 3. Results and discussion

### 3.1. Ion-exchange and structure

DRIFT spectra were collected to detect the changes of the chemical structure of the geopolymer due to the  $\text{NH}_4\text{OH}$  treatment. As visible in Fig. 2a, the geopolymer without  $\text{NH}_4\text{OH}$  treatment shows three main peaks at 3452, 1649 and 1254  $\text{cm}^{-1}$ , which are assigned to stretching H–O, bending H–O, and asymmetric stretching Si–O–T groups (T is Si or Al) in the geopolymer framework, respectively.<sup>41,42</sup> After the geopolymer was treated with  $\text{NH}_4\text{OH}$  for 15 min, 3 h and 24 h, three peaks appear at 3246, 3037 and 2848  $\text{cm}^{-1}$  (Figs. 2b–d), representing the appearance of anti-symmetric N–H stretching bands, as well as another new peak at 1454  $\text{cm}^{-1}$ , which is ascribed to the anti-symmetric bending H–N–H.<sup>43,44</sup> These peaks is an evidence that  $\text{NH}_4^+$  went in pores after  $\text{NH}_4\text{OH}$  treatment and the  $\text{NH}_4^+$ –geopolymer formed. This is corresponding to the XRF measurement results: the weight percentage of  $\text{Na}_2\text{O}$  decreased from 6.3 to 5.1 (Table 1), which is because the  $\text{Na}^+$  is continuously exchanged by  $\text{NH}_4^+$  during  $\text{NH}_4\text{OH}$  treatment, although the acetic acid (0.1 M) resulted larger level of exchange, decreased from 11.6 to 6.3. The  $\text{NH}_4^+$ –exchanged geopolymer enables the preparation of material with high acidity after calcination at temperature of 550–600  $^\circ\text{C}$ .<sup>14,17</sup>

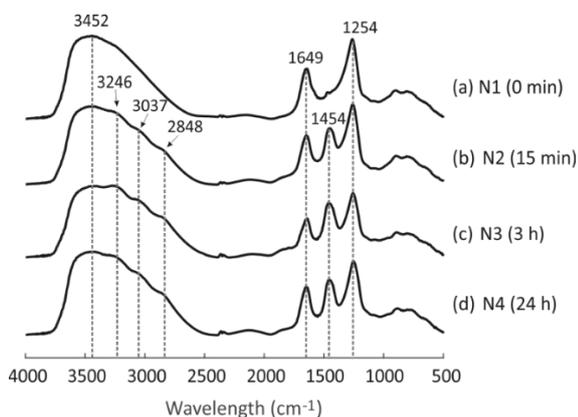


Figure 2. DRIFT spectra of four geopolymers with different  $\text{NH}_4\text{OH}$  treatment times, (a) N1, (b) N2, (c) N3 and (d) N4.

Table 1. Weight percentage of  $\text{Na}_2\text{O}$  and  $\text{SiO}_2/\text{Al}_2\text{O}_3$  molar ratio of the geopolymer before acetic acid treatment and four geopolymers after acetic acid and  $\text{NH}_4\text{OH}$  treatment, N1, N2, N3 and N4 measured by XRF analysis.

	$\text{Na}_2\text{O}$ (%)	$\text{SiO}_2/\text{Al}_2\text{O}_3$ molar ratio
Geopolymer before acetic acid treatment	11.6	3.54
N1	6.26	3.13
N2	5.61	3.16
N3	4.14	3.14
N4	5.13	3.12

The local Al and Si chemical environment changes after the  $\text{NH}_4\text{OH}$  treatment were also characterized using  $^{27}\text{Al}$  and  $^{29}\text{Si}$  MAS NMR. In  $^{27}\text{Al}$  NMR spectra (Figs. 3a–d), the peak at 55 ppm is assigned to Al in tetrahedral coordination and the small peak at 2 ppm to six-fold coordinated Al, arising from a small amount of non-framework Al.<sup>45</sup> The treatment does not change the positions of the peaks, but the peak at 2 ppm gradually vanishes as  $\text{NH}_4\text{OH}$  treatment time increase to 24 h. This may be because the extra-framework-Al was removed via  $\text{NH}_4\text{OH}$  treatment. The similar result was also found in zeolites.<sup>32</sup> In  $^{29}\text{Si}$  MAS NMR spectra (Figs. 3e–h), two partially overlapping peaks are observed. The smaller peak at -110 ppm corresponds to  $\text{SiQ}_4(\text{OAl})$ , which mainly comes from unreacted metakaolin.<sup>46</sup> The other peak is a typical broad geopolymer peak at -90 to -92 ppm. Normally, this peak contains four species,  $\text{SiQ}_4(4\text{Al})$ ,  $\text{SiQ}_4(3\text{Al})$ ,  $\text{SiQ}_4(2\text{Al})$  and  $\text{SiQ}_4(1\text{Al})$ , arranged from low to high frequency.<sup>47</sup> This peak shifts from -91.7 ppm (Fig. 3e) to -90.7 ppm (Fig. 3h) with increasing  $\text{NH}_4\text{OH}$  treatment time. This small shift was also found for zeolite Y after  $\text{NH}_4\text{OH}$  treatment in a previous study, which is ascribed to desilication impact of  $\text{NH}_4\text{OH}$ .<sup>32</sup> Removal of Si from the framework leads to an increased chemical shift. The decreasing input  $\text{Si}/\text{Al}$  ratio in geopolymer framework was also previously found to lead to increasing chemical shift.<sup>47</sup> The desilication was also found from XRF measurements, where the decreased  $\text{SiO}_2$ -to- $\text{Al}_2\text{O}_3$  molar

