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Submitted date: 02/11/2020 • Posted date: 03/11/2020
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Citation information: Ashling, Christopher; Macreadie, Lauren K.; Southern, Thomas J. F.; Zhang, Yiming; McHugh, Lauren N.; Evans, Rachel; et al. (2020): Guest Size Limitation in Metal-Organic Framework Crystal-Glass Composites. ChemRxiv. Preprint. https://doi.org/10.26434/chemrxiv.13177364.v1

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Guest Size Limitation in Metal-Organic Framework Crystal-Glass Composites

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Metal-organic framework crystal-glass composites (MOF CGCs) have previously been formed by embedding crystalline MIL-53(Al) within a ZIF-62 glass (aZIF-62) matrix. Here we highlight thermal stability considerations in the formation of MOF CGCs, and subsequently report the synthesis of two novel MOF CGCs, by incorporating MIL-118, and UL-MOF-1 within aZIF-62. These new materials, alongside the prototypical MOF CGC formed using MIL-53(Al), were studied using scanning electron microscopy, powder X-ray diffraction, and gas sorption techniques. The gas uptake in composites formed from MIL-118C and UL-MOF-1 is largely dominated by the aZIF-62 matrix, suggesting that to improve the porosity of the MOF CGC, the matrix porosity must be improved, or a percolation threshold must be overcome.

Introduction

Metal-organic frameworks (MOFs) are hybrid materials, containing inorganic nodes or clusters linked together by organic units, in continuous networks.1 These hybrid materials can be constructed with a variety of metal ions (typically d-block elements), and a multitude of polydentate ligands. At the time of writing, over 99,000 MOFs have been reported in the literature.2 Many of these structures possess high surface areas and there are reports of materials with calculated Brunauer–Emmett–Teller (BET) surface areas as high as 7,140 m2/g, with a theoretical potential of ~14,600 m2/g.3 Accordingly, they are of interest in several potential applications, such as sensing, gas storage, and water harvesting.4–6

The chemical and physical diversity of the MOF family means that they often exhibit a wide range of stimuliresponsive behaviour.7 Some, such as UiO-66, are commonly referred to as ‘rigid’ and display little, or no, structural change upon application of external stimuli.8 Others, however, undergo reversible structural transformations under pressure or temperature changes, these are known as flexible frameworks.9

Perhaps the prototypical example of flexibility in MOFs is the phenomenon of “breathing”. An example of a “breathing” MOF is Al3(bdc)3 (bdc benzene-1,4-dicarboxylate, C6H4O2), which is referred to as MIL-53 from hereon. MIL-53 undergoes a solidsolid phase transition from a narrow-pore phase at room temperature, to a metastable large-pore phase upon desolvation at high temperature.10 Such transitions are important for materials designed for molecular separations, catalysis and gas storage since the interaction strength between host and guest is dependent upon pore size. The breathing effect in MIL-53 dynamically changes the pore volume and, by extension, alters the guest uptake capacity.

Reversible breathing behavior represents just a small portion of the structural rearrangements exhibited by MOFs; others include recrystallization, interpenetrated lattice movements and irreversible collapse upon solvent/guest removal.11 The most extensive of these occurs in a subset of MOFs known as zeolitic imidazolate frameworks (ZIFs) which contain an imidazolate-derived linker (Im, C2H4N2), and adopt network topologies similar to those of inorganic zeolites.

Heating under ambient pressure results in several ZIF structures undergoing melting to highly viscous liquid phases.12 Upon cooling, these liquids solidify to form glasses, in which tetrahedral Zn2 ions are linked by imidazolate ligands in a continuous random network analogous to that of amorphous silica. The glass formed from ZIF-62, Zn(Im)1.75(bim)0.25 (bim, benzimidazolate, C2H4N2),13 (melting temperature, Tm = 437 °C),14 has been identified as a suitable host matrix for crystalline MIL-53 particles. Specifically, a physical mixture of ZIF-62 and the MIL-53 were heated to 450 °C for 15 mins, to allow sufficient liquid flow around the crystalline component.

Interestingly, the resulting materials recovered at room temperature, called MOF crystal-glass composites (MOF CGCs), stabilize the open-pore phase of MIL-53, even at room temperature. This stabilization causes a significant increase in the amount of CO2 adsorbed when compared to the uptake by the combination of the parent materials.15 The loading capacity of MIL-53 within the aZIF-62 matrix was also investigated showing that 60–70 wt% MIL-53 could be encapsulated in the composite, whilst retaining the MIL-53-lp state. As a result, a
composite was fabricated with a CO$_2$ capacity considerably greater than the phase-pure MIL-53 parent material.$^{16}$

To date, the MOF CGC formed from MIL-53 and the ZIF-62 melt-quenched glass ($a_z$ZIF-62) is the first of only three known examples of this class of materials.$^{15-17}$ The extension of this approach to other crystalline MOFs is dependent upon their structural integrity at the temperatures required for the fabrication of the MOF CGC (e.g. $T_m$, ZIF-62 = 437 °C).$^{14}$ This is further complicated by the lack of thermal stability data using standardized atmospheric conditions and heating rates, and furthermore by the lack of data on stability when held isothermally at elevated temperatures.$^{18}$ In turn, the lack of additional MOF CGC chemistries limits any further conclusions on the gas sorption and separation behavior of these materials, which is confined to N$_2$ and CO$_2$ adsorption on MIL-53 based samples only. Such considerations motivated us to provide further examples of MOF CGCs from different crystalline chemistries and architectures, and to evaluate their gas adsorption behavior.

![Fig. S1](image)

**Fig. 1.** Representations of a) MIL-118B, b) MIL-118C, c) UL-MOF-1, d) MIL-53-lp where: carbon – black, oxygen – red and M-O nodes replaced by blue polyhedra. Hydrogen atoms have been omitted for clarity. The unit cell is indicated by a black box with an overlay of crystallographic axes.

450 °C, and given the need for isothermal heat treatment at this temperature for CGC fabrication, this precluded further study of these specific materials (Fig. S12). To provide a more accurate evaluation of thermal stability, the remaining MOFs were heated to 450 °C for 1 min, under N$_2$, and allowed to cool to room temperature in situ. Ambient temperature powder X-ray diffraction (PXRD) data were then recorded (Fig. S11–10).

