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Comparing the observed[1-3] effect of porosity on Young's modulus of elasticity of polycrystalline brittle materials with the theoretical effect[4-7] of spherical pores generally a large discrepancy is obtained. Recently Hashin and Rosen[8] calculated the elastic properties of matrices containing arrays of parallel cylindrical fibers. In Hashin and Rosen's solutions, setting the elastic properties of the fibers identically equal to zero allows a new estimate to be made of the effect of porosity on elastic properties. As expected, introducing parallel cylindrical pores in a matrix results in considerable elastic anisotropy. Young's modulus parallel to the pores follows the law of mixtures. Hashin and Rosen results[*] perpendicular to the pores are expressed in terms of a bulk modulus and upper and lower bounds for the shear modulus, from which upper and lower bounds for Young's modulus can be computed directly.[+] Figure 1 illustrates the results for a matrix with Poisson's ratio (υ) = 0.25. For comparison included in the figure are the upper and lower bounds for a matrix ($\upsilon = 0.25$) containing spherical pores. Also included are the experimental data for alumina as compiled by Knudsen[9] expressed in terms of the exponential equation of Spriggs[2] given by $E = E_o e^{-3.95P}$, where E and E_o are Young's modulus of the porous and nonporous body, respectively, and P is the porosity. The results in

Fig. 1 indicate that the predicted curves for cylindrical porosity fall well below those for spherical porosity. But for a narrow region at low porosity, the experimental curve falls between the upper and lower bound for cylindrical porosity. For porosities less than about 15% the discrepancy between the experimental curve and the lower bound for the cylindrical porosity amounts to no more than a few percent.

The lower bound for cylindrical porosity can be superposed on Knudsen's compilation. From zero to approximately 15% porosity there are as many data points on one side of the curve as on the other. This suggests good agreement between experiment and theory over this range of porosity.

In experimental bodies, manufactured by sintering or hot-pressing, at least part of the porosity can be considered to be cylindrical, especially at higher porosities where the pores tend to be interconnected (open porosity) rather than isolated (closed porosity). Considering this and the results presented in Fig. 1 suggests that a matrix containing parallel cylindrical pores oriented perpendicularly to the applied stress might represent a better mechanical model for the prediction of the effect of porosity on Young's modulus of sintered or hot-pressed specimens, than a matrix containing spherical pores.

Table I lists computer results for upper and lower bound shear modulus.

FOOTNOTES AND REFERENCES

This work was done under the auspices of the U. S. Atomic Energy Commission.

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2. R. M. Spriggs, "Expression for Effect of Porosity on Elastic Modulus of Polycrystalline Refractory Materials, Particularly Aluminum Oxide," J. Am. Ceram. Soc., 44 [12] 628-29 (1961).
3. D. P. H. Hasselman, "On Porosity Dependence of Elastic Moduli of Polycrystalline Refractory Materials," J. Am. Ceram. Soc., 44 [9] 452-53 (1961).
4. J. M. Dewey, "Elastic Constants of Materials Loaded with Non-Rigid Fillers," J. Appl. Phys., 18 [6] 578-81 (1947).
5. I. K. MacKenzie, "The Elastic Constants of a Solid Containing Spherical Holes," Proc. Phys. Soc. (London), B63, 2-11 (1950).

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7. Z. Hashin, "Elastic Moduli of Heterogeneous Materials," J. Appl. Mech., 29 [1] 143-50 (1962).

8. Z. Hashin and B. W. Rosen, "The Elastic Moduli of Fiber-Reinforced Materials," J. Appl. Mech., 31 [2] 223-32 (1964).

* Hashin and Rosen's solutions are too complex to be repeated here. The reader is referred to the original paper (reference 8).

† Equations 17 and 89 from reference 8.

