

Toward 3D Printed Hydrogen Storage Materials Made with ABS-MOF Composites

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Abstract

The push to advance efficient, renewable, and clean energy sources has brought with it an effort to generate materials that are capable of storing hydrogen. Metal-organic framework materials (MOFs) have been the focus of many such studies as they are categorized for their large internal surface areas. We have addressed one of the major shortcomings of MOFs (their processibility) by creating and 3D printing a composite of acrylonitrile butadiene styrene (ABS) and MOF-5, a prototypical MOF, which is often used to benchmark H₂ uptake capacity of other MOFs. The ABS-MOF-5 composites can be printed at MOF-5 compositions of 10% and below. Other physical and mechanical properties of the polymer (glass transition temperature, stress and strain at the breaking point, and Young's modulus) either remain unchanged or show some degree of hardening due to the interaction between the polymer and the MOF. We do observe some MOF-5 degradation through the blending process, likely due to the ambient humidity through the purification and solvent casting steps. Even with this degradation, the MOF still retains some of its ability to uptake H₂, seen in the ability of the composite to uptake more H₂ than the pure polymer. The experiments and results described here represent a significant first step toward 3D printing MOF-5-based materials for H₂ storage.

Introduction

Hydrogen is attractive as a fuel for transportation because of its high energy density and its potential to be produced renewably.[1] In one scheme for generating H₂, solar energy is used to convert water into H₂. Through combustion, this H₂ will produce energy and be converted back into water. Tangential to developing these technologies are requirements for advanced H₂ storage materials. A number of approaches to H₂ storage have emerged in response to this need.[1] Storing H₂ as a liquid is one option. Unfortunately, liquid hydrogen requires cryogenic temperatures, which are impractical. The low density of liquid hydrogen would necessitate larger fuel tanks on automobiles. Any storage material would need to overcome these bottlenecks.

One of the major efforts within the research community is to develop metal-organic framework materials (MOFs) for H₂ storage.[2-5] MOFs are three-dimensional coordination polymers in which the interactions between a metal ion and multidentate organic molecules lead to production of empty cavities as part of the crystallographic unit. The cavities within MOF structures are noted for their ability to adsorb gases. It has been shown that some MOFs allow for gas storage at higher densities than can be reached in compressed gas cylinders.[6]

MOF-5 is a coordination polymer built around zinc ions and benzodicarboxylate ions and has the formula unit Zn₄O(BDC)₃. [4] MOF-5 was one of the first MOFs whose H₂ storage capacity pointed to the potential for MOF gas storage, in general. MOF-5 was chosen for this study because it is a prototypical MOF material,[4] is easy to synthesize in large quantities[7], and its gas storage capacities have been well characterized.[8]

While many are hopeful that MOFs will play a role in meeting gas storage needs, there are several limitations to the practical use of MOFs. Primary among these is MOF processibility. That is, generating usable objects from MOF powders has thus far been difficult. Current efforts to address this problem include growing larger crystals,[9] growing MOFs off of a solid substrate,[10-14] and incorporating MOFs into polymer films and spheres.[15-25]

With the issue of processibility in mind, we have set out to produce polymer-MOF composite materials that could be formed, molded, or extruded into any number of shapes. While films are appropriate for some applications, others applications, which include those that need high flow rates, require more complicated geometries. To push these boundaries of structured MOF composites, we produced an acrylonitrile-butadiene-styrene (ABS) MOF-5 composite that can be printed with a conventional thermoplastic 3D printer.

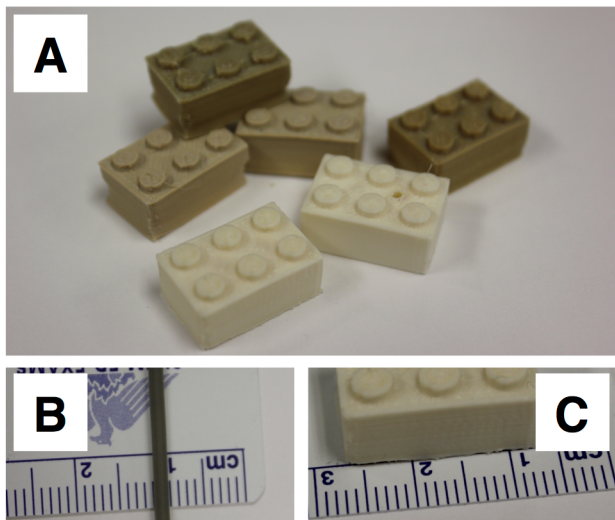


Figure 1. 3D printed ABS-MOF-5 composites. Panels A and C show printed Lego®-style bricks. Panel B shows the filament used in printing. A discoloration of the ABS occurs, primarily, in the casting step and does not indicate loss of the MOF structure, consistent with our previous study.[26]

We produced ABS-MOF-5 composites using the same methods that we developed for the production of 3D printable ABS-TiO₂ composite materials.[26] ABS is one of the most commonly used materials in thermoplastic 3D printing. We have characterized the chemical, thermophysical, and mechanical properties of the composite materials.

Importantly, we measured the H₂-uptake and release properties of the printed ABS-MOF-5 composite at room temperature, which is more appropriate for any useful device than the low temperature measurements normally used to assess material internal surface area.

While further system optimization is needed, our results show great promise for generating 3D printable polymer-MOF composites for hydrogen storage.

Materials and Methods[27]

Zinc acetate dihydrate was purchased from Baker Chemical. Benzene-1,4-dicarboxylic acid was purchased from Sigma Aldrich. Triethylamine (TEA) and N,N-

dimethylformamide (DMF) were purchased from EMD Millipore. Acetone was purchased from BDH chemicals. Acrylonitrile butadiene styrene (ABS) pellets (Resin: GPA 100, Color #: NC010, Color: Natural, Lot #: C14-0702K) were acquired from LTL Color Compounders, Inc.

MOF-5 Synthesis. MOF-5 was synthesized at room temperature according to a literature protocol.[7] Approximately 5 g of benzene-1,4-dicarboxylic acid and 8.5 mL of TEA were dissolved in 400 mL of DMF. In a separate flask, approximately 17 g of zinc acetate dihydrate was dissolved in 500 mL of DMF with stirring. These two mixtures were combined and MOF-5 formation proceeded over 2.5 hours. After the end of this time, the suspension was divided among Thermo Scientific polypropylene 750 mL Bio-Bottle tubes and centrifuged with a Sorvall RC 6+ centrifuge for 1 hour at 4000 rpm. The white paste was collected and isolated with vacuum filtration. During the filtration process, the product was washed with DMF.

