VARIATIONS IN ROCK DRILLING RATES CAUSED BY CHANGES IN AIR PRESSURE

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PREFACE

Interest in doing research on rock drilling rates with changes in air pressure was generated by the author's thesis advisor, Professor R. L. Peurifoy. Much of the published material on the subject of rock drills and drilling rates is not directly applicable to the construction industry. The intention throughout this study has been to produce practical results that would be of value to an individual engaged in quarry operations. Even though only two different pieces of drilling equipment and two types of material were used, the results of this project give an indication of what production can be obtained in similar conditions with this type equipment.

The author gratefully acknowledges the technical assistance and encouragement of his advisor, Professor R. L. Peurifoy, and expresses thanks to Professor R. L. Lowrey of the Mechanical Engineering Department, who gave much needed assistance on the instrumentation of the laboratory portion of this project. I also wish to thank the many people who assisted this project by either loaning of donating equipment, particularly, Mr. Guy James of Guy James Construction Co. Inc., Oklahoma City, who loaned the 600 cfm compressor and the track-mounted drill; Mr. Thomas Wilson of the Victor R. Phillips Co., Oklahoma City, for the loan of the jackhammer; the Timken Roller Bearing Co. Inc. for the donation of the bits used in the test; and to Standard Industries, Tulsa, for the use of their quarry in Ponca City. Acknowledgement is also given to the Central Propane Company, Stillwater; the Oklahoma Natural Gas Company, Stillwater; Lehland Equipment Company, Oklahoma City; American Meter Company, Tulsa; Griffith Well Cementing Company, Cushing; and the Agricultural and Mechanical Engineering Departments at Oklahoma State University for additional equipment supplied on a loan basis.

The assistance of Mr. Merrill and his crew of the Mechanical Maintenance Department at Oklahoma State University is also recognized.

Thanks are also due to my wife, Marjorie, and the children, who survived the ordeal of this project.

The typing of this thesis by Miss Natalia Crenwelge is also recognized.

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LIST OF ABBREVIATIONS AND SYMBOLS

Symbol	Meaning
A	Area
cfh	cubic feet per hour
cfm	cubic feet per minute
cm	centimeter
cps	cycles per second
cu ft	cubic feet
deg	degree
dev	deviation
E	Modulus of Elasticity
En	Energy
F	Fahrenheit Temperature
Fig.	Figure
freq (f)	frequency
ft	foot
ft-lb	foot-pound
hgt	height
hr	hour
in.	inch
in.-lb.	inch-pound
l	length
lb	pound

Symbol	Meaning
lin	linear
mat'l	material
max	maximum
min	minute
mm	millimeter
pcf	pounds per cubic foot
pres	pressure
psi	pounds per square inch
psig	pounds per square inch gage
sec	second
sq in.	square inch
temp	temperature
vol	volumetric
ϵ	strain
σ	stress
u	micro

CHAPTER I

INTRODUCTION

The need for additional research into the field of rock drilling with jackhammers and heavier track-mounted drills was recognized by R. L. Peurifoy, Professor of Construction Engineering at Oklahoma State University, when he noted on various construction jobs that the production rates of rock drills appeared to be less than the rates that should be expected, probably because of insufficient air pressure. Professor Peurifoy made a search of the literature and publications and wrote to the leading manufacturers of rock drilling equipment in an effort to obtain information that might be of interest to the construction industry. From his efforts he found that some drilling tests at various air pressures had been conducted, mostly by the manufacturers of rock drilling equipment. The results of these tests were either not directly applicable to the actual problems of rock drilling or were not published. This showed that additional research in the field of rock drilling at various air pressures was warranted.

A search of the available literature was made. In 1922 Seaman and Jerome conducted extensive research for the United

Verde Copper Company (1). They ran 1500 tests in an effort to determine the most economical air pressure for hammer-type rock drills. In their results they found little or no increase in mechanical efficiency above 90 psi, and they determined that the best operating pressure was about 95 psi. They believed that operating at pressures in excess of 95 psi for prolonged periods would increase the breakage of drill steel and would make operation at the higher pressures uneconomical. In the same year Day reported on the procedures used by manufacturers to determine the drilling speed, air consumption, blows per minute, force of blow, and operation in general (2). He concluded that the drilling rate of any drill with variations in air pressure was not a straight line, but a slight curve that showed a marked change of slope around 75 psi before decreasing in slope as it continued to 100 psi. Unfortunately this information is not as valuable today as it was in 1922. Since that time there have been numerous improvements in design and materials used in rock drilling machines.

From the period 1922 to 1950, there was little published material. In 1953 Cheetham and Inett examined the main factors affecting drilling rates, namely, air pressure, air consumption, thrust, rotation of drill steel, stroke length, lubrication, and flushing results (3). They concluded that a variation in the air pressure gave a nonlinear drilling rate, and that the most efficient drilling rate was between 60 to 80 psi. Later in 1958, Inett made additional studies on the factors affecting drilling performance and restated his belief on the effect of drilling rate variations with changes in air pressure (4).

The purpose of the project is to study the effect of variations in air pressure on the drilling rates of an Ingersoll-Rand medium size jackhammer and a Gardner Denver track-mounted drill. The results are limited to the models of equipment used in the tests and on the media used for drilling.

The results of the study are shown primarily through a graphical analysis. The drilling rates for the track-mounted drill are broken down into two sections, one for the concrete block, and the other for actual quarry drilling. The jackhammer tests were divided into two similar sections, but a further subdivision of the results by drill steel size was required to clarify the results. A theoretical analysis of the jackhammer is given as additional information to the jackhammer tests. A detailed list of equipment, design of the experiment, experimental procedure, results and their analyses, conclusions, and topics for further study are included.

CHAPTER II

DESIGN OF THE EXPERIMENT

The basic design of the experiment was to run controlled drilling tests on a homogeneous mass of material and on limestone. The homogeneous mass of material was a concrete block poured on the campus of Oklahoma State University, and the limestone was located in a quarry about sixty miles north of the campus at Ponca City, Oklahoma.

Statistical Layout

As neither the concrete nor limestone could be assumed to be completely homogeneous, a statistical approach to this problem was necessary. The test area was laid out with fourteen rows and seven columns. The columns were given the designations A through N and the rows 1 through 7. This gave an area containing ninety-eight holes. Forty-eight holes were required for both the drifter and jackhammer portions of the test which left two holes unassigned to cover any eventuality. For each pressure four test holes were drilled in each test media with both the track-mounted drill and the jackhammer. No two holes were drilled side by side with the same piece of equipment.

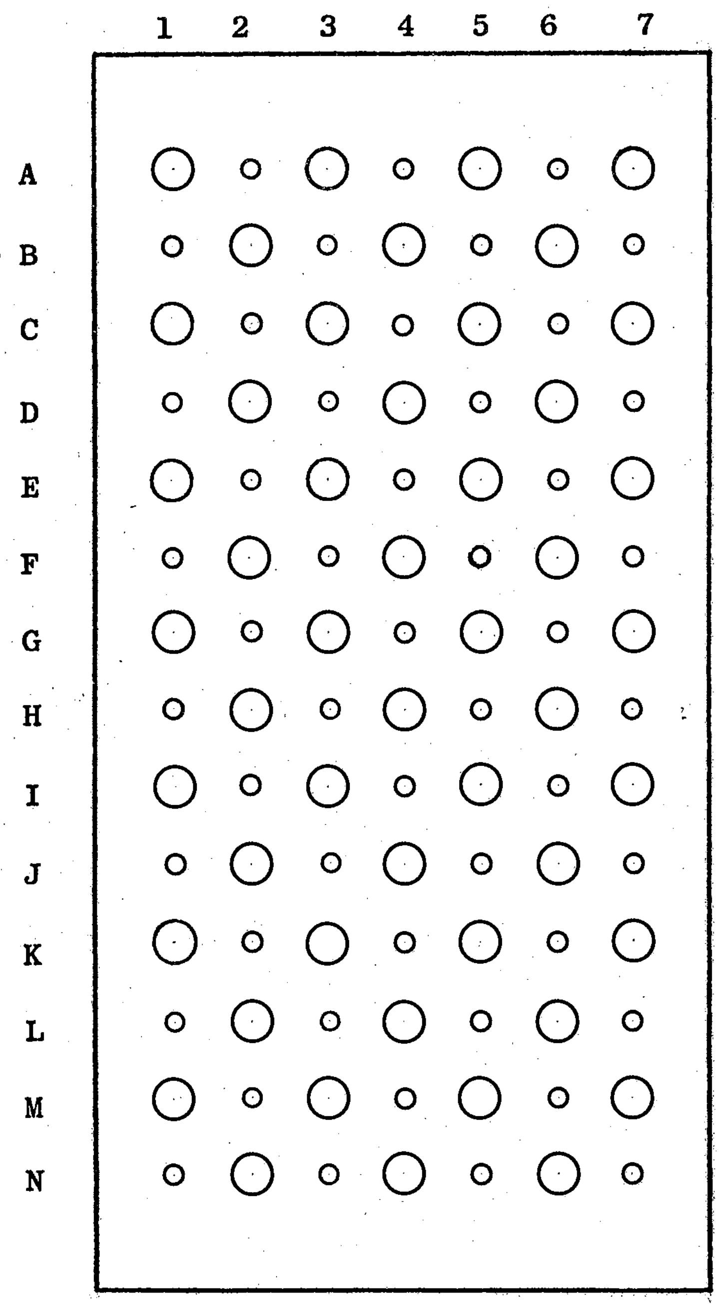


Fig. 1 Drilling Pattern

Holes were assigned to a pressure by the use of the statistical method of randomization with the use of a random number table (5). The four carbide insert bits for the track-mounted drill phase were designated as A, B, C, and D. Bit A was used for the first hole at a set pressure, and then was followed by bits B, C, and D, whenever succeeding holes were drilled at that pressure. There were only three carbide insert bits available for the jackhammer, so a different system was used. These bits were designated P, Q, and R, and were used for succeeding holes drilled at the same pressure. The bit for the fourth hole was selected at random.

To further randomize the experimental set-up, the order of drilling the holes was selected by randomization. The reason for using the random method for holes, bits, and pressures, was to lessen the effect of such variables as temperature, humidity, hardness of material, and wear on the bit that were present in the experiment. This system was important in drilling the concrete, but was probably more important in drilling in the limestone quarry where the hardness of the drilled material was sure to vary. By using this method, there was a greater chance that the mean of the drilling rates at a given pressure would be closer to the true mean.

Pressure Range

The pressure range studied was from 55 to 110 psi, which is the range in which contractors ordinarily operate. Manufacturers of modern compressors recommend that they be operated at 100 psi, but many contractors set the air regulator valve on the machine to obtain additional pressure. Since the demand on the compressor plus the line losses control the actual pressure at which the drill will operate, there may be times when equipment will be operated at pressures below 100 psi, even as low as the 50 to 60 psi range.

Temperature

Temperature measurements were taken at the beginning of every hole. The purpose was to see if there was any correlation between the drilling rate and temperature of free air at the time of drilling.

Method of Measurement

The method of measurement employed to obtain the objective of the test was to record the drilling time, pressure, temperature, hole depth, hole diameter, and bit diameter. Table I indicates the equipment used to measure the data and the unit of measurement obtained from the instrument.

TABLE I

METHODS OF MEASUREMENT

Observed Data	Units	Method of Measurement
Drilling Time	Secs	Stop Watch
Drilling Pressure	Psig	Bourdon Pressure-Gage, Circular Disk Pressure Recorder
Temperature	^{o}F	Thermometer
Hole Depth	In.	6 Ft. Tape Mounted on 3/4 In. Square Rod
Hole Diameter	In.	Inside Calipers and Machinists Rule
Bit Diameter	In.	Micrometer

CHAPTER III

SELECTION OF MAJOR EQUIPMENT AND MATERIALS

Track-Mounted Drill

The primary requirements for the selection of the track-mounted drill were that it be in good working condition and be of a common type used by the construction industry. The model used was a Gardner Denver (model AT) which mounted a drifter (model DH 123J-1) with a $4\frac{1}{2}$ inch size piston. The model that was used fulfilled both requirements.

Jackhammer

The jackhammer requirements were identical to those of the track-mounted drill. The model used was a medium class Ingersoll-Rand (model J-40) which weighed 57 pounds.

Air Compressors

In selecting an air compressor for this type experimental work, the first consideration was its size, and second, its method of compressing the air. It was deemed necessary to have a compressor capable of delivering 600 cubic feet per minute (cfm). This compressor capacity normally would run two air track drills of the size used in the test at a pressure approaching 100 psi (6). Since pressures up to 110 psi were needed in the drilling tests, a 600 cfm compressor was necessary. The air supplied to the drill had to be as uniform in pressure as possible to decrease the air regulation problems. Portable air compressors are made in two types, rotary and reciprocating. The rotary compressor produces air at a more uniform pressure than the reciprocating type, so it was the more desirable. The compressor used during the tests was a 600 cfm, Ingersoll-Rand, model R-600. This model had the capacity required and was a rotary type.

The field trials on the Oklahoma State University campus and at Ponca City made use of the 600 cfm compressor, but this compressor was not available when the theoretical jack-hammer tests were run. For this work a 125 cfm, Chicago-Pneumatic (model 125 RG-2) rotary compressor was used.

Air Pressure Regulator

The air pressure regulator had to have a rapid response to changes in air pressure to be effective in these tests. The regulator selected was a Fisher Governor Co., model 4100U-657, with a Wizard pilot control. This was a pressure differential type regulator with a diaphragm mechanism that controlled a double port, throttle plug valve. The Wizard pilot contained a Bourdon tube with a sensitivity of 2% of its range (0 - 250 psi). According to the manufacturer's information, this regulator could control 186,000 cfh or

3100 cfm for an inlet pressure of 115 psi and an outlet pressure of 100 psi. This gave a capacity greater than was required for the tests. This regulator handled test pressures with variations of plus or minus 1 psi in most cases.

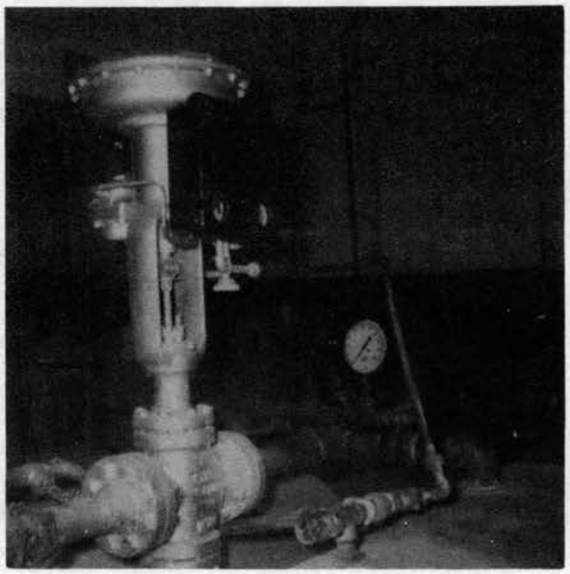


Fig. 2 Air Pressure Regulator

Air Pressure Recorder and Gage

To have an accurate record of the drilling pressure maintained during each trial, a circular disk air pressure recorder was used. Since the drilling pressure was sure to vary, it was important that an accurate record be maintained for evaluation of the test results. This recorder was capable of recording the pressure to one pound and had the added advantage of recording the time in 15 second intervals. The regulator used was manufactured by American Meter Company and had the capacity to record up to 150 psi. Each 360 degree revolution of the 12 inch paper disk took 24 minutes. It had an accuracy of one percent of the full scale reading.

