

Table 1: Manufacturer dataset for IG-110 and IG-430 [2, 3]

Grade	Coke source	Bulk density/g cm ³	Filler particle size/μm	Tensile strength/MPa	Young's modulus/GPa	Thermal conductivity/W m ⁻¹ K ⁻¹
IG-110	Petrol	1.77	10	25	9.8	120
IG-430	Pitch	1.82	10	37	10.8	140

Advanced novel characterisation of nuclear graphite microstructure via inverse modelling of Scanning Electron Microscopy, N₂ adsorption and Hg porosimetry

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Abstract

Nuclear grade graphite

Keywords: keyword, keyword, keyword

1. Introduction

2. Methodology

2.1. Materials

Virgin graphite samples of two grades, IG-110 and IG-430, were supplied by Toyo Tanso LtdTM, Osaka, Japan. The properties of both grades are tabulated (Table 1). IG-110 is employed in the three existing HTGRs worldwide, while IG-430 is designed to deliver increased density, strength, and thermal conductivity for future applications.[1] (Table 1).

NUMBER, SPACE,
UNIT

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check the big american
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careful not too many
self citations

2.2. Sample preparation

Cuboids were subsampled from virgin graphite blocks, with dimensions of approximately 10 mm x 10 mm x 100 mm. The subsamples were further subsampled into cuboids of side lengths 7 mm, providing 3 cuboids per grade. Samples were polished via SiC polishing pads up to a grit size of P5000, to minimise topographical variations induced by sample preparation that may cause artefacts during SEM imaging or low pressure gas adsorption [4, 2]. Samples were sonicated in 2-propanol for 24 h to remove any contaminants, such as silica particles introduced during polishing, then dried under vacuum for 12 h at $305 \pm 5^\circ\text{C}$ using the BELPREP-vac (MicrotracBEL, Japan) to remove any residual moisture introduced during sonication.

2.3. Scanning Electron Microscopy (SEM)

The JEOL IT510 Scanning Electron Microscope was employed to generate the contiguous set of individual micrographs from which the full composite micrograph was assembled. The Image Montage capability within the JEOLIn-Scope package performed this function, capturing multiple micrographs via a motorized stage, moving the electron beam over the specified area with a set overlap for each new micrograph. Stigmation, contrast, and brightness are automatically adjusted, with analysis of the metadata for all 1,350 micrographs demonstrating that shifts in contrast and brightness were insignificant, with no impact on the selection of the intensity threshold for the full composite (Table 2). Applied parameters are tabulated (Table 3).

A magnification of 1000X was selected as a compromise between a resolution sufficient for capturing the pore structure and area covered by each micrograph. Each micrograph represents $12,288 \mu\text{m}^2$ of sample surface, with each sample consisting of 225 micrographs, yielding a total imaging area of 2.765 mm^2 per sample. With 3 samples analysed per grade, the total scanned area per graphite grade is 8.294 mm^2 .

2.4. Composite assembly

Could talk here about how we wanted to do resin impeg like Kane et al, but did not have the chance, and explain this might introduce issues, also we could talk about how this is quite rough, and that this kind of sample preparation (i.e. no vibratory polishing, no resin impregnation) is not ideal and may have introduced both artefacts and noise. Additionally, sonication may have damaged the pore structure

Huang 2021 used 5000× magnification with 48 micrographs per sample, covering $0.13 \text{ mm} \times 0.13 \text{ mm}$ for their composite.

I actually did 0-14 so that is 15×15 which

Table 2: Contrast (C) and Brightness (C) Summary by Sample

Variant	Avg C (%)	Std C (%)	Avg B (%)	Std B (%)
IG430B	98.01	1.02	99.69	0.08
IG430C	98.16	0.82	99.83	0.08
IG110B	95.86	0.72	99.26	0.13
IG110C	94.03	0.93	99.38	0.13
IG110F	98.20	0.70	99.69	0.13

Table 3: Parameters for composite assembly captured with the JEOL IT510 SEM using Image Montage Mode

Parameters	Values
Magnification (\times)	1000
Resolution ($\mu\text{m}/\text{px}$)	0.1
Surface area per micrograph (μm^2)	12 288
Overlap (%)	10
Micrographs per sample (n)	196

Stitching/composite assembly, where the overlapping micrographs are assembled into a single composite per sample, was performed via an enhanced phase correlation type method, operated as an ImageJ plugin [5].