Solvent Casting ABS and MOF-5. ABS and MOF-5 were suspended and solvent cast using a previously described protocol.[26] Briefly, a total of 50 g of solid material were placed in a flask with 500 mL of acetone. The total amount of MOF-5 and ABS were altered to achieve different MOF-5 content. The suspension was sonicated using a VWR Symphony sonicator until the ABS had dissolved. The suspension was poured into a Teflon coated frying pan and placed on a hot plate set to 60 °C until the solvent had evaporated and a film had formed.

Extrusion and Filament Formation. The film was cut into squares and extruded with a DSM Xplore Micro 15 cc Twin Screw Compounder. The filaments produced in this first

step were not the correct size to be used by the 3D printer. These initial filaments were cut into smaller pieces and formed into 1.75 mm-wide filaments using a Filabot Wee Extruder.

3D Printing. The filaments were printed into multiple shapes using a Flashforge Creator 3D Printer with Dual Extruders. Structures were printed at a speed of 10 mm/s onto a heated platform. These settings are necessary to ensure a smooth printing process without clogging the printer heads for producing printed structures that don't peel off of the print bed as the extruded polymer cools.

Powder X-ray Diffraction. X-ray diffraction data were collected with a Rigaku Miniflex II, which employed a 450 W Cu K α ($\lambda = 0.1540462$ nm) X-ray source, an NaI scintillation counter detector, and a diffracted beam monochrometer. The samples, pieces of solvent-cast film, were mounted on aluminum holders.

Differential Scanning Calorimetry (DSC). DSC data were recorded using a TA Instruments DSC Q2000. For each measurement, around 3 mg of composite was placed in an aluminum Tzero pan and sealed with a hermetic lid (both the pan and the lid were obtained from TA Instruments). Samples were a) heated from 20 °C to 170 °C with the temperature increasing by 40 °C/minute; b) held at 170 °C for 2 minutes; c) cooled from 170 °C to 110 °C with the temperature decreasing by 40 °C/minute; d) held at 110 °C for 60 minutes (to drive off any remaining solvent); e) cooled from 110 °C to 20 °C with the temperature decreasing by 40 °C/minute; and f) held at 20 °C for 2 minutes. Steps (a), (b), (c), (e), and (f) were repeated twice.

Mechanical Testing. Dog bone structures, with a shape defined by the American Society for Testing and Materials (standard D638), were printed for ABS, ABS-1% MOF-5, ABS-5% MOF-5, and ABS-10% MOF-5. The tensile properties of these dog bone structures were analyzed using a Mark 10, Series 5 Universal Testing Machine using a travelling speed of 1.2 inches per minute.

H₂ Adsorption and Desorption Measurements. The full experimental details for the H₂ adsorption and desorption measurements are given in the Supporting Information. Briefly, samples for the desorption measurement were prepared by incubating a degassed, 3D printed structure for 28 hours at a H₂ pressure of 60.7 kPa. The chamber was quickly evacuated and the H₂ pressure was measured as a function of time. For the adsorption measurement, a 3D printed sample was degassed and exposed to 60.7 kPa of H₂ for two minutes, after which the pressure in the chamber was measured as a function of time.

Results and Discussion

We produced a range of composites with different MOF-5 mass percentages. With increasing mass percentage, we found that the solvent-cast films became increasingly heterogeneous, with clumps of MOF-5 distributed less evenly within the ABS. Because of this phase separation, we focused on making 3D printing filaments for the composites that contained up to 10% MOF-5.

We measured the glass transition temperature (T_g) for the ABS-MOF-5 composites at different weight percentages. T_g is especially relevant for our composite materials as this phase transition is critical for the ability of the polymer to print. The full results are shown in the supporting information and are summarized in Table 1. The data show that

the MOF-5 content has no real effect on T_g . This indicates that any interaction between the polymer and the MOF does not significantly affect the polymer-polymer interaction.

Table 1. Thermal and mechanical properties of ABS-MOF-5 composites

	Glass Transition Temperature (°C)	Average values at breaking point		Young's Modulus (MPa)
		Stress (MPa)	Strain (%)	
ABS	106	39 ± 4	10 ± 1	5.2 ± 0.4
1% MOF-5	106	49 ± 4	12 ± 2	6.5 ± 0.7
5% MOF-5	105	39 ± 1	14 ± 2	4.0 ± 0.5
10% MOF-5	105	48 ± 1	11 ± 1	6.2 ± 0.4
20% MOF-5	105	Composites at these percentages were unable to print structures for testing		
30% MOF-5	106			
40% MOF-5	106			
50% MOF-5	105			

We were able to generate 3D printing filaments with ABS, 1% ABS, 5% ABS, and 10% ABS. These filaments were produced for use within a commercially available 3D printer. It was important to us that any techniques we use be immediately scalable and adoptable. For instance, the compounding method that we employed is used by industry on a larger scale and is specifically used to produce the colored filaments that are currently used in 3D printers. Additionally, we wanted to use the same type of 3D printers most used by hobbyists in their own homes. As we continue to develop this technology, our aim is to optimize implementation.

Using the ABS-MOF-5 filaments, we printed dog bone structures to test the composite's mechanical properties. The stress and strain values describe the force and change in length at the structures breaking point. Young's modulus describes how the force required to pull the structure changes as its length increases. In general, it appears as though the MOF-5 strengthens the composite in comparison to the pure polymer. That is,

the stress at the breaking point increases from pure ABS for the 1% and 10% MOF-5 composites. We contend that the stress values for the 5% MOF-5 sample are likely due to inconsistent material heterogeneity. That is, some of the phase separation observed during solvent casting remains after the compounding step as well. As the gas uptake capacities of these materials, and not their mechanical properties, were the primary focus of this study we did not address it further in the experiments presented here. However, for future applications where specific mechanical properties are required, there are steps that can be taken to ensure homogeneous blending of the polymer and MOF. The first step is to modify the MOF structure to have stronger interactions with the polymer. This could involve post-synthetic functionalization of the MOF or producing the MOF using polymeric components.[19, 20, 28] Alternatively, Kashiwagi and co-workers have shown that altering the ratios of polymer:solvent and insert:solvent during the solvent casting steps can have noticeable effects on the homogeneity of the composite material.[29] We will use one of these approaches in the future for cases where we require homogeneously dispersed MOF materials within a polymer.