This relatively simple experiment highlighted the importance of performing thermal analysis of MOFs using an appropriate set of conditions, chosen according to the individual processing, or application requirements. For example, the intensities of the Bragg peaks in the PXRD pattern for MIL-68 (Fig. S2) were reduced to near negligible levels, alongside a significant reduction in intensities, or changes in the patterns, for MIL-120 and MIL-126(Sc) (Fig. S3–4). This is consistent with the thermal analysis performed by Volkringer et al., confirming that the first step in decomposition is due to ligand degradation.$^{24}$ An unreported recrystallization of CUMof-9 was also observed (Fig. S1), though the high-temperature phase was not identified. MIL-68, MIL-120, MIL-126, and CUMof-9 were therefore not studied further.

The PXRD patterns of the three remaining samples: MIL-118, UL-MOF-1, and MIL-53-np (Fig. 1a–d) displayed Bragg peaks in good agreement with their room temperature structures after heating to 450 °C (Fig. S5–10). UL-MOF-1 has been reported to display exceptional thermal stability ($T_m = 610$ °C); the structure consists of alternating two-dimensional antifluorite type lithium oxide layers connected by 2,6-dicarboxylate units (Fig. 1c).$^{26}$ No flexible behavior has been reported.

Conversely, MIL-118, Al$_2$(OH)$_2$[(C$_6$O$_4$H$_7$)$_2$ - benzene-1,2,4,5-tetracarboxylate], exhibits a water-driven reversible structural transition analogous to that of MIL-53.$^{23}$ MIL-118 is typically synthesized with excess ligand in the pores of the framework and is named MIL-118A (C2/c). Upon heating MIL-118A, this excess ligand is removed, resulting in the open-

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**Table 1.** Reported thermal stabilities of crystalline MOF component candidates

| MOF     | Composition                                      | Decomposition temperature, $T_d$ (°C) | Ref |
|---------|--------------------------------------------------|--------------------------------------|-----|
| CUMof-9 | Yb$_2$(2,6-ndc)$_2$(H$_2$O)$_2$                   | 550                                  | 20  |
| DUT-6   | Zn$_2$O(2,6-ndc)(bbp)(def)$_2$(H$_2$O)$_2$         | ~400*                                | 20  |
| DUT-8   | Ni$_2$(2,6-ndc)(dabco)                            | ~400*                                | 21  |
| MIL-68  | V(OH)(bdc)                                       | ~500                                 | 22  |
| MIL-118 | Al$_2$(OH)$_2$(C$_6$O$_4$H$_7$)                   | ~450                                 | 23  |
| MIL-120 | Al$_2$(OH)$_2$(C$_6$O$_4$H$_7$)                   | ~480                                 | 24  |
| MIL-126(Sc) | Sc$_2$(OH)$_2$(bpdc)$_2$X (X = OH or Cl)     | ~500                                 | 25  |
| UL-MOF-1| Li$_2$(2,6-ndc)                                   | 610                                  | 26  |

2,6-ndc = naphthalene-2,6-dicarboxylate  
bdc = benzene-1,4-dicarboxylate  
bpdc = biphenyl-4,4’-dicarboxylate  
bbp = benzene-1,3,5-tribenzoate  
def = N,N-diethylformamide  
dabco = 1,4-diazabicyclo[2.2.2]octane

* Experiments performed at 5 °C/min in the literature

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**Results and Discussion**

Several MOF candidates for the crystalline filler were selected by virtue of their reported thermogravimetric analyses (TGA) indicating the required stability to 450 °C (Table 1). These were synthesized using the published procedures (see Experimental, Fig. S1–10). Each of the eight frameworks selected was analyzed using TGA conducted at a standard heating rate of 10 °C/min under inert nitrogen (N$_2$), to confirm thermal stability (Fig. S11).

The onsets of thermal decomposition, $T_{50}$, for all samples except DUT-6 and DUT-8, were above 450 °C. The $T_{50}$s of these two materials were greater than the reported values due to the faster heating rate used in our evaluation compared to those employed in the literature. A small mass loss was observed at
pore framework, MIL-118B (Pbam), which is stable at high temperatures. Upon cooling, the framework adsorbs water to form the room temperature stable phase, MIL-118C (Pnam). The transition causes a shift from the rectangualr 1-D tunnels in MIL-118B to lozenge-shaped channels, with water molecules occupying the pores in MIL-118C. Temperature-induced breathing is observed between the MIL-118C and MIL-118B phases. (Fig. 1a–b).

MOF CGCs containing 50 wt% crystalline UL-MOF-1 and MIL-118 were synthesized using the method previously published in the literature. Briefly, the synthesis involved mixing the two crystalline components by ball-milling, pelletizing the mixture, and heating to 450 °C under argon (for full procedure see Experimental). These are referred to, as (crystal)x(glass)y where x = weight fraction of the crystalline material in the composite, consistent with prior nomenclature. The MOF CGC behavior was compared to a synthesized sample of (MIL-53)xZIF-62y.

Ambient temperature PXRD data were recorded for the three MOF CGCs. As expected, Bragg peaks present in the crystalline sample of UL-MOF-1 were also present in (UL-MOF-1)xZIF-62y. PXRD data for (MIL-53)xZIF-62y demonstrated the presence of the open-pore MIL-53 phase, per previous results.9 Interestingly, the PXRD data for (MIL-118)xZIF-62y indicated little change in lattice parameters from the synthesized MIL-118 sample, which remained in the low-temperature MIL-118C (Pnam) phase (Fig. 2, Table S1). This shows that, unlike the MIL-53 in (MIL-53)xZIF-62y, the MIL-118 encapsulated within the glass does not retain the high-temperature MIL-118B (Pbam) phase (Fig. 1a).

