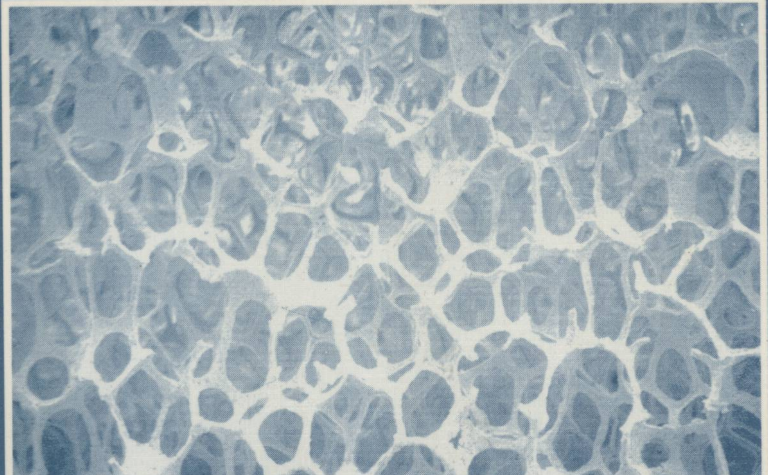
Key Engineering Materials
Volume 115

Porous Ceramic Materials

Fabrication, Characterization, Applications

Editor:

Dean-Mo Liu



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***Front cover illustration (book edition)**:*

Porous ceramic with fine open pore structure formed by modified foam method (p. 74).

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Specializing in the Field of

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Porous Ceramic Materials

Preface

The development of porous ceramic materials has brought a new challenge to a variety of industries because porous ceramics are more durable in severe environments and their surface characteristics permit them to satisfy specific functional purposes.

With the growing demands of porous ceramics for industrial applications, a number of technologies have been developed to fabricate these materials with an attempt to control their pore characters as well as to realize the pore-related properties in order to gain a deeper understanding of the relation between the various pore-related properties for optimization purposes.

To date, porous ceramic materials with more delicate and uniform pore structures and pore sizes ranging from a few hundred micrometers to a few nanometers can be achieved for diverse purposes by either physical or chemical processing. This is one of the purposes of this special volume to bring readers some or better understanding of the processing and properties of the porous ceramic materials.

This volume is a collection of papers covering the fabrication, property evaluation, characterization and applications of the porous ceramic materials developed to date. The editor hopes that the reader will find something to be interesting and worthwhile.

Based on this spirit, this volume includes fundamental theories, novel fabrication techniques, and special classes of ceramic materials involved in sensing and biomedical applications.

Fall 1995

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Recent Titles

Corrosion of Advanced Ceramics. Eds. R.J. Fordham, D.J. Baxter and T. Graziani

ISBN 0-87849-696-3: 252 pp (October 1995), SFr 120.00

Proc. of a Special Session as part of the 4th European Ceramics Society Conference held in Riccione, Italy, 1995. The primary objectives of the Special Session were twofold: 1. to review the current state of knowledge on corrosion mechanisms and to present some recent results in key areas; and 2. to highlight and review on-going activities in the field of standardisation of corrosion test methodologies.

Interfaces of Ceramic Materials - Impact on Properties and Applications
Eds. K. Uematsu, Y. Moriyoshi and Y. Saito

ISBN 0-87849-701-3: ca. 450 pp (October 1995), SFr 240.00

Proceedings of the 2nd Intl. Workshop held in Iitsuna Heights, Nagano, Japan, 1994. The objective of this workshop was to discuss various aspects relevant to the interface of ceramics from a number of standpoints that are as distant as possible. This aim was reached by presenting the contributions of a wide spectrum of specialists. The majority of papers have been prepared in review type so that researchers of other fields can easily gain very detailed understanding on the interfaces of ceramics. The topics covered reach from basic science to the frontier of advanced technologies.

Ceramic Matrix Composites
Eds. G.M. Newaz, H. Neber-Aeschbacher and F.H. Wöhlbier

ISBN 0-87849-698-x: 528 pp (1995), SFr 300.00

In this book, processing advances and application experience of CMCs are discussed by a number of researchers. In addition, microstructural and mechanical behavior of CMCs are presented as a complementary section. These papers present a coherent view of some of the recent advances in the field.

