ULTRASONIC TESTING AS A MEANS OF DETECTING FATIGUE DAMAGE IN CEMENT MORTAR

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ABSTRACT

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Body of Abstract

The purpose of this investigation was to detect fatigue damage prior to fracture by means of the change in attenuation of an ultrasonic signal. The investigation was carried out on cement mortar beams subjected to completely reversed flexure.

An ultrasonic signal of from 112,000 to 120,000 cycles per second was transmitted through the length of a cement mortar beam which was subjected to completely reversed flexure at the rate of 1,800 cycles per minute. The level of the output signal was plotted against signal frequency at intervals during the test to obtain a frequency response curve. A composite output was obtained by taking the area under this curve, and the drop in composite output as the test progressed was taken as an indication of fatigue damage within the mortar.

There was continuing drop-off in composite output with increasing numbers of cycles for a sufficiently high stress level. For a sufficiently low level of stress, there was no change in composite output with increasing numbers of cycles tested. It was concluded that this method may have possibilities as a means of investigating cumulative fatigue damage and associated phenomena.

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INTRODUCTION

Purpose. The purpose of this investigation was to detect fatigue damage prior to fracture by means of the change in attenuation of an ultrasonic signal. The investigation was carried out on cement mortar beams subjected to completely reversed flexure.

Background. The present investigation was an outgrowth of work done by Dr. J. T. McCall for the Michigan State University Engineering Experiment Station on the fatigue of plain concrete. The instigating idea was that if one could detect fatigue damage before fracture and follow its progress, this might lead to increased basic knowledge of the fatigue process, to a better understanding of the cumulative fatigue damage concept, and to further information on the "self-healing" of concrete. It was proposed to investigate cement mortar beams and limestone beams separately because of the greater uniformity of these concrete constituents, as compared to concrete beams. Moreover, an understanding of the contribution of the individual constituents should lead to a better understanding of the fatigue of concrete itself than could be obtained from an investigation on concrete alone. The present investigation represents a start towards this goal.

Current theories of fatigue and most of the literature on fatigue are based on fatigue of metals, and rest heavily on the phenomenon of slip. The fatigue of brittle materials has received much less attention and is apparently pursued as a separate topic. In particular, the literature on fatigue of concrete is quite limited; a comprehensive bibliography is given by Nordby.

The writer found nothing in the literature which would bear directly on this investigation. However, references cited in the BIBLIOGRAPHY are ones which were either helpful in suggesting ideas and increasing general knowledge in the area of ultrasonics or useful in developing the instrumentation, as the annotations in the BIBLIOGRAPHY indicate.

THE INVESTIGATION

Specimens. Test specimens were cement mortar beams 3 inches square and $14\frac{1}{2}$ inches long. They were made of type I portland cement and natural sand in the proportion 1:3.3 with a water/cement ratio of 0.52. The mortar was mixed in a Lancaster mixer and placed in steel molds in two layers; each layer was vibrated for five seconds. The beams were removed from the molds after twenty-four hours and placed in the moist room for three months. They were then removed to the testing laboratory where they were stored until used.

Instrumentation. The identification numbers for the equipment listed below refer to Figure 1.

(1) Sonntag model SF-1U universal fatigue testing machine, used to load the mortar beam (2) in flexure at 1,800 cycles per minute.

(3) General Ultrasonics model GU-400 (modified) ultrasonic generator, used to apply a CW (continuous wave) signal to

(4) barium titanate transmitting crystal (one inch in diameter by one inch thick), which transferred the CW electrical signal to the mortar beam in the form of a compression wave.

(5) Receiving crystal (same type as the transmitting crystal), which picked up the transmitted compression wave from the end of the mortar beam and converted it back to an electrical signal.