Scanning electron microscopy (SEM) images of MIL-53-mp, MIL-118, and UL-MOF-1 display micrometer-sized crystals (Fig. S13–S15). Samples of MIL-118 and MIL-53 display reasonable size and shape uniformity in comparison to UL-MOF-1 which comprises a range of morphologies from 10 μm cubic structures to 200 μm sheets (Fig. S15). This occurs despite (i) X-ray diffraction phase purity which matches the reported crystallographic information, and (ii) a single thermal decomposition event at the reported temperature.

The MOF CGCs formed in each case demonstrated self-supporting, contiguous, bulk morphologies. SEM performed upon deliberately fractured pieces of these materials did not contain distinguishable remnants of the respective parent crystalline phases at the surface of the composite (Fig. 3, S16–18). Their self-supporting nature, coupled with the smooth surface of the MOF CGCs, provides clear evidence of flow from the liquid ZIF-62 as it suffused through the pellet. However, a region of coarse material matching the morphology of MIL-118 was observed at a macroscale surface defect in the sample of (MIL-118)xZIF-62y (Fig. S17).

Prior work on MOF CGCs has investigated only the gas uptake behavior of a series of (MIL-53)xZIF-62y CGCs with carbon dioxide (CO2) and nitrogen (N2). A range of analyte gases was therefore employed here to investigate the factors underpinning gas uptake in MOF CGCs. Gas sorption isotherms were performed predominantly at 273 K, with further experiments performed for some gases at 77 K and 293 K. For full experimental methodology see Experimental.

A sample of pure aZIF-62 was prepared (see Experimental) and observed to exhibit porosity towards hydrogen (H2) (1.05 mmol/g at 77 K, and 0.18 mmol/g at 273 K) and carbon dioxide (CO2) (0.95 mmol/g at 273 K) (Fig. 4, Fig. S19). Both uptake amounts are significantly lower than crystalline ZIF-62, which adsors ~6.03 mmol/g H2 at 77 K and ~1.79 mmol/g CO2 at 273 K.27 These results are in accordance with previous studies which demonstrate porosity in ZIF-glass materials.28

Methane (CH4) adsorption for aZIF-62 was observed in this work at 0.21 mmol/g at 273 K (Fig. S19), in agreement with the reported measurement of 0.18 mmol/g and representing a decrease from the reported value of 1.21 mmol/g in the crystalline ZIF-62.29 Hysteresis is observed in the aZIF-62 isotherms as a result of the diffusion limitations through the amorphous structure, increasing in magnitude with the kinetic diameter of the adsorbent, also consistent with prior work.30,31

Remakably, in addition to the reported selectivity towards propane (C3H8) and propene (C3H6) by aZIF-62 by Frentzel-
Beyme et al.\textsuperscript{30} some selectivity towards ethene (C$_2$H$_4$) over ethane (C$_2$H$_6$) is observed here with uptakes of 0.46 and 0.29 mmol/g respectively (Fig. 4). Industrially, the separation of small hydrocarbons is currently performed using cryogenic high-pressure distillation processes, and accounts for a large portion of global energy expenditure. Membrane-based separation of these materials is reportedly tenfold less energy-intensive making development in this area both environmentally and economically desirable.\textsuperscript{32}

To understand how incorporation within a$_2$ZIF-62 affects the gas sorption properties of the crystalline MOF, we compare the results for the pure crystalline material to that of the MOF CGC. Samples of MIL-118C and (MIL-118)$_{0.5}$(a$_2$ZIF-62)$_{0.5}$ display identical trends in their adsorption isotherms of H$_2$, CH$_4$, and CO$_2$ indicating no significant change in the chemical environment of MIL-118 upon inclusion in the MOF CGC (Fig. 5a, Fig. S20). Since MIL-118C displays porosity to H$_2$ at 77 K, the negligible uptake of H$_2$ at 273 K is ascribed to temperature effects. However, the generally poor uptake capacity of MIL-118C is consistent with a dense atomic arrangement, in accordance with the published crystallographic information.\textsuperscript{23}

The adsorption of gases at 273 K by the 50 wt% composite material, (MIL-118)$_{0.5}$(a$_2$ZIF-62)$_{0.5}$, is broadly comparable to a linear combination of the parent materials (Table 2). This, however, is not the case for H$_2$ adsorption at 77 K. Here, the recorded composite uptake is greater than either of its parent components and more than double the weighted average of the parent materials; this may suggest the presence of macroporous interfacial regions.

Identical experiments were performed on UL-MOF-1 and (UL-MOF-1)$_{0.5}$(a$_2$ZIF-62)$_{0.5}$, and again, the generally poor adsorption to UL-MOF-1 is consistent with a dense structure (Fig. 5b, Fig. S20). The same thermal effects observed in the MIL-118 H$_2$ isotherms at 77K and 273 K were also observed for UL-MOF-1. The gas uptakes displayed by (UL-MOF-1)$_{0.5}$(a$_2$ZIF-62)$_{0.5}$ are broadly consistent with a linear combination of parent UL-MOF-1 and a$_2$ZIF-62 materials (Table 2). Interestingly, the 77 K H$_2$ sorption isotherm for (UL-MOF-1)$_{0.5}$(a$_2$ZIF-62)$_{0.5}$ also exhibits a twofold increase in gas uptake over the weighted average of its parent materials. The prediction of gas uptake through the weighted average of its components calculated here assume that the quantity of gas adsorbed in the MOF CGC is due to the combined individual contributions from the two composited materials, where their adsorption is identical to the isolated components. It is important to note, however, that the hysteresis observed in the CO$_2$ isotherms for both a$_2$ZIF-62 and the isolated crystalline MOFs is no longer present in the respective MOF CGCs. This suggests that the MOF CGC reaches equilibrium more rapidly than its isolated components, indicating that there may be new pathways for the gas to diffuse in the MOF CGC.

A CO$_2$ adsorption isotherm was also recorded at 273 K for the pure crystalline sample of MIL-53-np and is consistent with previously reported data (2.25 mmol/g (recorded), and 2.13 mmol/g (reported) (273 K), Fig. S21)\textsuperscript{15}. As expected, MIL-53-np displays a significantly higher uptake of C$_2$H$_4$ than C$_2$H$_6$, C$_3$H$_8$, or xenon (Xe), reaching 3.47 mmol/g (273 K). The observation of

![Image](image-url)

**Fig. 4.** Gas adsorption isotherms of a$_2$ZIF-62. Solid and open circles of the same colour indicate the adsorption and desorption respectively.

