Surface Profilometry and Petrophysical Measurements

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Abstract

The surfaces of rocks reveal much about their pore structure and petrophysical properties. Thin section analysis may be used to estimate porosity, permeability, grain size and sorting, and numerous other properties. In this paper, a method is proposed for estimating petrophysical properties of rocks from the characteristics of their surface profiles. These profiles may be obtained from either optical or stylus type profilometers. From a spectral analysis of these profiles, the petrophysical properties are obtained.

INTRODUCTION

Surface roughness measures the deviation of the peaks and valleys of a surface from the mean height. For rocks, larger grains imply rougher surfaces. A wide distribution in grain sizes will imply a wide distribution of length scales in the surface profile. A surface profile should, therefore, contain enough information to allow the prediction of petrophysical properties related to grain size and sorting (i.e. porosity and permeability). Several authors have related surface roughness to transport properties,[1,2,3] but all of these methods have involved difficult and time consuming image analysis techniques. Surface profilometry, however, is quick, simple, and involves portable equipment. This makes it an ideal technique for estimation of petrophysical properties of rocks.

SAMPLE PREPARATION AND MEASUREMENT

In order to investigate the basic properties of profilometry, several types of artificial samples were prepared. Sandpaper surfaces in various grit sizes were made to test the ability of the profilometer to differentiate grit sizes. These were also the simplest well-characterized surfaces imagined by the authors. Therefore it was a good starting point. Grit sizes of 220, 240, 320, 400, and 600 were measured. These grit size numbers correspond to the physical mesh size of a grid used to sort the grains for the sandpaper. Figure 1 is a plot of sieve opening versus mesh size for the sandpapers. The profilometer samples were prepared by mounting the paper

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on disks with constant thickness and parallel faces. These samples represent excellent calibration standards since they are reproducible and easily assembled.

Table I. Sample properties for the ceramics. P_d is the pore diameter(μm), ϕ is the porosity and K_a the air permeability.

Type	P_d	ϕ	k_a
P1/2	.5	.38	2.0
P1C	.6	.33	1.1
P3C	1.8	.45	12
P10C	8.5	.45	74

The second sample set discussed is a set of commercially available ceramics. All the ceramic surfaces were prepared from one-inch plugs. In order to test the influence of different methods of surface preparation, the surfaces were smoothed to different degrees. The least amount of smoothing involved sawing with a diamond blade. Additional smoothing involved grinding to remove long wavelength roughness and finally the smoothest surface was prepared by polishing.

No significant changes in the profiles were found for the different degrees of smoothing. This suggests that the residual surface roughness for these samples is due to grain plucking and that the surface grinding and polishing smoothed at length scales outside the range of the profilometer.

Table II. Statistical averages for the sandpaper profiles.

Grit	R_q	R_a	R_y
220	2343 ±355	1864 ±260	10882 ±1680
240	2140 ±196	1695 ±101	10632 ±1427
320	1330±90	1045±82	6696±587
400	987±86	800±64	4853±509
600	718±50	582±47	3560±257

The ceramic samples are ideal for scouting experiments because they are homogeneous, well-characterized and have a wide range of porosities and permeabilities. The samples used in the study and their petrophysical properties are given in Table I.

The measurements were made with a commercial, mechanical profilometer. The profilometer is essentially a diamond stylus which rides up and down on the surface of the rock. The stylus position is sensed by the position of a ferrite core within a coil. The scan lengths were all 3 millimeters in horizontal distance and had a maximum vertical deflection 100 microns. This apparatus allows the surface roughness to be examined on horizontal length scales varying between 1 millimeter and 3 microns. In all cases the tip radius of the stylus was 5 microns and the sampling interval was less than 1/2 this value. This limits the smallest measured spatial wavelength to distances slightly smaller than the tip radius.

Figure 2 shows a typical scan for a sandpaper sample. The height of the profilometer table is set so that the mean of the data is near the center position of the profilometer stylus. The table tilt is also adjusted so that there is no significant linear bias to the data. Both of these steps are necessary to keep the profilometer stylus on scale. Six scans were made for each sample to allow averaging of the data.

DATA ANALYSIS

Statistical Techniques: The simplest analysis used is to compute statistical parameters for the data. These include the arithmetic mean, R_a, the root mean square deviation, R_q, and the average height above the mean, R_m. These parameters are applicable to the physical description of surfaces. Table II lists the values for these measures of surface roughness for the sandpapers. All of these parameters correlate with the grit size as expected.

Spectral Techniques: A more sophisticated analysis involves using spectral techniques to determine the surface parameters. Power spectra for the scans were computed using fast Fourier transforms. Averages were performed on the six scans taken for each surface. The Fourier transform is given by:

$$f(\omega)=\int h(l)\exp(2\pi i\omega l)\,dl \qquad \textbf{(1)}$$

Where l is the horizontal distance along the profile, h(l) is the measured profile height, and ω is the spatial frequency.

The power spectrum is defined as:

$$S(\omega)=\frac{1}{L}|f(\omega)|^2 \qquad \textbf{(2)}$$

Because of limitations in the scan length, multiple scans must be averaged to obtain the signal-to-noise ratio necessary to interpret the data. The data are smoothed by adding the separate power spectra at each frequency and dividing by the number of scans. The average value of each of the trends was forced to zero and the linear trends were removed from the data. These corrections were usually quite small since the same process was performed mechanically by adjusting the table as described above. This implies the lowest spatial frequencies have been removed from the data and they are therefore not shown. All the profiles were digitized at 512 points per 3mm scan.