9. F. P. Knudsen, "Effect of Porosity on Young's Modulus of Alumina," J. Am. Ceram. Soc., 45 [2] 94-95 (1962).

Table I. Upper and lower bounds of shear modulus of matrices containing cylindrical pores

Porosity	Upper bound	Lower bound
0.05	0.8715	0.8445
0.10	0.7730	0.6864
0.15	0.6923	0.5379
0.20	0.6229	0.4076
0.25	0.5612	0.3000
0.30	0.5048	0.2152
0.35	0.4523	0.1508
0.40	0.4028	0.1034
0.45	0.3557	0.0694
0.50	0.3108	0.0455
0.55	0.2680	0.0289
0.60	0.2275	0.0178
0.65	0.1892	0.0105
0.70	0.1535	0.0058
0.75	0.1204	0.0030
0.80	0.0903	0.0014
0.85	0.0632	0.0005
0.90	0.0391	0.0001
0.95	0.0181	0.0000

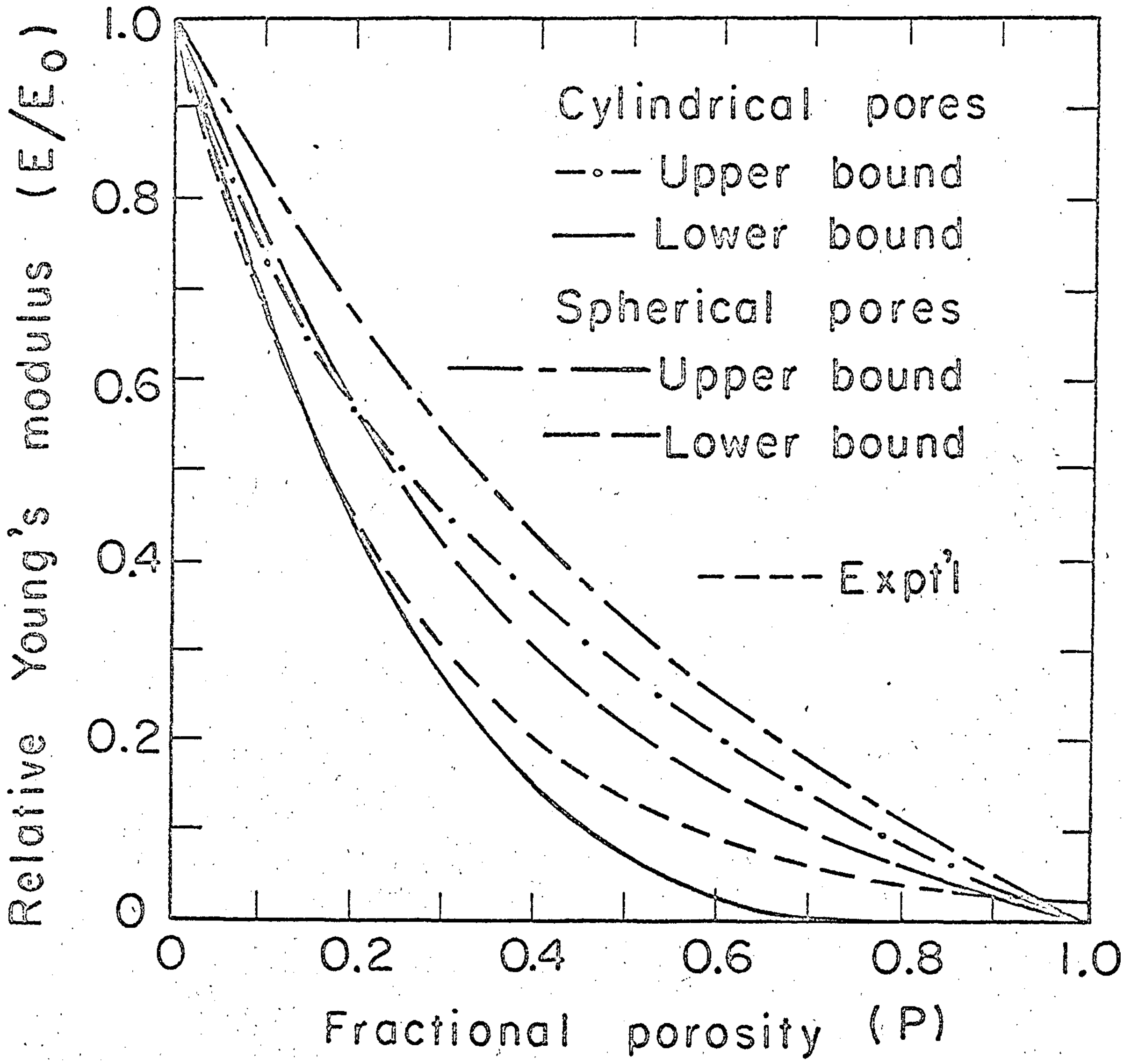

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Fig. 1. Calculated and observed effect of porosity on Young's modulus.