ROCK FRACTURE RESEARCH

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16. Abstract

In order to reduce the resistance of hard rocks to excavation by available cutters, and in order to reduce wear on cutters and thus to increase the efficiency of conventional tunneling machines and thus improve their rate of advance in hard rocks, surface active agents have been studied in controlled laboratory environments and have been experimented with in the field in actual tunneling operations.

The laboratory study utilized a notched beam test to measure the effectiveness of thirty different surface active agents on the amount of surface energy required to cause stable fracture in rock specimens. In addition to the type of rocks, geometry of the specimens, type of surface active agents, the effect of environment such as temperature and degree of saturations were studied. The principal mechanism responsible for weakening of rocks in the presence of surface active agents was believed to be that of stress activated corrosion.

The application of surfactants in the laboratory resulted in a reduction of up to fifty percent in rock strength, while limited experiments in the field have shown a 10 to 20 percent increase in the rate of advance. Substantial efforts both in the laboratory and in the field are needed to fully understand the mechanisms involved and to utilize the effectiveness of surfactants as weakening agents for hard rocks.

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I. INTRODUCTION

The cohesive strength of a solid material is influenced by the environment in which the strength measurement is made. For obvious reasons, the usual reference environment is air of controlled temperature and relative humidity; the influences of other environments can be assessed by comparing them to the reference conditions. The degree of influence depends upon many factors including the chemical and physical natures of the environment, its temperature, the rate of testing, the tensorial and time characteristics of the applied stress field and, of course, the nature of the material being tested.

Typically, materials which are brittle when tested in room temperature air show the greatest environmental sensitivity. A common example is ordinary window glass: its strength can be reduced by a factor of 2-3 simply by testing it wet or while submerged in water. Conversely, if tested in vacuuo, its strength increases and the time sensitivity of its strength, normally quite pronounced, disappears. Because of the magnitudes of these effects, the environment-strength phenomenon in glass has been studied by many investigators and a number of theories have been advanced to explain it, but a definitive understanding has not been achieved as yet (1, 2, 3).

A similar environmental sensitivity is exhibited by other brittle materials and, in fact, is exploited in

certain industrial comminution processes. By the artful choice of grinding aids, many crushing operations performed on ores, minerals and the like can be speeded up, reduced in energy consumption and made to produce finer, more uniformly-sized particles. A comprehensive review of this subject has been published recently (4).

Three theoretical explanations of these phenomena dominate the situation at present. The first derives from the Griffith analysis of the strength of brittle solids (5). This explanation takes the form of the well-known equation

$$\sigma = \sqrt{\frac{2E\gamma}{\pi C}} \qquad (1)$$

where σ is the nominal fracture stress, E is the modulus of elasticity, γ is the surface energy of the material and C is the characteristic dimension of the most serious flaw present in the sample. To explain the environmental sensitivity effect, it is pointed out that the value of the surface energy term will depend upon the medium contacting the surface and media can be found which will lower it, thereby lowering the tensile strength of the material. This reasoning appears sound and persuasive, but an ambiguity arises in the precise meaning and measurement of the surface energy of a solid in the context of a propagating crack. The uncertainty persists, reinforced by anomalous experimental observations, so the explanation cannot be accepted as conclusive.

The second approach also derives from the Griffith equation, supplemented by a stress corrosion postulate.

It was constructed to explain the strength-time effect in inorganic glasses. In essence, this says that moisture, either liquid or vapor, chemically and physically attacks the highly stressed glass at the Griffith crack tip, corroding it and causing the crack to grow slowly until it reaches a critical size, at which time the sample fractures. The nominal stress at delayed fracture is less than that required for immediate fracture: the strength-time effect is rationalized. There is abundant direct evidence that water corrodes glass, so this point cannot be argued. The presence of Griffith cracks on glass has also been established and observed physically. Both of these factors confer credence to the explanation. A serious anomaly in it has been found however: if slow crack growth is produced by the combined actions of stress corrosion, then the residual strength of stressed but unbroken samples should be reduced by the stress-time exposure, compared to similar samples with no prior stress history. Such has not been found to be the case; the strengths of two such differently stressed sample populations are the same, essentially.

The third explanation is best illustrated with crystalline minerals in which the Rehbinder effect, an increase in rock drilling rates with various chemical aids, is ascribed to enhanced mobility of near-surface dislocations (6). Presumably the mobility enhancement is produced by an interaction of the liquid drilling aid with the solid surface of the material being cut, though the precise nature of

the interaction is not fully understood. The Rehbinder effect is real and has been confirmed by numerous independent experiences. The enhancement of dislocation mobility has been observed experimentally with many different drilling aid-solid surface combinations and correlations of these measurements with macroscopic drilling studies argue powerfully for the validity of the explanation. One important obstacle to its complete acceptance, however, is the case of amorphous glasses. As mentioned, these exhibit the Rehbinder effect but their internal structure is such as to make dislocation models very difficult to postulate, despite recent work identifying localized microplastic flow in inorganic glasses.

In summary, then, the strength-environment sensitivity of solids is widely recognized and, in the context of rock drilling and comminution, is exploited with many brittle materials. Three explanations of it have been advanced and each has persuasive components, both theoretically and experimentally. At this time, however, no one of the three is generally accepted as conclusively correct. It is likely that future research will clarify the choice or evolve a new synthesis to replace them.

* * * * *

The work reported herein had two modest goals:

i) Through laboratory tests, to identify chemical agents which could improve the cutting rates of mechanical tunnelling machines in hard rock.

ii) To attempt field measurements whereby the effects

of such agents could be observed in a real tunnelling situation.

Both were achieved: effective agents were found in laboratory tests and some field experiments affirmed their potential usefulness.

II. LABORATORY STUDIES

As mentioned previously the Griffith theory predicts the tensile strength of a brittle material in terms of crack length, elastic constants, and the surface energy per unit area of the material. Therefore, the tensile strength determination cannot be achieved readily unless the unit surface energy and the characteristic crack lengths are known for the material. In this section the methods chosen for determination of the surface energy and the detection of cracks, and the description of the chemical treatments used to reduce the strength of the material, will be discussed.

A. Fracture Work

There are numerous methods suggested in the literature for determination of surface energy or fracture surface work of various brittle materials. These methods can be divided into four general categories:

1. Flexural test of notched beams
2. Tensile test on notched plates
3. Cleavage techniques
4. Behavior of a crack-containing compression member.

The results presented in this report were obtained using the flexure test. The specimens were rectangular beams with a sharp notch across the middle of the tension face to simulate the effect of a crack. The notches were of different depths and the beams were subjected to bending loads. There are three methods suggested in the literature for calculation of effective surface energy of the material from the results of this test (7). The effective surface energy values presented in this report were obtained according to Nakayama's method (8). This is based on the assumption that if a stable fracture is induced, the energy expended in the system should be equal to the surface energy of the newly produced area. It is pointed out that prior to fracture, the elastic energy of the system shown schematically in Figure 1 is stored partly in the beam and partly in the apparatus. At the time of fracture initiation, the total stored energy U_o is

$$U_c = U_s + U_a \tag{2}$$

where U_s and U_a refer to the elastic energy stored in the specimen and in the apparatus, respectively. Based on the comparison of stored energy U_o and the energy required to separate the test specimen, Nakayama was able to define two modes of fracture. Denoting the effective fracture energy as γ_{eff}, the energy required to separate the beam is

$$U_\gamma = 2A\gamma_{eff} \tag{3}$$

where A is the cross-sectional area of the beam. When $\Delta U = U_o - U_\gamma$ is greater than zero, the mode of fracture

is referred to as catastrophic and the excess energy is consumed as kinetic energy of the fragments. When $\Delta U<O$, the stored energy is not sufficient to complete the fracture and additional work is required. The mode of fracture in this case is referred to as stable. These modes of fracture are shown in Figure 2 by curves A and C, respectively.

According to Nakayama, by making an artificial crack the value of U_o can be markedly reduced and a semi-stable fracture (curve B in Figure 2) or a stable fracture (curve C) can be obtained. In such cases, the total stored energy, U_o, is transformed into fracture energy and $\Delta U = O$. For this stable mode of fracture:

$$U_\gamma = 2A\gamma_{eff} = V \int_O^{tc} f \, dt \qquad (4)$$

where

V = speed of the overall deflection

t = the time required for the completion of fracture

f = bending force

This method was selected as the most suitable one. The reasons for selection are:

1. Direct determination of input energy.
2. Minimum manipulation of the data to evaluate the fracture work and the changes occurring upon application of the physical and chemical treatments
3. Ease of adapting the test to the study of the effects of physical and chemical treatments.

4. Applicability of quantitative microscopy for the determination of the fractured surface area.

5. Ease of the preparation of the specimens.

The method has one deficiency however: it assumes that the fractured surface area is equal to the cross-sectional area of the specimen. For polycrystalline materials such as rocks this is not true. In rocks, failure is by the growth of a principal crack surrounded by an extensive network of sidecracks, the total area of which can be 20-100 times greater than the nominal cross section of the specimen. The character and degree of sidecracking can be changed by a variety of factors so it is necessary to determine the actual new surface generated during fracture if the experiment is to have precision and validity. This can be done through the use of quantitative microscopy.

B. Quantitative Microscopy

The amount of fracture surface area per unit volume can be measured by simple techniques on the microscope. The fundamental relationship which renders the problem tractable is

$$S_v = 2P_L \tag{5}$$

where S_v = surface area per unit volume

P_L = number of point intersections per unit length of test line.

Equation 5 was derived (9) for the case where the cracks were randomly oriented and it must be modified if the cracks deviate from being purely random. In the special case

where all of the crack surface is perpendicular to the viewing surface, Equation 5 becomes

$$S_v = P_L \tag{6}$$

Thus, there is a factor between one and two which relates P_L to S_v in any intermediate case where there is some preferred orientation of the fracture surfaces. In the case of rock samples removed from the interior of beams, there is a random distribution of cracks for untreated samples, but the tested beams showed a preferred orientation of cracks. Equation 6 has been used in this study since the oriented cracks are of primary interest.

The ultimate use of the quantitative microscopic investigation of fractured rock beams is to determine the amount of new surface area created which requires:

1) choose a test volume, V,
2) measure the average initial crack area, A_i in V from untested samples,
3) measure the final crack area A_f in V from tested samples,
4) subtract $A_f - A_i = \Delta A$, where ΔA represents the new surface area in the test volume, V.

