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TECHNICAL REPORT
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THE EFFECTS OF MOISTURE CONTENT ON THE ENERGY DISSIPATION CHARACTERISTICS OF PAPER HONEYCOMB

by

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FOREWORD

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TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

The effects of absorbed moisture on the energy-dissipating characteristics of paper honeycomb were first studied in the Structural Mechanics Research Laboratory at the Univeristy of Texas at Austin and reported in 1959. In this study, results of the former study are reexamined and most of the earlier experimental work is repeated using improved techniques. Results indicate that moisture content has no significant effect on average crushing strength, or the energy-dissipating capacity of paper honeycomb until the moisture content exceeds 14% of the dry weight of the sample. Taking into consideration the slow rate at which paper honeycomb absorbs moisture from the air, it is concluded that moisture content is not likely, under ordinary circumstances, to be a significant consideration in the use of paper honeycomb as a cushioning material. This conclusion is essentially the same as the one reached as a result of the earlier study.

Introduction

In May 1959 the Structural Mechanics Research Laboratory at the University of Texas at Austin reported on studies of the effects of moisture content on energy-dissipation characteristics of paper honeycomb(1). As a result of that study, it was concluded that the effects of moisture content on energy dissipation under dynamic loading are not as significant as the effects under static loading and that under dynamic loading, moisture contents of 14% or less do not significantly modify the energy dissipating characteristics. It was also observed that changes in impact velocities from 30 to 90 ft/sec had no significant effect on energy-dissipating characteristics regardless of moisture content. It was also pointed out that an investigation conducted at the Forest Products Laboratory(2) had shown that paper honeycomb attains a moisture content of 17% after 2 days of exposure at 80°F and 90% relative humidity. A 14-day exposure is required under the same conditions to attain a 20% moisture content. The maximum or equilibrium moisture content under those conditions is only slightly greater than 20%. Those tests also showed that if paper honeycomb is exposed to an atmosphere of 65% relative humidity at 80°F for 14 days, a moisture content of only 11% is attained. All of the Forest Products Laboratory tests were made on 4 × 4 × 3-inch samples. Obviously the rate at which moisture is absorbed will depend to some extent on the dimensions of the sample and, in particular, on the ratio of surface area to volume. It would be expected, however, that the rate of moisture absorption would be much lower for a 3' × 8' × 3-inch plank of honeycomb than it would be for a 4 × 4 × 3-inch sample.

It appears, on the basis of those earlier studies, that moisture content is not a problem under the ordinary conditions enccountered in the use of paper honeycomb as an energy dissipator for air drop.

From time to time, however, those earlier conclusions have been questioned by users of paper honeycomb, and some users remain unconvinced that moisture is not a problem. Questions which have been raised are not based on extensive investigations, but are prompted by isolated non-quantitative observations. To the best of the authors' knowledge, no other comprehensive investigations of the effects of moisture content on energy dissipation have been undertaken.

In view of these doubts which have occasionally risen concerning the effects of moisture content, it was decided that the results obtained in the earlier study, and the techniques used, should be reexamined.

After reexamining those earlier results, one can only conclude that moisture content does not become a problem so far as reduction in energy-dissipation capacity is concerned until the content exceeds about 14%. This, when coupled with the Forest Products Laboratory results, indicates that as was previously concluded moisture content is not going to be a problem so far as air-drop practice is concerned except under very unusual circumstances. However, reexamination of the experimental techniques used in the earlier studies has revealed some aspects which may be questionable and indicates a need for repeating a part of the earlier investigation with modifications in some of the procedures followed.

Revised Experimental Procedure

In the earlier study, 2' × 2' × 3-inch test samples were cut from selected planks and marked with identifying numbers. Immediately after these samples were oven-dried, they were weighed and placed in plastic bags along with the amount of water which, when absorbed in the paper, would make the moisture content some specified value, such as 10%. The bags were then sealed and shipped from the U.S. Army Natick Laboratories where they were prepared, to Austin, Texas for testing. They were left sealed in the plastic bags until just before testing.

The two details of this procedure which might raise some doubt as to the validity of the test results are (1) the oven drying, and (2) the moisturizing.

Oven Drying. There is no direct evidence to suggest that oven drying alters in any way the characteristics of the material. The possibility does exist, however, that subjecting the glue or the paper to high heat (250°F) for a prolonged period of time may cause some alteration in the properties which would appear in these tests as a moisture-content effect.

Moisturizing. It was assumed that if free moisture and a dry honeycomb sample were sealed in a watertight container, the moisture would be absorbed by the paper and in due time an equilibrium condition would be reached with a moisture content determined by the amount of water placed in the bag. Frequently, when the tests were being conducted, moisture would be found condensed on the inside of the plastic bag. Obviously, the specimens in those bags did not have the calculated moisture content, nor did any of the samples necessarily have the moisture that was absorbed uniformly distributed throughout the sample. It was assumed that the samples would be in the bags long enough for the moisture to become uniformly distributed, but no measurements were made to determine whether it was or not.

The new test procedures described below were designed to eliminate those questionable aspects of the old procedure.