(6) Rectifier and filter, used to convert the transmitted

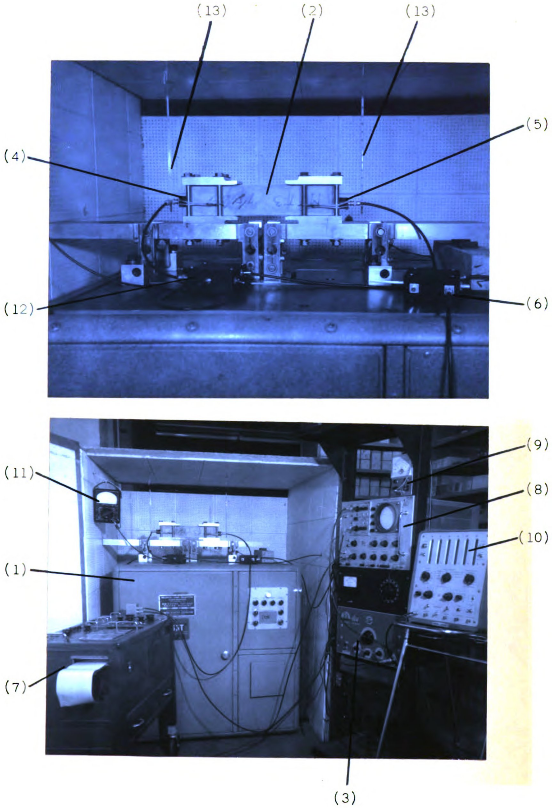

Figure 1. Instrumentation

signal to DC (direct current)for the

(7) Sanborn model 60-1300 chart recorder, used to register the level of the signal transmitted through the beam.

(8) Tektronix type 532 oscilloscope used to monitor input and output signals and to provide a DC calibrating voltage for the recorder.

(9) Fico model 323 vacuum tube voltmeter, used to check calibrating voltage.

(10) Hewlett-Packard model 523B electronic counter, used to measure frequency of signal output of the ultrasonic generator.

(11) Triplett model 630 multimeter, used to monitor transmitting crystal current.

(12) Meter rectifier.

(13) Thermometers.

Procedure. Basically, the experimental method consisted of converting a CW electrical signal into a compression wave which was applied to one end of the mortar beam, converting the transmitted compression wave at the other end of the beam again to an electrical signal, and recording the level of this output signal. Since the Sanborn recorder could not respond to a signal in the frequency range used, the CW output signal was rectified to present a DC signal to the recorder. A decrease in the level of the rectified output was taken as an indication of fatigue damage in the mortar beam. Rather than depend upon the rectified output level corresponding to a single input frequency (for reasons discussed in the APPENDIX, page 20), a composite output based on a range of input frequencies of from 112,000 to 120,000 cycles per second was used as follows: The CW signal input to the beam was varied over the desired frequency range. At intervals in this range the corresponding rectified output level was recorded on the Sanborn chart. Then the rectified output was plotted against input signal frequency to give a frequency response curve, as shown in Figures 2 and 3. The area between the frequency response curve and the Sanborn zero level was used as the composite output. This composite output may be considered to be a type of average output over a range of frequencies, and it was the change in composite output which was actually used as an indicator of fatigue damage. Frequency response curves were plotted before the cycling was started and periodically during the testing of each specimen. The data for the latter curves were taken while the fatigue machine was running, and required about fifteen minutes, or 27,000 cycles, of running time. The data were always taken by starting at the high frequency end of the frequency range used. When the mortar beam broke, the fatigue machine, which had a built-in cycle counter, was automatically shut off.

Test Results. Results of the test are based primarily on three specimens. Figures 2 through 5, which are described below, summarize the test results on these three specimens.

Figure 2 is a frequency response curve taken on specimen number three at 3,800 cycles. The variation of rectified output with input signal frequency shown on this curve is typical of response curves which were made while the cycling was in progress.

Figure 3 is a frequency response curve taken on specimen number three prior to the start of cycling. The deep dip in the curve at A in the figure is the most pronounced feature which distinguishes this from the later curve, Figure 2. This same feature, the exaggerated dip in rectified output level, was noted also on specimen number two prior to the start of cycling. It was not evident on the corresponding response curve for specimen number one, perhaps because for this specimen a narrower range of frequencies was used for the response curves than for those of specimens two and three.