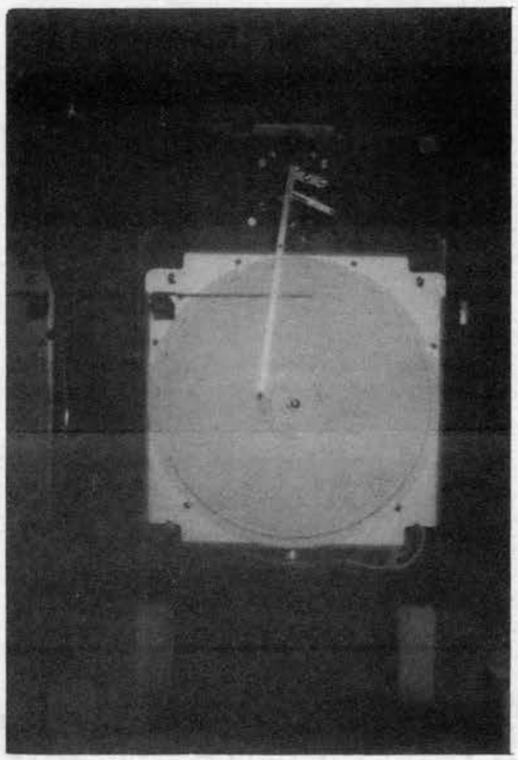


Fig. 3 Air Pressure Recorder

To insure that the recorder was reading the correct pressures, it was compared daily to the reading of a Bourdon gage that had been tested and calibrated on a dead weight tester. This gage was mounted on the outlet pipe leading from the reservoir tank. The Bourdon gage, a Jas. P. Marsh Corp. product, had a range of 0-200 psi, and had an accuracy of one percent of the full scale reading.

Reservoir Tanks

Even though a rotary type air compressor was used, it was necessary to have air reservoir capacity in addition to the capacity of the tank mounted on the rear of the compressor. The primary purpose of these tanks (two tanks of 50 cubic feet capacity each) was to act as an immediate source of air reserve between the compressor and the drill. Whenever a drill is started, there is a sudden large demand for air that is too great for the compressor to supply on an instantaneous basis. These tanks supplied much of the air for the initial surge to the drill and dampened out the air surge caused by the compressor as it tried to compensate for the sudden demand.

These tanks had a secondary purpose, which was to collect part of the moisture that was in the air. Much of the drilling was done in below freezing temperatures, and removal of this water was essential to the satisfactory completion of these tests.

Bits

In running a test of this type, various sizes and shapes of bits may be used. The most common bits in use today are the removable bits that are made either with the cutting edges heat treated or with tungsten carbide inserts for cutting edges. The case hardened steel bits are the cheaper of the two types, but they have a much shorter drilling life. The tungsten carbide, on the other hand, will have a bit life of at least 30 to 1 when compared to the steel bits, and even a higher ratio can be achieved as the rock gets harder (7). The tungsten carbide insert bits were selected for this project because of their durability. For the drilling tests to be valid, it was important that bit wear be negligible so as not to introduce an additional variable into the experiment. The bits used were $1\frac{1}{2}$ inch size for the jackhammer and 3 inch size for the track-mounted drill. These are common size bits available from regular suppliers.

Drill Steels

For the track-mounted drill a $1\frac{1}{2}$ inch diameter 10 foot drill steel was used. The only requirements for the drill steel were that it be straight and be of the same thread as the drill bits. The jackhammer drill steel was 7/8 inch hexagonal shape, in 2 and 4 foot lengths. The basic requirements for the jackhammer drill steels were the same as for the track-mounted drill. That is, the steels had to be straight and be able to fit the drill bit. The need for two drill steels was necessitated by the fact that the vertical alignment of the jackhammer at high pressures was hard to control when a test hole was started with a 4 foot drill steel. As the jackhammer bounced, its height above the drilled surface caused this difficulty. The solution to this was to use a 2 foot drill steel for approximately the first 18 inches, and then use a 4 foot drill steel to complete the test.

Concrete Block

The most reliable way to test the drilling rate of equipment is to have an actual record of the drilling pressure and to drill into a homogeneous material. In this project the homogeneous material was ready-mix concrete procured locally. The specification for the mix was that it had to have a 28-day compressive strength of 4000 psi. This was verified by taking three test cyclinders and performing The Test of Compressive Strength of Molded Concrete Cylinders in accordance with the American Society for Testing Materials (ASTM) Designation C 39-49. The results of the test were cylinders that fractured at 6,920, 6,752, and 6,579 psi. As a measure of the abrasion of the aggregate that was in the concrete, a Los Angeles Abrasion Test (ASTM Designation C 131-55) was run. The wear was 23.0 percent.

The concrete was mixed at the site and poured into forms

4 feet wide, 8 feet long, and 4 feet high that were below ground level. The top of the forms was approximately 2 feet below the surface of the ground. As the concrete was placed in the forms, it was vibrated to improve its homogeniety. Curing compound was applied to the exposed surface. The forms were removed after four days, and the concrete block was left undisturbed for the full 28-day curing period. Further information concerning the nature of the concrete used is found in Appendix E.

Limestone Quarry

To complete the field tests, drilling was done in limestone. The material that was used as the test media was softer than was desired, but a source of rock suitable for drilling other than limestone is nonexistant in this area. It was essential that the rock be fairly homogeneous and not badly stratified. The area selected for the tests had been used as a quarry before, and it was possible to measure the distance from the surface of the drilled area to the clay seams that were evident in the rock by measuring along a vertical face that was near the drilling site. This is shown in Fig. 4.

To further define the type of limestone used, a spectographic analysis of a specimen was performed by the Agronomy Department at Oklahoma State University. The results of the test showed that the material was composed of 78.75 percent calcium and magnesium carbonate and 21.25 percent impurities. The density of the material was 162 pounds per cubic foot.

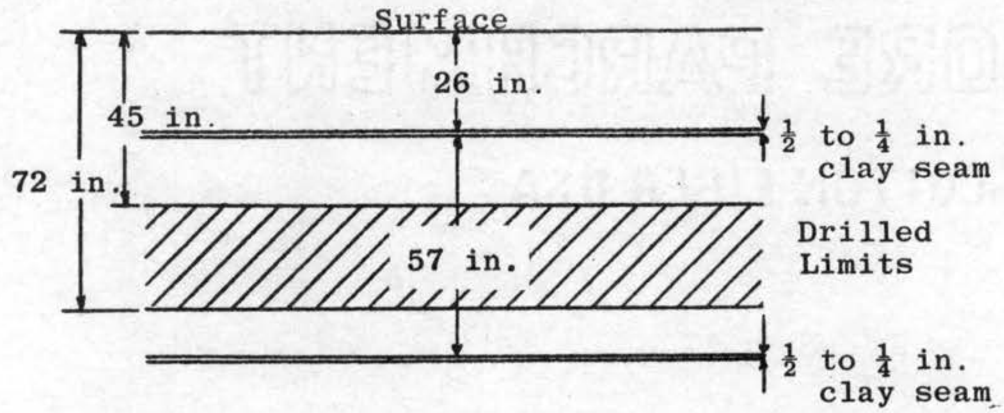


Fig. 4 Cross-Section Through Limestone

Oscilloscope

An oscilloscope on which was mounted a Polaroid camera was used to record the impact waves of the jackhammer during the theoretical analysis. A paper strip recorder was used initially, but it did not have as rapid a response as was required. The oscilloscope used was a dual beam, Model 502, made by Tektronix Inc., that had the capability of showing these waves. Only one channel was used at a time.

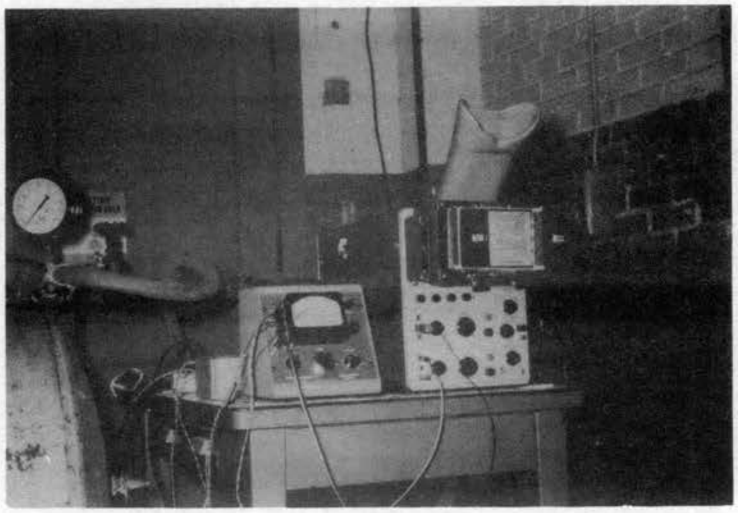


Fig. 5 BAM-1, and Oscilloscope With Polaroid Camera

Bridge Amplifier Meter

In a standard strain gage assembly for dynamic loading, a Wheatstone bridge is integrated into the system to produce a balanced circuit prior to the starting of a test run. Also, it is highly desirable to amplify the voltage differences that result so that a more distinct wave pattern will show on the oscilloscope. Both the Wheatstone bridge and amplifier were contained in a Bridge Amplifier Meter, Model BAM-1, manufactured by Ellis Associates.

Additional data on the above mentioned items of equipment, and a complete equipment list is found in Appendix A.

CHAPTER IV

EXPERIMENTAL PROCEDURE

Empirical Approach

The set-up of the equipment for the drilling tests was basically the same for both the jackhammer and track-mounted drill. The 600 cfm air compressor was connected to the air pressure regulator by a 2 inch rubber hose 22 feet long. The air passed through the regulator to the reservoir tanks which were connected in series, and then went by flexible rubber hose to the track-mounted drill or jackhammer. A 22 foot section of 2 inch hose connected the drifter to the regulator and, a 50 foot section of 3/4 inch hose was used for the jackhammer. The air pressure recorder was connected by a 7 foot length of $\frac{1}{4}$ inch rubber hose to a $\frac{1}{2}$ inch pipe that interconnected the air reservoir tanks at the top. Two Bourdon gages were placed in the system. The first was at the top rear section of the second receiver tank from the compressor, and the other was inserted just before the hose connection that joined the tanks to the drilling equipment. The track-mounted drill had a line oiler organic to the machine, but the jackhammer required a separate line oiler to be inserted into the line. A schematic diagram of the equipment is shown in Fig. 6.

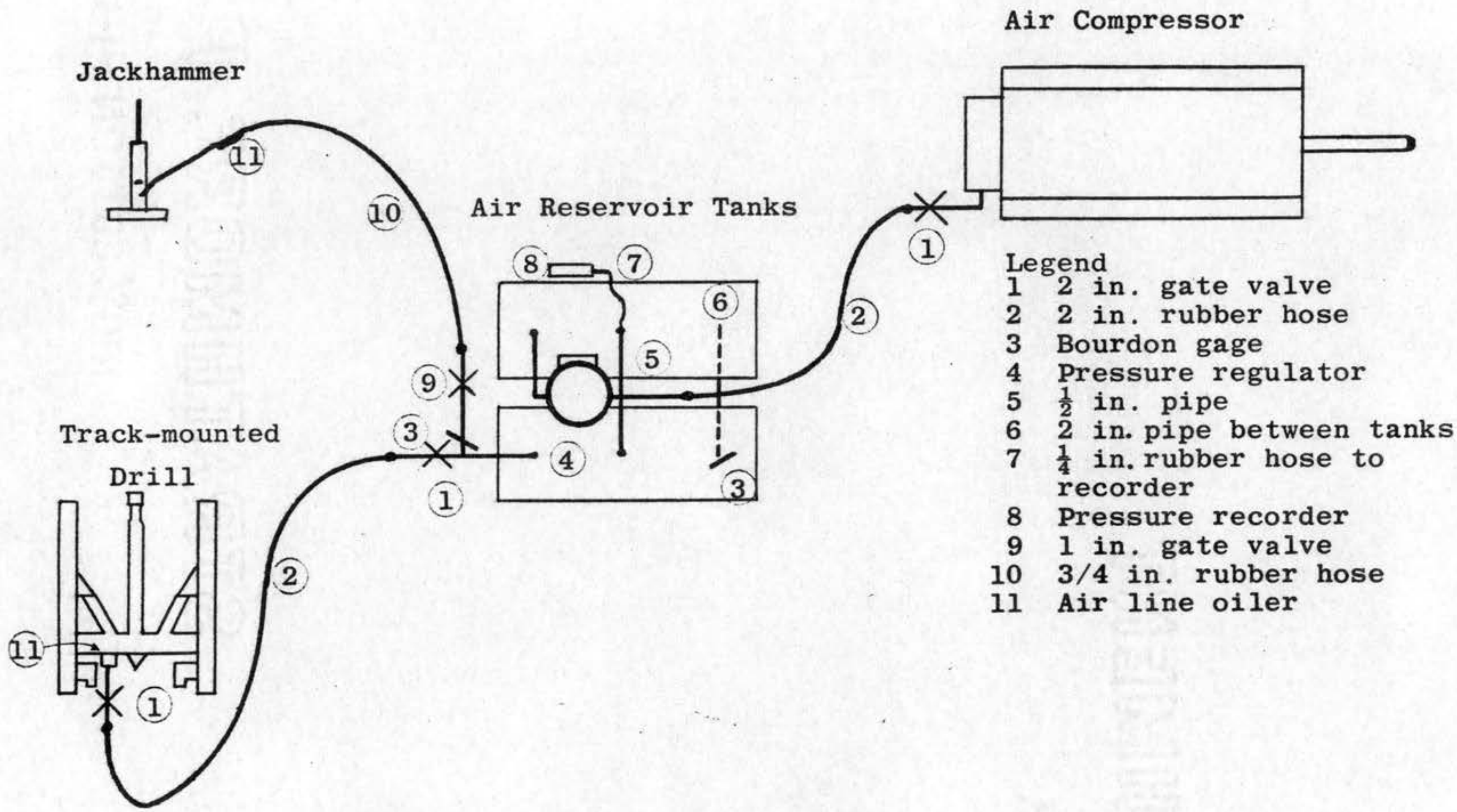


Fig. 6 Equipment Layout

In order to reduce the element of human variables being introduced into the experiment, set duties were assigned to the two individuals who conducted the test, and these duties remained unchanged until that phase of the experiment was finished. For example, the individual who held the jackhammer for the first hole that was drilled on the campus of Oklahoma State University operated the jackhammer for every jackhammer hole drilled there. The procedures used for each test hole on the concrete block on the Oklahoma State University campus were almost identical to those used at the Ponca City Quarry. The main difference in procedures used between the two areas were that the two individuals who conducted the tests exchanged duties, and the test hole center to center distances were different. The holes in the concrete block were spaced 6 inches on center, and those at the limestone quarry were spaced 12 inches on center. The test holes were marked with a 1½ inch hole approximately 1-2 inches deep and drilled with the jackhammer. The bit used was a 1½ inch steel throw-a-way type.

Each day the air pressure recorder was placed back into the system and calibrated. Its reading was checked against the Bourdon gage mounted on the outlet pipe from the second reservoir tank. Initially both Bourdon gages were used, but the gage mounted on the air reservoir tank froze due to the cold weather, and permanent damage resulted to it.

A loose leaf notebook contained all the data sheets in the order the holes were drilled. The paper disks for the air pressure recorder were arranged in order and had the hole number and pressure written on them prior to the start of a series of tests. This was done to avoid confusion between holes and pressures as the project progressed.

After the equipment was properly connected, and the location of the test holes indicated on the concrete or limestone, a practice hole was drilled to test the apparatus and the procedures used in compiling the data. An extra bit was used for this test.

In conducting these tests the operator had to control the downward force on the drilling machines. On the track-mounted drill there was a feed control that varied the downward force applied to the drifter. For the test holes drilled in the concrete, the chain that ran to the drifter was slackened, and the operator observed the slack in the chain. When the chain became taut, pressure was being exerted on the drifter, and the feed control had to be manually adjusted to relieve this tension. At the limestone quarry this chain was disconnected from the feed control to insure that the only weight on the bit was the weight of the drill steel and drifter.

The jackhammer operator applied no downward pressure, but merely held the machine in a vertical position.