Planks of commercially fabricated 80-0-1/2 untreated paper honeycomb were selected for the program by visually examining them for uniformity of cell size. Each plank was then cut into twelve 16 × 18-inch samples which were marked to identify the planks from which they were cut. The facings on each side of each sample were then perforated with a 3/16-inch rod to provide ventilation through each cell as shown in Fig. 1. Since the spacings and dimensions of the cells in this commercially fabricated honeycomb are non-uniform, the perforation of the facing is a very tedious hand process. The perforation is considered necessary, however, to speed up the moisturization procedure. Complete removal of the facing was tried but given up, because samples from which the facing had been removed tended to distort by warping during drying and moisturizing.

The exact details of each test will be tabulated, but the general procedure consisted of taking 2 samples from each set of 12 (one plank), and oven drying these two to establish the moisture content and, hence, the dry weight of each sample of the set. The remaining samples were then dehumidified in a dryer constructed for this purpose. The drier, or dehumidifier, shown in Fig. 2, consists of an airtight chamber with a bed of silica gel in the bottom and a fan which circulates the air through the silica gel and then through the specimens. In this chamber the moisture content can be reduced to about 2.5% referred to the oven-dry condition. To establish when equilibrium has been reached, samples are removed from the chamber periodically and weighed. Weights are plotted as a function of time, and when the curve appears to have become asymptotic to some value, equilibrium is assumed to have been reached.

To establish other than the minimum moisture contents, another specially constructed chamber is used. The chamber, shown in Fig. 3, is airtight and contains a circulating fan. The moisture content which a sample will reach in this chamber is determined by the vapor pressure within the chamber. This pressure is controlled by putting plastic trays of dilute sulfuric acid in the bottom of the chamber. The determination of the concentration of the solution required for reaching a given moisture content in the samples is discussed in the Appendix. To establish when equilibrium is reached, the same procedure used during the drying is followed. Specimens are removed from the chamber periodically and weighed.

Typical curves of moisture content versus time during oven drying, drying in the dehumidifier, and during moisturization are shown in Figs. 4 & 5.

When the desired moisture content is established, the specimens are tested in the laboratory stress-strain curve