Metal Matrix Composites
Eds. G.M. Newaz, H. Neber-Aeschbacher & F.H. Wöhlbier

ISBN 0-87849-697-1: 928 pp, 2-Vol. Set (October 1995) 400.00 SFr

This volume reflects recent developments in the area of Metal Matrix Composites, particularly in short fiber MMCs. The latter have best application potential for higher volume cost-effective automotive and industrial applications. The selected papers reflect the materials science and mechanics perspective of the individual authors. Overall, the volume contains considerable new information and recent advances in processing, microstructural characterization and thermomechanical behavior and modeling as discussed by many international researchers active in this field.

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The Porosity Dependence of Physical Properties of Materials: A Summary Review

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Keywords: Porosity, Porosity Dependence, Physical Properties, Mechanical Properties, Elastic Properties, Fracture Energy, Fracture Toughness, Crack Bridging, Strength, Hardness, Wear, Electrical Conductivity, Thermal Conductivity, Dielectric Constant

Abstract: A review of the porosity dependance of physical properties is presented, focused on an overall broad perspective. First, the hierarchy of those properties: 1) independent of porosity, 2) dependant only on the amount of porosity, and 3) dependant on both the amount and the character of the porosity is briefly noted. Then data trends and model needs and approaches are summarized for the third category, focusing on mechanical properties , but thermal and electrical conductivity are also addressed. Key points noted are the interrelated importance of percolation limits, pore character, and mixes of porosity. These in turn make models neglecting or obscuring pore character and it's broad variations being non- predictive. Next self consistency of models and data for interrelated properties are discussed. Models based on minimum solid area are shown to be the most consistent with several properties, but some modifications and improvements are needed to increase their accuracy and scope.

Introduction

The porosity dependance of material properties has long been studied both experimentally and analytically since porosity often has significant effects and very commonly occurs as a result of processing limitations, or as a necessity to obtain certain properties or balances of them. However, this is a large and complex field, resulting in most studies being very narrow relative to the overall scope of porosity effects, and hence of more limited use than often envisioned in their development. In order to utilize these studies and achieve a more accurate view a broader perspective is necessary. This paper strives to significantly broaden the perspective by summarizing much data and analysis from previous surveys(1-3). The first step is pointing out the existence and key aspects of the hierachy of porosity dependant properties, then realities of data trends and limitations and their implications for model needs are noted. This is followed by discussion of key models, their self consistency with the model assumptions, basic physics, and data, as well as needs for improvement.

Hiearchy of Porosity Dependance, Data Trends, and Model Needs

Though seldom discussed, and uncertainty in placement of some properties, there clearly is a (not fully defined) hierarchy of porosity dependance of properties(1) as follows:
1)Properties not dependant on porosity. These include most properties determined only by the atoms involved, their local arrangement, bonding, or both, e.g. molecular weight, lattice spacings, and hence theoretical density and thermal expansion coefficients, as well as melting and boiling temperatures (but not ablation rates, which clearly depend on surface area, hence surface-connected porosity). 2)Properties dependant only on the amount of porosity, but not it's character. Such properties are those dependant only on the amount of material present(in a give volume) such as heat capacity(per volume), refractive index, and dielectric constant (at least where pore surface charging is not significant, e.g. at lower dielectric

constants) and probably some Curie temperatures (i.e. where pores don't seriously effect domain structure). 3) Properties that depend on both the amount and one or more characteristics of the porosity. There are three subsets to this third set of properties, i.e. those properties where: a) the flux or stress transmission is mainly, or totally, through the solid phase, b) flux transmission through the pore phase is dominant, and c) where the flux transmission is shared by both phases.

The first subset, i.e. 3a), is of broad interest, and the focus of this chapter. This subset includes most, if not all, mechanical properties (since only solid phases can support/transmit stress), as well as much electrical conduction and considerable thermal conduction behavior (primarily at low to moderate porosity and temperature). These properties, as discussed elsewhere(1-3)and further later, depend primarily, or only, on one basic characteristic of the pores. Of the limited choices to reflect this characteristic, the minimum solid area (MSA) is recommended(3). Some corrections for other factors effecting mechanical properties are also noted. Properties dependant on flux/transport through the solid phase, i.e. electrical and thermal conductivity (the latter mainly at low to modest temperatures) show a very similar dependance to that for elastic properties(1,2). On the other hand, properties involving considerable, or dominant flux through the pore phase clearly depend on other pore characteristics, such as the degree of pore interconnection and tortuosity, and pore size. Such properties clearly include those dependant on fluid flow through pores, but can also include others such as electrical breakdown. Treatment of these topics represent substantial, specialized topics themselves, so they are not addressed in this chapter.

