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Validating 3D-printed porous proxies by tomography and porosimetry

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Validating 3D-printed porous proxies by tomography and porosimetry

Abstract

Purpose. The objective of this study was to evaluate how accurately a 3D printer could manufacture basic porous models. Geoscience research is evolving toward numerical prediction of porous rock properties, but laboratory tests are still considered standard practice. 3D printing digital designs of porous models (proxies) is a way to bridge the gap between these two realms of inquiry.

Design/methodology/approach. Digital designs of simple porous models were 3D-printed on an inkjet-style (polyjet) 3D printer. Porosity and pore-throat size distribution of proxies were measured with helium porosimetry, mercury porosimetry, and computed tomography image analysis. Laboratory results on proxies were compared with properties calculated on digital designs and CT images.

Findings. Bulk volume of proxies was by 0.6-6.7% lower than digital designs. 3D-printed porosity increased to 0.2-1.9% compared to digital designs (0-1.3%). 3D-printed pore throats were thinner than designed by 10-31%.

Research limitations/implications. Incomplete removal of support material from pores yielded inaccurate property measurements. The external envelope of proxies was 3D-printed at higher accuracy than pores.

Practical implications. Characterization of these simple models improves understanding of: 1) how more complex rock models can be 3D-printed accurately; and 2) how both destructive (mercury porosimetry) and non-destructive (computed tomography and helium porosimetry) methods can be used to characterize porous models.

Originality/value. Validation of 3D-printed porous models using a suite of destructive and non-destructive methods is novel.

Disciplines

Earth Sciences | Environmental Sciences | Geology

Comments

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ABSTRACT

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Validation of 3D-printed porous models using a suite of destructive and non-destructive methods is novel.
INTRODUCTION

Pore-scale transport processes are important to understanding of many real-world phenomena with significant implications to academia, industry, and government. For example, petroleum companies seek to predict the multiphase flow of hydrocarbons and other fluids to wellbores through complex pore networks at high temperatures and pressures (e.g., Xiong et al., 2016). Governments seek to understand aquifers to better predict the volume and rate of water that can be withdrawn for the needs of local populations, agriculture, and industry (e.g., Cosgrove and Rijsberman, 2014). Both industry and government are interested in how carbon dioxide will flow through reservoirs (e.g., Bacon et al., 2016) to design more efficient carbon sequestration projects for mitigating climate change.

In the last twenty years, significant effort has been made into the field of “digital rock physics” (DRP) where rock properties (e.g., transport, electrical, mechanical) are simulated numerically (e.g., Ferreol and Rothman, 1995; Deng et al., 2015). DRP has sought to provide non-destructive and fast methods as an alternative to traditional laboratory-based rock property measurements. DRP simulations run on computed tomography (CT) “photocopies” of natural rocks that represent 2D or 3D pore networks. Just like photocopying process introduces slight imperfections into the resulting copy, CT scanning results in imperfect copies of porous rocks due to uneven density distribution of sample constituents and the lower resolution of larger samples. When compared to laboratory results, digital simulations often differ significantly because they do not analyze the full pore-scale complexity (Guice et al., 2014; Ishutov et al., 2017a).

3D printing is a technology that could remove some of this uncertainty by providing a more accurate comparison between digital simulations and laboratory tests. This computer-controlled,
layer-by-layer technology enables the construction of lab-testable models with complex internal geometries (herein termed “proxies;” Ishutov et al., 2017a). This capability could allow simulation codes to be refined by implementing an iterative process of designing, 3D printing, and testing of proxies in the laboratory. In each iteration, elements of the digital model could be altered to observe the effects on lab-measured properties until the desired knowledge on the system is obtained.

When fields outside the geosciences 3D print porous models (e.g., Naing et al., 2005; Ang et al., 2006; Pires et al., 2014), they typically aim for high porosity designs (>50%), often called “scaffolds”, to obtain a desired material property while minimizing material use. 3D printing reservoir rocks poses a challenge because at lower porosities, the build material is more likely to interact with the previously printed material.

