



Cutting-edge research for a greener sustainable future

Accepted Manuscript

This article can be cited before page numbers have been issued, to do this please use: L. Zhang, R. Liang, C. Hang, H. Wang, L. Sun, L. Xu, D. Liu, Z. Zhang, X. Zhang, F. Chang, S. Zhao and W. Huang, Green Chem., 2020, DOI: 10.1039/C9GC04033A.



This is an Accepted Manuscript, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this Accepted Manuscript with the edited and formatted Advance Article as soon as it is available.

You can find more information about Accepted Manuscripts in the Information for Authors.

Please note that technical editing may introduce minor changes to the text and/or graphics, which may alter content. The journal's standard Terms & Conditions and the Ethical guidelines still apply. In no event shall the Royal Society of Chemistry be held responsible for any errors or omissions in this Accepted Manuscript or any consequences arising from the use of any information it contains.



rsc.li/greenchem

ARTICLE

Received 00th January 20xx, Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

www.rsc.org/



Lei Zhang, ^a c Rongran Liang, ^b Cheng Hang, ^a Haiying Wang, ^a Lin Sun, ^c Lei Xu, ^a Dairong Liu, ^a Zhenyi Zhang, ^d Xingmin Zhang, ^e Feifan Chang, ^a Shengyu Zhao, ^a and Wei Huang^{* a f}

Abstract: Porous crystalline materials, such as porous organic cages (POCs) and covalent organic frameworks (COFs), are important in a wide range of applications such as gas storage/separation, sensing and catalysis. The conventional synthetic approach for imine-based POCs and COFs usually involves the use of organic solvents/acid catalysts (such as AcOH or TFA). However, synthesizing and growing POCs crystals and COFs crystallites with enhanced crystallinity are not an easy-to-perform process, in which many reaction parameters need to be screened. To overcome these problems, we have proposed herein a facile and green synthetic strategy by adopting H₂O/organic solvent/MOH (M = Na, K, Cs) as the reaction media to produce a series of phenol-based POCs and COFs. X-ray crystallography and molecular simulations have been used to confirm their structures in addition to NMR, mass and FT-IR spectra, and gas sorption experiments reveal their porosity and sorption property. This new approach provides not only an efficient and alternative way to synthesize high crystalline POCs and even COFs but also an insight into the crystallization process of these two kinds of porous materials especially in the hydrous media.

Introduction

Published on 13 March 2020. Downloaded by Uppsala University on 3/13/2020 9:17:47 PM

Porous organic cages (POCs) or porous molecules as a new type of porous materials have emerged and made rapid developments in the past decade.¹⁻¹¹ In contrast to porous extended frameworks which are defined by strong and directional coordination or covalent bonds, these discrete organic cage molecules usually assemble into well-defined porous structures via weak intermolecular interactions to produce interconnected pores. And porous molecular crystallization and crystal packing are generally strongly

sensitive to solvent molecules¹²⁻¹³ as well as molecular recognition interactions.¹⁴⁻¹⁵ In general, the synthesis of POCs through imine condensation reactions is performed in suitable organic solvents with or without acid catalysts. However, screenings of suitable organic solvents remain tedious and some organic solvents are not environmentally friendly. It is still a common challenge to obtain high-quality single crystals of POCs suitable for X-ray diffraction characterization in some cases. Thus, developing environment-friendly and more facile method is an interesting field of research.

The same situation also exists in the synthesis of covalent organic frameworks (COFs) which are two- or threedimensional porous crystalline frameworks held together by covalent bonds.¹⁶⁻²⁴ The most extensively used synthetic route for the preparation of COFs is still solvothermal conditions, in which a variety of experimental parameters such as solvent combinations and ratios, the concentration of catalysts and reaction temperature are crucial to obtain COFs with enhanced crystallinity. In most cases, it is a tedious procedure to optimize the parameters and it is not easy to find suitable synthetic conditions. From a materials perspective, solvothermal reactions still remains big challenges such as scalability and processability in order to achieve practical applications of COF-based materials. To address the challenge, some other methods have been explored recently including triflates-catalization,25 aniline-modulated metal crystallization,²⁶ seed growth&second polymerzation,²⁷ and ptoluenesulfonic acid-catalization.28



^{a.} State Key Laboratory of Coordination Chemistry, Nanjing National Laboratory of Microstructures, School of Chemistry and Chemical Engineering, Nanjing University, Nanjing, Jiangsu Province, 210093, P. R. China. E-mail: whuang@nju.edu.cn

^{b.} Key Laboratory of Synthetic and Self-Assembly Chemistry for Organic Functional Molecules, Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences, 345 Lingling Road, Shanghai 200032, P. R. China