The fracture work, γ, of the sample can then be determined from rewriting Equation 4

$$\gamma = U/2\Delta A \tag{7}$$

where U is the measured work done to fracture the sample.

The microscopic sample is obtained from the interior of the beam specimen. The surface of the sample is polished and the crack area in the sample is measured directly on a microscope in the following way:

1) an eyepiece is placed in the microscope which has a reticle with a line drawn across the field of vision,
2) the effective length, L_o, of the reticle line is measured by placing a ruled microscope standard in place of the sample,
3) then on the sample, the number of intersections of visible cracks with the test line in the eyepiece are counted,
4) the sample is randomly positioned a large number of times, N, typically N = 50, and the number of intersections is recorded at each position,
5) the total number of intersections, I, is then divided by the total length of test line NL_o to give P_L

$$P_L = \frac{I}{NL} \tag{8}$$

6) the test volume, V, has been taken to be a standard size and thus the crack area in this volume is given by $P_L V$ from Equation 6.

The combination of Nakayama's method and quantitative determination of cracking made it possible to obtain a better estimate of the true surface energy of the rocks.

Throughout this report, γ_{eff} refers to the effective fracture work obtained by dividing input energy by the cross sectional area (Equation 4) and γ refers to the fracture work obtained by dividing the input energy by the measured change in internal crack area, ΔA (Equation 7).

III. RESULTS

A. Determination of Fracture Work

Figure 3 shows load versus deflection curves for two granite specimens with different depths of notch. Both of these specimens showed stable fracture, so the area under each curve gives the input energy. The input energy of the sample with 75% of the area broken is 5.1×10^5 ergs, and 3.4×10^5 ergs for the sample with 60% of the area broken.* Using Equation 3, the effective fracture work, γ_{eff}, for these two specimen is 5.3×10^4 ergs/cm^2 for the 75% broken area sample, and 4.4×10^4 ergs/cm^2 for the 60% broken area sample. If the amount of new surface created was a linear function of broken area, the effective fracture work would not have varied with the depth of notch.

Figures 4 and 5 show the variation of the input energy, U, as a function of the fraction of the beams broken for granite and marble respectively. These curves show the overall variation of input energy as given by the

*A beam specimen with a 0.25" notch has 75 percent of its area to be broken. A 0.4" notch gives a 60 percent of the area broken. This notation is used in the figures.

areas under the load-deflection curves. Figures 6 and 7 show the variation of effective fracture work, γ_{eff}, for the same samples of granite and marble. Brace (10), using a cleavage technique, has determined the surface energy of single crystals of quartz and other minerals. He found that the measured surface energies are between 100 and 1000 ergs/cm^2. The γ_{eff} shown in Figures 6 and 7 should also be in this region if the beams broke only in one plane. However, as can be seen from Figure 6 or 7, the values are two orders of magnitude larger than the values reported by Brace. The discrepancy was found to be due to the side cracking and microscopic investigations of the crack pattern were used to reduce this discrepancy. Figure 8 illustrates the side cracking that occurred in the fracture of one of the granite beams. Figure 8(a) shows a portion of the notch and the multiple crack pattern. Quantitative microscopy was applied to such samples, and the extent of side cracking was determined.

The following experiment was performed to be sure that this approach was valid. A number of notched beams of granite were taken to different stress levels where the testing machine was stopped and epoxy cement was applied to the sample to "freeze" the strain near the notch. The stress levels are shown in Figure 9(a), and the corresponding crack areas are shown in Figure 9(b). The smooth increase in measured area shows that the cracking which is observed does correspond to the failure cracking

of the sample. The new surface area shown in Figure 9(b), for the fully failed sample (#4), is equal to ΔA of Equation 7. The new crack area shown in Figure 9(b) represents all of the new surfaces created in a test volume at the center of the beam. No side cracking was observed in other regions of the beam, such as under the end supports. Thus, the new crack area measured in the test volume can be used as the total amount of new surface created in the sample.

Figure 10 shows the results of measuring the new crack area, ΔA, on samples of granite with different notch depths. The values of new area are 20 to 30 times greater than the broken cross-sectional area of the beam. From Equation 7, a fracture work of 2300 ergs/cm^2 can be calculated for the granite specimens. This value compares well with the values obtained by Brace for single crystals of quartz and other minerals.

B. Chemical Treatments

Table 1 contains a listing of 15 chemicals used to treat the rock samples. A short description of each chemical and the primary reasons for its effectiveness are given in the table. All of the chemicals except acetone were in water solution. The chemicals were added to the sample by soaking the entire beam under the chemicals for as long as one week although the fracture strength of the beams was not affected by the soaking times covered by the experiments: 2 minutes to 6 days. All of the chemicals lowered the fracture strength, as will be discussed below,

but of particular interest is the curve shown in Figure 11 where the surfactant FC170 was added during the testing and an immediate lowering of the stress was observed within the response time of the apparatus following exposure of the rock to the chemical.

The experiments for the effects of chemicals on the fracture strength of rocks were performed in the same manner as those for the untreated beams except that a dam of plasticine was formed around the notch to hold the liquid in the notch area during the test. The work done to break the beam samples, U, for each of the treatments is shown in Figure 12. The observation of a decrease in the amount of work implies, in the context of the Griffith criterion, that the surface energy decreased, the side cracking decreased, or both. The quantitative microscopy measurements of new crack area can determine the relative importance of these two effects. In addition to U, the measured new crack area ΔA is plotted in Figures 13 and 14 for room temperature and elevated temperatures (90°C). In all cases at 90°C, a decrease in U is accompanied by a decrease in ΔA, and the values of γ plotted in Figures 13 (b) and 14 (b) show a decrease of 50% for aluminum chloride at room temperature and for all the chemicals used in 90°C. This reduction of γ for aluminum chloride at room temperature was due to an increase of side cracking as well as a decrease of input energy, U. The general reduction of γ by all of the chemical treatments shown in Figure 14 also was due to

increasing the side cracking and reducing the input energy, U. It is interesting to note that aluminum chloride at 90°C causes no increase in side cracking but does decrease the input energy by 20%, which is consistent with the hypothesis that stress-activated corrosion is an important mechanism.

The relative importance of stress-activated corrosion as a mechanism can be inferred by changing the temperature of the testing. A comparison of Figures 13 and 14 shows the importance of a relatively small temperature change (25° to 90°C) on the chemically controlled fracture properties of granite samples. Two granite specimens were tested under liquid nitrogen (-195°C) and gave an input energy of 5×10^5 ergs as compared to 3×10^5 ergs for room temperature for the same depth of notch (60% broken area). This would indicate that the chemical effects were important in the samples tested with only the laboratory air environment.

The method of application can greatly influence the effect of chemicals. Preliminary experiments with the most effective chemicals have shown vacuum techniques or ultrasonic vibrations are effective in lowering the input energy necessary to break granite beams. If a fore-pump vacuum is first pulled on granite before aluminum chloride solution is added, the input energy is reduced from 4.7×10^5 ergs to 3.4×10^5 ergs (for beams with 75% broken area). This may be due to an increase in the penetration depth of the chemical.

The addition of chemical treatments to schist and gneiss showed sizable reductions in the input energy. The input energy for untreated schist and gneiss showed more scatter than for granite or marble but there is an average of 1.8×10^6 ergs for untreated schist beams with 60% of the area broken. Distilled water made little change in this value (down to 1.3×10^6 ergs), but both aluminum chloride and sodium chloride solutions lowered the input energy to 8×10^5 ergs. Gneiss showed less effect, going from an untreated value of 7×10^5 ergs to 5.5×10^5 ergs for both a silane and an aluminum chloride solution treatment

Appendix A contains the experimental results obtained from chemical treatment of granite, marble, gneiss and schist specimens. There is also a table of weight gains for various methods of chemical application. Sample load-deflection curves for the most effective chemical agents under the most effective application conditions were noted also.

IV. FIELD STUDIES

The purpose of the field studies was to see if the Rehbinder effect could be used to increase the cutting rate of a mechanical mole boring an actual tunnel in rock under realistic construction conditions. Most moles are constructed with a system which sprays water near the cutting head for dust control purposes so it seemed relatively straightforward to incorporate a surfactant supply into the spray. However, despite a number of attempts to do so in several

different tunnels under construction, successful tests were achieved only in one; in all the others, the necessity to maintain production frustrated useful measurements. Some of the ancillary reasons why field measurements were impossible included:

1) Insufficient or uncertain water supply at face of tunnel.
2) Missing, inoperative or poorly located nozzles on the mole.
3) Excessive natural water on the tunnel face.
4) Mole breakdowns or erratic and intermittent operation of the machine.
5) No water pumping capacity on the mole.

Many many man-days were spent at the following sites with no useful results to show for the effort:

1. McCook, Illinois - Limestone - Lawrence machine
2. Dorchester, Mass. - Argillite conglomerate - Lawrence machine.
3. Alsip, Illinois - Dolomitic limestone - Jarva machine.

The successful tests were carried out at the White Pine Copper Company mine at White Pine, Michigan, in a sandstone formation approximately 1600 feet below the surface. In this formation, an 18 foot diameter tunnel was being bored for ventilation use; at the time of the tests, the tunnel face was approximately 600 yards from the central vertical shaft of the mine and the tunnel was descending

at about 5° from the horizontal. According to the White Pine Company, the sandstone is red to gray in color, fine to medium to occasionally coarse in grain,and, at points, contains some shale. The boring machine was newly designed and constructed by Robbins of Seattle. The cutting head operates at 5 rpm, boring a hole 18 feet in diameter. Sixty-one rolling disk type cutters, eleven inches in diameter are forced against the tunnel face under a total thrust of 1.5 million pounds. A crew of five or six men was required to operate the machine. In the dry sandstone formation at the test site, the normal advance rate was 7/8 inch per minute so the 48 inch stroke required a bit less than one hour continuous operation before the cutter head was retracted, the machine advanced, the side anchor plates reset and boring was resumed. (For reasons to be discussed later, such continuous cutting for even one hour was rarely achieved.) A dust control system using thirteen spray nozzles puts water on the tunnel face. Five of these are stationary, in an arc of about 120° at the top of the cutter head, while eight are randomly located on the rotating face plate. The combined actions of the thirteen provide effective wetting of the face, at rates which can be controlled and measured by the flow meters. Often it is necessary, however, to clear one or more of the nozzles, since they foul quite frequently.

