We describe a route to synthesize a mechanically stable, non-flammable poly(acrylic acid)–calcium salt (the so-called mineral plastic) foam whose structure can be tailored. Main steps of the foam synthesis are: (1) foaming of the PAA-containing solution, (2) gelation of the continuous foam phase, and (3) drying of the hydrogel foam. The main challenge was to formulate an aqueous solution with a large amount of poly(acrylic acid), PAA, and calcium to yield a mechanically stable foam. The resulting PAA-based solid foams with pore sizes of around 220 μm can easily be dissolved, i.e. recycled, in an acidic solution.

1. Introduction

Polymer foams are ubiquitous in our daily life, mainly when it comes to insulation purposes (heat, sound). Among those, the insulation of buildings is one of the most important applications. However, the flammability of these insulation foams can cause severe problems in case of a fire. Therefore, non-flammable foams would be the solution to these safety issues but the severe problems in case of a fire. Therefore, non-flammable foams would be the solution to these safety issues but the foam whose structure can be tailored. The new material can be synthesized in aqueous solution and at ambient conditions, i.e. without hazardous solvents and without energy supply. The main challenge was to formulate an aqueous solution with a large amount of poly(acrylic acid), PAA. Having solved this issue, we (1) foamed the PAA-containing solution, (2) gelled the continuous phase of the foam, and (3) dried the hydrogel foam. Our proof-of-concept clearly shows that it is possible to synthesize mineral plastic foams via foam templating, i.e. via a process where the template does not need to be removed. With this work we are paving the way for the production of tailor-made sustainable mineral plastic foams which have enormous potential in the field of insulation applications, especially for heat insulation.

New concepts

So far there has been no such a thing as a sustainable, recyclable, and cheap plastic foam that does not burn! Having this challenge I mind, we developed a templating route for the synthesis of a mechanically stable, recyclable, cheap, non-flammable mineral plastic foam whose structure can be tailored. The new material can be synthesized in aqueous solution and at ambient conditions, i.e. without hazardous solvents and without energy supply. The main challenge was to formulate an aqueous solution with a large amount of poly(acrylic acid), PAA. Having solved this issue, we (1) foamed the PAA-containing solution, (2) gelled the continuous phase of the foam, and (3) dried the hydrogel foam. Our proof-of-concept clearly shows that it is possible to synthesize mineral plastic foams via foam templating, i.e. via a process where the template does not need to be removed. With this work we are paving the way for the production of tailor-made sustainable mineral plastic foams which have enormous potential in the field of insulation applications, especially for heat insulation.

The most important property in regard to the fact insulation foam applications, however, is that mineral plastic is not flammable. Another advantage in terms of its production is the very easy synthesis in water at room temperature and ambient pressure by simple addition of a carbonate or basic solution to a solution of Ca$^{2+}$ and PAA. However, since the formed mineral plastic has the consistency of chewing gum, it cannot be foamed in the hydrogel state and therefore, another strategy has to be applied. A promising strategy is one that has been developed for bio-based polymers and that consists of three steps: (1) foaming an aqueous solution of the respective polymer. (2) Gelling the continuous phase of the foam via chemically crosslinking the polymer, i.e. producing a hydrogel foam. (3) Drying the hydrogel foam and thus obtaining a solid foam. We generally followed this strategy but deviated from it in two ways. (a) The gelation happens via entanglement of PAA and is thus a physical gelation, i.e. the gelation can be reversed. (b) The conversion from the hydrogel to the solid (= mineral plastic) foam happens via complexation, i.e. a hydrogen bonded PAA network is converted into a PAA network held together via electrostatic interactions.

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In preliminary work we found that the above foaming strategy works but that the amount of PAA (0.1 M) used for the synthesis of non-foamed mineral plastic is much too low to end up with a homogeneously foamed material. Thus, the first challenge was to increase the amount of PAA considerably. In our work, we will show how we were able to formulate a solution with 2.75 M PAA and 2.4 M CaCl$_2$, mechanically foam it, gel it and finally dry the foam.

2. Experimental section

2.1. Chemicals

The polyacrylic acid (PAA) used has a mass average molar mass of $M = 101000$ g mol$^{-1}$ and was provided by BASF SE. The non-ionic surfactant Plantacare® 2000 UP was provided by BASF SE as well. The surfactant is an alkyl polyglycoside with alkyl chains between 8 and 16 carbon atoms and a head group composed of 1.5 glycoside units on average (see Scheme S1 in ESI† for molecular structure). Calcium chloride dihydrate (purity >99%, CaCl$_2$·2H$_2$O) and 37% hydrochloric acid (HCl, analytical grade) were purchased from Sigma-Aldrich Chemie GmbH. Ethanol (purity 99.9%) was purchased from VWR. All chemicals were used without further purification.