Figure 4 presents the test results for specimen number one. The upper graph in this figure shows how the composite output varied as the number of cycles increased. The lower graph shows how stress level was varied during the test on this specimen. The scale for number of cycles tested is the same for both graphs so that one can be compared to the other directly. The dashed line at 946 psi (pounds per square inch) represents the rupture strength as obtained from the average of seven beams tested statically with third-point loading. A chronological description of the test on specimen number one follows:

The time at which the fatigue machine was started was taken as zero cycles. Prior to this time, frequency response curves were made at intervals to check the reliability of the instrumentation. The composite output obtained before starting

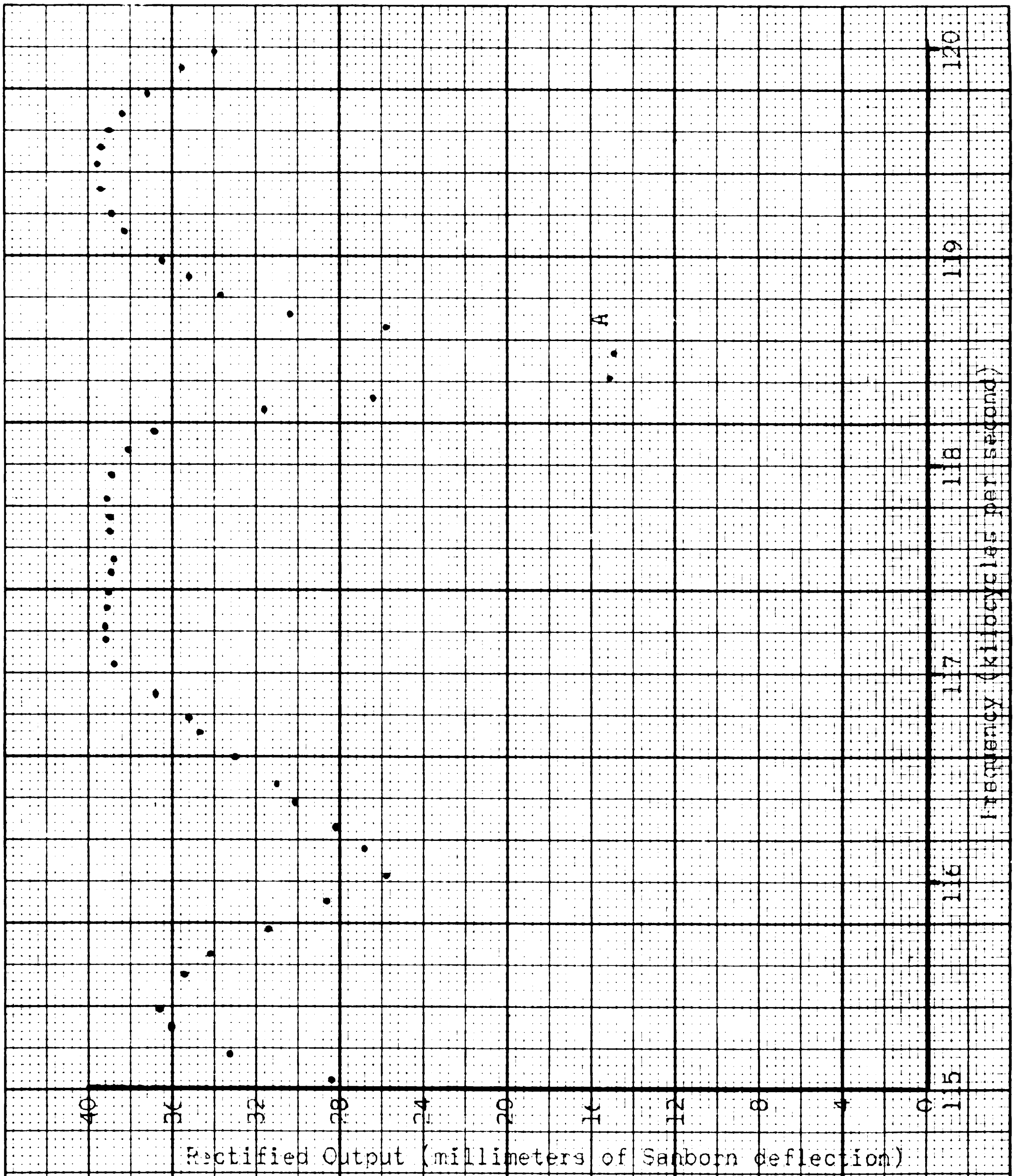

Figure 3. Frequency Response Curve Prior to Cycling.