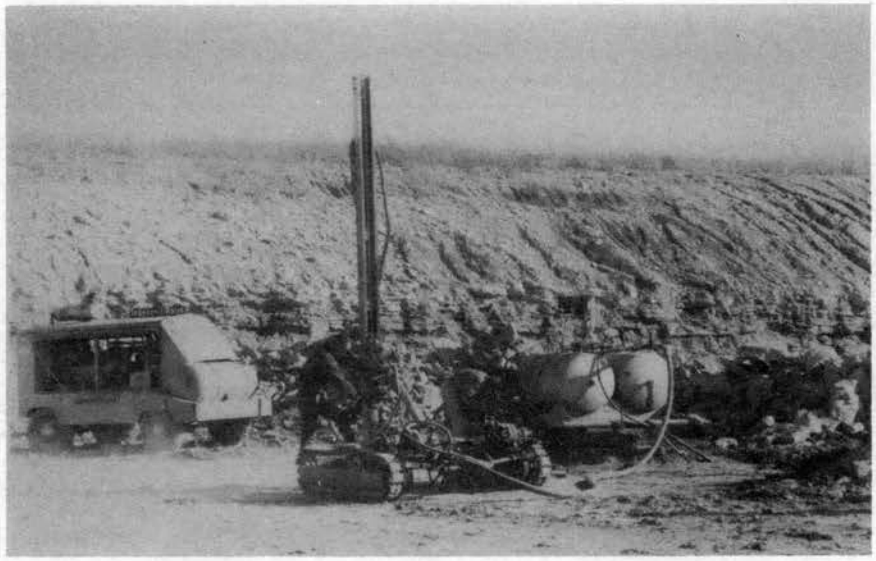


Fig. 7 Drilling in Limestone Quarry

Track-Mounted Drill

The procedure followed for the test drilling was as follows:

1. Complete heading of data sheet
2. Move equipment to correct marker hole
3. Check boom for vertical alignment
4. Measure gage of bit
5. Place bit on end of drill steel
6. Place circular disk in pressure recorder
7. Adjust pressure regulator to required pressure
8. Collar hole and blow out debris

9. Measure hole depth
10. Measure hole diameter
11. Recheck pressure
12. Read temperature
13. Zero stop watch
14. Commence test
15. Stop test
16. Blow out debris from hole
17. Measure depth of hole
18. Remove paper disk from pressure recorder
19. Remove bit from drill steel and measure gage
20. Insure all necessary data recorded on data sheet.

When the track-mounted drill was at the correct location, the boom alignment was checked with a carpenter's level. It was important that the drill steel be vertical to avoid having two holes intersect. The gage of the bits was checked with a micrometer to measure the bit wear. The designated bit was then placed on the drill steel, and the test hole was collared at the assigned pressure for that test. The collaring operation served two functions. First, it made it possible to start the test hole at full throttle, and second, it gave a check on the pressure regulation system. After the hole was collared, it was cleaned out by putting the air control handle on the "blow" setting. The bit and drill steel were then withdrawn from the hole, and the depth of the hole was measured with a 6 foot metal tape that was mounted on a

3/4 inch square by 5 foot long piece of plywood. This measuring device was passed through a three-legged 9 1/8 inch high ring stand that had a fine wire stretched across the center of the 3 1/8 inch diameter ring. The position of the legs on the concrete or rock surface was marked, and the depth of the hole measured. The measuring stand was removed, and the diameter of the hole was measured by placing inside calipers inside the hole and checking the diameter in two places 90 degrees apart. The caliper was then laid on a machinist's rule from which the diameter of the hole was read.

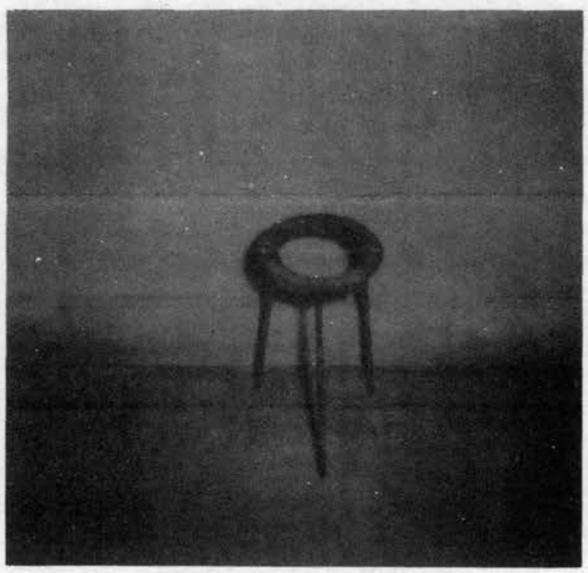


Fig. 8 Measuring Stand

The control of the pressure regulation system was the most difficult phase of the field tests. In practice runs before the actual drilling began, a number of different methods were tried to stabilize the system. The solution to the problem was to have the demand on the system prior to the start of drilling approximately the same as the demand during drilling. This was accomplished by placing the air control on the drill at the "blow" setting and bleeding excess air off through the hose normally used for the jackhammer. When the air system was in proper adjustment, a wave was produced on the air pressure recorder which fluctuated approximately one pound from the desired pressure. When the drill air control was changed from "blow" to "drill and blow", the pressure recorder showed a sudden drop in pressure, less than three pounds normally, followed by an almost equal rise above the test pressure. The system would then equalize and maintain a plus or minus 1 psi difference throughout the remainder of the test.

Once the pressure was properly adjusted, the temperature was recorded, and the stop watch setting returned to zero. The time keeper observed the air pressure recorder and at a wave peak gave a signal to the drill operator who moved the air control from the "blow" to the "drill and blow" position. The stop watch was started, and the air pressure recorder disk marked indicating the start of a test run. The drilling continued until the bottom of the drifter reached a yellow mark drawn on the boom. The test was then stopped, the time recorded, and the air pressure recorder disk marked. The drill steel and bit were moved after the debris in the hole was blown out. The measuring stand was placed where it had been initially when the collaring depth was measured, and again the measuring stick passed through the hole in the center. The depth of the hole was recorded, the paper disk was removed from the pressure recorder, the bit was removed from the drill steel, and the bit gage measured with a micrometer.

Jackhammer

The procedure followed by the jackhammer varied from the track-mounted drill procedure in that there was a change of drill steels in each test run. To obtain adequate drilling distance, the bit was removed from the 2 foot steel at the completion of its run and placed on a 4 foot length. The depth of hole for the new start was measured, the stop watch was set to zero, and the test steps were conducted in the same order as for the track-mounted drill for the remainder of the test.

Laboratory Measurements

Electrical measurements to determine the energy levels with changes in air pressure were undertaken for both the track-mounted drill and the jackhammer. The large size of the track-mounted drill made it impractical to conduct tests

DATA SHEET SHEET NO. P-86

VARIATIONS IN AIR PRESSURE vs ROCK DRILLING RATES

LOCATION Ponca City DATE 2 JAN 64 TIME 1340

MATERIAL Limestone HOLE NO. D-6

OPERATOR R. H. R. TIMER P. F. K. RECORDER P. F. K.

DRILL TYPE: DH 123 J ✓ IR J 40 ___

STEEL: LENGTH 10 Ft. SIZE 1 1/2 in SHAPE ⌀ NO. 2

BIT: SIZE 3 in. NO. D CARBIDE ✓ STEEL ___

SHAPE X AIR HOLES: NO. 5 LOCATION 4 sides, 1 ℄

AMBIENT TEMPERATURE: START 63 °F FINISH 63 °F

BIT:	START	FINISH	LOSS	% LOSS
In Gauge	3.014	3.014	0.0	—
Flats In	—	—	—	—

HOLE:	D-1 in	D-2 in	Avg D	D-1 in	D-2 in.	Avg Dia	Avg Vol
FINISH	71 5/8		71.625				
START	14 1/16		14.063	3.08		3.08	
DIFF.	57 9/16		57.562				
FINISH							
DIFF.							

AIR PRESSURE:	Desire Psi	Min Psi	Max Psi	Average Psi	% Variation
OPERATING	90	89	91	90	
BUFFER TANK	—	—	—	—	
RECORDER	—			90	

TIME:	Min-Sec	Min	Min-Sec	Min	Min Totals
FINISH	3-09	3.15			
START	0-00	0.0			
DIFF.	3-09	3.15			

RATE:	LINEAR			VOLUME		
	Depth in	Time Min	Rate In/Min	Vol Cu In	Time Min	Rate in^3/min
1	57.562	3.15	18.29			
2						
AVG						
TOTALS						

Fig. 9 Sample Date Sheet

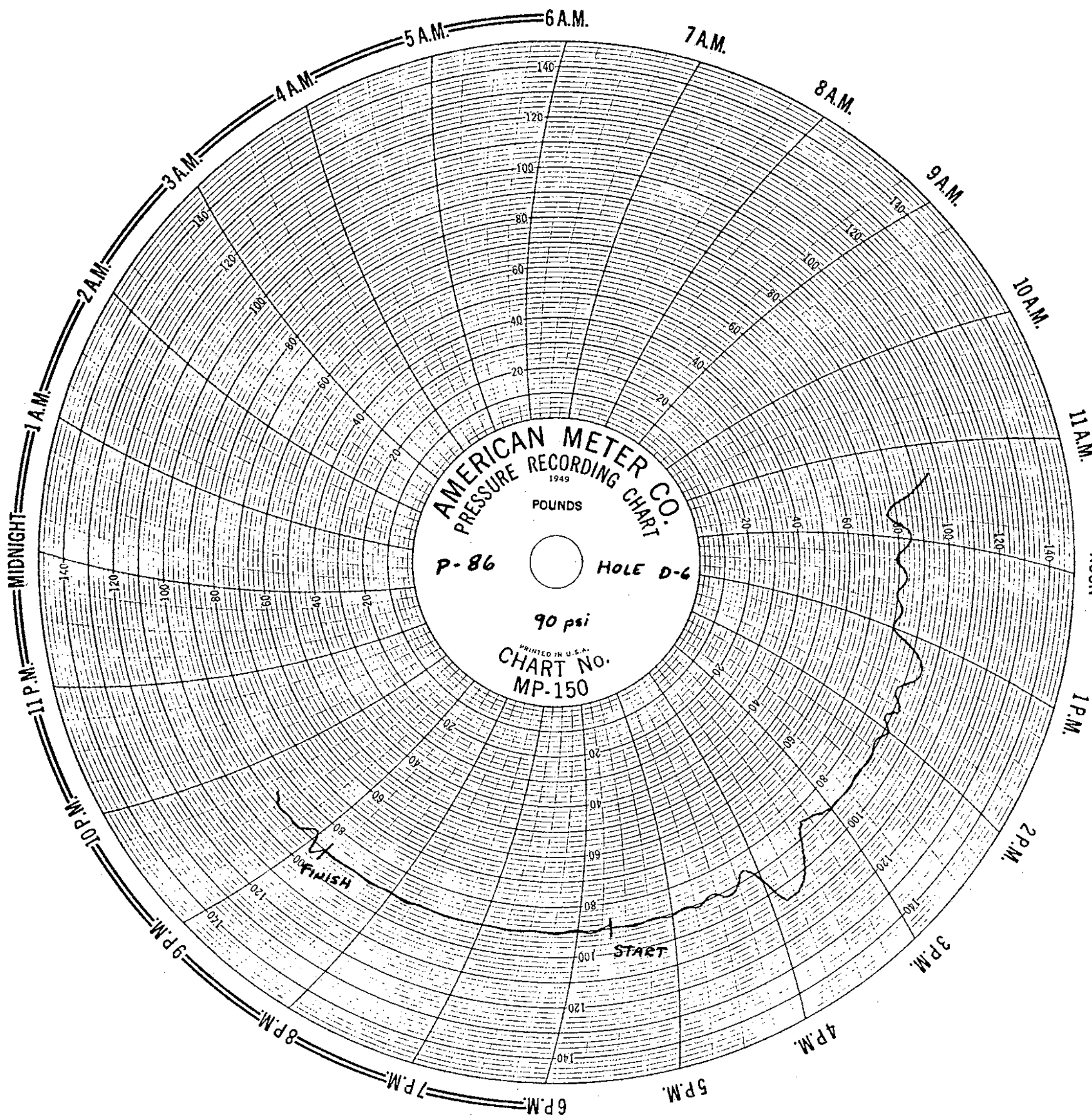


Fig. 10 Sample Air Pressure Disk

inside a laboratory, so the necessary electrical equipment was brought to the concrete block on the Oklahoma State University campus. Severe weather conditions during the time of the test had an adverse effect on the sensitivity of the electrical apparatus, and the results that were obtained were invalid. The jackhammer tests on the other hand, were not restricted by the problem of size, and a series of tests were conducted with the jackhammer at the Civil Engineering Laboratories on the Oklahoma State University campus.

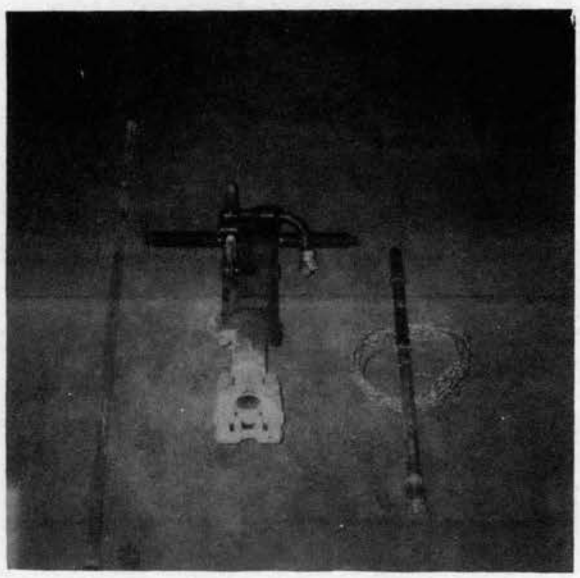


Fig. 11 Jackhammer, Drill Steels and Bits

The method used was to mount two SR-4 wire strain gages on opposite sides of the drill steel, and to run the leads to a Bridge Amplifier Meter (BAM-1) and variable resistance. The BAM-1 was connected to a cathode ray oscilloscope on which was mounted a Polaroid Camera. A schematic diagram of the circuitry is shown in Fig. 12, and a photograph of the equipment is shown in Fig. 5. An alternate method of measuring dynamic strain is with a ballast circuit.

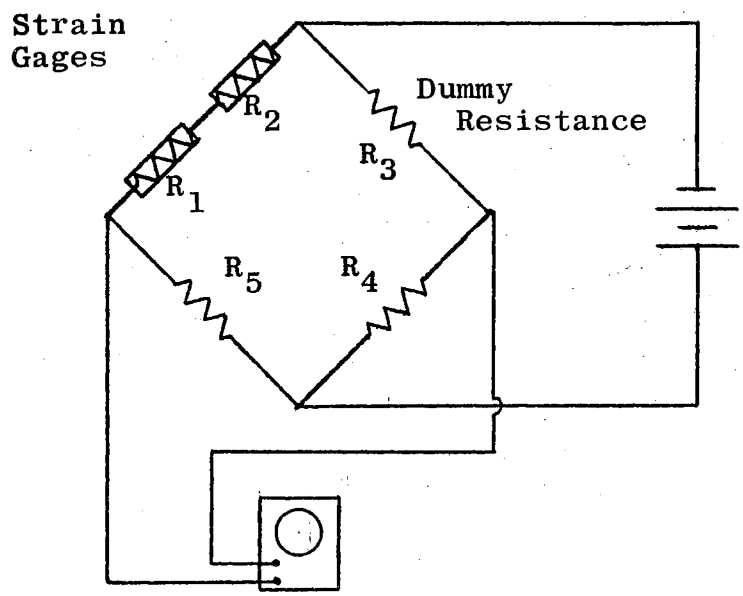


Fig. 12 Bridge Circuit

Strain gages work on the principles that the resistance of copper and iron wire changes with strain (8). To use a

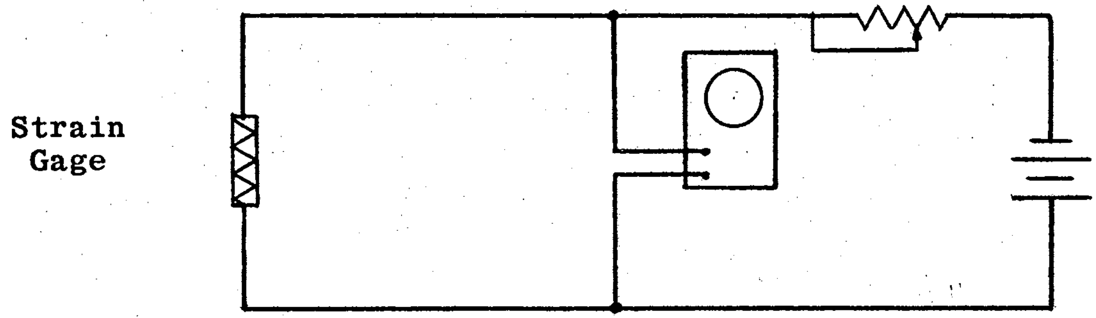


Fig. 13 Ballast Circuit

Wheatstone bridge arrangement to measure the strain, it is necessary to have four resistance legs which compose the bridge, a source of energy, and a method of sensing the change in resistance in the circuit.