Fractal Analysis: A self-similar profile is a continuous non-differentiable function which is correlated over many length scales. Also its statistical properties are unchanged under a change of scale. This type of function is called a fractal and has a fractal dimension (D) somewhere between the topological dimension (D_t) and the Euclidean dimension (D_e). For a one dimensional trace, such as a surface profile, the fractal dimension will take a value between one, the topological dimension, and two, the Euclidean dimension. For fractal dimensions close to the topological dimension, the curve approaches being differentiable. As the fractal dimension increases, the jaggedness of the curve increases, the correlation between nearby points decreases and the curve becomes space-filling.

However, surface profiles are not self-similar but self-affine. For a self-affine profile the coordinate parallel to the surface and the coordinate perpendicular to the surface scale differently.

The relation between the fractal dimension (D) and the slope (β) of the power spectrum is given by[4]:

$$D=\frac{5-\beta}{2} \qquad (3)$$

Equation 3 implies that for the fractal dimension to be between one and two, the slope of the power spectra must be between one and three.

RESULTS

Grain Size Determination(Pore Size Determination):- Grain size is one of the major determining factors of permeability. This next section describes the technique used to determine average grain size using surface profilometry.

Table III. Fitted parameters for the power spectra of sandpapers.

Grit	S_l	S_h	F_c (μm^{-1})
220	-.336	-4.00	$15.3\ 10^{-3}$
240	-.508	-3.94	$16.5\ 10^{-3}$
320	-.484	-4.74	$25.1\ 10^{-3}$
400	-.208	-4.56	$30.5\cdot10^{-3}$
600	-.961	-3.84	$40.9\cdot10^{-3}$

Table IV. Fitted parameters for the power spectra of the ceramics.

Type	S_l	S_h	$F_c(\mu m^{-1})$
p1/2a	-1.64	-4.26	$55.7 \cdot 10^{-3}$
p1c	-1.37	-4.10	$53.7 \cdot 10^{-3}$
p3c	-.772	-3.24	$19.4 \cdot 10^{-3}$
p10c	-.760	-3.26	$13.5 \cdot 10^{-3}$

The calculated power spectra for the sandpaper samples are plotted in Figure 3. Two distinct trends are obvious in the data, a small slope at low spatial frequencies (S_l) and a much steeper slope at large spatial frequencies (S_h).

A summary of the slopes is given in Table III. As shown in Figure 4, the cross-over frequency (F_c) occurs at a spatial frequency corresponding to the mesh size of the screen used to sieve the particles of the sand. This implies that the cross-over frequency has a physical interpretation in terms of grain size. For the ceramics this will be the key to determining the permeability from the profiles.

The spectral density plots for the ceramics is shown in Figure 5. Again the same characteristic shape to the spectral density plot is observed. This is consistent with observations of Brown and Scholz[5] who have observed a change in slope of the spectral density curve near a grain size for rock data. The slopes and cross-over frequencies are summarized in Table IV. In Figure 6, plots of the cross-over frequencies versus measured air permeabilities are shown. The permeability is proportional to the cross-over frequency squared. This result is expected from a capillary tube model and is consistent with the interpretation of the cross-over frequency in terms of an average grain size.

Porosity Determination: - Another important petrophysical property is porosity. Porosity is more difficult to determine from a one-dimensional scan than grain size since it occurs over many length scales. Standard techniques such as chord length analysis are difficult to apply since the Fourier spectrum does not allow a simple separation of surface waviness (long wavelength features associated with surface preparation) from actual surface features.

However, the slope of the power spectrum at long spatial wavelengths was found to correlate with the sample porosity. It has a correlation coefficient of .96 as shown in Figure 7.

The correlation with the slopes of the power spectra is qualitatively explained using the integrals of the power spectra. These integrals are shown in Figure 8. Each integral is normalized to the maximum value and therefore may be interpreted as a cumulative size distribution. The power spectrum at a given frequency is proportional to the amplitude of the Fourier component at that frequency. This amplitude is proportional to the total magnitude of surface variation. The normalized integral of the power spectra is therefore a cumulative distribution of the surface variations. The curvature of the distribution, which is related to the second derivative of the power spectrum. Therefore it is a sorting parameter and should be related to the sample porosity.

The full physical meaning of this distribution is not completely understood. At long enough spatial wavelengths the distribution must be influenced by surface preparation. As described above, the correlation between the porosity and sorting is qualitatively understood but a calculation from first principles has not yet been developed. The extension to real rocks samples and measured grain size distributions will be done in a future paper.

DISCUSSION

All of the high frequency slopes in Tables III and IV are greater than three. This implies that none of the data on length scales smaller than a grain size show fractal behavior. At long spatial wavelengths (500 microns-50 microns), only the two finest grained samples exhibit a slope corresponding to fractal behavior. The slopes indicate that the surface is too uncorrelated to be considered fractal.

The roughness at long spatial wavelengths also has physical meaning and is not just related to sample preparation. This was demonstrated by the correlation between the slopes and porosity and the lack of sensitivity to sample preparation. It is therefore thought that the roughness in this range is dominated by long range correlations in the porosity. It may be that other effects that depend on long range correlations (such as residual water saturation) could be predicted from the spectra in this regime.