^c Key Laboratory for Advanced Technology in Environmental Protection of Jiangsu Province, Yancheng Institute of Technology, Yancheng 224051, P. R. China

^{d.} Bruker Scientific Technology Co. Ltd, 66 Xixiaokou Road, Beijing 100081, P. R. China

^e Shanghai Synchrotron Radiation Facility, Shanghai Institute of Applied Physics, Chinese Academy of Sciences, 239 Zhangheng Road, Pudong New Area, 201204, P. R. China

^{f.} Shenzhen Research Institute of Nanjing University, Shenzhen, Guangdong Province, 518057, P. R. China

Electronic Supplementary Information (ESI) available: Detailed synthetic procedure for four POCs and four COFs, NMR and FT-IR spectra, TGA diagrams, optical microscope images, additional gas adsorption data, PXRD patterns, structural simulations and characterization data for related compounds (PDF). X-ray crystallographic data in CIF format for CCDC 1573819-1573821. See DOI: 10.1039/x0xx00000x

Recently, green synthesis via mild conditions and harmfulless or nontoxic solvents especially aqueous systems, as an easy-to-operate, sustainable, scalable and eco-friendly protocol, has drawn extensive attention in the laboratory an industry. Both POCs and COFs are needed to be synthesized by using a facile, mild and green condition. Inspired by the green synthesis, some research groups have exploited a fast, simple and scale-up green synthesis of COFs.²⁹⁻³² In addition, it is well-known that both POCs and COFs have been established based on the dynamic covalent chemistry (DCC) and many building units used in the synthesis of POCs can also be applied to COFs. In this regard, there should be no significant difference for them. So, is there a facile and green synthetic approach suitable for both POCs and COFs at the same time?

ARTICLE

Published on 13 March 2020. Downloaded by Uppsala University on 3/13/2020 9:17:47 PM.



Fig. 1 Schematic representation for the synthetic processes of the POCs and COFs via organic solvent/water/KOH approach.

In this work, we have developed a general, facile and green solution-phase synthetic strategy for constructing a family of highly crystalline POCs and COFs, particularly including three reported β -ketoenamine linked COFs. We adopt a wholly new reaction condition, organic solvent/water/MOH (M = Na, K, Cs), which is different from the typical systems comprising of organic solvents and acidic catalysts (Figure 1). The synthesis of phenol-based POCs or COFs can be facilely achieved (via solvent evaporation or in-situ precipitation, respectively) by refluxing an organic solvent/water solution of monomers in the presence of MOH (M = Na, K, Cs). Particularly, this method is believed to offer an easy and efficient way to grow single crystals of some POCs and COFs in a large scale, which are hard to be obtained by using the conventional methods.

Results and discussion

Synthesis and characterization of four POC crystals.

To better illustrate our synthetic approach, we have adopted *o*-hydroxyaryl arylaldehydes (**1-3**) and 1,3,5-triformylphloroglucinol (**Tp**) as monomers to construct four POCs and four COFs, respectively. Four POCs were synthesized by the condensation reactions of three *o*-hydroxy arylaldehydes (**1-3**) with (1*S*,2*S*) or (1*R*,2*R*)-cyclohexanediamine in a [3+6], [2+4] or [4+8]

cycloimination (Figure 2). The syntheses were performed dinine mixture of ethanol and water in the presence of MOH (M=CONA33K, Cs). Firstly, tetraaldehyde and 2 equiv. of KOH were dissolved in a mixture of EtOH/H₂O (in the rang of 1:1~3:1) and then 2 equiv. of (1*S*,*2S*) or (1*R*,*2R*)-cyclohexanediamine was added. The mixture was refluxed for additional 24 h. The resulting clear solution was allowed to slow evaporation in air at room temperature over several hours to weeks to afford single crystals of the organic cage. It is noted that both of the monomers were fully soluble in EtOH/H₂O (pH \approx 6~8) during the imine condensation and the homogeneous reaction conditions gave organic cages as red or yellow crystals (See ESI for details).



Fig. 2 Schematic illustration of the synthesis of the POCs and their structures. (a) Synthesis of the POCs from tetraaldehydes (1-3) and cyclohexanediamine. (b) Chemical structures of the four POCs. (c) Crystal structures for NC1-*S*, NC2-*R* and NC4-*R*.