Currently 3D printers can build proxies near the scale of the coarsest natural reservoir rocks (e.g., Ishutov et al., 2015; Head and Vanorio, 2016; Sukop et al., 2016; Ishutov et al., 2017b). While previous studies have attempted to “photocopy” natural porous rocks using CT (Ishutov and Hasiuk, 2014; Ishutov et al., 2015), no validation methods were established for 3D printing geologically relevant pore networks. For example, no methods exist for describing the accuracy or resolution of a 3D printer with respect to complex porous models.

In this study, porous models are built starting with a primitive solid (a cylinder) and complexity is added in the form of a cylindrical pore throat and a spherical pore body. These simple models characterize the accuracy of the 3D printing process with respect to reproducing “bulk” dimensions of a digital model (i.e., height, diameter, volume) as well as dimensions of the pore system (i.e., pore size, porosity, pore-throat size distribution).
METHODS

The following workflow was used to build and test porous proxies: digital design, 3D printing, post-processing, and validation (Ishutov and Hasiuk, 2014; Ishutov et al., 2015; Ishutov et al., 2017a,b).

3D Model Design

Geometric primitive shapes such as spheres and cylinders are commonly used to digitally model elements of pore networks (e.g., Lindquist and Venkatarangan, 2000; Andrä et al., 2013). The following four simple pore models were created using a free, on-line 3D design environment (Tinkercad.com) (Figure 1A):

1. Cylindrical bulk primitive with no pore throat or pore body (AP1).
2. Cylindrical bulk primitive with one cylindrical pore throat 700 μm in diameter aligned along the vertical axis of the model (AP2).
3. Cylindrical bulk primitive with one cylindrical pore throat 1000 μm in diameter aligned along the vertical axis of the model (AP3).
4. Cylindrical bulk primitive with one cylindrical pore throat 1000 μm in diameter aligned along the vertical axis of the model and a spherical pore body 2000 μm in diameter aligned at the center of the model (AP4).

Three copies of each model were 3D-printed: Group A – for CT scanning, helium porosimetry, and archival purposes, Group B – for mercury porosimetry, and Group C – for cutting and observing the internal structure and helium porosimetry. We refer to these 3D-printed models as “proxies” because they stand in for the digital model. Bulk properties of each design and proxy (e.g., bulk volume, porosity) were calculated geometrically (Table 1).
3D Printing

Proxies for this study were produced on an Object260 Connex3 3D printer at the Prototyping and Fabrication Service Center, College of Engineering, Iowa State University. Before 3D printing began, the digital model was “sliced” into a series of layers. Each layer was printed from bottom to top by an inkjet-style extruder that jetted droplets of polymer (Objet VeroWhitePlus RGD835) and support material (SUP705) onto the build platform (Table 2). Ultraviolet (UV) light cured these droplets before the build platform was lowered to 3D print the next layer. These steps were repeated until all layers have been printed. Wax support material was jetted into pores during 3D printing for two purposes: 1) to keep pores free of build material; and 2) to support build material that overhangs pores. The manufacturer listed the XY resolution as 1600 dots per inch (42 µm per dot) and accuracy as “20-85 µm on parts smaller than 50 mm.” Layer thickness was set at the finest possible setting (16 µm per layer).

Post-Processing

After 3D printing, proxies were removed from the build platform and heated to 70°C so the support material would liquefy and drain out of the pores. In addition, heated water (~70°C) was flushed through the model to improve this process. Visual inspection revealed that pore throats were through-going, suggesting that removal of the support material was at least partially successful.
Validation

The fidelity with which 3D printing and post-processing resulted in an accurate proxy was assessed in five ways. First, measurements of the height (n=10) and diameters (n=10 each at top, middle, and base of proxy) were taken with digital calipers (Mitutoyo CD-8 AX, precision ±0.01 mm) to calculate the bulk volume of all proxies.

Second, measurements of porosity and pore-throat size distribution were made on CT images (using Image Processing Toolbox in Matlab) collected for each proxy in Group A (Figure 1B-C, 2A). CT data were acquired with the following parameters: fan-beam x-rays, 80 kV voltage, sample bulk volume of 1000x800x1000 voxels, (15 µm)$^3$ voxel size, 360 raw images converted to 3.2 GB volume. Bilateral and median filters were applied to remove ring and beam hardening artifacts.