In the high spatial frequency region, the slope is always too steep, and the surface too correlated, to be fractal. This implies that on length scales smaller than a grain size, the surface is smooth and differentiable. This conclusion only holds for the artificial samples examined in this paper. Real rock samples may behave differently. In particular, highly cemented samples have been observed to exhibit fractal behavior in this range of spatial frequencies.[6] Preliminary rock sample data confirm this.

CONCLUSIONS

Profilometry provides a useful method for determining petrophysical properties. For the samples examined, porosity and permeability information can be extracted from the profiles. A characteristic length is easily determined from the spectra which is related to the sample grain size. The sample porosity is correlated with the slope of the power spectra at the lower spatial frequencies. Profilometry may, therefore, be a useful tool for quickly and easily determining petrophysical properties.

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6. Ibid.

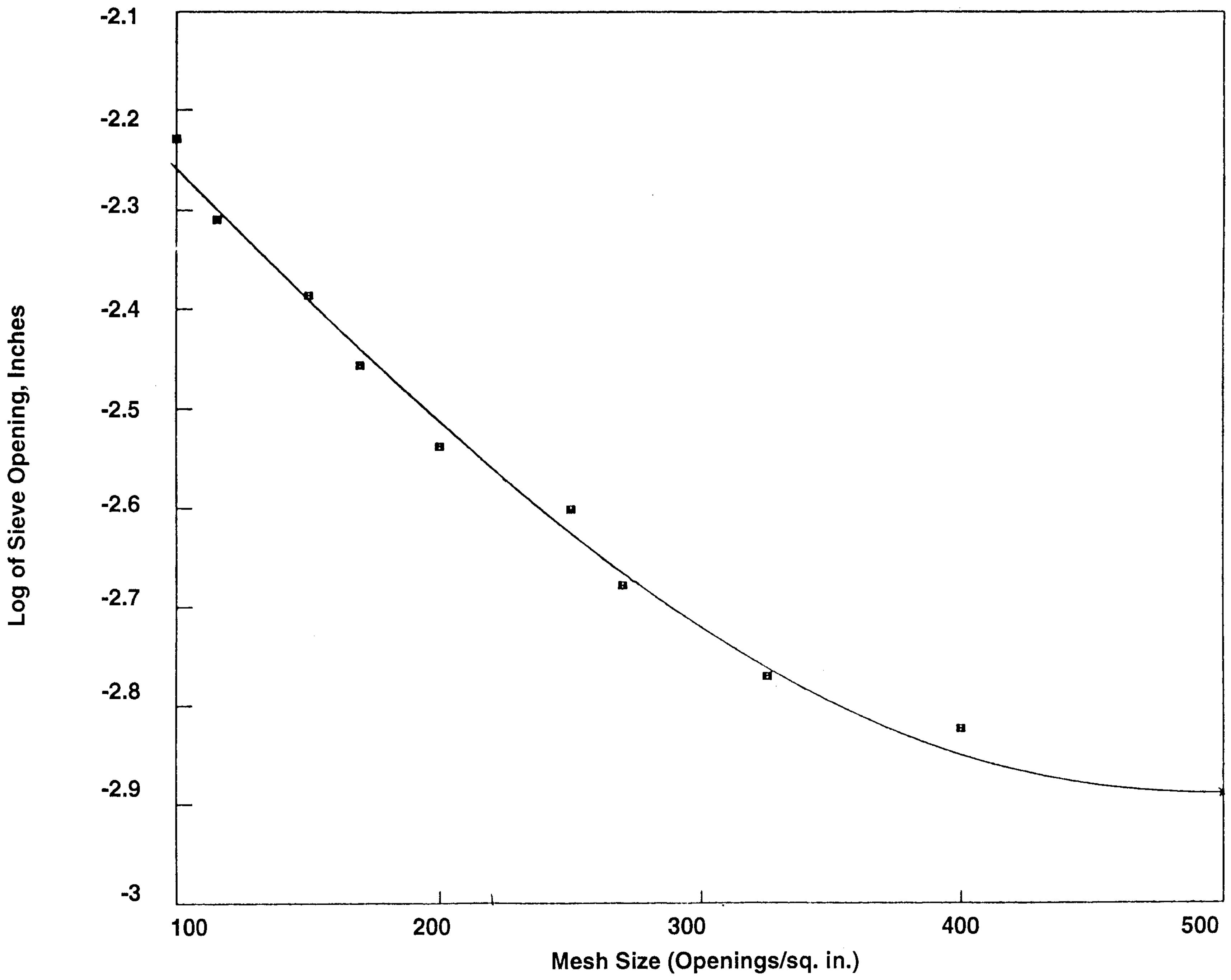

Fig. 1 - Mesh size versus largest grain size for sandpaper.

