Reference Diffraction Patterns, Microstructure, and Pore-Size Distribution for the Copper (II) Benzene-1,3,5-Tricarboxylate Metal Organic Framework (Cu-BTC) Compounds

L. Li  
Boise State University

I. Williamson  
Boise State University
Reference diffraction patterns, microstructure, and pore-size distribution for the copper (II) benzene-1,3,5-tricarboxylate metal organic framework (Cu-BTC) compounds

W. Wong-Ng, 1,a) J.A. Kaduk, 2 D.L. Siderius, 1 A.L. Allen, 1 L. Espinal, 1 B.M. Boyerinas, 1 I. Levin, 1 M.R. Suchomel, 3 J. Ilavsky, 3 L. Li, 4 I. Williamson, 4 E. Cockayne, 1 and H. Wu 1,5

1National Institute of Standards and Technology (NIST), Gaithersburg, Maryland 20899
2Illinois Institute of Technology, Chicago, Illinois 60616
3Argonne National Laboratory, Advanced Photon Source, Argonne, Illinois 60439
4Materials Science and Engineering Department, Boise State University, Boise, Idaho 83725
5Department of Materials Science and Engineering, University of Maryland, College Park, Maryland 20742-2115

(Received 22 May 2014; accepted 1 October 2014)

Cu-paddle-wheel-based Cu3(BTC)2 (nicknamed Cu-BTC, where BTC = benzene 1,3,5-tricarboxylate) is a metal organic framework (MOF) compound that adopts a zeolite-like topology. We have determined the pore-size distribution using the Gelb and Gubbins technique, the microstructure using small-angle neutron scattering and (ultra) small-angle X-ray scattering (USAXS/SAXS) techniques, and X-ray powder diffraction reference patterns for both dehydrated d-Cu-BTC [Cu3(C6H3O6)3] and hydrated h-Cu-BTC [Cu3(H2O)2(H2O)6.96] using the Rietveld refinement technique. Both samples were confirmed to be cubic Fm 3 m (no. 225), with lattice parameters of a = 26.279(3) Å, V = 18 148.31(6) Å3 for d-Cu-BTC, and a = 26.3103(11) Å, and V = 18 213(2) Å3 for h-Cu-BTC. The structure of d-Cu-BTC contains three main pores of which the diameters are approximately, in decreasing order, 12.6, 10.6, and 5.0 Å. The free volume for d-Cu-BTC is approximately (71.85 ± 0.05)% of the total volume and is reduced to approximately (61.33 ± 0.03)% for the h-Cu-BTC structure. The d-Cu-BTC phase undergoes microstructural changes when exposed to moisture in air. The reference X-ray powder patterns for these two materials have been determined for inclusion in the Powder Diffraction File. © 2014 International Centre for Diffraction Data.

[doi:10.1017/S0885715614001195]

Key words: metal organic framework (MOF), Cu-BTC, X-ray powder patterns, microstructure, porosity distribution

I. INTRODUCTION

One of the most investigated metal organic framework (MOF) materials is the highly porous [Cu3(C6H3O6)2]n, or Cu-paddle-wheel-based Cu3(BTC)2 (BTC = benzene-carboxylate, abbreviated as Cu-BTC) (Chui et al., 1999; Wang et al., 2002; Skoulidas, 2004; Lee et al., 2005; Wei and Han, 2005; Krungleviciute, 2007; Wu et al., 2010). This material, which is also known as HKUST-1 (Chui et al., 1999), has framework integrity, a high specific surface area and a chemically tunable structure. The robust microporous structure is reminiscent of the topology of zeolite LTA frameworks. According to Chui et al. (1999), two octahedrally coordinated Cu atoms in [Cu3(BTC)2(H2O)n] are connected to eight oxygen atoms of tetra-carboxylate units to form a dimeric Cu-paddle wheel. This material has a three-dimensional (3D) channel structure connecting a system of cages [largest with a diameter of approximately 10 Å (Skoulidas, 2004; Lee et al., 2005; Krungleviciute, 2007)], accessible through small square-shaped windows (about 3.5 Å in dimension).

The sorption properties of Cu-BTC for both CO2 and water have been reported by Wang et al. (2002). The pores themselves can contain up to ten additional water molecules per formula unit. The thermal stability of Cu-BTC crystals was also reported by Wang et al. (2002). It was found that a fully hydrated molecular sieve contains up to 40% mass water, and it is stable up to a temperature of about 573 K.

Force field calculations have been performed by Tafipolsky et al. (2010). In addition to predicting the structure, lattice-dynamic-dependent properties such as the bulk modulus and the observed negative thermal expansion effect of Cu-BTC are also quantitatively predicted. During the gas adsorption process, the gas uptake is attributed to the overlapping attractive potentials from multiple copper paddle-wheel units: each Cu(II) center can potentially lose a terminal solvent ligand bound in the axial position, providing an open coordination site for gas binding.

At present, despite extensive studies of the Cu-BTC phase, detailed information on pore-size distribution (PSD) and microstructure characteristics is still incomplete. The goal for this paper is threefold: (1) to determine the PSD for both dehydrated (d-Cu-BTC) and hydrated (h-Cu-BTC) samples using the Gelb and Gubbins technique; (2) to estimate the difference in microstructure of both d-Cu-BTC and h-Cu-BTC...
II. EXPERIMENTAL AND COMPUTATION APPROACH

A. Reference powder X-ray diffraction (XRD) patterns

1. Sample preparation

The dark blue Cu-BTC [Cu$_3$(C$_6$H$_3$O$_6$)$_2$] sample was obtained from Sigma-Aldrich Chemical Corporation under the commercial name of Basolite C300 (Lot STBC4614 V). This material, when left in air changes color from dark blue (turquoise) to light blue because of the hydration process. The dehydrated phase can be regenerated by heat treatment.

Two samples were prepared for the powder pattern determination. $d$-Cu-BTC was obtained by heat treating the as-received sample at 150 °C under vacuum for overnight (activation). $h$-Cu-BTC was prepared by exposing the as-received sample in air for 4 h. Sample mounting of $d$-Cu-BTC was performed inside a dry box with flowing Ar. The sample for synchrotron study ($h$-Cu-BTC) was loaded into a 0.7-mm-wide polyamide capillary tubing; both ends were sealed with epoxy.

The mass percent change of the sample while degassing was monitored using a high-pressure thermal gravimetric analyzer (Model: TGA-HP50) from TA Instruments. An amount of 51 mg of sample was used for the experiment. The sample was heated from room temperature to 150 °C under vacuum and then held at 150 °C under vacuum for approximately 4 h. As shown in Figure 1, the mass percent change was stable after 2 h of degassing.

