THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
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Final Report

A STUDY OF THE INFLUENCE OF FREQUENCY AND ADDED ABRASIVE ON VIBRATORY CUTTING OF CONCRETE AGGREGATES

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ABSTRACT

Promising results from the previous study with ultrasonics as a means for cutting concrete prompted a broader study of the influence lower frequencies and added abrasives as possible approaches to increasing the rate of cutting to a practical level.

Tests in the sonic range did show an increase in the rate of cutting with higher frequencies at constant amplitude. This confirmed the frequency squared relationship predicted from theoretical considerations. However, increased frequency was accompanied by faster tool wear. Similarly the addition of hard abrasives such as silicon carbide and boron carbide increased the cutting rate at the expense of greatly increased tool wear.

It is evident that shock impulses which are common to ultrasonic transducers and air operated jack hammers are the most important factor in cutting concrete by vibration. Further, it is evident that the air operated jack hammer is still the most efficient means for producing these impulses.

INTRODUCTION

This second phase of the study program is a continuation and broadening of the initial study entitled "An Ultrasonic Jack-Hammer" (ORA Report No. 04588-1-P). The report on the first program was concerned primarily with the use of ultrasonic energy as applied to the drilling of cement and plaster mixes. It was established that drilling of these materials could be accomplished without the aid of abrasive or coupling fluids. In addition, data were developed permitting the determination of the optimum tool and load conditions for the materials considered.

This investigation is divided into two parts:

1. The development and study of some special ultrasonic tools.

2a. Ultrasonic cutting with abrasive materials in fluid; and

b. sonic frequency cutting with abrasives in fluid.

Insofar as it was possible, the basis for the data was made common with the work in the initial study. Those techniques which differed or were at variance with the original techniques are described in this report.

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PART I SOME SPECIALIZED ULTRASONIC TOOLS

In the production of mechanical vibrations in the ultrasonic region, there are currently only two generic groups of transducers available; magnetostrictive and electrostrictive. While it is certainly true that these transducers can produce mechanical vibrations the amplitude of the motion at the output surfaces is hardly large enough to be measurable. It is because of the small motion produced, and because of the techniques that must be employed to magnify these vibrations that the development of velocity transformers for use with ultrasonic transducers becomes extremely important.

Essentially, aside from the limitations imposed on them by certain physical properties, the magnetostrictive and the electrostrictive transducers accomplish about the same thing. In making a comparison of the two devices, one finds as might be expected strong attributes for both. The magnetostrictive transducer in general can handle power levels several orders of magnitude larger than can the electrostrictive device, but with much lower efficiency. The electrostrictive transducer on the other hand will develop motional amplitudes somewhat larger than the magnetostrictive units. In general, the electrostrictive units are limited to use where low power levels are expected, and the magnetostrictive units are used for higher power levels despite their lower efficiency.

It is useful to recognize that mechanical vibratory systems demonstrate behavior analogous to electrical systems. It is essential that generator and load impedances be matched in electrical circuits if the greatest power transfer is to be achieved[1] Since mechanical behavior is identically similar it is essential that the same conditions apply to ultrasonic systems which are combinations of mechanical and electrical vibration elements. In brief, the impedance of the mechanical load imposed on the ultrasonic transducer must match the characteristic impedance of the transducer. The device used to achieve this impedance transformation is referred to as a "horn." The electrical analog of the horn is the transmission line transformer section.[2] Two different horn assemblies are shown in Figs. 1 and 2.

A MAGNETOSTRICTIVE, TWO-STEP TRANSDUCER

Figure 1 shows a magnetostrictive unit designed and built in The University of Michigan laboratory. The cylindrical sections of various diameters are in fact the horn; in this case a double-step horn. Each section of the horn is essentially a quarter-wave mechanical transmission line so proportioned that the low amplitude motion or velocity produced by the transducer is increased in magnitude by the horn so that the velocity of motion at the tip is considerably greater than the motion at the transducer. The unit pictured in Fig. 1 is capable of handling power levels of 1000 watts or more for short periods of time.

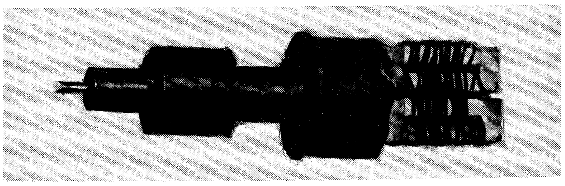


Fig. 1. Magnetostricrive transducer with double-step horn.

AN ELECTROSTRICTIVE, TWO-STEP TRANSDUCER

Figure 2 pictures an electrostrictive device consisting of a sandwich of steel and aluminum with a ceramic center. The ceramic material is strain sensitive to applied voltage fields. Basically the horn is identical with that shown in Fig. 1 except that it is made of magnesium instead of steel.

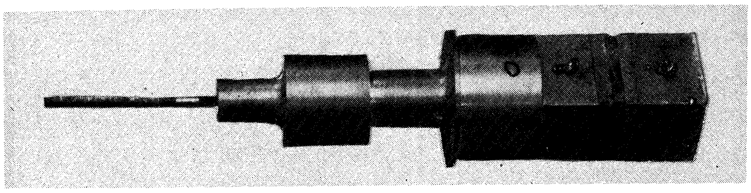


Fig. 2. Ceramic sandwich transducer with double-step horn.