The muck was taken from the tunnel face by a conveyor belt integrated into the machine. This dumped onto a second

system, 30 inches wide, eventually reaching the mine shaft some 600 yards away where the muck was lifted by a hoist cage to the surface. To make the 600 yard run, a number of conveyor segments were used; when operating properly the transfer points between them worked effectively. Unfortunately, these transfers frequently operated improperly, creating choked conditions which jammed the entire system and forced a suspension of cutting until the plug-up was cleared. Such delays plagued the entire experimental interval, making shutdowns very frequent and preventing sustained runs of any appreciable duration. The causes of the malfunction were numerous and basically trivial; as they were corrected, better operation of the entire system became available.

The second major source of down time was the cutters. Because of the experimental nature of the entire enterprise, frequent inspections and changes of these were necessary to measure wear, to replace jammed units, to install new types for test, and for other reasons. Again, this seriously impeded continuous operation of the machine but it, too, was regarded as a transient condition which would improve and stabilize as the job progressed.

The water-soluble surfactants studied were a commercial detergent (Tide), salt (NaCl), sodium hydroxide (NaOH) and aluminum chloride ($AlCl_3$). Laboratory tests indicated that the detergent and the salt should be effective while the soda and the aluminum chloride would not. All

were used in concentrations of less than 1% by weight, again following laboratory test results. Initially each surfactant was mixed in water to form a much stronger solution and this was bled into the dust control spray system at a rate which provided the final low concentration on the tunnel face. It was hoped that the effect of various concentrations of each solvent on the machine advance rate could be studied but such had to be deferred to a later time, because of the frequent down periods which were encountered:

The results can be summarized as follows:

1) In many instances the cutting time intervals were very short, less than an hour, weakening the value of the data taken therein.

2) In better (longer) runs the beneficial effects of the detergent and the salt solutions appear to be real. The detergent improved the machine advance rate by about 10-12%, compared to plain water, while the salt solution, on the average, showed about the same effect.

3) The sodium hydroxide and aluminum chloride solutions did not cause improvements in the machine advance rate. There is a possibility that lower concentrations of these two might be more effective.

4) The influences of concentration of detergent and salt are unknown. Since they would be expected to be important in both cases, further work would be desirable.

5) Though not apparent from the data, no hazardous

or harmful side effects were evident when the surfactants were used. The system operation was not stabilized well enough to assess conclusively any effects on cutter wear or life but the initial impression was reassuring: no trouble from the surfactants.

It was difficult to define the level of precision in these experiments, for a variety of reasons. The machine advance was calculated by using a scale to measure the separation of marks made on the tunnel wall at specified intervals of operating time. Ideally, this would be based on several hours of uninterrupted cutting; such rarely occurred. (The actual measurement between marks could be done to within ±1/8 inch so the error from this source does not seem excessive.) Also ideally, the machine should be boring in a straight run, under conditions of constant thrust and power consumption. Because of alignment problems, this did not prove possible and the consequences of these variations could be appreciable.

Another source of trouble was the stability of the spray system. Quite often nozzles would foul, reducing the amount of liquid placed on the face of the tunnel and this was not easily detected until cutting was suspended and the cutter head inspected. Obviously this could produce variations in advance rate.

Finally, even under the best of conditions a tunnel environment is not the easiest place in which to perform brief experiments with great precision. Instead, resort

must be made to long time observations in which average trends and effects can be observed to permit confident conclusions to be formed. Because of system interruptions principally due to conveyor and cutter problems, such was not possible in these tests.

V. CONCLUSIONS

On the basis of the work to date, it appears reasonable to conclude that two effective surfactants for the sandstone formation were found: a commercial detergent and salt, both in water solutions. Increases in the tunnelling machine advance rate for both were of the order of 10-12% compared to plain water. The two other water solutions, of aluminum chloride and of sodium hydroxide, did not improve the advance rate in the same formation. No deleterious side effects from the use of any of the four agents were evident, through neither the use nor observation periods were realistically prolonged.

On the basis of these preliminary results, further field studies appear warranted. It is not realistic to attempt such work in an actual tunnel being constructed under competitive bid conditions, however. The financial pressures are too intolerant of the delays inherent in experimentation so other, alternative methods of field study should be utilized.

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APPENDIX A

ADDITIONAL DATA ON CHEMICAL TREATMENTS

This appendix contains the experimental results obtained from chemical treatments of granite, marble, gneiss and schist specimens. Sample load-deflection curves are included for the most effective chemical agents under the most effective application conditions.

TABLE 1

LIST OF CHEMICAL AGENTS AND DESCRIPTION

Reagent	% Conc. in H_2O	Description	Possible Effect
Distilled Water	--	H_2O	Dissolution
Acetone	Pure Acetone	Dimethyl ketone	Dissolution
Sodium hydroxide	0.05	NaOH	Dissolution
Aluminum chloride	0.1	$AlCl_3.6\ H_2O$	Chemical attack or dissolution
Armeen 8D octaylemin	1.0	Quaternary amine	Surface energy reduction and possible chemical attack
Alipal CO-436	1.0	Quaternary amine	Ditto
Arquad 2C-75	1.0	Quaternary amine	"
FC 170	1.0	Contains a relatively flourinated and solubilizing group	"
FX 172	1.0	Ditto	"
Zonyl S-13	0.1	Fluorochemical surfactant fluoroalkyl phosphate free acid	"
Zonyl A	0.1	Fluorochemical surfactant non-ionic	"
Z 6020 silane	0.1	An amino functional compound (coupling agent)	"
A 1110 silane	0.1	Ditto	"
A 1120 silane	0.1	"	"
A 187 silane	0.1	Epoxy functional (coupling agent)	"

TABLE 2

WEIGHT CHANGE ACCOMPANYING DIFFERENT APPLICATION TECHNIQUES

Specimen*	Test Period (Mins)	Weight Change (Gms)
VAT 1A	15	1.15
VAT 1B	15	1.10
VAT 2A	30	1.90
VAT 2B	30	1.12

*i. Specimens VAT 1A and VAT 2A were kept in a vacuum environment when the chemical was introduced.

ii. Specimens VAT 1B and VAT 2B were simply immersed in the same chemical.

iii. All specimens have 75% of their areas broken.

TABLE 3

INFLUENCE OF ENVIRONMENTS ON THE STRENGTH OF GRANITE BEAMS*

Environment	Temp. (°C)	Ultimate Load (kgms)	Input Energy (10^4 ergs)	ΔA cm^2	γ $ergs/cm^2$
Air (no treatment)	25	18.4	57.0	125	2300
Alipal	25	15.8	49.0	-	-
Armeen 8D	25	16.5	42.0	-	-
Arquad 2C-75	25	17.9	54.0	-	-
Z-6020 Silane	25	17.2	46.5	124	1870
Aluminum Chloride	25	14.9	45.0	188	1200
Aluminum Chl. with Vacuum	25	13.8	36.0	-	-
Aluminum Chl. with Ultrasonic	25	14.6	39.5	-	-
Aluminum Chloride	90	14.5	34.0	188	905
Zonyl S-13	25	17.2	49.5	130	1900
FX 172	25	16.0	50.5	143	1750
Acetone	25	16.5	49.0	-	-
Distilled Water	90	15.4	42.0	125	1680
Zonyl A	90	16.8	44.0	220	1000
Distilled Water	25	15.9	48.0	-	-
Zonyl A	25	16.5	49.5	-	-

*Area of specimens broken = 75%

TABLE 4

INFLUENCE OF ENVIRONMENTS ON THE STRENGTH OF MARBLE BEAMS

% Area Broken	Environment	Ultimate Load (kgms)	Input Energy (10^4 ergs)
75	Air	22.1	35.8
75	Aluminum Chloride	17.0	28.5
75	Sodium Chloride	19.5	30.7
75	FC 170	18.7	31.6
75	Armeen 8D	17.8	29.4
100	Air	54.5	101.0
60	Air	14.5	21.4
60	A 187 Silane	15.4	14.8
60	Distilled Water	15.9	18.0
60	Sodium Hydroxide	15.4	16.2
60	A 1120 Silane	14.5	16.2
60	Aluminum Chloride	17.5	19.5
60	A 1110 Silane	10.0	14.5

*All environments at 25°C temperature

TABLE 5

INFLUENCE OF ENVIRONMENT ON STRENGTH OF GNEISS BEAMS**

Environment*	Ultimate Load Kgms.	Input Energy (10^4 ergs)	ΔA cm^2	γ $ergs/cm^2$
Air	18.2	69.0	-	-
Aluminum Choride	16.0	56.0	101	2760
A 1120 Silane	15.3	53.0	-	-

*All environments at 25°C temperature.

**Area of specimens broken = 60%

TABLE 6

INFLUENCE OF ENVIRONMENT ON STRENGTH OF SCHIST BEAMS*

Environment*	Ultimate Load Kgms.	Input Energy (10^4 ergs)	ΔA cm^2	γ $ergs/cm^2$
Air	49	180	155	5800
Distilled Water	26.5	132	-	-
Aluminum Chloride	26.0	80	101	3960
A 1120 Silane	26.2	118	-	-
Sodium Hydroxide	26.3	81	-	-

*Area of specimens broken = 60%

**All environments at 25°C temperature

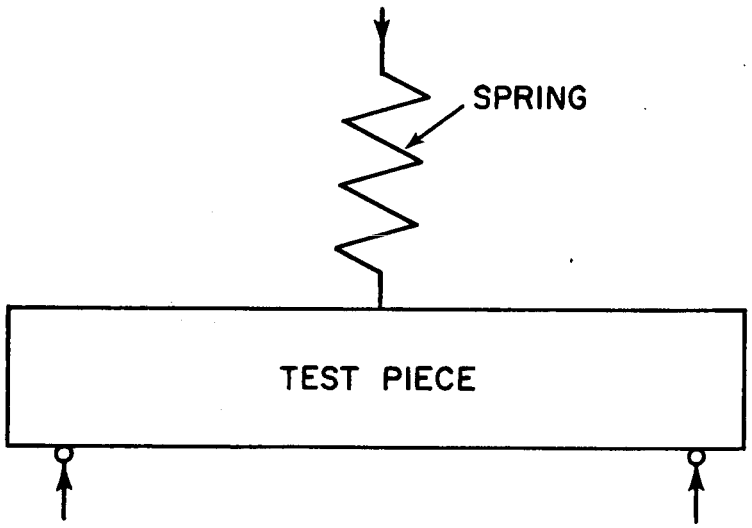

Figure 1. Schematic of Bending System.