2. Powder XRD (laboratory and synchrotron)

a. Conventional laboratory X-ray

The $d$-Cu-BTC powders were mounted in atmosphere-controlled zero-background cells. The X-ray powder pattern was measured on a Bruker D2 Phaser diffractometer (Certain trade names and company products are mentioned in the text or identified in illustrations in order to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose) (30 kV, 10 mA, 5°–130° 2θ in 0.02° steps, 1 s step$^{-1}$) equipped with a LynxEye position-sensitive detector.

b. High-resolution synchrotron diffraction

High-resolution synchrotron X-ray powder diffraction data were collected using beamline 11-BM at the Advanced Photon Source (APS), Argonne National Laboratory using a wavelength of 0.412 21 Å. Discrete detectors covered a final angular range from 0° to 45°, with data points collected every 0.001° in 2θ at a scan speed of 0.01° s$^{-1}$. The instrumental optics of 11-BM incorporate two platinum-striped mirrors and a double-crystal Si (111) monochromator, where the second crystal has an adjustable sagittal bend (Wang et al., 2008). The diffractometer is controlled via EPICS (Dalesio et al., 1994). A vertical Huber 480 goniometer positions 12 perfect Si (111) analyzers and 12 Oxford-Danfysik LaCl$_3$ scintillators, with a spacing of 2° in 2θ (Lee et al., 2008). Capillary samples are mounted by a robotic arm and spun at $\approx$ 90 Hz. Data are normalized to incident flux and collected while continually scanning the diffractometer 2θ arm. A mixture of NIST standard reference materials, Si (SRM™ 640c) and Al$_2$O$_3$ (SRM™ 676) is used to calibrate the instrument, where the Si lattice constant determines the wavelength for each detector. Corrections are applied for detector sensitivity, 2θ offset, and small detector wavelength differences, before merging the data into a single set of intensities evenly spaced in 2θ.

c. Rietveld refinements and powder reference patterns

The Rietveld refinement technique (Rietveld, 1969) with the software suite GSAS (Larson and von Dreele, 2004) was used. A structural model of Cu$_3$(C$_6$H$_3$O$_6$)$_2$(H$_2$O)$_3$ based on single-crystal results (Chui et al., 1999) was used for the refinements. The organic ligands were modeled as rigid bodies. Only the three orientation angles and the center of the molecule ($x$, $y$, $z$) are refined. The peak profiles were described using the anisotropic strain tensor model of GSAS profile function #4 (GSAS). Preferred orientation was modeled using fourth-order spherical harmonics. The background was modeled using a three-term shifted Chebyshev function, and 9–14-term diffuse scattering functions were included.

The central C$_6$H$_3$ core of the organic ligand was modeled as a rigid body of 1/3-occupancy atoms. The Euler rotation angles are fixed by symmetry, and were not refined. The center of the molecule is constrained to lie on a threefold axis, so only one translational parameter was refined. The C1–C3 compounds using the small-angle X-ray scattering and ultra-small-angle X-ray scattering technique (SAXS/USAXS), and small-angle neutron scattering (SANS) technique; and (3) to determine their experimental reference X-ray powder patterns, and to make them widely available as a useful reference for non-destructive phase identification and characterization through submission to the Powder Diffraction File (PDF, 2014). Reference patterns that have been prepared in our laboratories for other porous materials included MOF74 [M$_2$(2,5-dihydroxyterephthalate), $M$ = (Mn, Co, Ni, Zn); Wong-Ng et al., 2012], ZIF8 [Bis(2-methylimidazolyl)-Zinc,C$_6$H$_4$N$_4$Zn; Wong-Ng et al., 2011], OMS2 (K$_{0.1}$MnO$_2$·0.08H$_2$O; Espinal et al., 2012), and NaY zeolite (Na$_{56}$Al$_{56}$Si$_{138}$O$_{384}$; Wong-Ng et al., 2013).
bond was subjected to a restraint of 1.47(1) Å, the C₃–O₁ bond was 1.26(2) Å, the Cu–O₁ bond was 1.94(2) Å, and the O₁–O₁ non-bonded distance was 2.24(3) Å. The O₁–C₃–C₁ angle was subject to a restraint of 117.5(3)°.

Reference patterns were obtained with a Rietveld pattern decomposition technique. In this technique, the reported peak positions were derived from the extracted integrated intensities, and positions calculated from the lattice parameters. When peaks are not resolved at the resolution function, the intensities are summed, and an intensity-weighted d-spacing is reported. They are corrected for systematic errors both in d-spacing and intensity. In other words, these patterns represent ideal specimen patterns.

B. Microstructural studies

1. Sample preparation

Powder samples were prepared in a dry box and sealed in plastic tape. The d-Cu-BTC samples were maintained in a dry environment and retained a dark blue color, whereas h-Cu-BTC were stored in air prior to measurement and were light blue in color. The d-Cu-BTC solid material was estimated to have a skeletal (X-ray) mass density of 0.89 g cm⁻³ (using formula Cu₃C₁₈H₂₄O₁₂). This gives a scattering length or atomic form-factor densities of 7.416 × 10¹⁴ m⁻² for X-rays and 1.683 × 10¹⁴ m⁻² for neutrons. The corresponding scattering contrast factors for the solid/void interface are 54.99 × 10²⁸ m⁻³ for X-rays and 2.832 × 10²⁸ m⁻³ for neutrons, and the predicted SAXS/SANS intensity ratio, based on measurements of the same sample, is therefore 19.42. The h-Cu-BTC solid material was established to have a skeletal (X-ray) mass density of 1.07 g cm⁻³ [using formula Cu₃C₁₈H₂₄O₁₂,6.96(H₂O) from our X-ray study]. This gives X-ray and neutron-scattering length (atomic form-factor) densities of 9.115 × 10¹⁴ and 1.573 × 10¹⁴ m⁻², respectively. The corresponding scattering contrast factors, based on the solid/void interface, are then 83.09 × 10²⁸ m⁻³ (X-rays) and 2.474 × 10²⁸ m⁻³ (neutrons), giving a predicted SAXS/SANS intensity ratio of 33.58 for SAXS and SANS measurements of the same sample.

2. USAXS measurements

USAXS measurements were made at ChemMatCARS sector 15-ID at the APS. The APS USAXS instrument, including some of its more recent additions such as a 2D pinhole geometry SAXS capability, are described elsewhere (Ilavsky et al., 2009, 2013). Using Si (220) optics, the X-ray energies used were 12 keV (λ = 1.033 Å) and 17 keV (λ = 0.729 Å) for the main USAXS Q range (Q = 0.0001 to ≈ 0.1 Å⁻¹), but the Q range was extended down to 0.0003 Å⁻¹ using Si(440) optics and X-ray energies of 21 keV (λ = 0.590 Å) and 24 keV (λ = 0.517 Å). Incident X-ray beam sizes as small as 0.5 × 0.5 mm and as large as 0.8 mm vertical × 2.0 mm horizontal were used. Although powder samples were used, data were normalized to the data from runs measured with mean thicknesses, τₐ, given by τₐ = 0.115 mm for d-Cu-BTC, and τₐ = 0.068 mm for h-Cu-BTC. USAXS data, which are intrinsically slit-smeared, were corrected for parasitic background scattering, and were absolute-calibrated using a primary method. The slit-smeared, absolute-calibrated USAXS data were merged with, and at high Q replaced by, 2D pinhole-geometry SAXS data obtained at the same time. The 2D data were slit-smeared to match the USAXS data before being normalized to and merged with the latter. The combined data were then desmeared to produce datasets of dΣ/dΩ vs. Q over a combined Q range of 0.0003 to ≈1 Å⁻¹, or as high as 1.2 Å⁻¹. Data reduction and analysis were carried out using the Irena macro package written in Igor Pro (Jemian and Ilavsky, 2009).

