UNCLASSIFIED

AD NUMBER
AD883617
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; MAY 1971. Other requests shall be referred to Office of Naval Research, Washington, DC 20360.**
AUTHORITY
ONR ltr 13 Jan 1971

THIS PAGE IS UNCLASSIFIED

HPC 70-122

AD883617

AD No. ____
DDC FILE COPY

MONSANTO/WASHINGTON UNIVERSITY
ONR/ARPA ASSOCIATION

STRENGTH OF SHORT FIBER REINFORCED COMPOSITES

BY

R. E. LAVENGOOD

PROGRAM MANAGER
ROLF BUCHDAHL

MONSANTO RESEARCH CORPORATION
A SUBSIDIARY OF MONSANTO COMPANY
800 N. LINDBERGH BOULEVARD ST. LOUIS, MISSOURI 63166

BEST
AVAILABLE COPY

Security Classification

DOCUMENT CONTROL DATA - R & D

1. ORIGINATING ACTIVITY (Corporate author)

Monsanto Research Corp.

2a. REPORT SECURITY CLASSIFICATION

Unclassified

2b. GROUP

3. REPORT TITLE

Strength of Short Fiber Reinforced Composites

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

R. E. Lavengood, Monsanto Co., St. Louis, Mo.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
March 1971	31	9

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
N00014-67-C-0218	HPC 70-122
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT

This document is subject to [redacted] foreign nations [redacted] appr[redacted] of Material Sciences, Office [redacted]

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Office of Naval Research Washington, D. C. 20360

13. ABSTRACT

The structural utility of short glass fiber reinforced composites is experimentally investigated for fiber volume fractions from 0.15 to 0.5. The strength and stiffness of systems with randomly oriented fibers are compared with those of similar composites with aligned fibers. The ultimate strength of both types of material increases in a reasonably linear fashion with volume fraction. For all volume fractions, strength of the random composites is slightly higher than the longitudinal and much higher than the transverse strength of equivalent composites with aligned fibers. The modulus of the random system is approximately two-thirds the longitudinal and twice the transverse modulus of the unidirectional material. The structural utility of the flow molded material is greatest in uniaxial, stiffness critical situations. The greater strength and planar isotropy of the random composites make them preferable in all strength limited or multi-axial applications.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
composites						
strength						
aligned fibers						
random fibers						
off-axis properties						
modulus						

HPC 70-122

STRENGTH OF SHORT FIBER REINFORCED COMPOSITES

BY

R. E. LAVENGOOD

MARCH 1971

MONSANTO/WASHINGTON UNIVERSITY ASSOCIATION
HIGH PERFORMANCE COMPOSITES PROGRAM
SPONSORED BY ONR AND ARPA
CONTRACT NO. N00014-67-C-0218, ARPA ORDER 876
ROLF BUCHDAHL, PROGRAM MANAGER

MONSANTO RESEARCH CORPORATION
800 NORTH LINDBERGH BOULEVARD
ST. LOUIS, MISSOURI 63166

FOREWORD

The research reported herein was conducted by the staff of the Monsanto/Washington University Association under the sponsorship of the Advanced Research Projects Agency, Department of Defense, through a contract with the Office of Naval Research, N00014-67-C-0218 (formerly N00014-66-C-0045), ARPA Order No. 876, ONR contract authority NR 356-484/4-13-66, entitled "Development of High Performance Composites."

The prime contractor is Monsanto Research Corporation. The Program Manager is Dr. Rolf Buchdahl (phone 314-694-4721).

The contract is funded for $7,000,000 and expires 30 April 1972.

STRENGTH OF SHORT FIBER REINFORCED COMPOSITES

R. E. Lavengood

ABSTRACT

The structural utility of short glass fiber reinforced composites is experimentally investigated for fiber volume fractions from 0.15 to 0.5. The strength and stiffness of systems with randomly oriented fibers are compared with those of similar composites with aligned fibers. The ultimate strength of both types of material increases in a reasonably linear fashion with volume fraction. For all volume fractions, strength of the random composites is slightly higher than the longitudinal and much higher than the transverse strength of equivalent composites with aligned fibers. The modulus of the random system is approximately two-thirds the longitudinal and twice the transverse modulus of the unidirectional material. The structural utility of the flow molded material is greatest in uniaxial, stiffness critical situations. The greater strength and planar isotropy of the random composites make them preferable in all strength limited or multiaxial applications.

(Contribution HPC 70-122 from the Monsanto/Washington University Association sponsored by the Advanced Research Projects Agency, Department of Defense, under Office of Naval Research Contract No. N00014-67-C-0218, formerly N00014-66-C-0045.)

STRENGTH OF SHORT FIBER REINFORCED COMPOSITES

R. E. Lavengood

Introduction

There is currently a growing interest in composites reinforced with a two dimensionally random array of fibers. This is due in part to the expanding use of random mat and sheet molding compounds and also to the design simplifications permitted by the planar isotropy of these materials. The elastic properties of random composites have been investigated previously and can be readily predicted (1). The ultimate properties are subject to much more variation and yet have been studied less. The purpose of this investigation is to determine the potential strength of epoxy reinforced with randomly oriented glass fibers and to compare their structural utility with similar composites reinforced with aligned fibers.

Specimen Preparation

Random composites were prepared by vacuum impregnating Owens-Corning M-700 random glass fiber mat. Two matrix resins were used. The first, Epon 828* plus 20 phr Curing Agent Z*, is a relatively brittle material typical of the epoxy matrices normally used in fiber glass composites. The second, Epon 815* plus 66 phr Versamid 140**, is a more ductile resin which was

*Shell Chemical Co.

**General Mills

found in earlier studies to give better transverse composites and crossplies (2). The resin and curing agent are mixed thoroughly at room temperature and then heated to 50°C to reduce the viscosity. The water-like mixture is poured into a 2" x 6" compression mold which is preheated to 90°C. Four layers of random mat are placed on top of the resin and the mold is placed in a 90°C vacuum oven at 0.1 mm hg. for 20 minutes. The top of the mold is then put in place and the composite pressed for 30 minutes at 100°C and 40 psi followed by 60 minutes at 120°C and 100 psi. This rather complicated process was devised to produce specimens with very low void content and thoroughly wetted interfaces. The actual void content was below the resolution limit of the commonly used gravimetric technique. The transparency of the 1/8" thick, 20 v/o sample shown in Figure 1 is probably the best indication of the overall quality of this material.

The aligned fiber samples were prepared by extruding molding compound into oriented, "B" staged, rods and then compression molding the rods. The matrix resin was Epon 828 plus 30 phr methylene dianiline. This material has mechanical properties similar to those of the 828/Z used with the random systems. The molding compound contained 50 volume percent of 1/8 inch long glass fibers. This loading level and the fiber length were shown in earlier studies to give optimum properties in flow molded specimens.

