ON THE FRACTURE ENERGY OF GLASS

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FOREWORD

This research memorandum has been written under contract NONR - 3219 (01) (x). The memorandum was prepared by Dr. J. O. Outwater, Principal Investigator under this contract, and Mr. Gerry and summarizes part of the work to date on the fracture energy of glass. It was carried out under the direction of the U. S. Naval Research Labor tory.

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ON THE FRACTURE ENERGY OF GLASS

John O. Outwater* and Donald J. Gerry**

ABSTRACT

The fracture energy of glass has been measured at crack velocities ranging from 10^{-7} ~~to 10^{-2}~~ cms. per sec. both in normal air and in various environments. It shows no minimum value but decreases logarithmically as the velocity gets less. The effects of repeated loading on the crack propagation rate are strongly dependent on the frequency of the loading. These results differ from the effects in metals where the crack propagation rate is substantially independent of the loading frequency and are in accord with predictions based on the theory of glass acting as a ductile material.

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ON THE FRACTURE ENERGY OF GLASS

Introduction

The use of glass as a potential structural material has spurred interest in the fracture process. Glass has certain advantages as a structural material over metals but these are often overshadowed by the serious disadvantage of crack propagation and static fatigue under comparatively low loads. The understanding of such mechanisms is by no means complete.

Charles (1), and others have shown the dependence of strength on environmental conditions and on applied stress. They postulated a chemically activated stress corrosion cell at the crack tip. Shand (2) has expanded these data analytically to show the effects of speed of crack propagation on the fracture energy. Values of fracture energy at speeds of about .01 to .04 cm/sec. have been obtained experimentally by Nakayama (3) while Roesler (4) obtained values of fracture energy at speeds of about 10^{-6} to 10^{-4} cm/sec. by measuring the spread of a conical crack in a glass block under pressure from a blunt punch. In no case, however, has the fracture energy been measured over a wide spectrum of velocities to show the continuous dependence of fracture energy on the velocity of fracture and in a manner that can readily reveal the effects of various environments.

This work does that. The simple technique described enables us readily to determine the effects of environments on the fracture energy and also the effects of repeated loading on the velocity of fracture. These data are of direct importance to the understanding of the behavior of glass under long term stress and they also give an insight into the mechanism of failure. The velocities of crack propagation using this technique range from 10^{-7} cm/sec. up to .01 cm/sec. and so show what happens and what influences the behavior of glass in the earlier phases of

crack propagation to ultimate failure.

The Griffith theory of fracture is accepted with glass (5) but, in contrast to the Griffith theory, it is noted that if a comparatively low stress is applied to glass specimens then any surface microcracks will grow at an extremely low speed but, in growing, the stress concentration at their root will increase thereby accelerating their growth until the crack becomes sufficiently large to cause the catastrophic failure of the specimen. It is the initial phase of very slow crack growth that may be critical and it is just this phase that lends itself so well to study by the technique described below.

Experimental Procedure:

In order to obtain a constant crack velocity, it is necessary to expose the crack tip to the same load regardless of the length to which the crack has penetrated. This is accomplished by subjecting a plate to double torsion so that a crack is propagated down its center along a prescribed line. Fig. 1 shows the rectangular specimen loaded through four small hemispheres. They are arranged as for four point flexure and cause a crack to develop and extend along a prescribed groove down the middle of the plate. The profile of the crack edge is by no means perpendicular to the surface of the glass plate, but, as the loading is identical as the crack lengthens, the profile of the crack will be independent of its length. The length of the crack then will be directly proportional to the area of fresh surface. Using this method of loading, we can compute the fracture energy directly from the load and the geometry of the specimen as in Appendix I and Fig. 2. The crack velocity can be increased merely by increasing the load. As the elastic constants of the plate can be determined under static conditions, and as they remain constant as the crack lengthens, we can readily determine the fracture energies for different crack velocities.

This method is adaptable for use in a compression testing machine for more rapid propagation and also under deadweights where very slow speeds indeed can be checked over a period of weeks. The technique is also useful with pulsating loads and the effects of the rapidity of pulsation and also of their magnitude can be demonstrated.