In examining the two devices pictured, one may see a flange on the largest diameter cylinder. This flange was provided for mounting purposes and is located at a nodel plane. A nodal plane by definition is a plane where there is no motion. Since the nodal plane has no motion, mounting the system at this point will not couple any energy out of the system through the frame. Actually, certain types of load cause the nodal plane to be shifted so that there can be energy losses from the system at this point.

The two horns shown were both threaded for the insertion of tools. The transducer in Fig. 1 has a short chisel point tool. The tool in Fig. 2 was made approximately one-half wavelength in length. At the latter conditions, the ends of the tool should move violently with a nodal plane at the center. It was found that while the end did have a large amplitude of motion, the center also was quite active. This indicated a superimposed bending mode arising out of some asymmetry. When the tool was threaded to give it teeth, it would saw through plaster with ease. It would also cut concrete but the rate was quite slow.

AN ELECTROSTRICTIVE, THREE-STEP TRANSDUCER

In view of the modest success achieved with the two-step horn, and recognizing that it was not possible to measure the impedance of the type of loads being developed, a three-step horn with a high velocity ratio was designed. Figure 3 shows this system. Note the location of the nodal plane mounting flange. The same design equations which were used to develop the previous horns were again used for the three-step horn. The expected level of motional amplitude did not develop with this particular configuration. It is possible that, in terms of electrical transmission line theory, the frequency passband for the three sections did not overlap sufficiently, or stated another way, the system was not tuned to the same frequency throughout its length. There is no correspondingly rigorous theory for mechanical systems at these high frequencies.

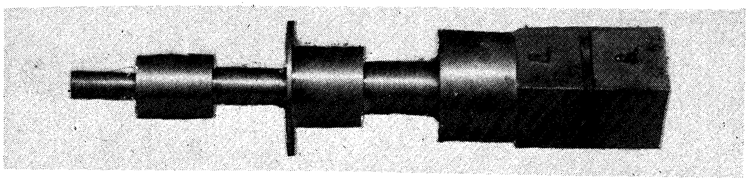


Fig. 3. Ceramic sandwich transducer with triple-step horn.

A HIGH RATIO, SINGLE-STEP TRANSDUCER

With the experience involving the three-step horn in mind, a radical departure from general practice was tried. It is shown in Fig. 4. An extreme step was produced in the horn and the tool mounted as shown. This extreme step horn developed motional amplitudes greater than any which had yet been tried. However, the limited heat dissipation restricted the power level to 80 watts continuous so that it was possible to completely damp or stall the tool by hand contact.

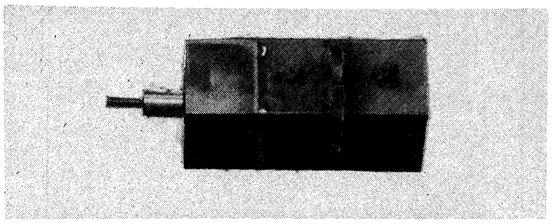


Fig. 4. Ceramic sandwich transducer with extreme area change on horn.

A PORTABLE TRANSDUCER

Interest developed in the possibility of matching impedance by the use of hand held tools. The assembly shown in Fig. 5 was developed for this purpose. Basically the unit was designed around the two-step horn systems of Figs. 1 and 2. Several interesting features concerning this horn became apparent. Note that there is a saw blade mounted to the threaded rod inserted in the end of the horn. The original length of this rod and blade was again one-half wavelength. In this case, however, there was a clearly defined nodal point in the center of the rod so that the resulting high stress level fatigued both the rod and the blade so that the outer quarter wavelength broke off. The saw blade tool was quite effective in cutting plaster, but again, the rate in concrete was painfully slow.

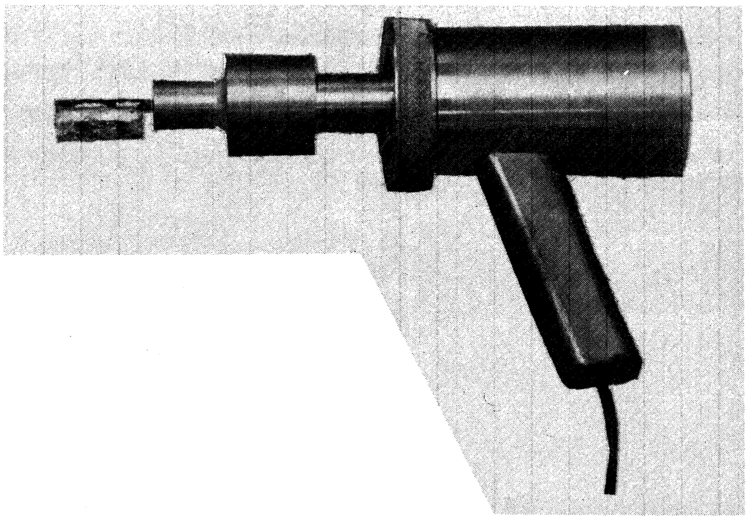


Fig. 5. Hand held transducer and horn assembly with saw blade tool mounted.

