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This note compares published theoretical expressions[1-4] for the elastic moduli of two-phase systems with experimental results obtained for a sodium borosilicate glass containing dispersions of spherical tungsten particles. The glass used was of the same composition as the D-glass (16% Na_2O, 14% B_2O_3, 70% SiO_2) used in previous investigations.[5,6] The techniques of specimen preparation and measurement of Young's modulus were identical to those employed for the D-glass containing angular dispersions of alumina.[6 *] Tungsten particle size was approximately 30μ. Figure 1 shows the microstructure of a glass-tungsten composite containing 40 volume percent tungsten. Table I gives the experimental and theoretical results, which are also illustrated in Fig. 2. For the theoretical calculation, glass property values were taken as Young's modulus = 805 kilobars[6] and Poisson's ratio = 0.197.[5] Tungsten elastic properties were taken as Young's modulus = 3550 kilobars[7] and shear modulus = 1481 kilobars.[7] Young's modulus for the predictions of Kerner,[1] Hashin and Shtrikman,[3] and Hashin[2] were calculated from the

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corresponding equations for the bulk and shear modulus. Kerner's predictions coincided with Hashin's approximate equation for spherical phase geometry and Hashin and Shtrikman's lower bound for arbitrary phase geometry. Experimental results fall between Hashin's upper bound for spherical phase geometry and Hashin and Shtrikman's lower bound for arbitrary phase geometry, in agreement with theory. It is of interest to note here that similar results were obtained for the same glass containing angular dispersions of sapphire.[6] It, therefore, appears that for this type of two-phase system, composed of a matrix containing random dispersions with Young's modulus higher than the matrix, dispersion shape, at least macroscopically, plays little or no role.

REFERENCES AND FOOTNOTES

1. E. H. Kerner, "Elastic and Thermoelastic Properties of Composite Media," Proc. Phys. Soc. (London), B69, 808-13 (1956).

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

4. Z. Hashin and S. Shtrikman, "A Variational Approach to the Theory of the Elastic Behavior of Multiphase Materials," J. Mechanics and Physics of Solids, 11 [2] 127-40 (1963).

5. D. P. H. Hasselman and R. M. Fulrath, "Effect of Small Fraction of Spherical Porosity on Elastic Moduli of Glass," J. Am. Ceram. Soc., 47 [1] 52-53 (1964).

6. D. P. H. Hasselman and R. M. Fulrath, "Calculated and Observed Effect of Alumina Dispersions on Young's Modulus of a Glass," J. Am. Ceram. Soc., 47 [4] 218 (1965).

* Attempts to investigate the effect of spherical particles of alumina on the elastic properties of the glass were unsuccessful, due to the formation of some porosity in the alumina during spheroidization introducing uncertainties in the elastic properties of the alumina.

7. Handbook of Chemistry and Physics, 36th Ed., p. 1976. Chemical Rubber Publishing Co. (1954-55). 3173 pp.

Table I. Calculated and observed effect of spherical tungsten dispersion on Young's modulus of a sodium borosilicate glass (E_o = 805 kilobars)

Volume percent tungsten	Spherical phase geometry*			Arbitrary phase geometry+		Paul‡		Cubical inclusion	Observed
	Upper bound	Lower bound	Approximate§	Upper bound	Lower bound§	Upper bound	Lower bound		
10	918	907	914	982	914	1080	870	1001	909 ± 14**
20	1053	1015	1039	1172	1039	1354	953	1186	1055 ± 11
30	1206	1137	1182	1359	1182	1629	1049	1388	1180 ± 2
40	1386	1289	1349	1598	1349	1903	1166	1545	1375 ± 3
50	1592	1479	1548	1850	1548	2188	1312	1760	1599 ± 5

* Reference 3

\+ Reference 4

‡ Reference 2

§ Identical to Reference 1

** Standard deviation

FIGURE LEGENDS

Fig. 1 Microstructure of a sodium borosilicate glass containing 40 volume percent tungsten.

Fig. 2 Experimental and theoretical results for Young's modulus of a sodium borosilicate glass matrix as a function of volume content of spherical tungsten particles.