Figure 2 shows the powder X-ray diffraction (XRD) data for the ABS-10% MOF-5 composite, ABS, and different forms of MOF-5. We find that the MOF-5 within our composite shows a similar scattering pattern to a form that has been degraded by humidity.[30] XRD patterns for the other composites (1%, 5%, 20%, 30%, and 50%) are found in the supporting information and also show incorporation of degraded MOF-5.

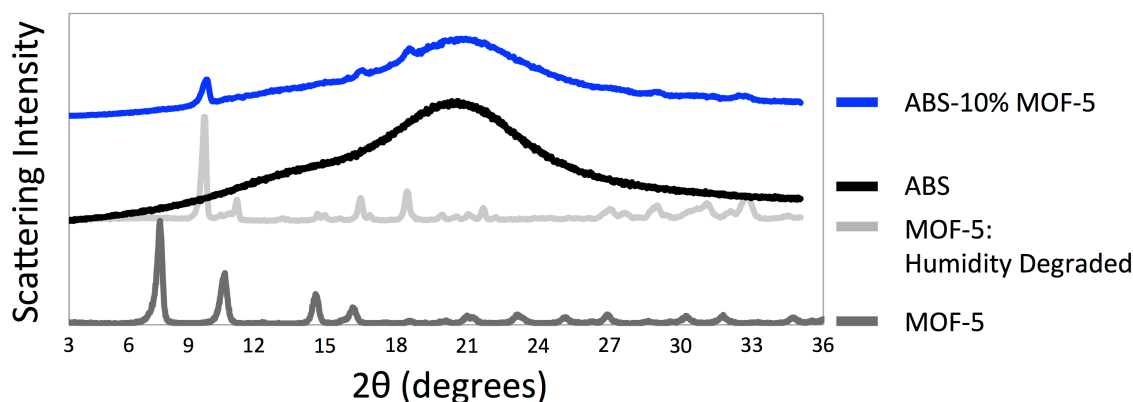


Figure 2. XRD spectra of the ABS-10% MOF-5 composite. Gray: spectra for MOF-5 in its powdered form. Black: spectra for ABS. Blue (offset): spectra for ABS-10% MOF-5 composite. This spectrum shows several scattering peaks from MOF-5 (8.9, 15.7, 17.8, 28.6, and 33.9 degrees) clearly shown overlaid on top of the characteristic, broad ABS spectrum.

We expect that there are two likely steps where ambient humidity may have played a role in altering the MOF-5 structure. The building where material production was carried out often experiences ambient humidity levels above 70% relative humidity. A previous study showed that MOF-5 degradation becomes measurable when exposed to 50% relative humidity for 24 hours.[30] In our protocols, the most likely step where humidity plays a role was the filtering process during the MOF-5 synthesis. A slurry of MOF-5 and chloroform (or DMF) was filtered through a 0.45 μm -pore filter. This process was time consuming and was often allowed to proceed over 24 hours. There were multiple filtering steps for each batch synthesized. The ambient humidity in the building could have affected the stability of the MOF-5. Another possibility could have been that the MOF-5 degraded during solvent casting. While process took, on average, around an hour, there is lower likelihood for the decomposition to have occurred during this step. A final step where humidity may play a role is during the compounding step, where ABS and MOF-5 are blended together at 195 °C. However, we expect that once MOF-5 is incorporated

into the polymer (after the solvent casting step), the MOF will be less susceptible to ambient humidity. In support of this assertion, Cohen and coworkers have shown that MOFs within a polymer matrix are less susceptible to humid conditions.[17, 20]

While we are working with a degraded form of MOF-5 in our composites, further measurements of H_2 uptake by our 3D printed objects remain valuable. That is, in this proof-of-concept material, is the MOF still accessible within the polymer. Previous research has shown that even the degraded MOF-5 structures maintain some ability to uptake H_2 . [30] So, although the absolute capacity of MOF-5 may be somewhat diminished, showing that it retains its ability to adsorb H_2 within the 3D printed composite is a necessary measurement for showing the potential for any H_2 storage by a 3D printed MOF structure. With this in mind, we set out to determine if the compromised MOF-5 structures in our printed ABS-MOF-5 objects would retain their ability to adsorb gas molecules.

We tested the ability of MOF-5 to function within the ABS matrix after 3D printing (Figure 3 and Table 2). Specifically, we measured the material's capacity to adsorb H_2 along with the rate of H_2 adsorption and desorption. For this study, we compared the properties of the ABS-10% MOF-5 composite with that of pure ABS. Previous studies have shown the ability of MOFs to adsorb gas molecules while incorporated into a composite film.[15-20] The results, presented here, show that the degraded MOF-5 within our composite retains its capacity to adsorb gas molecules in a more complex polymer environment.