3. SAXS measurements

The principal purpose of the SAXS measurements was to provide a better signal-to-noise ratio at high Q, effectively extending the maximum Q of the combined USAXS/SAXS data. In addition to providing better SAXS data at high Q, the 2D SAXS measurements also captured several low-angle XRD peaks at higher Q values. The incident X-ray beam size for SAXS was smaller than for USAXS, and was typically 0.15 mm × 0.15 mm. The X-ray energy used was the same as used for the associated USAXS scans.

Conventional pinhole geometry 2D SAXS data were obtained at the APS USAXS facility at ChemMatCARS, APS sector 15-ID, using a separately mounted Dectris 100 K Pilatus 2D position-sensitive detector. SAXS measurements were carried out either immediately before or immediately after the corresponding USAXS scans, and typical exposure times were 30 s. The Q values for the 2D SAXS data were calibrated using silver behenate. The 2D SAXS data were corrected for parasitic (empty beam) scattering and circularly averaged about the incident beam position on the 2D detector, using the Nika macro package written in Igor Pro (Ilavsky, 2012). The data were also slit-smeared to match the slit-smeared USAXS data, then normalized and merged with the absolute-calibrated USAXS data, and finally the combined ID data were desmeared using the well-established algorithm by Lake (1967).

4. SANS measurements

SANS measurements were carried out using the NIST NG3SANS 30 m instrument at the NIST Center for Neutron Research (NCNR). This instrument is described elsewhere (Glinka et al., 1998). The wavelength, λ, used was 5.0 Å with the instrument’s rotating helical neutron velocity selector providing a Δλ/λ wavelength resolution of ≈13%. Several sample-to-detector configurations were used with matched instrument neutron guide collimations to produce an overall Q range from 0.004 to ≈0.2 Å⁻¹. The main USAXS d-Cu-BTC and h-Cu-BTC samples were measured with the same sample thicknesses as given above for USAXS. Using the NCNR SANS reduction and analysis macro suite (Kline, 2006), the SANS data were corrected for electronic and parasitic scattering background, and the absolute scattering intensity was calibrated using standard beam attenuators. The data were circularly averaged about the beam center on the instrument’s 2D position sensitive detector, and data for different instrument configuration inter-normalized and merged to produce neutron-based dΣ/dΩ vs. Q over the full range specified. Apart from the applicability of neutron-scattering contrast factors in place of X-ray contrast factors, the other principal difference for the SANS measurements, as compared
plications of water oxygen sites (OW1, OW2, and OW3) given in
First, oxygen atoms were randomly placed at the lattice posi-
water molecules, a slightly different technique was necessary.
using cubic voxels with side length 0.2 Å or smaller. For the
via the voxel technique described by Palmer
Tables I(a) and I(b) (determined from Rietveld re
eter. For both the
value of the PSD at a particular pore diameter is then the frac-
point without overlapping the material framework. The
is equal to the diameter of the largest sphere containing that
point without overlapping the material framework. The
value of the PSD at a particular pore diameter is then the frac-
tion of the free volume with local pore size equal to that diame-
ter. For both the d-Cu-BTC and h-Cu-BTC structures, we
first reconstructed the Cu-BTC material framework from the
XRD crystal structure data, identified the coordinates of each
atom in the framework, and then drew a van der Waals
exclusion sphere around each atom (van der Waals radii
of N2 with this diameter as the computational probe is expect-
ated diameter of 3.681 Å was used as the probe gas. Use
of N2 with this diameter as the computational probe is expect-
ed to yield an accessible surface area that correlates well with
the BET surface area measured by N2 adsorption (Walton and
Snurr, 2007). Reported uncertainties are 95% confidence inter-
vals based on standard t-tests.

C. Pore-size distribution

Computational methods were used to estimate the PSD,
the skeletal porosity, and the gas-accessible pore volume
and surface area of Cu-BTC. The chosen technique of comput-
ing the PSD was the method of Gelb and Gubbins (1999) in
which the local pore size at any given location in the material
is equal to the diameter of the largest sphere containing that
point without overlapping the material framework. The
value of the PSD at a particular pore diameter is then the frac-
tion of the free volume with local pore size equal to that diame-
ter. For both the d-Cu-BTC and h-Cu-BTC structures, we
first reconstructed the Cu-BTC material framework from the
XRD crystal structure data, identified the coordinates of each
atom in the framework, and then drew a van der Waals
exclusion sphere around each atom. Van der Waals radii
were 1.40 Å for Cu, 1.20 Å for H, 1.70 Å for C, and 1.52 Å
for O (Bondi, 1964; Rowland and Taylor, 1996). The PSD
of the dehydrated structure was then numerically calculated
via the voxel technique described by Palmer et al. (2011)
using cubic voxels with side length 0.2 Å or smaller. For the
hydrated structure, which requires the inclusion of hydrate
water molecules, a slightly different technique was necessary.
First, oxygen atoms were randomly placed at the lattice posi-
tions of water oxygen sites (OW1, OW2, and OW3) given in
Tables I(a) and I(b) (determined from Rietveld refinements
using synchrotron diffraction technique, as discussed below).
The fractional occupancies shown in Table I required the inclusion of 111 (rounded from 111.36) oxygen atoms that
belong to water molecules. Second, hydrogen atoms were
placed around each of the water oxygen (using bond length
of 0.9584 Å and bond angle of 104.45°), where the orientation
of the hydrogen atoms was selected randomly. The PSD of
this particular realization of the h-Cu-BTC structure was then computed using the same voxel technique used for the
d-Cu-BTC structure with similarly sized voxels. Finally, the
PSD analysis was repeated using 20 separate realizations of
the h-Cu-BTC structure and a final average PSD was comput-
ed from the ensemble of randomly generated structures.
Uncertainty in the PSD was estimated using a jackknife
analysis.

The skeletal porosity (the volume fraction of the crystal
unit cell not occupied by the van der Waals spheres surround-
ing each atom) was computed by Monte Carlo integration. The
pore volume and surface area were characterized by the
so-called accessible volume and accessible surface area met-
rics, which were computed as described by Frost et al.
(2006) and Duren et al. (2007) in which the framework
atoms were assigned the radii listed above and N2 with as-
signed diameter of 3.681 Å was used as the probe gas. Use
of N2 with this diameter as the computational probe is expect-
ed to yield an accessible surface area that correlates well with
the BET surface area measured by N2 adsorption (Walton and
Snurr, 2007). Reported uncertainties are 95% confidence inter-
vals based on standard t-tests.

III. RESULTS AND DISCUSSION

A. Structure and XRD reference patterns

Figures 2 and 3 give the results of the Rietveld refinements
for the d-Cu-BTC and h-Cu-BTC samples. In Figure 2, tick marks indicate peak positions for these phases. The
difference pattern is plotted on the same scale as the other

with the USA XAS, SANS studies, was the use of a much larger
6.35 mm diameter circular incident beam.

TABLE IA. Atomic coordinates and isotropic displacement factors for Cu3(C9H3O6)2; values inside brackets are standard deviations; a = 26.279 19(3) Å, V =
18 148.31(6) Å3, Z = 16, D1 = 0.89 g cm−3; Ueq is the equivalent isotropic displacement factor (Fischer and Tillmanns, 1988).