More specific details about the preparation of the molding compound are given in Reference 4.

Tensile specimens were 1/2 inch wide strips, 6 inches long, with a 3 inch gage length. A constant crosshead speed of 0.02 inches per minute was used and strains were monitored with a 2 inch strain gage extensometer. All tests were run at 23°C.

Test Results and Discussion

Typical tensile stress-strain curves for composites with different volume fractions of glass fibers are shown in Figure 2. The curves for the filled materials are all essentially linear to failure and all terminate between one and two percent elongation.

The effect of fiber volume fraction on strength is shown more clearly in Figure 3. The line is a least squares fit of the data and serves to emphasize the linear increase in strength with increasing volume fraction. The equation of this particular line is

$$\sigma = 10.5 + 59.6\,\phi \tag{1}$$

where σ and ϕ are strength and fiber volume fraction, respectively.

Existing theories predicting the strength of random composites are based on the assumption that strength is an additive property. This implies that the strength of a random composite will be equal to the average of the strength vs. orientation angle for a similar unidirectional composite. This approach seems to have been originated by Horio and Onogi (5) who used an improper transformation equation to derive the following expression:

$$\sigma = (\sigma_1 \quad \sigma_t)^{1/2} \qquad (2)$$

where σ_1 and σ_t are the longitudinal and transverse strengths of an equivalent unidirectional composite.

More recently, Lees (6) derived the following equation:

$$\sigma = \frac{2\tau}{\pi}\left(1 + \frac{\sigma_t}{\sigma_m} + \ln \frac{\sigma_t \sigma_m}{\tau^2}\right) \qquad (3)$$

where τ = composite shear strength

and σ_m = matrix stress at ultimate composite elongation.

With a similar approach, Chen (7) concludes that the predictive equation should be:

$$\sigma = \frac{2\tau}{\pi}\left(2 + \ln \frac{\xi\, \sigma_c \sigma_m}{\tau^2}\right) \qquad (4)$$

where σ_c = the rule of mixtures strength for an equivalent unidirectional composite

ξ = a strength efficiency factor which relates the strength of a unidirectional short fiber composite to the rule of mixtures prediction.

Evaluation of these equations is complicated because all the terms vary with volume fraction. The calculation of σ_c is straightforward and, for an upper bound approximation, we can let ξ equal to one. An estimate of σ_m can be obtained from the data in Figure 2. The last two terms are more difficult to estimate; however, it has been shown that τ and σ_t are about the same for glass epoxy composites. While there are no reliable techniques for predicting σ_t, the transverse strengths of composites with a similar matrix are available in the literature (8,9). The values of σ_c, σ_m, and σ_t, thus determined, are listed in Table 1. These were substituted into equations 2, 3 and 4 to obtain the curves shown in Figure 4. These may be compared with the curve for equation 1, which represents the experimental data. It is apparent that equations 2, 3 and 4 do not adequately predict the strength of these composites.

The series of composites with Epon 815/Versamid matrix was prepared with the expectation that the ductility of the matrix and the improved adhesion would lead to higher strength composites. The experimental results in Figure 5 show that this did not occur. The strengths of the composites are essentially the same for both matrices. This implies that the fracture is not initiated by failure of the matrix or interface. The other possible source of crack initiation is tensile fracture of the glass fibers.

Fiber stress will be greatest in those fibers which are aligned with the axis of the specimen. Since glass is linearly elastic to failure, the ultimate stress of these fibers can be estimated as follows:

$$\sigma_g = E_g \, \varepsilon_c \tag{4}$$

where σ_g = maximum fiber stress

E_g = modulus of the fibers (i.e., 10.5×10^6 psi)

and ε_c = ultimate composite strain.

The data for the 828/Z composites were used to calculate the fiber stress values shown in Figure 6. The apparent strength of most of these fibers is between 150 and 200 ksi. The maximum value of 220 ksi is about 60% of the strength normally associated with E glass roving and is reasonable for glass that has been chopped (by the manufacturer) and converted to mat. The tendency for the fiber strength to decrease with increasing volume fraction can be attributed to the fiber damage due to compaction during the molding cycle.

This behavior is in striking contrast to that of composites reinforced with aligned short fibers. A previous study of composites in which the reinforcing fibers were oriented by flow processing showed that the strength of such materials does not reflect fiber strength. The completely different fracture patterns characteristic of random and aligned systems are shown in Figure 7. The crack propagates directly across the random fiber specimen, normal to the applied stress, as if the material were homogeneous. Both fibers and matrix are broken in the process. The jagged fracture surface of the aligned system results from a crack propagating along and between fibers which are slightly misoriented (3). In this case, the fracture is confined to the matrix and interface so the strength of the glass fibers cannot contribute directly to composite strength.

The longitudinal strength of composites with oriented fibers is shown in Figure 8 along with the "least squares" line for the strength of random composites (i.e., Eq. 1). Over the entire range of volume fractions, the strength of the composites are about the same for both orientations. This unexpected result must be regarded as fortuitous since the failure mechanisms are so different.

Despite the above result, from a strength viewpoint the structural utility of these composites is not the same because of the anisotropy of the unidirectional composites. The low transverse strength of such materials greatly complicates design when multiaxial loads are present. Strength as a function of angle for random and aligned composites with 50 volume percent fibers are compared in Figure 9. Although the strengths are similar in the axial direction, the random composites are clearly superior in all other directions. Specifically, the transverse strength of the oriented composites is less than 1/6 that of the random composites.

A comparison of the potential usefulness of these composites must also consider their relative stiffnesses, and again anisotropy is important. The modulus as a function of angle for the same 50 volume percent random and aligned composites is shown in Figure 10. In this case neither of the composites is clearly superior. The tensile modulus of the random system is about two-thirds the longitudinal and twice the transverse modulus of the unidirectional material. The preference for one material over the other, on the basis of modular properties, would therefore depend on the application. In uniaxial applications the oriented material would be superior, while multiaxial applications would favor the random composites.

Summary and Conclusions

The strength of composites reinforced with randomly oriented glass fibers increases linearly with volume fraction. Maximum strengths of 35 to 42 ksi are achieved with 50 volume percent fibers. At loading levels above 50 percent the strength decreases due to extreme fiber damage. For all loading levels, the strength of the random composites is somewhat greater than that of equivalent composites in which the reinforcing fibers were aligned by flow processing. This, coupled with the planar isotropy of the random composites, makes them superior to the aligned system for all strength limited applications. Composites with aligned fibers are best suited for uniaxial situations in which the high longitudinal stiffness can be utilized.

Acknowledgment

The author wishes to express his gratitude to Messrs. C. N. Rasnick and W. J. Neff for their assistance in the experimental phase of this study.