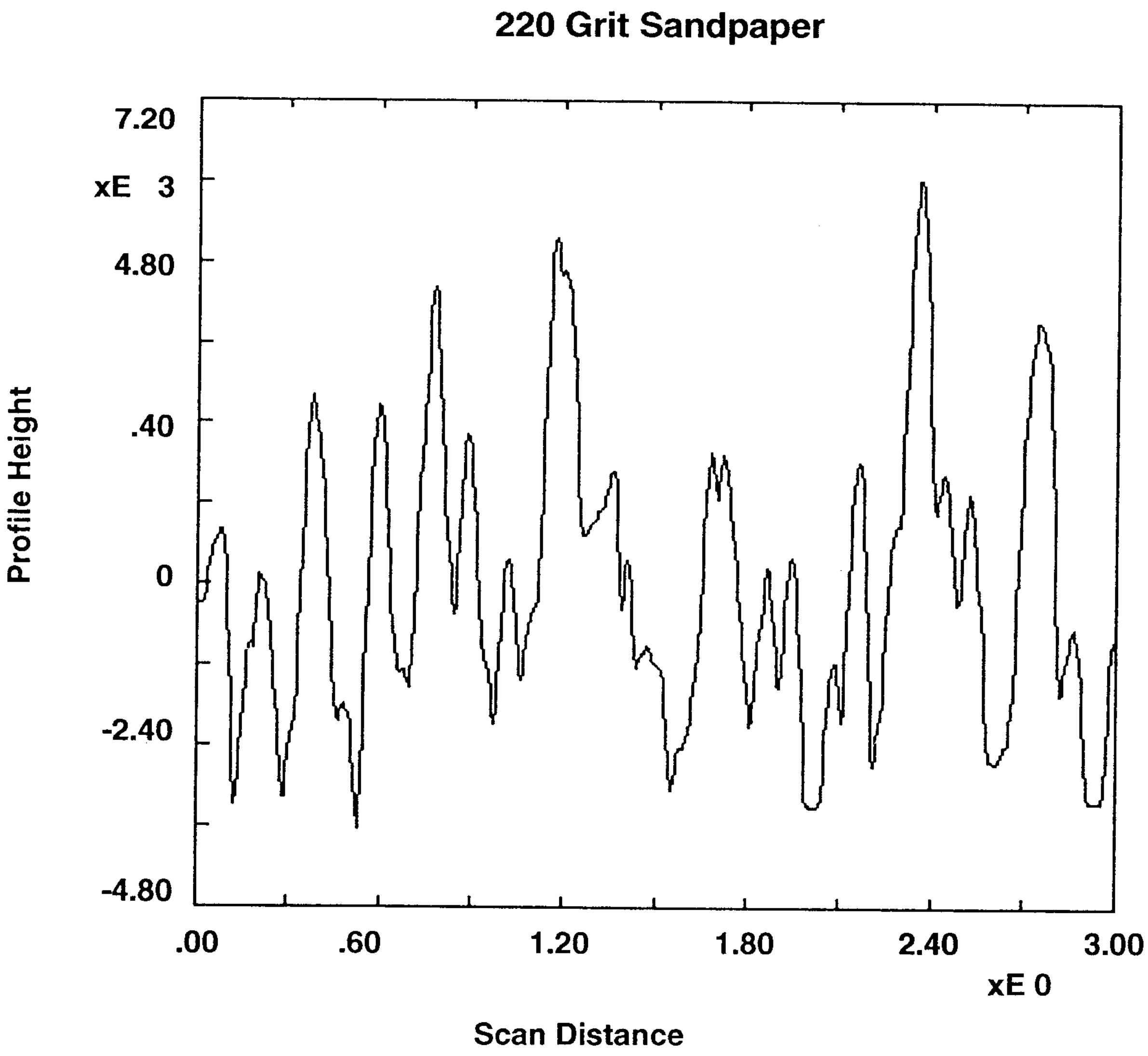

Fig. 2 - Scan profile for 220 sandpaper. Scan length is 3 mm.