NC1-S was obtained by the imine condensation reaction between tetraaldehyde **1** and (1*S*,2*S*)-cyclohexanediamine in the presence of EtOH/H₂O/MOH (M = K, Cs). Red block single crystals of **NC1-S** were isolated from a mixture of ethanol and water in a yield of 43% (see Section S-2 and Figure S27) without any other by-products. Its ESI-MS spectrum-displays the [3+6] cage structure with a molecular-ion peak at m/z = 1364.17 (Figure S21). Crystallographic analysis shows that the [3+6] tubular cage **NC1-S** crystallizes in the tetragonal space group of $P4_32_12$ (Figure 2c and Table S-1), which is different from our previously reported racemic **NC1**.³³ Pore size distributions (5.0, 5.7, and 6.5 Å) calculated by non-local density functional

ARTICLE

Journal Name

theory from Ar sorption analysis for **NC1-S** (Figure S40) are consistent with the structural measurement (Figure S32).

NC2-R and NC3-R were synthesized by the condensation reaction between tetraaldehyde 2 and (1R,2R)-cyclohexanediamine in [2+4] and [3+6] cycloimination in the presence of EtOH/H₂O/MOH (M = Na, K, Cs). They can be directly collected from their respective mother solutions in pure phase by controlling evaporation temperature (see SI for detailed experimental methods). NC2-R was isolated directly as yellow block crystals in 35% yield (Figure S27). It adopts [2+4] configuration in which the two tetraaldehyde components are nearly perpendicular to each other and four (1R,2R)-cyclohexanediamine units lie on every corner of the cage (Figures 2b-c). NC2-R exhibits compressed tetrahedral configuration similar to that of CC3,14 although the cage window and cavity diameters are relatively smaller. In contrast to polyhedral morphology of NC2-R crystals, NC3-R crystallizes as needle-like crystals in a yield of 44% within several hours (Figure S27). However, no single crystals of NC3-R suitable for X-ray crystallographic analysis could be obtained. As an instead, the structure of NC3-R was confirmed by the presence of a clear positive [3+6] molecularion peak at m/z = 1407.00 in the ESI-MS (Figure S23), as well as related FT-IR, ¹H and ¹³C NMR spectra (see SI), which indicate that NC3-R may be analogous to the configuration of NC1-S (Figure 2b).

NC4-S crystals were obtained in a yield of 30% by the condensation reaction between tetraaldehyde **3** and (1*R*,2*R*)-cyclohexanediamine in the presence of EtOH/H₂O/MOH (M = Na, K, Cs). X-ray structural analysis (Figure 2) and ESI-MS spectrum (Figure S24) of **NC4-***R* reveal that it is a [4+8] organic cage in the '*Z*' geometry, like a double-[2+4] cage. So it comes to a conclusion that subtle alterations of the tetraaldehyde precursors could result in totally different cage configurations. To control the formation of these cage structures, the design of the tetraaldehedes, in particular the angle between the two adjacent phenyl planes, is very important. The ideal angles for the construction of [3+6] configuration may lie in the range 116~180°. However, The resulting cage topologies not only depend on the angles or chemical functionality tice of the precursors, but also on multiple parameters such as softwart effect, temperature, and molecular interactions in the system. Additionally, no keto-enol tautomerism is observed in the structures of four imine cages, in which all compounds adopt the same enol form in their solid state.

Synthesis and characterization of COFs.

We also successfully expand our stratege to synthesize four phenol-based COFs including one new COF (COF-NJU-1) and three reported β -ketoenamine linked COFs (**TpPa-1**, **TpBD** and TpTph),^{25,34-35} as seen in Figure 3. The synthetic protocol for the COFs was the same as that described aboved for the above POCs except the organic solvent component (Figure S33). Taking COF-NJU-1 as an example, tetraaldehyde 1 and KOH (1:2, molar ratio) were dissolved in water to form a clear solution, and a N,N'diethylformamide (DEF) solution of benzidine (2 equiv. corresponding to tetraaldehyde 1) was added under stirring to afford a crystalline red-brown precipitate (73% yield) after 24 h (see SI for detailed data). It is noted that ethanol may be not a suitable choice of solvent in this case because EtOH/H₂O/KOH combination did not result in the formation of crystalline COF-NJU-1. We therefore screened several organic solvents including acetonitrile, 1,4-dioxane, N,N'-dimethylformamide (DMF) and DEF for preparing COF-NJU-1 and found that DEF/H₂O/KOH was the optimal combination (Figure 3a).