This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by the Office of Naval Research under Contract No. N00014-67-C-0218.

REFERENCES

1. Lavengood, R. E. and Goettler, L. A., in preparation.
2. Ishai, O. and Lavengood, R. E., Israel J. of Tech., Vol. 8, No. 1-2, 1970, pp. 101-109.
3. Holladay, H. P. and Calfee, 24th Annual S.P.I. Technical Conference, Reinforced Plastic Division, Section 15-C, 1969.
4. Andersen, H. M. and Morris, D. C., 23rd Annual Technical S.P.I. Conference, Reinforced Plastics/Composites Division, Section 17-E, 1968; (AD 869813).
5. Horio, M. and Onogi, S., J. of Applied Physics, Vol. 22, No. 7, July 1951, pp. 971-977.
6. Lees, J. K., Polymer Engineering and Science, Vol. 8, No. 3, July 1968, pp. 195.
7. Chen, P. E., Fourth Annual Symposium on High Performance Composites, April 8-9, 1969; (AD 855272).
8. Tock, R. W. and McMackins, D. E., 67th National A.I.Ch.E. Meeting, February 1970; (AD 865291).
9. Ishai, O. and Lavengood, R. E., 24th Annual Technical S.P.I. Conference, Reinforced Plastics/Composites Division, 1969, Section 11-F; (AD 848752).

TABLE 1

v/o	σ_c	σ_m	σ_t
0	10.5	10.5	10.5
10	34.5	--	4.0
20	58.5	4.9	4.2
30	82.4	4.6	4.3
40	106.3	4.5	5.4
50	130.3	4.1	5.5
60	154.2	3.0	6.4

LIST OF FIGURES

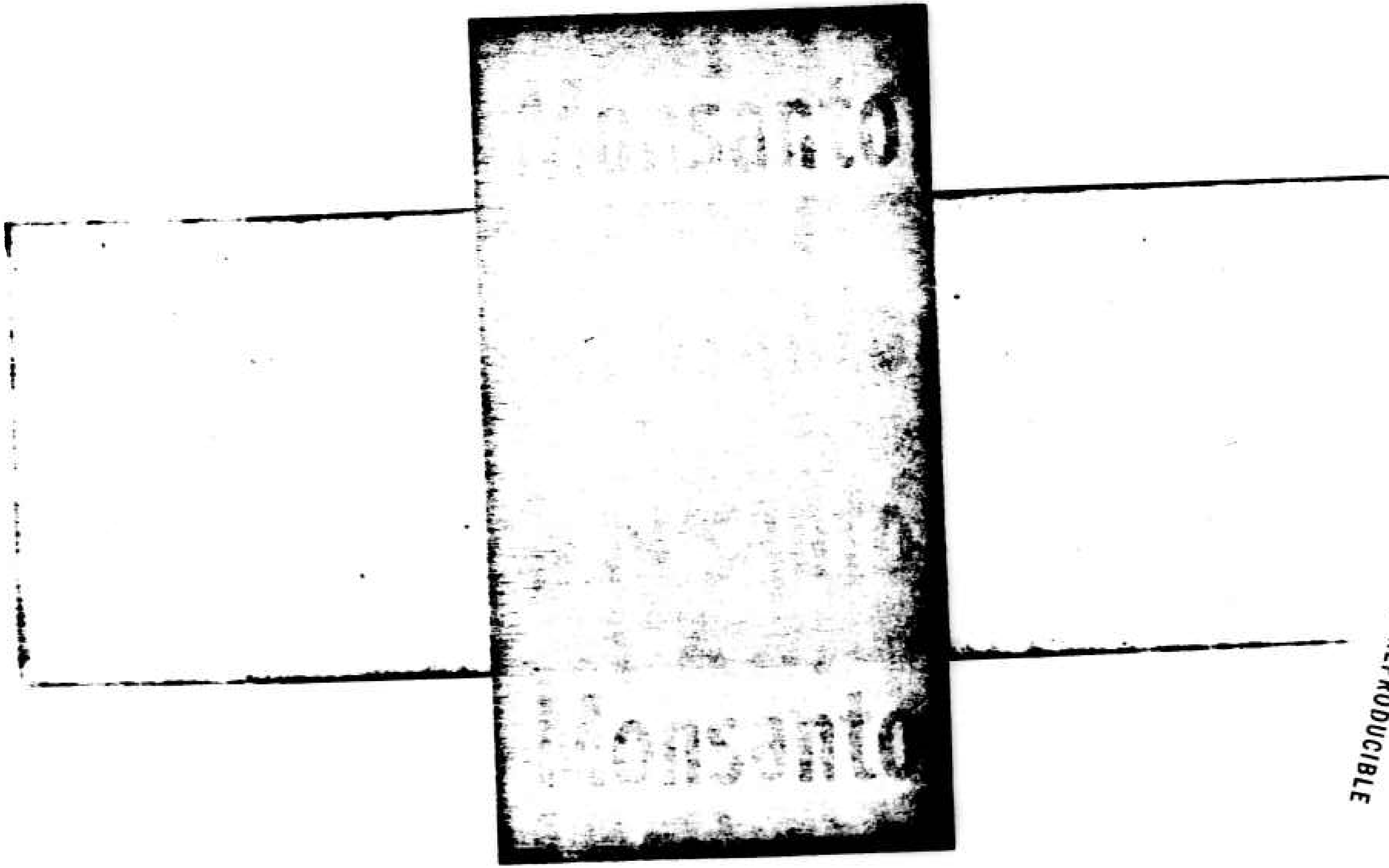

Figure 1. Typical 1/8" thick composite containing 20 volume percent of random glass fiber.