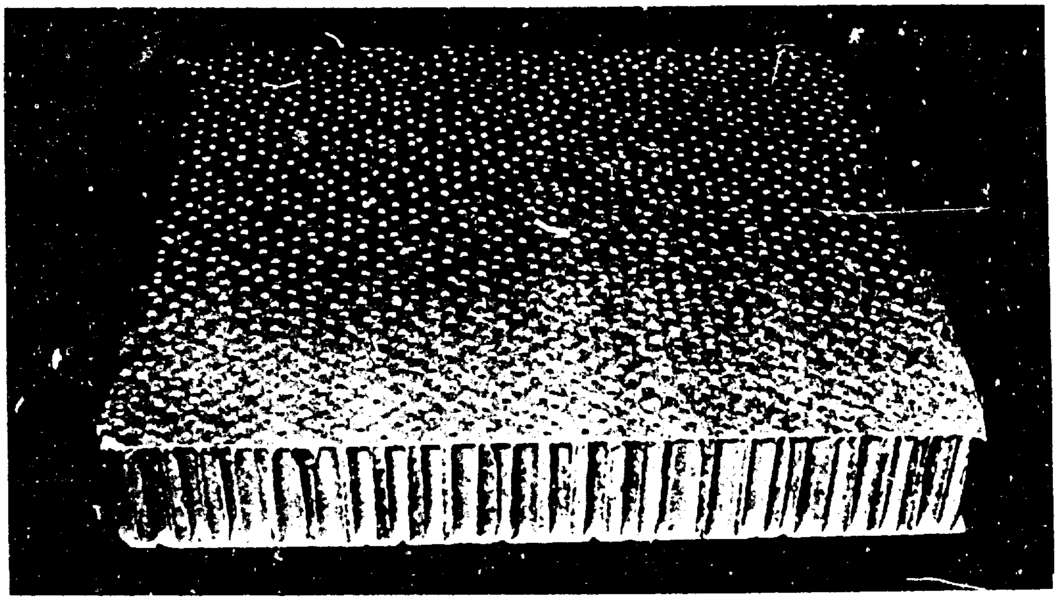

Fig. 1 Perforated Honeycomb

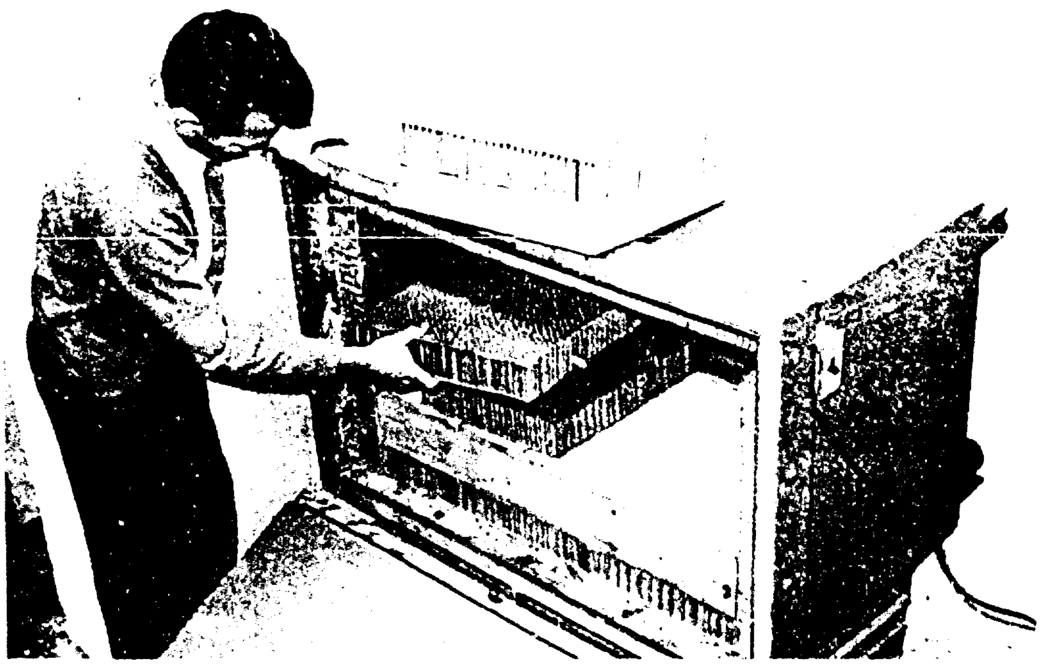

Fig. 2 Dehumidifier

Fig. 3 Moisture Chamber

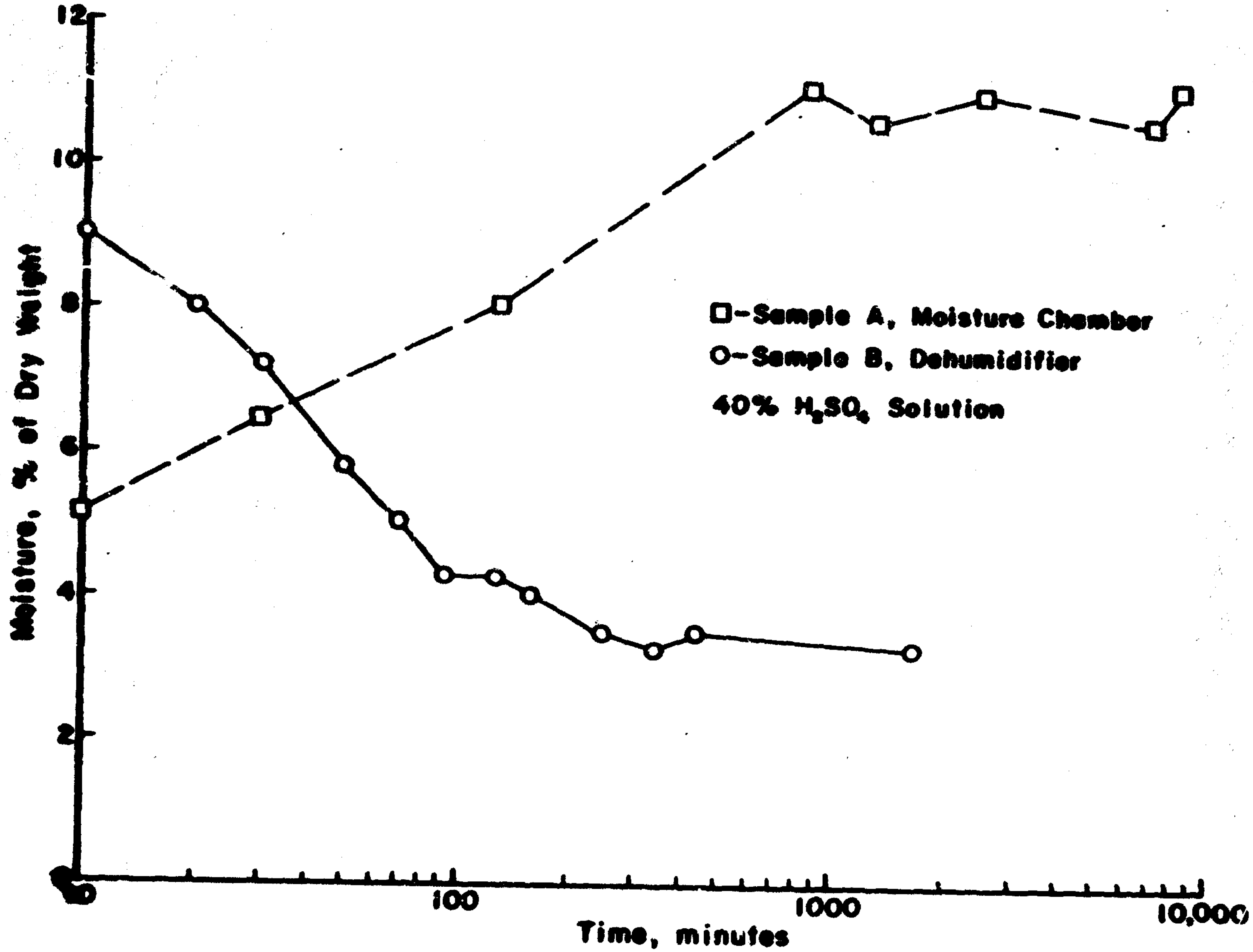

Fig. 4 Moisturizing and Drying Curve

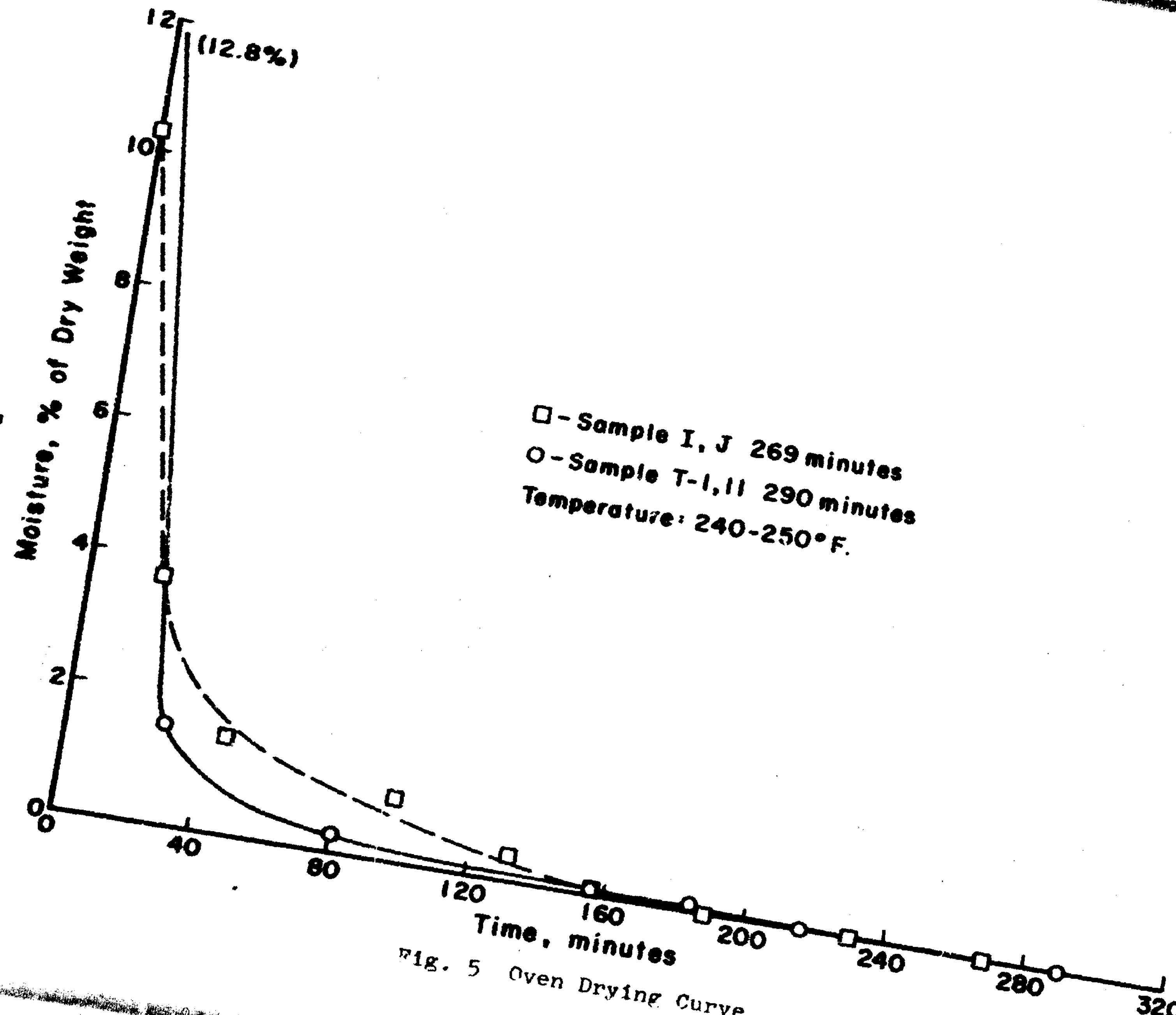

Fig. 5 Oven Drying Curve

generator shown in Fig. 6. For a 561 lb. mass and the impact velocity of 24 ft/sec provided by this tester, a two-pad stack of specimens 2 square feet in area is required. Consequently, each set of 12 specimens provides for 6 tests.

In addition to determining the effect of moisture content on energy dissipation or average crushing strength, a special set of tests has been conducted to determine whether oven drying has any effect, not connected with the loss of moisture, on energy dissipation.

Test Results

The details of the treatment of each sample (each set of two pads) and the average crushing strengths are shown in Tables I, II, and III.