CLOSED LOOP OPERATION

It was felt that a feedback loop closing the system, so that the operator would not be required to tune the oscillator, would be desirable. As a result, strain gages were located at the nodal plane where high stress levels exist.[3] The strain gages did in fact develop high strain indications when the system was excited. In closing the feedback loop however, it was found that there were several natural frequencies for the system, and that the best phase amplitude relationship did not necessarily exist at the mechanical resonance point. The result was that more often than not, the system responded at some frequency other than the desired one.

A band-pass filter was included in the amplifier to limit the response range with some success. Despite these techniques, however, the system could not be made to function properly because of the effects of load changes.

A method for developing the desired feedback voltage is currently available.[4] The feedback voltage is developed through the use of a bridge circuit which is predicated on the motional rather than the electrical impedance of the transducer system so that the system is assured of operation at the proper frequency. Time limitations precluded the construction and testing of such a system.

A wide variety of informal tests were performed with the hand held systems, and while these tests did not contribute substantaiIly to the rate at which drilling could be accomplished, they did add materially to the general knowledge concerning the behavior of such systems.

PART II. CUTTING EXPERIMENTS

ULTRASONIC EQUIPMENT

For the most part, the technique used for the ultrasonic tests was identical with that used and described in the first report. The ultrasonic transducer and horn were mounted on a counterbalanced, parallel-motion table so that specific static loads could be applied to the tool and workpiece. The ultrasonic equipment was identical with that used initially with the exception of the horn which was replaced due to severe wear. In addition, the rotating table system was modified so that a variety of table speeds could be utilized. For the tests of record, two speeds were used: 5.14 and 19.1 rpm. These values were selected for convenience and accuracy in resetting them on the dial of the Vickers transmission.

MATERIALS

The materials used for the tests were made as nearly like the original materials as possible. The same cement, the same sand, and the same plaster were still available and were used. Compressive tests made on the specimens gave values which were for the purposes of this test identical with those determined from the original specimens. The major difference between the test procedure used in the first test series, and the procedure used for the tests reported here was the inclusion of the abrasive fluid slurry. Eleven different abrasives were tested: ten silicon carbides, and one boron carbide. The grain size varied from 60 to 220 for the silicon carbides, and the boron carbide grain size used was 240.

PROCEDURE FOR ULTRASONIC TESTS

A 1-in. diam metal dam about 3/4 in. high was placed over the spot where drilling was to occur, and the dam was sealed to the surface with plastic clay putty. One-half gram of the selected abrasive was placed inside the dam, and a small quantity of water with soluble oil was added.

A static load based on the optimum revealed in the first test series was placed on the loading platform, and the tool was brought into contact with the workpiece. The power was then applied to the transducer, and the tool was allowed to penetrate approximately 0.020 in. at which time the clock was started. After the tool had penetrated an additional predetermined amount, the clock was stopped, and the penetration rate determined from this figure.

It was planned originally that considerable penetration would be measured. However, the abrasive action on the tool was so great that rebuilding the tool-horn assembly would have been necessary. Several exploratory tests showed that the rate of penetration was for all practical purposes constant once the surface material had been penetrated. Therefore, the shortening of the tests had little effect on the validity of the results.

SONIC EQUIPMENT

There were certain fundamental limitations involved in the use of the sonic frequency excitation equipment. Basically, the shaker is a large-scale loudspeaker with a spring supported mass excited through a "voice coil." Because of the spring suspension, the system is necessarily rather soft, and because of the physical dimensions involved in the location of a nodal point at low frequencies it was impossible to utilize the nodal point for static load application. The application of the ambient or static load was accomplished through control of the amplitude of excursions of the mass.

The techniques essential for control of the sonic equipment and for making the necessary measurements had to be more sophisticated than those used for the ultrasonic frequency range.

Figure 6 shows the equipment for the sonic tests. The horizontal tube seen in the upper left hand corner of the picture is the lens shield of the Optron. This is an electron-optical device capable of following complex motion in a plane. The Optron and oscilloscope permitted the position as well as the complex motion of the tool to be measured to well within 0.005 in.