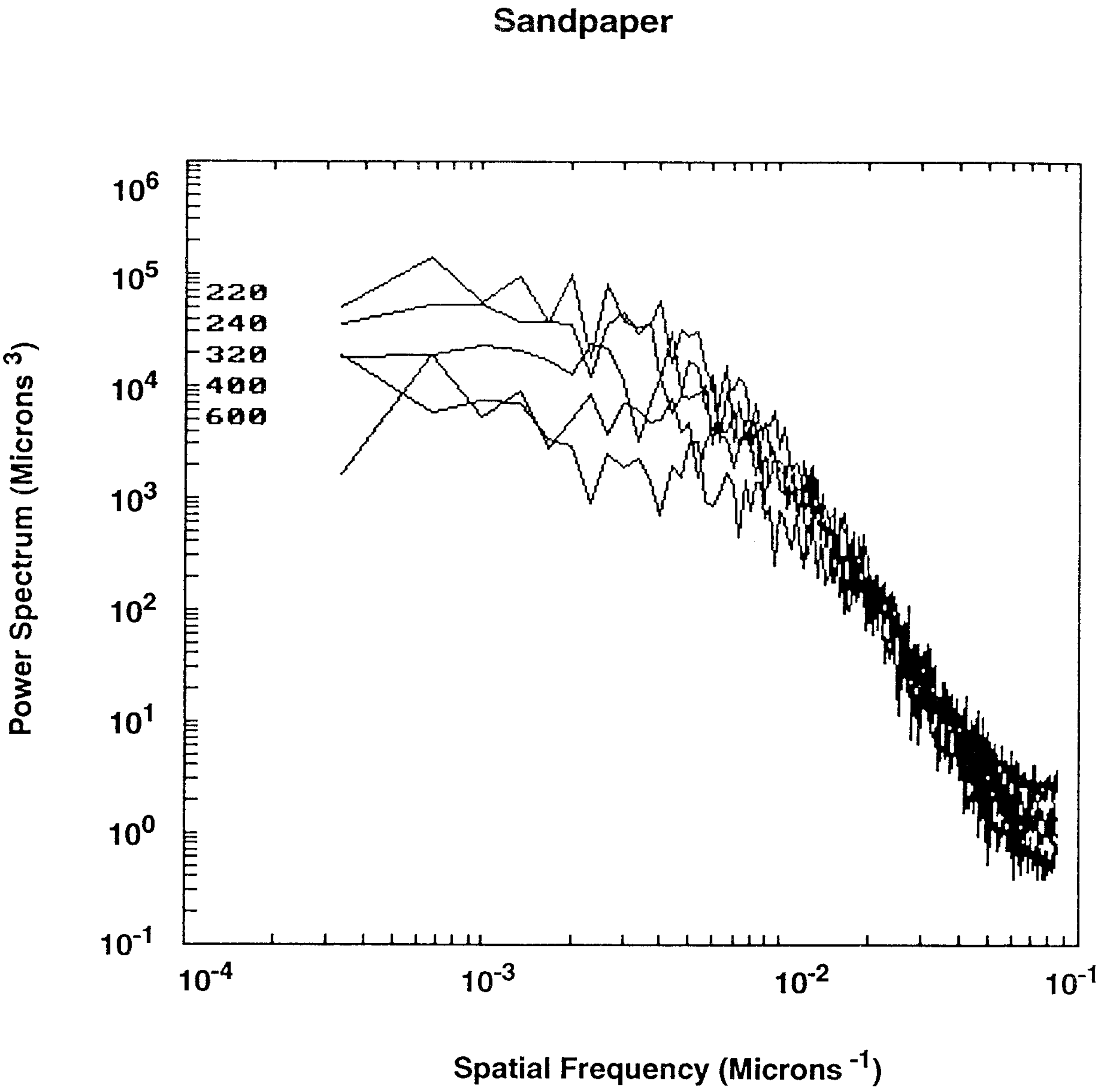

Fig. 3 - Power spectra for sandpaper profiles. Change in slope corresponds to the grit size.

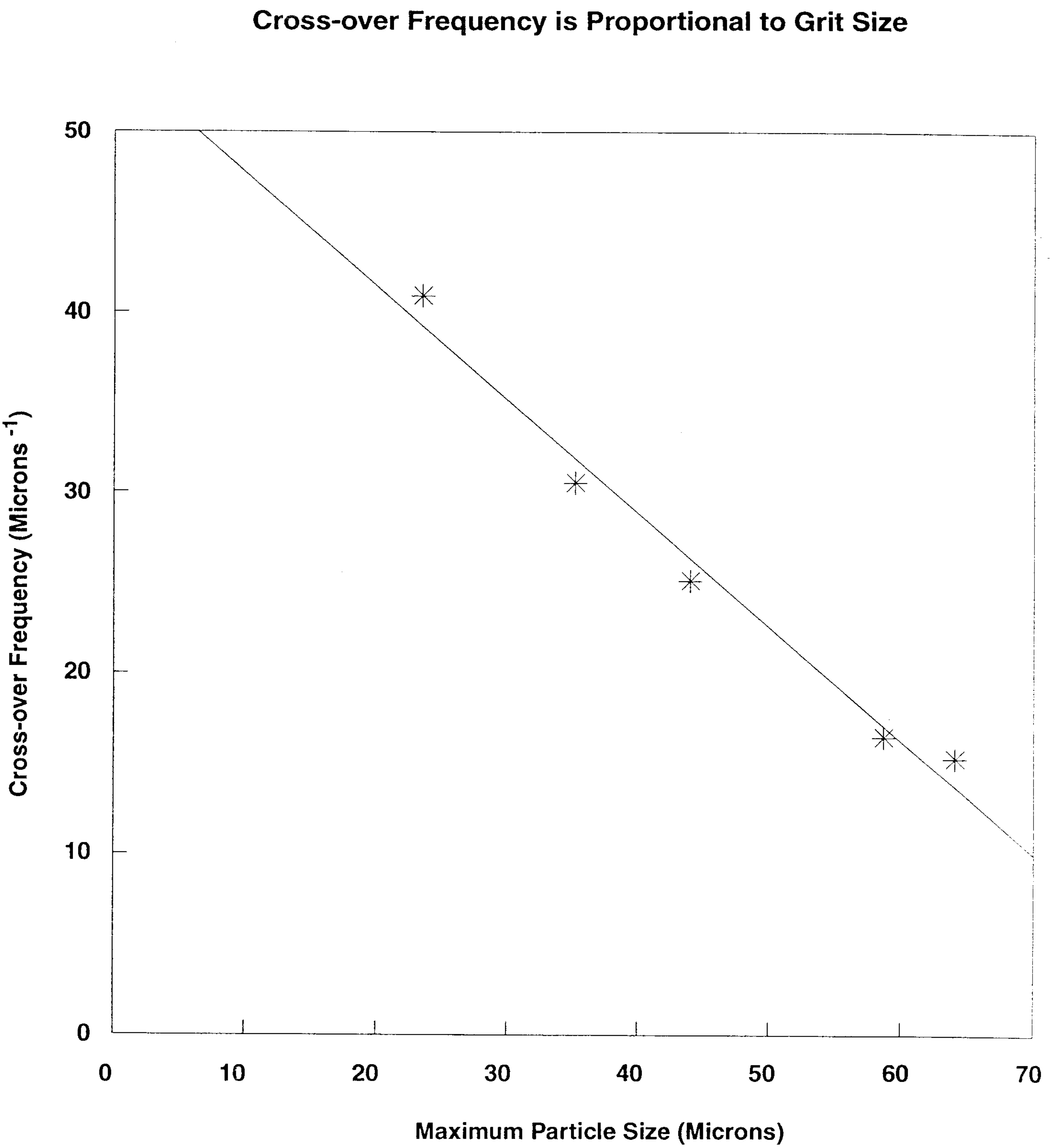

Fig. 4 - Correlation of grit size with cross-over frequency for the sandpaper samples.