While the third category of porosity dependance above is of greatest interest, it is important to recognize, as is seldom done, that the other two categories (i.e. 1 and 2) exist and that there can be variations and transitions between the three categories as well as within them as a function of both the porosity and the test conditions. Thus, at high levels of very fine porosity, surface atom relaxation may begin to have measurable effects on lattice spacings and theoretical density, thus changing that property from the first to the second or third category. Similarly, very fine porosity may also begin to effect refractive index and dielectric constant due respectively to scattering and surface charging of fine pores. Some properties may also show little or no porosity dependance over some range of porosity and character. For example, limited numbers of larger pores or more, smaller, pores along boundaries of larger grains so they have limited effects on magnetic or electrical domains should have limited porosity dependance of domain dependant properties. Similar effects occur within the third category. Thus, larger pores, more open porosity, and higher temperatures increase thermal transport via convective and radiative transport through pores, giving transitions from category 3a to 3b or 3c.

Turning now to data trends, the focus will be primarily on mechanical properties and secondarily on thermal and electrical conductivity. The almost universal trend for these properties plotted as the logarithm of the absolute property levels (or their relative level, i.e. their value at any P divided by their level at P =0)vs the volume fraction porosity (P) is illustrated in Fig.1. Such semilog plots show three basic characteristics:1) first a very nearly linear region (i.e. closely following an e^{-bP} dependance, where b= the slope of the semilog plot of properties vs P, and e= the Naperian log base) over the first 1/2 to 2/3 of the pertinent P range, 2) then a region where the property decrease with increasing P accelerates, i.e. a roll over in the property decrease, and 3) the culmination of this roll over with the property percipitiously decreasing to zero at a specific volume fraction porosity, P_C, which is the percolation limit for the solid phase defining the particular porosity. Note that P_C is generally <1, often substantially so and defines the pertinent P range for that type of porosity. All three characteristics show a substantial range in the values characterizing them (e.g. the initial slope, i.e. b value, the P range for the accelerated decrease, and P_C). There is a qualitative interrelation between these parameters, i.e. a higher slope (b value) means a lower P range where properties decrease faster and a lower P_C, and vice versa. All of this shows substantial impact of processing/pore character on property-porosity relations.