2.2. Sample preparation

15 mL of the reaction solution were prepared by mixing 7.5 mL of a 4.8 M CaCl$_2$–HCl solution (CaCl$_2$·2H$_2$O dissolved in 37 wt% HCl) with 7.5 mL of a 5.5 M polyacrylic acid (PAA) solution and 0.17 g Plantacare® 2000 UP (0.45 wt%). The reaction solution was immediately transferred to a 250 mL round bottom flask. The reaction solution was foamed at $T = 35$ °C by using a KPG stirrer with a 68 mm × 24 mm ($L \times W$) stirring blade. Stirring time was 30 min or 60 min and stirring speeds were 400 rpm, 1000 rpm, or 1600 rpm (see Table 1).

The resulting yellowish (the yellowish color originates from impurities of Plantacare® 2000 UP) liquid foam was put into cylindrical vials (25 mm in diameter and 60 mm in height) and stored at $T = 16$ °C for 24 hours to gel the continuous phase of the foam, i.e. to make a hydrogel out of the continuous phase. Thus, we will call the resulting system a hydrogel foam.

The hydrogel foam was then treated with an ammonia solution [mass ratio of hydrogel foam to ammonia solution = 1:10] and kept for 6 hours. The hydrogel foam became white and hard, i.e. it became a mineral plastic foam. For studying the influence of the ammonia content on the structure of the mineral plastic foam we treated the hydrogel with 25 wt%, 20 wt%, 18 wt%, and 15.5 wt% ammonia solutions (see Fig. 5 in Section 3.3). Note that the treatment with NH$_3$ produces ammonium chloride, which thermally decomposes into NH$_3$ and HCl. Since these substances are harmful they must be removed if the mineral plastic foam is to be used e.g. as insulating material. Thus, NH$_3$Cl was removed from the mineral plastic foams by washing the samples three times for 5 min with absolute ethanol (mass ratio of mineral plastic foam to ethanol = 1:10). In addition, we washed some samples with ethanol–water mixtures to test the influence of water on the swelling behavior (see Fig. 7 in Section 3.4). Finally, the mineral plastic foams were freeze-dried.

2.3. Methods

Bubble and pore diameter determination. The determination of the gas bubble diameters (hydrogel foam) and the pore diameters (mineral plastic foam) was carried out with the help of photographs, which were obtained with a Zeiss AxioZoom.V16 microscope with a Zeiss Axiocam 503 mono camera (Carl Zeiss AG, Germany). The software ImageJ was used for the determination of bubble and pore diameters.

Mechanical properties. Mechanical compression tests were carried out with the universal testing machine zwickiLine 5kN from Zwick/Roell equipped with a 5 kN force transducer and regulated by the software testXpert III. Stress ($\sigma$)–strain ($\epsilon$) curves were recorded with normal forces and a testing speed of 1 mm min$^{-1}$.

Thermogravimetric analysis. The thermogravimetric analysis (TGA) of the dried mineral plastic foams were carried out on a Jupiter STA 449 F3 (Netzsch GmbH & Co. KG, Germany) by heating from $T = 30$ °C to $= 1200$ °C with a heating rate of 10 K min$^{-1}$ under air flow.

Scanning electron microscopy. The Scanning Electron Microscopy (SEM) pictures were taken on a Hitachi TM 3000 Tabletop SEM using 15 kV acceleration voltage.

Density determination. The density was calculated by determining the volume of the sample with a caliper and the mass of the sample with a balance.

3. Results & discussion

3.1. Dissolution of PAA

Mineral plastic is formed from a solution consisting of 0.1 M PAA and 0.1 M CaCl$_2$ to which a volume-equivalent 0.1 M NaCO$_3$ is added. However, we found that the concentrations of PAA and CaCl$_2$ were too low for the synthesis of mechanically stable mineral plastic foams (see Fig. S1 in ESI†). Thus, the concentration of PAA was increased to 1.0 M, which is reported as successful mineral plastic synthesis with an equimolar CaCl$_2$ concentration. However, the PAA-CaCl$_2$ solutions became turbid independent of the PAA concentration at a CaCl$_2$ concentration higher than 1.0 M. The critical concentration for turbidity of the PAA-CaCl$_2$-solution is between 1.0 M and 1.25 M CaCl$_2$ (Fig. 1). This turbidity results from a phase
separation and two demixed phases with different density appear after storage of the solution. The demixing is reversible and the solutions become clear again upon dilution with water or HCl or temperature increase.