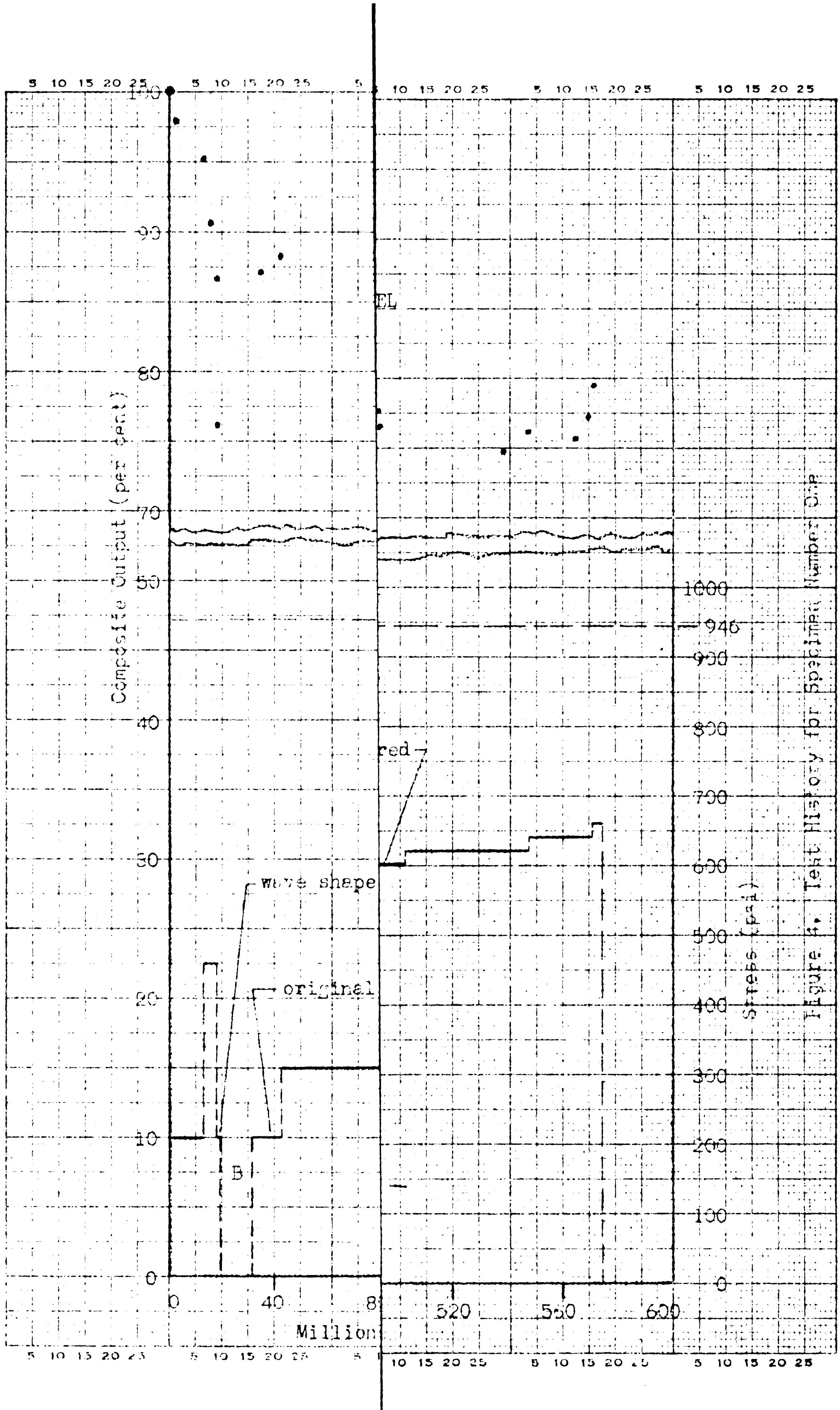

Figure 4. Test History for Specimen Number C-8

the fatigue machine is plotted as 100 per cent at zero cycles. The fatigue machine was run first at a 200 psi stress level (completely reversed bending) for 13.5 million cycles. There was no significant change in output during this time.

The stress level was then increased to 450 psi for 4.6 million cycles. During this period there was a significant decrease in rectified output level and a flattening of the frequency response curve (that is, less variation in rectified output level over the frequency range used).