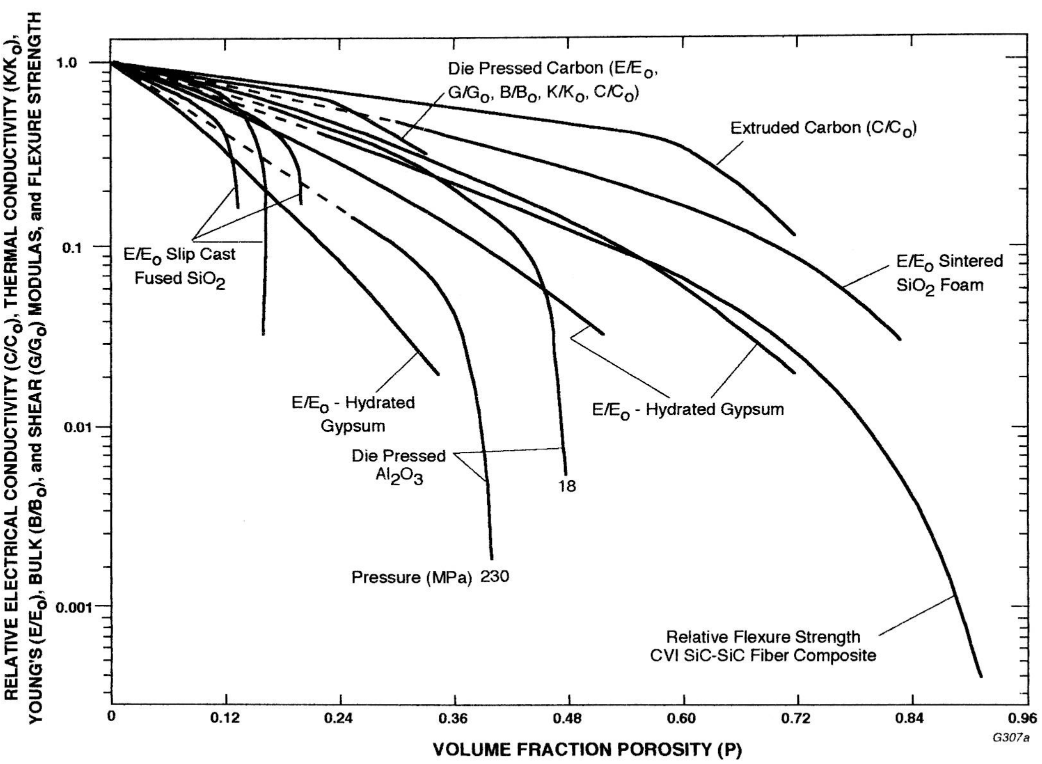

Figure 1) Examples of plots of the logrithms of various relative physical properties(i.e. the value at some porosity P divided by the value at $P=0$ versus (a linear scale of) P for various materials at 22 C. Curves for different SiO_2, and Al_2O_3, and carbon bodies from a previous survey(2), as well as fiber composites(4) and gypsum materials(5) . Note the expected effect of die pressing pressure (in MPa) for pressed and sintered Al_2O_3, i.e. denser packing, higher initial slope (b value), and lower P roll-over and P_C(projected) with higher pressure; lower initial slope and higher (projected) P_C for extruded vs die pressed carbon, and varying, but higher, initial slopes and lower (projected) P_C values for colloidally processed (slip cast) versus foamed SiO_2.

The nearly universal data trends of Fig. 1for catagory 3a behavoir define some of the basic needs of property-porosity models, namely that they yield the broad range of trends there. However, in order for the models to be of use for prediction, i.e. projecting the properties before measurement, as opposed to simply curve fitting (i.e. projection of the properties via extrapolation, hence only after measurement), they must do this while also relating these trends to processing via pore character (discussed later). Obviously, to be of broad value models must be consistent with the basic physics of the specific property, as well as closely related properties, and the porosity involved. Though not widely recognized, models must be able to account for mixes of porosity for three reasons. First, this is essential since many bodies start with mixed porosity, e.g. inter- and intra- particle or agglomerate pores which differ in not only location, and possibly size, but also shape (often related to location). Second, pore character, and changes of this with the level of porosity, e.g. due to diffusion effects (such as inter-to intra- particle porosity changes) or other effects of processing changes to change P, must be accounted for. Third, it can be important to account for frequent inhomogeneity in the spatial distribution of the porosity (which can be very important, but has been almost totally neglected in evaluating models). It is also of considerable value to have models that, at least reasonably, reflect behavior over the complete range of applicable porosity, rather than just a restricted range, e.g. only for foam materials.

A critical factor impacting the above issues and having broad ramifications is the issue of accounting for processing-pore character effects. This is essential not only from the standpoint of range and accuracy of the models, but also their practical utility. Models that do not clearly define the effects of differing pore character on properties are of, at best, limited use in selecting a processing approach- porosity level and type to achieve a desired balance of properties. Obscuring the processing-porosity relations also greatly reduces the opportunity for use of processing-porosity-property relations to aid in the challenging task of characterizing the porosity. The coupling of pore character and processing also provides insight into significant property anisotropy that can result and the common problem of inhomogeneity of porosity. Both of these seriously neglected issues are discussed later.

Basic Model Parameters and Approaches

Stress- based models

There are two basic model approaches to mechanical properties, namely a local stress-strain$^{(6-11)}$ or a load bearing or solid cross sectional area basis$^{(1,2,6)}$. These may be evaluated on a global scale (i.e. as an average), or more commonly on a local pore scale (note, the cross sectional area basis also has applicability to thermal and electrical conductivities, as shown later). The most important models have been recently reviewed$^{(1,2,9-11)}$, and so are summarized and updated here. It is clear that both stress (or flux) concentrations and cross sectional area can be factors in the mechanical (and conductive) properties of porous bodies. The question is whether the local stress or the load carrying area is dominant, or whether both are important, and over what P ranges. Because of the complexity of the problem, and the resultant simplifying assumptions made to make the problem tractable, the "correctness" of the models can only be determined from extensive comparison with data.