To determine the crystal structure of **COF-NJU-1**, both experimental and theoretically simulated PXRD patterns were collected. The simulations were carried out by using Materials Studio version 7.0. Similar to the previously reported 2D dual-pore COF-BTA-BZ,³⁶ the condensation of **1** and benzidine could theoretically produce two possible frameworks. One holds a dual-pore structure and the other possesses a single-pore skeleton (Scheme S1). The formation of a single-pore COF could be ruled out



ARTICLE

Journal Name

Fig. 3 Synthetic scheme for the construction of four COFs and their PXRD patterns. (**A**) Synthesis of **COF-NJU-1** using tetraaldehydes 1 and benzidine under DEF/H₂O/KOH condition. (**B**) PXRD patterns of **COF-NJU-1** experimentally observed (black), refined (red), Simulated XRD patterns of dual-pore AA, dual-pore AB and difference plot between the experimental and refined PXRD patterns. (**C**) The structure of **COF-NJU-1** in AB and AA stacking modes, respectively. (**D**) Schematic representation of the synthesis of **TpPa-1**, **TpBD** and **TpTph** under DMF/H₂O/KOH condition. (**E-G**) PXRD patterns of **TpPa-1**, **TpBD** and **TpTph** experimentally observed (black), refined (red), simulated XRD patterns of dual-pore AA (orange), dual-pore AB (blue) and difference plot between the experimental and refined PXRD patterns (gray). (Inset images showing the photographs of four COFs).

by comparing the experimental PXRD pattern of the as-obtained crystallites with the simulated one of the single-pore isomer, which clearly indicated significant difference between them (Figure S46). For the dual-pore COF, simulated PXRD patterns of two distinguishable packing fashions (eclipsed (AA) and staggered (AB)) were generated, as shown in Figure 3b. Comparison between them and the experimental PXRD profile revealed that COF-NJU-1 should adopt AA stacking. The experimental PXRD exhibited diffraction signals at 2.70°, 4.72°, 5.46°, 7.24°, 9.89 ° and 26.14°, which were assigned to 100, 110, 200, 210, 130 and 001 facets, respectively. In order to further corroborate the stacking model of COF-NJU-1, pore size distribution profile was generated from HK theory based on N₂ sorption data (Figure S41). It revealed the presence of two main pore size distributions at ~10.6 and 24.3 Å , which were consistent with the calculated values of 9.9 and 23.2 Å for the dual-pore COF with eclipsed packing structure, suggesting that the 2D layers of COF-NJU-1 adopted eclipsed stacking. Pawley refinement was performed to determine the unit cell parameters of COF-NJU-1 with AA stacking model, which yielded a = b = 39.10 Å, c = 3.38 Å, $\alpha = \beta =$ 90°, and γ = 120°, with factors of R_P = 1.56% and R_{WP} = 2.26%. The difference plot indicates that the experimental PXRD pattern is well reproduced by the refined pattern (Figure 3b). The as-synthesized COF-NJU-1 was characterized by Fourier transform infrared spectroscopy (FT-IR). The spectrum of COF-NJU-1 showed the nearly complete disappearance of C=O resonance, indicating that tetraaldehyde 1 was mostly consumed during the reaction. In addition, a strong stretching vibration band at 1625 cm⁻¹ was observed, confirming the formation of C=N linkage (Figure S36). The solid-state cross-polarization with magic angle spinning (CP/MAS) $^{13}\mbox{C}$ NMR spectrum exhibited a resonance signal at 168.4 ppm, corresponding to the chemical shift of imine carbon atoms in COF-NJU-1 (Figure S18). Scanning electron microscopy (SEM) of asprepared COF powders showed that the COF crystallites have flower-like morphology. (Figure S34a). In addition, the transmission electron microscopy (TEM) images showed rod-like crystals with a diameter of ~30 nm (Figure S34e).

To further demonstrate the generality of this solution-phase approach, three reported β -ketoenamine linked COFs were prepared via the same synthetic conditions. As far as we are aware, β -ketoenamine linked COFs have been synthesized via various approaches^{28,34-35} and investigated as proton-conductive membranes,³⁷ catalyst supports³⁸ and energy storage devices,³⁹ due to their high hydrolytic and chemical stability. In this work, **TpPa-1**, **TpBD** and **TpTph** can be obtained as red or orange crystallites-with high yields of 89, 83 and 86% under the same condition of DMF/H₂O/KOH, respectively (Figures 3d, S33). It is worth emphasizing that the organic solvent component is DMF in these three cases. The obtained PXRD patterns of the **Tp** series COFs show relatively high intensive first peaks at 4.63°, 3.44°, 2.69° (±0.02, 2 ϑ) for **TpPa-1**, **TpBD** and **TpTph**, which could be attributed to the reflection from (100) planes (Figures 3e-g). The experimental PXRD patterns are in good agreement with the simulated AA eclipsed stacking models, which match well with the previous reports in literature.²⁸ FT-IR spectra of the four COFs also agree well with the reported ones (Figure S37), in which the strong peaks at ~1580 cm⁻¹ (-C–N) and 1250 cm⁻¹ (-C=C) show the formation of the β -ketoenamine linked COFs. In addition, the SEM and TEM images exhibit the ribbon-like morphology for all three **Tp** series COFs (Figure S34).