<table>
<thead>
<tr>
<th>Atom</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>Occ.</th>
<th>Ueq</th>
<th>Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>0.283 61(2)</td>
<td>0.283 61(2)</td>
<td>0.0</td>
<td>1.0</td>
<td>0.010 34(13)</td>
<td>48</td>
</tr>
<tr>
<td>O1</td>
<td>0.256 15(5)</td>
<td>0.183 07(5)</td>
<td>−0.051 98(5)</td>
<td>1.0</td>
<td>0.0150(5)</td>
<td>192</td>
</tr>
<tr>
<td>C1</td>
<td>0.321 73</td>
<td>0.178 27</td>
<td>−0.113 48(8)</td>
<td>1.0</td>
<td>0.0110(6)</td>
<td>96</td>
</tr>
<tr>
<td>C2</td>
<td>0.364 78(12)</td>
<td>0.200 01(8)</td>
<td>−0.135 22(12)</td>
<td>1.0</td>
<td>0.0110(6)</td>
<td>96</td>
</tr>
<tr>
<td>C3</td>
<td>0.296 31(8)</td>
<td>0.203 70(8)</td>
<td>−0.069 82(9)</td>
<td>1.0</td>
<td>0.0150(5)</td>
<td>96</td>
</tr>
<tr>
<td>H1</td>
<td>0.379 77(14)</td>
<td>0.229 70(11)</td>
<td>−0.120 22(14)</td>
<td>1.0</td>
<td>0.0143(8)</td>
<td>96</td>
</tr>
</tbody>
</table>

TABLE IB. Atomic coordinates and isotropic displacement factors for Cu3(C9H3O6)2(H2O)9.6; values inside brackets are standard deviations. Because of the
disordered situation and the low X-ray scattering factor for H, hydrogen atoms of the water molecules were not located, a = 26.3103(11) Å, V =
18 213 (2) Å3, Z = 16, D1 = 1.07 g cm−3; Ueq is the equivalent isotropic displacement factor (Fischer and Tillmanns, 1988).

<table>
<thead>
<tr>
<th>Atom (Framework molecule)</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>Occ.</th>
<th>Ueq</th>
<th>Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>0.285 31</td>
<td>0.285 31</td>
<td>0.0</td>
<td>1.0</td>
<td>0.058(2)</td>
<td>48</td>
</tr>
<tr>
<td>O1</td>
<td>0.2572(3)</td>
<td>0.1822(3)</td>
<td>−0.0514(3)</td>
<td>1.0</td>
<td>0.066(5)</td>
<td>192</td>
</tr>
<tr>
<td>C1</td>
<td>0.3225</td>
<td>0.17748</td>
<td>−0.1124(4)</td>
<td>1.0</td>
<td>0.079(7)</td>
<td>96</td>
</tr>
<tr>
<td>C2</td>
<td>0.3657(6)</td>
<td>0.1993(4)</td>
<td>−0.1343(6)</td>
<td>1.0</td>
<td>0.079(7)</td>
<td>96</td>
</tr>
<tr>
<td>C3</td>
<td>0.2963(6)</td>
<td>0.2037(6)</td>
<td>−0.0702(6)</td>
<td>1.0</td>
<td>0.066(5)</td>
<td>96</td>
</tr>
<tr>
<td>H1</td>
<td>0.3808(7)</td>
<td>0.2291(5)</td>
<td>−0.1192(7)</td>
<td>1.0</td>
<td>0.103(10)</td>
<td>96</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Atom (Oxygen atoms)</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>Occ.</th>
<th>Ueq</th>
<th>Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>OW1</td>
<td>0.1307(6)</td>
<td>0.1307(6)</td>
<td>0.1307(6)</td>
<td>0.80(2)</td>
<td>0.04</td>
<td>32</td>
</tr>
<tr>
<td>OW2</td>
<td>0.2287(10)</td>
<td>−0.0364(9)</td>
<td>−0.0364(9)</td>
<td>0.32(1)</td>
<td>0.04</td>
<td>96</td>
</tr>
<tr>
<td>OW3</td>
<td>0.1390(9)</td>
<td>0.1696(7)</td>
<td>0.0</td>
<td>0.57(2)</td>
<td>0.04</td>
<td>96</td>
</tr>
</tbody>
</table>
Table II gives the lattice parameters of these compounds [all adopt space group \( Fm\overline{3}m \) (no. 225)]. The lattice parameter of the CO\(_2\) adsorbed compound \( \text{Cu}_3(\text{C}_9\text{H}_3\text{O}_6)\text{O}_2(\text{CO}_2)_{4.41} \) is included in this table for comparison (Wu et al., 2010). As expected the lattice parameters for the \(\text{d-Cu-BTC}\) sample \([a = 26.279\text{ Å}(3)\text{ Å}]\) are smaller than that of \(\text{h-Cu-BTC}\) \([26.3103(11)\text{ Å}]\). Tables III(a) and III(b) give the representative bond distances. The refined orientation angles and the center of the Cu-BTC molecules using the rigid body model are 134.44°, 35.53°, −60.32°, \(x = 0.343\text{ Å}(35)\text{ Å}, y = 0.156\text{ Å}(5)\), \(z = 0.156\text{ Å}(5)\text{ Å}\) for \(\text{d-Cu-BTC}\), \(\text{Cu}_3(\text{C}_9\text{H}_3\text{O}_6)\text{O}_2\), and 134.44°, 35.53°, −60.32°, \(x = 0.343\text{ Å}(35)\text{ Å}, y = 0.156\text{ Å}(3)\text{ Å}, z = 0.156\text{ Å}(3)\text{ Å}\) for \(\text{Cu}_3(\text{C}_9\text{H}_3\text{O}_6)\text{O}_2(\text{H}_2\text{O})_{6.96}\).

Figures 4(a), 4(b), 5(a), and 5(b) give the structure of the \(\text{d-Cu-BTC}\) and \(\text{h-Cu-BTC}\) viewing down the \([100]\) direction and the \([110]\) direction of the cubic cell, respectively. These diagrams reveal the 1 nm size channels with a fourfold symmetry. The nano-channels intersect to give a 3D-connected network of pores. Both Figures 4(b) and 5(b) reveal a honeycomb arrangement. The copper species have free binding sites in the nano-spaces, which facilitate the formation of adducts with electroactive molecules. In the dehydrated case, Cu has a fivefold coordination environment (four oxygen and one Cu) while in the hydrated case, Cu has a sixfold coordination in which the sixth member is a water molecule. The water molecules mainly occupy three specific sites, namely, being coordinated to Cu and becoming a terminal water ligand (OW3), which are directed from the Cu atoms to the interior of the nanopores. There are two possible positions of coordination to each Cu, one on each side of the extension of the Cu–Cu-axis, but only one side is occupied by a water

TABLE II. Unit-cell parameters for \(\text{Cu}_3(\text{C}_9\text{H}_3\text{O}_6)\text{O}_2\) and \(\text{Cu}_3(\text{C}_9\text{H}_3\text{O}_6)\text{O}_2(\text{H}_2\text{O})_{6.96}\) [space group \( Fm\overline{3}m \) (no. 225), \(Z = 16\)]. \(D_s\) refers to calculated density. Values inside brackets are standard deviations.