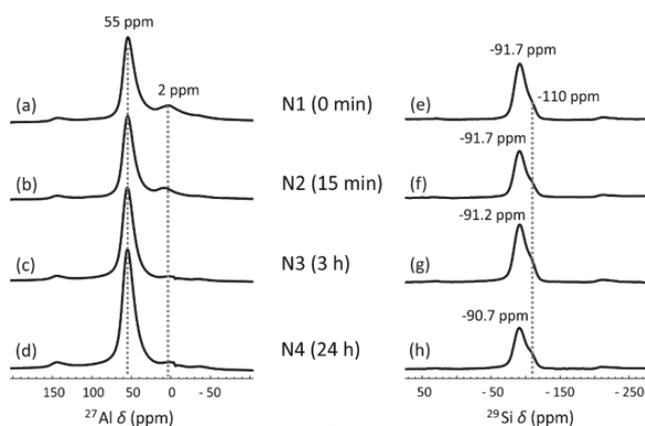
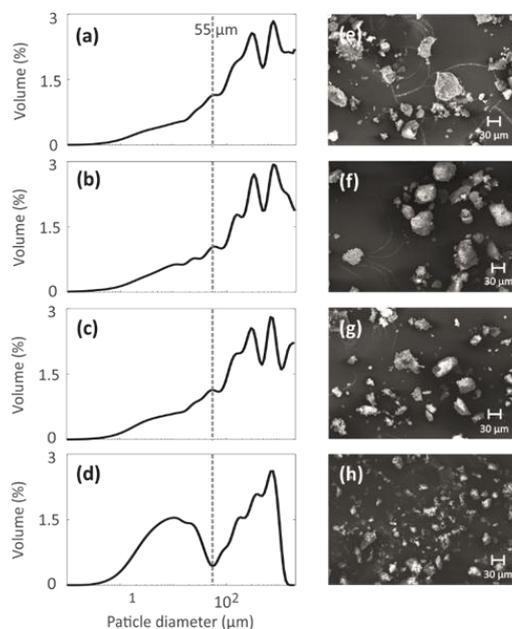


Figure 3. (a–d)  $^{27}\text{Al}$  and (e–h)  $^{29}\text{Si}$  MAS NMR spectra of (a, e) N1, (b, f) N2, (c, g) N3 and (d, h) N4.

ratio from 3.16 to 3.12 as the  $\text{NH}_4\text{OH}$  treatment time increased from 15 min to 24 h (Table 1).

### 3.2. Particle size

Particle size distributions of the geopolymer powders were measured to investigate the effect of the mild  $\text{NH}_4\text{OH}$  treatment on geopolymer particles. The particle size distributions in Figs. 4a–d show that the  $\text{NH}_4\text{OH}$  treatment lasting for 0–3 h (N1, N2 and N3) does not alter the particle size. However, the  $\text{NH}_4\text{OH}$  treatment lasting for 24 h (N4) leads to a decrease in particle size. The particles with similar sizes are visible in the SEM images (Figs. 4e–h). The reason for the decreased particle size is hypothesized to be the desilication caused by the  $\text{NH}_4\text{OH}$  treatment. As the Si–O bonds break, the large particles become smaller while breaking into multiple smaller pieces. The formation of crystal fragments of ZSM-5 zeolite due to desilication was also observed in a previous



study.<sup>48</sup> Figure 4. (a–d) Particle size distributions and (e–h) SEM images of four geopolymers with different  $\text{NH}_4\text{OH}$  post-treatment

times: (a, e) 0 min (N1), (b, f) 15 min (N2), (c, g) 3 h (N3) and (d, h) 24 h (N4).

### 3.3. Pore structure

The effect of  $\text{NH}_4\text{OH}$  treatment on the pore structure of the geopolymer were studied by  $\text{N}_2$  physisorption,  $^1\text{H}$  cryoporometry,  $^1\text{H}$  NMR relaxometry and  $^{129}\text{Xe}$  NMR methods as described below.