Fig. 4 (a) PXRD patterns of **COF-NJU-1** before and after the 7-day treatment with organic solvents, HCl and NaOH. (b) N_2 adsorption and desorption isotherms of three POCs (**NC4-***R* was measured by Ar) and four COFs. PXRD patterns of **COF-NJU-1** synthesized in different ratios of (c) KOH, and (d) DEF/H₂O.

Porosity

All POCs show good hydrolytic stability except for **NC3-R** and **NC4-R**, which can be evidenced by their consistent PXRD patterns before and after the immersion in pure water up to one week (Figure S25). **COF-NJU-1** also shows good stability in water, organic solvents and even 1 M HCl (Figures 4a, S26). All of the desolvated POCs were obtained by using supercritical carbon dioxide activation, and PXRD measurements were performed to check the structural stability of all samples before and after desolvation (Figure S19). The thermogravimetric analysis (TGA) of all POCs and COFs in N₂ atmosphere showed thermal stabilities up to 300 C°, indicating the high thermal stability of theses materials (Figures S38, S39), similar to those reported by other groups. The four COFs were activated at

180°C under a high vacuum to provide the activated COFs, and PXRD measurements were performed to check the structural stability of all samples before and after gas sorption. (see Section S-7 in SI). The porosity of the materials has been investigated. As displayed in Figure 4b, the four POCs show type-I N₂ (or Ar) sorption isotherms, where the Brunauer-Emmett-Teller (BET) surface areas of NC1-S, NC2-R, NC3-R, and NC4-R (Ar) were calculated to be 779.0, 3.7, 213.1 and 455.6 $m^2\ g^{\mbox{-}1}\mbox{, respectively. Argon was used as the}$ probe molecule for the sorption measurement of NC4-R because of its weak N₂ adsorption at 77 K (Figure S38), which may be attributed to the existence of structural changes or slow N₂ diffusion.⁴⁰⁻⁴¹ The four COFs also exhibit type-I N₂ sorption isotherms (Figure 4b), from which the BET surface areas of COF-NJU-1, TpPa-1, TpBD and TpTph were calculated to be 1080.8, 1247.4, 768.7 and 658.4 m² g⁻¹, respectively. Those values of BET for TpPa-1, TpBD and TpTph are lower than those of reported TpPa-1 (1432), TpBD (1400) and TpTph (1020) synthesized via an organic terracatta process.²⁸ The possible reason is attributed to the discrepancy of activation process during solvent removal from the pores or the COF crystallinity.

Discussion

Published on 13 March 2020. Downloaded by Uppsala University on 3/13/2020 9:17:47 PM.

Many attempts to produce all the four cages via traditional syntheses (organic solvents/acid catalysis) have also been performed in a series of organic solvents. Only flower-like polycrystals NC1-S could be crystallized from DMF/MeOH or DMF/1,4-dioxane, but such polycrystals were hard to be characterized by single-crystal XRD (Figure S28). Attempts to crystallize NC2-R, NC3-R and NC4-R under conventional experimental conditions always led to amorphous powders, even after careful screening of a series of organic solvents (Table S-2). In contrast, the single crystals of four POCs could be easily obtained by using the organic solvent/ H_2O/MOH (M = Na, K, Cs) method. Obviously, alkali hydroxide and water played important roles during the consensation synthesis especially in the crystallization process. To further support our hypothesis, some control experiments have been performed. Reactions of tetraaldehyde monomers 1 and (15,25) or (1R,2R)-cyclohexanediamine in EtOH/H₂O without adding KOH resulted in a cloudy solution since tetraaldehyde monomers and the resultant cages were hard to dissolve in EtOH/H₂O. It is hard to grow high-quality single crystals under such a heterogeneous condition. When 2 equivalents of potassium hydroxide was introduced into the afore-mentioned suspension, the mixture became clear quickly and could give rise to POC crystals via evaporation over a period of time. We think this dissolution process is a phenol-involved acid and alkali neutralization (saltforming reaction), and the resultant salts are easy to dissolve in the mixture of ethanol and water. However, some procuors with large chromophore which tend to aggregate may be not soluble in such polar reaction solvents. To further investigate the optimal amount of KOH during the the COF synthesis, COF-NJU-1 was chosen as a model compound. As shown in Figure 4c, PXRD patterns of COF-NJU-1 obtained from varied KOH ratios indicate that the optimal amount may lie in the rang of 2~6 equiv. In addition, NaOH and CsOH had the same effects as KOH in some cases, and the only difference is that their corresponding phenolates have different solubility in water/ethanol. Namely, sodium phenolate that the lowest solubility, while cesium phenolate is that the phenolate is the middle. Such a trend in solubility is the same as that of their basicity (NaOH < KOH < CsOH).