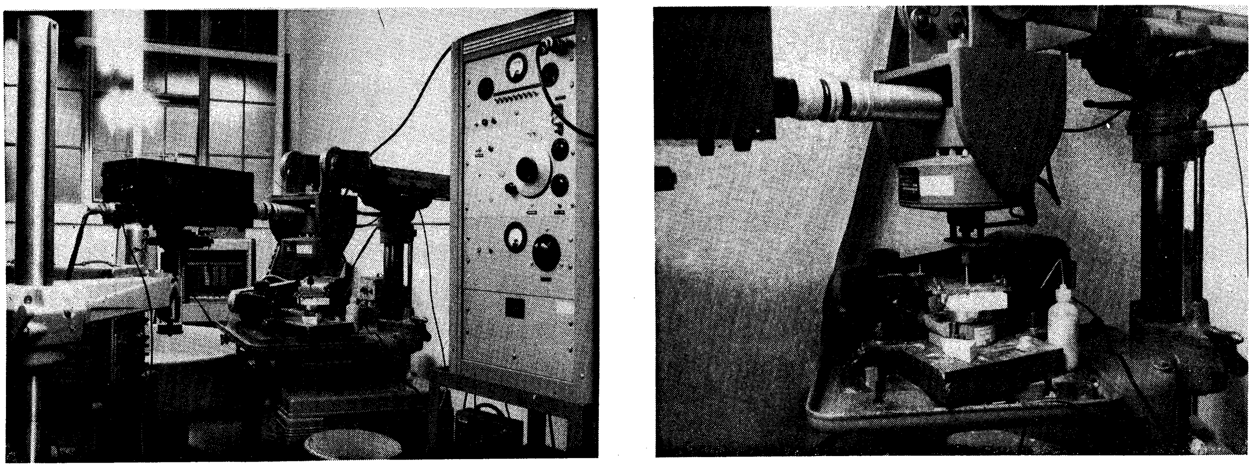


Fig. 6. Shaker and Optron in position.

PROCEDURE FOR SONIC TESTS

The oscillogram in Fig. 7 shows the motion of the tool-mass system against time for a 35 cps frequency and 0.125 in. motion. The rebound after contact is clearly visible. In preparing for a test run, the Optron was optically locked on the target mounted on the upper extension of the mass system. Without engaging the work, the amplitude of motion of the tool was set at the desired value as shown on the oscilloscope screen. With the abrasive material in place, the tool was lowered into contact with the workpiece and the amplitude adjusted by additional lowering of the shaker until the amplitude was half that originally set. The tool was permitted to penetrate the rotating specimen 0.100 in. before the timer was started. Since the blunt end of the tool developed a corner radius of 0.075 in., the initial depth before timing permitted the whole tool to be engaged before measurements were made.

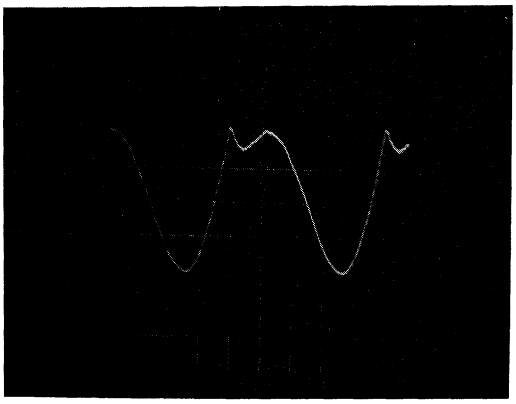


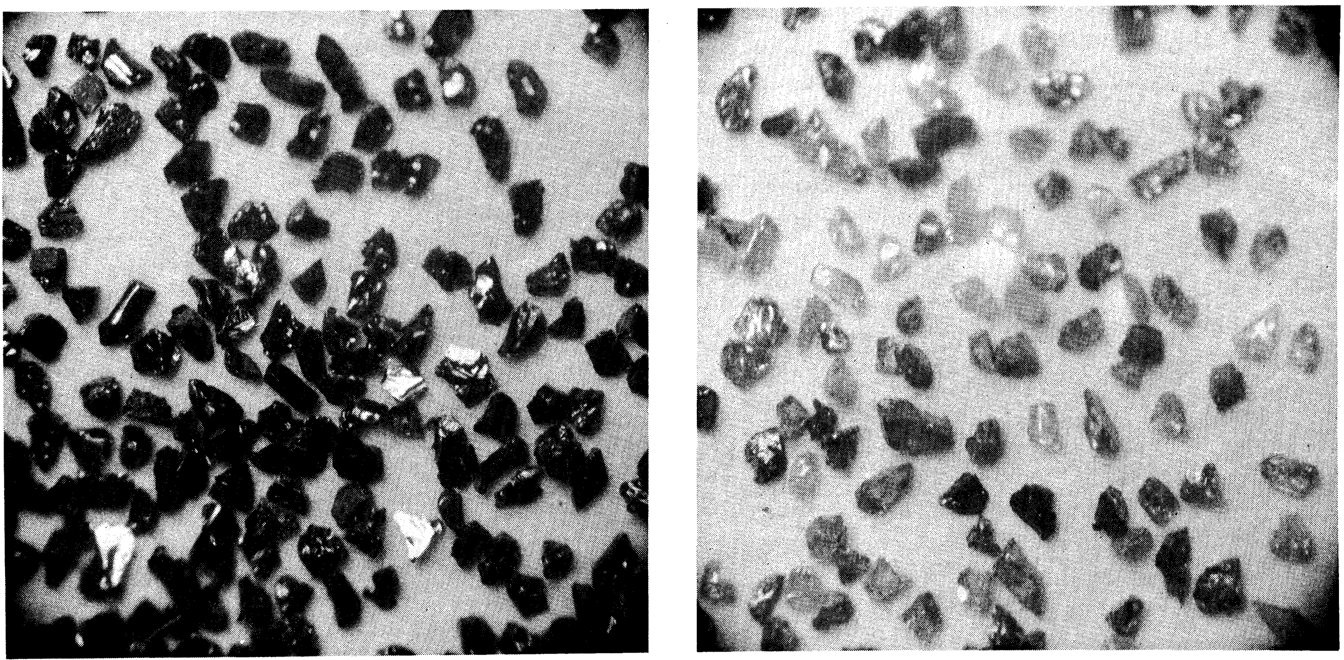
Fig. 7. Oscillogram of tool motion, 35 cps, 0.125 in. deflection.