It is important to note that the pH decreases as the CaCl$_2$ concentration increase (Fig. 1). The observed proton release is caused by Ca$^{2+}$ complexation and thus substitution of the proton of the carboxylic acid groups even at the low pH. We assume that the high Ca$^{2+}$ concentration leads to the formation of electrostatic interactions between the Ca$^{2+}$ ions and the COO$^-$ groups of the PAA, i.e. to the formation of a coacervate, which, in turn, phase separates from the aqueous solution containing protonated PAA. This assumption is supported by the reported formation of coacervates between Ca$^{2+}$ and PAA at a different pH.$^{19,20}$ Coacervates are thermodynamically stable phases and can therefore be formed using different pathways due to the principle of the path independence reaching a thermodynamic equilibrium.

Consequently, since addition of HCl reverts the coacervate formation by protonation of the carboxylic acid groups (Fig. 2), the proton concentration needs to be increased as much as possible to be able to work with a one phase solution, which is required for foaming with the maximum amount of PAA and CaCl$_2$.

With 6.0 M HCl we were finally able to increase the PAA concentration by a factor of 27.5 and the CaCl$_2$ concentration by a factor of 24 compared to the original system described by Sun et al.$^{1}$ The system of choice for all following measurements thus consisted of 2.75 M PAA, 2.4 M CaCl$_2$, and 6.0 M HCl.

3.2. Foaming of PAA–CaCl$_2$ solutions

We recall that a homogeneous solution of low viscosity was required for foaming. The solutions to be foamed consisted of 2.7 M polyacrylic acid (PAA), 2.4 M calcium chloride (CaCl$_2$), 6.0 M hydrochloric acid (HCl), 0.45 wt% Plantacare$^{R}$ 2000 UP. The solutions were foamed with the help of a KPG-stirrer and immediately gelled by cooling down to $T = 16$ °C. For the foaming process we used different stirring speeds $v_{\text{stirring}}$ and stirring times $t_{\text{stirring}}$ to study the influence of the shear forces on the bubble size and the bubble size distribution. We determined the bubble sizes and the bubble size distributions of the resulting hydrogel foams with an optical microscope.

As expected the bubble size decreases with both an increase of $v_{\text{stirring}}$ and $t_{\text{stirring}}$ (see Table 1 and Fig. 3). In other words, the
more energy is used for foam generation the smaller are the bubbles. The mean bubble diameter decreased from 289 \( \mu m \pm 170 \mu m \) to 168 \( \mu m \pm 54 \mu m \) when the stirring time is doubled (from 30 min to 60 min) at 1000 rpm (see Fig. 3a and c). Increasing the stirring speed from 400 rpm to 1000 rpm for the same stirring time of 60 min (see Fig. 3b and c) also reduced the mean bubble diameter by nearly about half (from 308 \( \mu m \pm 143 \mu m \) to 168 \( \mu m \pm 54 \mu m \)). Simultaneously, the bubble size distribution became narrower with decreasing mean bubble size. However, we observed no significant change of the mean bubble size (from 168 \( \mu m \pm 54 \mu m \) to 173 \( \mu m \pm 84 \mu m \)) when the stirring speed was increased from 1000 rpm to 1600 rpm (see Fig. 3c and d), while the bubble size distribution increased. The former observation, i.e. that the bubble size does not depend linearly on the stirring speed but levels off at a specific stirring speed, is in line with previous observations (see Fig. S1, ESI† in the study published by Schüler et al.\textsuperscript{21}).

The latter observation, i.e. the increase of the bubble size distribution, can be explained with an “overwhipping” of the foam: at the highest stirring speed the shear forces are so high that bubbles are destroyed directly after their formation.

In summary, longer stirring times \( t_{\text{stirring}} \) and higher stirring speeds \( v_{\text{stirring}} \) result in smaller bubble sizes and narrower bubble size distributions. At stirring speeds above 1000 rpm the bubble sizes do not change significantly but the samples are overwhipped, which is why we used \( v_{\text{stirring}} = 1000 \text{ rpm} \) and \( t_{\text{stirring}} = 60 \text{ min} \) for the synthesis of mineral plastic foams.