Water is also found to be important for accessing high quality POC crystals and COF crystallites. We also carried out control experiments to prepare POCs by strring and heating a DMF/EtOH/KOH solution tetraaldehydes of and cyclohexanediamine but without the presence of water (DMF was used owing to its better dissolving capacity for alkali metal phenoxides). However, no single crystals could be formed by slow evaporation even over a period of long time. Similar results were found in the synthesis of COFs. In addition, the PXRD results of the different products obtained from varying the ratios of DEF/H₂O suggest that the optimal ratio of DEF/H₂O may lie in the rang of 1:1~3:1 for the formation of COF-NJU-1 (Figure 4d), in accordance with aformentioned results in the synthesis of POCs.

To our knowledge, water as an agent to regulate the chemical equilibrium was also realized in some COFs' synthesis. Wan et al.42,43 demonstrated that the introduction of water into the reaction system could greatly improve the formation of highly ordered surface covalent organic frameworks (SCOFs). They thought that a small amount of water could improve the reversibility of reaction and self-healing abilities of the SCOFs. Dichtel and co-workers⁴⁴ also reported that the addition of water was necessary to generate the imine COF, and the high volume percentage of water (up to 17%) could reliably induce better crystallinity and maintain high yields. In contrast, the same phenomenon was observed in our reaction system but the water contents could reach as high as 50% volume percentage (see section S2 in SI). Actually, water in our synthetic system plays important roles as a solvent to dissolve tetraaldehyde salts besides as an agent to adjust the reversibility of imine condensation. More importantly, the introduction of water is vital and indispensable for the crystallization process of our POCs and COF with high crystallinity.

Actually, the POCs and COFs herein are constructed under the basic (or weak basic) and aqueous solution, which is different from the typical acid-catalyzed imine condensation reactions. In the synthesis of imine-involved crystalline materials, Lewis or Bronsted acid (such as CF₃CO₂H or CH₃CO₂H) is generally employed to catalyze and facilitate the imine formation and exchange, and a small amount of water, coming from the reaction product or even external addition, is found to modulate the reaction equilibrium. In our phenol-based imine condensation system, the possible process could be divided into two steps: First, tetraaldehde monomers and NaOH (or KOH, CsOH) could form the 'tetraaldehyde salts', which make them easily soluble in organic solvent/H₂O to produce a homogeneous solution; Second, the 'tetraaldehyde salts' react with diamines to produce crystalline cages or framework structures in the presence of a large amount of water. In this dynamic covalent equilibrium, we think that the introduction of alkali hydroxide and water would mitigate the imine condensation rate, there are two possible reasons to explain this process: (i) the solvated 'tetraaldehyde salts' surrounded by water molecules provide "barriers" to somehow weaken the attack of diamines; (ii) the formation of imines proceeds not smoothly in water-containing

system due to the risk of hydrolysis. However, the decrease of imine condensation rates in our case is believed to be beneficial for the formation of high crystalline POCs and COF since it allows for the sufficient rearrangement and self-correction. As for the removal of alkali ions in the final products, it is likely that the alkali phenolates are neutralized by the carbon dioxide from air during the slow evaporation and crystallization process.

Conclusion

In conclusion, we have demonstrated an efficient and green solution-phase synthetic method for the crystal growth of phenol-based POCs and COFs. The discovery of organic solvent/water/MOH (M = Na, K, Cs) synthetic method offers not only a simple solution-phase strategy suitable for POCs and COFs simultaneously, but also uncovers a corner about crystallization process of POCs and COFs especially in the hydrous media. It also opens up new possibilities for the exploration of more POCs and COFs as well as some other phenol-based materials.

Conflicts of interest

The authors declare no competing financial interests.

Acknowledgements

Published on 13 March 2020. Downloaded by Uppsala University on 3/13/2020 9:17:47 PM.

We thank Prof. Xin Zhao from Shanghai Institute of Organic Chemistry (Chinese Academy of Sciences) for his very helpful advices. This work was supported by the National Natural Science Foundation of China (Nos. 21871133 and 21801127), the Natural Science Foundation of Jiangsu Province (Nos. BK20191024 and BK20171334), and Science, Technology and Innovation Commission of Shenzhen Municipality (No. JCYJ20180307153251975).