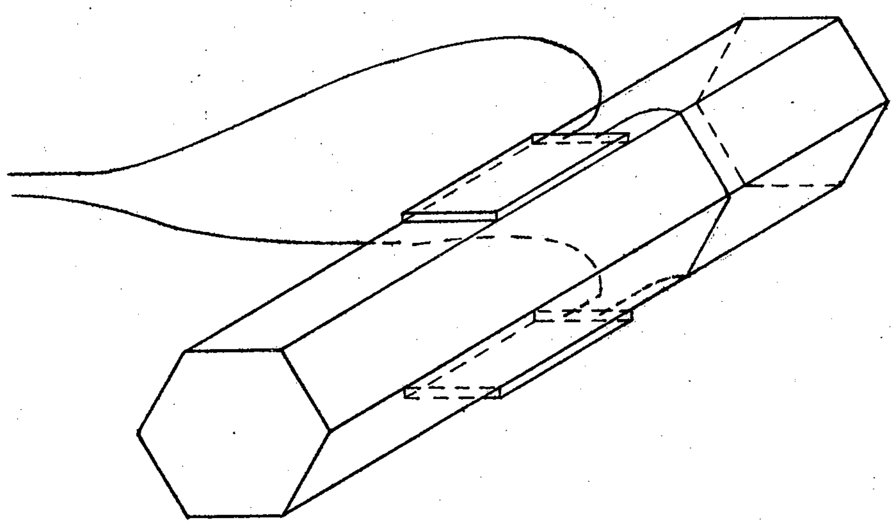


Fig. 14 Strain Gages Mounted on Drill Steel

The strain gages, R_1 and R_2 were connected in series and mounted exactly opposite on a 2 foot drill steel about 8 inches from the end that fits into the jackhammer. The strain gages were placed in this fashion to cancel any bending effects that would be present during a test run. One lead from the strain gages was connected to the BAM-1, and the other to a variable resistance. R_3 was connected to the strain gages and the BAM-1 which contained R_4 and R_5. The BAM-1 was connected to the oscilloscope. All cable in the circuits was two wire shielded type to eliminate outside interference. The leads on the strain gages were approximately 25 feet long to permit the wire to be coiled on the drill steel during the test.

The air supply and regulation equipment was identical to that used in the field tests with the exception that the Ingersoll-Rand 600 cfm compressor was replaced with a Chicago-Pneumatic rotary 125 cfm air compressor. The material drilled was concrete.

Once the electrical equipment was connected, the bridge was balanced. This was an exacting procedure that had to be carefully done since the amount of strain recorded was measured by the unbalance of the Wheatstone bridge. R_3 was adjusted until it equaled the sum of R_1 and R_2. R_4 and R_5 were legs in the BAM-1 so were adjusted by a knob on the machine. The BAM-1 was balanced first without power, and then was balanced with the bridge power switch on. The system was rechecked.

To obtain the full scale reading on the BAM-1, the calibration button was depressed, and the maximum calibration scale that would register on the meter was 0.5. For a calibration setting of 0.5, the needle deflection was 0.44 on the meter. The oscilloscope jack was inserted into the BAM-1 which automatically disconnected the meter on the BAM-1. When the calibration button was pushed again, the vertical displacement on the scope was 3mm. When this procedure was finished, the circuit was balanced and the following was true.

$$\frac{R_1 + R_2}{R_3} = \frac{R_5}{R_4}$$

or

$$\frac{R_1 + R_2}{R_3} = \frac{R_3}{R_4}$$

A number of practice pictures were taken with the camera mounted on the scope to obtain the best sensitivity setting and sweep time on the scope. Once the test pressure was reached, the lens on the camera was opened. The jackhammer was started, and after a time interval of five to ten seconds of operation, a trip switch on the oscilloscope was actuated, and a single wave sweep moved across the scope. The jackhammer was then turned off. The background grid on the scope was illuminated, then turned off. The camera lens was then closed, and in approximately 10 seconds the film was removed from the camera. Representative pictures of the wave forms are shown in Figures B-1 through B-3 in Appendix B. The step by procedure followed was:

1. Balance circuit with power switch off
2. Balance circuit on BAM-1 with power switch on
3. Recheck balance on BAM-1
4. Press calibration button on BAM-1 and select calibration scale
5. Record BAM-1 meter deflection
6. Bring horizontal axis on oscilloscope to zero line
7. Connect scope to BAM-1
8. Press calibration button on BAM-1 and read vertical displacement on scope
9. Adjust pressure regulator to test pressure
10. Adjust Polaroid camera and open lens
11. Start jackhammer
12. Trip switch to release single wave sweep
13. Stop jackhammer
14. Illuminate grid for 2 seconds
15. Close camera lens
16. Remove print from camera
17. Record sweep time and sensitivity setting from scope
18. Recheck balance
19. Examine pressure disk for average drilling pressure
20. Unwrap wire from drill steel

CHAPTER V

TEST RESULTS

The results of this project are presented in tables and figures on the following pages.

TABLE II

ACTUAL DRILLING RATES

Pressure psig	Concrete Linear in./min	Concrete Volumetric in.^{3}/min	Limestone Linear in./min	Limestone Volumetric in.^{3}/min
		Track-Mounted Drill		
55	9.34	67.92	13.02	95.78
60	10.02	72.63	13.97	102.93
65	9.21	67.61	15.98	117.84
70	10.53	76.79	15.30	112.97
75	11.98	87.34	14.59	107.50
80	12.49	90.24	16.08	118.81
85	12.51	91.05	17.57	130.13
90	14.96	109.00	18.99	140.59
95	12.48	91.77	18.21	134.47
100	14.61	105.79	19.92	147.75
105	14.94	108.48	19.13	141.40
		Jackhammer - 2 Ft. Steel		
55	10.01	19.25	12.78	23.94
60	10.72	20.56	12.85	24.04
65	11.10	21.50	13.65	25.76
70	11.65	22.57	12.53	23.74
75	12.41	23.73	15.00	28.04
80	13.45	25.72	13.48	25.29
85	13.92	27.02	13.74	25.00
90	13.97	27.88	13.60	25.43
95	13.40	25.96	15.87	29.86
100	14.30	27.95	14.59	27.26
105	15.51	29.56	15.28	28.58

TABLE II (Continued)

Pressure psig	Concrete Linear in./min	Concrete Volumetric $in.^3/min$	Limestone Linear in./min	Limestone Volumetric $in.^3/min$
	Jackhammer - 4 Ft. Steel			
55	9.52	18.20	13.29	24.90
60	9.93	19.04	13.59	25.40
65	9.65	18.69	13.77	25.99
70	11.04	21.39	14.18	27.85
75	11.45	21.89	15.51	28.98
80	11.83	22.62	14.74	27.66
85	12.22	23.73	15.25	28.51
90	13.01	25.03	15.22	28.45
95	13.08	25.34	16.40	30.85
100	13.26	25.91	15.56	27.08
105	13.48	25.68	15.97	29.86
	Jackhammer - 2 + 4 Ft. Steel			
55	9.72	18.58	13.00	24.52
60	10.21	19.58	13.32	24.89
65	10.14	19.64	13.72	25.90
70	11.26	21.82	13.58	25.71
75	11.79	22.55	15.33	28.63
80	12.39	23.68	14.28	26.80
85	12.80	24.86	14.71	27.50
90	13.34	25.96	14.62	27.34
95	13.19	25.55	16.18	30.44
100	13.62	26.63	15.22	28.45
105	14.14	26.95	15.33	29.40