#### Pore volume, pore surface area and pore size

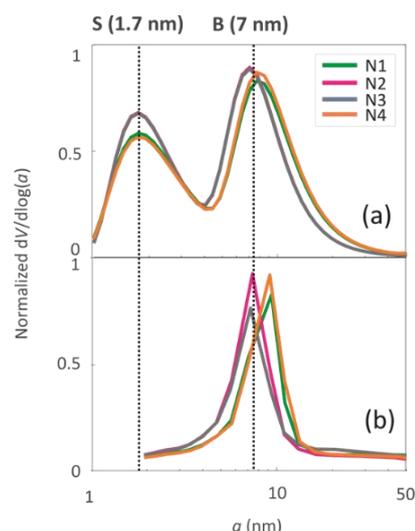
The pore volumes, the average pore sizes, and the surface areas of the four samples were measured by  $\text{N}_2$  sorption isotherms (Table 2). The micropore volume decreases and the mesopore volume increases as the  $\text{NH}_4\text{OH}$  treatment time increases. The average mesopore size is also found to increase. This means that  $\text{NH}_4\text{OH}$  treatment enlarges some micropores to mesopores and already existing mesopores to bigger mesopores. The average pore surface area acquired from both BET and t–plot analysis in the system decreases as a function of treatment time. This, as expected, shows the impact of the desilication caused by  $\text{NH}_4\text{OH}$  treatment on enlarging micropores to mesopores and perhaps introducing additional mesopores within the geopolymer framework.

The pore size distributions of the samples were determined by  $\text{N}_2$  sorption<sup>33</sup> and  $^1\text{H}$  NMR cryoporometry<sup>30,31</sup> measurements. The  $\text{N}_2$  pore size distribution obtained by the BJH method (desorption curve) are limited into the mesoporous range, while the NMR cryoporometry can probe both micro- and mesopores.<sup>51</sup> The pore size distributions (Fig. 5a) fitted from NMR cryoporometry (Fig. S3) include two peaks for all the samples, one from micropores and another from mesopores. The mesopore peak is centred around 7 nm, being in a good agreement with the single peak observed by  $\text{N}_2$  sorption (Fig. 5b). The micropore peak is centred around 1.7 nm. According to the  $\text{N}_2$  sorption data shown in Table 2, the micropore volume decreases while mesopore volume increases with longer  $\text{NH}_4\text{OH}$  treatment time.

Table 2. Pore volumes, pore sizes and surface areas of the four geopolymers measured by  $\text{N}_2$  sorption.

	Pore volume ( $\text{cm}^3/\text{g}$ )		Pore size (nm)	Surface area ( $\text{m}^2/\text{g}$ )	
	Micropore (t–plot)	Mesopore (BJH)	Mesopore (BJH)	Average (BET)	Micropore (t–plot)
N1	0.00385	0.256	6.54	130	14.1
N2	0.00321	0.261	6.61	126	12.5
N3	0.00213	0.264	6.66	123	10.1
N4	0.00130	0.274	7.43	112	7.89

Figure 5. Pore size distributions of the four geopolymers derived from (a)  $^1\text{H}$  cryoporometry NMR data and (b)  $\text{N}_2$



desorption data analysed with BJH method.

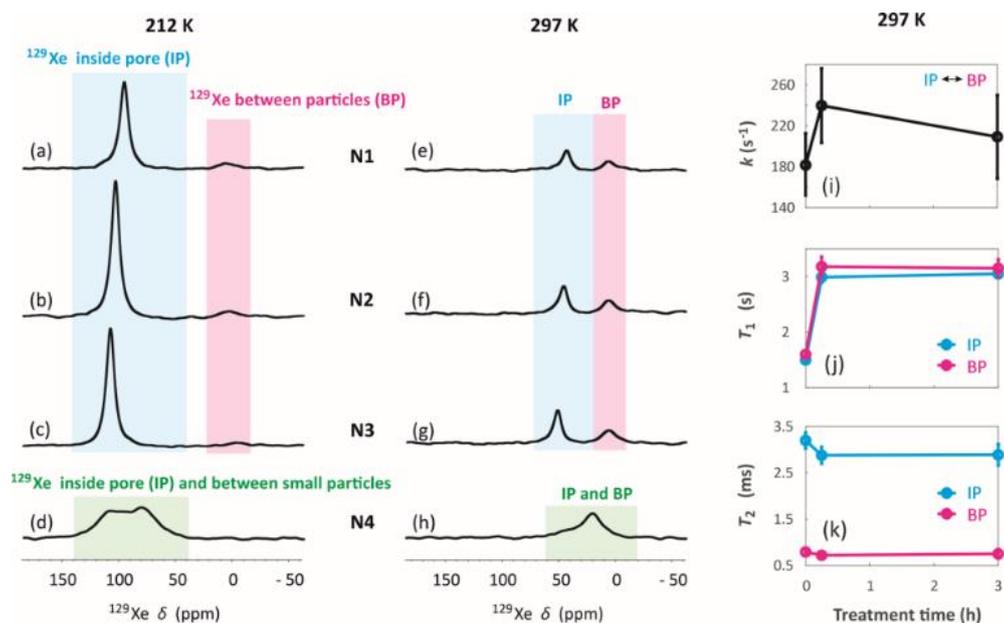
#### Pore accessibility and exchange detected by $^{129}\text{Xe}$ NMR