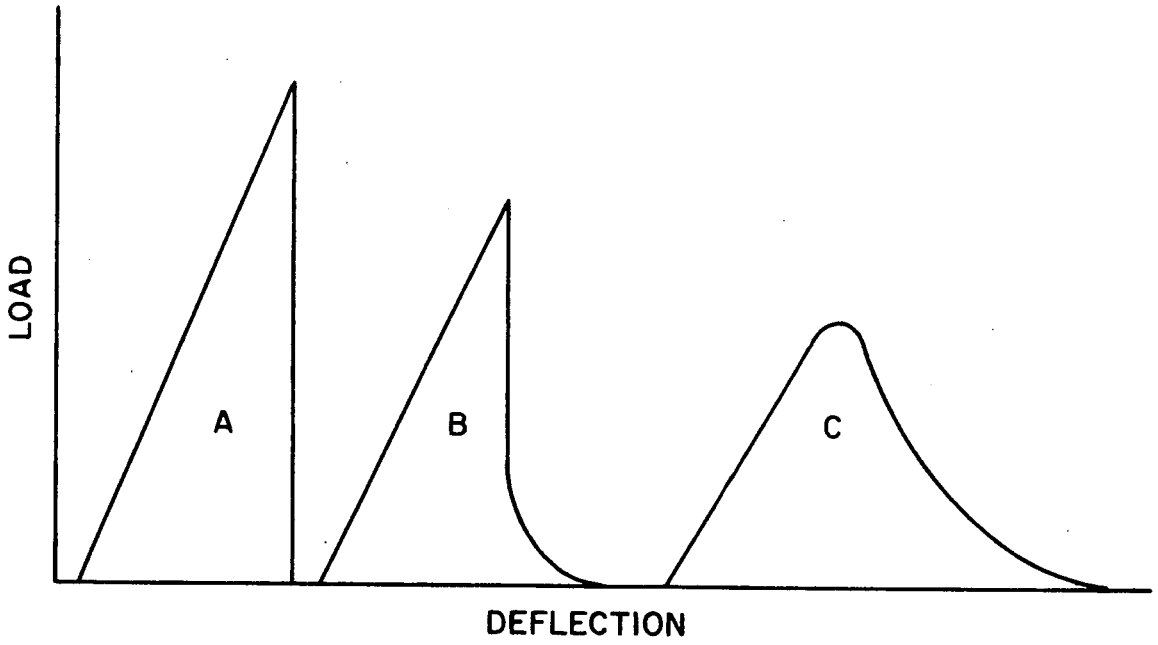

Figure 2. Typical Load-Deflection Curves.
A - Unstable, B - Semistable, C - Stable
After Nakayama Method (Reference 7)

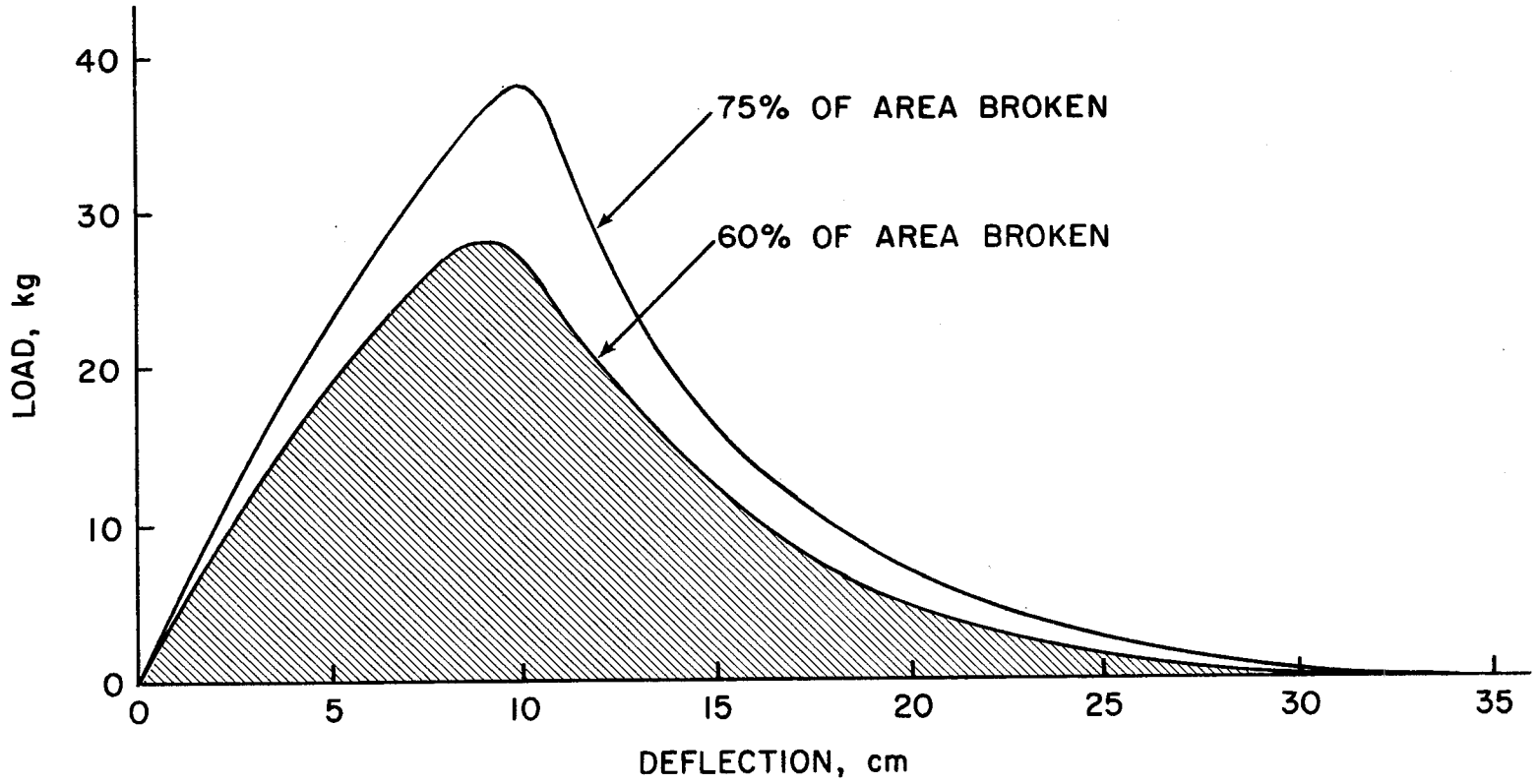

Figure 3. Load-Deflection Curves for Two Granite Beams with Different Notch Depths.

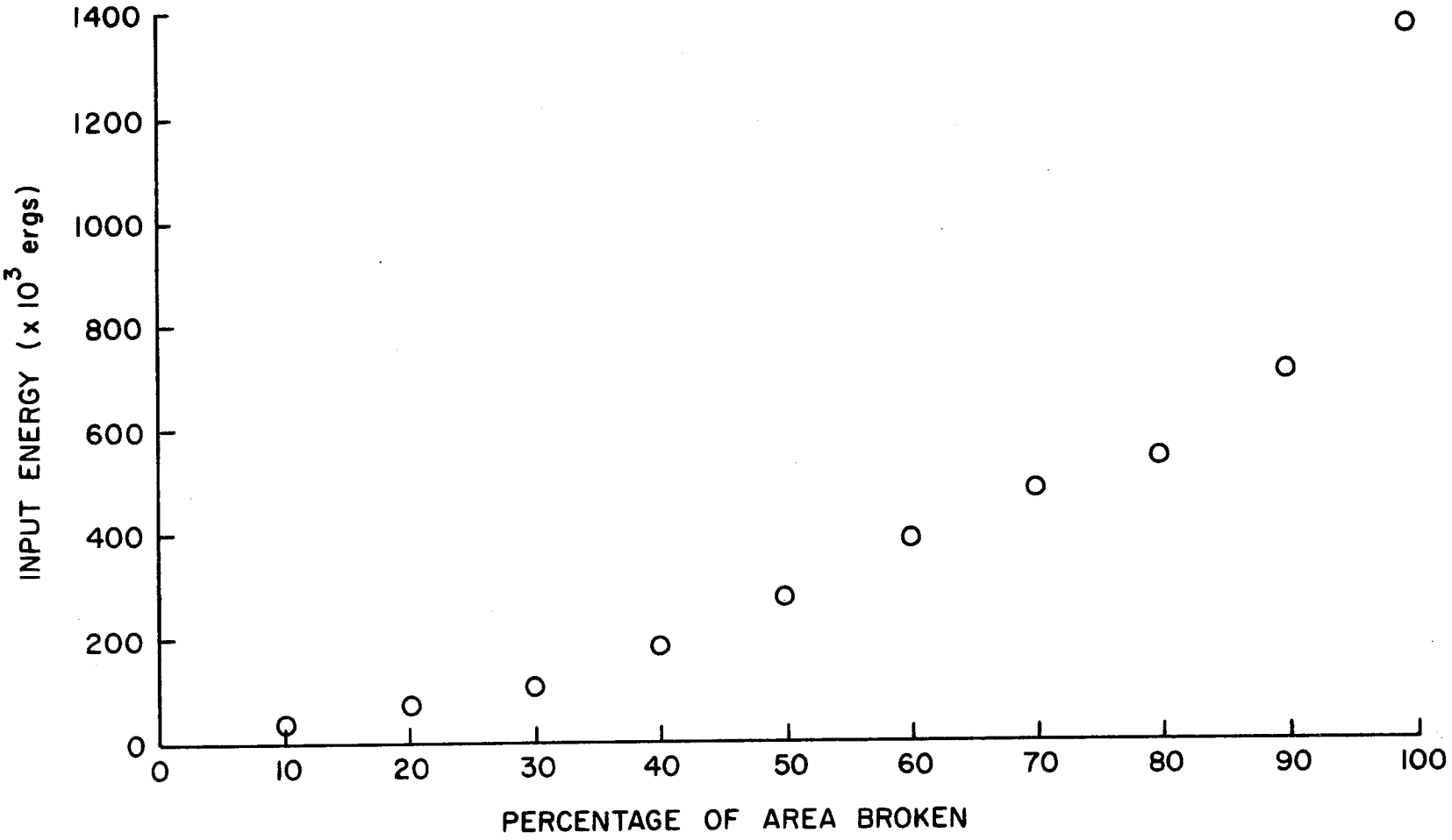

Figure 4. Input Energy vs. Percentage of Area Broken for Granite.