This method optimises micrograph position globally, is sub-pixel accurate and smooths the transitions between micrographs by a non-linear intensity blending function. Further information on the exact function of this can be found in the Supplementary Information.

The resulting composite micrographs display no visible delineation between individual micrographs, cover an area comparable with previous works, are of high resolution, and distinguish porosity and bulk (Figure 1 [6, 7]).

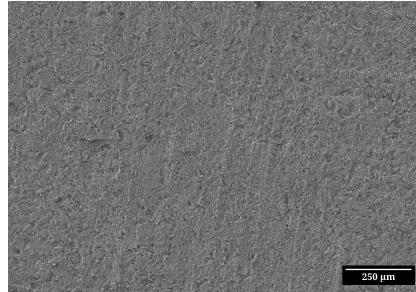


Figure 1: Fully assembled SEM composite: IG-430 Sample C, 1000 \times magnification, 5 kV accelerating voltage. Bar = 250 μm .

2.5. Computation of Channel Porosity

2.5.1. Intensity/Greyscale Thresholding

Per 8-bit micrograph E (pixel values $0 \leq E(x, y) \leq 255$), the intensity histogram $H(i)$ is computed for $i = 0, 1, \dots, 255$.

$$H(i) = \sum_{x=1}^M \sum_{y=1}^N \mathbf{1}\{E(x, y) = i\},$$

where M and N are the micrograph width and height (in pixels), and

$$\mathbf{1}\{E(x, y) = i\} = \begin{cases} 1, & \text{if the pixel at } (x, y) \text{ has intensity } i, \\ 0, & \text{otherwise.} \end{cases}$$

The indicator function $\mathbf{1}\{E(x, y) = i\}$ yields 1 where a given pixel greyscale value equals i , and 0 otherwise. The double sum $\sum_{x=1}^M \sum_{y=1}^N$ performs this operation across each pixel in the micrograph resulting in a histogram $H(i)$ of 256 bins, each bin representing number of pixels in the micrograph at each greyscale value i .

Intensity thresholding, performed on $H(i)$, determines a greyscale value at which porosity and bulk (i.e., foreground and background) are distinguished.

Global automatic thresholding algorithms optimise by different criteria (i.e. maximisation of inter-class variance, minimisation of intra-class variance) to determine threshold(s). Thresholding aims to select an intensity value that classifies porosity and bulk in a way that minimises both Type I and II errors,

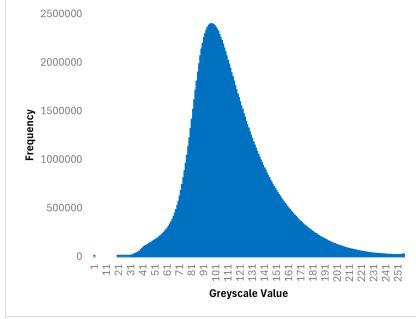


Figure 2: PLACEHOLDER DRAFT: Histogram of greyscale values for IG-430 Sample F, 1000 \times , Showing skewness and unimodality

as evaluated by the operator (i.e., false positives, classifying a pore where one is not present, and false negatives, not classifying a pore where one is present).

A test of all 17 of the available automatic thresholding methods available in ImageJ demonstrated that none of the available automatic global intensity thresholding algorithm effectively distinguished between porosity and bulk with the sensitivity required to allow the classification of pores for the given histogram (Figure 3). This is primarily because no histogram $H(i)$ generated by this method exhibited more than one peak, this statistically there were no classes to be separated (Figure 2).

Evaluation of all 17 automatic global intensity thresholding algorithms available in ImageJ revealed that non were able to distinguish between porosity and bulk with the sensitivity required to allow the classification of pores for the given histogram (Figure 3). In every case, the histogram $H(i)$ produced by this method exhibited only a single peak, yielding no statistically distinct intensity classes (Figure 2). Automatic thresholding selects a threshold between modes/classes, consequently, no global intensity thresholding method could distinguish porosity and bulk in this dataset.