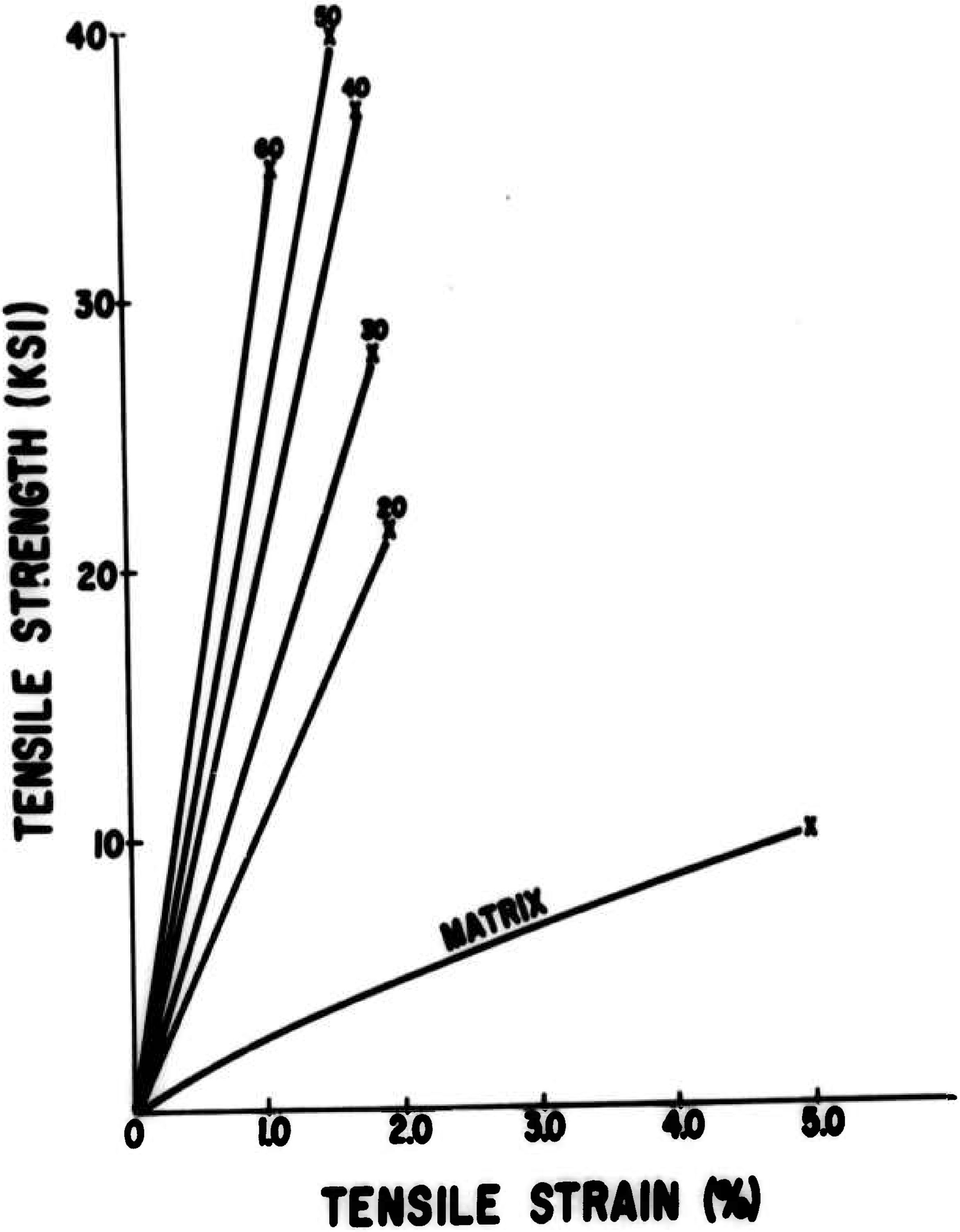

Figure 2. Typical stress-strain curves for composites showing the effect of filler loading level on mechanical performance. The numbers at the ends of the curves indicate the volume percent of glass fibers.

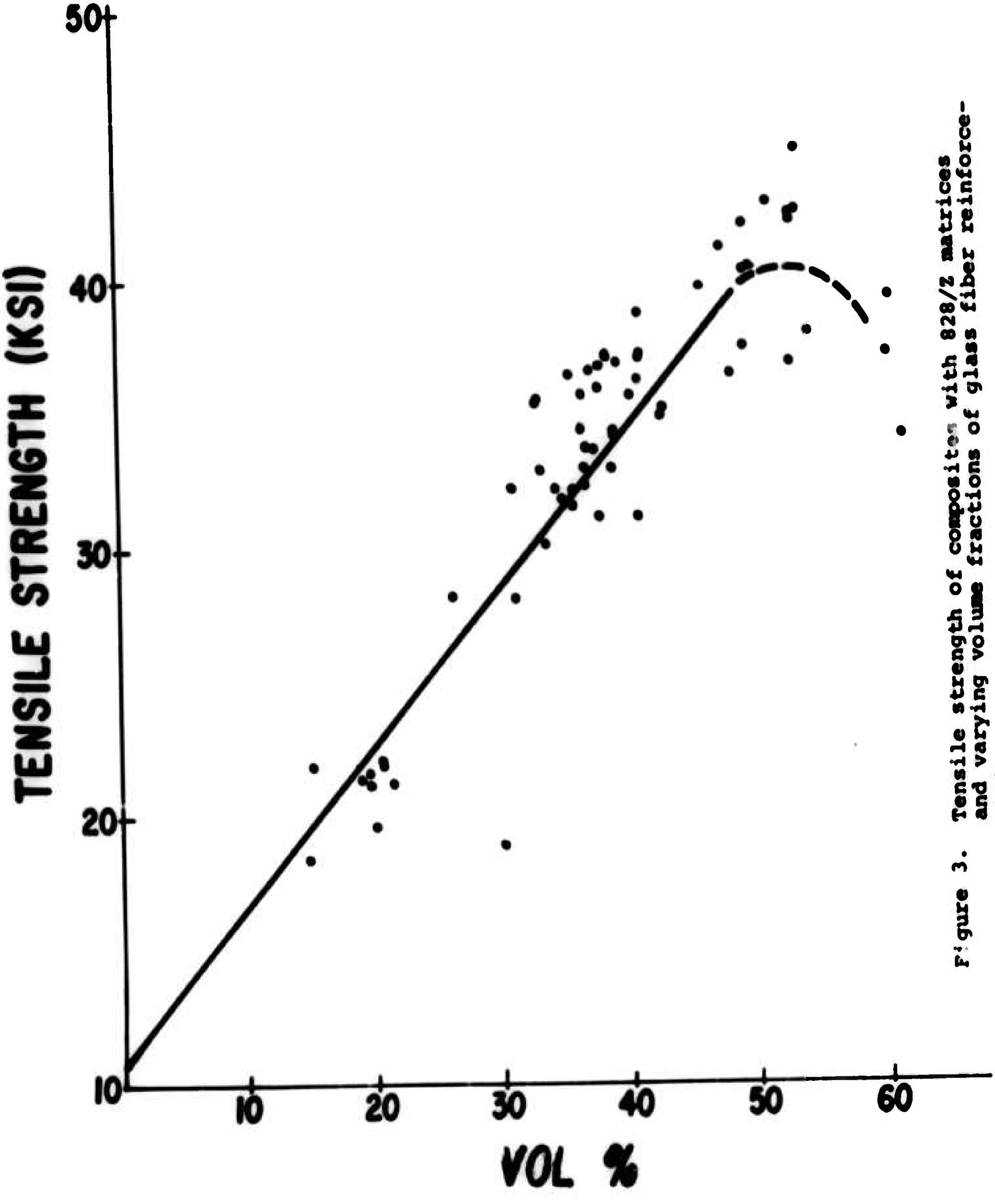

Figure 3. Tensile strength of composites with 828/Z matrices and varying volume fractions of glass fiber reinforcement.