The Influence of Crack Velocity on Fracture Energy:

All the tests were run on plate glass of composition: SiO_2, 71.7%; NaO_2, 13.5%; CaO, 11.7%; MgO, 2.5%; SO_3, 0.3%; Al_2O_3, 0.2%; Fe_2O_3, 0.1% supplied by Pittsburgh Plate Glass Co., Pittsburgh, Pa. The results are shown in Fig. 3. The plates were used without any treatment and the tests were run in the atmosphere and also under water. There was no difference observable within the scatter of the experimental points themselves of the fracture energies under water and of those in normal air. These results then neither confirm or deny the influence of water on surface energy as there is surely sufficient water present in the atmosphere together with that absorbed on the glass surface to make the environments equivalent. The velocities below 10^{-4} cm/sec. were measured by means of hanging a deadweight on a platform supported from the two small loading hemispheres as in Fig. 4 and measuring the progress of the crack at daily or weekly intervals. The greater velocities were measured by loading with an Instron testing machine and measuring the crack velocity while the crosshead was descending. It was interesting to note that exactly the same load in fact was needed to propagate the crack regardless of its length into the plate. This is in accord with theory.

An interesting point that can be noted from Fig. 3 is that the velocity of fracture does not become zero under a threshold value of fracture energy. It does become progressively smaller as the velocity is reduced. This implies that a crack will always propagate under load although the velocity may be exceedingly small.

It is also interesting to note that the tip of the crack is loaded in proportion to the force pushing down on the plate and that the velocity derives from this loading. Charles (1) indicated that the velocity of a crack would be related to the tensile stress across the crack as $da/dt = k\ \sigma^n$ where n and k are constants and σ is the stress. If now we insert our values of crack propagation velocity and appreciate that our values of stress are proportional to the loading then we would obtain a relationship:

$$(da_1/dt)/(da_2/dt) = (P_1/P_2)^n \quad \text{or} \quad (da_1/dt)/(da_2/dt) = (G_{11}/G_{12})^{n/2}$$

From Fig. 3 we can obtain a value of n as 17.6 for our method of loading. This compares with 16 which Charles obtained on glass rods in flexure (1). Accordingly, it appears that the velocity of cracks in the fatigue range can be readily predicted from Charles formula.

The Effects of Kerosene and Surface Active Agents on the Fracture Energy:

By merely immersing the plate in kerosene during the fracture process it is shown that the fracture energy is somewhat increased at higher crack velocities through exclusion of air by this means. This is shown in Fig. 3. Four surface-active organic silanes were used to show their effects on surface energy:

1. $(MeO)_3\ SiCH_2\ CH_2\ NHCH_2\ CH_2NH_2$- Trimethoxysilypropylethylenediamine*
2. $(CH_3COO)_3\ SiCH = CH_2$ - Vinyltriacetoxysilane.
3. $(HO)_n\ O_{3-n}\ Si\ CH_2\ CH_2\ COOH$ - Carboxyethylsilicic acid*
4. $(MeO)_3\ SiCH_2\ CH_2\ CH_2\ Cl$ - Chloropropyltrimethoxysilane.*

These are substances used to encourage the bonding of resins to glass and it was suspected that they might have a preferential absorption on glass and hence reduce the fracture energy. In fact they did not change the fracture energy indicating that any possible reaction with the glass surface even at slow velocities

* Supplied by Dow Corning Co., Midland, Michigan.

was not great enough to affect the fracture energy within our limits of measurement.

The Effects of Repeated Loading:

If the propagation of a crack depended solely on the length of time that the glass remained under a stress of a certain magnitude, then, provided we loaded the specimen in such a way as to keep the distribution of time under load the same for two specimens, we should expect a crack in both specimens to propagate the same distance. Such loading can be done by varying the frequency of linear loading and unloading. If the total time of the cyclical loading is the same in both cases, then the proportion of time spent at any given percentage of the maximum load will be the same. The load on the specimen was made to vary linearly between two levels at two different speeds. The distances of crack propagation are shown in Table I. The velocity of crack propagation is distinctly greater at higher rates of loading whereas the length of crack propagated each cycle is about 5 times greater with the slow rate of loading than with the fast. This observation is in direct opposition to that observed with metals where the length of crack propagated per cycle is independent of the rate of loading according to Rowe and Meck (6). This suggests that the mechanism of fatigue crack propagation in glass is fundamentally different from that in metals. The fact that it is indeed lower for higher rates of loading is in agreement with Marsh (7) where he postulates that the yield strength of glass will be predictably higher for greater rates of loading. The ratio of loading rates is about 15 and this would indicate a threshold flow stress being raised by 10% which might, in turn, account for the difference between the crack propagation per cycle for the two rates. With metals the effects of rates of loading are far less pronounced and we could therefore expect much less effect of the rate on the crack growth per cycle.