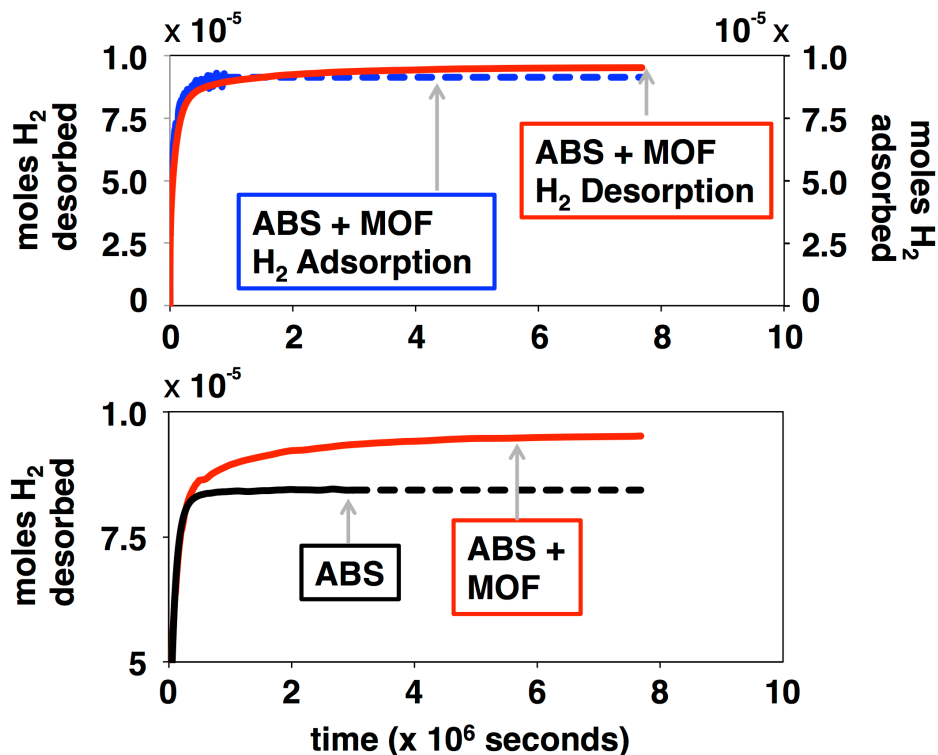


Figure 3. H₂ adsorption and desorption profiles of ABS-10% MOF-5 and pure ABS. The top panel shows H₂ adsorption (blue) and desorption (red) by ABS-10% MOF-5. The bottom panel shows H₂ desorption from ABS-10% MOF-5 (red) and pure ABS (black). The bottom panel has a re-scaled y-axis to highlight the difference in capacity between ABS-10% MOF-5 and ABS. The dashed lines in both the top and bottom panels indicate an extrapolation of the data to longer times.

The capacity of the ABS-10% MOF-5 for H₂ adsorption is clearly greater than that of pure ABS, indicating that the MOF retains its properties within the 3D printed matrix. A closer examination of this data bolsters our assessment in a number of ways. First, the measured H₂ capacity per gram of printed material is 1.15 times greater for the ABS-10% MOF-5 composite than pure ABS (Table 2). Further, the specific H₂ capacity (an average of 6.1×10^{-4} mass % of H₂ at 60.7 kPa) by the MOF within the ABS composite is comparable to the absolute adsorption of H₂ by pure MOF-5 at room temperature (1.6×10^{-3} mass % H₂, estimated from reference 21).[3] By this estimation, we retain 33% of the theoretical MOF-5 H₂ capacity for the structurally degraded MOF-5 within our

composite. This capacity corresponds to that found for MOF-5 exposed to greater than 50% relative humidity for 24 hours found by an earlier study.[30] This finding shows that H₂ will still be adsorbed by MOF-5 within a 3D printed ABS composite and that it shows no further degradation from humidity once the composite has been formed. Both of these conclusions are crucial for demonstrating the applicability of our approach.

Table 2. H₂ capacity of printed composites

	ABS	ABS-10% MOF-5 H ₂ Desorption	MOF-5 H ₂ Adsorption
g of H ₂ per g of composite	2.64×10^{-6}	3.01×10^{-6}	2.95×10^{-6}
g of H ₂ specifically bound to MOF-5 per g of MOF-5 within the composite	-	6.3×10^{-6}	5.8×10^{-6}

Further analysis of the rates of adsorption and desorption kinetics (supporting information) by ABS and the ABS-10% MOF-5 composites gives information about how gas diffuses through and interacts with the individual components within the composite materials. H₂ exhibits a multi-exponential diffusion through ABS with rates on the order of 10^{-3} and 10^{-4} s^{-1} . This is expected as ABS is a complicated multicomponent system; it is produced when acrylonitrile and styrene are polymerized in the presence of already-synthesized polybutadiene. The rate data indicate that the adsorption of H₂ by the ABS-10% MOF-5 composite has a similar profile to that of pure ABS; the only difference between ABS and ABS-10% MOF-5 coming from an absolute difference in H₂ storage capacity. This observation is consistent with a model in which both the polymer and the MOF are involved in H₂ storage within the composite. It is also consistent with H₂ having to diffuse through the polymer to get to the MOF. The desorption rates from the ABS-

10% MOF-5 composite has a different profile than the desorption from ABS.

Specifically, H₂ desorption from ABS-10% MOF-5 is slower than absorption of H₂ by the same material. We observe a slower rate component ($1 \times 10^{-5} \text{ s}^{-1}$) in the fitting of the data for the desorption of H₂ from ABS-10% MOF-5. This slow component accounts for nearly 20% of the decay data, which roughly corresponds to the percentage of H₂ bound specifically to MOF-5 within the composite.. This result is consistent for the case where H₂ has a specific adsorption to the material of interest. That is, because H₂ has a strong interaction with the MOF-5, the rate of diffusion out of MOF-5 is slower than its diffusion through ABS.

Conclusions

Taken together, these data signal the potential for 3D printing of polymer-MOF composite materials. Importantly, our research indicates that environmental molecules can access MOFs at the interior of the printed material and that MOF-5. The current study shows, specifically, that MOF-5 retains its capacity to store H₂ in 3D printed objects. This conclusion is corroborated by our previous study with printed ABS-TiO₂ composites where molecules in aqueous solution could access nanoparticles within a printed structure.[26] For applications that involve chemical storage, this property is crucial because it shows that storage can be optimized by increasing the content of MOF content of the composite. That H₂ storage is possible for MOF-5 within the interior of the printed composite is indicative that our composites are different from materials that incorporate MOFs by synthesizing them on the outside of some preformed, or printed, substrate.[10-14] Future studies in which MOFs are incorporated into 3D printing

polymers in their non-degraded states will feature a more complete analysis of the interior pore structure found in the composite materials.

The capacity to process MOFs into any possible geometry could lead to a number of new devices that take advantage of different MOF properties (gas adsorption and catalysis, among others). Efforts are certainly required to optimize these systems. In our study, for example, the measurements were made at room temperature (MOF gas storage increases with decreasing temperature) using a generic 3D printed structure that had not been designed for gas permeation and storage. Further, covalently incorporating the MOFs onto a polymer may increase the weight percentage of MOFs within a printable composite.[19, 20]

While we do observe some MOF-5 degradation through the incorporation process, we have identified areas where we can better maintain its structural integrity. Specifically, we contend that replacing the filtration steps with filtration in atmospherically controlled environments, such as a glove box, or with isolating material with centrifugation will maintain the MOF-5 structure. Another possibility is to remove the solvent casting step and directly blend the MOF-5 powder with ABS. Importantly, though, we do show that the MOF is not further degraded once it is incorporated into the polymer. As there is other evidence that casting MOFs within polymer films increases their resistance to degradation in humid environments,[17] we expect that our 3D printed ABS-MOF-5 composites will show similar stabilities.

The research presented here is an important first step towards designing and 3D printing H₂ storage devices. The potential geometries available to 3D printed materials coupled to

the various different MOF structures lead to a number of possibilities for optimizing any printed device. Our study will contribute to these future efforts by showing that MOFs can easily be incorporated into 3D printing polymers while maintaining their functionality.