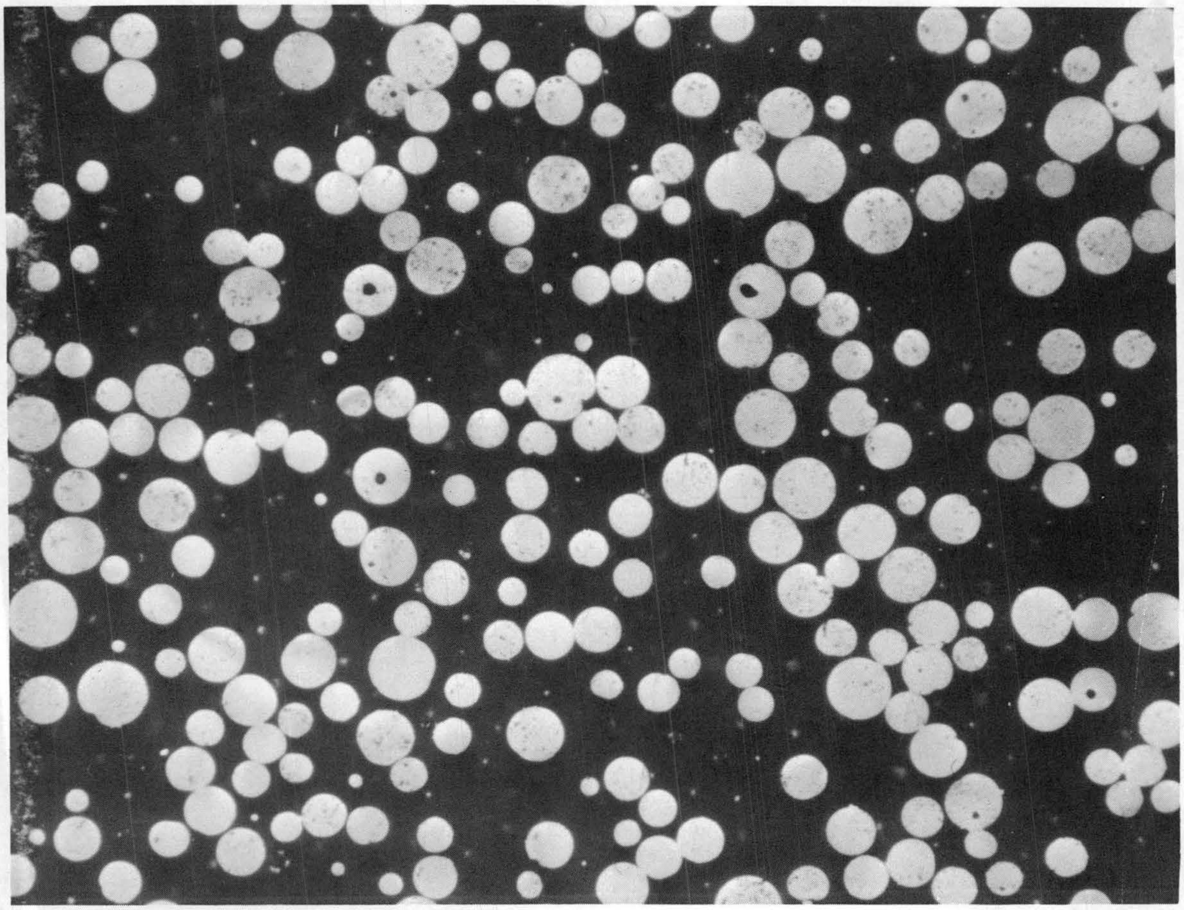

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Fig. 1

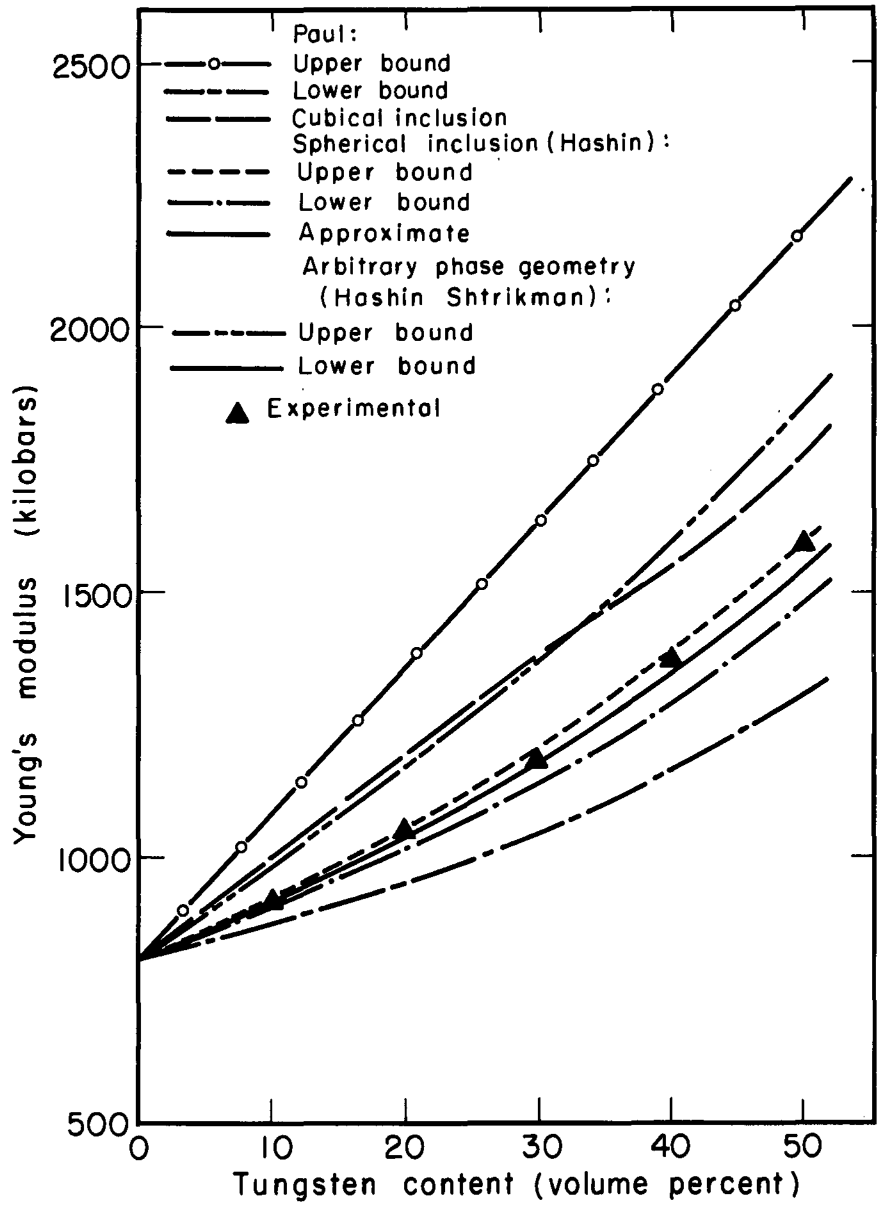

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Fig. 2