<table>
<thead>
<tr>
<th>Compounds (\text{Cu}_3(\text{C}_9\text{H}_3\text{O}_6)\text{O}_2)</th>
<th>(a) (Å)</th>
<th>(V) (Å(^3))</th>
<th>(D_s) (g cm(^{-3}))</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{Cu}_3(\text{C}_9\text{H}_3\text{O}_6)\text{O}_2)</td>
<td>26.279 19(3)</td>
<td>18 148.31(6)</td>
<td>0.89</td>
<td>This work</td>
</tr>
<tr>
<td>(\text{Cu}_3(\text{C}_9\text{H}_3\text{O}_6)\text{O}_2(\text{CO}<em>2)</em>{3.41})</td>
<td>26.305(3)</td>
<td>18 202.61</td>
<td>1.16</td>
<td>Wu, 2010</td>
</tr>
</tbody>
</table>

\(\text{Cu}_3(\text{C}_9\text{H}_3\text{O}_6)\text{O}_2(\text{H}_2\text{O})_{6.96}\) | 26.3103(11) | 18 213(2) | 1.07 | This work |

TABLE IIIA. Selected bond distances for \(\text{Cu}_3(\text{C}_9\text{H}_3\text{O}_6)\text{O}_2\); values inside brackets are standard deviation uncertainties. As noted in the text, all of these bonds were subject to distance restraints.

<table>
<thead>
<tr>
<th>Atom</th>
<th>Atom</th>
<th>Distances (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>Cu</td>
<td>2.4980 (13)</td>
</tr>
<tr>
<td>Cu</td>
<td>O(_i)</td>
<td>1.9297 (13)</td>
</tr>
<tr>
<td>O(_i)</td>
<td>C(_3)</td>
<td>1.2756 (14)</td>
</tr>
<tr>
<td>C(_i)</td>
<td>C(_3)</td>
<td>1.486(2)</td>
</tr>
</tbody>
</table>

TABLE IIIIB. Selected bond distances for \(\text{Cu}_3(\text{C}_9\text{H}_3\text{O}_6)\text{O}_2(\text{H}_2\text{O})_{6.96}\); values inside brackets are standard deviation uncertainties. As noted in the text, all of these bonds were subject to distance restraints.

<table>
<thead>
<tr>
<th>Atom</th>
<th>Atom</th>
<th>Distances (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>Cu</td>
<td>2.628(10)</td>
</tr>
<tr>
<td>Cu</td>
<td>O(_i)</td>
<td>1.9516(6)</td>
</tr>
<tr>
<td>Cu</td>
<td>OW(_3)</td>
<td>2.32(2)</td>
</tr>
<tr>
<td>O(_i)</td>
<td>C(_3)</td>
<td>1.274(5)</td>
</tr>
<tr>
<td>C(_i)</td>
<td>C(_3)</td>
<td>1.480(4)</td>
</tr>
</tbody>
</table>

Figure 2. (Color online) Results of the Rietveld refinement of the \(\text{d-Cu-BTC}\) phase (using synchrotron radiation). Tick marks indicate peak positions for these phases (bottom tick marks). The difference pattern is plotted on the same scale as the other patterns up to 5° in 2θ. For 2θ > 5°, the scale has been magnified ten times; for 2θ > 14°, the scale has been magnified 50 times.

Figure 3. (Color online) Results of Rietveld refinement of the \(\text{h-Cu-BTC}\) phase (using laboratory X-ray). Tick marks indicate peak positions for these phases (bottom tick marks). The difference pattern is plotted on the same scale as the other patterns. For 2θ > 22°, the scale has been magnified ten times, and for 2θ > 53° the scale has been multiplied by 40.
molecule oxygen. Other partially occupied sites for water are near the center of the main pore.

The Cu–O bond distances reported in Tables III(a) and III(b) are typical distances found in Cu–O containing compounds (Nimmermark \textit{et al.}, 2013). The bond valence calculations for the Cu sites in both compounds suggested that the valence state for Cu is essentially 2 (2.03 in \textit{d}-Cu-BTC and 2.10 in \textit{h}-Cu-BTC, respectively), and no significant strain is associated with these sites. The slightly longer Cu–Cu distance of 2.628 (10) Å in \textit{h}-Cu-BTC as compared with 2.4980 (13) Å in \textit{d}-Cu-BTC is possibly because of the additional coordination of Cu to O (water) in \textit{h}-Cu-BTC, therefore weakening the Cu–Cu bond.

To confirm the stability of the Cu$_3$(C$_6$H$_3$O$_6$)$_2$ structure, we used first-principles total energy minimization approach, based on density functional theory, to determine the ground state of the compound (Kresse and Furthmuller, 1996). We also added van der Waals interaction in the calculation. Projector-augmented wave pseudopotentials were applied in conjunction with a plane wave expansion of the wavefunctions (Blochl, 1994; Kresse and Joubert, 1999). The generalized gradient approximation was used to approximate the exchange and correlation functional, using the PBE parameterization (Perdew \textit{et al.}, 1996). Relaxations of atomic positions and lattice vectors were performed until residual forces were converged to 0.01 eV Å$^{-1}$. In comparison with the structural data shown in Tables I(a) and II, the structure of Cu$_3$(C$_6$H$_3$O$_6$)$_2$, proposed by experiment, is energetically stable and the binding energy of Cu in the compound was found to be $\sim$7.2 eV Cu$^{-1}$.

\section*{B. Pore-size distribution, pore volume, and surface area}

Figures 6(a) and 6(b) display a schematic representation of Cu-BTC (based on the crystal structure data given in
Tables III(a) and III(b) for two cases: (a) \(d\)-Cu-BTC structure and (b) \(h\)-Cu-BTC structure, with the positions and orientations of water molecules assigned randomly. In both cases, van der Waals radii have been drawn about each constituent atom to indicate the approximate space taken up by the framework atoms. The schematic representations display three main pores of differing sizes present in both \(d\)-Cu-BTC and \(h\)-Cu-BTC. The \(h\)-Cu-BTC structure in Figure 6(b) shows water molecules from one particular realization of the hydrated structure. The \(d\)-Cu-BTC structure contains three main cages (or pores) of roughly spherical shape, of which the diameters are, in decreasing order, approximately 12.6, 10.6, and 5.0 Å. The largest and smallest cages are connected by an aperture with approximate diameter 3.5 Å, whereas the largest and middle-sized cages are connected by apertures of approximate size 6.6 Å. We note that the small- and middle-sized cages are not directly connected. The free volume (that not occupied by the framework atoms) for the \(d\)-Cu-BTC structure is approximately \((71.85 \pm 0.05\) % of the total volume.

The PSD in Figure 7 was computed for \(d\)-Cu-BTU using the structure shown in Figure 6(a). The three main cages are clearly identified by the large peaks in PSD, and the PSD reveals that approximately 68.35% of the free volume is attributed to these main pores for the \(d\)-Cu-BTC structure. For the \(h\)-Cu-BTC structure, shown in Figure 6(b), three main cages are still present, but the two largest cages each have a film of water molecules at their surfaces, which alter both the free volume and the effective pore sizes. The free volume of the \(h\)-Cu-BTC structure is approximately \((61.33 \pm 0.03\) % of the total volume. The PSD of the \(h\)-Cu-BTC structure in Figure 7 indicates that the effective pore sizes of the two largest pores are reduced to 10.2 and 7.2 Å (note that the peak of this pore size in the distribution is split). The diameter of the smallest cage, however, is unchanged at 5.0 Å, indicating that water molecules do not occupy the interior of the smallest cage. This is confirmed by examination of the atomic coordinates of water given in Tables III(a) and III(b) and by visual inspection of Figure 6(b). The presence of water molecules also reduces the portion of the free volume assigned to the main pores to approximately 39.86%, with the majority of the free volume lost to portions of the structure with local pore size smaller than 5.0 Å.