The effects of repeated loading were duplicated with the specimen submerged in kerosene. The results were the same indicating that environment had little effect on the propagation per cycle.

Conclusions:

The following conclusions can be obtained as a result of this work:

1. The fracture energies of plate glass have been measured in the fatigue range and they show no minimum value.
2. Velocities of fracture can be predicted from a formula of the type $da/dt = k\ \sigma^n$ where n is about 17.6.
3. Immersion in water or silane based surface active materials have no measurable effect on the fracture energy. Immersion in kerosene appears to increase the fracture energy at higher velocities only.
4. The crack propagation velocity under repeated loading was dependent on the cycling frequency. This result could be predicted from the flow stress postulate of Marsh (7).

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APPENDIX

Theoretical Analysis of Method of Determining the Energy of Fracture

A central load of P is transmitted symmetrically through two points of loading on a rectangular section of glass of thickness t with a distance between the supporting points of w as in Fig. 2. Let θ be the angle of twist of each half, M_T the applied twisting moment, a the crack length, J the polar moment of inertia of the half and G the modulus of elasticity.

Then $\theta = M(a/JG) = Pwa/4JG$ as $M_t = Pw/4$

also $\theta = 2y/w$ where y is the displacement of P

So: $y = Pw^2a/8GJ$

But the compliance $C = y/P$

So: $C = w^2a/8JG$

and $dC/da = w^2/8JG$ which is a constant for the specimen and it should particularly be noted that it is independent of a.

Thus the surface energy of fracture $\mathcal{G}_1 = \frac{P^2}{2t} \frac{dC}{da} = \frac{P_w^2 2}{16\ tJG}$ (8)

These values or $\mathcal{G}_{J1} = \frac{y}{Pa} \frac{P^2}{2t}$ can readily be evaluated experimentally to give a value of $\mathcal{G}_1$ that may be determined directly from the load on the specimen. The particular advantage of this method of determining $\mathcal{G}_1$ is that the load needed to propagate the crack does not change according to the length of the crack so a stable crack is possible and computation is minimal.

BIBLIOGRAPHY

1. Charles, R. J. "Static Fatigue of Glass" Journal of Applied Physics, Vol. 29, Number 11, November 1958, pp. 1554-60.

2. Shand, E. B. "Fracture Velocity and Fracture Energy of Glass in the Fatigue Range," Journal of the American Ceramic Society, Vol. 44, Number 1, 1961.

3. Nakayama, J. "Direct Measurement of Fracture Energies of Brittle Heterogeneous Materials" Journal of the American Ceramic Society, Vol. 48, Number 11, November, 1965.

4. Roesler, F. C. "Brittle Fractures Near Equilibrium" Proc. Phys. Soc., LXIX, 10, 1956.

5. Griffith, A. A. "The Phenomenon of Rupture and Flow in Solids" Phil. Trans. London, Ser. A 221, 1920, pp. 163-196.

6. Rowe, G. H. and Meck, H. R. "Stress Rupture of Metals Under Increasing Stress" Trans. ASME 87D (J. Basic Eng.) 4, pp. 875-878, December, 1965.

7. Marsh, D. M. "Plastic Flow and Fracture of Glass" Proc. Roy. Soc., Series A, Vol. 282, 1964, pp. 33-43.

8. Irwin, G. R. "Structural Aspects of Brittle Fracture" Applied Materials Research, Vol. 3, No. 2, 1964, pp. 65-81.

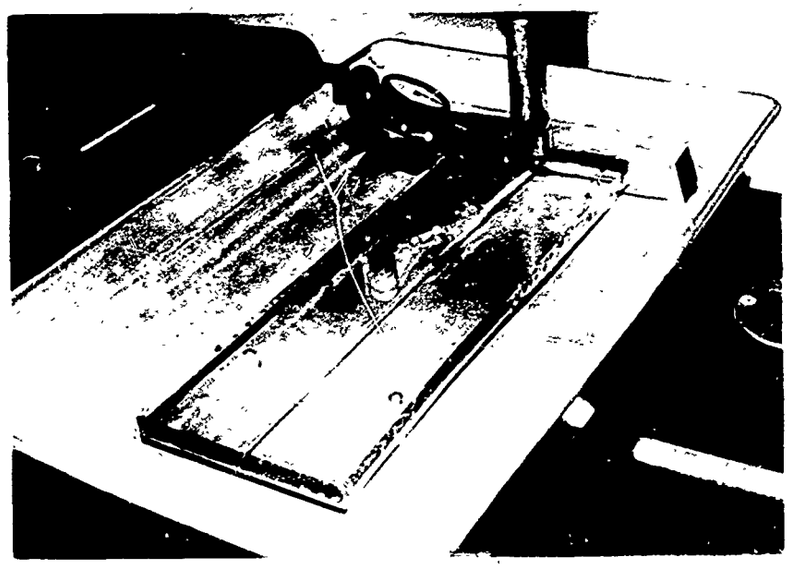


Fig. 1. Fracture energy specimen being loaded in an Instron testing machine to determine the compliance of the specimen prior to propagating the crack.