After a very definite downward trend in composite output was established at 450 psi, the stress level was reduced to 200 psi for 1.5 million cycles. The frequency response curves during this period were significantly flatter and at a lower level than those taken during the previous 200 psi run. No change in level or shape of the frequency response curves occurred during this 1.5 million cycles.

The fatigue machine was then shut off for a four-day period (at B on Figure 4). This period of time is plotted as an equivalent number of cycles on the figure. At the start of the rest period, the frequency response curve was comparable in both shape and level of rectified output to that of the 200 psi run just preceding. At the end of the rest period, the output level had increased significantly and the response curve was less flat.

The stress level was again set to 200 psi--for 10.8 million cycles. The shape of the frequency response curve retained some resemblance to that at the end of the rest period. However, by the end of 3.3 million cycles, the curve had flattened out somewhat and the rectified output level was slightly lower than at the end of the rest period. No additional changes were noted during the rest of this period.

Next, the stress level was increased to 300 psi for 202.5 million cycles. Initially, the level of the frequency response curve was slightly greater and the curve was less flat than at the end of the preceding 200 psi run--more like the shape of the response curve obtained during the original 200 psi run. The frequency response curves taken during this period were remarkably consistent both as to output level and as to shape. Over the whole 202.5 million cycles there was a slight decrease in output level. However, for any portion of this period comparable in length to other runs, the change in output level was imperceptible.

The stress level was then increased in steps,

36.5 million cycles at 450 psi

3.2 million cycles at 480 psi

4.9 million cycles at 500 psi

34.0 million cycles at 520 psi

with no significant change noted in the output.

At the next step, when the stress level was increased to 540 psi for 20.7 million cycles, there seemed to be a slight drop in the level of the rectified output at the lower frequencies (below 117,000 cycles per second).

During the rest of the test on specimen number one:

30.0 million cycles at 560 psi

29.7 million cycles at 580 psi

98.2 million cycles at 600 psi

44.2 million cycles at 620 psi

23.9 million cycles at 640 psi

4.4 million cycles at 660 psi (fracture)

the output level on the low frequency side of the response curve continued to drop off. Because of this, at the end of the 600 psi run, the frequency response curve was significantly different in shape from that at the end of the 520 psi run. It should be noted that this change took place over a span of 178 million cycles, whereas there was a greater change in 4.6 million cycles during the first run at 450 psi before the rest period. However, when viewed on the semi-logarithmic plot of Figure 5, the slope of the curve (rate of change of composite output) during the 178 million cycles appears to be nearly the same as that during the 4.6 million cycles.

The specimen broke approximately in the center of the beam after a total of 562,910,000 cycles, while running at the 660 psi stress level.

Figure 5 is a semi-logarithmic plot of composite output versus number of cycles tested, for three specimens. The plot for specimen number one is from the same data as that for Figure 4, and hence the variation in stress level on this specimen must be kept in mind when comparing the curves shown in Figure 5. Specimen number two was run at a constant stress level of 550 psi and broke at 38,000 cycles tested. Only one frequency response curve was taken after the start of cycling because of