References

- 1. D. Xu and R. Warmuth, J. Am. Chem. Soc., 2008, **130**, 7520-7521.
- 2. X. Liu, J. Sun and R. Warmuth, *Tetrahedron*, 2009, **65**, 7303-7310.
- T. Tozawa, J. T. A. Jones, S. I. Swamy, S. Jiang, D. J. Adams, S. Shakespeare, R. Clowes, D. Bradshaw, T. Hasell, S. Y. Chong, C. Tang, S. Thompson, J. Parker, A. Trewin, J. Bacsa, A. M. Z. Slawin, A. Steiner and A. I. Cooper, Nat. Mater., 2009, 8, 973-978.
- J. R. Holst, A. Trewin and A. I. Cooper, *Nat. Chem.*, 2010, 2, 915-920.
- Y. H. Jin, B. A. Voss, R. D. Noble and W. Zhang, Angew. Chem. Int. Ed., 2010, 49, 6348-6351.
- Q. Wang, C. Yu, C. Zhang, H. Long, S. Azarnoush, Y. Jin and W. Zhang, *Chem. Sci.*, 2016, 7, 3370-3376.
- H. Ding, Y. Yang, B. Li, F. Pan, G. Zhu, M. Zeller, D. Yuan and C. Wang, *Chem. Commun.*, 2015, **51**, 1976-1979.

- M. W. Schneider, H.-J. Siegfried Hauswald, <u>R. Stall and</u> M. Mastalerz, *Chem. Commun.*, 2012; 48:09863:9863:33A
- G. Zhang, O. Presly, F. White, I. M. Oppel and M. Mastalerz, *Angew. Chem. Int. Ed.*, 2014, **53**, 1516-1520.
- N. Giri, M. G. Del Popolo, G. Melaugh, R. L. Greenaway, K. Ratzke, T. Koschine, L. Pison, M. F. C. Gomes, A. I. Cooper and S. L. James, *Nature*, 2015, **527**, 216-220.
- A. G. Slater, M. A. Little, A. Pulido, S. Y. Chong, D. Holden, L. Chen, C. Morgan, X. Wu, G. Cheng, R. Clowes, M. E. Briggs, T. Hasell, K. E. Jelfs, G. M. Day and A. I. Cooper, *Nat. Chem.*, 2017, **9**, 17-25.
- 12. X. Liu and R. Warmuth, *J. Am. Chem. Soc.*, 2006, **128**, 14120-14127.
- T. Hasell, J. L. Culshaw, S. Y. Chong, M. Schmidtmann, M. A. Little, K. E. Jelfs, E. O. Pyzer-Knapp, H. Shepherd, D. J. Adams, G. M. Day and A. I. Cooper, *J. Am. Chem. Soc.*, 2014, **136**, 1438-1448.
- 14. T. Hasell, S. Y. Chong, K. E. Jelfs, D. J. Adams and A. I. Cooper, *J. Am. Chem. Soc.*, 2012, **134**, 588-598.
- T. Hasell, S. Y. Chong, M. Schmidtmann, D. J. Adams and A. I. Cooper, Angew. Chem. Int. Ed., 2012, 51, 7154-7157.
- A. P. Côté, A. I. Benin, N. W. Ockwig, M. O'Keeffe, A. J. Matzger and O. M. Yaghi, *Science*, 2005, **310**, 1166-1170.
- X. Han, J. Zhang, J. Huang, X. Wu, D. Yuan, Y. Liu and Y. Cui, Nat. Commun., 2018, 9, 1294.
- S.-L. Cai, Y.-B. Zhang, A. B. Pun, B. He, J. Yang, F. M. Toma, I. D. Sharp, O. M. Yaghi, J. Fan, S.-R. Zheng, W.-G. Zhang and Y. Liu, *Chem. Sci.*, 2014, **5**, 4693-4700.
- 19. T.-Y. Zhou, S.-Q. Xu, Q. Wen, Z.-F. Pang and X. Zhao, *J. Am. Chem. Soc.*, 2014, **136**, 15885-15888.
- Z.-F. Pang, T.-Y. Zhou, R.-R. Liang, Q.-Y. Qi and X. Zhao, Chem. Sci., 2017, 8, 3866-3870.
- 21 G. Lin, H. Ding, R. Chen, Z. Peng, B. Wang and C. Wang, J. Am. Chem. Soc., 2017, **139**, 8705-8709.
- 22. S.-Y. Ding and W. Wang, *Chem. Soc. Rev.*, 2013, **42**, 548-568.
- 23. P. J. Waller, F. Gándara and O. M. Yaghi, *Acc. Chem. Res.*, 2015, **48**, 3053-3063.
- N. Huang, P. Wang and D. Jiang, *Nat. Rev. Mater.*, 2016, 1, 16068.
- M. Matsumoto, R. R. Dasari, W. Ji, C. H. Feriante, T. C. Parker, S. R. Marder and W. R. Dichtel, *J. Am. Chem. Soc.*, 2017, **139**, 4999-5002.
- T. Ma, E. A. Kapustin, S. X. Yin, L. Liang, Z. Zhou, J. Niu, L.-H. Li, Y. Wang, J. Su, J. Li, X. Wang, W. D. Wang, W. Wang, J. Sun and O. M. Yaghi, *Science*, 2018, **361**, 48-52.
- A. M. Evans, L. R. Parent, N. C. Flanders, R. P. Bisbey, E. Vitaku, M. S. Kirschner, R. D. Schaller, L. X. Chen, N. C. Gianneschi and W. R. Dichtel, *Science*, 2018, **361**, 52-57.
- 28. S. Karak, S. Kandambeth, B. P. Biswal, H. S. Sasmal, S. Kumar, P. Pachfule and R. Banerjee, *J. Am. Chem. Soc.*, 2017, **139**, 1856-1862.
- 29. Y. Liu, Y. Wang, H. Li, X. Guan, L. Zhu, M. Xue, Y. Yan, V.