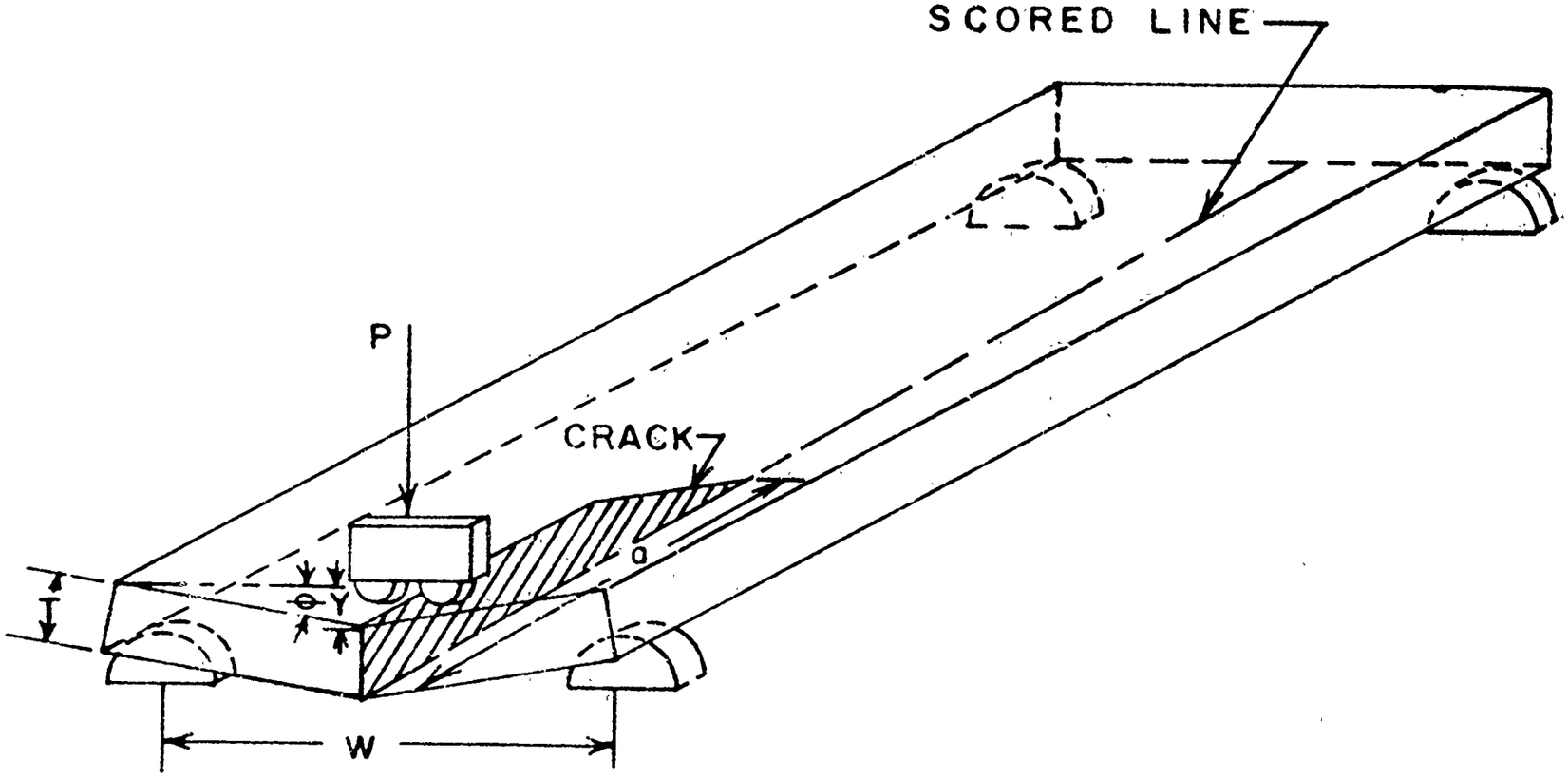


FIG. 2 SCHEMATIC OF TEST APPARATUS