Third, helium porosimetry (Micromeritics Accupyc II 1340 helium pycnometer) was used to determine the proxy porosity and grain density in Groups A and C using Boyle’s Law.

Fourth, Group C proxies were cut in half and imaged with an optical microscope (DinoXcope) to characterize the extent of support material remaining in proxy pores (Figure 2B).

Finally, mercury porosimetry analysis was carried out in low pressures to measure pore-throat size and porosity. The low-pressure mercury intrusion was sufficient for all proxies in this study as the smallest pore-throat diameter in proxies in Group B exceeded 700 µm (<14 psi). AP2, AP3, and AP4 proxies were measured with AutoPore V 9600 (Micromeritics Analytical Services, Norcross, GA, USA) from 0-45 psi (~0.31 MPa), 130° contact angle, 480 dynes/cm$^2$ interfacial tension, 20°C mercury temperature. AP1 proxies were measured with a Quantachrome PoreMaster33 (Department of Geological and Atmospheric Sciences, Iowa State University)
RESULTS

Model Dimensions and Visual Inspection

Mean height of proxies was 10.01 mm ($1\sigma = 0.01$ mm) representing a departure of $+0.10\%$ from design (Table 3). Mean diameter of proxies was 9.95 mm ($1\sigma = 0.05$ mm) representing a departure of $-0.50\%$ from design. Mean bulk volume of proxies was $0.77 \text{ cm}^3$ ($1\sigma = 0.018 \text{ cm}^3$) representing a departure of $-2.05\%$ from designed bulk volume. Proxy volume was combined with mass to calculate bulk density, which averaged $1.16 \text{ g/cm}^3$ ($1\sigma = 0.01 \text{ g/cm}^3$) (Table 3). No support material was observed in proxies of Group A (Figure 2A), but support material was observed inside proxy pores of Group C (Figure 2B) that led to greater inaccuracy in pore-throat size.

CT Image Analysis

Pore-throat diameters were measured on each of the 800 CT images of Group A proxies and averaged. Solid proxies (AP1) had no visible pore throats. Pore throats in AP2, AP3, and AP4 proxies were 1.1%, 7.3%, and 1.1% smaller than designed, respectively (Table 4). The complex geometry of the pore in model AP4 made it difficult to accurately quantify due to its complex shape, but we estimated that it was 26% smaller than design. Porosity measured by CT in Group A differed from design by only 0.1 to 1.0 percentage points. The external and internal surfaces of all proxies displayed rugosity from gaps between the ends of 3D-printed layers (Figure 1C); these “artifact” pores introduced during 3D printing have been described previously (e.g., Duty...
et al., 2017). Mean layer thickness was 52 µm, approximately three times the designed thickness of 16 µm (Table 4).

**Helium Porosimetry**

Helium porosities of Group A porous proxies were 0.4-0.6 percentage points higher than designed (Table 3) and 0.5-0.9 percentage points higher than CT porosity (Table 4). Helium porosity of AP1 proxies in Group A (0.2%) and in Group C (0.1%) was larger than designed porosity (0%) and might serve as an approximation of artifact porosity between layers and/or build material droplets. Group C proxies, which displayed visual evidence of pore clogging by support material, had even lower porosities than Group A proxies (Figure 3).

**Mercury Porosimetry**

Mercury porosimetry results for Group B proxies showed prominent peaks for modal pore-throat sizes (Figure 4). Pore-throat diameters were compared between digital models, CT images of Group A proxies, and mercury intrusion results on Group B proxies (Table 4). AP1 had a minor peak at 92-µm that might indicate an artifact porosity formed between 3D-printed layers or polymer droplets that were also evident in CT images (Figure 1C). AP2 showed an increase diameter in mercury intrusion by 11% compared to digital design. AP3 and AP4 showed a decrease in mercury-measured pore throats by 20% and 31%, respectively. Mercury measured artifact porosity of 0.3% in a solid proxy AP1 was within 0.1-0.2 percentage points to helium- and CT-measured values (Table 4). Mercury porosimetry showed an increase in porosity for proxies AP2 and AP4 to 0.6% and 1.5% from designed 0.5% and 1.3%, but also showed a decrease to 0.8% from designed 1% for AP3.
DISCUSSION