The accessible surface area and volume of Cu-BTC was computed using \(N_2\) as the probe gas. For \(d\)-Cu-BTC, the accessible surface area was found to be \((2175.9 \pm 1.5) \text{ m}^2 \text{ g}^{-1}\). In hydrated form, the accessible surface area was found to be \((1291.9 \pm 13.9) \text{ m}^2 \text{ g}^{-1}\), considerably reduced from that of the dehydrated structure. With the same \(N_2\) probe, the accessible volume of \(d\)-Cu-BTC was computed as \((0.2978 \pm 0.0004) \text{ cm}^3 \text{ g}^{-1}\) and that of the \(h\)-Cu-BTC structure was computed as \((0.088 21 \pm 0.001 22) \text{ cm}^3 \text{ g}^{-1}\). Both metrics highlight the reduction in surface area and volume available to adsorbate gases that results from hydration of Cu-BTC.
C. Microstructures by SANS and USAXS/SAXS

Figures 8(a) and 8(b) present the combined USAXS/SAXS data for the $d$-Cu-BTC and $h$-Cu-BTC samples with fits for feature-size distributions. Although the scattering from all samples is similar at low $Q$ [Figure 8(a)], $d$-Cu-BTC stored under dry conditions shows little or no scattering from fine features at high $Q$ [Figure 8(b)]. We also note that both $d$-Cu-BTC and $h$-Cu-BTC exhibit discrete small-angle diffraction peaks in the high-$Q$ part of the small-angle regime [Figure 8(b)]. There is a clear distinction in the scattering profiles between $d$-Cu-BTC and $h$-Cu-BTC samples over the central part of the USAXS $Q$ range. The $h$-Cu-BTC data exhibit significantly more scattering intensity over this range. However, the small-angle diffraction peaks at high $Q$ in these plots are less prominent in the $h$-Cu-BTC spectra than in the $d$-Cu-BTC spectra. The fact that the XRD peak intensity decreases as H$_2$O is adsorbed into the structure of Cu-BTC suggests that, whereas H$_2$O contributes to a new denser phase, the resulting sample is less crystalline than that of the $d$-Cu-BTC case, and a glassy phase also appears to be formed.

Size distributions that assume spherical scattering features were obtained from the scattering curves using the entropy maximization algorithm, MaxEnt (Potton et al., 1988). The main USAXS scattering profile is not attributable to a single-feature population of specific size but is associated with scattering from an extended size range of features, possibly comprising a fractal morphology. While present for both $d$-Cu-BTC and $h$-Cu-BTC samples, the prominence of scattering features over such an extended scale regime is clearly more pronounced in the case of $h$-Cu-BTC material. These points are illustrated in Figures 9(a) and 9(b). The prominence of the discrete fine features in the left-hand plot is because of the logarithmic size scale used and the fact that $V(D)$ is a volume fraction density distribution function (in units of volume fraction per unit Å increment; Potton et al., 1988). The integrated volume fraction is much less than that for the extended range of scattering features larger than $\approx 100$ Å.

While the integrated volume fraction over the scale range from 100 to $10^4$ Å (1 μm) is not insignificant even in the case of $d$-Cu-BTC material, that for $h$-Cu-BTC accounts for much of the sample volume, and we can assume that the microstructural effects of H$_2$O adsorption from the air are very significant for the whole powder morphology. We note that the increase in the volume fraction of scattering features extends to $\approx 5000$
Å, but not to the largest features, and this corresponds to the $d$-Cu-BTC and $h$-Cu-BTC data lying almost on top of each other for $Q < 0.001 \, \text{Å}^{-1}$.

### D. USAXS/SANS intensity comparison

Figure 10 presents USAXS/SAXS and SANS data from the $d$-Cu-BTC and $h$-Cu-BTC samples. The X-ray to neutron intensity comparison is important for the Cu-BTC system. The larger than predicted USAXS/SANS intensity ratios for both the $d$-Cu-BTC and $h$-Cu-BTC cases indicate that the H$_2$O adsorbed in the $h$-Cu-BTC case is completely incorporated into the solid structure. If this were not so and free H$_2$O occupied the space between grains in $h$-Cu-BTC, the SANS contrast factor would increase for $h$-Cu-BTC, compared with $d$-Cu-BTC, whereas the SAXS contrast factor would significantly decrease. This would reduce the USAXS/SANS intensity ratio for $h$-Cu-BTC, compared with $d$-Cu-BTC. Clearly, this does not happen and the USAXS/SANS contrast factor ratio actually increases.

We also note that the scattering intensity increases for both USAXS and SANS for the $h$-Cu-BTC case. While an increase in scattering contrast factor is predicted, the very

---

**TABLE IVA. X-ray powder pattern for dry Cu$_3$(C$_9$H$_3$O$_6$)$_2$Fm$3\overline{m}$ (no. 225), $a = 26.279 \, 19(3) \, \text{Å}, V = 18 \, 148.31(6) \, \text{Å}^3$. The symbols "M" and "+" refer to peaks containing contributions from two and more than two reflections, respectively. The symbol * indicates the particular peak has the strongest intensity of the entire pattern and is designated a value of "999".**