![Image](image-url)

**Fig. 5.** Gas adsorption isotherms of samples of a) (MIL-118)$_{0.5}$(a$_2$ZIF-62)$_{0.5}$ and b) (UL-MOF-1)$_{0.5}$(a$_2$ZIF-62)$_{0.5}$. Solid and open circles of the same colour indicate the adsorption and desorption respectively.

### Table 2. Predicted and experimentally measured gas uptake of MOF crystal-glass composites based on the combination of their parent materials. Experimental temperatures of 273 K unless otherwise stated.

| Sample/gas | Crystalline MOF (mmol/g) | a$_2$ZIF-62 (mmol/g) | Weighted Average (mmol/g) | Measured MOF CGC (mmol/g) |
|------------|-------------------------|----------------------|--------------------------|---------------------------|
| MIL-118    |                         |                      |                          |                           |
| Methane    | 0.016                   | 0.212                | 0.114                    | 0.122                     |
| Carbon Dioxide | 0.152             | 0.947                | 0.550                    | 0.485                     |
| Hydrogen (77 K) | 0.440               | 1.051                | 0.746                    | 1.632                     |
| UL-MOF-1   |                         |                      |                          |                           |
| Methane    | 0.015                   | 0.212                | 0.113                    | 0.113                     |
| Carbon Dioxide | 0.051             | 0.947                | 0.499                    | 0.370                     |
| Hydrogen (77 K) | 0.320               | 1.051                | 0.686                    | 1.527                     |
two-step isotherms when using larger hydrocarbons is consistent with pore-opening behavior where MIL-53-np expands to the MIL-53-Ip phase, as comprehensively illustrated in the literature.\textsuperscript{10}

Consistent with our prior work, the MOF CGC exhibits appreciable porosity. However, due to fixation of the MIL-53-Ip phase within the (MIL-53)$_{0.25}$(a$_2$ZIF-62)$_{0.75}$ composite, the pore opening behavior of pure phase MIL-53 is no longer observed, and all recorded isotherms of (MIL-53)$_{0.25}$(a$_2$ZIF-62)$_{0.75}$ display Langmuir-type behavior, often with hysteresis in the desorption branch. The CO$_2$ sorption of a sample of (MIL-53)$_{0.25}$(a$_2$ZIF-62)$_{0.75}$ displayed similar CO$_2$ uptake behavior to that recorded previously (1.33 mmol/g (recorded), and 1.14 mmol/g (reported))\textsuperscript{30}. The sample of (MIL-53)$_{0.25}$(a$_2$ZIF-62)$_{0.75}$ also displayed poor adsorption of both N$_2$ and CH$_4$ (<0.13 and <0.36 mmol/g at 273 K, respectively), since neither component of the CGC strongly adsorbs these gases (Fig. S22).

Since this sample, unlike (MIL-118)$_{0.5}$(a$_2$ZIF-62)$_{0.5}$ and (UL-MOF-1)$_{0.5}$(a$_2$ZIF-62)$_{0.5}$, demonstrates a permeable crystalline component, further gas sorption experiments using larger gases were performed (Fig. 6). A considerable difference between the uptake of C$_2$H$_6$ and C$_3$H$_8$ is observed in a sample of (MIL-53)$_{0.25}$(a$_2$ZIF-62)$_{0.75}$ which is typical of the a$_2$ZIF-62 component but is not observed in MIL-53. This result evidences the contribution of the adsorption properties of a$_2$ZIF-62 to the overall composite characteristics.

Of the gases employed, the most striking result was that of C$_2$H$_6$, where the composite adsorbs far less than the combination of the parent materials. A weighted average C$_2$H$_6$ adsorption of MIL-53 (3.47 mmol/g) and a$_2$ZIF-62 (0.23 mmol/g) for a 25 wt% MIL-53 mixture would be 1.04 mmol/g, where an uptake of only 0.69 mmol/g is observed for the composite. However, the adsorption isotherm for C$_2$H$_6$ to (MIL-53)$_{0.25}$(a$_2$ZIF-62)$_{0.75}$ shows an increase in uptake on desorption, strongly indicating that the system had not reached equilibrium. This is likely due to poor diffusion of C$_2$H$_6$ through the a$_2$ZIF-62 matrix as a result of the comparatively large kinetic diameter of the gas. Though the MIL-53 component in the composite would be the dominant contributor to the gas uptake, adsorption to this component is greatly hindered whilst encapsulated within a matrix which is poorly permeable to the analyte gas.

Conclusions

Thermal analysis of a selection of crystalline MOFs revealed that two: UL-MOF-1, and MIL-118, are suitable for inclusion within a MOF glass (a$_2$ZIF-62) matrix. Despite reported TGA evidence to the contrary, several other crystalline MOFs were observed to undergo partial or complete collapse at the processing temperatures required for composite formation. This highlights the necessity of detailed thermal characterization and the avoidance of an over-reliance on constant-rate TGA experiments.\textsuperscript{18}

It is clear from this research that to expand the scope of MOF CGCs to include frameworks with more diverse properties, new synthetic pathways must be explored. Two of such avenues may lie in (i) the utilization of coordination polymers or MOFs with lower melting temperatures, or (ii) exchanging the crystalline glass-forming MOF for a premade glass MOF. In doing so, the temperatures required for the fabrication of the MOF CGC may be reduced as the glass transition temperature ($T_g$) occurs at a lower temperature than the melting temperature ($T_m$) used here.\textsuperscript{33–36}

The adsorption behavior of the resultant two new MOF CGCs is dominated by contributions from the a$_2$ZIF-62 matrix, which prevents the diffusion of molecules with a kinetic diameter larger than that of C$_2$H$_6$. Development of more permeable a$_2$MOFs may aid in the expansion of MOF CGC applicability. Alternatively, work on overcoming percolation thresholds in MOF CGCs would mean guest diffusion is primarily controlled by the crystalline MOF component. This would allow further control of interactions leading to multifunctional materials with the ability to act as both molecular sieves and separators.