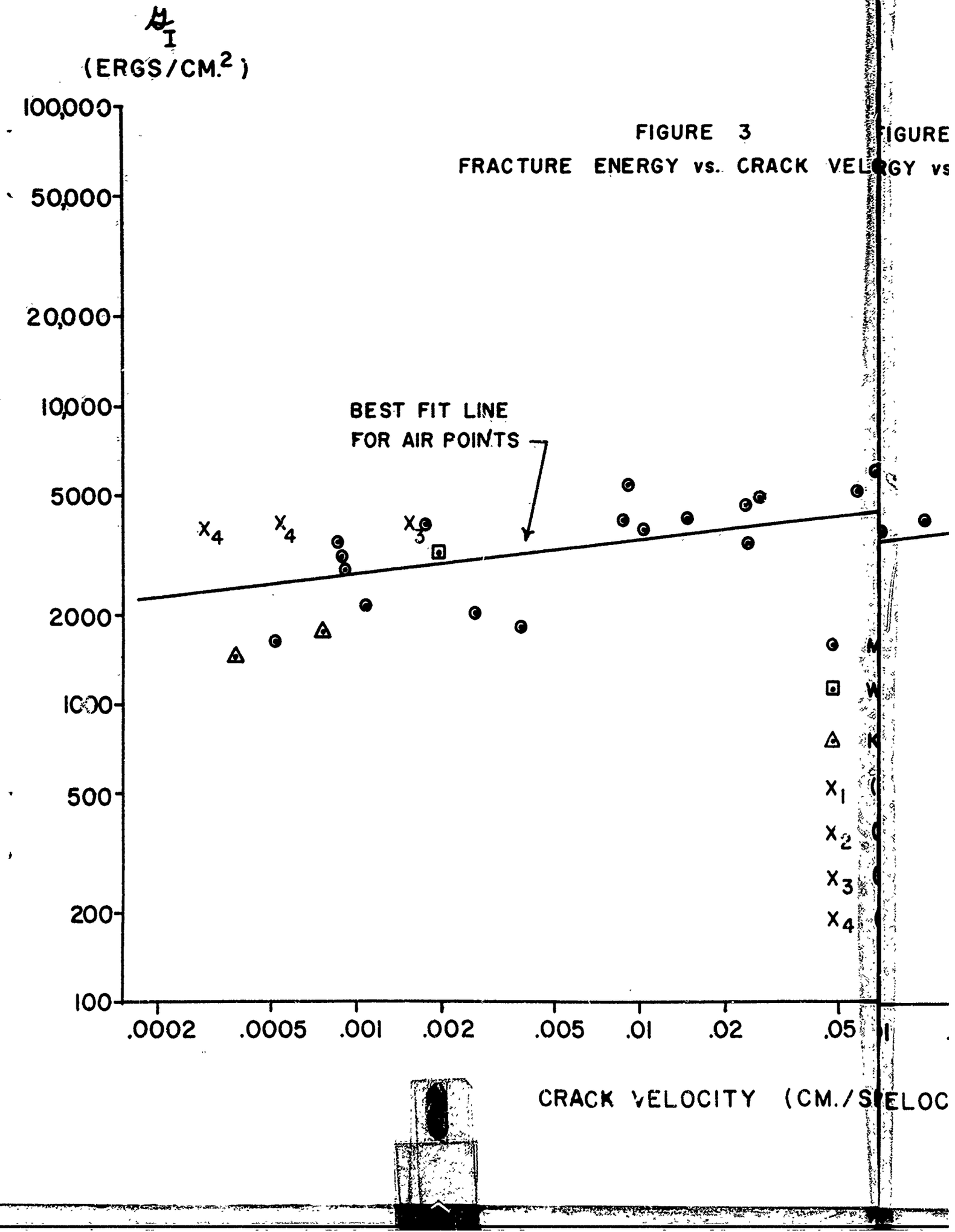
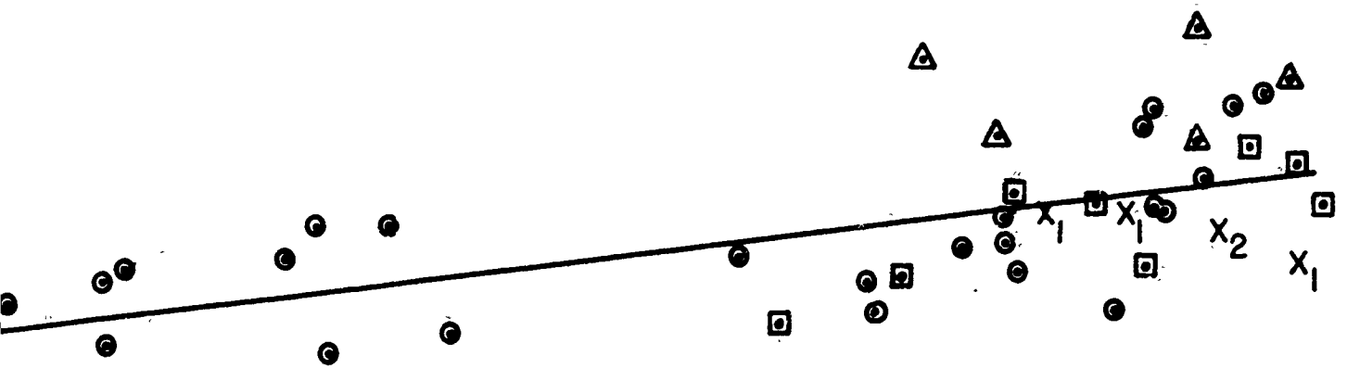