Accuracy of external dimensions

Proxies in this study documented that the accuracy for printing the external envelope of the proxy was higher than for internal features like pores. Proxies in Groups A-C were 10-60 µm taller than designed and 60-150 µm thinner. While the heights (9.98-10.06 mm) were within the manufacturer’s stated accuracy range of “20-85 µm,” the diameters were not (9.85-10.06 mm). This difference resulted in a bulk volume that was on average 0.91% smaller (range = 748-798 mm³) than designed. Such a change in bulk volume resulted in minor errors in porosity calculations (~ ±0.4 percentage points for a proxy with 40% porosity, ±0.01 percentage points for proxies with 1% porosity). We interpreted the larger variability in diameters to result from the rugosity related to the individual 3D-printed layers that was observed for external and internal surfaces in CT (Figure 1C). Droplet formation in these layers was governed by the interaction between the viscous, elastic, and surface forces that were dependent on the drop shape and size (Guo et al., 2016). The complexity of droplet morphology could affect the resolution of printing for flat, non-porous models (e.g., Bussman et al., 2000; Castrejón-Pita et al., 2013), yet this has not been established for porous proxies.

Accuracy of pore geometries

More important to the goal of this study was the accuracy with which pore geometries were reproduced. Pores were between 11% larger and 31% smaller than designed. This size variability resulted in a decrease in the CT-measured porosity and yet an increase in helium and mercury porosity. This discrepancy was attributed to limitations of the validations methods. For example,
porosity and pore-throat diameters measured by CT were close to design (Figure 3), but given the voxel size of $(15 \, \mu m)^3$, artifact pores (possibly existing between polymer droplets) could not be captured in the CT images. Mercury porosity was generally higher than designed, yet pore-throat diameters were up to 30% smaller than designed. CT and optical imagery showed that proxies 3D-printed from the same digital model might not be identical in terms of porosity and pore-throat sizes due to incomplete removal of support material in the pore space during post-processing (Figure 2). This artifact was also proved by the differences in helium porosity measured on Groups A and C (Figure 3). From these observations, it seems that in order to make an accurate pore network with a polyjet printer, one must edit the pore network digitally to account for the effects of 3D printing, making the pores 10-30% larger to account for the downsizing that occurs during 3D printing.

Artifact Pores

We propose three types of artifact pores occur in our proxies: edge pores, interdrop pores and support material pores. Edge pores occur at the horizontal edges of build layers (Figure 5A) and likely form due to positional inaccuracy during printing and/or interaction between build and support material. We posit that interdrop pores form as relict interstitial spaces between droplets of deposited build material (Figure 5B) and account for higher helium and mercury porosities than measured in CT data. In addition, incomplete removal of the wax support material can create a second type of artifact pores within this support material in the proxy pore space that results in inaccurate measurements of pore sizes by mercury porosimetry and porosity by helium porosimetry (Figure 5B). The characteristics of these pores are difficult to predict because they
are formed by dissolution of the support material as well as factors related to the removal process (e.g., temperature, pressure).

Volume change of the proxy may occur due to support wax removal occurring at elevated temperatures (> 70°C), and warping of the material may occur due to UV curing and subsequent drying. Post-processing procedures should be developed to remove the support material in a way that minimizes damage to the build material.

Prior studies reported that accuracy of 3D printed models decreased with smaller pore widths (e.g., Maher et al., 2010; Head and Vanorio, 2016), and we observed this phenomenon as well. Future studies should optimize support material to be more easily removed. In addition, future investigations should focus on the pore wall, where build material and support material meet, because inaccuracies there can affect surface area and roughness, which in turn affect macroscale flow properties like permeability. Yeong et al. (2006) proposed a new method for scaffold inkjet printing using trapezoidally shaped drops. The drop shape was controlled by the printing frequency or when the print head moved at a slower speed. This frequency translated into higher-mass droplets being deposited at a particular location. For porous proxies, this method could allow a significant reduction in interdrop artifact porosity measurable and allow the quantification of total effective porosity with helium porosimetry.