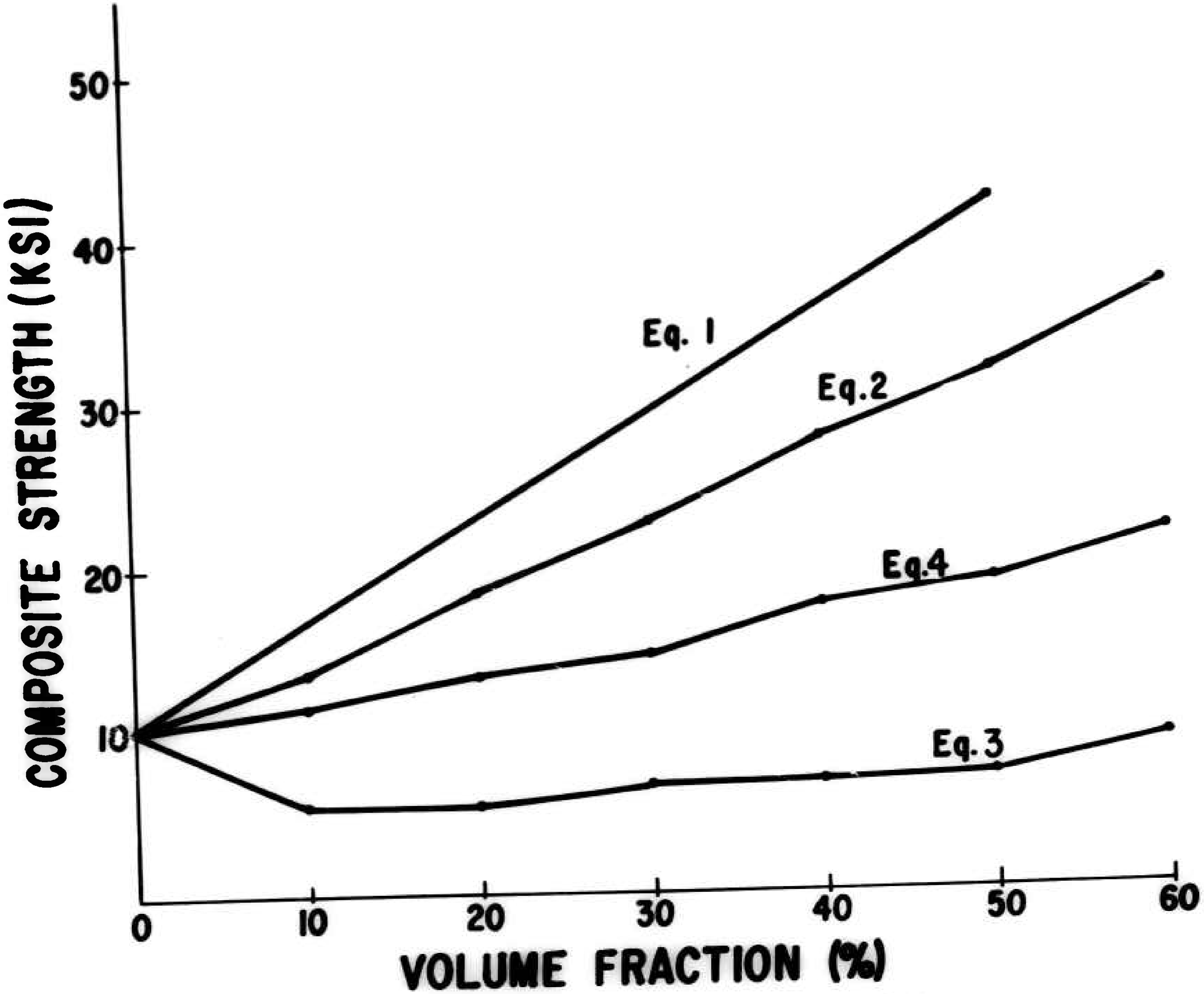

Figure 4. A comparison of experimental data (Eq. 1) with predictive equations for the strength of random composites.