The pore accessibility was probed by  $^{129}\text{Xe}$  NMR, as the  $^{129}\text{Xe}$  chemical shift is able to distinguish intra and interparticle pores.<sup>13</sup>  $^{129}\text{Xe}$  in a small pore has larger chemical shift than  $^{129}\text{Xe}$  outside the pores.<sup>22</sup>

The  $^{129}\text{Xe}$  spectra were collected at variable temperatures from 212 to 324 K to study pore accessibility (Fig. S1). As seen in Fig. 6, two peaks are observed for samples N1, N2 and N3 at low (212 K) and high (297 K) temperatures. The tall peak labelled as IP around 110 ppm at 212 K is assigned to Xe in small pores inside the particles. The chemical shift and its relatively small temperature dependency implies that the IP signal arises predominantly Xe atoms in micropores.<sup>5,22</sup> The small peak labelled as BP around 6 ppm is attributed to Xe between larger particles (55 to 250  $\mu\text{m}$ ).<sup>5,22</sup> Due to the large interparticle void spaces, the chemical shift of the BP peak is close to free gas shift and almost independent of temperature. In contrast, a single, very broad peak is observed for the N4 sample in the chemical shift range of 50 and 130 ppm at 212 K. This is interpreted to be a consequence of smaller particle size of the N4 sample. According to Fig. 4d, contrary to other samples, N4 sample lots of particles in the range of 0.04 to 55  $\mu\text{m}$ . Due to the decreased particle size, exchange is faster between the intraparticle and interparticle pool, resulting in partially exchange averages signals (intermediate exchange region).

Exchange rates  $k$  of Xe between the intraparticle and interparticle pores of N1, N2 and N3 were determined by selective inversion recovery experiments (Fig. S2).<sup>24</sup> The observed exchange rates (Fig. 6i) are in the range of 140 – 270  $\text{s}^{-1}$ , and within the error bars they are independent of the  $\text{NH}_4\text{OH}$  treatment time.

$^{129}\text{Xe}$   $T_1$  and  $T_2$  relaxation times (Figs. 6j and 6k) also reflect the dynamics of Xe in the geopolymer samples. Within the error bars,  $T_1$  relaxation times (1.5 – 3 s) of the IP and PB peaks are equal due to exchange averaging, as the relaxation rates



( $0.3 - 0.7 \text{ s}^{-1}$ ) are much smaller than the exchange rates ( $140$  to  $270 \text{ s}^{-1}$ ).  $T_1$  is longer ( $3 \text{ s}$ ) for the  $\text{NH}_4\text{OH}$  treated samples N2 and N3 than for the untreated N1 sample ( $1.5 \text{ s}$ ). This may be a consequence of changed surface interactions due to the partial  $\text{Na}^+ - \text{NH}_4^+$  ion exchanges.  $T_2$  relaxation times ( $0.5 - 3.5 \text{ ms}$ ) are much shorter than  $T_1$  relaxation times. According to relaxation modelling, fluctuations in the isotropic chemical shift are known to be dominating  $T_2$  relaxation mechanism of  $^{129}\text{Xe}$  in porous materials because of large chemical shift between the exchanging sites.<sup>52</sup> Because  $T_2$  rates ( $300 - 2000 \text{ s}^{-1}$ ) are higher than the exchange rates ( $140 - 270 \text{ s}^{-1}$ ),  $T_2$  values are not exchange averaged;  $T_2$  of  $^{129}\text{Xe}$  in the intraparticle site is longer (about  $3 \text{ ms}$ ) than in the interparticle site (about  $0.7 \text{ ms}$ ).

#### Pore types and connectivity detected by $^1\text{H}$ NMR relaxation

The 1D  $^1\text{H}$   $T_2$  and  $T_1$ , as well as 2D  $T_2-T_2$  and  $T_1-T_2$  measurements of water absorbed in the geopolymer samples

were performed to investigate how the pore types and connectivity change with the  $\text{NH}_4\text{OH}$  treatment. When water is inside the geopolymer,  $T_2$  and  $T_1$  relaxation times reflect the pore size.<sup>4,17</sup>

Four peaks are observed in the  $T_2$  distributions shown on the top of  $T_2-T_2$  maps in Figs. 7a-d. The shortest  $T_2$  peak (label S) around  $T_2 = 1 \text{ ms}$  is interpreted to arise from water in the  $1.7 \text{ nm}$  micropores. The peaks (label B) in the region of  $6-36 \text{ ms}$  are assumed to represent water in the  $7 \text{ nm}$  mesopores. The longest  $T_2$  peak (label BP) is assigned for water in large voids in between the particles. The BP signal of the N4 sample has smaller amplitude and shorter  $T_2$  than the other samples. This is because the smaller particles of N4 leave less space for the free water between the particles.