A human-in-the-loop (HITL) approach was therefore undertaken, as illustrated in the process diagram (Figure 4). The composite was subsampled and examined to determine the threshold at which porosity and bulk are best separated. This threshold, along with a pore diameter threshold, were applied to the

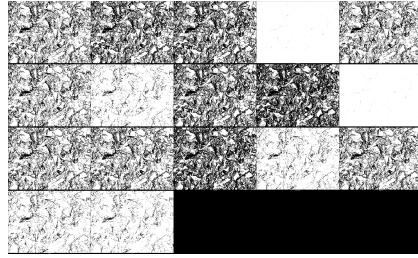


Figure 3: Thresholded Micrograph of IG-430 Sample C at 1000 \times Magnification. Methods are placed sequentially from right to left, row by row. (a) Default (b) Huang (c) Huang2 (d) Intermodes (e) IsoData (f) Li (g) MaxEntropy (h) Mean (i) MinError(I) (j) Minimum (k) Moments (l) Otsu (m) Percentile (n) RenyiEntropy (o) Shanbhag (p) Triangle (q) Yen

full composite. The intensity threshold was higher in this work than in previous optical microscopy works, at 0.95 ± 0.075 normalized between 0–1 over the 8-bit range of 0–255, capturing the pore throats rather than pore contours. [7, 6].

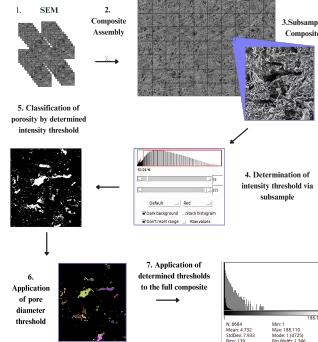


Figure 4: Full thresholding workflow detailing the process of micrograph generation, composite assembly, subsampling, intensity thresholding, and pore diameter thresholding.

An output from this process is exemplified, selected at random, which demonstrates delineation of pores (Figure 5).

2.5.2. Pore Diameter Thresholding

Pore size thresholds were imposed in this work, as in previous studies [8, 6, 7], to restrict the automated recognition of pores to a range (i.e., only counting

Much more detail on
table captions and figure
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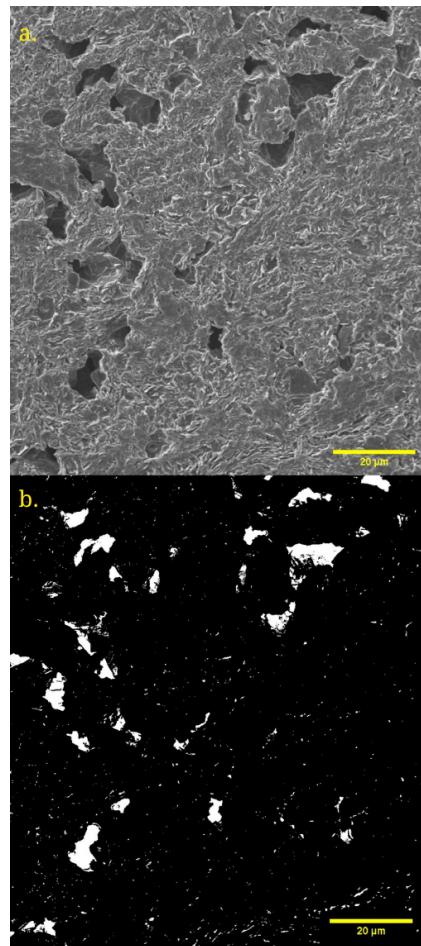


Figure 5: DRAFT: IG430F raw (a) and following intensiy thresholding (b)

Table 4: Effect of different pore area thresholds on a subsection of IG-430F, showing the resulting pore count, total area, average pore size, and percentage area.

Area Threshold (μm^2)	0	0.5	1	2	4	8
Count	254261	11375	6	4085	2812	1881
Total Area (μm^2)	71219	56722	53361	50063.63	46518	41161
Average Size (μm^2)	0.28	4.987	8.229	12.255	16.543	21.883
% Area	4.786	3.812	3.586	3.364	3.126	2.766

pores $> 12.5 \mu\text{m}^2$) where classification is deemed reliable. This approach is inherently limited by the practical difficulty of objectively determining whether any given pore classification is correct.