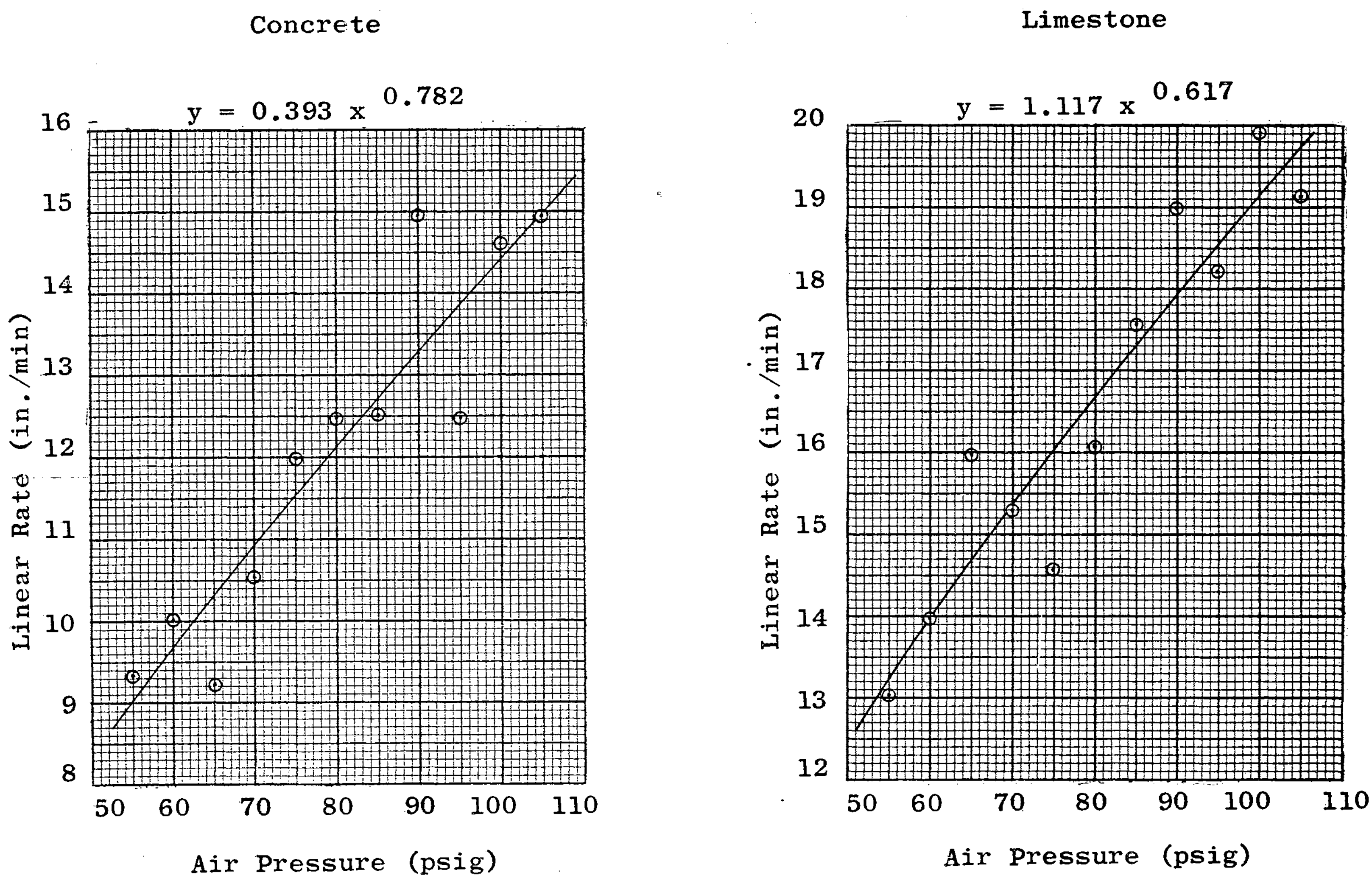


Fig. 15 Linear Drilling Rates for Track-Mounted Drill

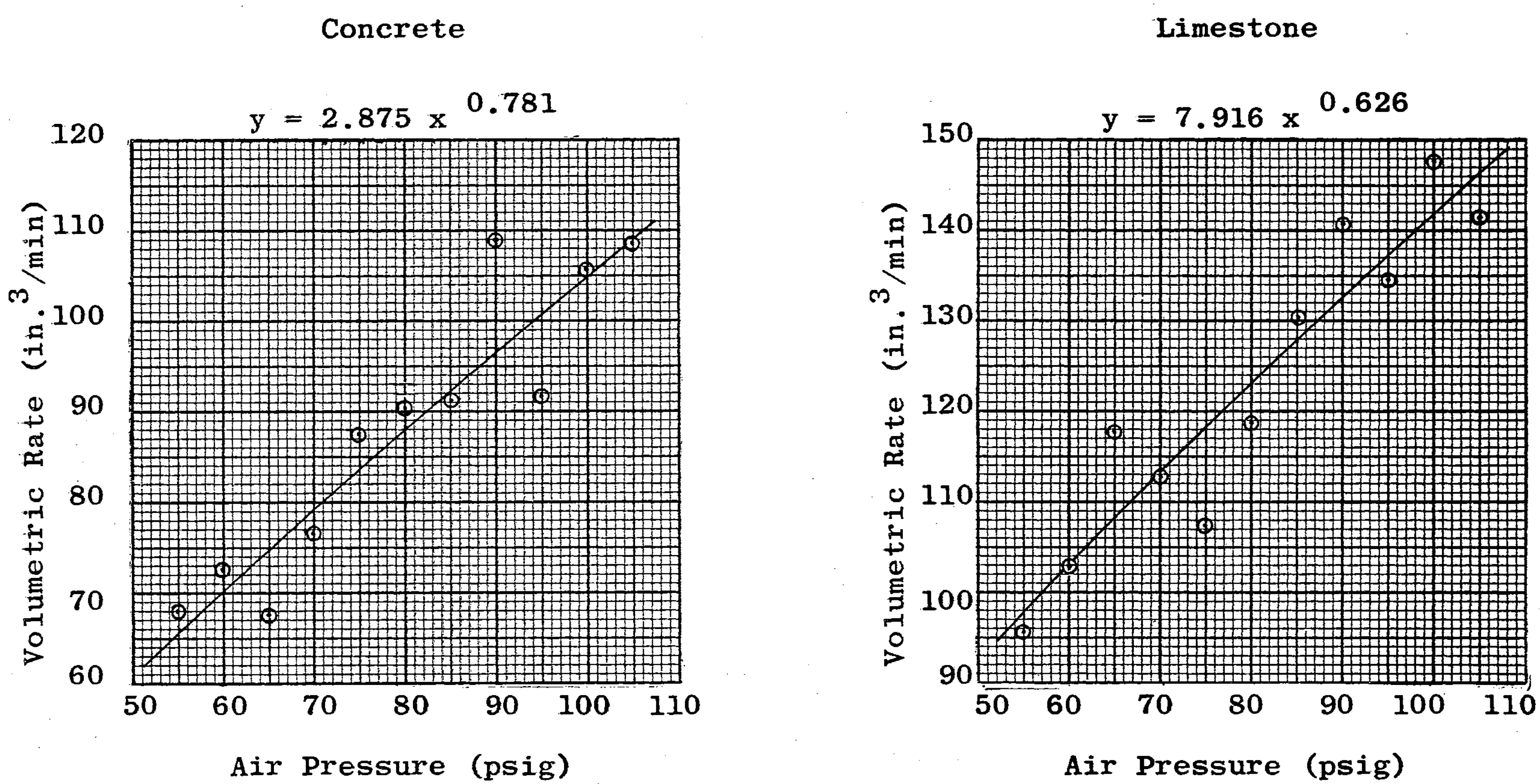


Fig. 16 Volumetric Drilling Rates for Track-Mounted Drill

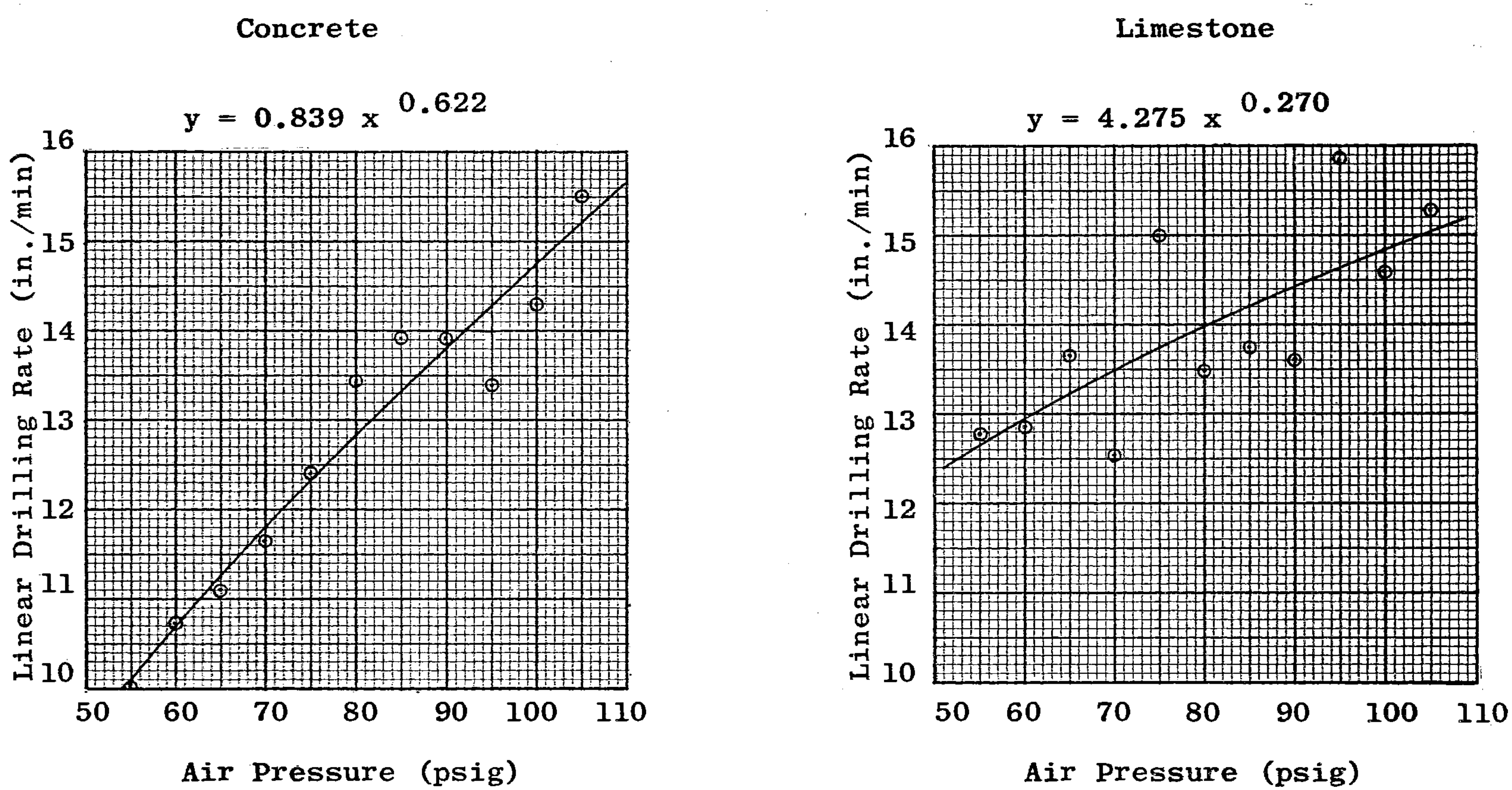


Fig. 17 Linear Drilling Rates for Jackhammer - 2 Foot Drill Steel

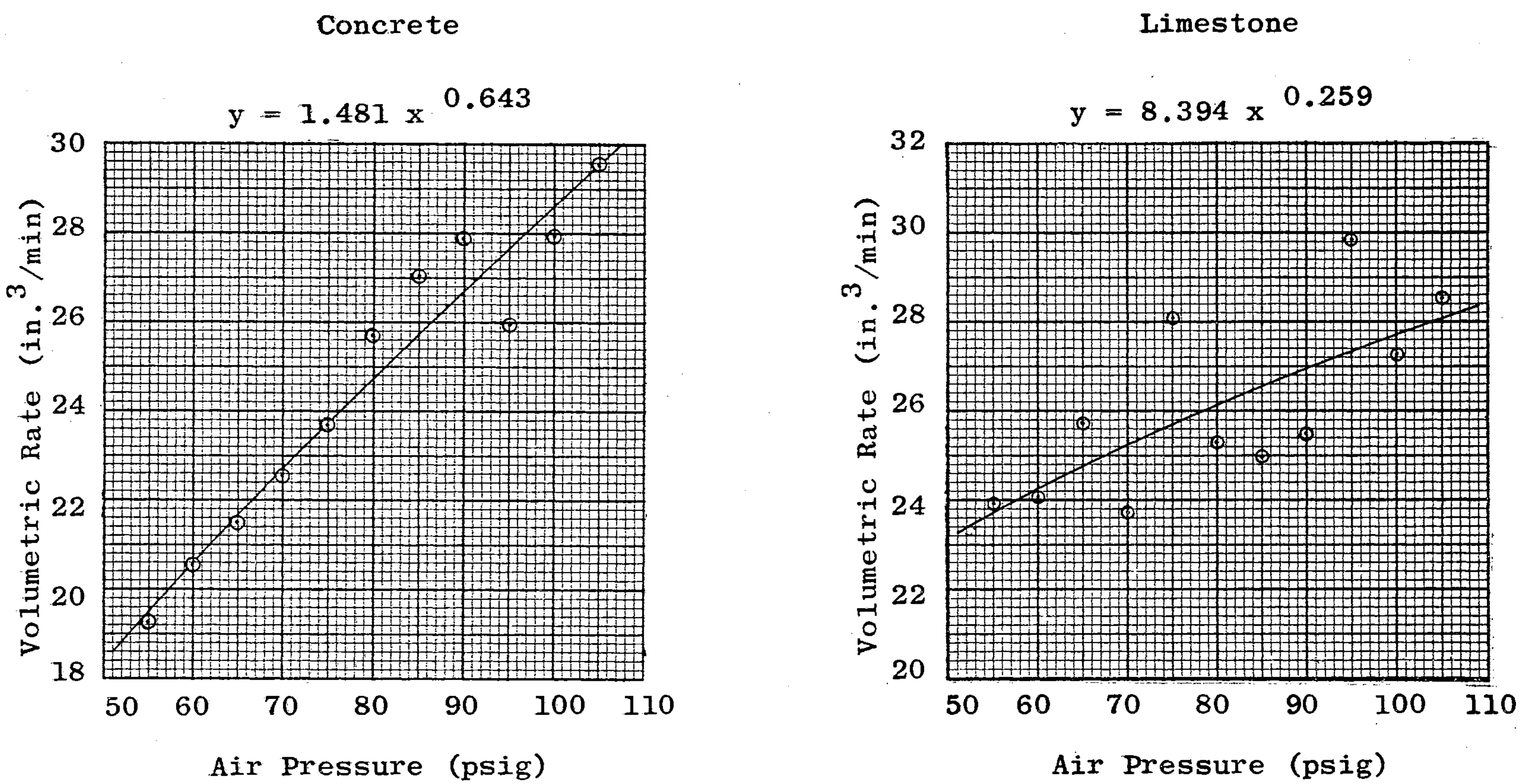
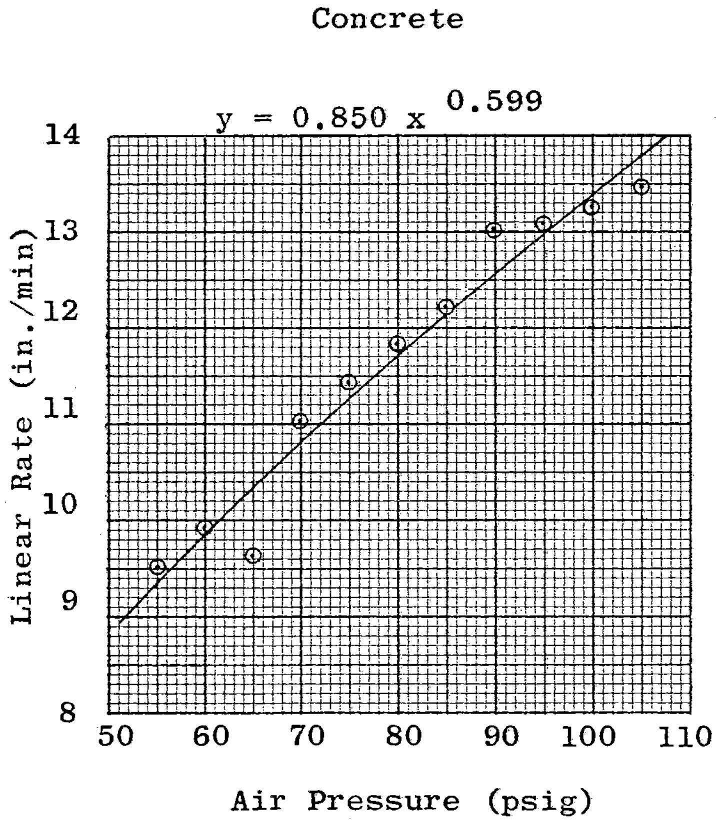


Fig. 18 Volumetric Drilling Rates for Jackhammer - 2 Foot Drill Steel



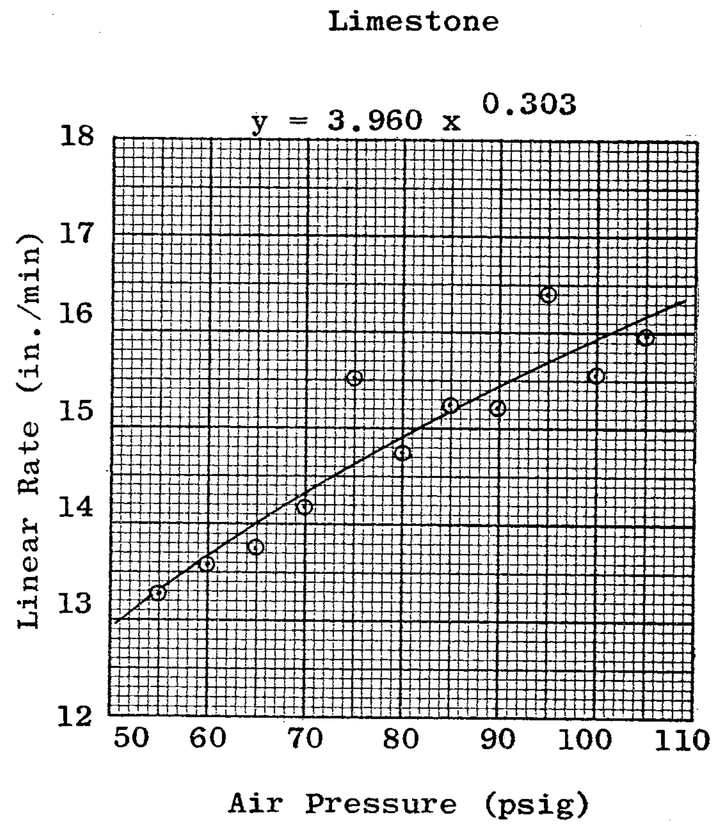


Fig. 19 Linear Drilling Rates for Jackhammer - 4 Foot Drill Steel

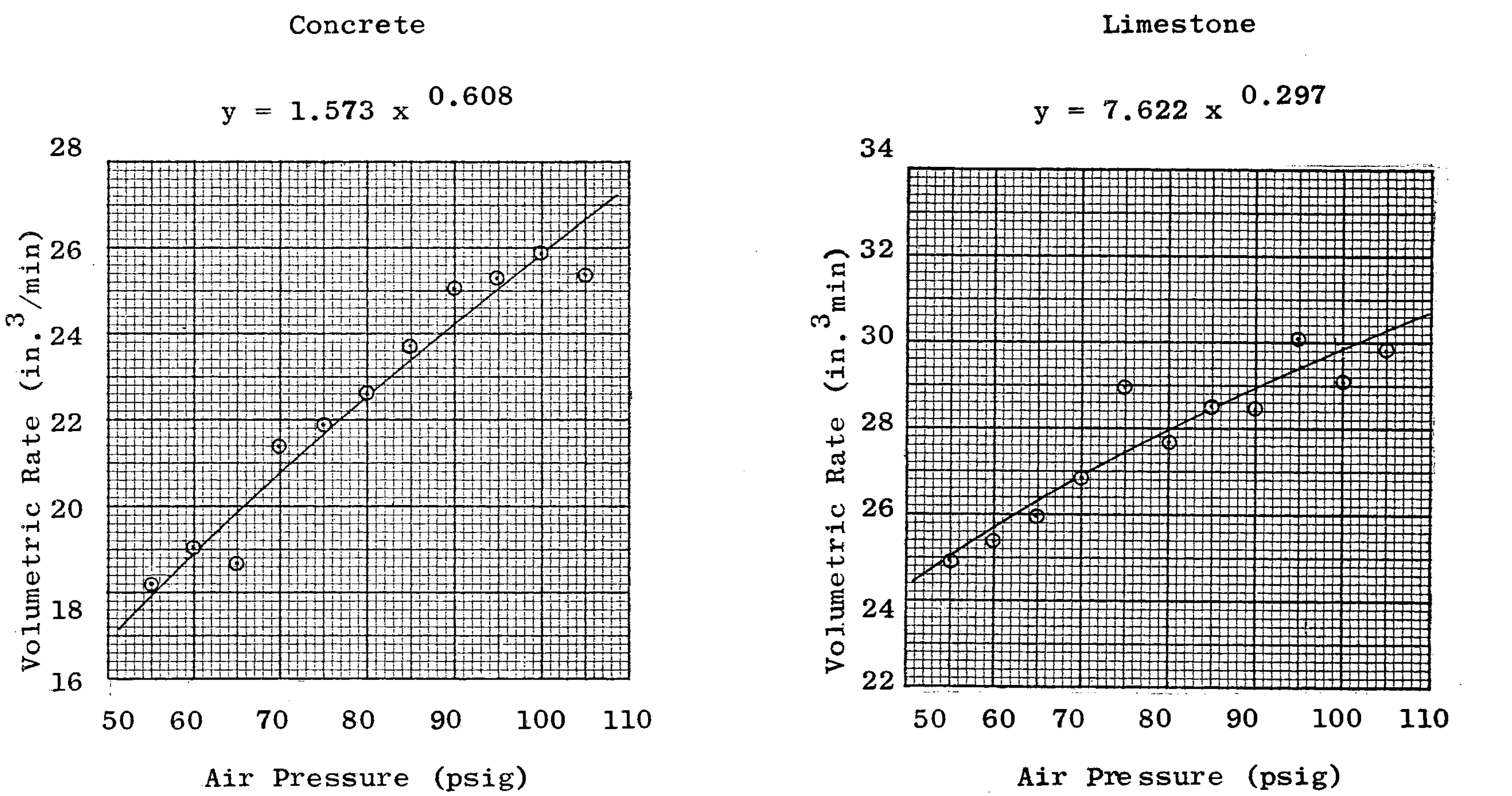
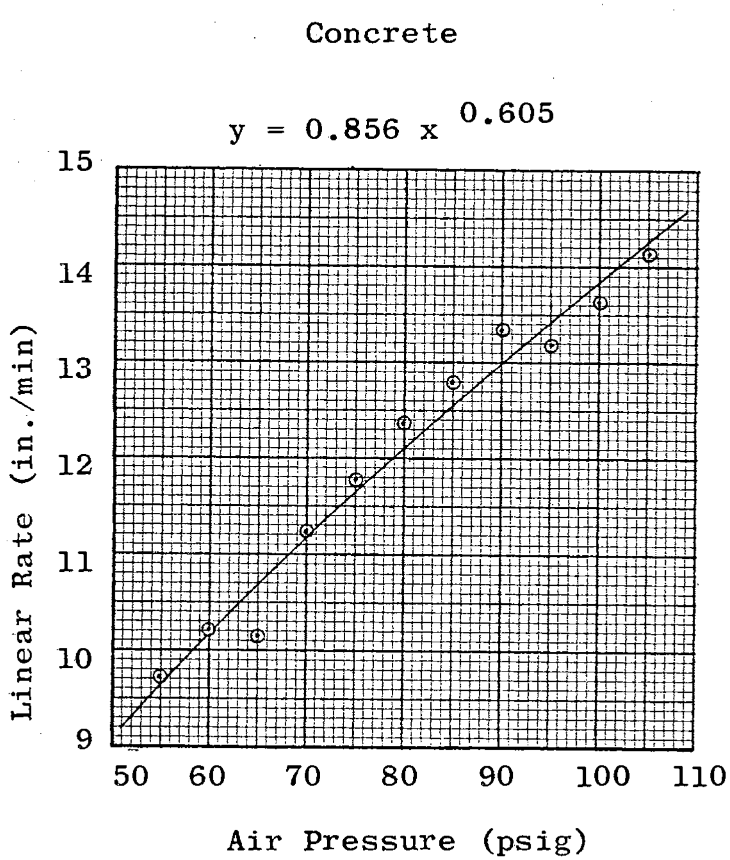