Experimental

Material Synthesis

CUMOF-9. Ytterbium(III) chloride hexahydrate (1.08 g, 2.79 mmol) and water (6.13 mL) was added to a Teflon lined autoclave and stirred for 2 mins. 2,6-naphthalenedicarboxylic acid (0.103 g, 0.476 mmol) and trimethylamine (0.111 mL) were added to the solution and the mixture was stirred for a further 5 mins. The suspension was then sealed and placed in a 145 °C preheated oven for 4 hrs. The reaction vessel was allowed to cool to room temperature (RT) and the product was isolated by filtration under vacuum and washed with ethanol (30 mL) before drying in the oven at 70 °C overnight.

DUT-6. Zinc nitrate tetrahydrate (0.142 g, 0.543 mmol), 2,6-naphthalenedicarboxylic acid (0.017 g, 0.079 mmol), and benzene-1,3,5-tribenzoic acid (0.054 g, 0.123 mmol) were dissolved in N,N-diethyformamide (DEF, 10 mL). The mixture was sonicated for 5 min and heated to 100 °C for 24 hrs in a Pyrex tube. After cooling to RT the product was isolated by decanting the mother liquid and was washed with DEF. Yield: 49%. The resulting solid was immersed in dichloromethane.
(DCM) for 2 days. During this time the DCM was replaced with fresh DCM three times. Elemental analysis calculated (%) for C_{12}H_{21}O_{33}N_{2}Zn: C 55.5, H 7.67, O 19.34, Zn 9.44; found: C 56.2±0.3, H 7.66±0.07, O 19.95±0.09, Zn 8.01±0.08, Zn 9.22±0.05.

**DUT-8(Ni).** Nickel nitrate hexahydrate (0.407 g, 1.40 mmol) in 6 mL DMF, 2,6-naphthalenedicarboxylic acid (0.303 g, 1.40 mmol) in 15 mL DMF and 1,4-diazabicyclo[2.2.2]octane (0.100 g, 0.89 mmol) in 9 mL methanol (MeOH) were mixed. Subsequently the mixture was transferred into a Teflon vessel (50 mL) and heated in an autoclave to 120 °C at a heating rate of 4 °C/min and held at that temperature for 48 hrs. After cooling to RT over 3 hrs, the sample was washed three times, first with 30 mL N,N-dimethylformamide (DMF) and then with 30 mL ethanol and finally with 30 mL DCM. Afterwards, a washing step with 150 mL of DCM was continued for 3 days. The resulting solid was filtered in an argon flow and activated under dynamic vacuum at 393 K for 4 hrs.

**MIL-53.** Aluminum nitrate nonahydrate (26 g, 6.93 x10^{-2} mol) and terephthalic acid (5.76 g, 4.96 x10^{-2} mol) were dissolved in water (100 mL) and placed into a Teflon-lined autoclave and placed in an oven at 220 °C for 72 hrs. The resulting powder was washed with deionized water (3 x 30 mL) and dried in a vacuum oven at 150 °C for 24 hrs. MIL-53 was activated by heating at 330 °C for 72 hrs, and then to 450 °C for 6 mins before cooling to RT.

**MIL-68.** Aluminum nitrate nonahydrate (1.4 g, 6.57 mmol), benzene-1,4-dicarboxylic acid (0.6 g, 3.61 mmol), and tetrahydrofuran (THF, 16 mL) were added to a 50 mL round bottom flask and refluxed for 3 days at 70 °C. The resultant white powder was washed with THF (3 x 15 mL) and dried at RT overnight. To remove excess linker from the pores, the product was activated by heating to 300 °C at 1 °C/min and held for 8 hrs.

**MIL-118.** Aluminum nitrate nonahydrate (150 mg, 7.04 x10^{-4} mol) and benzene-1,2,4,5-tetracarboxylic acid (50 mg, 1.97 x10^{-4} mol) were added to a Teflon lined autoclave before adding water (5 mL). The autoclave was sealed and placed into a 210 °C preheated oven for 24 hrs. The product of this was isolated by replacing the liquid with water (20 mL) and centrifuging (2500 rpm, 10 mins) twice. The resultant white powder was placed in a 70 °C preheated oven overnight.

**MIL-120.** Aluminium nitrate nonahydrate (1.44 g, 6.76 mmol), 1,2,4,5-benzenetetracarboxylic acid (0.225 g, 0.885 mmol), sodium hydroxide (4 M, 1.53 mL), and water (9 mL) were added to a Teflon lined autoclave and placed in a 210 °C preheated oven and held for 24 hrs. The resulting white powder was filtered and washed with water (40 mL) before being transferred to a 100 mL round-bottom flask with water (60 mL) and refluxed at 100 °C for 10 hrs. The product was centrifuged (2500 rpm, 15 mins) and dried in the over at 70 °C overnight. Further to the reported method, MIL-120 was heated to 280 °C to produce a white powder with a PXRD pattern matching the predicted pattern.

**MIL-126(Sc).** Scandium nitrate hydrate (85 mg, 0.368 mmol), biphenyl-4,4'-dicarboxylic acid (68 mg, 0.281 mmol), DMF (6.25 mL), conc. hydrochloric acid (37%, 25 μL) were added to a 25 mL screw-top jar and sonicated until dissolution (~15 mins). The clear solution was placed into a 120 °C preheated oven for 24 hrs. The product was transferred to a centrifuge tube and centrifuged (2500 rpm, 15 mins) to collect a white powder. This powder was stood in DMF (10 mL) overnight and centrifuged again (2500 rpm, 10 mins) and acetone exchanged three times over three days before collecting the product by centrifuging (2500 rpm, 5 mins), decanting the liquid and drying in a 60 °C preheated oven overnight.