### 3.3. From hydrogel foams to mineral plastic foams

**Prerequisites for mineral plastic formation.** As already described, the generated foams (see Section 3.2) were gelled via cooling down to \( T = 16 \text{ °C} \). At this temperature gelation happens via entanglement of different polyacrylic acid (PAA) chains and hydrogen bonds between the carboxyl groups of

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**Fig. 3** Optical microscope pictures of hydrogel foams. The samples were foamed at \( T = 35 \text{ °C} \) at different stirring speeds and stirring times with a KPG mixer and subsequently gelled at \( T = 16 \text{ °C} \). The solutions consisted of 2.75 M PAA, 2.40 M CaCl\(_2\), 6.0 M HCl and 0.45 wt% Plantacare® 2000 UP. The foaming conditions and resulting bubble sizes are given in the legends and are listed in Table 1.
different PAA chains (see Fig. 4). Note that the hydrogel foam is still no mineral plastic foam! To obtain a mineral plastic foam the continuous phase of the foam must be converted from a mainly hydrogen bonded PAA network to a network in which the PAA chains are cross-linked by amorphous calcium carbonate (CaCO₃) nanoparticles¹⁻³ or by calcium ions⁴ (this work). Thus, the system needs to have a high pH, i.e. a high number of carboxylate groups, as well as accessible Ca²⁺ ions. The addition of a base causes the deprotonation of the carboxyl groups of the PAA in the hydrogel foam – the resulting carboxyl anions form a network through electrostatic interactions with the calcium ions, i.e. a mineral plastic foam is formed.

Challenge: finding a proper base. Sun et al.¹ used sodium carbonate for the complexation of the carboxylic groups of the PAA with amorphous calcium carbonate (CaCO₃) nanoparticles. However, sodium carbonate cannot be used for the synthesis of mineral plastic foams, because CO₂ is produced during deprotonation of the carboxyl groups, which would change the foam structure. Another base could be an alkali hydroxide.⁷ However, at high hydroxide ion concentrations calcium hydroxide (Ca(OH)₂) is formed which forms highly insoluble CaCO₃ with CO₂ in water. The precipitation of CaCO₃ reduces the amount of accessible Ca²⁺ ions and thus hinders the formation of mineral plastic in the continuous phase of the hydrogel foam. Indeed, we observed that mineral plastic foams are not formed if we use a 4.0 M LiOH solution for the complexation – instead a white precipitate, namely crystalline calcite (CaCO₃), is obtained (see Fig. S2 in ESI†). A third option is to use ammonia (NH₃) as base and it turned out that this is indeed the base of choice. In order to test the influence of the ammonia content on the structure of the mineral plastic foam we treated the hydrogel foam with ammonia solutions of different concentrations, namely

![Fig. 4](image-url) Schematic drawing of the conversion from a hydrogel foam (top) to a mineral plastic foam (bottom) obtained by increasing the pH-value. (top) At low pH-values the gel is formed via hydrogen bonding between the carboxyl groups of the PAA. Note that electrostatic crosslinking between the calcium ions and a small amount of carboxylate groups also contributes to gelation. This contribution, however, is not shown for simplicity. (bottom) At high pH-values the gel is formed via electrostatic interactions between the carboxylate anions of the PAA and the calcium ions. Chloride ions are not shown for simplicity.

25 wt% NH₃, 20 wt% NH₃, 18 wt% NH₃, and 15.5 wt% NH₃. The results are shown in Fig. 5.

As can be seen in Fig. 5, the opening degree of the solid foams becomes smaller, the pore surfaces get smoother and the mean pore diameter increases with decreasing ammonia content (from 25 wt% to 15 wt% NH₃). Starting with an open-cell foam with porous surfaces and a mean pore diameter of around 150–200 μm at 25 wt% NH₃ one ends up with a closed-cell foam with smooth surfaces and much larger pores (the number of pores is too low to determine a mean pore size) at 15 wt% NH₃. Furthermore, in the latter case, the pores are no longer spherical.

The swelling ability of mineral plastic had already been described by Sun et al.¹ When swollen with water, the mineral plastic transforms into a highly viscous liquid, which can flow. In our case, a flow of the continuous phase destroys the foam since the system wants to minimize its surface area leading to compact structures. In other words, the more water we offer (the lower the NH₃ concentration) the more pronounced the swelling should be, i.e. the more the foam structure is destroyed in a given period of time. This is indeed what we observe: the opening degree of the solid foam and the porosity of the pore surface decrease (see Fig. 5b and c) until they are completely lost (see Fig. 5d) with increasing amount of water in the base solution.