<table>
<thead>
<tr>
<th>$d$ (Å)</th>
<th>$l$</th>
<th>$h$</th>
<th>$k$</th>
<th>$l$</th>
<th>$d$ (Å)</th>
<th>$l$</th>
<th>$h$</th>
<th>$k$</th>
<th>$l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.172</td>
<td>22</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>13.140</td>
<td>999*</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7.9235</td>
<td>49</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>7.5862</td>
<td>965</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>6.0289</td>
<td>86</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>5.8762</td>
<td>11</td>
<td>4</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>5.0574</td>
<td>77</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4.6456</td>
<td>111</td>
<td>4</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>4.1551</td>
<td>16</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>3.9617</td>
<td>8</td>
<td>6</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3.6798</td>
<td>25</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>3.5117</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>3.2849</td>
<td>3</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>3.2105</td>
<td>8</td>
<td>6</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3.0970</td>
<td>26</td>
<td>6</td>
<td>6</td>
<td>0M</td>
<td>3.0345</td>
<td>67</td>
<td>7</td>
<td>5</td>
<td>1M</td>
</tr>
<tr>
<td>2.8673</td>
<td>10</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>2.8014</td>
<td>18</td>
<td>6</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>2.6821</td>
<td>3</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>2.6412</td>
<td>8</td>
<td>7</td>
<td>5</td>
<td>5+</td>
</tr>
<tr>
<td>2.5769</td>
<td>8</td>
<td>8</td>
<td>6</td>
<td>2</td>
<td>2.5405</td>
<td>81</td>
<td>7</td>
<td>7</td>
<td>3M</td>
</tr>
<tr>
<td>2.5287</td>
<td>11</td>
<td>10</td>
<td>2</td>
<td>2M</td>
<td>2.5406</td>
<td>2</td>
<td>9</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>2.3695</td>
<td>25</td>
<td>7</td>
<td>7</td>
<td>5</td>
<td>2.3228</td>
<td>3</td>
<td>8</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>2.2873</td>
<td>25</td>
<td>10</td>
<td>4</td>
<td>4M</td>
<td>2.2873</td>
<td>25</td>
<td>8</td>
<td>8</td>
<td>2M</td>
</tr>
<tr>
<td>2.2290</td>
<td>19</td>
<td>11</td>
<td>3</td>
<td>3M</td>
<td>2.2210</td>
<td>4</td>
<td>10</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>2.1889</td>
<td>7</td>
<td>8</td>
<td>8</td>
<td>4M</td>
<td>2.1675</td>
<td>40</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>2.1315</td>
<td>23</td>
<td>10</td>
<td>6</td>
<td>4M</td>
<td>2.1108</td>
<td>29</td>
<td>11</td>
<td>5</td>
<td>3M</td>
</tr>
<tr>
<td>2.0521</td>
<td>19</td>
<td>8</td>
<td>8</td>
<td>6+</td>
<td>2.0094</td>
<td>3</td>
<td>9</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>1.9642</td>
<td>45</td>
<td>11</td>
<td>7</td>
<td>3+</td>
<td>1.9587</td>
<td>4</td>
<td>12</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>1.9217</td>
<td>51</td>
<td>9</td>
<td>9</td>
<td>5</td>
<td>1.8965</td>
<td>4</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>1.8819</td>
<td>5</td>
<td>11</td>
<td>7</td>
<td>3M</td>
<td>1.8771</td>
<td>5</td>
<td>14</td>
<td>0</td>
<td>0M</td>
</tr>
<tr>
<td>1.8444</td>
<td>4</td>
<td>11</td>
<td>9</td>
<td>1</td>
<td>1.8399</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>1.8091</td>
<td>11</td>
<td>9</td>
<td>9</td>
<td>7M</td>
<td>1.8049</td>
<td>19</td>
<td>14</td>
<td>4</td>
<td>0M</td>
</tr>
<tr>
<td>1.7758</td>
<td>16</td>
<td>13</td>
<td>5</td>
<td>5M</td>
<td>1.7758</td>
<td>16</td>
<td>11</td>
<td>7</td>
<td>7M</td>
</tr>
<tr>
<td>1.7403</td>
<td>6</td>
<td>14</td>
<td>4</td>
<td>4</td>
<td>1.7106</td>
<td>7</td>
<td>14</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>1.6858</td>
<td>6</td>
<td>9</td>
<td>9</td>
<td>9M</td>
<td>1.6824</td>
<td>2</td>
<td>12</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>1.6298</td>
<td>13</td>
<td>16</td>
<td>2</td>
<td>0+</td>
<td>1.6174</td>
<td>22</td>
<td>16</td>
<td>2</td>
<td>2+</td>
</tr>
<tr>
<td>1.5847</td>
<td>11</td>
<td>15</td>
<td>5</td>
<td>5M</td>
<td>1.5847</td>
<td>11</td>
<td>13</td>
<td>9</td>
<td>5M</td>
</tr>
<tr>
<td>1.5379</td>
<td>20</td>
<td>12</td>
<td>12</td>
<td>2</td>
<td>1.5275</td>
<td>26</td>
<td>14</td>
<td>10</td>
<td>0M</td>
</tr>
<tr>
<td>1.5172</td>
<td>2</td>
<td>14</td>
<td>10</td>
<td>2M</td>
<td>1.4878</td>
<td>12</td>
<td>14</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>1.4662</td>
<td>3</td>
<td>11</td>
<td>11</td>
<td>9</td>
<td>1.4600</td>
<td>10</td>
<td>16</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>1.4444</td>
<td>4</td>
<td>15</td>
<td>9</td>
<td>5M</td>
<td>1.4337</td>
<td>2</td>
<td>16</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>1.4169</td>
<td>10</td>
<td>14</td>
<td>12</td>
<td>2M</td>
<td>1.4104</td>
<td>3</td>
<td>17</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>1.3948</td>
<td>2</td>
<td>15</td>
<td>9</td>
<td>7</td>
<td>1.3928</td>
<td>7</td>
<td>16</td>
<td>10</td>
<td>0+</td>
</tr>
<tr>
<td>1.3774</td>
<td>3</td>
<td>18</td>
<td>6</td>
<td>2</td>
<td>1.3644</td>
<td>3</td>
<td>19</td>
<td>3</td>
<td>1+</td>
</tr>
<tr>
<td>1.3359</td>
<td>9</td>
<td>19</td>
<td>5</td>
<td>1M</td>
<td>1.3273</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>0</td>
</tr>
</tbody>
</table>

Continued
significant increase in scattering is mostly attributable to more scattering features emerging in the h-Cu-BTC case, as discussed above. Finally, we note that both USAXS/SANS intensity ratios are somewhat larger than the predicted. This is most likely because of the much larger incident beam cross-section for SANS averaging over regions of poorer powder packing (or smaller effective sample thickness), whereas for USAXS the sample has been surveyed into a position where substantial material is present in the beam.

E. Reference X-ray powder patterns

The reference patterns for the d-Cu-BTC and h-Cu-BTC phases are given in Tables IV(a) and IV(b). In these patterns, the symbols “M” and “+” refer to peaks containing contributions from two and more than two reflections, respectively. The symbol* indicates that the particular peak has the strongest intensity of the entire pattern and has been designated a value of “999”. The intensity values reported are integrated intensities rather than peak heights. These patterns will be submitted for inclusion in the PDF.

IV. SUMMARY

The structure and reference X-ray patterns for d-Cu-BTC and h-Cu-BTC [Cu₃(C₈H₅O₆)₂ and Cu₃(C₈H₅O₆)₂(H₂O)₆.₉₆, respectively] have been determined using both conventional laboratory X-ray technique and synchrotron X-ray techniques, respectively. Water of hydration was found partially occupying three sites in the main pore: a disordered site coordinated to Cu, and two other sites occupying the main pore. Unit-cell expansion was observed from d-Cu-BTC to h-Cu-BTC [V increases from 18 148.31(6) to V=18 213 (2) Å³, respectively].