*Future use of polyjet printers in porous rock analysis*

Polyjet 3D-printed samples can be used in a variety of rock characterization studies, for example replicating the pore space and performing fluid-flow experiments. Previous studies on polyjet 3D printers attempted to use more complex pore networks to replicate pore and fracture system of aquifers and reservoir rocks and measure their transport properties, such as hydraulic
conductivity and permeability (e.g., Sukop et al., 2016; Suzuki et al., 2016). While the geometry of pores or fractures was similar to designs, incomplete removal of the support material was not fully resolved. These discrepancies were attributed to roughness of fracture surfaces and clogging of fracture apertures with support material, as seen in this study. A better system for removing support material from pores and fractures in polyjet proxies or a more suitable material should be developed for further use in building porous models. Fahad et al. (2013) presented gel-like support materials consisting of methylcellulose and alkene glycol. These gels are soft and hence can be removed easily under temperatures of 50°C.

In application to polyjet rock proxies, the support wax could serve as an analog for natural cement occurring in a rock fracture. Deposition and/or dissolution of this wax could mimic the diagenesis and mineralization of cements in reservoir rocks.

A validation workflow for the use in future studies of polyjet proxies could be as the following:

1) helium porosimetry: to evaluate porosity in a non-destructive way and infer about possible reduction of porosity due to the residual support material;
2) CT scanning: to quantify the porosity and pore sizes non-destructively and infer about the need to evaluate smaller pores destructively;
3) mercury porosimetry: to measure pores smaller than 500 µm in a destructive way;
4) cutting proxies to observe the removal of the support material from the pore space; and
5) thin-section/SEM imaging to characterize and quantify artifact porosity
CONCLUSIONS

Our study shows that 3D-printed pore throats are thinner than in a digital model, a fact that must be accounted for when designing a porous proxy for 3D printing. Low-pressure mercury intrusion porosimetry can measure consistently larger porosities and smaller pore-throat sizes than designed that can be attributed to the artifact pores during 3D printing.

Post-processing of polyjet proxies must be improved to remove all support wax from proxy pores without damaging the model. High-pressure mercury porosimetry may not be ideal method to measure pore-throat sizes because mercury intrusion can damage or deform the geometry of this relatively weak material at high pressures. CT and helium porosimetry can be used in concert to quantify the porosity and pore sizes of the porous proxies provided that CT resolution can capture the smallest proxy pores and if these pores are connected from outside to inside to be measured with helium. With further advances in 3D printing, rock property simulation techniques can be improved by identifying the scale of pore network and parameters that affect rock properties offering an additional way to characterize natural porous rocks.
REFERENCES


Sukop, M.C., Pilar, N., Garcia, S.M. and Florea, L.J. (2016), “3D printed karst limestone core for...


**Author Biographies**

**Franciszek J. Hasiuk** is an assistant professor at Iowa State University. He received his PhD from the University of Michigan (Ann Arbor) before working for at ExxonMobil Upstream Research in Houston. An expert in the petrophysics and geochemistry of carbonate rocks, he uses 3D printing to build porous models in the hopes of better understanding the flow processes and properties of natural reservoir rocks.

**Sergey Ishutov** is a Ph.D. candidate in geology at Iowa State University. He holds Bachelor of Science in petroleum geology from University of Aberdeen (Scotland) and Master of Science in
geology from California State University Long Beach. Sergey has extensive experience in the analysis of tomographic data of reservoir rocks, 3D printing of porous models, acquisition and characterization of helium and mercury porosimetry data, and seismic reflection data.

Artur Pacyga received Bachelor of Science in geology from Iowa State University in 2015. As an undergraduate researcher, he was involved in 3D printing the models used in this study and making measurements of their dimensions.

FIGURE CAPTIONS

Figure 1. Model types designed for this study. (A) CAD designs. (B) CT images of proxies. AP1 – solid model. AP2 – model with axial cylindrical pore throat. AP3 – model with axial cylindrical pore throat. AP4 – model with axial cylindrical pore throat and central spherical pore. d – diameter of pore or pore throat. (C) Magnified areas of images in (B).

Figure 2. 2D cross sections of proxies in Groups A and C. (A) CT images of Group A, with locations indicated in Figure 1. (B) Optical images of surfaces cut in the middle of each proxy in Group C taken with DinoXcope. AP4 proxy was cut twice to image pore and pore throat. Image-based measurements are in Table 4.