The sonic series of tests were made in such a manner that the tool developed maximum velocity at the instant of contact.[5] Examination of Fig. 7 shows that the slope of the curve is greatest at the instant of contact, hence the impulse force was greatest at that instant. The tool point was permitted to assume its natural shape in the sonic series of tests since wear was very rapid and since it was not necessary to make exact comparisons with other data. It was not possible at sonic frequencies to collect a valid set of data on the cement water mix (neat) since impulsive forces or amplitudes large enough to cause any drilling action were great enough also to cause cracking and breaking failure of the specimen.

ABRASIVE MATERIALS

The primary abrasive materials used in the test series were two different grades of silicon carbide in various grain sizes. The grades varied from number 60 to number 220 grain size. The two grades were ordinary grey silicon carbide and the green silicon carbide grade. Essentially the difference between the two grades lies in the iron content of the grey carbide. The grey shade is designated by number of grain size and the letter "C," while the green grade is designated by number of grain size and the letters "GC."

Photomicrographs of the two materials in the number 60 grain size are shown in Fig. 8. Note that aside from the obvious difference in the color of the two grades, the angularity, shape, size, etc., are practically the same for both materials. This persisted throughout the full range of grain sizes.



(a) 60C grade (b) 60GC grade

Fig. 8. Photomicrographs of silicon carbide.

An additional test series was run with boron carbide as the abrasive. A supply of 240 grain size boron carbide was available and the smaller grain size seemed appropriate for the ultrasonic tests. In addition, boron carbide has a hardness nearest that of diamond. On the Knoop hardness scale, diamond is rated at 8500, boron carbide is rated at 3634, silicon carbide at 2875, tungsten carbide at 1800, and silicon dioxide (sand) at 958.

ACTION OF ABRASIVES

In making a microscopic examination of the debris left at the bottom of the hole as a result of the drilling operation, several points of note were observed. It appeared that the majority of the abrasive particles left at the bottom of the hole were unaltered in size or shape. In effect, the abrasive particles themselves were not being broken down by the pounding of the tool. The size of the grains of sand (aggregate) however were severely reduced and somewhat polished as a result of the action of the tool and abrasive.

Examination of the bottom of the hole, showed a boundary layer about the thickness of the grain diameter. This layer while impervious to the effects of solvents, water, or compressed air jets, was soft enough to be easily removed with a pick. Complete grains of the abrasive material were found embedded in the boundary layer at random locations. It was not possible to determine if the abrasive had displaced grains of sand, or if it worked into the interstices between the sand grains. It is certain however that the layer at the bottom of the hole was greatly weakened. In all probability, this was responsible for the absorbtion of considerable energy from the tool.

On occasion, the abrasive material would pack at the bottom of the hole when operating at sonic frequencies. When packing occurred, drilling itself completely ceased, and in effect, the tool packed the hole and backed itself out. The packing action did not occur with any regularity, but when it did occur, it invalidated that particular test run. It is considered likely that the packing may have been due to a particle of clay acting as a binder for the debris and abrasive particles.

Test Results

Due to the fixed nature of the physical parameters involved in an ultrasonic transducer, it is not possible to vary the frequency of such a device over much of a range. In order to investigate the influence of frequency on drilling rate, it was necessary to go to a nonresonant low-frequency device. The initial exploratory tests were run at constant frequency, amplitude, and without abrasive material.

VARIABLE LOW-FREQUENCY RESULTS

Figure 9 represents the relationship between the rate of penetration and the frequency of impact, maintaining the amplitude of the tool motion constant at 0.122 in. from contact to the point of maximum lift. Since the data are plotted on log-log coordinates, the straight line relation indicates that there is an exponential relation between the penetration rate and the frequency. It happens in this case that the penetration rate is proportional to the frequency squared as might be expected since the impulsive force according to

Newton's second law is equal to the mass acceleration product, F = ma. In this system, the acceleration (a) is the product of the amplitude (r), and the angular velocity (ω) squared; hence, $F = mr\omega^2$. This relation is of significance since it indicates that the impulsive force at impact is the dominant factor in the removal of the work material.