Published on 13 March 2020. Downloaded by Uppsala University on 3/13/2020 9:17:47 PM

View Article Online DOI: 10.1039/C9GC04033A

Valtchev, S. Qiu and Q. Fang, *Chem. Sci.*, 2019, **10**, 10815-10820.

- 30. J. Lu, F. Lin, Q. Wen, Q.-Y. Qi, J.-Q. Xu and X. Zhao, *New J. Chem.*, 2019, **43**, 6116-6120.
- 31. M. M. Unterlass, Angew. Chem. Int. Ed., 2018, **57**, 2292-2294.
- 32. D. Stewart, D. Antypov, M. S. Dyer, M. J. Pitcher, A. P. Katsoulidis, P. A. Chater, F. Blanc and M. J. Rosseinsky, *Nat. Commun.*, 2017, **8**, 1102.
- 33. L. Zhang, L. Xiang, C. Hang, W. L. Liu, W. Huang and Y. C. Pan, *Angew. Chem. Int. Ed.*, 2017, **56**, 7787-7791.
- S. Kandambeth, A. Mallick, B. Lukose, M. V. Mane, T. Heine and R. Banerjee, *J. Am. Chem. Soc.*, 2012, **134**, 19524-19527.
- 35. B. P. Biswal, S. Chandra, S. Kandambeth, B. Lukose, T. Heine and R. Banerjee, *J. Am. Chem. Soc.*, 2013, **135**, 5328-5331.
- 36. Y. Tian, S.-Q. Xu, R.-R. Liang, C. Qian, G.-F. Jiang and X. Zhao, *CrystEngComm.*, 2017, **19**, 4877-4881.
- H. S. Sasmal, H. B. Aiyappa, S. N. Bhange, S. Karak, A. Halder, S. Kurungot and R. Banerjee, *Angew. Chem. Int. Ed.*, 2018, **57**, 10894-10898.
- P. Pachfule, S. Kandambeth, D. Díaz Díaz and R. Banerjee, *Chem. Commun.*, 2014, **50**, 3169-3172.
- C. R. DeBlase, K. E. Silberstein, T.-T. Truong, H. D. Abruña and W. R. Dichtel, *J. Am. Chem. Soc.*, 2013, **135**, 16821-16824.
- 40. F. Rodriguez-Reinoso, J. de D. Lopez-Gonzalez and C. Berenguer, *Carbon*, 1982, **20**, 513-518.
- 41. T. X. Nguyen and S. K. Bhatia, *Langmuir*, 2008, **24**, 146-154.
- 42. C.-Z. Guan, D. Wang and L.-J. Wan, *Chem. Commun.*, 2012, **48**, 2943-2945.
- 43. X.-H. Liu, C.-Z. Guan, S.-Y. Ding, W. Wang, H.-J. Yan, D. Wang and L.-J. Wan, *J. Am. Chem. Soc.*, 2013, **135**, 10470-10474.
- 44. B. J. Smith, A. C. Overholts, N. Hwang and W. R. Dichtel, *Chem. Commun.*, 2016, **52**, 3690-3693.

A facile solution-phase synthetic approach for phenol-based porous

organic cages and covalent organic frameworks

Lei Zhang, Rongran Liang, Cheng Hang, Haiying Wang, Lin Sun, Lei Xu, Dairong Liu, Zhenyi Zhang, Xingmin Zhang, Feifan Chang, Shengyu Zhao, and Wei Huang*

Graphic Abstract



A general solution-phase synthetic strategy is developed to construct both porous organic cages (POCs) and covalent organic frameworks (COFs) by simply stirring and heating organic solvent/water solutions of aldehydes and amines in the presence of MOH (M = Na, K, Cs). The generality and transferability of this approach are demonstrated by successful growing of high-quality crystals for four POCs and four COFs.