Figure 3. Designed, helium and CT-measured porosities for Groups A and C. Unity line (green) is a modeled 1-to-1 correlation between porosities.
Figure 4. Pore-throat size distributions for Group B proxies from low-pressure mercury porosimetry.

Figure 5. Schematic of a proxy explaining possible 3D printing artifacts. (A) Polymer droplet jetting on the build platform with rugosity. (B) 3D-printed layers show rugosity of solid elements at a finer scale that creates artifacts in proxies. Wax support material may clog the pores in proxies due to incomplete post-processing (removal of support material by water flushing and drying) and/or uncured support material. Proxy droplets should be ~42 µm, according to the manufacturer. Proxy layers were measured and on average 51.7 µm thick.
TABLES

Table 1. Digital measurements of simple model properties. These values correspond to designed dimensions in CAD models. $D$ – diameter; $h$ – height; $V$ – volume. Errors are zero on these digital measurements.

<table>
<thead>
<tr>
<th>Model</th>
<th>Model $D$ &amp; $h$ (mm)</th>
<th>Bulk $V$ (mm$^3$)</th>
<th>Throat $D$ (mm)</th>
<th>Throat $V$ (mm$^3$)</th>
<th>Pore $D$ (mm)</th>
<th>Pore $V$ (mm$^3$)</th>
<th>Intersect $V$ (mm$^3$)</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP1</td>
<td>10</td>
<td>785.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>AP2</td>
<td>10</td>
<td>785.4</td>
<td>0.7</td>
<td>3.85</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>AP3</td>
<td>10</td>
<td>785.4</td>
<td>1</td>
<td>7.85</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>AP4</td>
<td>10</td>
<td>785.4</td>
<td>1</td>
<td>7.85</td>
<td>2</td>
<td>4.19</td>
<td>1.57</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 2. Composition of build material, Stratasys Objet VeroWhitePlus RGD835, and support material, SUP705. Errors for percent abundances were not reported by the manufacturer.

<table>
<thead>
<tr>
<th>CAS</th>
<th>Component</th>
<th>% in RGD835</th>
<th>% in SUP705</th>
</tr>
</thead>
<tbody>
<tr>
<td>--</td>
<td>Acrylic monomer</td>
<td>&lt;30</td>
<td></td>
</tr>
<tr>
<td>5888-33-5</td>
<td>Isobornyl acrylate</td>
<td>&lt;25</td>
<td></td>
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<td>--</td>
<td>Phenol, 4,4’-(1-methylethylidene)bis-, polymer with \</td>
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</tr>
<tr>
<td></td>
<td>(chloromethyl)oxirane, 2-propenoate</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>Diphenyl-2,4,6-trimethylbenzoyl phosphine oxide</td>
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<td>52408-84-1</td>
<td>Acrylic acid ester</td>
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<td>&lt;0.3</td>
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<td>108-65-6</td>
<td>Propylene glycol monomethyl ether acetate</td>
<td>0.1-0.125</td>
<td></td>
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<tr>
<td>7664-38-2</td>
<td>Phosphoric acid</td>
<td>0.002-0.015</td>
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<td>--</td>
<td>Poly(oxy-1,2-ethanediyl), α-(1-oxo-2-propenyl)-ο-hydroxy-</td>
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<td>Polyethylene glycol</td>
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<td>56-81-5</td>
<td>Glycerin</td>
<td>&lt;25</td>
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<tr>
<td>--</td>
<td>Phosphine oxide, phenylbis(2,4,6-rimethylbenzoyl)</td>
<td>&lt;0.5</td>
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</table>
Table 3. Measurements of 3D-printed model properties (height – \( h \), diameter – \( D \), mass) and calculation of bulk volume (\( V \)) and bulk density (\( \rho \)). Differences between designed and measured properties were calculated as % residuals. Models listed by analysis groups: A – helium porosimetry; B – mercury porosimetry; C – CT analysis. Errors were as follows: lengths ±0.01 mm, mass ±0.0001 g, density ±0.003 g/cm\(^3\).