The most extensively developed local stress-strain model is based on a concept introduced by Hashin (originally for composites)$^{(7)}$. Each porous body to be analyzed is conceptually reconstructed from solid balloons of the same material as the body. The balloons have an infinite range of sizes, but with each balloon having the same P as the body to be analyzed. It is assumed that finer and finer balloons can fill all of the interstices between the balloons so the only porosity in the reconstructed body is due to the one pore centered in each balloon. It is then assumed that a pressure applied to this reconstructed body is uniformly distributed around each porein the balloons so strains can be rigorously calculated to obtain bulk modules and a similarly calculated or estimated shear modules, from which Young's modules and Poission's ratio can at least be bounded. A derivative of this approach is to imbed such a balloon in a matrix reflecting the average properties of the body to be analyzed. Various improvements and extensions of these approaches have been recently summarized by Ramakrishnan and Arunachalam$^{(9,10)}$ for porous bodies, and Christensen$^{(11)}$ for composites.

While the above approach is rigorous in it's mechanics, a general and a specific issue is the pertinence of it's mechanics, as discussed below. A very critical specific issue is it's much less rigorous treatment of the porosity, i.e. it's "universalization" of all porosity to spherical pores (in the balloons). This leaves very uncertain the accuracy and the range of porosity in terms of both the amount and character to which it is applicable, and thus also no indication of it's possibilities for handling combinations of porosity. Another specific issue is the treatment of the porosity dependence of Poission's ratio,especially treating the value for fully dense material as a parameter that converges to a value of 0.25 at P=1. There is no physical basis$^{(12)}$, nor experimental evidence$^{(13)}$ to support this proposed convergence. This approach also totally neglects percolation limits, i.e. P_C values, which is a typical problem of applying composite models to treat porosity.

A key issue with the above, and any stress based, approach is the role and treatment of stress concentrations$^{(14,15)}$. For elastic properties, for which the above models were proposed, there is the basic question of the extent of stress concentrations effects. Thus, unless there were to be local plastic deformation in some cases (e.g. in metals, some plastics, and ceramics at high temperature) and not in others (e.g. most ceramics over most of their temperature range), there should be no intrinsic effects of stress concentrations on elastic properties since these remain linear to high levels of theoretical strengths. Never the less, stress concentrations continue to be an important focus for many elastic property-porosity models, probably in part because stress concentrations appear to be a logical factor in other mechanical properties, especially strengths. However, even for these other properties with isolated, i.e. dilute concentrations of, pores, where the situation is simpler, there are still three basic questions regarding the applicability of stress concentrations(14). First, there are no stress concentrations for stresses parallel with alined cylindrical pores of any cross sectional shape. However, there is clearly a reduction of properties (in proportion to the reduced area), despite the absence of such concentrations. This supports an area basis for modeling and seriously questions a controlling role of stress concentrations. Second, is the issue of whether the maximum or integrated average stress concentration is most important. While the maximum concentration is important, there are compressive components which greatly reduce average concentrations. Third, is the fact that peak stress concentrations vary significantly with stress state, e.g. are progressively less going from uniaxial flexure to true tension, to biaxial tension to uniaxial compression(14).

For non dilute porosity cases (which becomes significant at P as low as 5-10%) there is the important issue of interaction of stress concentrations from adjacent pores(14). Much analysis shows that increasing pore interaction reduces the stress concentration level, commonly significantly, such that at highly interactive levels of porosity, the primary load carrying material of the body becomes the webs between the pores, i.e. the minimum solid area , Figs.2 &3(14)(which also suggests a connection to electrical and thermal conductivity discussed further later). This is consistent with the reduction of peak stress concentrations with increasing complexity of stress state as noted above in view of the complex stresses generated around pores, especially when they are not far from one another (e.g. center to center spacings < 2 pore diameters). Such interactions of stress concentrations raise questions regarding models based on such concentrations. Finally stressed based elasticity-porosity models generally give limited, or no, direct clues of their relation to other mechanical properties, or other properties, e.g. electrical and thermal conductivity.