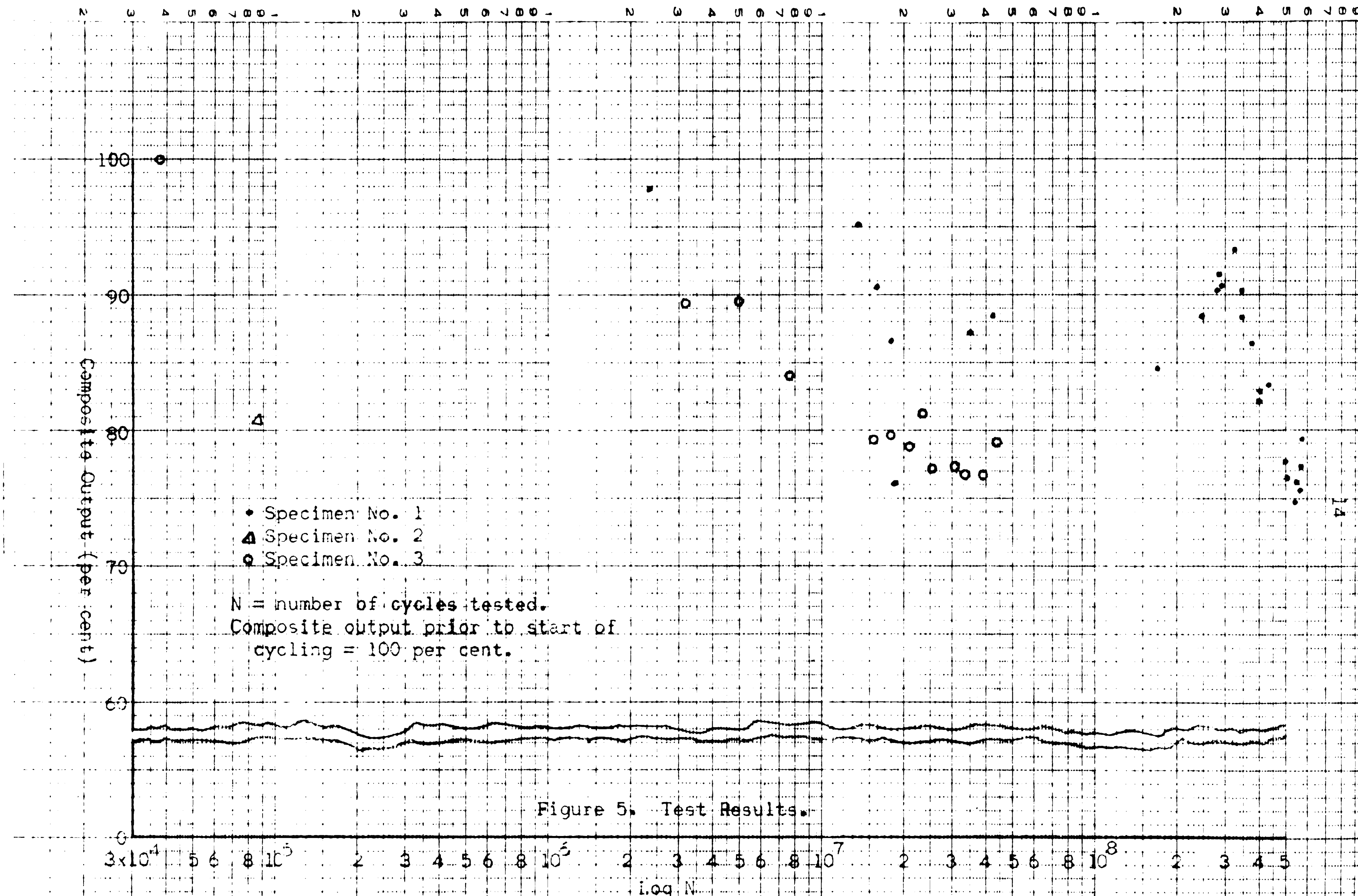

Figure 5. Test Results.

the relatively short running time. However, this was consistent with the other specimens tested, with respect to drop in composite output. Specimen number three was run at a constant stress level of 450 psi and had not broken at the time of writing.

Figures 4 and 5 are quantitative in a relative way; that is, the trend is as shown. In the present investigation there were two items which detracted from the data as an absolute measure, and which could be corrected for in any subsequent investigation:

1. The nonlinearity of the Sanborn deflection, due to biasing the zero level off-center on the chart. Correcting this would cause a greater fall-off in composite output than Figures 4 and 5 indicate.
2. The calibrating voltage for the Sanborn recorder decreased during the test on specimen number one and was not discovered until the next specimen was being set up. Correcting this would probably result in a more pronounced decrease in composite output during the latter part of the run on specimen number one.

Conclusions. On the basis of Figures 4 and 5, the following conclusions were drawn:

1. A definite decrease in composite output occurred with increasing cycles tested at a sufficiently high stress level.
2. At a sufficiently low stress level, there was no change in composite output with increasing cycles tested.

3. A possible evidence of "healing" is indicated after the rest period at B on Figure 4.

4. Figure 4 indicates that after damage at a medium stress level and subsequent rest, increased damage may not accrue until a higher stress level than that at which damage originally occurred.