As in (Table 4), significant changes in the total pore count result from minor alterations in the threshold. However, the total area of pores exhibits far less variation as a function of pore diameter threshold (Table 4). When combined with individual analyses of the resulting PSDs and sensitivity analysis at each threshold as per (Figure 6), a pore area threshold of $1 \mu\text{m}^2$ (diameter = $1.12 \mu\text{m}$) was selected as a compromise between type I and II errors.

Crucially, setting such a threshold does not imply that no pores exist below this limit. Rather, it acknowledges that the confidence in classifying pores below the threshold is too low for reliable use. In this work, the limitations of any single technique are compensated by the strengths of others. during modelling, an interval is selected over which the channel porosity determined from SEM imaging can reliably constrain the outputs of the inverse modelling process. Thus, no type II errors are introduced in the final model due to pore size thresholding, thanks to the combined use of alternative techniques and the ability to specify an interval within PoreXpert v.3.

2.5.3. Channel Porosity Analysis and Calculation

Channel porosity was calculated using the “Analyse Particles” function in ImageJ. This function scans the micrograph pixel by pixel, identifying pixels surpassing the intensity threshold, and groups them into connected regions via

Does it make sense to say this about I and II errors

This part really requires Peter’s insight as to the actual functioning of the program

This is not the key issue. The real thing is the accuracy of the pore size distribution generated by SEM. For example, the modelling would I think be distorted completely by assuming that 3% of

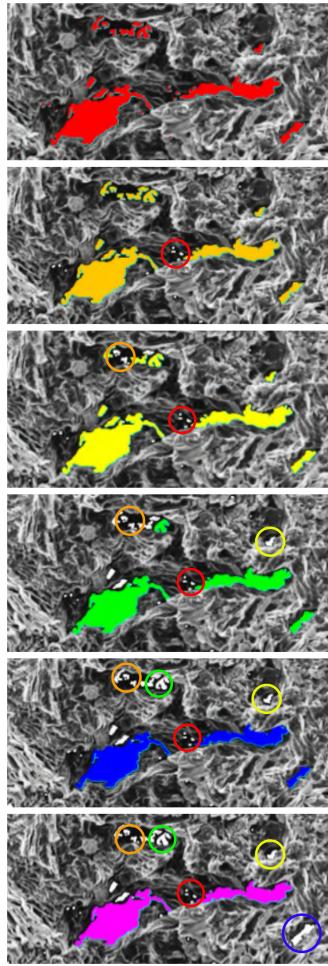


Figure 6: Effect of minimum area threshold on pore identification in subsample of IG-110 Sample B. Highlighted circles denote features which surpassed the previous threshold(s) only, indicated by colour. Thresholds applied (a-f, left-to-right, top-to-bottom): None, $0.5 \mu\text{m}^2$, $1 \mu\text{m}^2$, $2 \mu\text{m}^2$, $4 \mu\text{m}^2$, and $8 \mu\text{m}^2$.

a flood-fill algorithm. Connectivity is defined based on the 8-connected (Moore neighbourhood) criterion, whereby a pixel at (x, y) is considered connected to its eight immediate neighbours:

$$(x - 1, y - 1), (x - 1, y), (x - 1, y + 1), (x, y - 1), \\ (x, y + 1), (x + 1, y - 1), (x + 1, y), (x + 1, y + 1)$$

I say channel porosity here, but this needs to be made consistent everywhere

Any two pixels that exceed the intensity threshold and are either directly adjacent or diagonally connected are classified as belonging to the same region (pore). The function then computes the area of each pore by converting the pixel count into physical area (i.e., 10 pixels per micrometre). Regions that do not meet the area threshold are omitted. The final results are a pore size distribution (PSD) and the channel porosity (%).

The result of intensity thresholding followed by pore diameter thresholding at 1.12 m diameter is exemplified, demonstrating a high degree of accuracy as evaluated by the operator, especially given the particular focus at this stage in excluding Type I rather Type II errors (Figure 7)

2.6. Helium (He) Pycnometry

Helium pycnometry measures the volume of solids, from which density can be derived for a known mass, via gas displacement, applying Boyle's Law for multiple states (Eq. 1).

$$P_1 V_1 = P_2 V_2. \quad (1)$$

The dataset containing Skeletal density measurements, and calculations of Closed Pore Volume (CPV), Open Pore Volume (OPV), and Specific Pore Volume (SPV) generated by Jones et al. [2] was used. This dataset represents measurements performed on IG-110 and IG-430 sampled from the same block as those samples which underwent SEM imaging in this work.