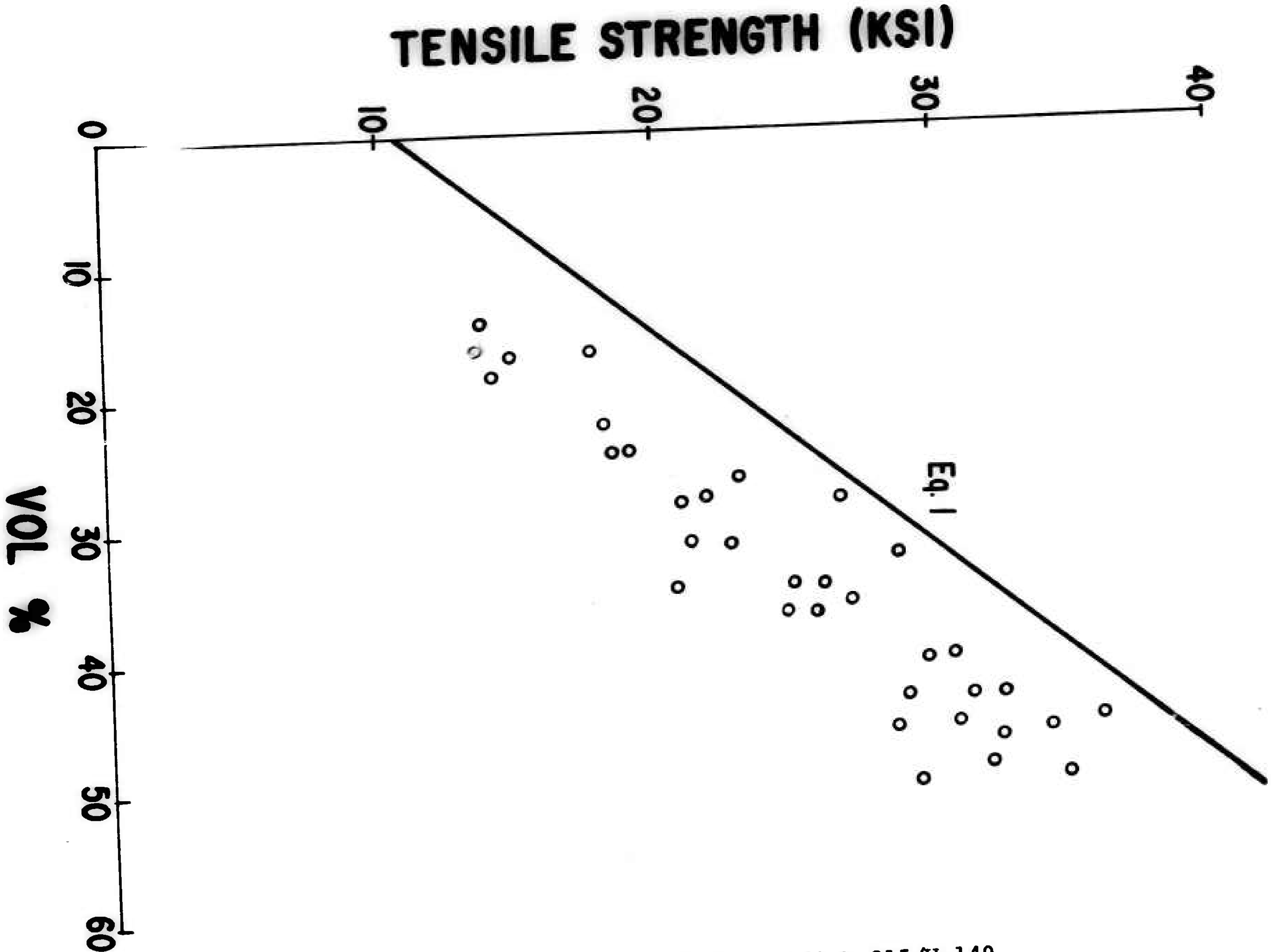

Figure 5. Tensile strengths of composites with 815/V-140 matrices and varying volume fractions of glass fibers.

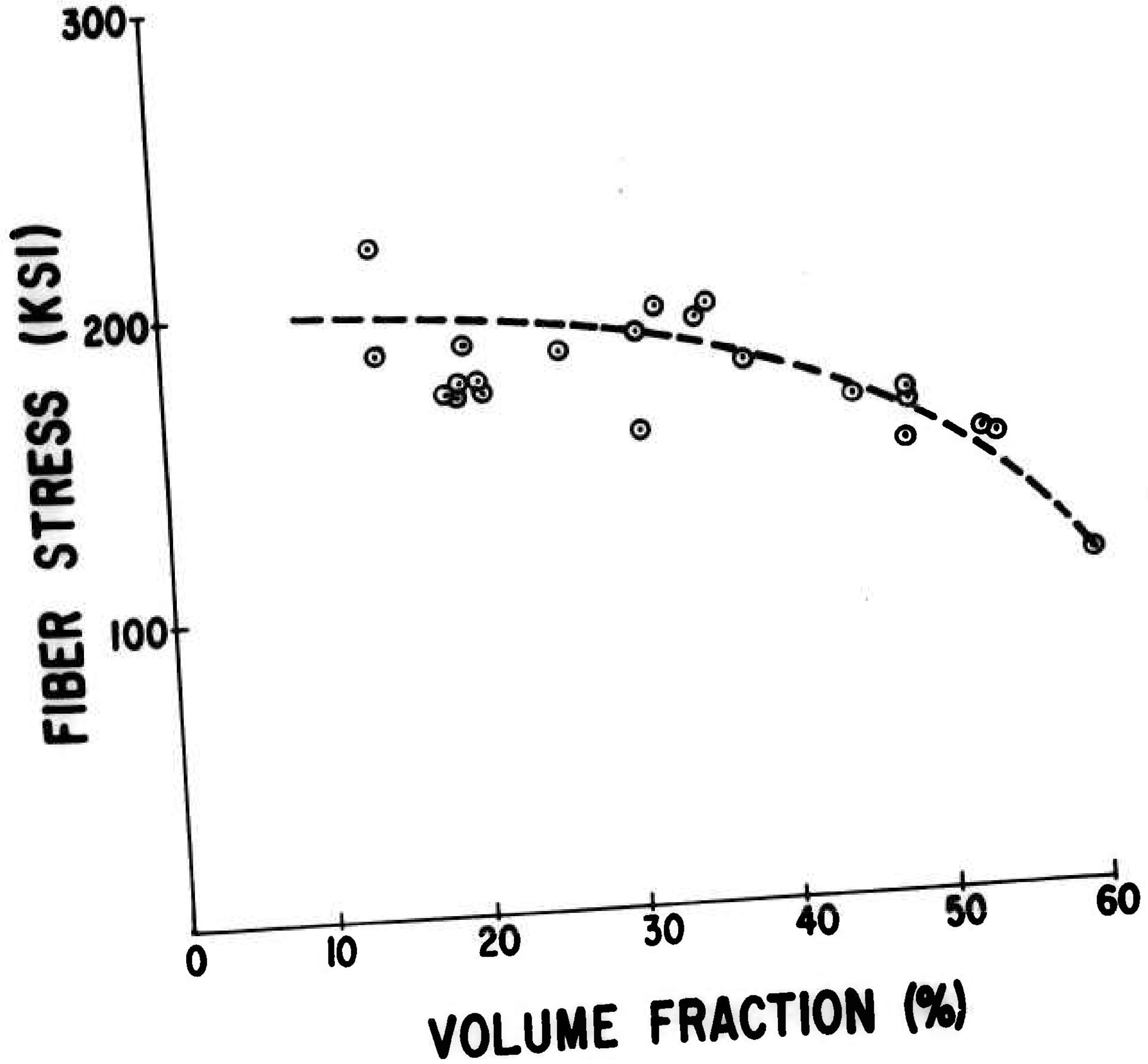

Figure 6. Maximum fiber stress developed in composites with 828/Z matrices.