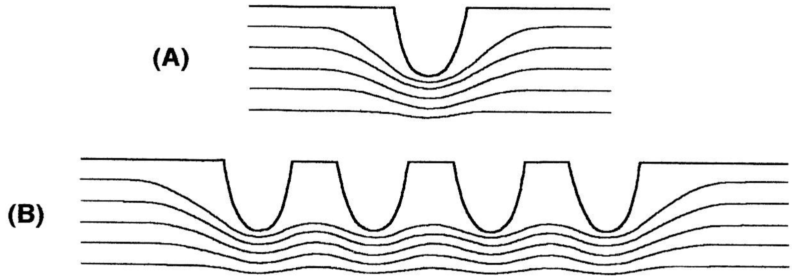

Figure 2) Schematic showing that as the density of notches (which can also be viewed as half pores, i.e. exposed at the surface) or holes increases relative to the specimen dimensions, the stress concentration decreases, i.e. the load becomes almost totally carried by the remaining solid web, which is the MSA (see Fig.3 for definition).The effect of notches, hence of porosity, on flux lines for electrical or thermal conductivity is the same or very similar.

The above issues manifest themselves in experimental inconsistencies with stress based models. Thus, there is no evidence that porosity effects vary with the differing stress concentrations of different stress statse. In fact in the one case of porosity effects on mechanical properties possibly depending on stress state, i.e. tensile vs compressive strength, the trends are opposite those for correlation with stress concentrations. Thus, despite lower stress concentrations in compressive versus tensile loading, the former gives the same or higher porosity dependence(2,6). Further, while there is some correlation between pore stress concentrations and porosity dependance of elastic properties, there are significant deviations, with minimum solid area models giving more consistent results(15). More generally, these stress-based models have not shown guidance for handling different , or mixed porosities. Also, the most widely used of these models has been shown to be less accurate for composites, on which it's derivation is based(11).

Minimum Solid Area Models

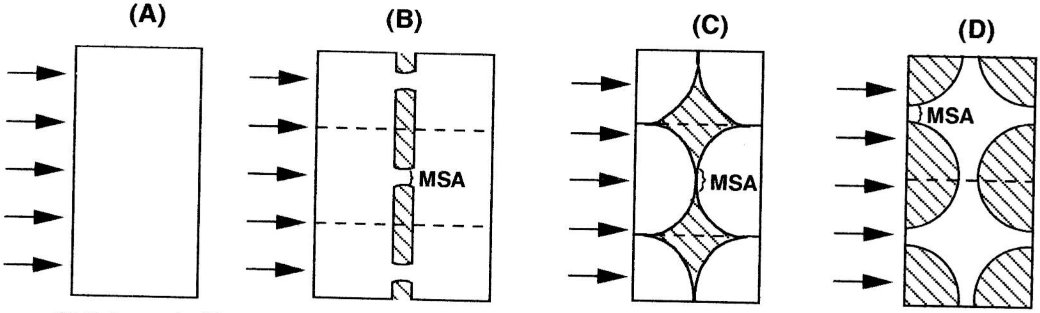

Figure 3) Schematic illustrating the rational and definition of minimum solid area (MSA). A) shows a uniform body on which a uniform stress or flux of electrons or phonons is impinging. Since the body is uniform the average and minimum solid areas are equal so no differentiation is needed. B) shows a body with isolated pores (cross hatched areas) where the MSA is defined, and clearly is a major factor controlling the transmittal of the stress or flux. C) and D) show respectively the MSA for idealized bodies respectively of bonded uniform spherical particles or an idealized foam (cross hathed ares are the pores).

A basic, but seldomly addressed, issue is what parameter(s) to use for properties dependant on pore character. Parameters such as the amount or degree of open and closed porosity; the coordination number (of the particles defining the pores, the pores themselves, or both), pore size, pore shape; and minimum solid area have been suggested. Until recently there was no systematic evaluation which of these were appropriate and practical parameters. However, use of idealized models; i.e. of bodies of regular stacking of uniform spherical particles or pores, shows that of these parameters only minimum solid area (Fig.3) and pore shape encompass all of the characteristics needed(3). Both reflect the extent of open and closed porosity and it's coordination along with that of the surrounding particles, as well as of each other. However, pore shape was seen as including some extraneous information, and being much more difficult to define and measure. Thus, minimum solid area was seen as a practical parameter that was appropriate for properties dependant on the solid phase, i.e. the stress or flux in it.