Fig. 20 Volumetric Drilling Rates for Jackhammer - 4 Foot Drill Steel



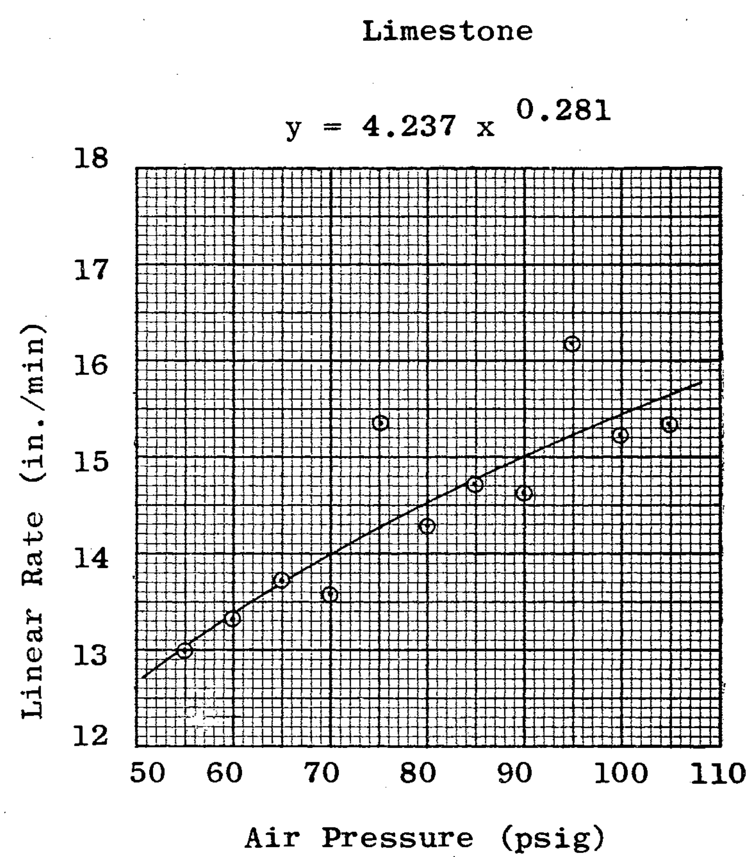


Fig. 21 Linear Drilling Rates for Jackhammer - 2 and 4 Foot Drill Steels

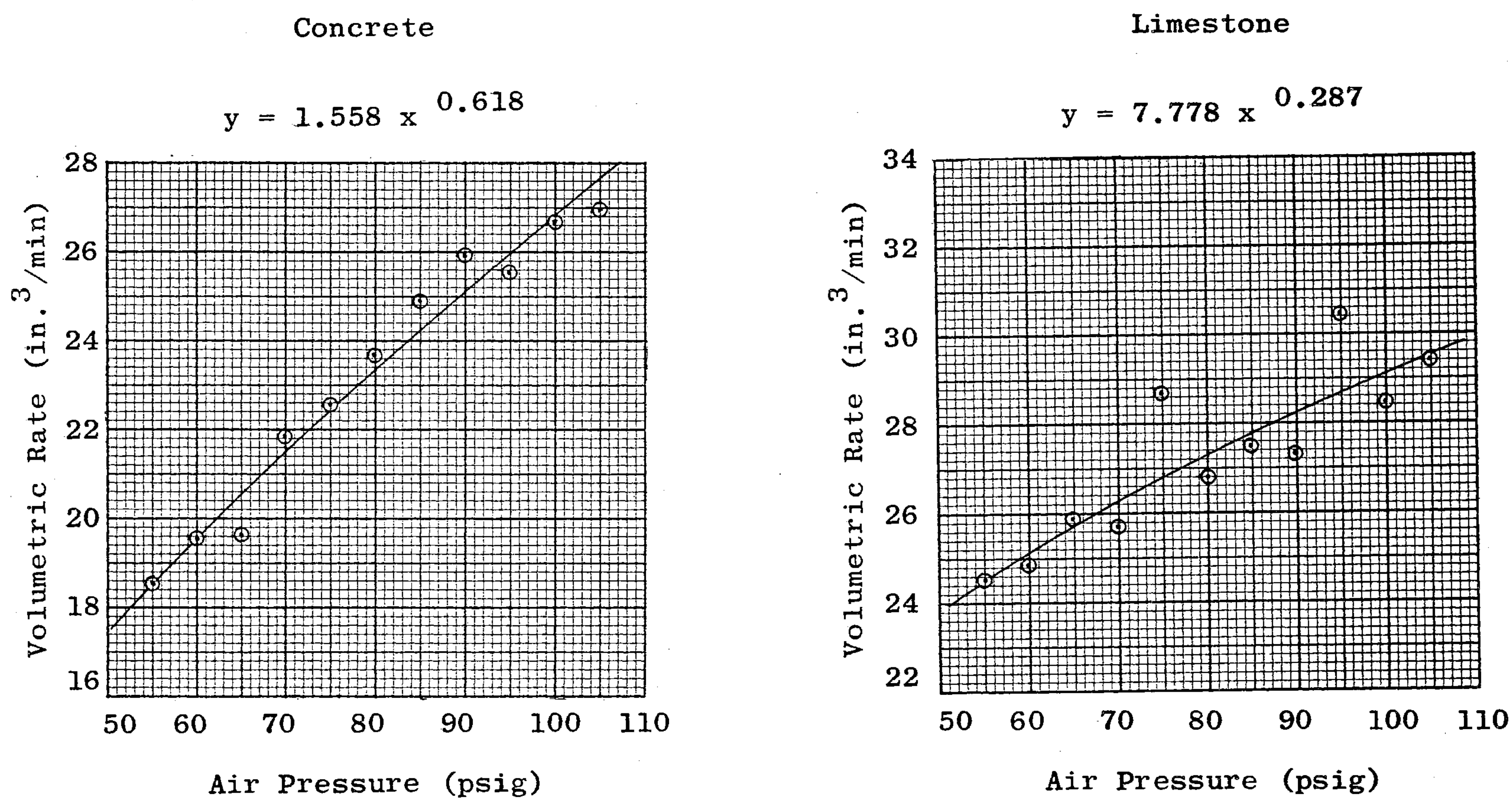


Fig. 22 Volumetric Drilling Rates for Jackhammer - 2 and 4 Foot Drill Steels

TABLE III

DRILLING RATES FROM CURVE OF BEST FIT

	Concrete				Limestone			
Pres psig	Linear in./min	Per Cent of 80	Volumetric in.^{3}/min	Per Cent of 80	Linear in./min	Per Cent of 80	Volumetric in.^{3}/min	Per Cent of 80
				Track-Mounted Drill				
55	9.03	74	65.81	75	13.23	79	97.41	79
60	9.67	80	70.44	80	13.96	84	102.86	83
65	10.29	85	74.98	85	14.67	88	108.15	88
70	10.91	90	79.45	90	15.35	92	113.29	92
75	11.51	95	83.85	95	16.02	96	118.29	96
80	12.11	100	88.19	100	16.67	100	123.17	100
85	12.70	105	92.47	105	17.31	104	127.94	104
90	13.28	109	96.69	110	17.93	108	132.60	108
95	13.85	114	100.86	114	18.53	111	137.17	111
100	14.42	118	104.98	119	19.13	115	141.65	115
105	14.98	124	109.06	124	19.72	118	146.05	118
				Jackhammer - 2 Ft. Steel				
55	10.15	79	19.49	78	12.63	90	23.72	91
60	10.72	83	20.61	83	12.93	93	23.27	93
65	11.27	88	21.70	87	13.21	95	24.77	95
70	11.80	92	22.76	92	13.48	96	25.26	96
75	12.32	96	23.79	96	13.73	98	25.71	98
80	12.82	100	24.80	100	13.98	100	26.15	100
85	13.32	104	25.78	104	14.21	102	26.56	102
90	13.80	108	26.75	108	14.43	103	26.96	103
95	14.27	111	27.70	112	14.64	105	27.34	105
100	14.73	115	28.63	115	14.84	106	27.70	106
105	15.19	118	29.54	119	15.04	108	28.06	108

TABLE III (Continued)

	Concrete				Limestone			
Pres psi	Linear in./min	Per Cent of 80	Volumetric in.^{3}/min	Per Cent of 80	Linear in./min	Per Cent of 80	Volumetric in.^{3}/min	Per Cent of 80
				Jackhammer - 4 Ft. Steel				
55	9.37	80	17.99	80	13.32	89	25.03	90
60	9.87	84	18.97	84	13.67	92	25.68	92
65	10.35	88	19.92	88	14.01	94	26.30	94
70	10.83	92	20.83	92	14.32	96	26.88	96
75	11.28	96	21.73	96	14.63	98	27.44	98
80	11.73	100	22.60	100	14.92	100	27.97	100
85	12.16	104	23.45	104	15.19	102	28.48	102
90	12.58	107	24.28	107	15.46	103	28.96	104
95	13.00	111	25.09	111	15.71	105	29.43	105
100	13.40	114	25.88	115	15.96	107	29.88	107
105	13.80	118	26.66	118	16.20	109	30.32	108
				Jackhammer - 2 and 4 Ft. Steels				
55	9.65	79	18.53	79	13.07	90	25.54	90
60	10.17	84	19.55	84	13.40	92	25.16	92
65	10.68	88	20.54	88	13.70	94	25.75	94
70	11.17	92	21.51	92	13.99	96	26.30	96
75	11.64	96	22.44	96	14.27	98	26.83	98
80	12.10	100	23.36	100	14.53	100	27.33	100
85	12.56	104	24.25	104	14.78	102	27.81	102
90	13.00	107	25.12	108	15.02	103	28.27	104
95	13.43	111	25.97	111	15.25	105	28.71	105
100	13.85	114	26.81	115	15.47	107	29.13	107
105	14.27	118	27.63	118	15.68	108	29.55	108

TABLE IV

TEMPERATURE AND AVERAGE DEVIATION FROM CURVE OF BEST FIT

Pressure, psig	Track-Mounted Drill				Jackhammer			
	Concrete		Limestone		Concrete		Limestone	
	Temp °F	Dev in./min	Temp °F	Dev in./min	Temp °F	Dev in./min	Temp °F	Dev in./min
55	21	+0.31	43	-0.21	48	+0.13	32	-0.07
60	18	+0.35	44	+0.01	50	+0.04	31	-0.08
65	25	-1.08	41	+1.31	56	-0.54	28	+0.02
70	21	-0.37	43	-0.05	45	+0.09	32	-0.41
75	17	+0.47	44	-1.43	56	+0.15	34	+1.06
80	25	+0.38	59	-0.59	55	+0.29	33	-0.25
85	21	-0.19	51	+0.26	57	+0.24	33	-0.07
90	27	+1.68	56	+1.06	50	+0.34	35	-0.40
95	14	-1.37	37	-0.32	63	-0.24	34	+0.93
100	21	+0.19	56	+0.79	52	-0.23	34	-0.25
105	27	-0.04	50	-0.59	49	-0.13	35	-0.35