In summary, we were able to identify a proper base for the deprotonation of the carboxylic groups of the PAA. We observe that the foam structure changes significantly (is destroyed) with decreasing NH₃ content (increasing water content) in the base solution. We discuss this observation in terms of swelling and argue that water is the swelling agent, which is why the loss of structure goes along with an increasing amount of water.
(decreasing amount of NH₃) in the base solution. To prove this hypothesis, we changed the washing protocol and used ethanol–water mixtures instead of pure ethanol. The results will be shown and discussed in Section 4.1.

**Proof-of-concept.** For further investigations, we took the hydrogel foam made with a solution consisting of 2.7 M PAA, 2.4 M CaCl₂, 6.0 M HCl and 0.45 wt% Plantacare® 2000 UP with a KPG-stirrer foamed at the optimum foaming conditions with a stirring speed of $v_{\text{stirring}} = 1000$ rpm, a stirring time of $t_{\text{stirring}} = 60$ min, and a temperature of $T = 35$ °C. The continuous phase of the foam was physically gelled by cooling down to $T = 16$ °C directly after foaming. The resulting hydrogel foam (see Fig. 6, top) had a mean bubble size of around 170 μm ($168 \pm 54$ μm). Treating the hydrogel foam with a solution containing 25 wt% NH₃ we obtained the mineral plastic foam (see Fig. 6, bottom) we were aiming at with a mean pore size of around 220 μm ($223 \pm 190$ μm). The final step was washing with pure ethanol. Comparing the mean bubble with the mean pore size, one sees that we managed to make a solid foam out of the liquid template, i.e. the concept of “foam templating” described in the Introduction works. The larger mean pore size and pore size distribution (compared to the bubble size/bubble size distribution) is caused by coalescence and coarsening processes of the hydrogel foam during the treatment with 25 wt% NH₃. Nevertheless, we managed to synthesize a mineral plastic foam via foam templating! This “proof-of-concept” is the basis for future work, which should deal with the control of the pore size and the pore size distribution of mineral plastic foams.

4. Material properties

4.1. Swelling & self-healing capacity

Fig. 7 shows freeze-dried mineral plastic foams. The templating hydrogel foams were washed with ethanol containing different amounts of water before freeze-drying. With increasing amount of water the swelling of the hydrogel increases up until all bubbles are squeezed out. One can connect this behavior with the self-healing capacity of mineral plastic hydrogels: the bubbles disconnect the material, which, in turn, tries to “heal” the disconnections. Consequently, the surfaces become smoother due to an increased swelling of the templating hydrogel structure with increasing amount of water. Looking at Fig. 7, one sees the following trends with increasing amount of water in the washing process: (a) all pore surfaces are porous. (b) The outer surface of the sample becomes smoother but the pore surfaces are still porous. (c) The outer shell (200–400 μm) of the sample surface is closed-cell and the pore surfaces are smooth. Pore surfaces in the inner part of the sample are still porous. (d) Almost all pore surfaces are smooth.

The morphology of the sample surface was influenced by the water content of the ethanol–water mixture solution. The reference sample is the sample which was washed with...
absolute ethanol (see Fig. 5a and 7a). The sample surface of the sample washed with a solution consisting of 10 vol% water and 90 vol% ethanol was smooth compared to the sample washed with absolute ethanol (compare Fig. 7a and b). This smooth sample surface would allow a simple surface coating. When the water content of the ethanol solution was 20 vol%, the sample surface was closed-pored to a depth of 200–400 μm and the pore surfaces were smooth in this area. If the sample was washed only once with pure water for few seconds, then almost the entire pore surface was smooth. This type of mineral plastic foam would be an alternative material for thermal insulation due to the closed pore structure with smooth pore surface.

The low salt content in the ethanol–water mixture can lead to the diffusion of water along the concentration gradient into the mineral plastic foam. This binds the water, which is why the mineral plastic foam swells at different depths depending on the water content. The mineral plastic behaves like a highly viscous liquid in the swollen state. The swollen mineral plastic flows to minimize the surface.