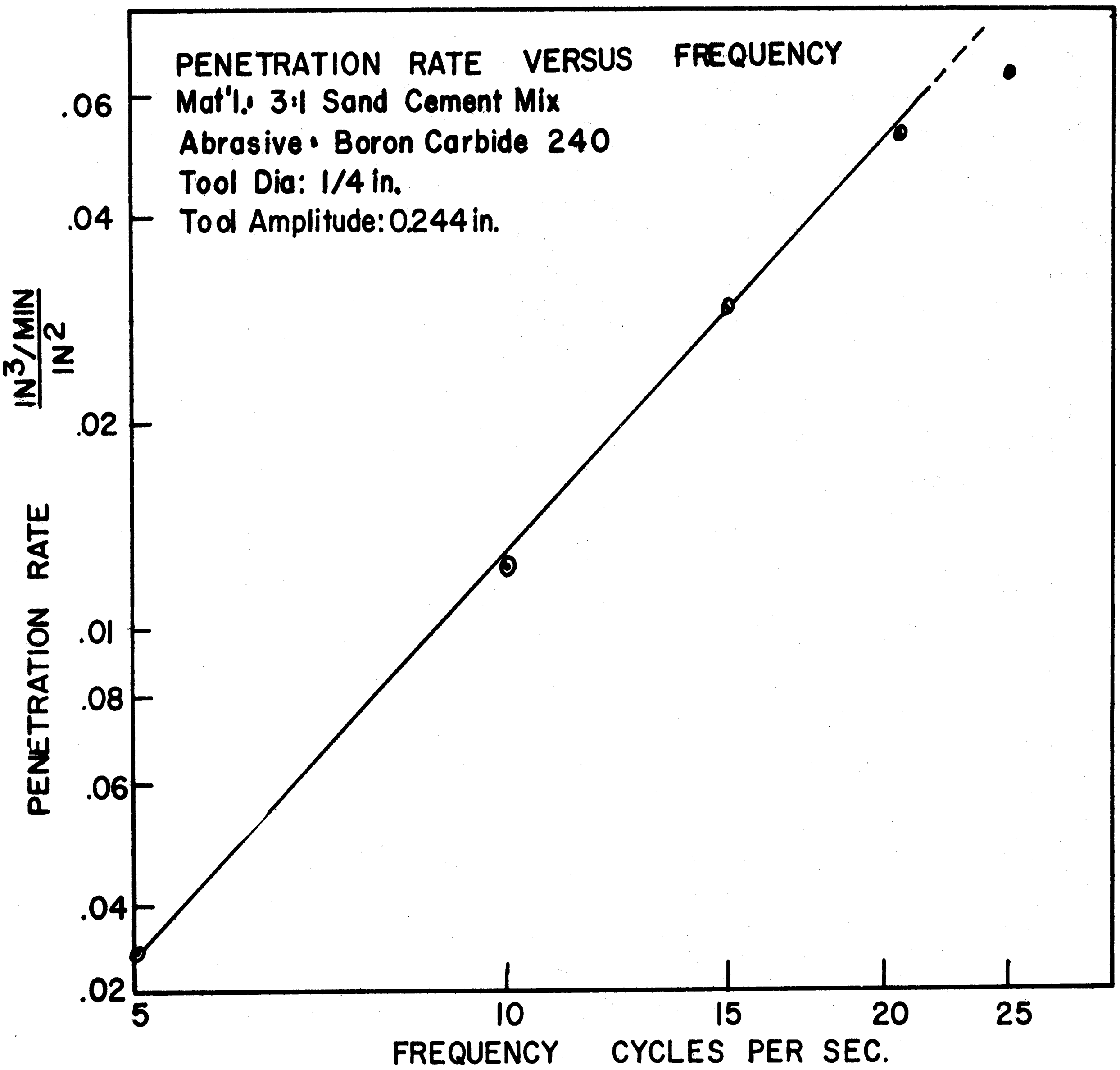


Fig. 9. Graphical relation between frequency and penetration rate for boron carbide 240 abrasive.

Normally the curve of Fig. 9 would be expected to intersect the zero point on both axes, that is, with no motion, there should be no material removal or drill penetration. The curve does not, however, intersect as might be expected, but instead crosses the frequency axis at some point slightly below 5 cps. This indicated that there is a minimum energy level (or impulsive force level) below which the material is not removed. This too is to be expected.

Continuing this vein of investigation, a series of tests was run with the number 60 grain size, grey silicon carbide at several frequencies and amplitudes. The results plotted in Fig. 10 on log-log coordinates again demonstrates the frequency-squared behavior. Note that for each amplitude of motion, the axis crossing projection indicates an apparent minimum frequency below which no drilling may be expected to occur.

The influence of the material on drilling rate for various frequencies was next investigated as shown in Fig. 11. Again, note that the curves do not appear to cross the axis near zero. The data in this series seemed to group itself into two areas in which the speed of table rotation was involved. The data did not provide a confidence level high enough to make specific observations possible, yet it is apparent that the penetration rate is related to the speed at which the table is rotated, and again, that the rate is found to be highest for the less brittle but lower strength materials.

Considerable significance can be attached to the grain size of the abrasive used as is pointed out in Figs. 12 and 13. The relation between grain size and the penetration rate appears as a straight line function on semi-log paper indicating that the penetration rate is a function of the grain size raised to some power. Table I relates the grain size number with the size of the seive opening.[6] Based on the assumption that the penetration is an exponential function of the grain diameter, i.e., $P = f(D^h)+c$, the exponent is found to vary between 0.4 and 0.6. Assuming that the exponent is actually 0.5, one could conclude that the penetration rate is inversely proportional to the cross-sectional area of the abrasive grain, or following the development in the development in the appendix, directly proportional to the abrasive grain stress.