Supporting Information. The Supporting Information contains a more complete description of materials and methods, X-ray diffraction data, DSC data, mechanical testing data, description of the H₂ adsorption and desorption measurements along with kinetic fitting for these measurements.

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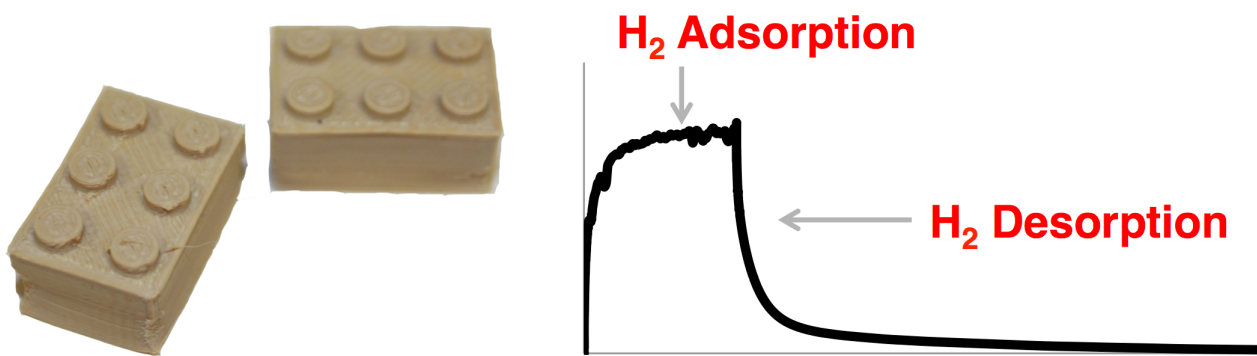
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Supporting Information for:

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Contents:

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- II. Differential Scanning Calorimetry
- III. Mechanical Testing
- IV. H₂ Adsorption/Desorption Measurements

I. Powder X-ray Diffraction

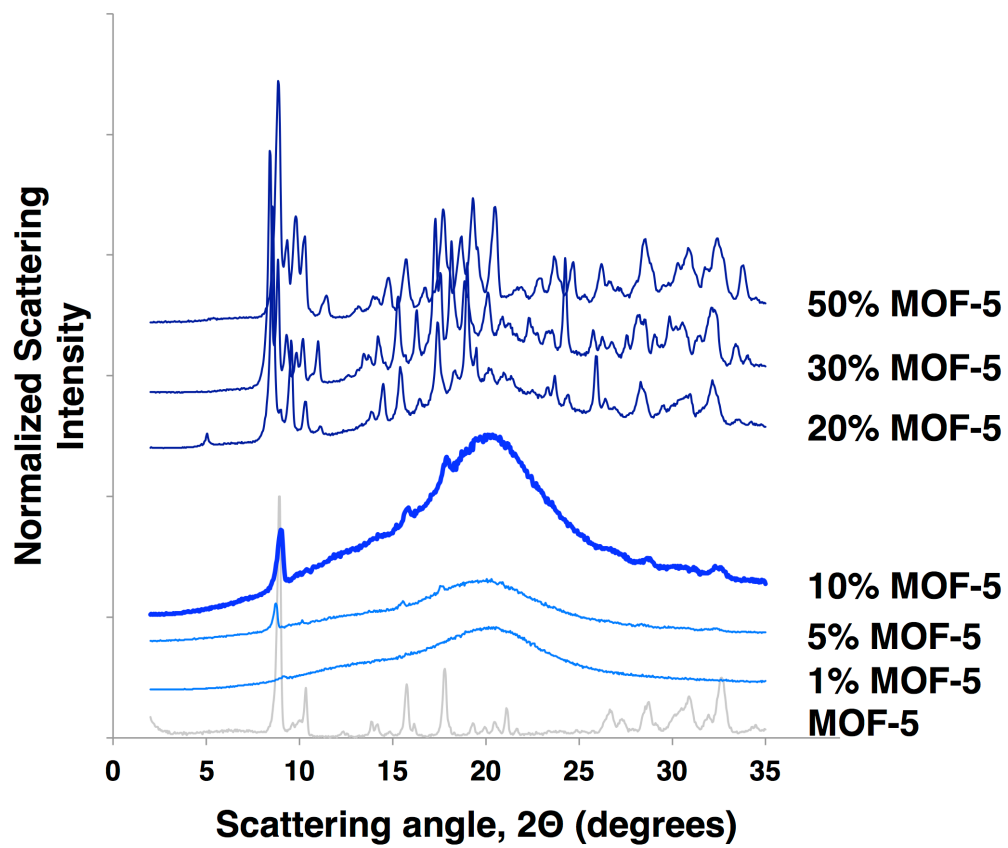


Figure S1. Powder X-ray diffraction data for the ABS-MOF-5 composite materials.

II. Differential Scanning Calorimetry

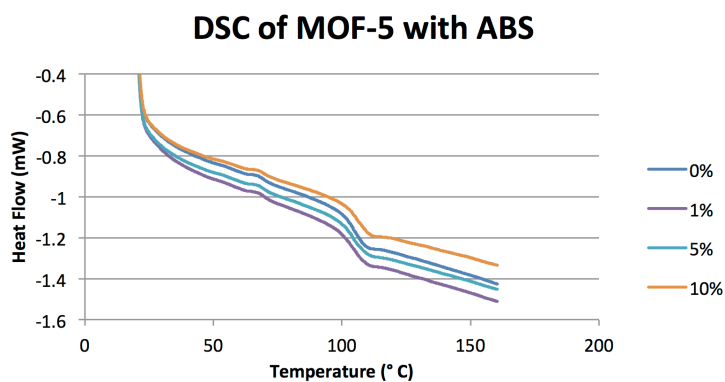


Figure S2. DSC measurements for ABS, ABS-1% MOF-5, ABS-5% MOF-5, and ABS-10% MOF-5.