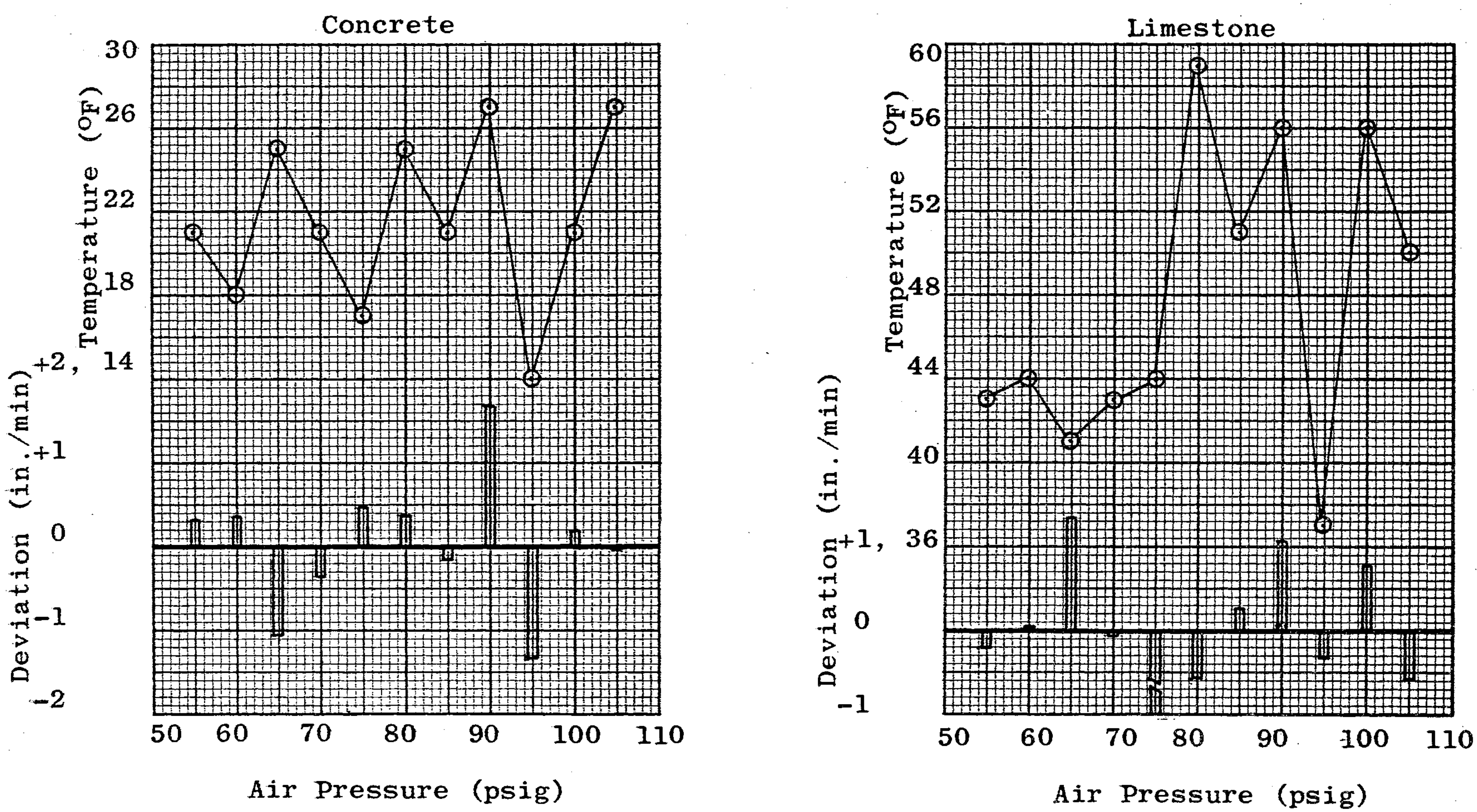


Fig. 23 Correlation Between Temperature and Air Pressure for Track-Mounted Drill

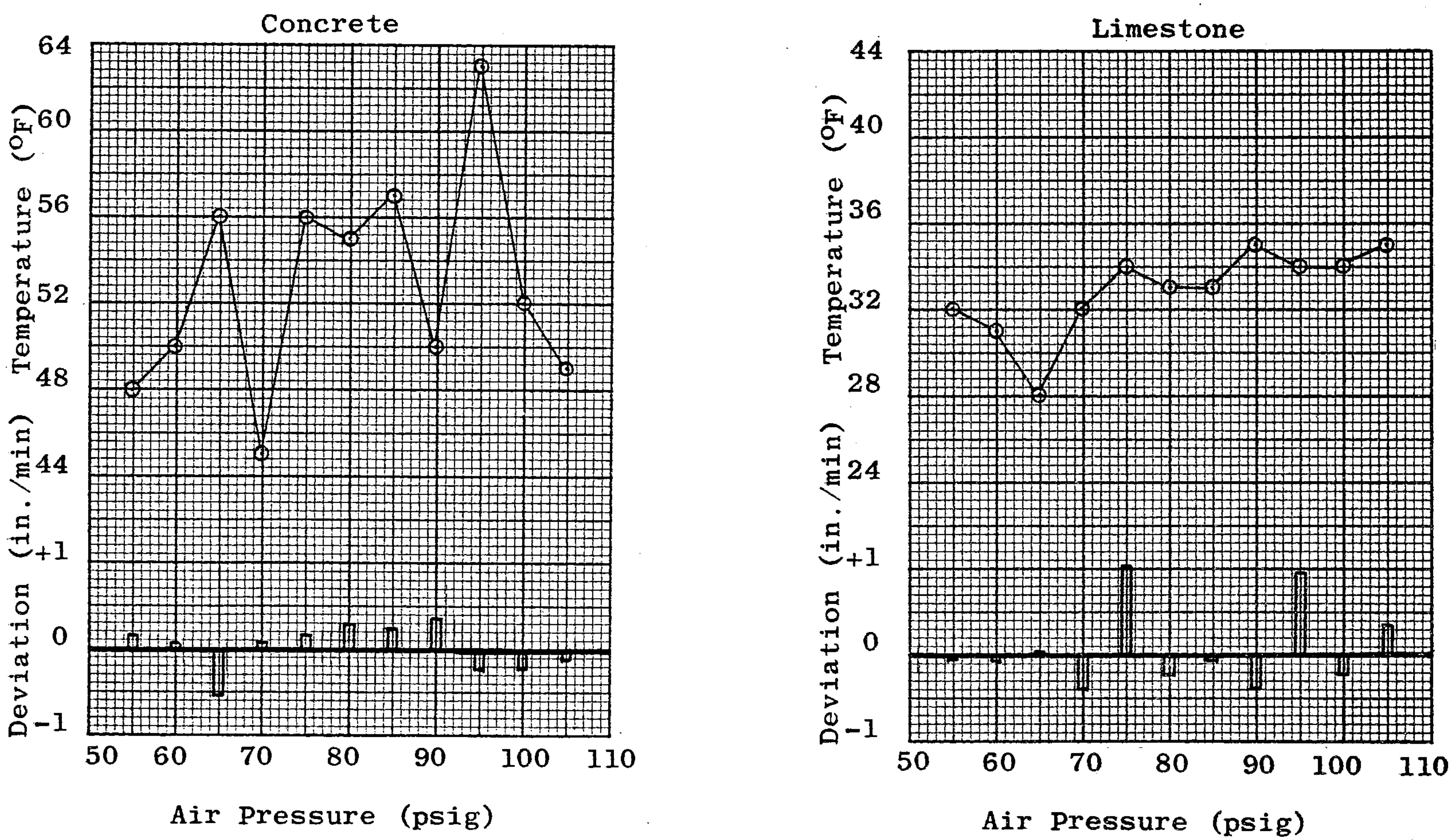


Fig. 24 Correlation Between Temperature and Air Pressure for Jackhammer

TABLE V

AVERAGE HOLE DIAMETERS

Pressure	Track-Mounted Drill		Jackhammer	
psig	Concrete in.	Limestone in.	Concrete in.	Limestone in.
55	3.045	3.060	1.560	1.545
60	3.040	3.067	1.562	1.547
65	3.060	3.062	1.570	1.550
70	3.048	3.060	1.570	1.552
75	3.047	3.062	1.560	1.547
80	3.033	3.067	1.560	1.545
85	3.045	3.070	1.572	1.542
90	3.045	3.070	1.565	1.542
95	3.060	3.065	1.570	1.547
100	3.035	3.072	1.577	1.542
105	3.040	3.067	1.557	1.542

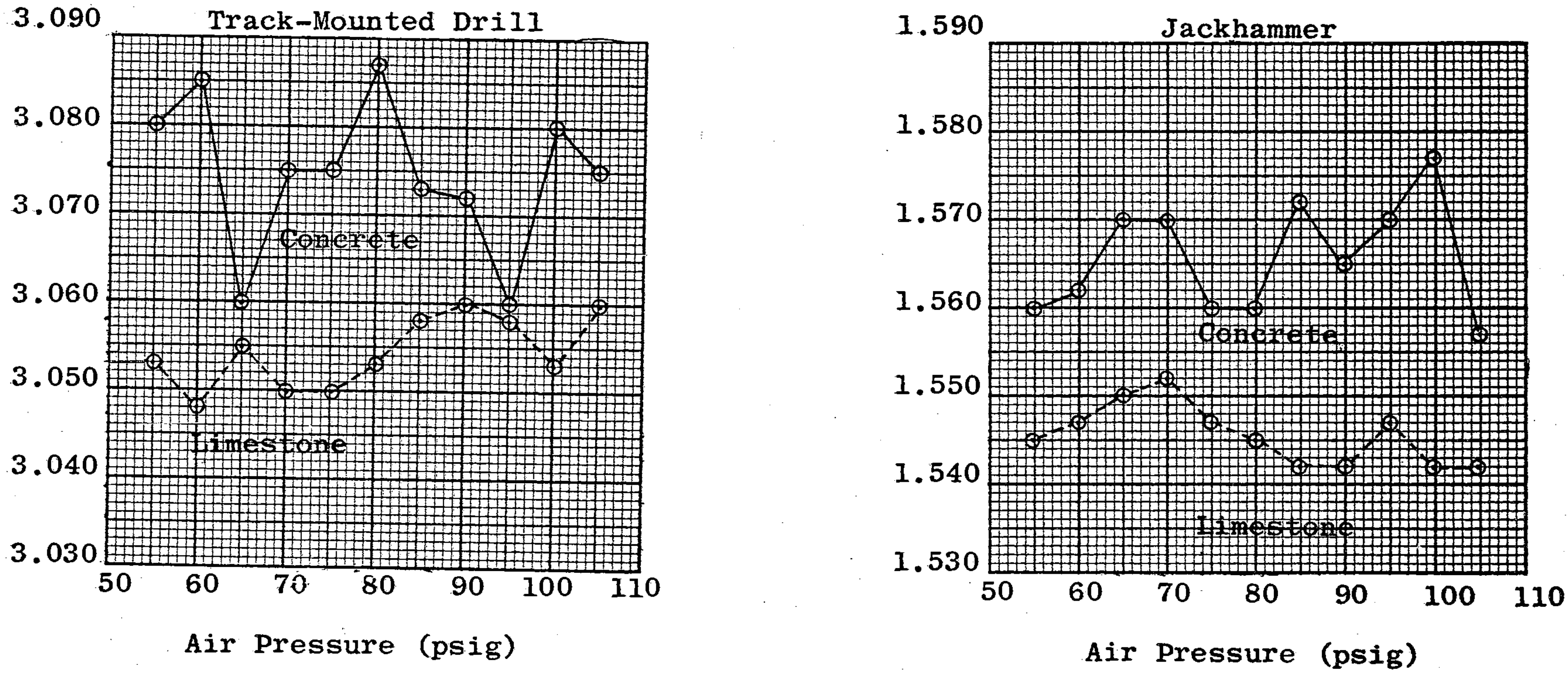


Fig. 25 Correlation Between Hole Diameters and Air Pressure

TABLE VI

RESULTS OF LABORATORY MEASUREMENTS

Pressure psig	Strain u in./in.	Stress psi	Energy/Blow ft-lbs	Work (ft-lbs/sec) Max.	Actual
56	845	25.350	12.99	346.2	346.2
60	905	27.150	14.90	407.5	407.5
64	914	27.420	15.21	424.0	391.8
71	1020	30.600	18.91	540.0	491.0
75	1011	30.330	18.60	545.0	527.0
79	1038	31.140	19.59	590.0	561.0
85	1096	32.880	21.84	686.0	616.0
90	1128	33.840	23.12	727.0	613.0
94	1301	39.030	30.80	992.5	810.0