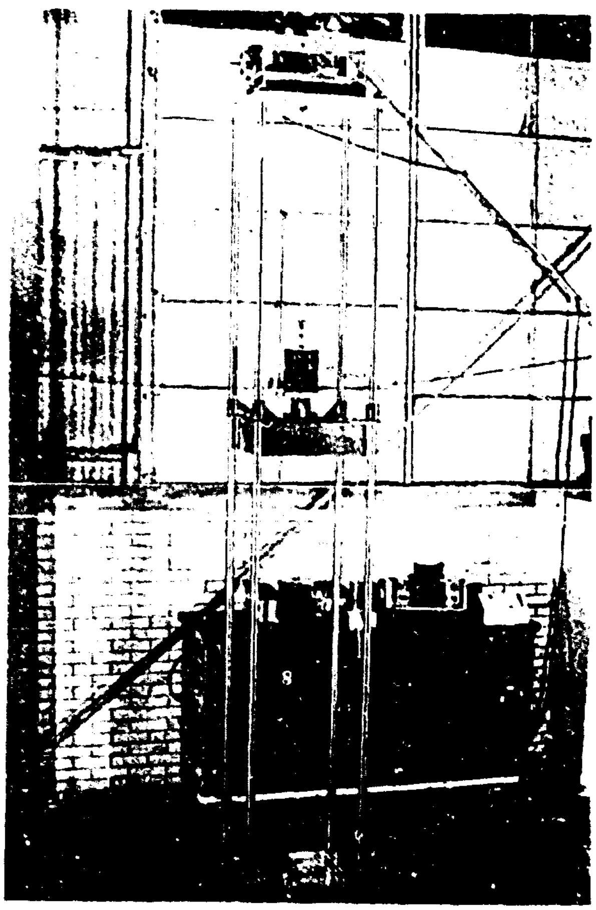

Fig. 6. Stress-Strain Curve Generator

Table 1

Variation of Crushing Strength with Moisture Content

Sample	Moisture Content (%)	Average Crushing Stress (psf)	Sample Treatment
D1,11	0	5490	oven dried
*E1,11	0	No data	oven dried
*F1,11	0	No data	oven dried
D2,10	4.5	5660	dehumidifier
E2,10	5.0	5250	dehumidifier
F2,10	4.7	5550	dehumidifier
D3,7	9.9	5450	as received**
E3,7	9.4	5370	
F3,7	9.4	5500	
D4,8	14.1	4750	moisture chamber
E4,8	14.6	4800	moisture chamber
F4,8	14.1	4830	moisture chamber
T2,10	15.7	4330	moisture chamber
T3,7	15.6	4500	moisture chamber
T4,8	15.6	4320	moisture chamber
T5,9	15.9	4060	moisture chamber
T6,12	15.6	4140	moisture chamber
D6,12	16.4	3860	moisture chamber
E6,12	16.8	3920	moisture chamber
*F6,12	16.5	No data	moisture chamber
S2,10	17.4	3900	moisture chamber
S3,7	16.8	4010	moisture chamber
S4,8	17.5	3730	moisture chamber
D5,9	22.0	3580	moisture chamber
E5,9	22.0	3530	moisture chamber
F5,9	22.0	3650	moisture chamber

*No average stress obtained-equipment malfunction.

**"As received" means at the moisture content attained while in storage.

Series D, E, & F were prepared as described above, i.e., 2 sample pads were oven-dried and tested, 2 were dried in the dehumidifier, 2 were tested "as received", and the remaining 6 pads were moisturized until equilibrium was established at the indicated moisture contents.

Series S and T were added after the D, E, & F series had been completed, to obtain additional data points in the 14 to 18% moisture range. The dry weights of the specimens in the S & T series were established by oven-drying one sample just as they were for the other series. However, average crushing strengths were not determined for the oven-dried samples.

Table II

Effects of Facing Paper Perforation

Sample	Perforated	Moisture Content (%)	Average Crushing Stress (psf)	Sample Treatment
M1,11	yes	0	4910	oven dried
M2,10	yes	0	5270	oven dried
*G1,11	yes	0	No data	oven dried
M4,8	no	9.5	5100	as received
M6,12	no	9.5	5020	as received
G3,7	yes	10.7	5400	as received
G4,8	no	11.4	5050	as received
G4,9	no	10.5	5100	as received

*No average stress obtained-equipment malfunction.

The M & G series are incomplete in the sense that there are 4 tests rather than 6, in each series. These tests were included to provide some data regarding the effects that perforating the facing might have on the crushing strength. The results in this tabulation may also be compared to the results shown in Table I for the "as received" condition. All specimens shown in Table I were perforated. These results indicate that if the perforations have any effect, it is one of increasing rather than decreasing the average crushing strength. The average 4 unperforated specimens is 5067 psf, while for 4 perforated specimens the average is 5430 psf. This is surprising, but at the present time is not believed to be a significant difference. The effect should be investigated further, but in consideration of the relatively small difference noted, the normal variation in crushing strengths, and the fact that all test results in this study other than those shown in Table II were obtained with perforated specimens, it is not appropriate to pursue the subject further in this study of moisture effects.