$T_1$  distributions are shown on the right of the  $T_1-T_2$  maps in Figs. 7e-h.  $T_1$  values are systematically longer than  $T_2$  values. The  $T_1$  distributions include two peaks around  $5$  and  $50 \text{ ms}$ ,

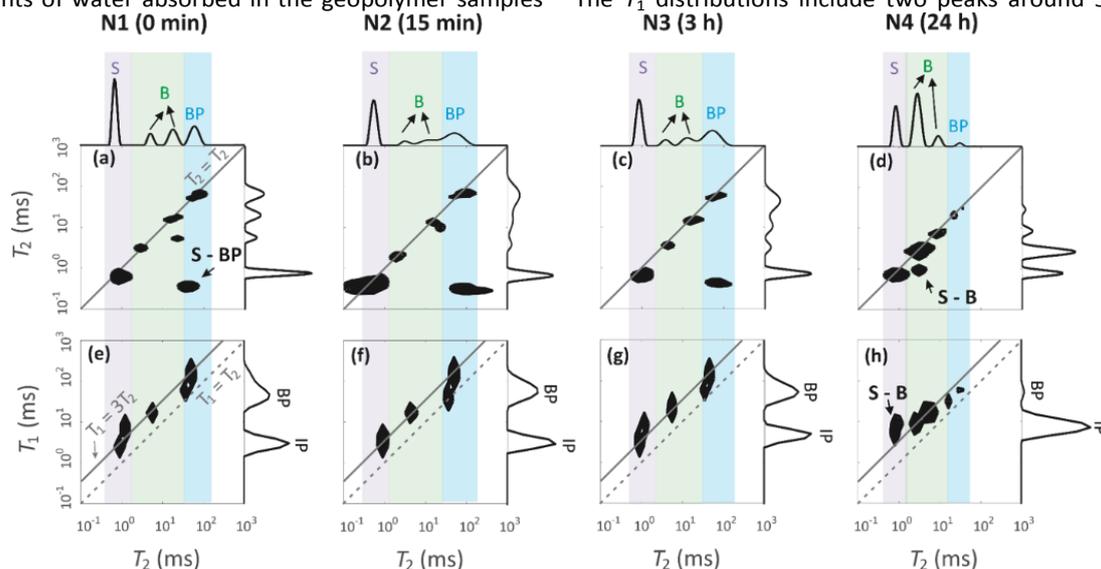


Figure 7. (a-d)  $^1\text{H}$   $T_2-T_2$  exchange spectra of water in the geopolymer samples measured with mixing time of  $0.2 \text{ ms}$ . (e-h)  $^1\text{H}$   $T_1-T_2$  correlation spectra.  $T_2$  and  $T_1$  distributions measured by CPMG and saturation recovery experiments are shown on the top and right of the 2D plots.

which are attributed to the water inside the intraparticle pores (IP) and the water inside the interparticle pores (BP). The micropore and mesopore peaks S and B observed in the  $T_2$  distributions are expected to fuse in the  $T_1$  distributions due to exchange; this implies that the micropore–mesopore exchange rate of water is between the  $T_1$  and  $T_2$  relaxation rates, i.e., in the range of 200 – 1000 s<sup>-1</sup>. The cross-peak S–BP visible in the  $T_2$ – $T_2$  exchange maps (Figs. 7a–d) show that there is also exchange between the intraparticle and interparticle pools. The  $T_1$ – $T_2$  maps show the correlations between the  $T_1$  and  $T_2$  relaxation time values and confirm the above-mentioned interrelated assignments of the peaks in the  $T_1$  and  $T_2$  distributions.

#### 4. Conclusions

This work studies the effect of mild NH<sub>4</sub>OH treatment to a metakaolin-based geopolymer in terms of ion-exchange, chemical structure, particle size and pore structure.

- 1) The obtained DRIFT, accompanied with XRF results show that ion-exchange of charge balancing alkali cations (i.e., Na<sup>+</sup>) with NH<sub>4</sub><sup>+</sup> was successfully achieved by this treatment.
- 2) The solid-state NMR spectra and XRF data proved the NH<sub>4</sub>OH treatment removed the extra-framework-Al out of geopolymer structure and also lead to the desilication of geopolymer framework.
- 3) The particle size reduction resulted from NH<sub>4</sub>OH treatment were found by both laser diffraction particle-size analysis and SEM.
- 4) After the NH<sub>4</sub>OH treatment, the pore volume and pore size were enlarged, but the pore accessibility and pore connectivity were not altered, as revealed by N<sub>2</sub> sorption isotherms, <sup>129</sup>Xe and <sup>1</sup>H NMR.