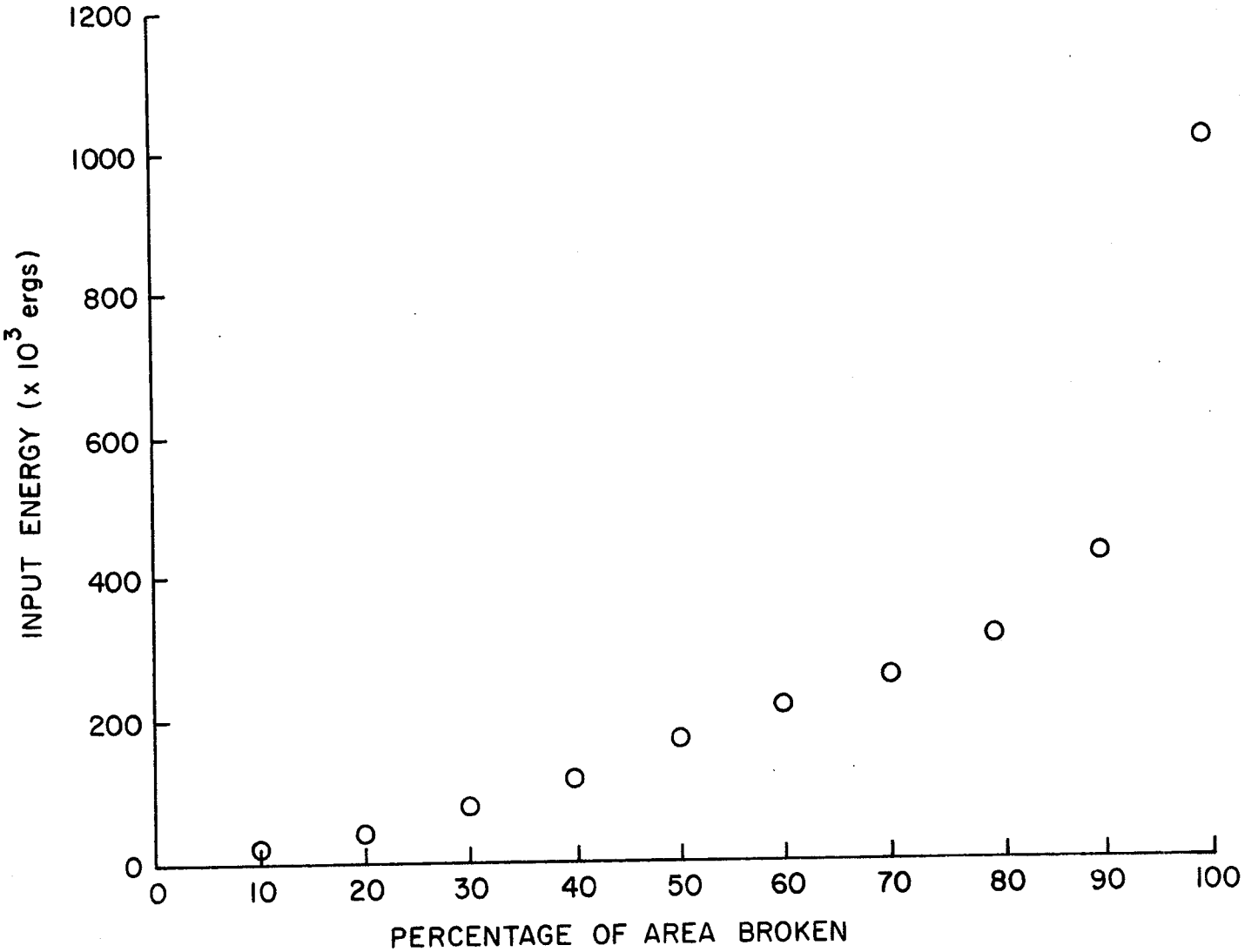

Figure 5. Input Energy vs. Percentage of Area Broken for Marble.

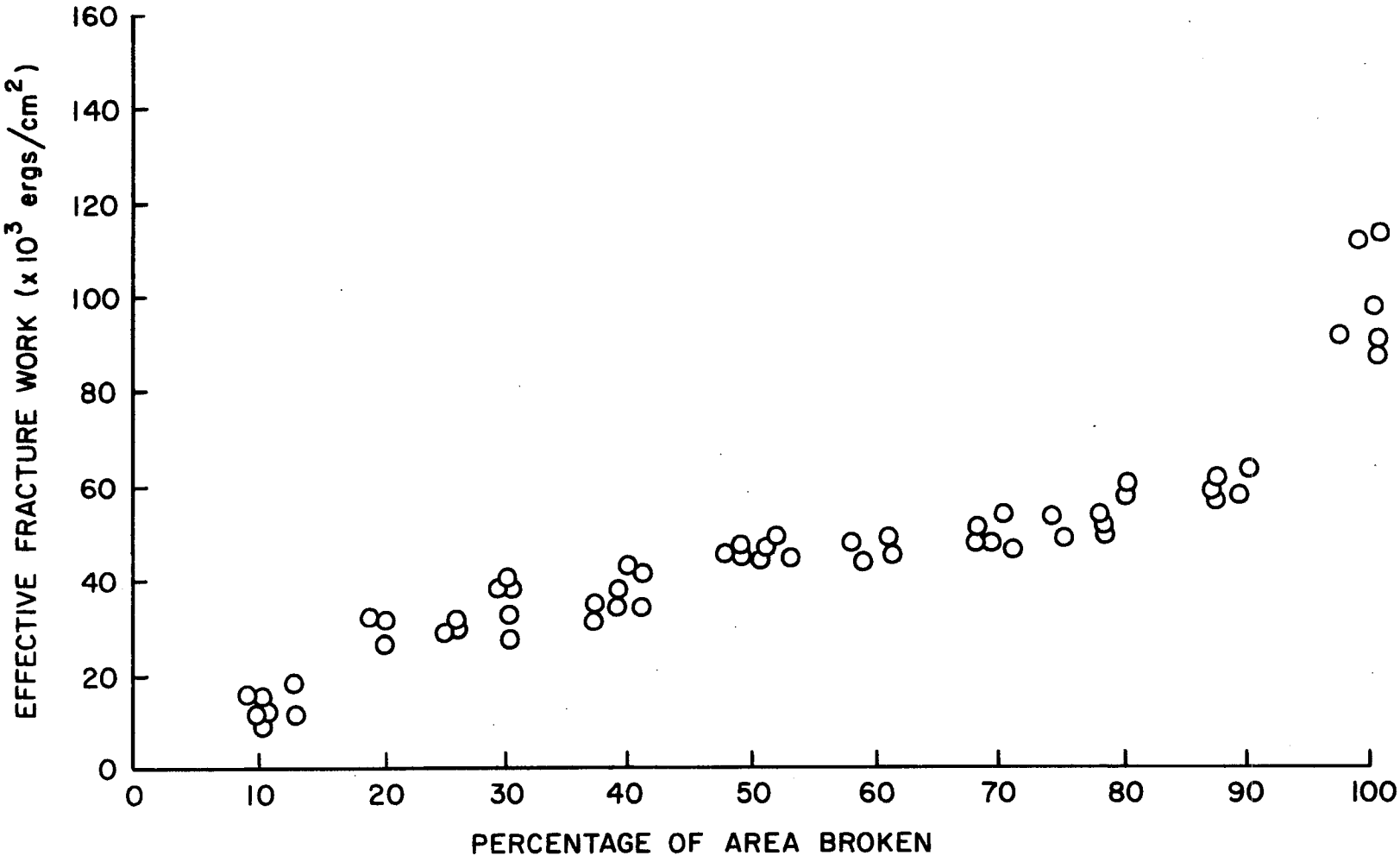

Figure 6. Effective Fracture Work vs. Percentage of Area Broken for Granite.