<u>For Further Study</u>. Some of the questions raised below might be answered directly by a person well versed in three-dimensional wave propagation theory. Nevertheless, the writer deems the following items worthy of further consideration:

1. Develop a method of isolating the location of fatigue damage indicated by the method presented.
2. Eliminate standing wave effects, possibly by means of white noise or by pulse methods, to facilitate item (1).
3. Determine the cause of or explanation for the sharp dip in the frequency response curve at A on Figure 3.
4. Determine the cause of a random lateral shift in the frequency response curve of anywhere from two to one hundred cycles per second. This did not appear to be due to temperature or to any change in instrumentation.
5. Eliminate the modulation effect on the output signal due to the 1,800 rpm cycling of the fatigue machine. This might be explained in terms of a nonlinear operation of the barium titanate crystal.
6. Determine the direct physical explanation for the drop in the level of the output signal.

7. Investigate the possibility of applying dislocation theory to fatigue damage in mortar and concrete.

8. In conjunction with item (7), investigate any connection between energy loss, dislocation theory, and drop in output level.

9. Develop the method presented to the point where it can be used to answer questions concerning cumulative fatigue and under- and over-stressing with a reasonable certainty.

10. Continue this type of investigation with limestone and with plain concrete as suggested in the INTRODUCTION.

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APPENDIX

EXPERIMENTAL TECHNIQUES

The first of the following sections presents an overall view of the development of the method used, citing the major difficulties encountered. Subsequent sections give more details on instrumentation components.

Evolution. The original idea was that one could set the ultrasonic generator to an arbitrary frequency (one which would give a large output), transmit a signal through the beam, and use the signal attenuation as a measure of fatigue damage. The first preliminary runs were rather discouraging in that there seemed to be no regularity to observed changes in output signal. By a laborious process of questioning, checking, and double-checking, three factors eventually emerged as contributing to the randomness of the signal changes: (1) crystal contact with the specimen, (2) signal frequency, and (3) temperature.

Contact between crystal and specimen was originally maintained by pressure, through a grease film at the surface of contact. This was all right for static checks; but not for dynamic, long-term tests. Variations in signal due to change in crystal contact could not be avoided. This difficulty was overcome by cementing the crystals to the specimen.

That signal frequency affected output was obvious from the start; but the subtleties involved were not so obvious. Any frequency above 120,000 cycles per second was attenuated so severely in being transmitted through the beam that it was planned originally to use a constant signal frequency in the vicinity of 120,000 cycles per second which would give a large enough signal to be usable with the available instrumentation, although it was recognized that a higher frequency would be more desirable from the standpoint of "flaw" detection. Due to crystal frequency response, specimen geometry, crystal location on the specimen, and possibly other factors, peaks were obtained in the output signal level at various frequencies in the range from 112,000 to 120,000 cycles per second. The one which gave the highest peak was picked as the operating frequency. However, it was found that the ultrasonic generator changed frequency as a result of change in ambient temperature. Moreover, the effect on the level of the output signal depended upon whether the original operating frequency had been at a true peak or at one side of the peak; the effect on signal output if the original operating frequency had been below that of the peak selected was just opposite to the effect obtained if it had been a higher frequency than that of the peak. This, plus the fact that one division on the tuning dial of the generator was equivalent to about a 2000 cycle per second change in frequency, led to the addition of trimmers on the generator tuning condenser so that frequency could be precisely set, and to the introduction of the electronic counter into the instrumentation so that frequency could be accurately measured. This was still not adequate, however, and so the frequency response curve was introduced. It was found that even at no load and constant temperature, if two frequency response curves were made at different times, they might coincide if one were superimposed on the other, yet be shifted laterally from each other on the frequency scale. It was thus seen that checking at one particular frequency was uselss, and the frequency response curve (see page 6 for a description) was adopted as a means of comparison. The area under the curve was taken arbitrarily as a quantitative measure of output level.

Aside from the frequency change noted above, temperature affected output level in yet another way. The output of the crystal itself was temperature dependent. Before the frequency response curve was introduced, a futile attempt was made at temperature compensation by using four crystals (two on the test beam, two on an unloaded beam) in a bridge arrangement. The idea of using a thermistor arrangement for temperature compensation was considered and discarded also. The complexity of factors affecting the frequency response curve indicated that it would be next to impossible to have all the components in a temperature compensating network sufficiently well-matched as to give consistent results. Accordingly, the temperature effect was avoided by having the ambient temperature stabilized the same each time a frequency response curve was run.