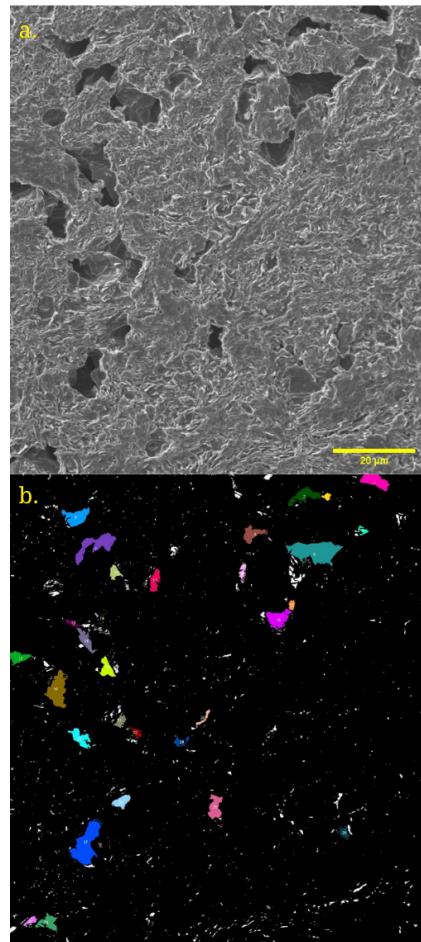


Figure 7: Draft: IG-43F subsample a. Raw and b. After intensity and pore diameter thresholding

A Pycnomatic ATC pycnometer (Thermo Fisher Scientific, Italy) was used to generate this dataset. Measurements were performed at a temperature of $20.00 \pm 0.01^\circ\text{C}$, in ten replicates per sample, calculating the arithmetic mean.

Solid phase volume V_{SOLID} was calculated assuming a theoretical density of 2.26 g cm^{-3} for an idealised graphite crystal.

2.7. Mercury (Hg) Intrusion Porosimetry

Mercury intrusion porosimetry operates on the fundamental principle that the pressure at which a non-wetting fluid intrudes a given pore is inversely proportional to the diameter of that pore (i.e., the larger the pore, the easier it is for the non-wetting fluid to enter it). The exact physical relationship between diameter and applied pressure is governed by the Laplace Equation (Eq. 2)

$$d = \frac{-4\gamma \cos \theta}{P} \quad (2)$$

The pore diameter d is calculated using the equation:

- d (m): Pore diameter
- γ (N/m): Surface tension of the fluid
- θ (degrees): Contact angle of the fluid with the surface
- P (Pa): Pressure

Values of 140° and 130° were used for advancing and receding contact angles respectively, while a value of 0.480 N m^{-1} was assumed for the surface tension of mercury [9].

In this work, the dataset generated by Jones et al. [2] was used, representing measurements performed on IG-110 and IG-430 sampled from the same block as those samples which underwent SEM imaging in this work.

2.8. Nitrogen (N_2) Adsorption

Low-pressure gas adsorption isotherms were obtained using a BELSORP-max volumetric gas adsorption instrument (MicrotracBEL, Japan).

The dataset generated by Jones *et al.* [2] was used in this work, again representing measurements performed on IG-110 and IG-430 sampled from the same block as those samples which underwent SEM imaging in this work.

3. Modelling

PoreXpert is a quasi-Bayesian model which proceeds inversely from effect (the percolation) to cause (the void network). The software constructs an 8 dimensional parameter space, composed of 5 numerical parameters which represent the physical characteristics of the pore network, and 3 constraining Boolean parameters, for example, to avoid structures where features overlap each other. A Boltzmann-annealed amoeboid simplex searches over this parameter space to find the set of parameters that produces a percolation curve minimally different from the intrusion curve derived from Hg porosimetry and N₂/Kr adsorption. The intrusion curve is formed of experimental output from both methods as mercury porosimetry cannot reach sufficient pressure to probe the smallest voids of interest, and therefore, the percolation characteristic is extended to smaller void sizes by Grand-Canonical Monte-Carlo interpretation of N₂ adsorption. The final result is a simulated pore network with the correct porosity and percolation properties, on which many simulations, such as pore-fluid permeability and tortuosity, and sample ageing under radiation, can be performed (Figure 10 [10]).