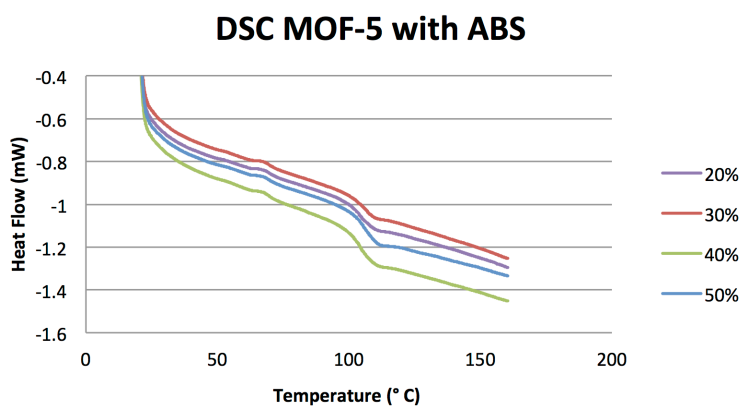


Figure S3. DSC measurements for ABS-20% MOF-5, ABS-30% MOF-5, ABS-40% MOF-5, and ABS-50% MOF-5.

III. Mechanical Testing

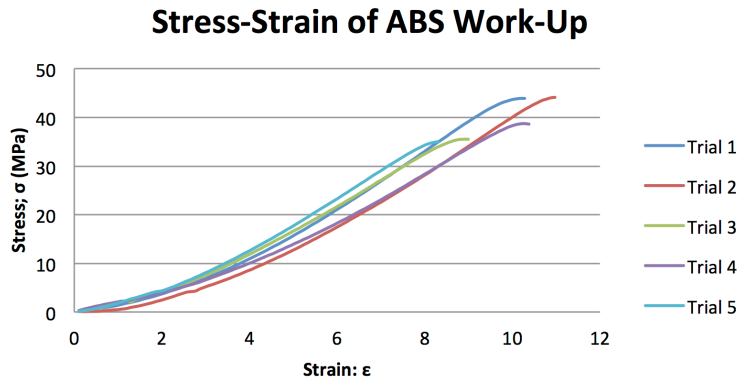


Figure S4. Stress-Strain curve for ABS

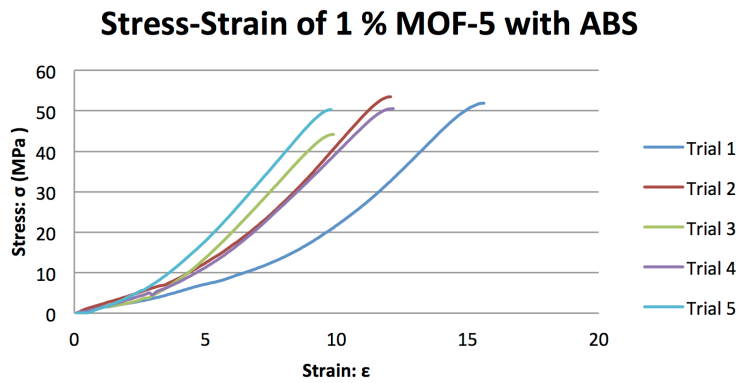


Figure S5. Stress-strain curve for ABS-1% MOF-5

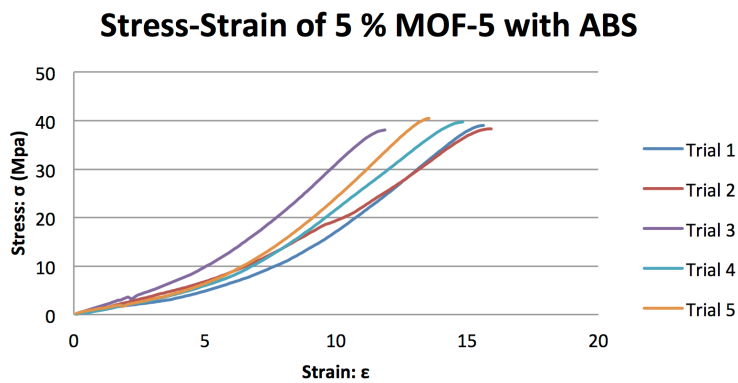


Figure S6. Stress-strain curve for ABS-5% MOF-5

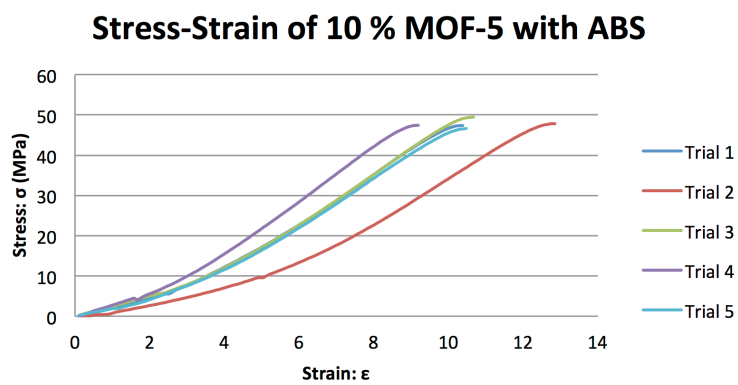


Figure S7. Stress-strain curve for ABS-10% MOF-5

IV. H₂ Adsorption/Desorption Measurements

H₂ Desorption from ABS Measurements

H₂ desorption measurements were recorded using an instrument whose schematic is shown in Figure S9. The data shown in Figure 3 and Table 2 in the manuscript were recorded by capacitance diaphragm gauge 1 (CDG 1). The sample was degassed into the combination of the sample chamber (SC) and the preparation chamber (PC) by heating to 103 °C for 3 days under vacuum. The ABS sample had a nominal mass of 6.4831 g when nearly empty of gas. The sample was loaded with H₂ gas at a pressure of 71.7 kPa for 2 days. For the desorption experiment, chambers SC and PC were evacuated with valves 1 and 2 (v_1 and v_2) open. For the measurements, only v_1 remained open. The measurement volume included the combination of SC (0.194 L) and PC (0.309 L). The ABS sample degassed into SC and PC. The pressure rise was recorded by calibrated capacitance diaphragm gauge 1 (CDG 1). In a separate test, pressure readings from CDG1 were checked against a NIST calibrated standard pressure gauge and were found to be accurate to within 0.7%. The pressure change (from time = 0) is converted to moles of H₂ using the ideal gas law and the volume of the combined chambers. The total measurement uncertainty is better than 1% (67% confidence interval). The spinning rotor gauge (SRG) was used to measure background outgassing rates of the chamber.