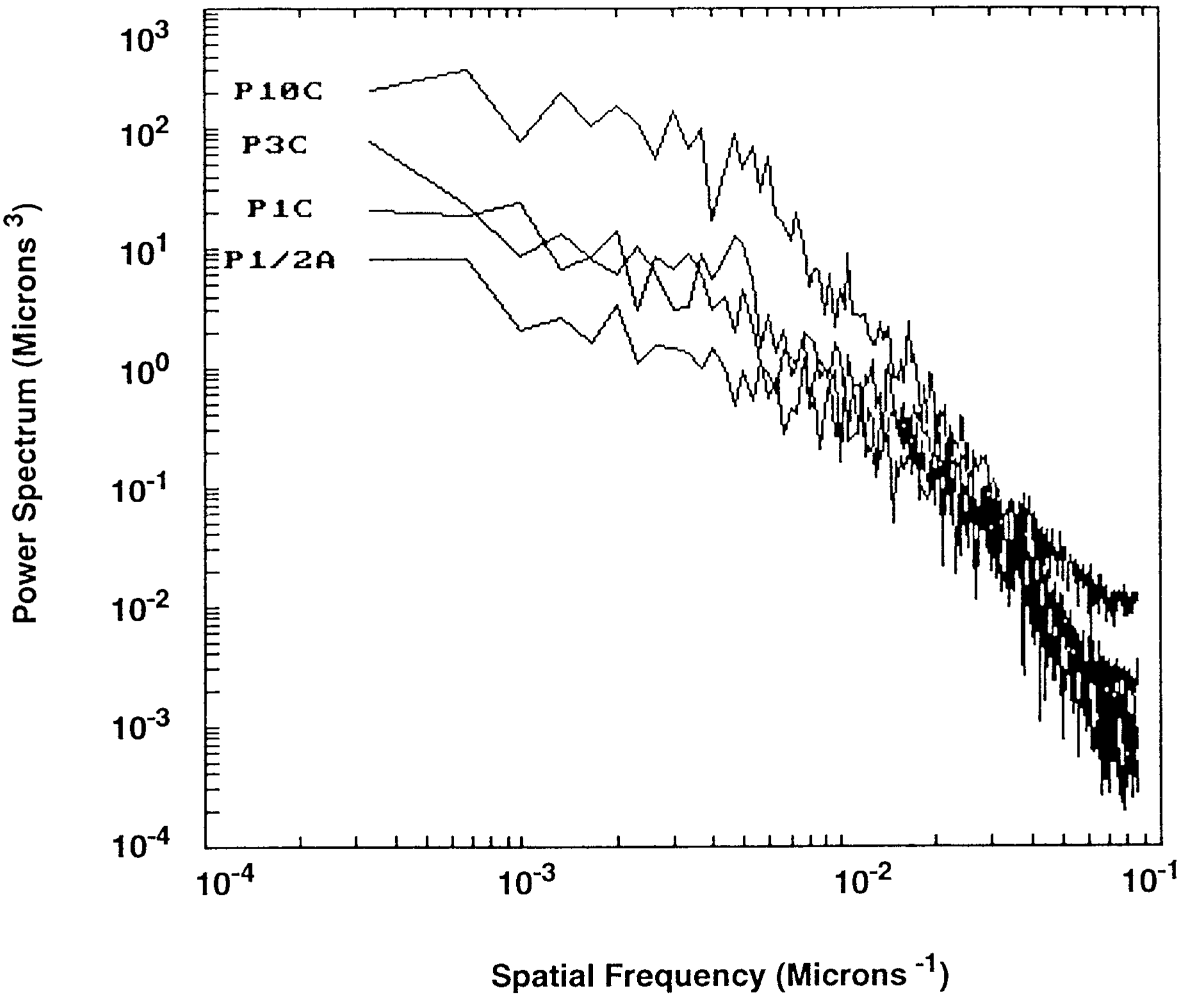
Coors Ceramics

Fig. 5 - Power spectra for Coors ceramics.