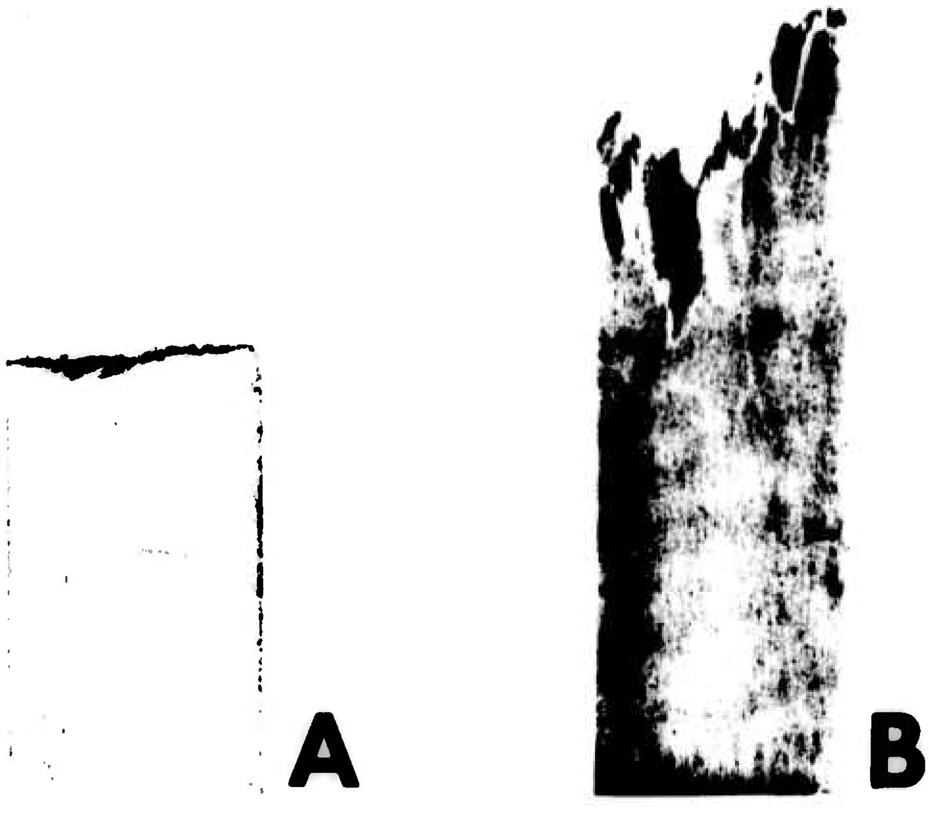

Figure 7. Typical fracture patterns for (a) randomly oriented and (b)aligned fiber composites.

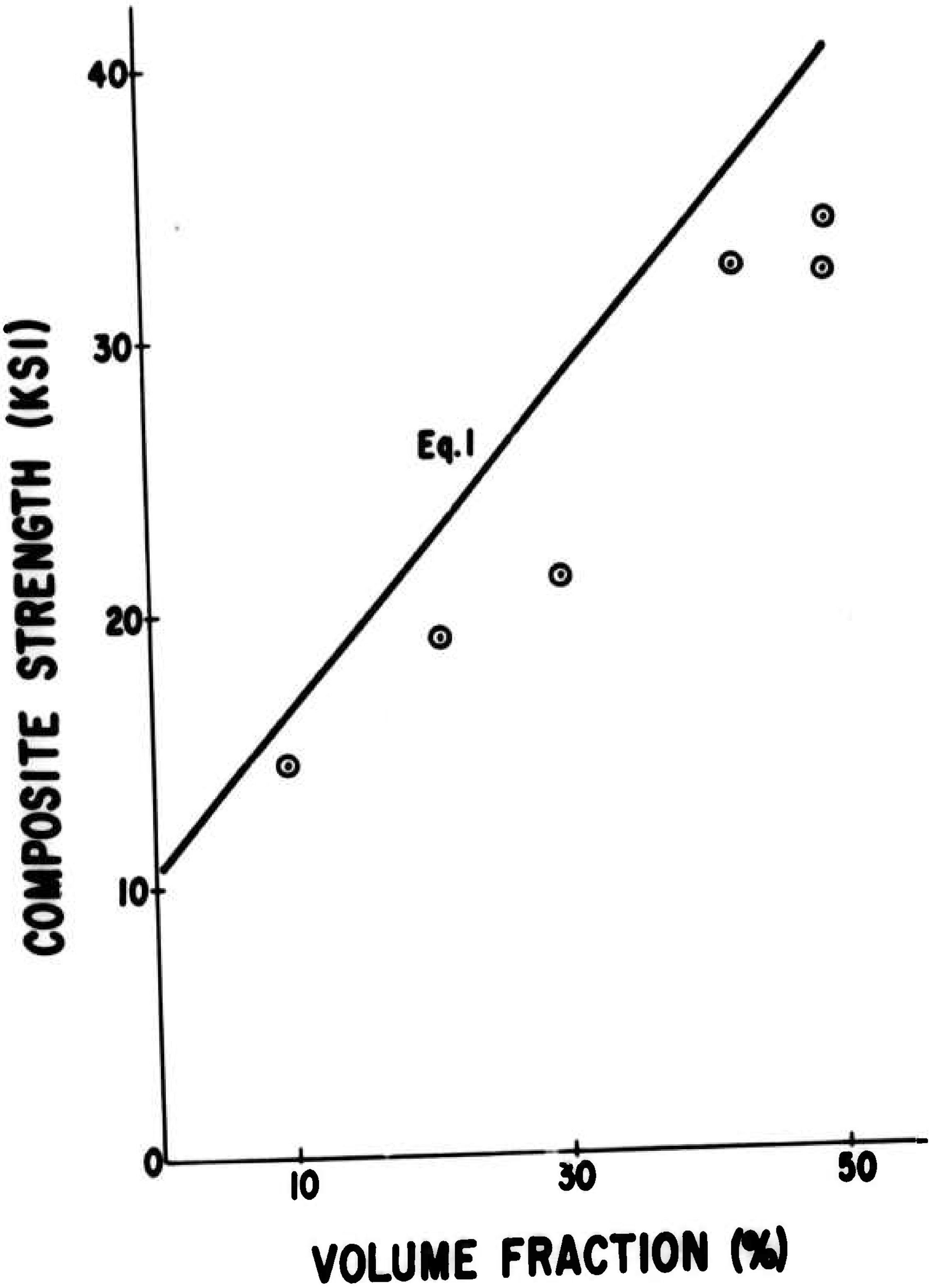

Figure 8. Longitudinal strength of unidirectional short fiber composites compared with the strength of similar material with random orientation (i.e., Eq. 1).