TABLE I

ABRASIVE GRAIN SIZE TABLE

FROM GM 4272-M[6]

Grain Size Number	Sieve Opening, in.
60	0.0117
80	0.0083
120	0.0049
180	0.0035
220	0.0029

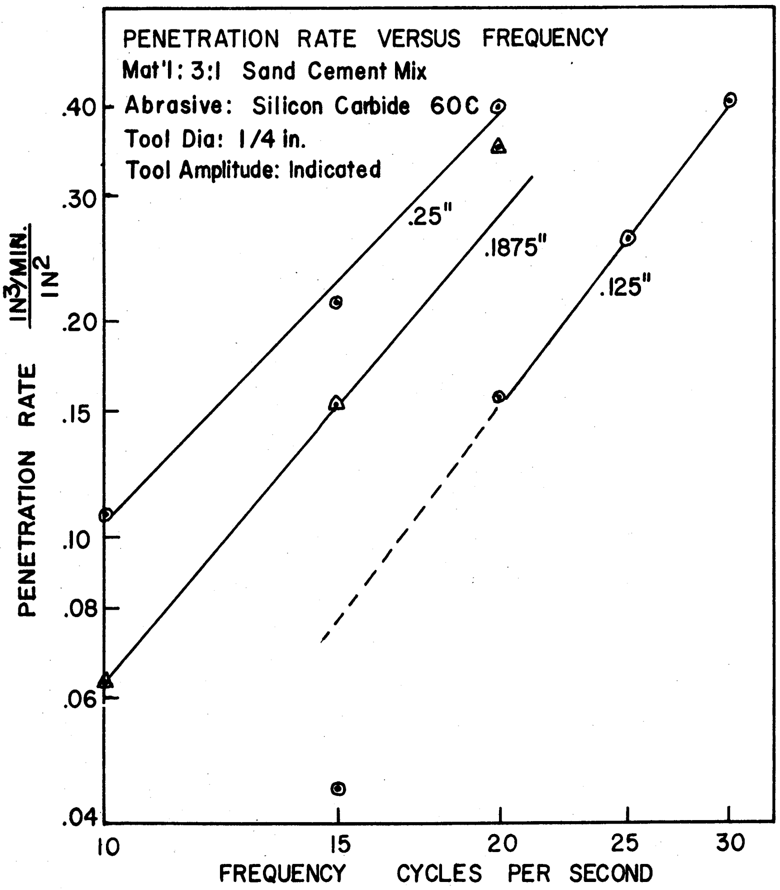


Fig. 10. Graphical relation between frequency and penetration rate for silicon carbide 60C at various amplitudes.

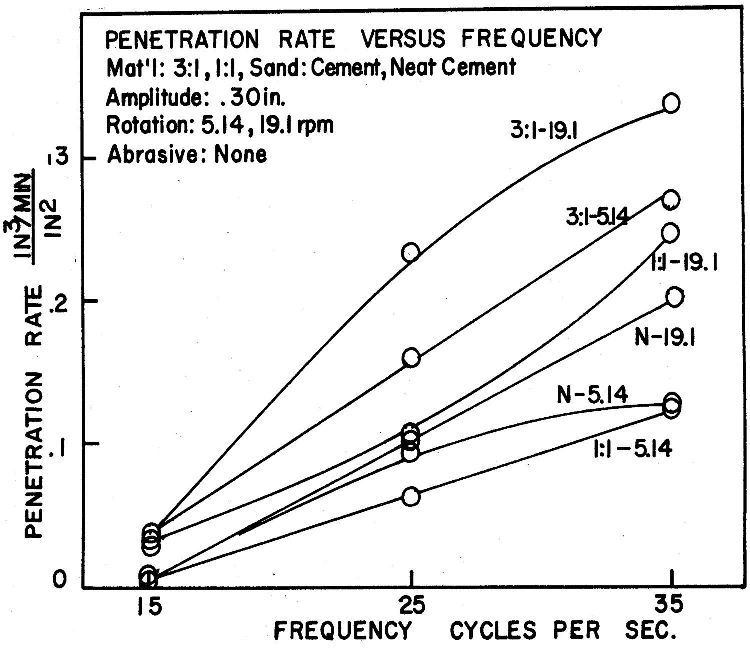


Fig. 11. Graphical relation between frequency and penetration rate for various materials without abrasive, at several rotative speeds.