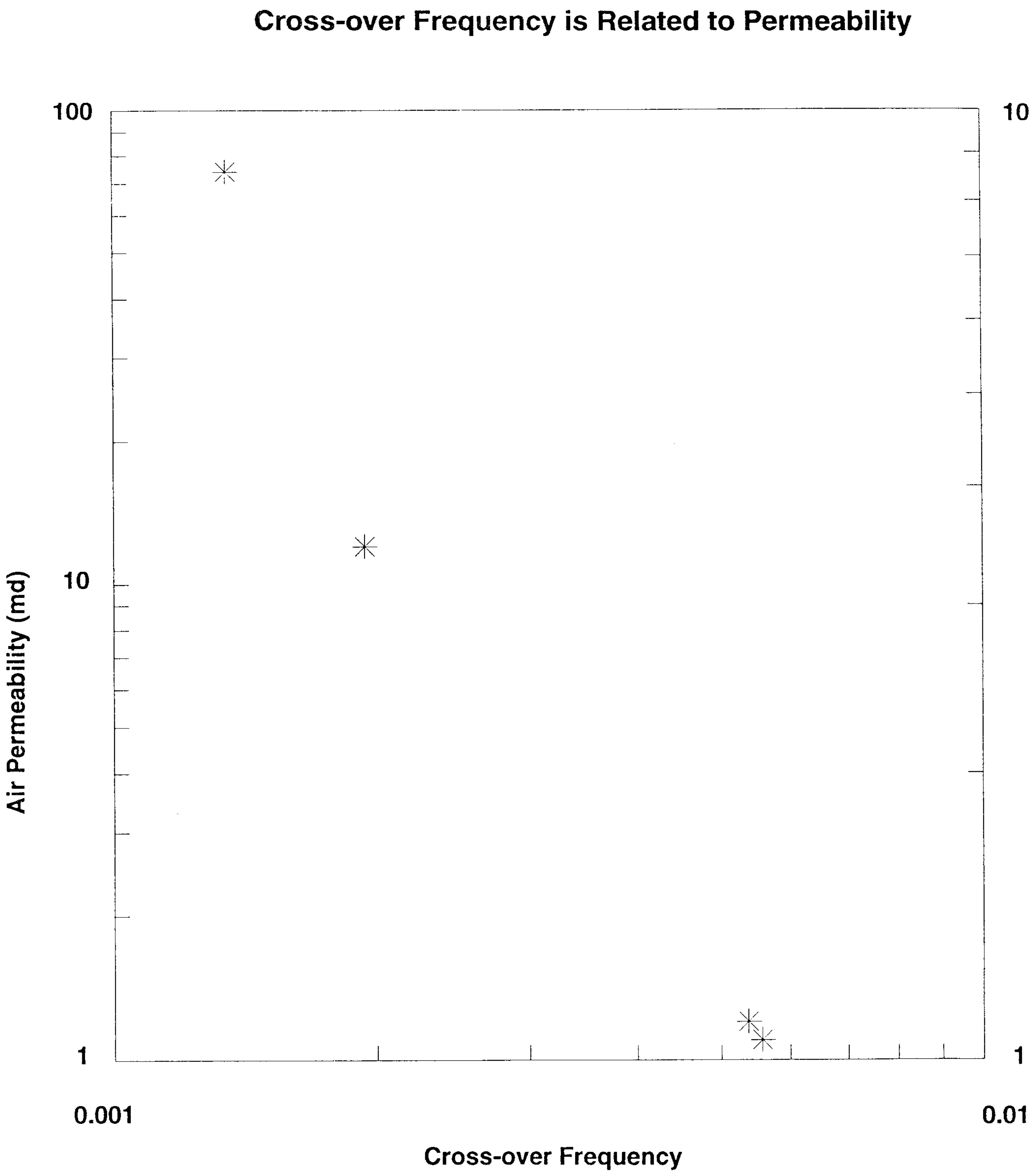

Fig. 6 - Correlation of the air permeability with the cross-over frequency for the ceramics.