The variations in moisture contents for the "as received" specimens is somewhat puzzling. It was expected that these values would be quite uniform. A part of the variation may be attributed to making the tests on different days. There was a 2-day interval between the M series tests and the G series, but all the tests for a particular series were made on the same day. A total of 4 weighings is involved in each moisture content determination. An error of 1 gram in a weighing is an error of 0.25%. If these errors are all of the same sign, the 4 weighings would result in a total error of 1.0%. Thus a maximum variation of ±1% or a 2% spread, as a consequence of weighing errors is possible. It is not considered very likely, however, particularly in view of the smaller variations observed in the other tests, such as the D, E, & F series. A more acceptable conclusion is that the difference in moisture content shown in Table II are real differences caused perhaps by the location of the specimens while they were in storage awaiting testing. At any rate, when all the results are examined, it is seen that these variations of 1 to 2% in moisture content are not significant in the range of moisture content where they occur.

Table III

Oven-Drying Effects

Sample	Moisture Content (%)	Average Crushing Stress (psf)	Sample Treatment
Z1,2	0	5030	oven dried
Z3,4	0	4880	oven dried
Z5,6	0	5020	oven dried
Z7,8	0	5210	oven dried
Z9,10	0	5270	oven dried
*Z11,12	0	No data	oven dried
X9,10	0	4820	oven dried
X11,12	0	5160	oven dried
Y1,2	0	4780	oven dried
Y3,4	0	5060	oven dried
X5,6	3.0	4940	dehumidifier
X7,8	3.0	5230	dehumidifier
Y5,10	6.3	5200	oven dried
Y11,12	6.3	5000	moisture chamber
X1,2	10.3	4490	dehumidifier
X3,4	10.3	4830	moisture chamber
Y6,7	10.6	4890	oven dried
Y8,9	10.2	4920	moisture chamber

*No average stress obtained-equipment malfunction.

The Z-series of specimens were all oven dried and tested in that condition to establish the crushing strength of this particular honeycomb in the oven-dry condition. The X-series specimens were dried in the dehumidifier, with the usual oven drying of 2 specimens to establish the initial dry weights of all specimens. After drying in the dehumidifier, specimens were remoisturized in the moisture chamber as indicated. The Y-series specimens were all dried in the oven, and then remoisturized as shown. These tests were designed to reveal the effects, if any, of the moisture history and, in particular, the effect of oven drying.

The individual crushing strengths shown in Tables I, II, and III are averages over that portion of the stress-strain curve between 0 and 70% strain. To obtain these average values, the procedure outlined in Ref. 3 was followed. A stress-strain curve typical of all those obtained in this investigation is shown in Fig. 7.