**ULMOF-1.** Lithium nitrate (0.345 g, 5.00 x10^{-3} mol), naphthalene-2,6-dicarboxylic acid (0.565 g, 2.61 x10^{-3} mol), ammonium fluoride (38 mg), and DMF (15 mL) were added to Teflon lined autoclave and placed in a 180 °C preheated oven and held for 5 days. Upon cooling, the reaction mixture was transferred to a centrifuge tube and the liquid was replaced with ethanol (20 mL). The sample was stirred for 5 mins before centrifuging (3000 rpm, 5 mins) to collect a white powder which was dried in an oven at 60 °C overnight.

**ZIF-62.** Zinc nitrate hexahydrate (1.65 g, 5.54 x10^{-3} mol) and imidazole (8.91 g, 0.13 mol) were added to a 200 mL screw-top jar, dissolved in DMF (75 mL) and stirred for 1 hr. Once complete dissolution was achieved, benzimidazole (1.55 g, 1.31 x10^{-2} mol) was added and heated to 130 °C for 48 hrs. The product was allowed to cool to RT and crystals were separated by vacuum-assisted filtration and washed with DMF (40 mL) and DCM (40 mL) before being dried in an oven at 60 °C overnight.

**aqZIF-62.** 150 mg of ZIF-62 was heated to 450 °C for 15 mins and cooled under argon.

**MOF CGC materials.** ZIF-62 and the corresponding crystalline material were ball-milled together using a Retsch MM400 instrument, in appropriate wt% ratios using a 7-mm-diameter stainless steel ball for 15 min, at a frequency of 30 Hz. The mixed powder was pressed in a 13-mm-diameter dye at 0.74 GPa for 1 min. The pellet was then clamped between glass slides, heated to 450 °C at a rate of 20 °C/min under an argon (Ar) atmosphere, and held for 15 min before being allowed to cool to RT.

**Characterization**

**Powder X-ray Diffraction.** Data were collected on ground samples of the composite materials with a Bruker D8 Advance powder diffractometer using Cu Ka radiation (λ = 1.5418 Å) and a LynxEye position-sensitive detector in Bragg–Brentano (θ–θ) parafocusing geometry at RT. Diffraction patterns were recorded at 26 values of 5–40° with a time/step of 0.75 s over 1724 steps through a 0.012 mm Ni filter.
**Scanning Electron Microscopy.** SEM was performed using a Thermo ScientificTM Phenom ProX scanning electron microscope. Powder and monolithic samples were prepared for SEM by securing to aluminum SEM pin stubs using carbon tape. Samples were coated in gold using an Emtech K575 sputter coater.

**Thermogravimetric Analysis.** Thermogravimetric analysis was performed using a TA Q500 TGA. All scans were performed at 10 °C/min with a nitrogen protective gas and allowed to cool to RT with air.

**Gas Sorption.** Samples were degassed overnight at the specified temperature for 12 hrs on before transferring to the analysis port of a Quantachrome iQ2 instrument. Sample weight was measured post-degas activation. Sample temperature was accurately equilibrated at 273 K and 293 K with a temperature-controlled water bath and at 77 K with liquid N$_2$. Gas adsorption measurements were performed using ultra-high purity (99.99%) gases.

**Conflicts of interest**

There are no conflicts to declare.

**Acknowledgements**

T. D. B. thanks the Royal Society for both a university research fellowship (UF150021) and a research grant (RSG[R1]180395). T. D. B. and L. N. M. thank the Leverhulme Trust for a Philip Leverhulme Prize (2019). C. W. A. thanks the Royal Society for a Ph.D. studentship (RG160498) and the Commonweal Scientific and Industrial Research Council for additional support (C2017/3108). T. J. F. S. thanks the EPSRC (EP/1937468) for a Ph.D. studentship. S. K. acknowledges funding by DFG (FOR2433).