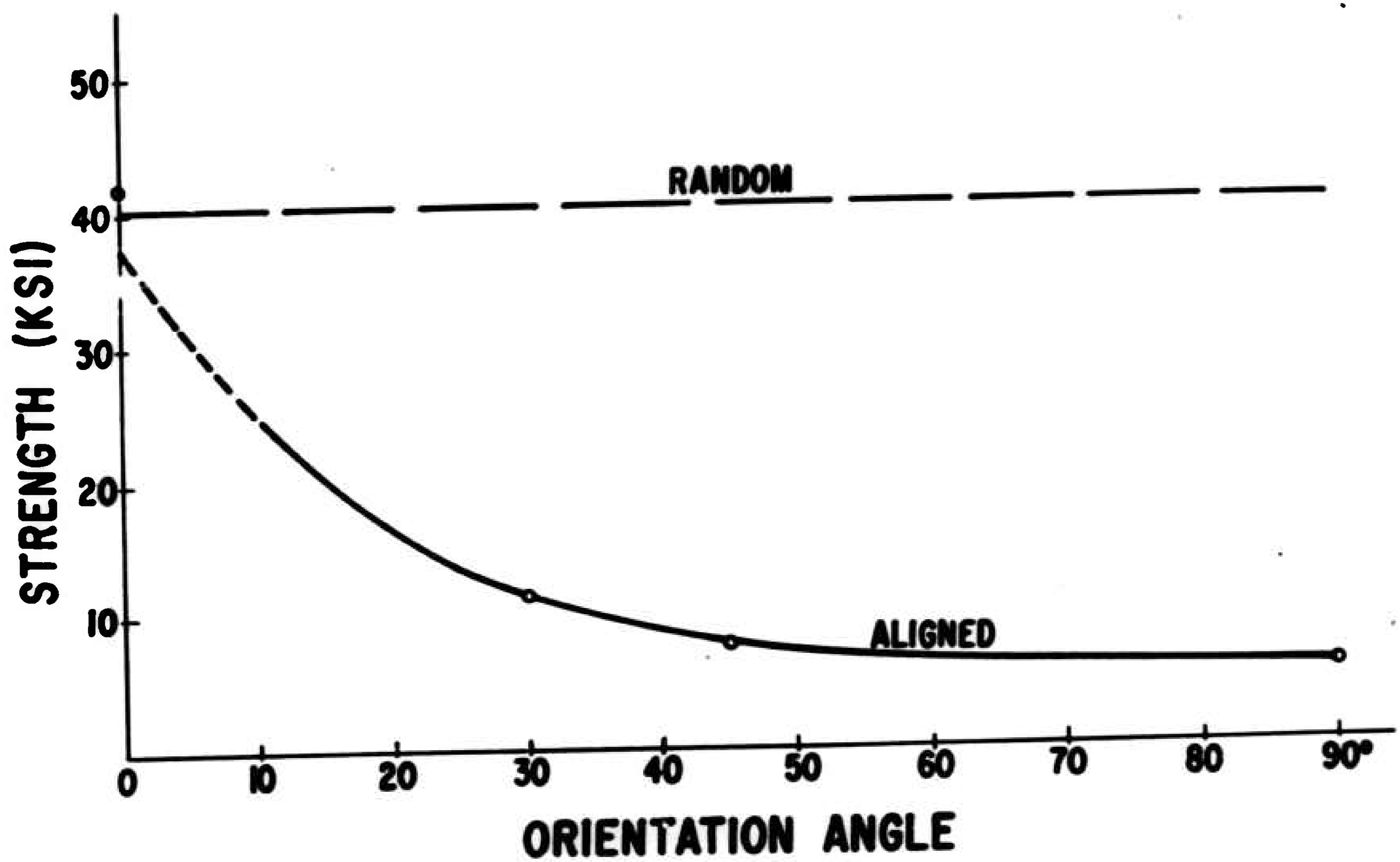

Figure 9. Tensile strength vs. angle for comparable composites reinforced with random and aligned fibers.

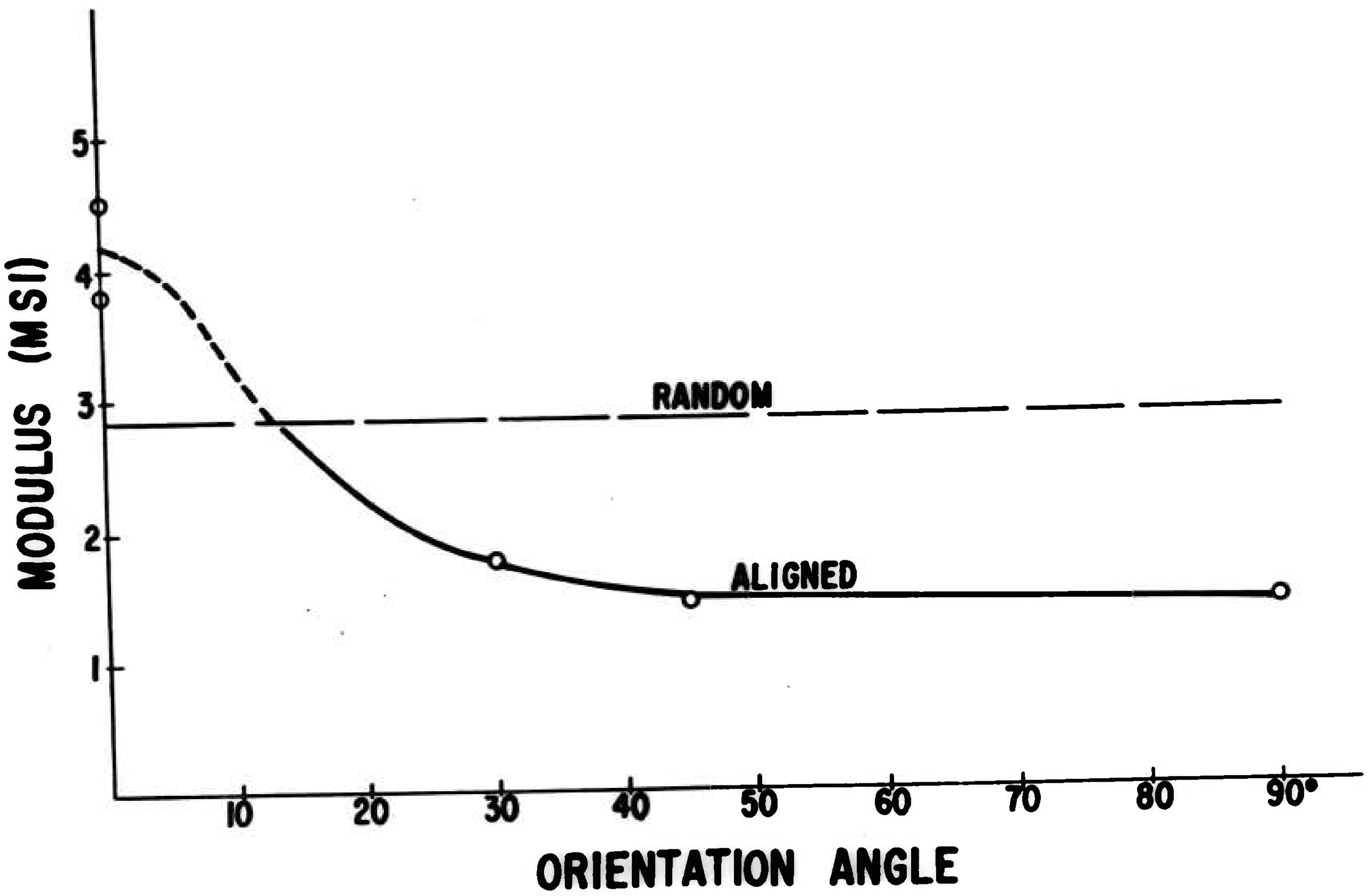

Figure 10. Stiffness vs. angle for comparable composites reinforced with random and aligned fibers.