<table>
<thead>
<tr>
<th>Model</th>
<th>Bulk ( h ) (mm)</th>
<th>Bulk ( D ) (mm)</th>
<th>Bulk ( V ) (mm(^3))</th>
<th>Residual ( h ) (%)</th>
<th>Residual ( D ) (%)</th>
<th>Residual ( V ) (%)</th>
<th>Mass (g)</th>
<th>Bulk ( \rho ) (g/cm(^3))</th>
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<tbody>
<tr>
<td>AP1-A</td>
<td>10.03</td>
<td>9.93</td>
<td>775.8</td>
<td>0.3</td>
<td>-0.7</td>
<td>-1.2</td>
<td>0.90</td>
<td>1.16</td>
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<td>AP1-B</td>
<td>10.03</td>
<td>10.06</td>
<td>798.2</td>
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<td>0.6</td>
<td>0.6</td>
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<td>9.92</td>
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<td>1.6</td>
<td>0.89</td>
<td>1.16</td>
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<td>9.92</td>
<td>773.9</td>
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<td>-0.8</td>
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<td>1.15</td>
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<td>9.97</td>
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<td>10.01</td>
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<td>775.2</td>
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<td>-0.5</td>
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<td>SD</td>
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<td>0.7</td>
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</table>

Table 4. Comparison of mercury porosimetry, helium porosimetry, and CT measurements for 3D-printed models. Errors are calculated as percent differences from digital designs and mentioned in the text.

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>AP1</th>
<th>AP2</th>
<th>AP3</th>
<th>AP4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pore Diameter of Digital Model</td>
<td>(µm)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2000</td>
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<td>Pore Diameter of 3DP Model, CT</td>
<td>(µm)</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>Pore-Throat Diameter of Digital Model</td>
<td>(µm)</td>
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<td>1000</td>
<td>1000</td>
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<tr>
<td>Pore-Throat Diameter of 3DP Model, CT mean</td>
<td>(µm ±1σ)</td>
<td>-</td>
<td>692±79</td>
<td>927±70</td>
<td>989±65</td>
</tr>
<tr>
<td>Pore-Throat Diameter of 3DP Model, Mercury</td>
<td>(µm)</td>
<td>92</td>
<td>780</td>
<td>795</td>
<td>685</td>
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<tr>
<td>Porosity of Digital Model</td>
<td>(%BV)</td>
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<td>0.5</td>
<td>1.0</td>
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<td>Porosity of 3DP Model, CT</td>
<td>(%BV)</td>
<td>0.1</td>
<td>0.5</td>
<td>0.9</td>
<td>1.0</td>
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<tr>
<td>Porosity of 3DP Model, Mercury</td>
<td>(%BV)</td>
<td>0.3</td>
<td>0.6</td>
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<td>Layer Thickness, CT mean</td>
<td>(µm)</td>
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</table>
Figure 1. Model types designed for this study. (A) CAD designs. (B) CT images of proxies. AP1 – solid model. AP2 – model with axial cylindrical pore throat. AP3 – model with axial cylindrical pore throat. AP4 – model with axial cylindrical pore throat and central spherical pore. d – diameter of pore or pore throat. (C) Magnified areas of images in (B).
Figure 2. 2D cross sections of proxies in Groups A and C. (A) CT images of Group A, with locations indicated in Figure 1. (B) Optical images of surfaces cut in the middle of each proxy in Group C taken with DinoXcope. AP4 proxy was cut twice to image pore and pore throat. Image-based measurements are in Table 4.

601x275mm (72 x 72 DPI)
Figure 3. Designed, helium and CT-measured porosities for Groups A and C. Unity line (green) is a modeled 1-to-1 correlation between porosities.
Figure 4. Pore-throat size distributions for Group B proxies from low-pressure mercury porosimetry.
Figure 5. Schematic of a proxy explaining possible 3D printing artifacts. (A) Polymer droplet jetting on the build platform with rugosity. (B) 3D-printed layers show rugosity of solid elements at a finer scale that creates artifacts in proxies. Wax support material may clog the pores in proxies due to incomplete post-processing (removal of support material by water flushing and drying) and/or uncured support material. Proxy droplets should be ~42 µm, according to the manufacturer. Proxy layers were measured and on average 51.7 µm thick.

458x252mm (72 x 72 DPI)