**Notes and references**

1. H. Furukawa, K. E. Cordova, M. O’Keeffe and O. M. Yaghi, *Science*, 2013, **341**, 120444.
2. P. Z. Moghadam, A. Li, X. W. Liu, R. Bueno-Perez, S. D. Wang, S. B. Wiggins, P. A. Wood and D. Fairen-Jimenez, *Chem. Sci.*, 2020, **11**, 8373–8387.
3. O. K. Farha, I. Erzyazici, N. C. Jeong, B. G. Hauser, C. E. Wilmer, A. A. Sarjeant, R. Q. Snurr, S. T. Nguyen, A. Ö. Yazaydin and J. T. Hupp, *J. Am. Chem. Soc.*, 2012, **134**, 15016–15021.
4. T. Islamoglou, Z. Chen, M. C. Wasson, C. T. Buru, K. O. Kirlikoglu, U. Afnir, M. R. Mian and O. K. Farha, *Chem. Rev.*, 2020, **120**, 8130–8160.
5. I. M. Hönick, I. Senkovska, V. Bon, I. A. Baburin, N. Bönis, S. Raschke, J. D. Evans and S. Kaskel, *Angew. Chemie - Int. Ed.*, 2018, **57**, 13780–13783.
6. H. Kim, S. Yang, S. R. Rao, S. Narayanan, E. A. Kapustin, H. Furukawa, A. S. Umans, O. M. Yaghi and E. N. Wang, *Science*, 2017, **356**, 430–434.
7. F. X. Coudert, *Chem. Mater.*, 2015, **27**, 1905–1916.
8. J. Hajek, C. Caratelli, R. Demuyunck, L. Vanduyfhuys, M. Waroquier and V. Van Speybroeck, *Chem. Sci.*, 2018, **9**, 2723–2732.
9. A. Schneemann, V. Bon, I. Schwedler, I. Senkovska, S. Kaskel and R. A. Fischer, *Chem. Soc. Rev.*, 2014, **43**, 6062–6096.
10. T. Loiseau, C. Serre, C. Huguenard, G. Fink, F. Taulelle, M. Henry, T. Bataille and G. Férey, *Chem. - A Eur. J.*, 2004, **10**, 1373–1382.
11. E. J. Carrington, C. A. McAnalney, A. J. Fletcher, S. P. Thompson, M. Warren and L. Brammer, *Nat. Chem.*, 2017, **9**, 882–889.
12. T. D. Bennett, J.-C. Tan, Y. Yue, E. Baxter, C. Ducati, N. J. Terrill, H. H.-M. Yeung, Z. Zhou, W. Chen, S. Henke, A. K. Cheetham and G. N. Greaves, *Nat. Commun.*, 2015, **6**, 8079.
13. R. Banerjee, A. Phan, B. Wang, C. Knobler, H. Furukawa, M. O’Keeffe and O. M. Yaghi, *Science*, 2008, **319**, 939–944.
14. T. D. Bennett, Y. Yue, P. Li, A. Qiao, H. Tao, N. G. Greaves, T. Richards, G. I. Lampronti, S. A. T. Redfern, F. Blanc, O. K. Farha, J. T. Hupp, A. K. Cheetham and D. A. Keen, *J. Am. Chem. Soc.*, 2016, **138**, 3484–3492.
15. J. Hou, C. W. Ashling, S. M. Collins, A. Krajez, C. Zhou, L. Longley, D. N. Johnstone, P. A. Chater, S. Li, M.-V. Coulet, P. L. Llewellyn, F.-X. Coudert, D. A. Keen, P. A. Midgley, G. Mali, V. Chen and T. D. Bennett, *Nat. Commun.*, 2019, **10**, 2580.
16. C. W. Ashling, D. N. Johnstone, R. N. Widmer, J. Hou, S. M. Collins, A. F. Sapnik, A. M. Bumstead, P. A. Midgley, P. A. Chater, D. A. Keen and T. D. Bennett, *J. Am. Chem. Soc.*, 2019, **141**, 15641–15648.
17. S. Li, S. Yu, S. M. Collins, D. N. Johnstone, C. W. Ashling, A. F. Sapnik, P. A. Chater, D. S. Keeble, L. N. M. McHugh, P. A. Midgley, D. A. Keen and T. D. Bennett, *Chem. Sci.*, 2020, **11**, 9910–9918.
18. C. Healy, K. M. Patil, B. H. Wilson, L. Hermanspahn, N. C. Harvey-Reid, B. I. Howard, C. Kleinjan, J. Kolien, F. Payet, S. G. Teifer, P. E. Kruger and T. D. Bennett, *Coord. Chem. Rev.*, 2020, **419**, 213388.
19. F. A. A. Paz and J. Klinowski, *Chem. Commun.*, 2003, **9**, 1484–1485.
20. N. Klein, I. Senkovska, K. Gedrich, U. Stoeck, A. Henschel, U. Mueller and S. Kaskel, *Angew. Chemie - Int. Ed.*, 2009, **48**, 9954–9957.
21. N. Klein, C. Herzog, M. Sabo, I. Senkovska, J. Getzschmann, S. Paasch, M. R. Lohe, E. Brunner and S. Kaskel, *Phys. Chem. Chem. Phys.*, 2010, **12**, 11778–11784.
22. B. Seoane, V. Sebastián, C. Télez and J. Coronas, *CrystEngComm*, 2013, **15**, 9483–9490.
23. C. Volkering, T. Loiseau, N. Guillou, M. Haouas, F. Taulelle, N. Audebrand, I. Margioliak, D. Popov, M. Burghammer and C. Riekel, *Cryst. Growth Des.*, 2009, **9**, 2927–2936.
24. C. Volkering, T. Loiseau, M. Haouas, F. Taulelle, D. Popov, M. Burghammer, C. Riekel, C. Zoteva, F. Cuevas, M. Latroche, D. Phan, C. Knöfel, P. L. Llewellyn and G. }
25 R. J. Marshall, C. T. Lennon, A. Tao, H. M. Senn, C. Wilson, D. Fairen-Jimenez and R. S. Forgan, J. Mater. Chem. A, 2018, 6, 1181–1187.

26 D. Banerjee, S. J. Kim and J. B. Parise, Cryst. Growth Des., 2009, 9, 2500–2503.

27 R. N. Widmer, G. I. Lampronti, S. Anzellini, R. Gaillac, S. Farsang, C. Zhou, A. M. Belenguer, C. W. Wilson, H. Palmer, A. K. Kleppe, M. T. Wharmby, X. Yu, S. M. Cohen, S. G. Telfer, S. A. T. Redfern, F. X. Coudert, S. G. MacLeod and T. D. Bennett, Not. Mater., 2019, 18, 370–376.

28 C. Zhou, L. Longley, A. Krajnc, G. J. Smale, A. Qiao, I. Erucar, C. M. Doherty, A. W. Thornton, A. J. Hill, C. W. Ashling, O. T. Qazvini, S. J. Lee, P. A. Chater, N. J. Terrill, A. J. Smith, Y. Yue, G. Mali, D. A. Keen, S. G. Telfer and T. D. Bennett, Nat. Commun., 2018, 9, 1–9.

29 L. Longley, S. M. Collins, S. Li, G. J. Smale, I. Erucar, A. Qiao, J. Hou, C. M. Doherty, A. W. Thornton, A. J. Hill, X. Yu, N. J. Terrill, A. J. Smith, S. M. Cohen, P. A. Midgley, D. A. Keen, S. G. Telfer and T. D. Bennett, Chem. Sci., 2019, 10, 3592–3601.

30 L. Frentzel-Beyme, M. Kloß, P. Kolodzeiski, R. Pallach and S. Henke, J. Am. Chem. Soc., 2019, 141, 12362–12371.

31 L. Frentzel-Beyme, M. Kloß, R. Pallach, S. Salamon, H. Moldenhauer, J. Landers, H. Wende, J. Debus and S. Henke, J. Mater. Chem. A, 2019, 7, 985–990.