The changes in particles size and pore characteristics are considered to be due to desilication caused by NH<sub>4</sub>OH treatment.

In this study the NH<sub>4</sub>OH treatment was carried out under mild conditions (0.02 M at room temperature) to ensure maintaining the structural integrity of geopolymers. This resulted in limited ion-exchange efficiency as well as limited impact on the pore characteristics of the prepared materials. This work provides a new approach of simplifying the synthesis of ion-exchanged geopolymers with modified porosity as low-cost functional materials for catalysis and adsorption applications. Further investigation on the impact of NH<sub>4</sub>OH treatment under harsher conditions (for instance, NH<sub>4</sub><sup>+</sup> concentration ≥ 0.1M, and moderate temperature range (323 K–353 K)) would be of high interests.

#### Conflicts of interest

There are no conflicts to declare.

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#### Notes and references

- 1 H. Xu and J. S. J. Van Deventer, The geopolymerisation of alumino-silicate minerals, *International Journal of Mineral Processing*, 2000, **59**, 247–266.
- 2 P. Sazama, O. Bortnovsky, J. Dědeček, Z. Tvarůžková and Z. Sobalík, Geopolymer based catalysts—New group of catalytic materials, *Catalysis Today*, 2011, **164**, 92–99.
- 3 J. Davidovits, PROPERTIES OF GEOPOLYMER CEMENTS.
- 4 J. Li, S. Mailhot, H. Sreenivasan, A. M. Kantola, M. Illikainen, E. Adesanya, L. Kriskova, V.-V. Telkki and P. Kinnunen, Curing process and pore structure of metakaolin-based geopolymers: Liquid-state 1H NMR investigation, *Cement and Concrete Research*, 2021, **143**, 106394.
- 5 J. Li, S. Mailhot, H. Sreenivasan, A. M. Kantola, V.-V. Telkki and P. Kinnunen, 129Xe NMR analysis reveals efficient gas transport between inborn micro-, meso- and macropores in geopolymers, *Cement and Concrete Research*, 2022, **155**, 106779.
- 6 Z. Liu and S. Ihl Woo, Recent Advances in Catalytic DeNOX Science and Technology, *Catalysis Reviews*, 2006, **48**, 43–89.
- 7 N. Tang, K. Yang, Y. Alrefaei, J.-G. Dai, L.-M. Wu and Q. Wang, Reduce VOCs and PM emissions of warm-mix asphalt using geopolymer additives, *Construction and Building Materials*, 2020, **244**, 118338.
- 8 T. H. Tan, K. H. Mo, T.-C. Ling and S. H. Lai, Current development of geopolymer as alternative adsorbent for heavy metal removal, *Environmental Technology & Innovation*, 2020, **18**, 100684.
- 9 S. A. Rasaki, Z. Bingxue, R. Guarecuco, T. Thomas and Y. Minghui, Geopolymer for use in heavy metals adsorption, and advanced oxidative processes: A critical review, *Journal of Cleaner Production*, 2019, **213**, 42–58.
- 10 M. I. M. Alzeer, K. J. D. MacKenzie and R. A. Keyzers, Facile synthesis of new hierarchical aluminosilicate inorganic polymer solid acids and their catalytic performance in alkylation reactions, *Microporous and Mesoporous Materials*, 2017, **241**, 316–325.