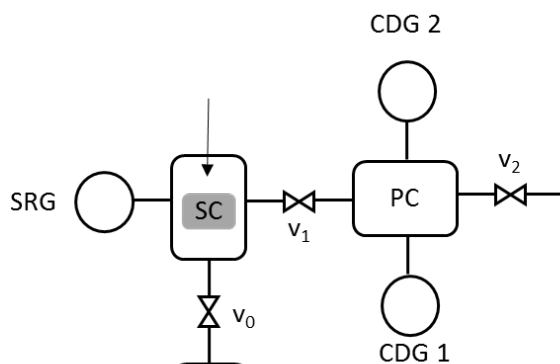


Figure S8. Schematic of the instrumentation used to record H₂ desorption from the ABS-MOF-5 composites. SRG: spinning rotor gauge. SC: sample chamber. v_0 , v_1 , and v_2 : valves. PC: preparation chamber. CDG 1: capacitance diaphragm gauge (133 Pa). CDG 2: capacitance diaphragm gauge (133 kPa).

After the data were recorded and voltage readings converted into moles of H₂ desorbed, the data were normalized and fit with a double exponential model using MatLab. Shown in Figure S10 are the data, fits and residuals.

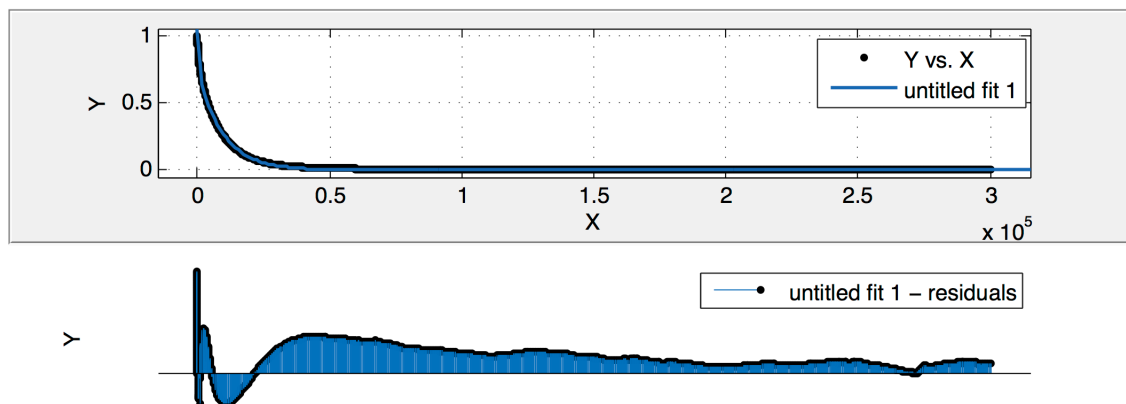


Figure S9. Fit to the data: H₂ Desorption from ABS. Top panel: data (black dots) and fit (blue line). Bottom panel: residuals from the fit.

The fit parameters from MatLab are given below.

$$f(x) = a \cdot \exp(b \cdot x) + c \cdot \exp(d \cdot x)$$

$a = 0.2437$ (95% confidence bounds: 0.2411, 0.2462)

$b = -0.0009057$ (95% confidence bounds: -0.0009198, -0.0008916)

$c = 0.7246$ (0.7219, 0.7272)

$d = -0.0001012$ (95% confidence bounds: -0.0001016, -0.0001008)

Goodness of fit

SSE 0.4136

R-Square 0.9995

RMSE 0.00597

H₂ Desorption from ABS-10% MOF-5 Measurements

H₂ desorption measurements were recorded using an instrument whose schematic is shown in Figure S10. The data shown in Figure 3 and Table 2 in the manuscript were recorded by capacitance diaphragm gauge 1 (CDG 1). The sample was degassed into the combination of the sample chamber (SC) and the measurement chamber (MC1) by heating to 103 °C for 3 days under vacuum. The ABS-10% MOF-5 sample had a nominal mass of 6.3952 g when nearly empty of gas. The sample was loaded with H₂ gas at a pressure of 60.7 kPa for 2 days. For the desorption experiment, chambers SC and MC1 were evacuated with valves 1 and 2 (v_1 and v_2) open. For the measurements, only v_1 remained open. The measurement volume included the combination of SC (0.194 L) and MC1 (0.275 L). The ABS sample degassed into SC and MC1. The pressure rise was recorded by calibrated capacitance diaphragm gauge 1 (CDG 1). In a separate test, pressure readings from CDG1 were checked against a NIST calibrated standard pressure gauge and were found to be accurate to within 0.7%. The pressure change (from time = 0) is converted to moles of H₂ using the ideal gas law and the volume of the combined chambers.

The total measurement uncertainty is better than 1% (67% confidence interval). The spinning rotor gauge (SRG) was used to measure background outgassing rates of the chamber.

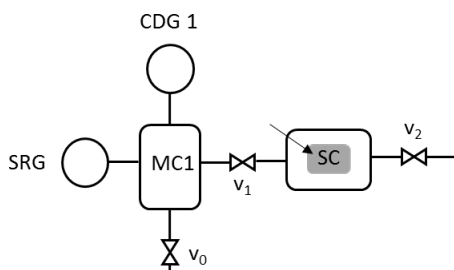


Figure S10. Schematic of the instrumentation used to record H₂ desorption from the ABS-MOF-5 composites. SRG: spinning rotor gauge. MC1: measurement chamber 1. SC: sample chamber. v₀, v₁, and v₂: valves. CDG 1: capacitance diaphragm gauge (133 Pa). After the data were recorded and voltage readings converted into moles of H₂ desorbed, the data were normalized and fit with a double exponential model using MatLab. Shown in Figure S12 are the data, fits and residuals.

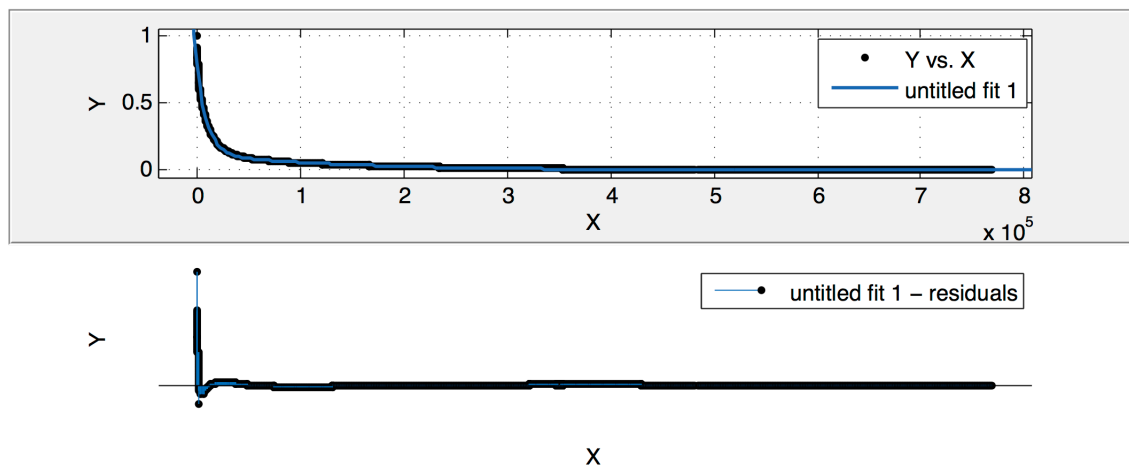


Figure S11. Fit to the data: H₂ Desorption from ABS-10% MOF-5. Top panel: data (black dots) and fit (blue line). Bottom panel: residuals from the fit.