All of the average crushing strengths given in the Tables

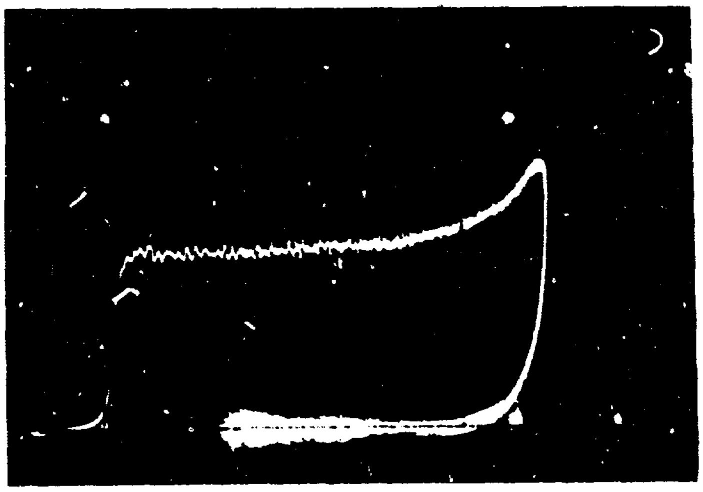

Fig. 7 Typical Stress-Strain Curve

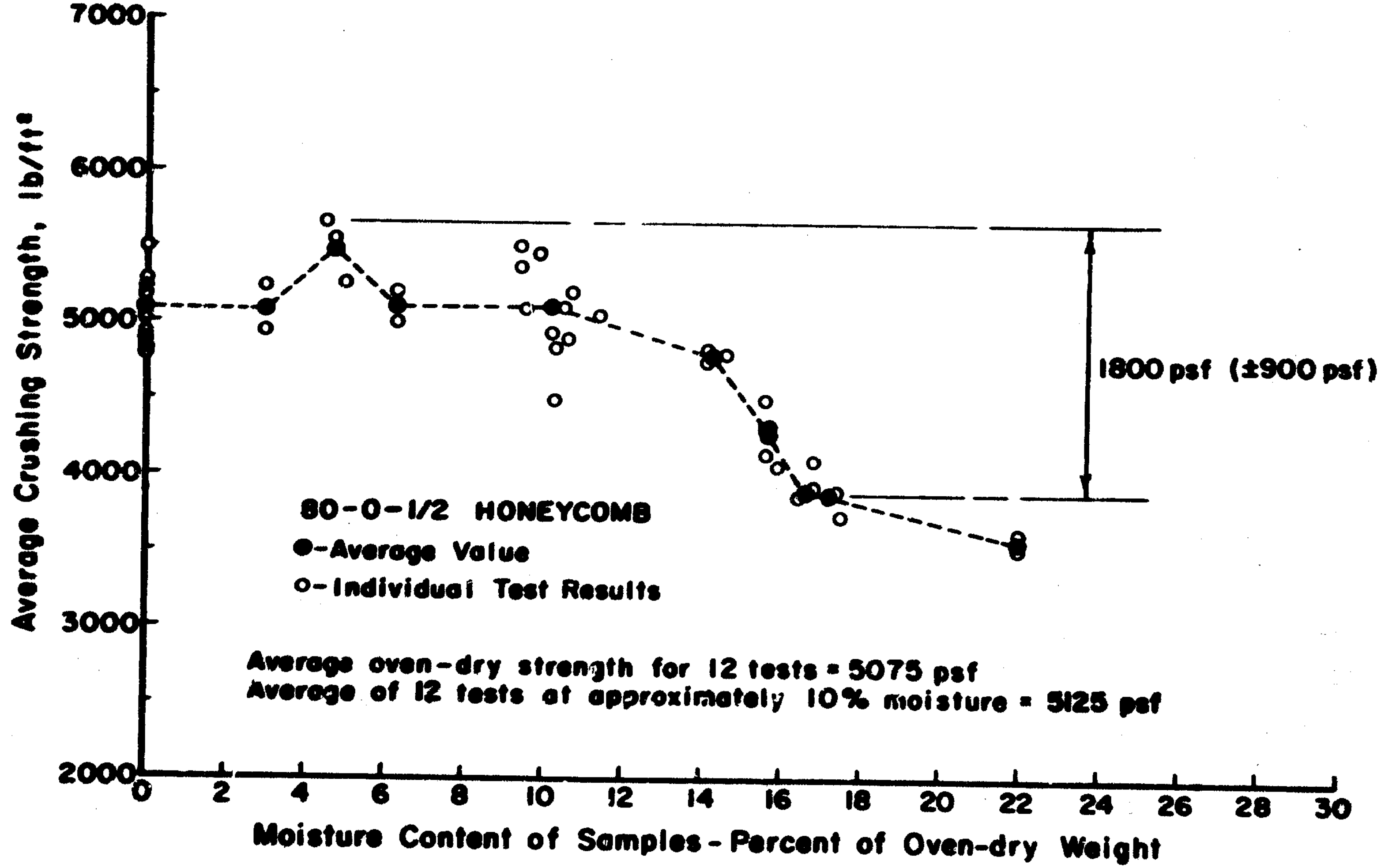

Fig. 8 Variation of Average Crushing Strength with Moisture Content

are shown in Fig. 8 plotted as a function of moisture content. It is clear from this presentation that there is no significant variation in crushing strength with moisture content in the range from zero to 12% moisture. In fact, the lowest crushing strength for individual oven-dried specimens is essentially the same as the crushing strengths at 14% moisture. The presently specified tolerance of ±900 psi for the average crushing strength covers the entire range of crushing strengths observed between the oven-dried condition and 16% moisture. This means that the effect of moisture on crushing strength in this range is less than the effect of manufacturing variations which are presently considered acceptable. It might also be considered to mean that if the moisture content at the time of test could be specified, the present ±900 psf tolerance limits might be reduced. For this conclusion to be acceptable, it would have to be shown that at the time of testing, the moisture contents can exceed 15%. Experience with honeycomb testing in the Engineering Mechanics Research Laboratory indicates that moisture content is not likely to exceed 12% under normal climatic conditions.

Conclusions

1. Moisture content has no significant effect on average crushing strength until a content of approximately 14% has been exceeded. Thus the results of this investigation are in agreement with those of the study made in 1958.

2. Oven drying has no apparent effect on average crushing strength other than the effect related to the moisture content.

3. The moisture history of a specimen has an insignificant effect on average crushing stress in comparison to the effect of moisture content at the time of testing.

4. There are other factors, which cannot be pin-pointed at the present time, which cause greater variations in average crushing strength between 0 and 10% moisture content than can be attributed to the moisture content.

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2. Hopf, J. P., Equilibrium Moisture Content of Paper Honeycomb and its Effect on Energy Absorption, Forest Products Laboratory, Project No. 7-87-03-004B, Report No. 1, Dec. 1955.

3. Engineering Mechanics Research Laboratory, The University of Texas (Austin), A Dynamic Stress-Strain Curve Generator, May 1967.