Crystals. The following factors represent major considerations in using the barium titanate crystals.

1. Coupling. Lubriseal, a stopcock grease, was used to couple the crystals to the beams for all static checks. For the dynamic checks, three types of adhesive were tried:

a) Lepages contact cement, which gave too much attenuation;

b) Duco cement, which would not maintain a proper bond consistently; and

c) Pliobond, which proved to be satisfactory.

Pliobond was applied to both the specimen and to the crystal. The crystal was immediately pressed firmly against the specimen so as to make a thin adhesive bond at the interface, and positioned while the adhesive was still reasonably fluid. The crystal was held in position under pressure, usually overnight. The Pliobond joint gave consistent results throughout the cycling, and yet the crystal was easily removed by applying a steady shear force across the joint.

2. Maximum current. If too much power is applied to a barium titanate crystal, it will heat up and lose its polarization. The output then drops to a negligible value. After some preliminary checks, twenty-five milliamperes of crystal current was taken as the maximum safe value. The multimeter, item (11) in Figure 1, was used to ensure that twenty-five milliamperes of crystal current was not exceeded when making an initial set-up on a specimen. The final figure used during the test was set well below twenty-five milliamperes. The multimeter, by monitoring the transmitting crystal current, was also used to indicate that the adhesive bond was consistent during the test. One crystal which did overheat in the early stages of the investigation was repolarized satisfactorily by the application of 4,500 volts DC overnight. Incidentally, the multimeter is shown mounted away from the fatigue machine, since vibration would

damage the meter movement bearings.

3. Electrical contact. Several methods of making electrical contact with the face of the crystal which was against the specimen were tried. These included (a) two coats of silver paint on the end face of the specimen, with a lead fastened to the coating for electrical contact, and (b) a piece of brass shim stock sandwiched between the crystal and specimen, with a portion brought out for electrical connection. The best method, however, was to cement a tiny piece of brass shim stock to the side of the crystal adjacent to the face which would contact the specimen, carefully solder a lead to this piece of shim stock, then coat the connection with silver paint and paint a strip to the face of the crystal which contacted the specimen. The crystal was then cemented directly to the specimen. The crystals are furnished with an evaporated coating on each face; if this becomes worn, it can be replaced satisfactorily by silver paint. DuPont conductive silver, number 4817, was used with good results.

4. Shielding. The crystal was covered by a copper cylinder to eliminate pick-up from stray electrical fields present in the laboratory.

5. Location. Each crystal was located on the neutral axis of the end face of the specimen in such a position that a maximum signal output was obtained. The position was determined by trial and error. It may well be that different positions would be optimum at different frequencies; this was not investigated.

It was noted that the output level varied greatly for different positions on the end faces; and also, that for a given position of the crystals on the end faces, the output level could be altered significantly by placing another crystal or metal washer or the like at various locations on the sides of the specimen (coupled through a grease film). All of this indicates a pronounced standing wave effect in the specimen.

<u>Generator</u>. The ultrasonic generator as received had a very "dirty" output signal. It seemed desirable to clean this up; and it was accomplished by

1. increasing the filtering on the bias power supply,
2. separating the variable power supply of the oscillator plates from that of the screen grids, and
3. disconnecting the rectifier cooling motor (not needed for the low power used).

In addition, half the power amplifier tubes were removed in order to bring the low power operation (required because of the crystal limitations) to a stable condition.

<u>Recording</u>. The Sanborn recorder was not too satisfactory for long-term testing because of excessive zero drift and change in gain. This was compensated for by adjusting zero level and calibrating before each frequency response curve was taken.

<u>Miscellaneous</u>. Several times during the investigation either a very fine wire grid cemented to--or a silver paint grid painted on--the sides of the specimen was used in an effort to

see if fine cracks developed before fracture. Any interruption in the continuity of the grid stopped an auxiliary cycle counter which was synchronized with the cycle counter on the fatigue machine. No indication of surface cracks prior to fracture were obtained by this method, however.