- 11 H. Chen, Y. J. Zhang, P. Y. He, C. J. Li and L. C. Liu, Facile synthesis of cost-effective iron enhanced hetero-structure activated carbon/geopolymer composite catalyst for NH<sub>3</sub>-SCR: Insight into the role of iron species, *Applied Catalysis A: General*, 2020, **605**, 117804.
- 12 Y. J. Zhang, L. C. Liu, L. L. Ni and B. L. Wang, A facile and low-cost synthesis of granulated blast furnace slag-based cementitious material coupled with Fe<sub>2</sub>O<sub>3</sub> catalyst for treatment of dye wastewater, *Applied Catalysis B: Environmental*, 2013, **138–139**, 9–16.
- 13 M. I. M. Alzeer, K. J. D. MacKenzie and R. A. Keyzers, Porous aluminosilicate inorganic polymers (geopolymers): a new class of environmentally benign heterogeneous solid acid catalysts, *Applied Catalysis A: General*, 2016, **524**, 173–181.
- 14 D. Verboekend, G. Vilé and J. Pérez-Ramírez, Hierarchical Y and USY Zeolites Designed by Post-Synthetic Strategies, *Advanced Functional Materials*, 2012, **22**, 916–928.
- 15 S. Karakus, *New Trends in Ion Exchange Studies*, BoD – Books on Demand, 2018.
- 16 S. J. O'Connor, K. J. D. MacKenzie, M. E. Smith and J. V. Hanna, Ion exchange in the charge-balancing sites of aluminosilicate inorganic polymers, *J. Mater. Chem.*, 2010, **20**, 10234–10240.
- 17 T. R. Barbosa, E. L. Foletto, G. L. Dotto and S. L. Jahn, Preparation of mesoporous geopolymer using metakaolin and rice husk ash as synthesis precursors and its use as potential adsorbent to remove organic dye from aqueous solutions, *Ceramics International*, 2018, **44**, 416–423.
- 18 D. Wisser and M. Hartmann, <sup>129</sup>Xe NMR on Porous Materials: Basic Principles and Recent Applications, *Advanced Materials Interfaces*, 2021, **8**, 2001266.
- 19 Y.-Q. Song, Magnetic Resonance of Porous Media (MRPM): A perspective, *Journal of Magnetic Resonance*, 2013, **229**, 12–24.
- 20 M. A. Javed, S. Komulainen, H. Daigle, B. Zhang, J. Vaara, B. Zhou and V.-V. Telkki, Determination of pore structures and dynamics of fluids in hydrated cements and natural shales by various <sup>1</sup>H and <sup>129</sup>Xe NMR methods, *Microporous and Mesoporous Materials*, 2019, **281**, 66–74.
- 21 B. Zhou, S. Komulainen, J. Vaara and V.-V. Telkki, Characterization of pore structures of hydrated cements and natural shales by <sup>129</sup>Xe NMR spectroscopy, *Microporous and Mesoporous Materials*, 2017, **253**, 49–54.
- 22 V. V. Terskikh, I. L. Moudrakovski, S. R. Breeze, S. Lang, C. I. Ratcliffe, J. A. Ripmeester and A. Sayari, A General Correlation for the <sup>129</sup>Xe NMR Chemical Shift–Pore Size Relationship in Porous Silica-Based Materials, *Langmuir*, 2002, **18**, 5653–5656.
- 23 K. V. Romanenko, A. Fonseca, S. Dumonteil, J. B. Nagy, J.-B. d'Espinose de Lacaillerie, O. B. Lapina and J. Fraissard, <sup>129</sup>Xe NMR study of Xe adsorption on multiwall carbon nanotubes, *Solid State Nucl Magn Reson*, 2005, **28**, 135–141.
- 24 A. D. Bain and J. A. Cramer, A Method for Optimizing the Study of Slow Chemical Exchange by NMR Spin-Relaxation Measurements. Application to Tripodal Carbonyl Rotation in a Metal Complex, *Journal of Magnetic Resonance, Series A*, 1993, **103**, 217–222.
- 25 J. H. Lee, C. Labadie, C. S. Springer and G. S. Harbison, Two-dimensional inverse Laplace transform NMR: altered relaxation times allow detection of exchange correlation, *J. Am. Chem. Soc.*, 1993, **115**, 7761–7764.
- 26 J. E. M. Snaar and H. Van As, A method for the simultaneous measurement of NMR spin-lattice and spin-spin relaxation times in compartmentalized systems, *Journal of Magnetic Resonance (1969)*, 1992, **99**, 139–148.
- 27 Y.-Q. Song, L. Venkataramanan, M. D. Hürlimann, M. Flaum, P. Frulla and C. Straley, T<sub>1</sub>–T<sub>2</sub> Correlation Spectra Obtained Using a Fast Two-Dimensional Laplace Inversion, *Journal of Magnetic Resonance*, 2002, **154**, 261–268.
- 28 J. H. Strange, M. Rahman and E. G. Smith, Characterization of porous solids by NMR, *Phys. Rev. Lett.*, 1993, **71**, 3589–3591.
- 29 O. V. Petrov and I. Furó, NMR cryoporometry: Principles, applications and potential, *Progress in Nuclear Magnetic Resonance Spectroscopy*, 2009, **54**, 97–122.
- 30 R. M. E. Valckenborg, L. Pel and K. Kopinga, Combined NMR cryoporometry and relaxometry, *J. Phys. D: Appl. Phys.*, 2002, **35**, 249.
- 31 D. W. Aksnes, K. Førlund and L. Kimtys, Pore size distribution in mesoporous materials as studied by <sup>1</sup>H NMR, *Physical Chemistry Chemical Physics*, 2001, **3**, 3203–3207.
- 32 J. Van Aelst, D. Verboekend, A. Philippaerts, N. Nuttens, M. Kurttepel, E. Gobechiya, M. Haouas, S. P. Sree, J. F. M. Denayer, J. A. Martens, C. E. A. Kirschhock, F. Taulelle, S. Bals, G. V. Baron, P. A. Jacobs and B. F. Sels, Catalyst Design by NH<sub>4</sub>OH Treatment of USY Zeolite, *Advanced Functional Materials*, 2015, **25**, 7130–7144.
- 33 E. P. Barrett, L. G. Joyner and P. P. Halenda, The Determination of Pore Volume and Area Distributions in Porous Substances. I. Computations from Nitrogen Isotherms, *J. Am. Chem. Soc.*, 1951, **73**, 373–380.
- 34 B. C. Lippens and J. H. de Boer, Studies on pore systems in catalysts: V. The t method, *Journal of Catalysis*, 1965, **4**, 319–323.
- 35 G. Pickett, Modification of the Brunauer–Emmett–Teller Theory of Multimolecular Adsorption, *J. Am. Chem. Soc.*, 1945, **67**, 1958–1962.
- 36 R. L. Vold, J. S. Waugh, M. P. Klein and D. E. Phelps, Measurement of Spin Relaxation in Complex Systems, *The Journal of Chemical Physics*, 1968, **48**, 3831–3832.
- 37 S. Meiboom and D. Gill, Modified Spin-Echo Method for Measuring Nuclear Relaxation Times, *Review of Scientific Instruments*, 1958, **29**, 688–691.
- 38 J. L. Markley, W. J. Horsley and M. P. Klein, Spin-Lattice Relaxation Measurements in Slowly Relaxing Complex Spectra, *The Journal of Chemical Physics*, 1971, **55**, 3604–3605.
- 39 S. Godefroy and P. T. Callaghan, 2D relaxation/diffusion correlations in porous media, *Magnetic Resonance Imaging*, 2003, **21**, 381–383.
- 40 L. Venkataramanan, Y.-Q. Song and M. D. Hürlimann, Solving Fredholm integrals of the first kind with tensor product structure in 2 and 2.5 dimensions, *IEEE Transactions on Signal Processing*, 2002, **50**, 1017–1026.