The solid cross sectional area normal to the reference (i.e. stress or conduction) direction (Fig.2) clearly must correlate with many mechanical properties, as well as those of conduction through the solid phase. Both average and minimum solid areas (which are the same for the reference direction normal to alined cylindrical, or prismatic, pores of any cross section) might be considered. However, it is generally assumed that the cross sectional areas of prime control and interest are the minimum, rather than average, solid area (Fig.3). Various models have been derived over the years for various idealized pore geometries (Fig.4), assuming that various mechanical properties directly correlate with the minimum solid areas calculated (from geometry, assuming pores of uniform ,size, shape, and stacking(s) of the shape selected)(1-3,16). The individual models for a fixed ,idealized, pore shape were basically derived in isolation, i.e. uncoordinated with other similar models, and were initially seen as potentially representing a range of (unspecified) real porosity beyond their immediate shape. However, it was subsequently shown that these models collectively reflected the significant porosity-property variations over the range of real porosity(1-3,16). Thus pores between various stackings of particles reflect more rapid property decreases and lower P_C values as the particle stacking becomes denser. Spherical and various orientations of cubic pores reflect respectively bubbles and more angular voids (e.g, from burn-out of irregular particles) with intermediate to lower initial property decreases and intermediate to high P_C with increasing P. Cylindrical pores represent more elongated pores having the lowest, or an intermediate, property decrease with P and respectively intermediate or high P_C values, depending on the stress or flux axis being parallel or perpendicular to the alined cylindrical pores. It is also clear that these models all have the same basic property-P shape and

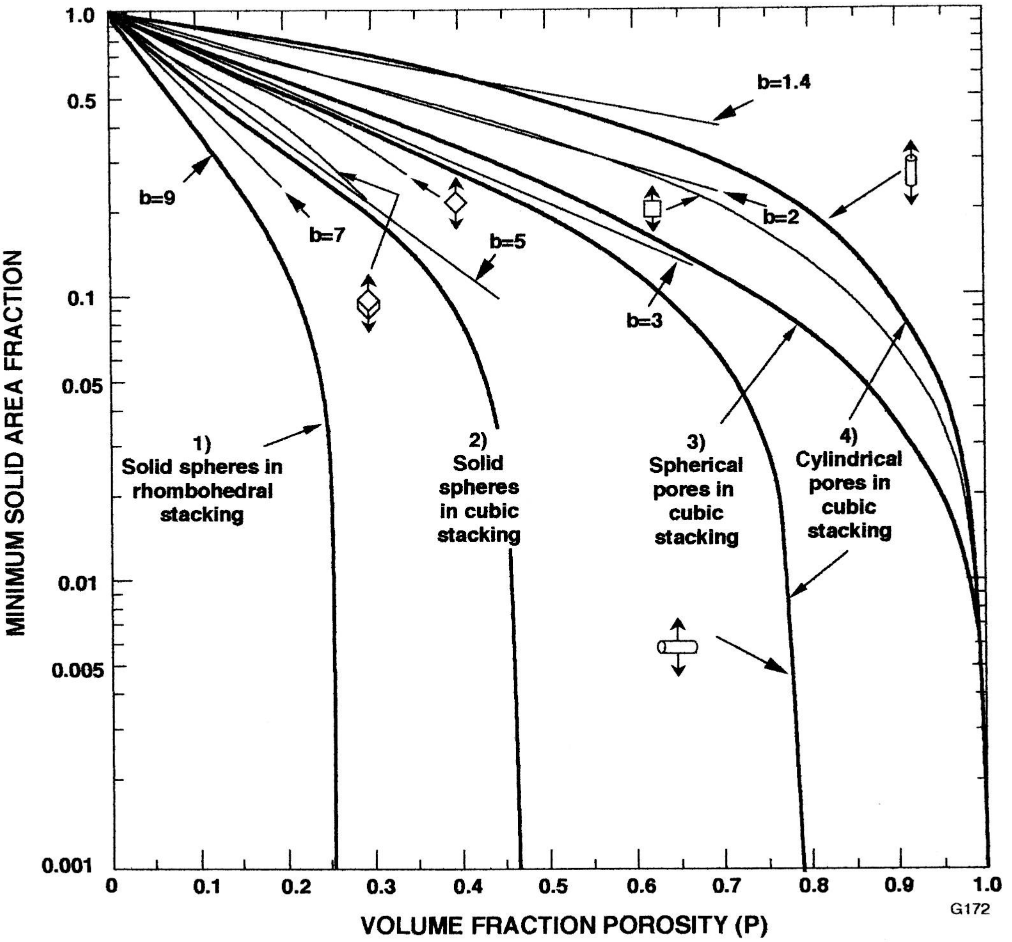

Fig. 4) Calculated MSA for various indicated pore geometries. Appropriate properties will simply be the value at P =0 times the MSA at the appropriate P. Note also: 1) because of the siomilarity in shape, curves for combinations of different porosity can be obtained by interpolation between the curves (based on a rule of mixtures), and 2) the curves show the same basicrange and character of shapes as shown by data (Fig.1).