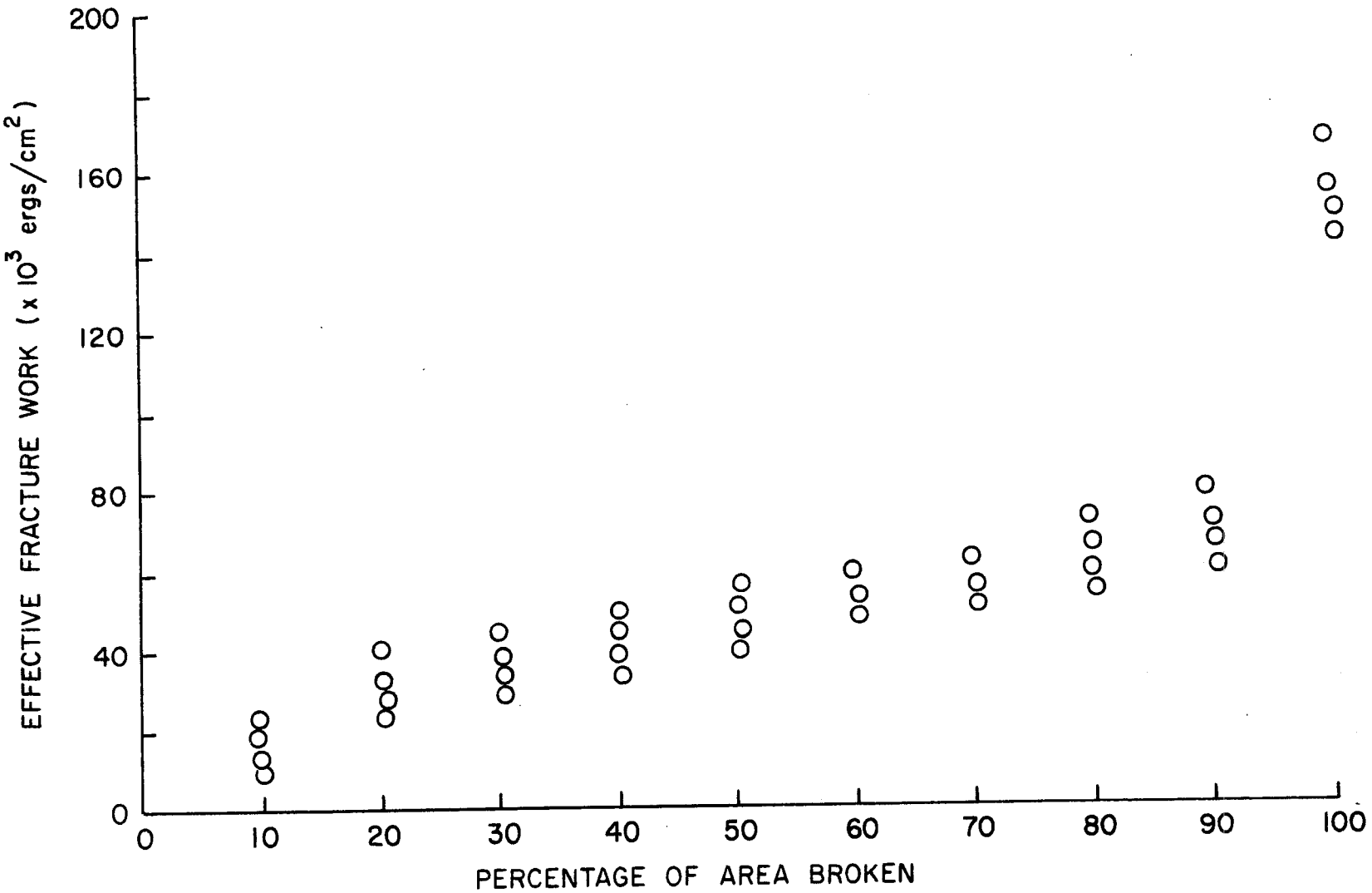

Figure 7. Effective Fracture Work vs. Percentage of Area Broken in Marble.

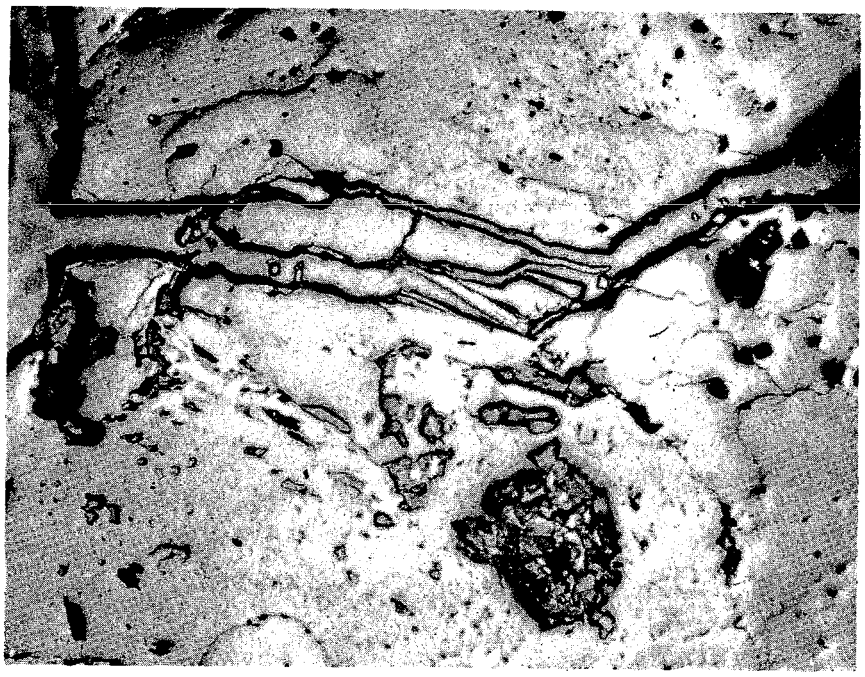

Figure 8a. Showing Part of the Notch and Extensive Side Cracking in Granite. 50X

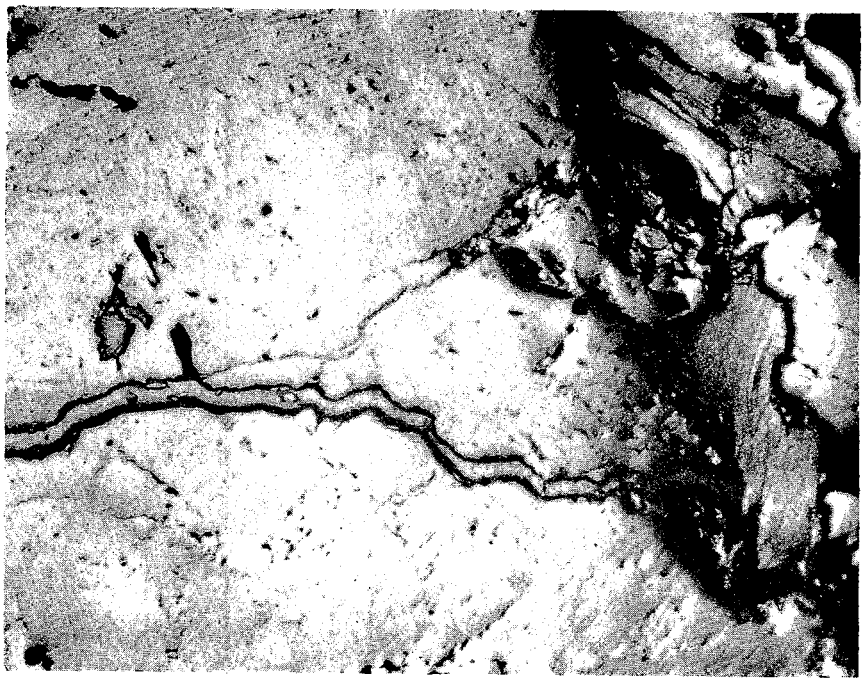

Figure 8b. Showing the Deflection of the Fracture Path Around a Hard Grain in the Granite. 50X

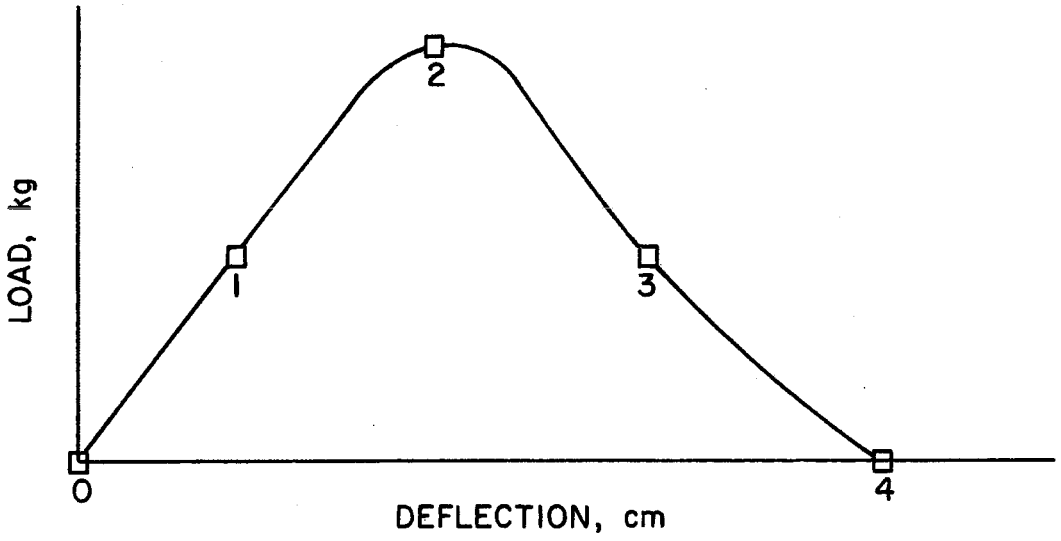

Figure 9a. Load-Deflection Curve for Notched Samples.

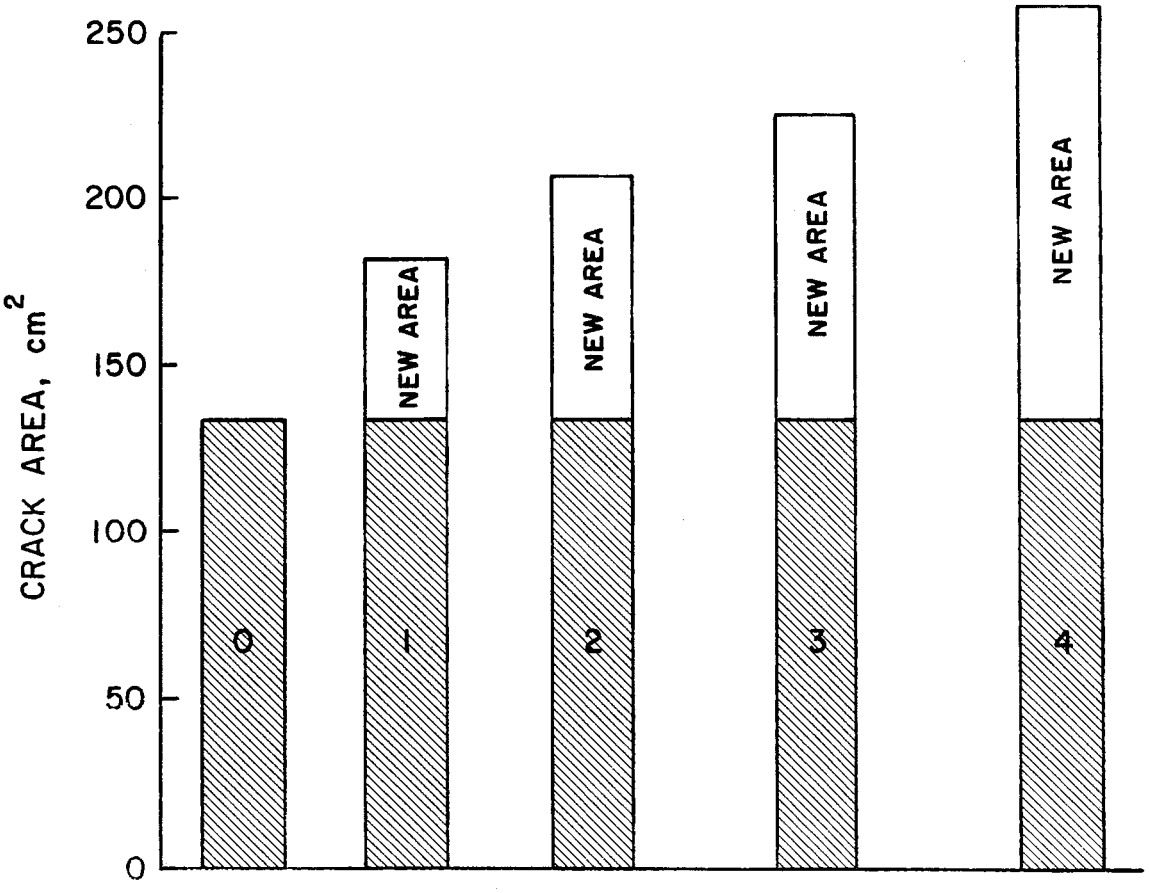

Figure 9b. Crack Area for Specific Points from Figure 9a.