During modelling, the approximation type that best reflects the depth of imaging into the porous structure is selected (Figure 8, [10]). Approximation Type 1 *Surface connected throats only* is likely the optimal approximation for the channel porosity dataset constructed in this work, as a consequence of the stringent intensity threshold applied. However, due to stability challenges in this early compilation, approximation Type 2 *Surface connected throats and the visible volumes of connected pores* was applied instead (Figure 8).

Channel porosity data were entered into the PoreXpert v.3 interface including a minimum and maximum pore diameter as per (Figure 4), the model was

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Without being able to run it, you could not verify, so I think it would be better to just specify the approximation type.

make it myself, make it clearer and nicer

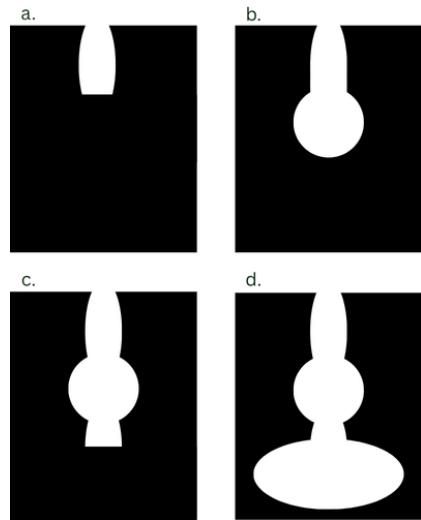


Figure 8: Approximation types 1-4, white is the porosity which is visible to the SEM and black is the bulk of the sample. a. Surface connected throats only b. surface connected throats and the visible volumes of connected pores c. surface connected throats, the visible volumes of connected pores and any throats below them d. All vertically aligned features in the top layer, connected and unconnected to the surface.

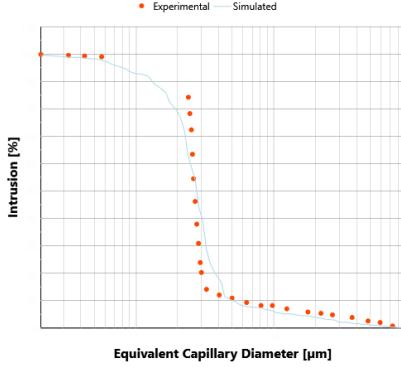


Figure 9: Fitting simulated intrusion curve to experimental curve as per (Figure ??). Orange dots denote experimental datapoints, the blue line is the simulated percolation curve resulting from a pore network of 5 numerical parameters.

able to adjust the extent of the PSD which the channel porosity estimates, optimising effectively to a minimal distance distance of 1.91% deviation from the experimental curve

(Figure 9)

Initial outputs of PoreXpert modelling are congruent with manufacturer data with manufacturer datasets, as exemplified for IG-110 Sample B. Crucially, the linear trend line shows only a weak correlation between open porosity estimate and distance between simulated and experimental percolation characteristic ($r^2 = 0.32$) (Figure 11). Thus, taking the average over all stochastic generations is a valid measure of this method's estimate of open porosity.

Initial modelling generated plausible data...

4. Results

The completed workflow of SEM imaging and computational composite analysis yielded estimates of channel porosity for both graphite grades (Table 5). IG-110 samples exhibited channel porosity values ranging from 3.14-3.38%, while IG-430 samples showed greater variability, ranging from 2.30-3.66%

Area contribution distribution is represented graphically for both graphite

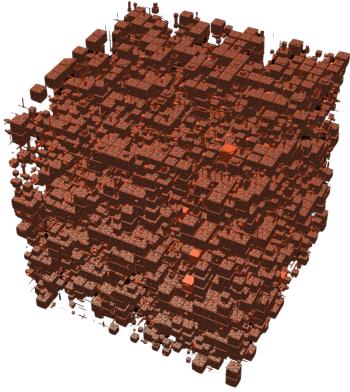


Figure 10: Visualisation of the pore network resulting from the integration of channel porosity and experimental data by the workflows above. 1.91% distance between simulated and experimental curves, following the application of Approximation Type 2 (Figure 8). Channel Porosity estimation was averaged over the top 9 layers of a unit cell 20x20x20. The result of one generation of stochastic number generation. Run in Direct Mode as Batch mode remained unstable in this early compilation