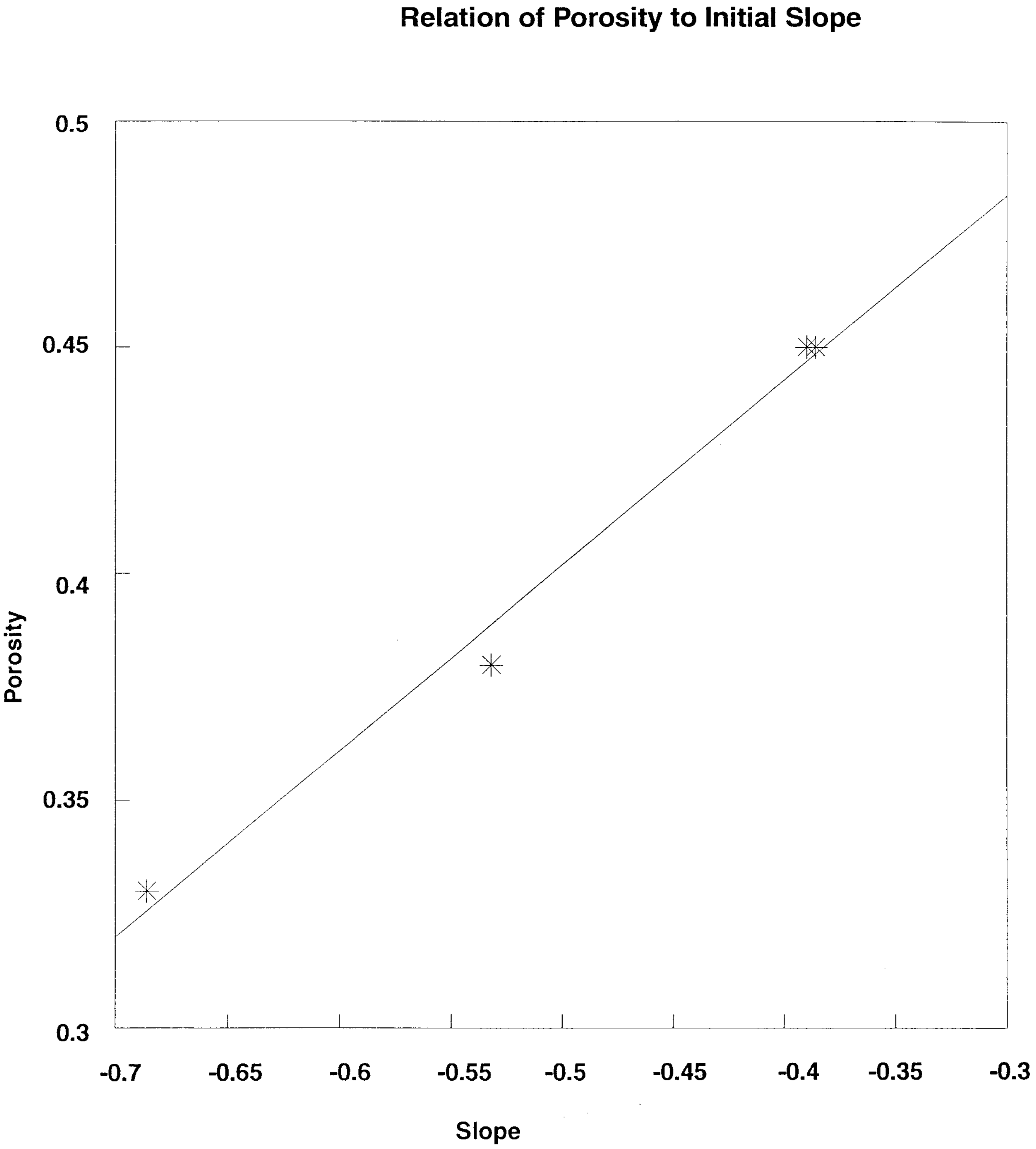

Fig. 7 - Correlation of porosity and low frequency slope.

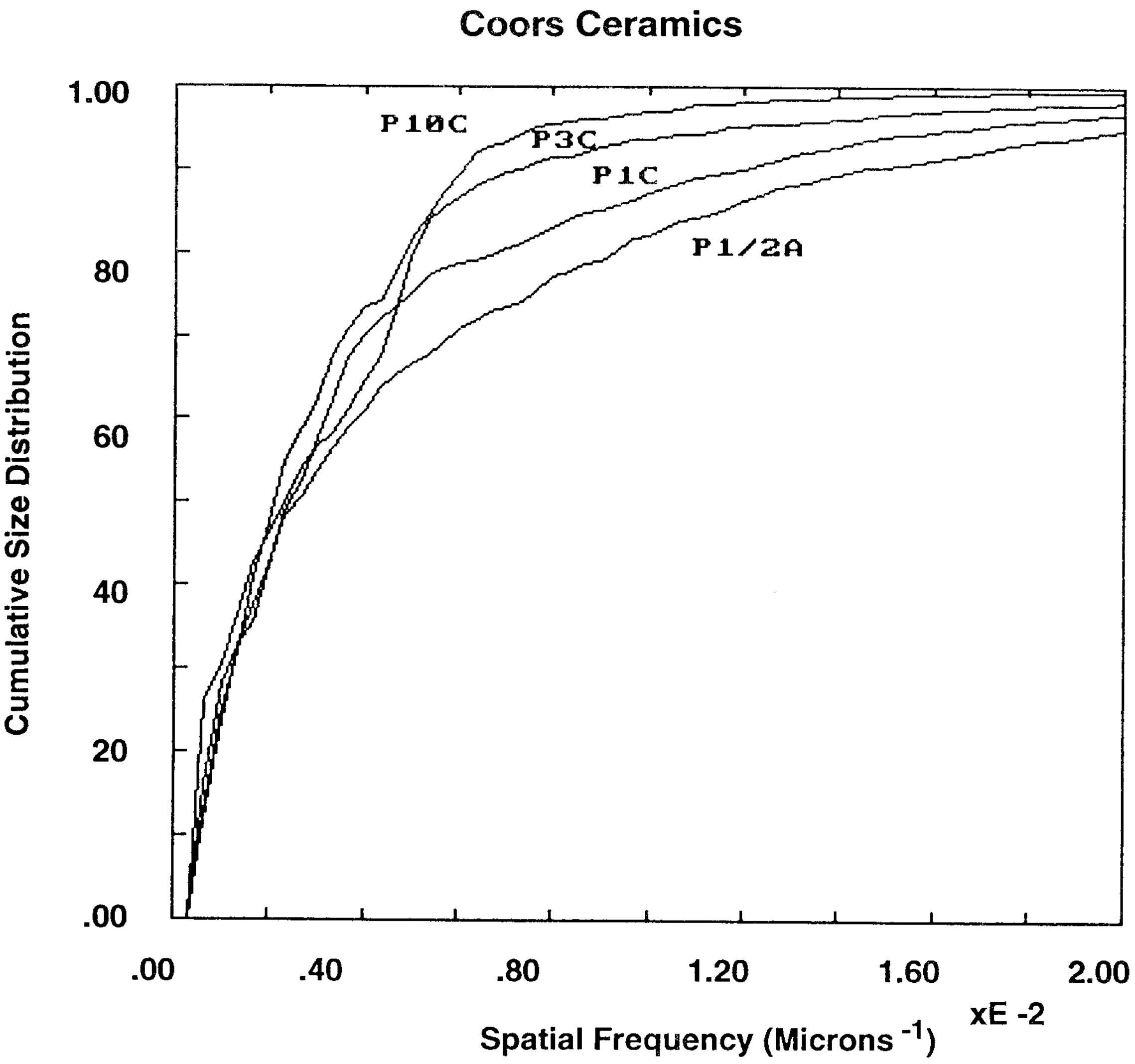

Fig. 8 - Cumulative size distribution for the ceramics.