- 41 F. G. M. Aredes, T. M. B. Campos, J. P. B. Machado, K. K. Sakane, G. P. Thim and D. D. Brunelli, Effect of cure temperature on the formation of metakaolinite-based geopolymer, *Ceramics International*, 2015, **41**, 7302–7311.
- 42 M. S. Mohd Basri, F. Mustapha, N. Mazlan and M. R. Ishak, Rice Husk Ash-Based Geopolymer Binder: Compressive Strength, Optimize Composition, FTIR Spectroscopy, Microstructural, and Potential as Fire-Retardant Material, *Polymers*, 2021, **13**, 4373.
- 43 M. Mookherjee, M. D. Welch, L. L. Pollès, S. A. T. Redfern and D. E. Harlov, Ammonium ion behaviour in feldspar: variable-temperature infrared and  $^2\text{H}$  NMR studies of synthetic buddingtonite,  $\text{N(D,H)4AlSi}_3\text{O}_8$ , *Phys Chem Minerals*, 2005, **32**, 126–131.
- 44 I. Mihailova, I. Uzunov and D. Mehandjiev, WASTE COPPER SLAG/ALUMINIUM DROSS-BASED GEOPOLYMER.
- 45 P. He, M. Wang, S. Fu, D. Jia, S. Yan, J. Yuan, J. Xu, P. Wang and Y. Zhou, Effects of Si/Al ratio on the structure and properties of metakaolin based geopolymer, *Ceramics International*, 2016, **42**, 14416–14422.
- 46 M. R. Wang, D. C. Jia, P. G. He and Y. Zhou, Influence of calcination temperature of kaolin on the structure and properties of final geopolymer, *Materials Letters*, 2010, **64**, 2551–2554.
- 47 Q. Wan, F. Rao, S. Song, R. E. García, R. M. Estrella, C. L. Patiño and Y. Zhang, Geopolymerization reaction, microstructure and simulation of metakaolin-based geopolymers at extended Si/Al ratios, *Cement and Concrete Composites*, 2017, **79**, 45–52.
- 48 W. C. Yoo, X. Zhang, M. Tsapatsis and A. Stein, Synthesis of mesoporous ZSM-5 zeolites through desilication and re-assembly processes, *Microporous and Mesoporous Materials*, 2012, **149**, 147–157.
- 49 R. Ghezini, M. Sassi and A. Bengueddach, Adsorption of carbon dioxide at high pressure over H-ZSM-5 type zeolite. Micropore volume determinations by using the Dubinin–Raduskevich equation and the “*t*-plot” method, *Microporous and Mesoporous Materials*, 2008, **113**, 370–377.
- 50 S. Lowell and J. E. Shields, *Powder Surface Area and Porosity*, Springer Science & Business Media, 2013.
- 51 J. Mitchell, J. B. W. Webber and J. H. Strange, Nuclear magnetic resonance cryoporometry, *Physics Reports*, 2008, **461**, 1–36.
- 52 P. Håkansson, M. Asadullah Javed, S. Komulainen, L. Chen, D. Holden, T. Hasell, A. Cooper, P. Lantto and V.-V. Telkki, NMR relaxation and modelling study of the dynamics of SF<sub>6</sub> and Xe in porous organic cages, *Physical Chemistry Chemical Physics*, 2019, **21**, 24373–24382.

## Abstract figure