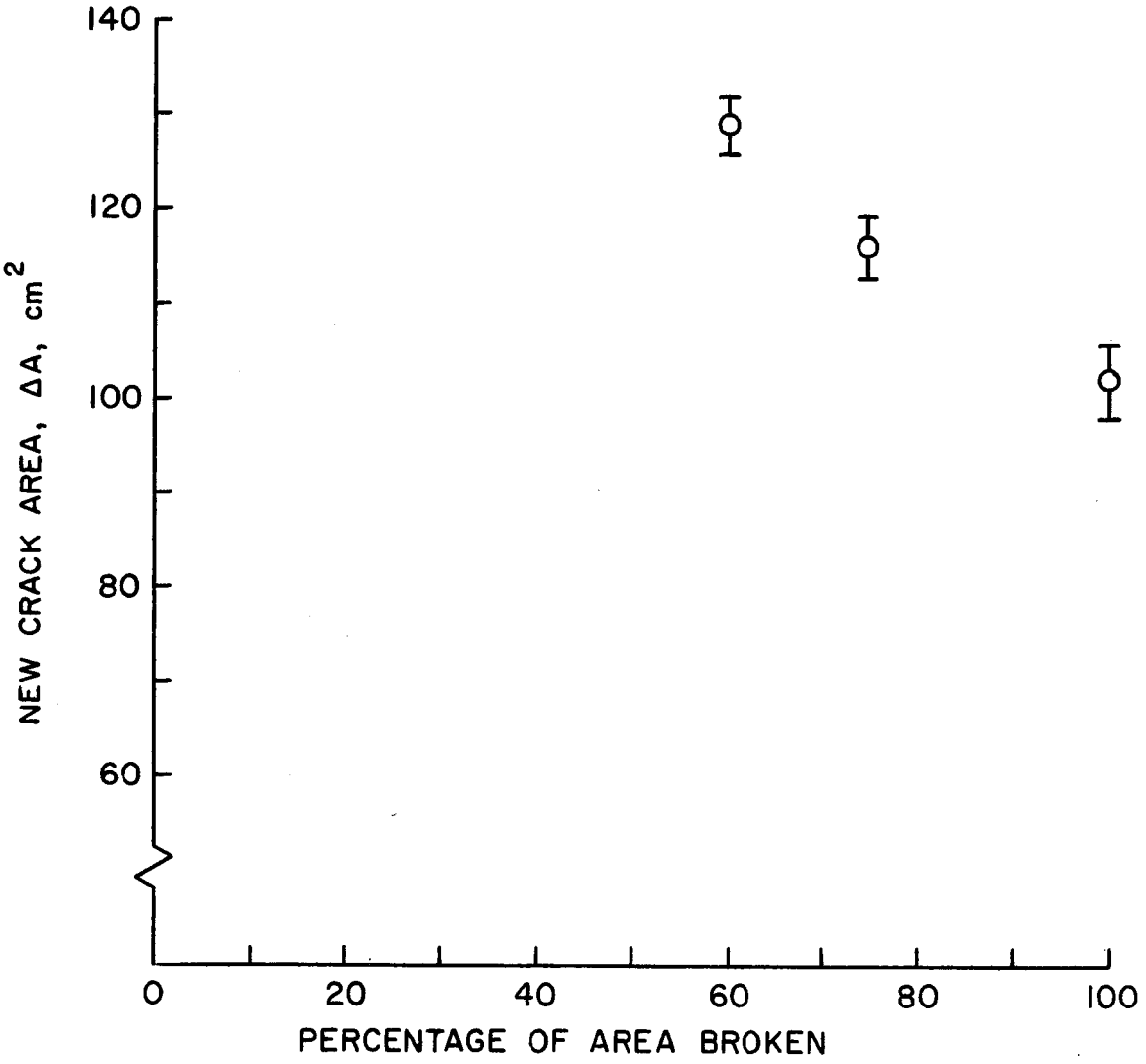

Figure 10. Variation of ΔA with Percentage of Area Broken.

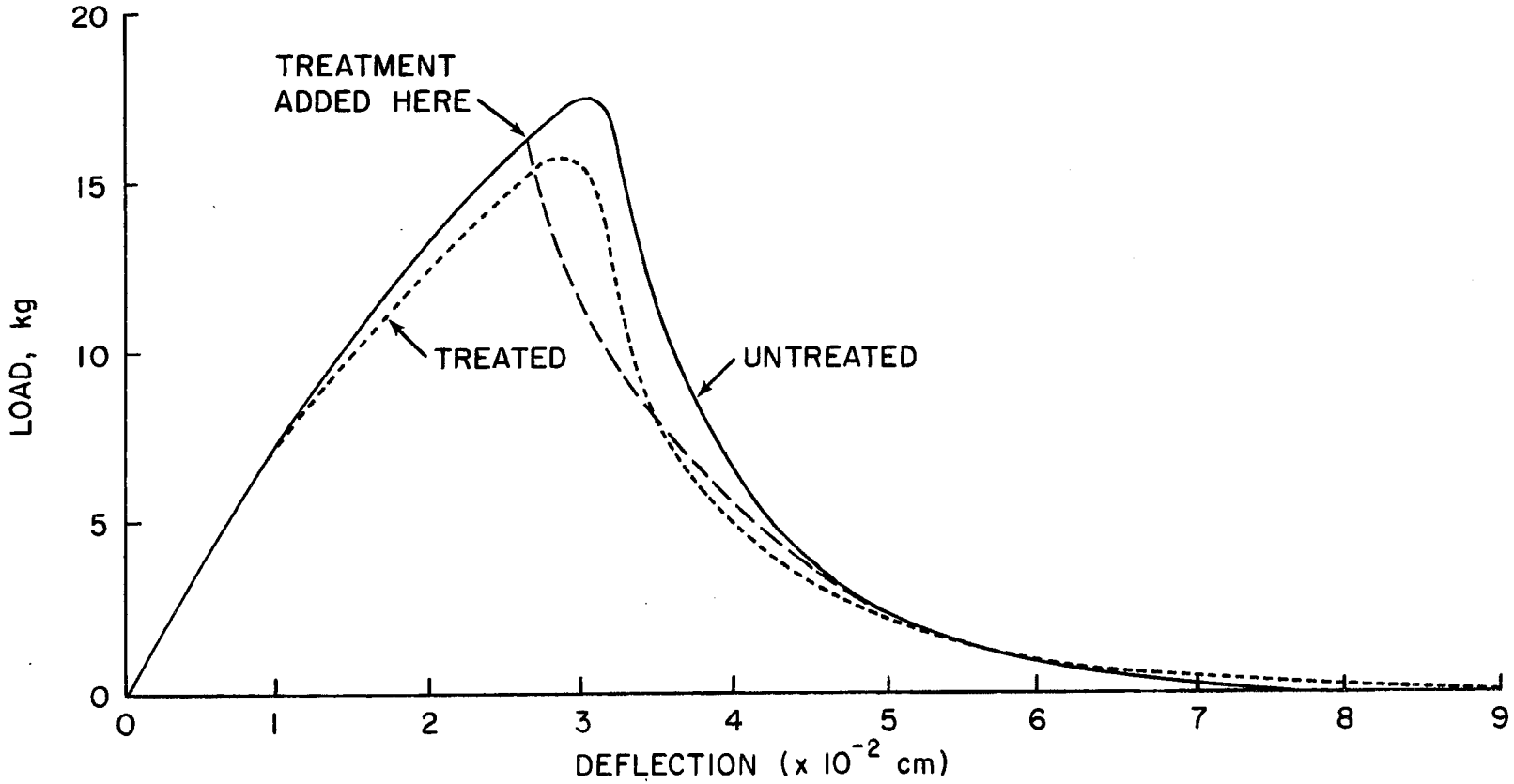

Figure 11. Load-Deflection Curves for Untreated and Treated Granite Beams.