The fit parameters from MatLab are given below.

$$f(x) = a \cdot \exp(b \cdot x) + c \cdot \exp(d \cdot x)$$

a = 0.1205 (95% confidence bounds: 0.1204, 0.1206)

b = -6.986E-6 (95% confidence bounds: -6.992E-6, -6.979E-6)

c = 0.6091 (95% confidence bounds: 0.6089, 0.6094)

d = -0.0001008 (95% confidence bounds: -0.0001009, -0.0001007)

Goodness of fit

SSE 4.481

R-Square 0.9969

RMSE 0.003773

H₂ Adsorption by ABS-10% MOF-5 Measurements

H₂ adsorption measurements were recorded using an instrument whose schematic is shown in Figure S11. The data shown in Figure 3 and Table 2 in the manuscript were recorded by the differential gauge (CDG 2). The sample was placed in the sample chamber (SC) and degassed heating to 103 °C for 3 days under vacuum. The ABS sample had a nominal mass of 6.3952 g when nearly empty of gas. The sample chamber and reference chamber (Ref P) were initially filled to the same H₂ pressure (60.7 kPa). The two chambers were isolated from one another by closing valve 2, and the pressure difference between the two chambers were measured using CDG 2 using the reading from the capacitance diaphragm gauge (CDG 3) of Ref P as the reference. In a separate test, pressure readings from CDG2 were checked against a NIST calibrated standard pressure gauge and were found to be accurate to within 0.7%. The pressure change (from time = 0) is converted to moles of H₂ using the ideal gas law and the volume of SC (0.194 L). The total measurement uncertainty is better than 1% (67% confidence interval).

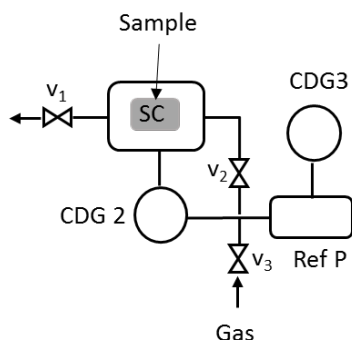


Figure S12. Schematic of the instrumentation used to record H₂ desorption from the ABS-MOF-5 composites. SRG: spinning rotor gauge. MC1: measurement chamber 1. SC: sample chamber. v_0 , v_1 , and v_2 : valves. CDG 1: capacitance diaphragm gauge (133 Pa).

After the data were recorded and voltage readings converted into moles of H₂ adsorbed, the data were normalized and fit with a double exponential model using MatLab. Shown in Figure S10 are the data, fits and residuals.

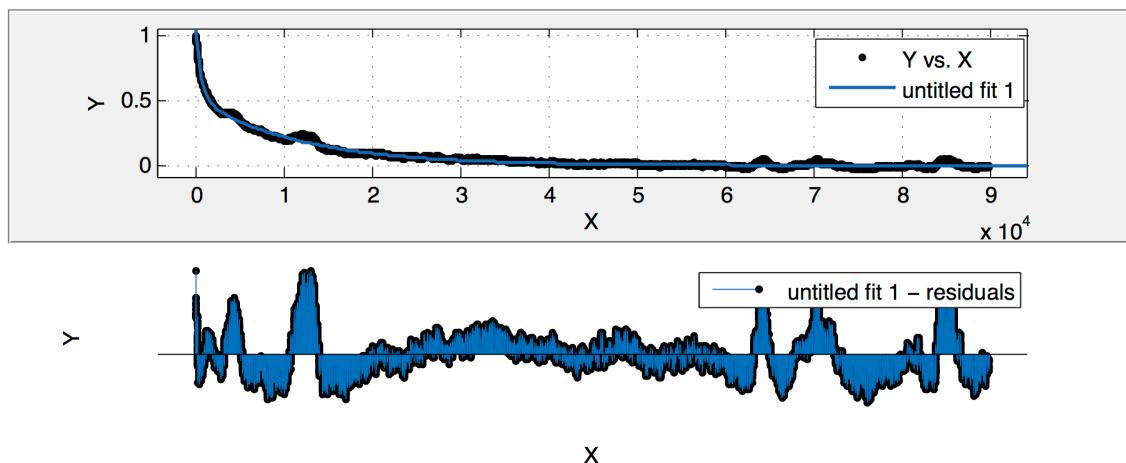


Figure S13. Fit to the data: H₂ Adsorption from ABS-10% MOF-5. Top panel: data (black dots) and fit (blue line). Bottom panel: residuals from the fit.

The fit parameters from MatLab are given below.

$$f(x) = a \cdot \exp(b \cdot x) + c \cdot \exp(d \cdot x)$$

a = 0.5097 (95% confidence bounds: 0.5083, 0.5111)

b = -0.00008561 (95% confidence bounds: -0.00008587, -0.00008534)

c = 0.4293 (95% confidence bounds: 0.4256, 0.4329)

d = -0.001457 (95% confidence bounds: -0.001479, -0.001435)

Goodness of fit

SSE 8.88

R-Square 0.9852

RMSE 0.01551

Compilation of rate analyses

Table S1. H₂ adsorption and desorption rates. Data a fit with:

$$n = P_1 e^{k_1 t} + P_2 e^{k_2 t} + P_3 e^{k_3 t}$$

	H ₂ Desorption				H ₂ Adsorption	
	ABS		ABS-10% MOF-5		ABS-10% MOF-5	
	P	k (s ⁻¹)	P	k (s ⁻¹)	P	k (s ⁻¹)
Rate 1	25	9x10 ⁻⁴	83	1x10 ⁻⁴	46	1x10 ⁻³
Rate 2	75	1x10 ⁻⁴	17	7x10 ⁻⁶	54	9x10 ⁻⁵