The above results show that variation of the NH₄ concentration and the composition of the washing mixture allows to obtain mineral plastic foams of very different structures. This, in turn, means that different properties and thus applications of the foams should be feasible. For example, open-cell foams with a porous pore surface could be an interesting material for sound insulation, while closed-cell foam could be an alternative material for thermal insulation.

### 4.2. Pyrolysis: Ca²⁺-content of mineral plastic foams

In the TGA curves (see Fig. 8), the evaporation of water in the mineral plastic foams can be seen first. PAA is pyrolyzed at T = 450 °C. Thereafter, another pyrolysis step appears. The thermal decomposition of calcium carbonate (CaCO₃) to carbon dioxide (CO₂) and calcium oxide starts at T = 700 °C. Since no carbonate was used in the synthesis the carbonate must be formed during the pyrolysis of PAA from the carboxylate groups and the complexed calcium ions as it was also observed previously. The mineral plastic foam contained 38 wt% CaCO₃ using a 25 wt% ammonia solution and 37 wt% CaCO₃ by using a 12 wt% ammonia solution for complexing the calcium ions with the carboxylate groups of the PAA (see Fig. 8). The CaCO₃ content is consistent with the results of Sun et al. who report a CaCO₃ content of 39 wt% in their mineral plastic.

### 4.3. Mechanical properties of mineral plastic foams

A Young’s modulus of (48.3 ± 0.2) MPa was determined via the slope of the linear part of the stress–strain curve (see Fig. S3 in ESI†). According to Gibson and Ashby, the relative Young’s modulus (Efoam/Epolymer) is proportional to the squared relative density (ρfoam/ρpolymer)² which is indeed the case (see ESI†).

### 4.4. Non-flammability and recyclability of mineral plastic foams

Firstly, the mineral plastic foam is not flammable as illustrated in the video “Non Flammability” provided in the ESI†. As described in Section 4.2, the PAA thermally decomposes when the mineral plastic foam is exposed to an open flame for a few seconds. The high inorganic content prevents the igniting of the mineral plastic foam and – equally important – the decomposition leads to the production of CO₂, which acts as a fire extinguisher.

Secondly, the mineral plastic foam can be dissolved – and thus recycled – simply by adding an acidic solution. In the video “Recyclable” provided in the ESI† we used a 6 M HCl solution to speed up the dissolution. However, any other acidic solution with a lower acid content would also work – it would simply take longer. The reason for the recycability is the CO₂–HCO₃⁻–CO₃²⁻ equilibrium. At pH < 4 all HCO₃⁻ and CO₃²⁻ ions are dissolved and produce carbon dioxide, while at pH > 12 only CO₃²⁻ forms from the CO₂ in air. Since we work with ammonia concentrations between 15–25%, our pH is always >12, i.e. CaCO₃ is formed with the existing calcium ions. Vice versa, if the pH is decreased to <4, no HCO₃⁻ and CO₃²⁻ can exist and CO₂ evaporates.

### 5. Conclusions & outlook

We have synthesized the first solid foam consisting of mineral plastic. The main obstacle was to increase the PAA and CaCl₂ concentration of the original mineral plastic (0.1 M) such that we obtain a mechanically stable foam. This was solved by decreasing the pH to ~1. At this low pH no coarcervate was formed, i.e. we were able to foam a homogeneous solution which contained 2.7 M PAA and 2.4 M CaCl₂, i.e. 27 times more PAA as compared to the original system.

Cooling from 35 to 16 °C one obtains a hydrogel foam, whose continuous phase had to be converted to mineral plastic by a pH increase using ammonia solution. The mineral plastic foam was not flammable and could be dissolved by addition of HCl. The pore size and structure could be varied by multiple
parameters such as the stirring speed, the surfactant concentration but also the ammonia concentration or the water content in the alcohol washing solution. Playing around with these tuning parameters one can synthesize a range of pore sizes as well as open-pore and closed-pore structures. The study of structure–property relationships is beyond the scope of the present study. However, due to the wide structural variations, we expect a wide range of both mechanical and insulation (thermal or sound) properties. Future work should focus on the continuous production of such foams with adjustable, monodisperse pores, which would enable us to determine structure–property relationships. We emphasize that it is possible to synthesize the new material in aqueous solution at ambient conditions, i.e. without hazardous organic solvents and without energy supply. However, for large scale production, a way to avoid the need for the high amount of HCl must be found.

Conflicts of interest
The University of Konstanz and Stuttgart have registered a national patent for the process to produce mineral plastic foams described in this article (DE 102020002914).

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Notes and references