FIGURE 3

FRACTURE ENERGY vs. CRACK VELOCITY vs

RE 3

vs. CRACK VELOCITY



LEGEND

- ⊙ MOIST AIR
- ⊡ WATER IMMERSION
- △ KEROSENE
- X_1 $(MeO)_3SiCH_2CH_2CH_2NHCH_2CH_2NH_2$
- X_2 $(CH_3COO)_3SiCH=CH_2$
- X_3 $(HO)_nO_{3-n}SiCH_2CH_2COOH$
- X_4 $(MeO)_3SiCH_2CH_2CH_2Cl$

.02 .05 .1 .2 .5 1 2 5 10

OCITY (CM./SEC. x 10^3)

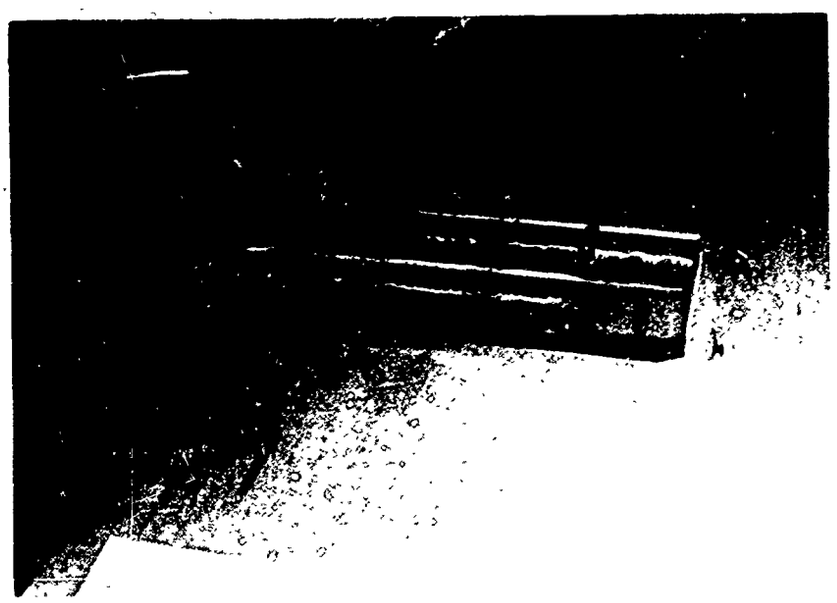


Fig. 4. Fracture energy specimen being loaded by deadweight to determine the fracture energy at slow rates of crack propagation.

TABLE I

DETAILS OF REPEATED LOADING

LINEAR LOAD AND UNLOAD RATE	CYCLES/SEC.	CYCLE TIME (SEC.)	$\Delta a/\Delta T$ (IN./SEC.)	Δa/CYCLE
HIGH	0.5	1.98	0.000208	0.000417
LOW	0.045	22.2	0.000104	0.002320
HIGH	0.55	1.82	0.000728	0.001325
LOW	0.05	19.8	0.000312	0.006250
HIGH	0.5	1.98	0.000261	0.000522
LOW	0.045	22.2	0.000104	0.002320
HIGH	0.416	2.4	0.001460	0.0035
LOW	0.0434	23.1	0.000625	0.0144
HIGH	0.367	2.73	0.000728	0.00199
LOW	0.04	25.0	0.000522	0.01302