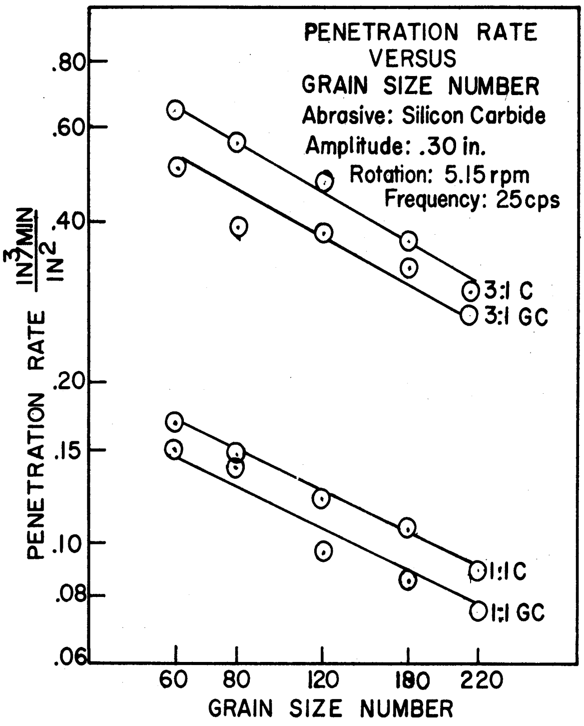


Fig. 12. Penetration rate vs. grain size number for 25 cps.

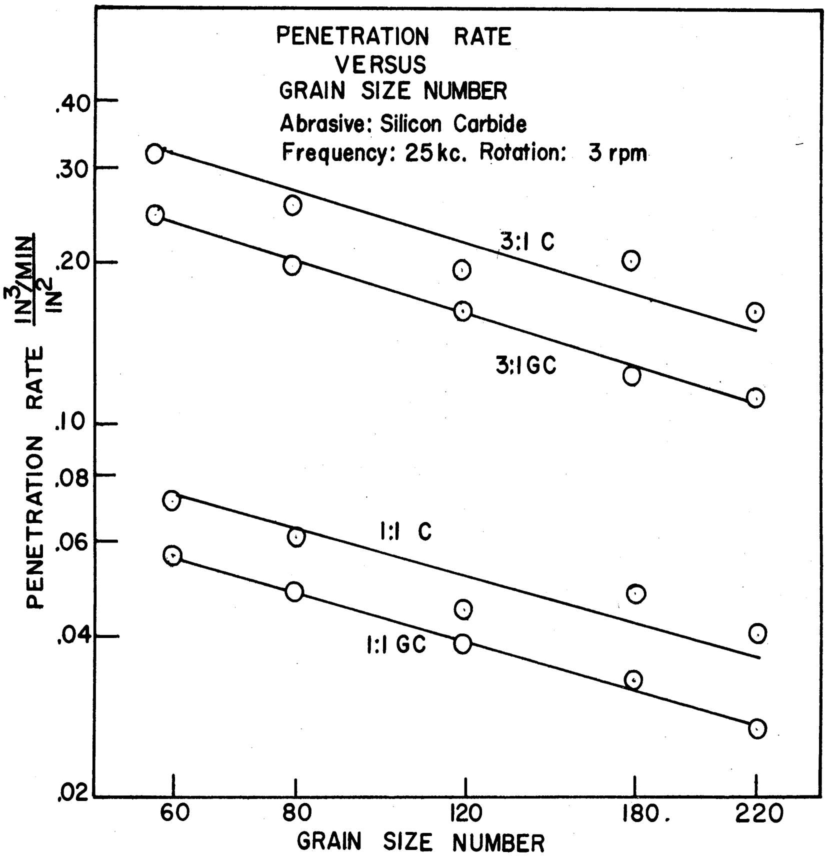


Fig. 13. Penetration rate vs. grain size number for 25 kc.

Conclusions

The results of the series of tests described in the two reports covering this project indicate that there is little likelihood that the techniques developed and used to date will find use in the large-scale breaking up of pavement. There are, however, certain areas where the use of ultrasonic drilling methods show promise. The very feature which limits ultrasonic drilling speed, that is the breaking up of the work material in minute rather than gross pieces, makes its use for more precise hole forming realizable. It appears then that the most attractive use for ultrasonic drilling as it is known currently, is in those applications where better dimensional control of the hole is required than can be achieved with the air-operated hammer.

The efficacy of the technique described in this report as a means of evaluating certain properties of abrasive materials is demonstrated by the repeatability of the data collected. In the evaluation of abrasive materials, it is noteworthy that the green carbide, which is highly rated in the trade, did not develop as high a penetration rate as did the grey carbide. An evaluation of the reasons for this behavior was not developed but it undoubtedly is related to the greater toughness of the grey carbide.

In the drilling tests performed, it became apparent that with the work materials used, there was very little destruction of the abrasive material, but rather a distinct reduction of the work material grain size, as well as a polishing and rounding effect. The workpiece itself developed a boundary layer ahead of the tool. The boundary layer thickness was dimensionally about equal to the diameter of the abrasive particle. The strength properties of the boundary layer were observed to be considerably lower than the properties of the parent material.

The tests reported herein are not exhaustive in that there are additional areas of interest which might bear closer investigation. It would seem reasonable that there should be some relationship between the minimum frequency or amplitude at which material removal commences and the compressive or shock resistant nature of the material. It would be of some value to explore the relation of the higher derivatives of displacement to the failure or cutting rate of certain materials.

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