TABLE IV.A. Continued

<table>
<thead>
<tr>
<th>d (Å)</th>
<th>I</th>
<th>h</th>
<th>k</th>
<th>l</th>
<th>d (Å)</th>
<th>I</th>
<th>h</th>
<th>k</th>
<th>l</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3010</td>
<td>9</td>
<td>20</td>
<td>2</td>
<td>2M</td>
<td>1.2963</td>
<td>5</td>
<td>19</td>
<td>7</td>
<td>1M</td>
</tr>
<tr>
<td>1.2762</td>
<td>4</td>
<td>18</td>
<td>10</td>
<td>0</td>
<td>1.2703</td>
<td>3</td>
<td>18</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>1.2528</td>
<td>8</td>
<td>20</td>
<td>6</td>
<td>2M</td>
<td>1.2361</td>
<td>3</td>
<td>16</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>1.2266</td>
<td>5</td>
<td>17</td>
<td>11</td>
<td>7M</td>
<td>1.2161</td>
<td>12</td>
<td>19</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>1.2096</td>
<td>2</td>
<td>18</td>
<td>12</td>
<td>2</td>
<td>1.2058</td>
<td>2</td>
<td>21</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>1.1848</td>
<td>3</td>
<td>14</td>
<td>14</td>
<td>10</td>
<td>1.1764</td>
<td>7</td>
<td>21</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>1.1569</td>
<td>4</td>
<td>16</td>
<td>16</td>
<td>2</td>
<td>1.1491</td>
<td>4</td>
<td>19</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>1.1351</td>
<td>7</td>
<td>18</td>
<td>14</td>
<td>4M</td>
<td>1.1319</td>
<td>6</td>
<td>21</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>1.1155</td>
<td>2</td>
<td>23</td>
<td>5</td>
<td>1</td>
<td>1.0998</td>
<td>2</td>
<td>21</td>
<td>9</td>
<td>7M</td>
</tr>
<tr>
<td>1.0764</td>
<td>2</td>
<td>16</td>
<td>14</td>
<td>12+</td>
<td>1.0702</td>
<td>3</td>
<td>23</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>1.0623</td>
<td>3</td>
<td>22</td>
<td>8</td>
<td>8</td>
<td>1.0429</td>
<td>3</td>
<td>23</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>1.0056</td>
<td>5</td>
<td>25</td>
<td>7</td>
<td>3M</td>
<td>1.0048</td>
<td>2</td>
<td>26</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>0.9821</td>
<td>2</td>
<td>18</td>
<td>14</td>
<td>14</td>
<td>0.9416</td>
<td>5</td>
<td>23</td>
<td>13</td>
<td>9M</td>
</tr>
<tr>
<td>0.8688</td>
<td>2</td>
<td>23</td>
<td>19</td>
<td>5</td>
<td>0.8590</td>
<td>2</td>
<td>26</td>
<td>16</td>
<td>2</td>
</tr>
</tbody>
</table>

TABLE IV.B. X-ray powder pattern for dry Cu₃(C₈H₅O₆)₂(H₂O)₆.₉₆, Fm 3m (no. 225), a=26.3103(11) Å, and V=18 213(2) Å³. The symbols “M” and “+” refer to peaks containing contributions from two and more than two reflections, respectively. The symbol * indicates the particular peak has the strongest intensity of the entire pattern and is designated a value of “999”.

<table>
<thead>
<tr>
<th>d (Å)</th>
<th>I</th>
<th>h</th>
<th>k</th>
<th>l</th>
<th>d (Å)</th>
<th>I</th>
<th>h</th>
<th>k</th>
<th>l</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.190</td>
<td>102</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>13.154</td>
<td>999*</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7.9330</td>
<td>103</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>7.9592</td>
<td>999*</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>6.0361</td>
<td>90</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>5.8832</td>
<td>9</td>
<td>4</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>5.0635</td>
<td>117</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4.6511</td>
<td>136</td>
<td>4</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>4.3851</td>
<td>59</td>
<td>6</td>
<td>0</td>
<td>0M</td>
<td>4.1601</td>
<td>20</td>
<td>6</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3.6842</td>
<td>32</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>3.6486</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>3.4254</td>
<td>73</td>
<td>7</td>
<td>3</td>
<td>1M</td>
<td>3.2144</td>
<td>27</td>
<td>7</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>3.0381</td>
<td>57</td>
<td>7</td>
<td>5</td>
<td>1M</td>
<td>3.0381</td>
<td>57</td>
<td>5</td>
<td>5</td>
<td>5M</td>
</tr>
<tr>
<td>2.8880</td>
<td>11</td>
<td>7</td>
<td>5</td>
<td>3</td>
<td>2.8047</td>
<td>21</td>
<td>6</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>2.6311</td>
<td>13</td>
<td>8</td>
<td>6</td>
<td>0</td>
<td>2.5800</td>
<td>7</td>
<td>8</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>2.5436</td>
<td>48</td>
<td>7</td>
<td>7</td>
<td>3M</td>
<td>2.5317</td>
<td>11</td>
<td>6</td>
<td>6</td>
<td>6M</td>
</tr>
<tr>
<td>2.4429</td>
<td>6</td>
<td>10</td>
<td>4</td>
<td>0</td>
<td>2.3724</td>
<td>16</td>
<td>7</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>2.2988</td>
<td>40</td>
<td>9</td>
<td>5</td>
<td>5M</td>
<td>2.2901</td>
<td>19</td>
<td>10</td>
<td>4</td>
<td>4M</td>
</tr>
<tr>
<td>2.2561</td>
<td>6</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>2.2316</td>
<td>15</td>
<td>9</td>
<td>7</td>
<td>3M</td>
</tr>
<tr>
<td>2.2237</td>
<td>6</td>
<td>10</td>
<td>6</td>
<td>2</td>
<td>2.1701</td>
<td>39</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>2.1341</td>
<td>16</td>
<td>12</td>
<td>2</td>
<td>2M</td>
<td>2.1113</td>
<td>23</td>
<td>9</td>
<td>7</td>
<td>5M</td>
</tr>
<tr>
<td>2.0608</td>
<td>7</td>
<td>9</td>
<td>9</td>
<td>1</td>
<td>2.0545</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>1.9396</td>
<td>11</td>
<td>12</td>
<td>6</td>
<td>2</td>
<td>1.9240</td>
<td>27</td>
<td>9</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>1.7902</td>
<td>3</td>
<td>14</td>
<td>4</td>
<td>2</td>
<td>1.7780</td>
<td>4</td>
<td>11</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>1.6607</td>
<td>3</td>
<td>11</td>
<td>11</td>
<td>3</td>
<td>1.6317</td>
<td>5</td>
<td>16</td>
<td>2</td>
<td>0M</td>
</tr>
<tr>
<td>1.6193</td>
<td>7</td>
<td>14</td>
<td>8</td>
<td>2M</td>
<td>1.6193</td>
<td>7</td>
<td>16</td>
<td>2</td>
<td>2M</td>
</tr>
<tr>
<td>1.5293</td>
<td>7</td>
<td>14</td>
<td>10</td>
<td>0</td>
<td>1.4896</td>
<td>5</td>
<td>14</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>1.3090</td>
<td>6</td>
<td>16</td>
<td>12</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Using N$_2$ as the probe gas, the accessible surface area was found to be (2175.9 ± 1.5) m$^2$ g$^{-1}$ for d-Cu-BTC and (1291.9 ± 13.9) m$^2$ g$^{-1}$ for h-Cu-BTC, considerably reduced from that of the dehydrated structure. Furthermore, the accessible volume was computed as (0.2978 ± 0.0004) cm$^3$ g$^{-1}$ for d-Cu-BTC and (0.0882 21 ± 0.0012) cm$^3$ g$^{-1}$ for h-Cu-BTC. Both metrics highlight the reduction in surface area and volume available to adsorbate gases that results from hydration of Cu-BTC.

Using a combination of USAXS, SAXS, and SANS, we have established that Cu-BTC undergoes both microstructural and structural change when exposed to moisture in the air. The H$_2$O adsorbed is incorporated into the solid skeletal structure with an increase in density. The fact that the XRD peak intensity decreases as H$_2$O is adsorbed into the structure of Cu-BTC suggests that, whereas H$_2$O contributes to a new denser phase, the resulting sample is less crystalline than that of the d-Cu-BTC case.

**ACKNOWLEDGEMENTS**

This work utilized facilities supported in part by the National Science Foundation under Agreement No. DMR-0944772. ChemMatCARS Sector 15 is principally supported by the National Science Foundation/Department of Energy under grant number NSF/CHE-0822838. Use of the Advanced Photon Source was supported by the U. S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357. Partial financial support from ICDD through the Grants-in-Aid program is also acknowledged.