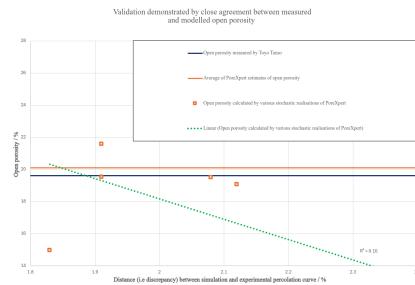


Figure 11: DRAFT: Needs to be reformatted for publication, if we choose to keep it. Validation of modelled open porosity by comparison of modelled open porosities generated by PoreXpert with manufacturer data for IG-110, which estimates a 19.62% open porosity [2]

Table 5: Pore Size Distribution (PSD) and summary characteristics for IG-110 and IG-430 samples, tabulating number of pores, total pore area, and channel porosity.

Sample	n / pores	Total Area / μm^2	Channel Porosity / %
IG110 B	8,684	41,091	3.14
IG110 C	7,075	49,755	3.27
IG110 F	8,296	50,735	3.38
IG430 B	6,848	32,983	2.30
IG430 C	13,026	49,534	2.94
IG430 F	6,819	56,794	3.66

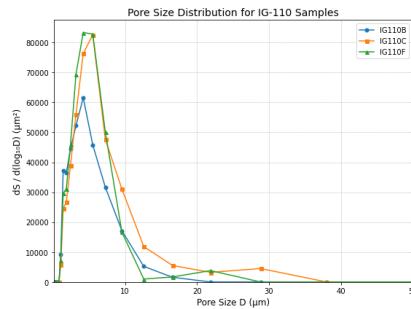


Figure 12: DRAFT: I want to recheck my code on these distributions

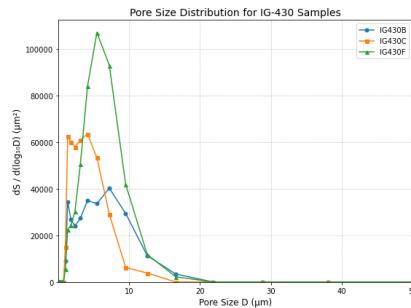


Figure 13: DRAFT: I want to recheck my code on these distributions

grades (Figure 12, 13). The area of each logarithmic bin (spanning 0.1-100 μm on the x-axis) was summed then divided by the bin width in $\log_{10}(D)$ to derive $dS/d(\log_{10} D)$, with the x-axis then linearised. y-axis values represent area density in μm^2 per $\log_{10}(D)$.

IG-110 and IG-430 both exhibit a peak in the sub-10 μm range. This is the inverse of trends observed in previous OM-based analyses, where the majority of the porosity is contributed by pores above this range [6]. [11] found that porosity as by classified SEM, albeit with a different distribution, was 3% for IG-110, which is highly congruent with the 3.14-3.38% range derived in this work.

Interpolation increases confidence in the basic functionality of this method. Adjustment of the intensity threshold to match previous OM works (i.e., pore contours and pore throats are no longer distinguished, via a reduction in intensity threshold) produces highly similar channel porosity values. Specifically, [7] estimated a channel porosity of 14.73% for IG-110, with [6] deriving 14% for the same grade, highly congruent with the approximately 13-14% figure this method derives with an adjusted intensity threshold, but also illustrating the scale of the impact in intensity threshold selection on the final channel porosity estimate.