Appendix

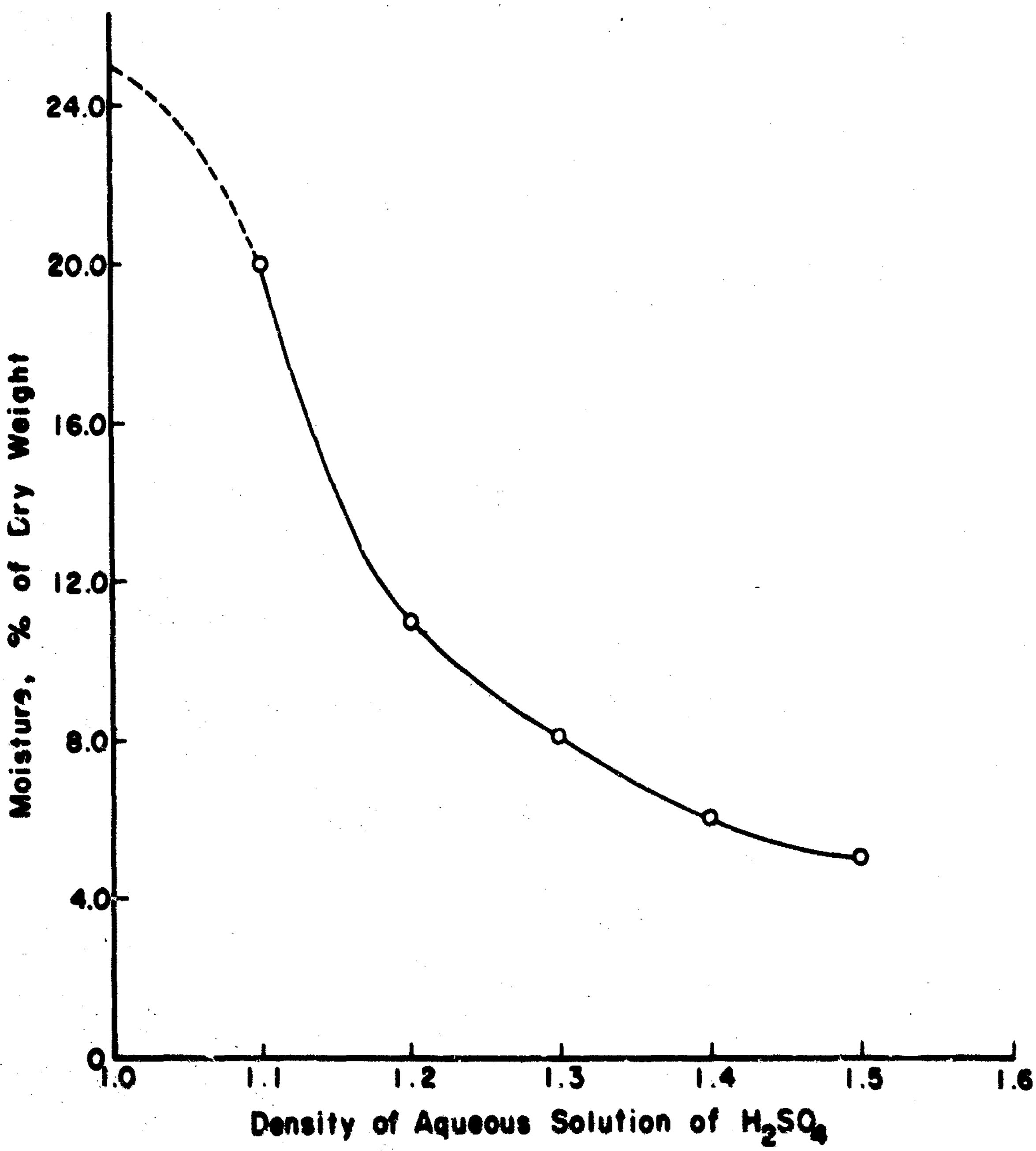
Moisturizing Paper Honeycomb over Aqueous Solutions of Sulfuric Acid in a Closed Chamber

The relative humidity, or the vapor pressure, at a given temperature over a mixture of sulfuric acid and water in a closed vessel is a very precise function of the density of the solution. The density, of course, is a function of the amount of acid in the solution. This suggests that a given moisture content in paper honeycomb samples can be rather simply achieved by enclosing the sample in a vessel along with a tray containing an aqueous solution of sulfuric acid of the proper density.

The Handbook of Chemistry and Physics contains tables of vapor pressure, relative humidity, and density of solution, for various sulfuric acid concentrations. Some representative values are tabulated as follows.

Density of Solution	% Sulfuric Acid Weight	Vol.	Relative humidity (%)	Vapor Pressure at 20°C (mm Hg)
1.0	0	0	100	17.4
1.1	15	7.9	93.9	16.3
1.2	27.9	18.4	80.5	14.0
1.3	39.7	28.0	58.3	10.1
1.4	50.5	38.3	37.1	6.5
1.5	60.1	49.0	18.8	3.3
1.6	69.0	60.0	8.5	1.5
1.7	77.7	72.0	3.2	0.6

The equilibrium moisture contents of paper honeycomb in various ambient relative humidities have been determined experimentally and the results are shown in the following figure as a function of the density of the sulfuric acid solution. The moisture absorbed by the honeycomb is somewhat sensitive to temperature as well as the sulfuric acid concentration. Since there was no temperature control on the moisturizing chamber, the temperature fluctuated somewhat. Consequently, the curve shown should not be regarded as precise.



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13. ABSTRACT

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	ROLE	WT	ROLE	WT	ROLE	WT
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Energy dissipation	7					
Paper honeycomb	7					
honeycomb structures	7					
Impact shock	4					
Insulation	4					

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