cover the range of property-P variations reflected by data (Fig.1). Because of the basic similarities in shape of the curves for various pore types, it is reasonable to combine them by simplerule of mixtures interpolation between the curves representing the appropriate pore constituents of the porosity present in a given body(1,2). Since such interpolation can , in principle, be done for any combination of the different porosity, it also allows for changing porosity. However, note that there is sufficient variation in the property (minimum solid area) - P curves that a simple expression such as $(1-P/P_C)^n$, where the exponent n is a variable, cannot accurately fit them all. Further, based both on the areal dependance of conductivity and the similarity of stress and conductive flux contours (Fig.2) the models were assumed to be applicable to electrical and thermal conductivity respectively at any temperature or other conditions where solid conduction dominates (i.e. where radiation, convective, or fluid transport across pores is not significant). This assumption of similar mechanical and conductive properties provides an additional check on the models. This check has proved positive(1,2), thus providing a significant extension of their use of MSA models.

Collectively the above minimum solid area model approach is in many respects the mirror image of the stress based approach of the previous section. Thus, it is much more rigorous in it's treatment of porosity, i.e. shape, stacking, mixes, and changes, but is less rigorous in it's mechanics. On the other hand, while a correlation of mechanical (and conductive) properties with minimum area is expected, how accurate this correlation is for various properties and porosities (both quantity and character) cannot be explicitly determined from the models. Thus, considering only the minimum solid area normal (not parallel) to the reference direction is logical for a uniaxial stress (or conduction), i.e. to give Young's modules, and uniaxial tensile or compressive strengths. However, the correlation with minimum solid area is more uncertain for more complex stackings of pores or particles, and for shear and multiaxial stressing ,i.e. shear and bulk moduli, and multiaxial strengths. The applicability of these minimum solid area models, as with stress-based, and other models must thus be judged by extensive comparison with data, as noted earlier.

Comparison of Models and Porosity-Property Data

Some, but not extensive comparison of local stress based models has been made(9,10) at 22 C, but no correlation of it's fitting data as a function of pore character has been made. In fact the range of pore character it has been evaluated against has been limited. Thus, though not given by the investigators(10), the average b value for the bodies evaluated was ~3±1, consistent with approximately spherical porosity(2). Further, the impact of the effectively data or "curve" fitting adjustment , i.e. convergence, of Poission's ratio on the data-model agreement, and how realistic the resultant Poission's ratio values are has not been examined at all, other than the question of the convergence of Poission's ratio(12,13).

Minimum solid area (MSA) models have recently been shown to agree with the more limited mechanical and conductive property data for bodies with pores approximating some of the idealized models(1) and with extensive ceramic and more limited metal data for normal porosities covering a diversity of compositions and processing(2). The data for bodies made partly, or totally, with tubular or spherical pores (including foam materials), or ceramic balloons, as well as spherical particles generally agreed in both overall property-P curve shape, as well as in specific parameters, i.e. initial slopes (b values), and the roll over P range and P_C values of appropriate MSA models. This agreement encompassed SiO_2- based glass, polycrystalline ceramic, and plastic materials, and metals for Young's modules, both tensile and compressive strength, as well as hardness, and thermal and electrical conductivity at 22 C. (There were some deviations for strength and hardness, and especially fracture toughness, as discussed further later, as will limited higher temperature results.) The overall agreement demonstrated that variation in the spherical or tubular pore size, or the size of spherical particles had little, or no, effect so long as there was reasonable homogeneity (discussed further latter) and they were smaller than the flaw size controlling strength. It also shows that random stacking of pores or particles is approximately the same as simple cubic stacking, as expected both theoretically and experimentally(1,2).

Detailed comparison of the much larger data base for ceramics and other materials with normal porosities is prevented by the almost complete absence of any porosity characterization beyond the amount of porosity, i.e. P. However, of the order of half of the porosity studies give enough basic processing