5. Discussion

5.1. Channel Porosity Overestimation due to connectivity algo

This algorithm is likely to yield at least a slight overestimation of the channel porosity. This is because such an inclusive definition means that two or more pores, connected by a narrow neck or even simply with adjacent pixels, would be classified as a single pore. Notably, this would not change the final channel porosity (%), at least in isolation, but would result in a rightward shift in the PSD. Skeleton segmentation is for fine-grade nuclear graphite likely to be a more accurate approach than a simple connectivity algorithm as used here would be a key improvement if implemented [3]

5.2. Pore Fragmentation and Implications for Modelling

The application of a maximum pore diameter is a key part of the modelling as initial modelling where this was not implemented failed to yield reliable results. It is believed that this is due to the impossibility of the model fitting an plausible network on the premise that pores from 1.12 μm diameter upwards represent only 3 % of the sample surface. Imposing an upper threshold as the simple max of the pore diameters identified by SEM is an uncomplicated initial solution which has more logical implications (i.e., to state that between 1.12 and 20 μm diameter, 3% of the sample surface is represented by porosity). This threshold varied between 13-26 μm in this work, which should cover the vast majority of the porosity, particularly given the pore fragmentation issue described below.

Specifically, the use of a simple Moore neighbourhood connectivity, when combined with the fact that Erosion and Dilation binary operations were not applied, means that pores which the operator identifies as a single pore are in more than one case instead defined as two or more pores. Not only this but these split pores may not then surpass the pore diameter threshold of 1.12 μm . (e.g., a pore of 10 μm diameter might be split into 2 pores, 1 of 9 μm diameter and another of 1 μm diameter, which would be discarded due to the pore diameter threshold, reducing the channel porosity % and shifting rightward the pore size distribution).

The end result is that it is difficult to describe the pore size distribution derived from SEM as it currently stands, as completely impenetrable. Crucially, the production of reasonable results from the modelling as above depends on an accurate constraint of the pore diameter interval (i.e., the channel porosity figure of 3% refers only to porosity between 1.12 and 25 μm diameter) and so not only the SEM-derived pore size distribution but the PX modelling which uses it, has at least some reduction in reliability due to the pore fragmentation issue. However, this is likely a soluble problem, as follows.

5.3. Proposed Future Workflow

-Just my idea of an improved workflow: 1. Resin Impregnation 2. SEM (see if we can go to 2kV) 3. Otsu Thresholding (We have clear bimodality thanks to Resin impregnation) 4. Skeleton segmentation (Avizo software needed?) 5. Apply improved pore diameter thresholds, or maybe do not do any at all as no longer needed? At least lowered. 6. Modelling

6. Supplementary Information

One advantage of this method is the avoidance of error propagation by consecutive registration steps, as simply placing micrograph A relative to micrograph B, and then micrograph B relative to micrograph C, would result in accumulation of errors. This method builds a graph whose nodes are the micrographs, and edges are the measured pairwise shifts between the micrographs. It then finds the set of micrograph positions that minimise the total squared registration error across the entire graph, a form of globally optimised registration [5].

This stitching method also allows sub-pixel accuracy, which is crucial for accurate pore measurement. For any two micrographs A and B , which are shifted relative to each other (i.e., micrograph B is shifted two pixels up and 10 pixels left of micrograph A) then their Fourier transforms would have the same magnitude but different phases. A normalized cross-power spectrum isolates the phase difference, and the Inverse Fourier transform yields a correlation map with peaks indicating possible translations between the micrographs. The complexity of real images and the periodicity of the Fourier transform means that the correlation map is not a single peak, but rather a set of peaks, each representing a possible translation. This method therefore selects the n highest local maxima and finds the peak with the best correlation, which it defines as the true translation between the two micrographs [5]. Finally, sub-pixel accuracy in that shift is achieved by applying a parabolic interpolation around the selected peak to refine the translation estimate.

Additionally, a non-linear intensity blending function eliminates the visible seams between micrographs, which can occur even when the micrographs are perfectly aligned due to shading variations. This blending assigns a weight to each pixel in a tile, working as a function of the distance from the tile edge, with a tunable parameter controlling this weighting function. In non-overlapping regions, the centre of the micrograph, the weight is essentially 1, so the original pixel value is preserved exactly. In overlapping regions, intensities are a convex combination of the original values. Crucially, because the weights sum to 1 everywhere, blended intensity is simply a weighted average of the original intensities. Thus, the final composite micrograph is still a valid representation of the original micrographs, but the seams have been removed. [5] Testing indicated that adjustment of the blending parameter a had no discernable impact on the final composite micrograph, and therefore no impact on the final porosity values. Inversely, the removal of the visible seams between micrographs did increase confidence that in the following steps, the subsample used to determine the intensity threshold was representative of the full composite micrograph.

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