32 D. S. Sholl and R. P. Lively, Nature, 2016, 532, 435–437.

33 S. S. Nagarkar, H. Kurasho, N. T. Duong, Y. Nishiyama, S. Kitagawa and S. Horike, Chem. Commun., 2019, 55, 5455–5458.

34 A. M. Bumstead, M. F. Thorne and T. D. Bennett, Faraday Discuss., 2020, DOI:10.1039/d0fd00011f.

35 C. Das, T. Ogawa and S. Horike, Chem. Commun., 2020, 56, 8980–8983.

36 T. D. Shaw, Bikash Kumar; Hughes, Ashlea R.; Ducamp, Maxime; Keen, David A.; Coudert, François-Xavier; Blanc, Frederic; Bennett, ChemRxiv, 2020, 10.26434/chemrxiv.11956599.v1.
Supporting Information

Guest Size Limitation in Metal-Organic Framework Crystal-Glass Composites

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Contents:
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2. Thermogravimetric Analysis
3. Scanning Electron Microscopy
4. Gas Sorption
Powder X-ray Diffraction

**Figure S1:** Powder X-ray diffraction pattern of CU-mof-9 as synthesised, CU-mof-9 after heating to 400 °C, and a simulated CU-mof-9 PXRD pattern using published crystallographic information.¹

**Figure S2:** Powder X-ray diffraction pattern of MIL-68 as synthesised, and MIL-68 after heating to 450 °C, and simulated MIL-68 PXRD pattern using published crystallographic information.²
Figure S3: Powder X-ray diffraction pattern of MIL-120 as synthesised, MIL-120 after heating to 450 °C and a simulated MIL-120 PXRD pattern using published crystallographic information.\textsuperscript{3}

Figure S4: Powder X-ray diffraction pattern of MIL-126 as synthesised and MIL-126 after heating to 450 °C, and a simulated MIL-126 PXRD pattern using published crystallographic information.\textsuperscript{4}
Figure S5: Powder X-ray diffraction pattern of MIL-118 as synthesised, a simulated MIL-118A PXRD pattern, MIL-118 after heating to 450 °C, and a simulated MIL-118C PXRD pattern using published crystallographic information.\textsuperscript{5}

Figure S6: Powder X-ray diffraction pattern of UL-MOF-1 as synthesised and UL-MOF-1 after heating to 450 °C, and a simulated UL-MOF-1 PXRD pattern using published crystallographic information.\textsuperscript{6}
Figure S7: Pawley refinement of UL-MOF-1 powder X-ray diffraction pattern.

Figure S8: Pawley refinement of MIL-118A powder X-ray diffraction pattern.
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Figure S10: Pawley refinement of MIL-53-np powder X-ray diffraction pattern.

Table S1: Lattice parameters from published crystallographic files, and the corresponding lattice parameters of the crystalline material as determined by Pawley refinements.3,6

| Sample                        | Lattice parameters |  
|-------------------------------|--------------------|  
|                               | \(a\) (Å)          | \(b\) (Å)  | \(c\) (Å)  | \(\beta\) (°) | Rwp   |  
| MIIL-118C                     | 12.132             | 6.619    | 17.227    | 90             | -     |  
| \((\text{MIIL-118})_{0.5}(\alpha_7\text{ZIF-62})_{0.5}\) | 12.127             | 6.431    | 17.459    | 90             | 11.152 |  
| UL-MOF-1                      | 10.302             | 5.345    | 8.662     | 98.659         | -     |  
| \((\text{UL-MOF-1})_{0.5}(\alpha_7\text{ZIF-62})_{0.5}\) | 10.316             | 5.373    | 8.727     | 98.547         | 7.677 |
Thermogravimetric Analysis

Figure S11: Thermogravimetric analysis, performed at 10 °C/min under nitrogen gas on the MOFs listed in Table 1 in the main manuscript.

Figure S12: Thermogravimetric analysis of a) DUT-6, and b) DUT-8, displaying the normalised mass loss and the first differential of the normalised mass with respect to time. This experiment was performed at a heating rate of 10 °C/min under a nitrogen protective atmosphere.
Figure S13: Scanning electron microscopy images of MIL-53-np.
Figure S14: Scanning electron microscopy images of MIL-118C.
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Figure S16: Optical (upper left) and scanning electron microscopy (upper right, lower left and lower right) images of a shard of (MIL-53)$_{0.25}$(α$_6$ZIF-62)$_{0.75}$. 
Figure S17: Optical (upper left) and scanning electron microscopy (upper right, lower left and lower right) images of a shard of (MIL-118)$_{0.5}$($\alpha$ZIF-62)$_{0.5}$. The lower-right image is an enhanced view of the surface defect highlighted in red.
Figure S18: Optical (left) and scanning electron microscopy (right) images of a shard of (UL-MOF-1)$_{0.5}$(a$_2$ZIF-62)$_{0.5}$. 
Gas Sorption

Figure S19: Gas adsorption isotherms of $\alpha_{2}$ZIF-62. Solid and open circles of the same colour indicate the adsorption and desorption respectively.

Figure S20: Gas adsorption isotherms of a) MIL-118, and b) UL-MOF-1. Solid and open circles of the same colour indicate the adsorption and desorption respectively.

Figure S21: Gas adsorption isotherms of MIL-53-np. Solid and open circles of the same colour indicate the adsorption and desorption respectively.
Figure S22: Gas adsorption isotherms of (MIL-53)$_{0.25}$(a$_7$ZIF-62)$_{0.75}$. Solid and open circles of the same colour indicate the adsorption and desorption respectively.

References

1. F. A. A. Paz and J. Klinowski, Chem. Commun., 2003, 9, 1484–1485.
2. K. Barthelet, J. Marrot, G. Férey and D. Riou, Chem. Commun., 2004, 4, 520–521.
3. C. Volkringer, T. Loiseau, M. Haouas, F. Taulelle, D. Popov, M. Burghammer, C. Riekel, C. Zlotea, F. Cuevas, M. Latroche, D. Phanon, C. Knöfelv, P. L. Llewellyn and G. Férey, Chem. Mater., 2009, 21, 5783–5791.
4. R. J. Marshall, C. T. Lennon, A. Tao, H. M. Senn, C. Wilson, D. Fairen-Jimenez and R. S. Forgan, J. Mater. Chem. A, 2018, 6, 1181–1187.
5. C. Volkringer, T. Loiseau, N. Guillou, G. Férey, M. Haouas, F. Taulelle, N. Audebrand, I. Margiolaki, D. Popov, M. Burghammer and C. Riekel, Cryst. Growth Des., 2009, 9, 2927–2936.
6. D. Banerjee, S. J. Kim and J. B. Parise, Cryst. Growth Des., 2009, 9, 2500–2503.