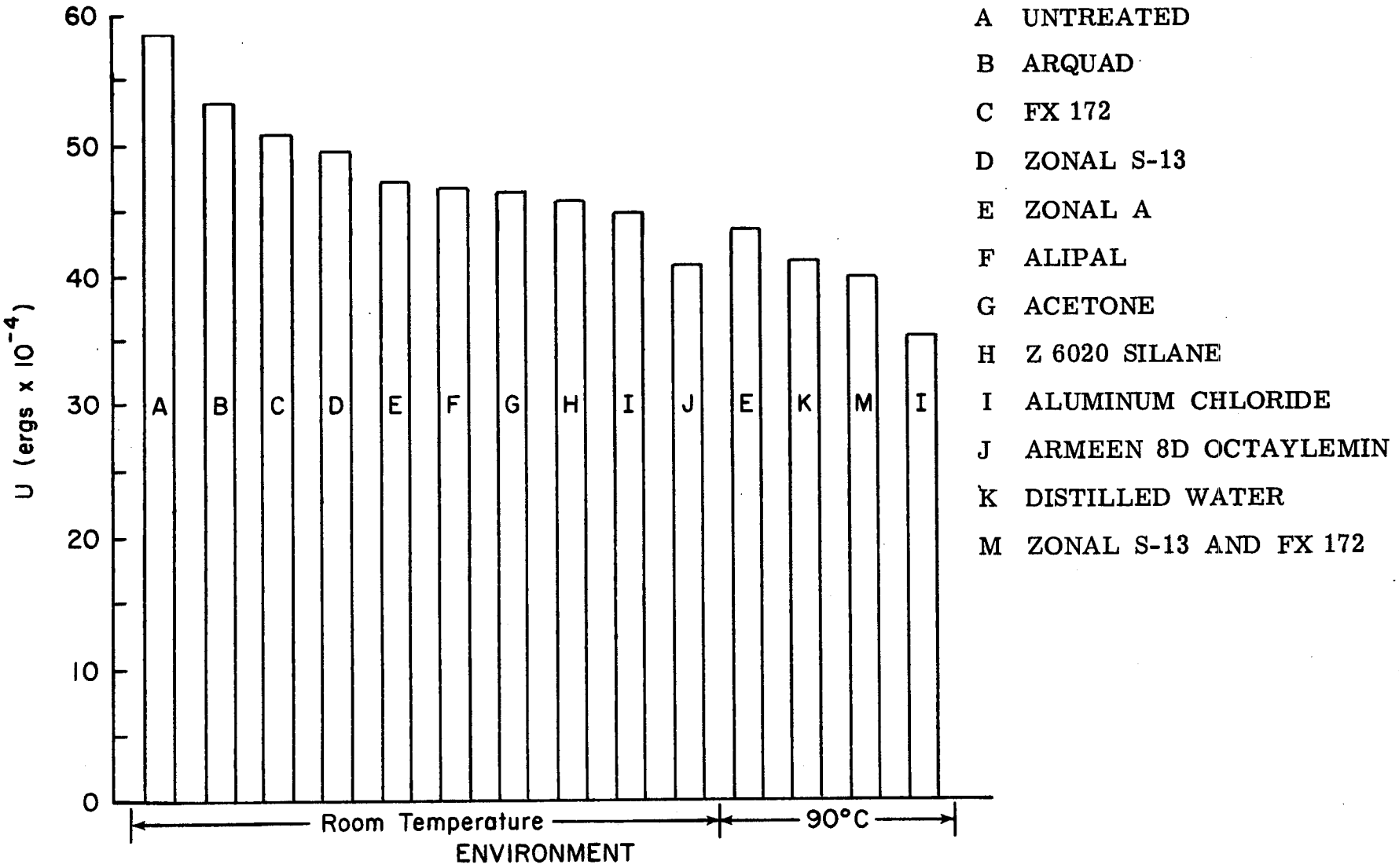

Figure 12. Effect of Environment on Input Energy.

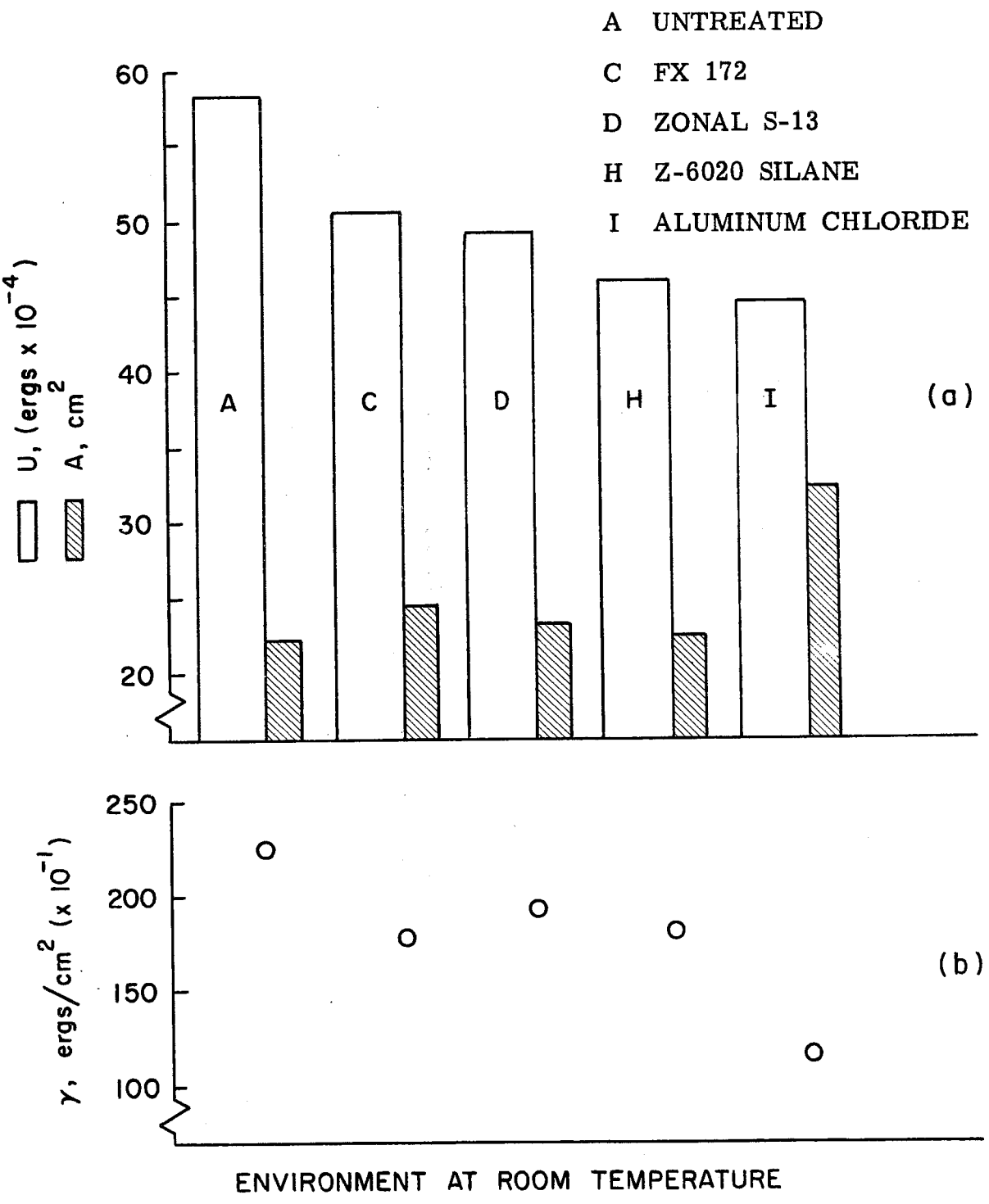

Figure 13. Effect of Environment on Measured Crack Area and γ at Room Temperature.

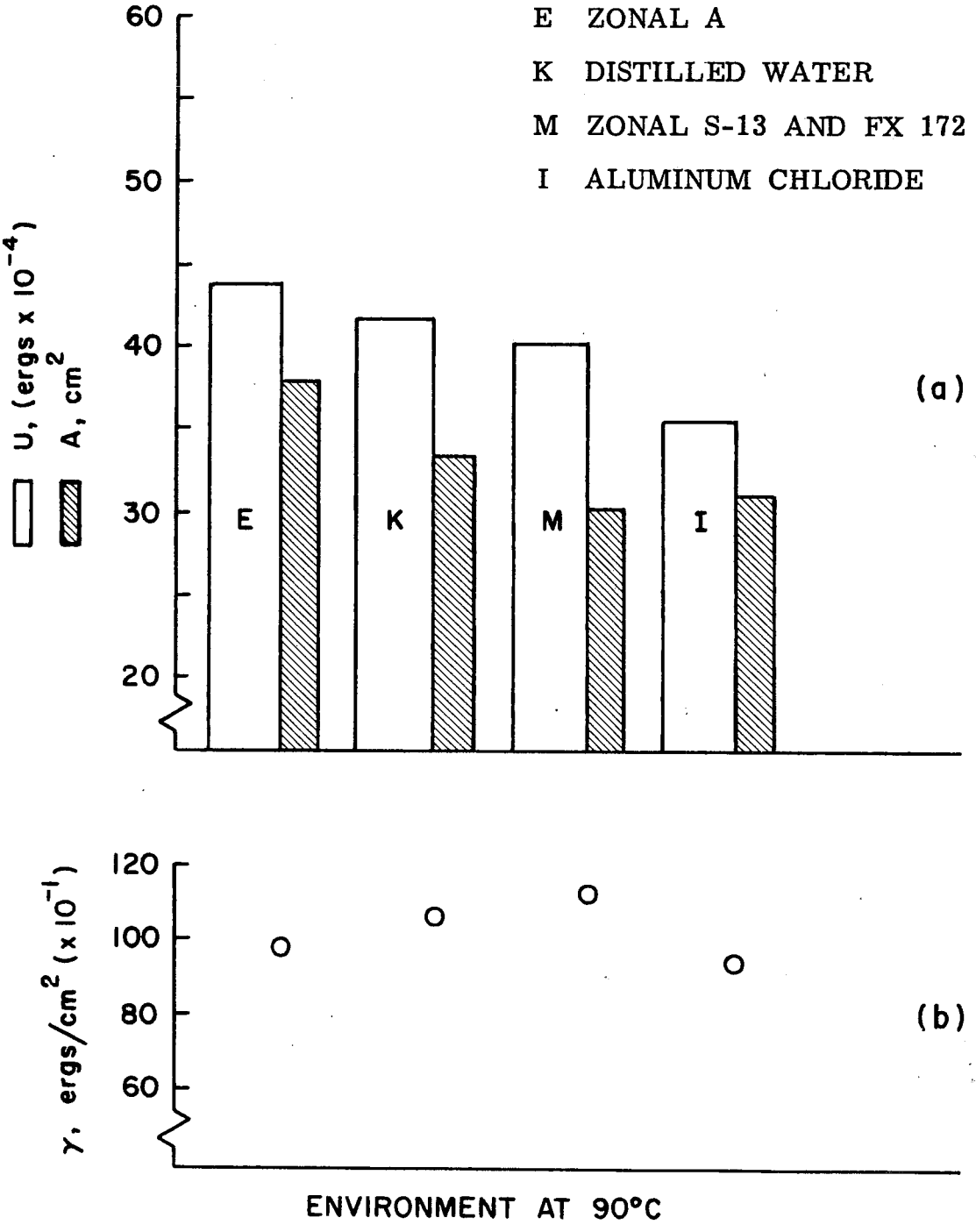

Figure 14. Effect of Environment on Measured Crack Area and γ at 90° C.

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