$$y = 52.031\, x^{0.692}$$

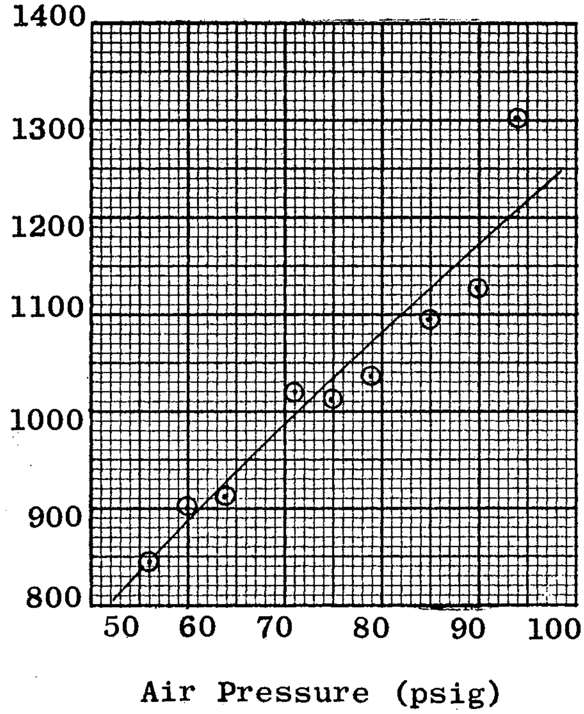


Fig. 26 Strain

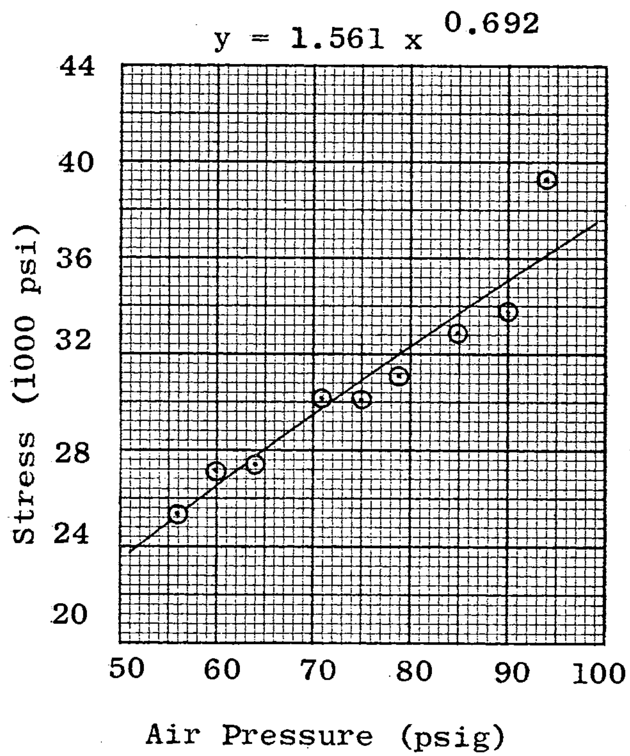


Fig. 27 Stress

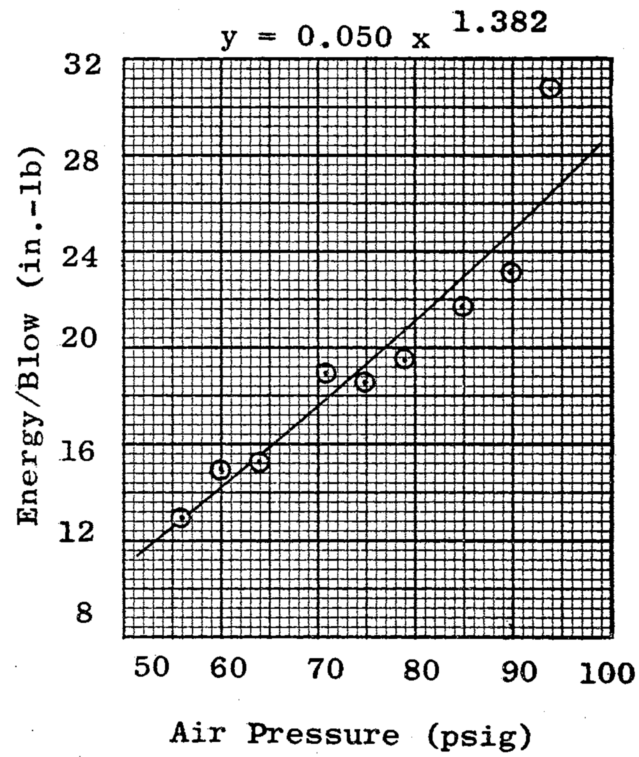


Fig. 28 Energy per Blow

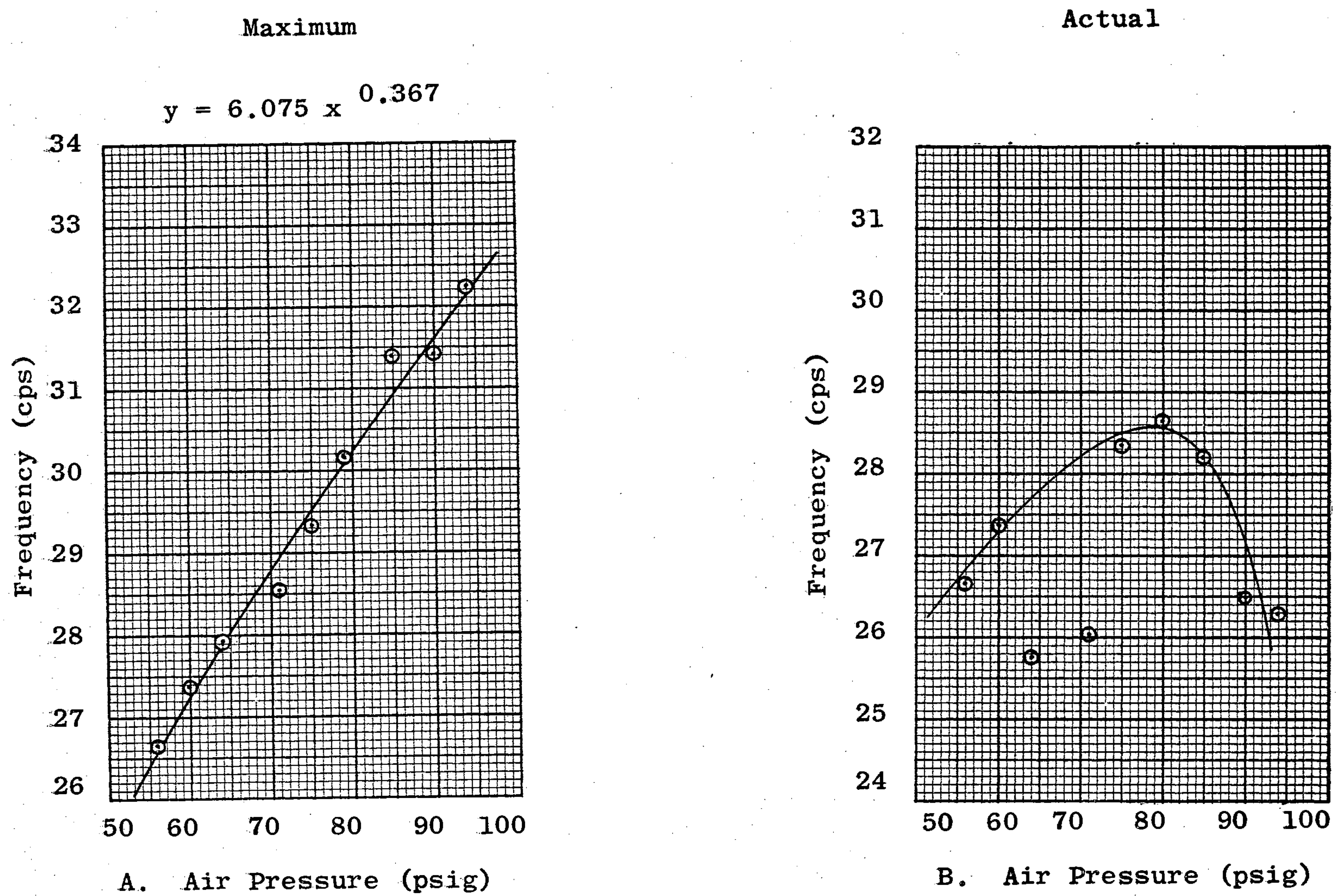


Fig. 29 Operating Frequencies of Jackhammer

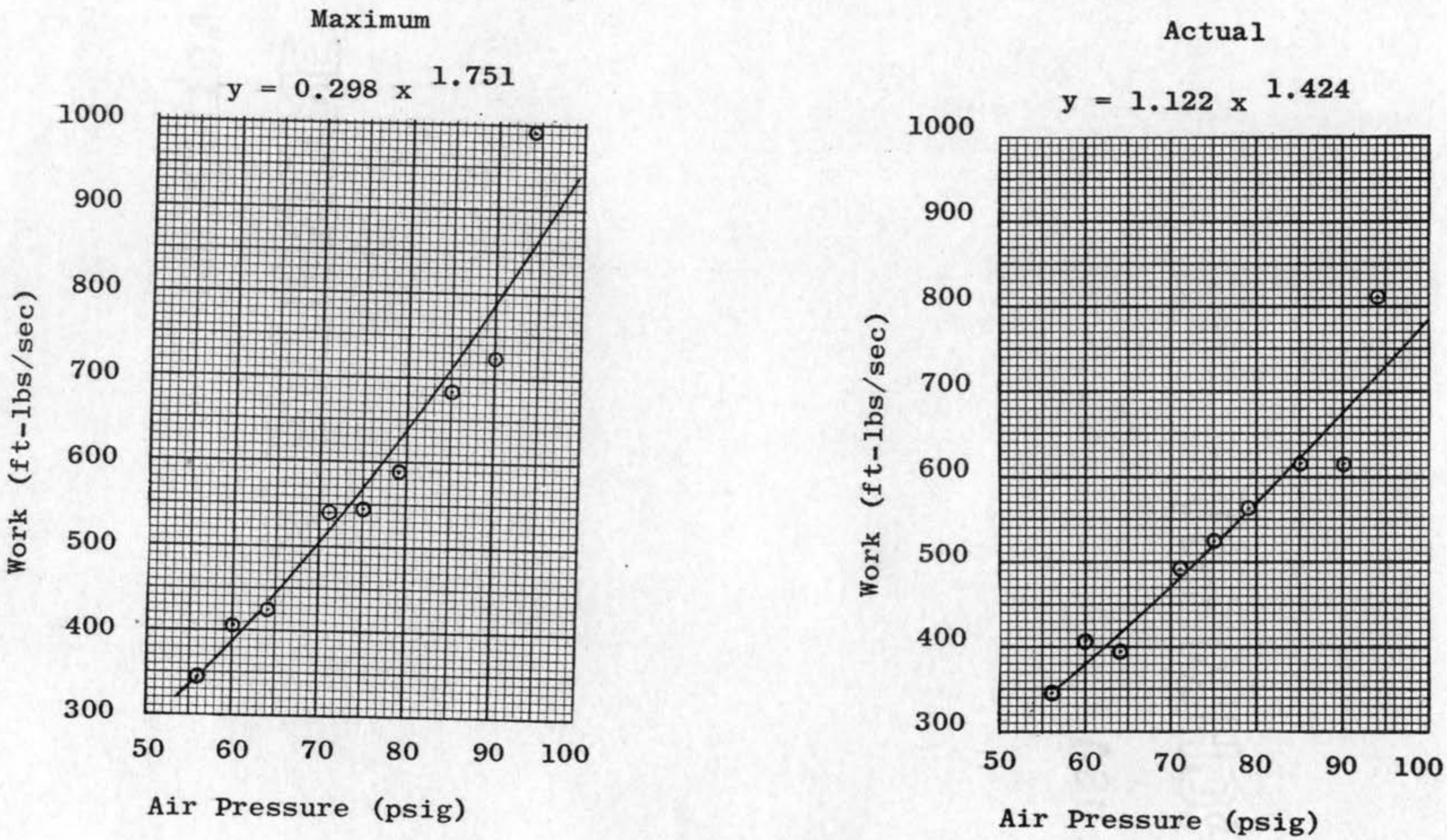


Fig. 30 Work Output From Jackhammer

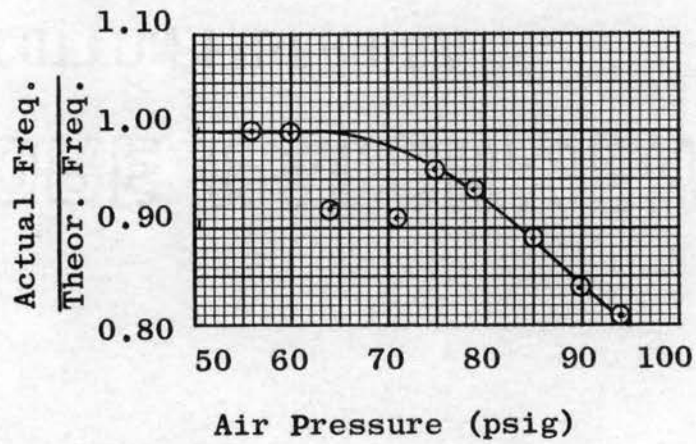


Fig. 31 Ratio of the Actual to the Theoretical Frequencies

TABLE VII

Laboratory Results Compared to a Standard at 80 Psig

Pres psig	Stress	Per Cent	Max Work	Per Cent	Act Work	Per Cent
55	25.00	77	335	52	338	59
60	26.45	82	386	61	380	67
65	28.00	86	442	69	423	74
70	29.50	91	505	79	470	82
75	30.95	96	569	89	520	91
80	32.40	100	638	100	570	100
85	33.75	104	710	111	621	110
90	34.55	107	788	124	674	118
95	36.40	112	866	136	729	128

CHAPTER VI

ANALYSIS OF RESULTS

Empirical Results

Initially, this project was designed to analyze air pressures from 55 to 110 psi, but the 600 cfm air compressor was unable to supply sufficient air pressure to operate the drifter or jackhammer consistently at pressures exceeding 108 psi. Consequently, there are no test results at 110 psi.

The empirical analysis is shown in the form of tables and figures in the preceeding chapter. The observed data (Appendix B) contains the critical information relative to each test hole. After this information was assembled, the volumetric and linear drilling rates contained in Table II were calculated. Table II is designed to permit a comparison of the linear and volumetric drilling rates at the test pressures for both the drifter and the jackhammer on the concrete block and at the limestone quarry. Throughout these tests, the linear and volumetric rates for the two drills were higher in the limestone than in the concrete. The limestone material was noticeably more soft than the concrete.

A graphic analysis of the linear and volumetric rates for the drifter and the jackhammer in limestone and in concrete is illustrated in Figs. 15 through 22. Only two figures (Figs. 15 and 16) are required for the track-mounted drill results, whereas, six figures (Figs. 17 through 22) were needed to show the jackhammer drilling rates. This condition was caused by a change of drill steels required in the jackhammer tests to achieve the necessary drilling depth. The 2-foot and 4-foot drill steels were treated as separate entities, and then the rates were averaged to give combined 2 and 4 foot drilling rates.

In Figs. 15 through 22 the average volumetric and linear drilling rates were plotted graphically, and a curve of best fit was drawn for these points. The method of least squares was used which gave an exponential curve in the form $y = kx^n$ (9). All of the linear and volumetric drilling rate curves exhibited a curve which was concave downward. The information required to plot these curves was calculated on an IBM 1620 computer, and a sample program is shown in Appendix C.

Even though a compressor supplies air at 100 psi, it is rare and usually only under ideal circumstances that a piece of drilling equipment will operate at that pressure. A more realistic figure is around 80 psi which takes into consideration line losses and leaks present in most systems. Table III shows the drilling rates from the curve of best fit, and the percentage value of each drilling rate when compared to the value at 80 psi. This table showed that an individual test hole drilled with either the track-mounted drill or jackhammer had approximately the same volumetric and linear drilling rate when expressed as a percentage of the rate at 80 psi. Also, the percentage range is greater on holes drilled on the concrete block than for those in the limestone quarry.

To ascertain whether the temperature of the free air had any effect on the drilling rates, Table IV, and Figs. 23 and 24, were drawn to show the temperature, and the deviation of the drilling rates from curve of best fit for the test pressures. The values used for the jackhammer were obtained from the combined 2 and 4 foot drill steel results. Based on the results shown in these figures, no direct correlation exists between the temperature of the free air and the drilling rates at the various test air pressures.

In Table V and Fig. 25 the average hole diameters for different pressures were examined for a trend indicating that the hole diameters varied with different air pressures. The hole diameters used for the jackhammer portion of the correlation were the average results of the holes drilled with the 2 and 4 foot drill steels. The results showed that there was no correlation between the diameter of the hole and the air pressure used to drill the hole.

Laboratory Results

The laboratory phase of this project was conducted to check the empirical results with laboratory measurements obtained using the jackhammer. The 600 cfm air compressor was not available when these tests were run, so a 125 cfm air compressor was substituted. Ordinarily a 125 cfm compressor would supply sufficient air pressure to operate two jackhammers of the size used in the test, but this compressor was unable to hold a pressure in excess of 94 psi and had a very slow recovery cycle. Prior to the test runs, different methods were employed to solve these problems, but no method used proved reliable. The result was that the test pressures were not always in even 5 psi increments and pressures to 105 psi could not be attained. The average air pressure during the actual drilling was read from the air pressure recorder disk.

The basic data for the laboratory analysis is contained in Table VI. This information was obtained from analyzing the Polaroid pictures taken at test pressures. The actual frequency is either equal to or less than the maximum frequency. The maximum frequency was the value that would have been obtained if the jackhammer had performed without missing a beat, whereas, the actual frequency is a measure of the actual number of beats that occurred over the measureable time base of the picture.

The results of the laboratory measurements are shown in Table VII and graphically in Figs. 26 through 31. In these figures the actual results are placed on the graph, and a curve of best fit is drawn. With the exception of Figures 29 and 31 the curves of best fit were obtained by using the method of least squares which gave a curve in the form $y = kx^n$. The graphs showing energy per blow (Fig. 28), and work output (Fig. 30) have a curve that is concave upward, whereas the strain curve is concave downward. Both the actual frequency curve (Fig. 29) and the ratio of the actual frequency to the theoretical frequency to the theoretical frequency curve (Fig. 31) were drawn by using the visual method for a curve of best fit. In both cases two points fall outside the other values. These two points were plotted, but not considered in the drawing of the curve as they were thought to be nonrepresentative samples. In the operating frequency curve (Fig. 29), it is evident that the actual frequency reaches a peak at a point just short of 80 psi and decreases as the air pressure is increased. The curve pattern on the ratio of the actual to the theoretical frequency indicates that the jackhammer has an increase in the number of missed beats as the air pressure is increased.

In Table VII a comparison is made of the stress, maximum work, and the actual work in the 2 foot drill steel at air pressures from 55 to 95 psi to the values measured at 80 psi. The stress laboratory results ranged from 77 to 112 percent and compared favorably with the empirical results contained in Table III for a jackhammer drilling in concrete with a two foot drill steel.

CHAPTER VII

SUMMARY

The objective of this project was to study the effect of variations in air pressure on the drilling rates of an Ingersoll-Rand jackhammer and a Gardner Denver track-mounted drill while drilling on a concrete block and in a limestone quarry. The different hardnesses of the two materials drilled had the greatest effect on the results, but the results obtained from each material were consistant for that material. The change in drilling rate for a change in air pressure was a nonlinear relationship, and there was no one point on any drilling rate curve where there was a noticeable change in slope which would suggest a more efficient drilling rate at any particular pressure. The laboratory analysis made of the jackhammer to correlate strain to the drilling rate showed that there was a definite relationship between the strain in the drill steel and the drilling rate at the pressures tested.

Recommendations for Further Study

This project was primarily designed to test two different type drilling machines at a pressure range at which they might be required to operate in an actual quarry. As the work progressed questions arose which were not within the scope of this report, but are believed of sufficient importance to warrent additional study.

First, it would be highly desireable to have a standardized classification of rock that would indicate a materials resistance to drilling. Existing methods of rock classification are too vague to obtain any correlation between the rock classification and its resistance to drilling.

Second, the range of test air pressures should be increased to at least 150 psi to ascertain if increased efficiency can be obtained at higher pressures.

Third, an analysis should be made of the effects from increasing or decreasing the vertical force on the drills at various air pressures.

Fourth, a study should be conducted to examine the changes in drilling rates caused by using different size bits at different air pressures.

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APPENDIX A

EQUIPMENT IDENTIFICATION

1. Air Compressors
   125 cfm Capactiy
      Manufacturer: Chicago Pneumatic Tool Co.
      Model No.: 125 RG-2
      Type: Two stage, portable, rotary
      Engine fuel: Gasoline
      Serial No.: 72311R0-1
      Prior Usage: 59.6 hours

   600 cfm Capacity
      Manufacturer: Ingersoll-Rand Co.
      Model No.: R-600
      Type: Two stage, portable, rotary
      Engine fuel: Diesel
      Serial No.: 600 AR 22207
      Prior Usage: 239 hours

2. Air Pressure Control
   Air Pressure Regulator
      Manufacturer: Fisher Governor Co.
      Model No.: 4100U-657, with Wizard Pilot (4101U)
      Type: Pressure differential
      Valve type: Double port, throttle plug
      Valve Size: 2 in.
      Bourdon tube range: 0 to 250 psig
      Bourdon tube material: Bronze

   Reservoir Tanks
      Manufacturer: Unknown
      Size: 50 cu. ft., each
      Working pressure: 125 psig

3. Air Pressure Measurement
   Air Pressure Recorder
      Manufacturer: American Meter Co.
      Type: 24 hour - 24 minute disk recorder
      Bourdon tube range: 0 to 150 psig
      Bourdon tube material: Ni-span
      Least subdivision, pressure: 2 lbs
      Least subdivision, time: 15 secs
      Precision: 1% of full scale reading
      Serial No.: PR 39433

Bourdon Pressure Gages
Manufacturer: Jas. P. Marsh Corp.
Model: Mastergage
Range: 0 to 200 psig
Least subdivision: 2 lbs
Precision: 1% of full scale reading

Manufacturer: Marshalltown Co.
Model: Test
Range: 0 to 200 psig
Least subdivision: 1 lb
Precision: 1% of full scale reading

Dead Weight Tester
Manufacturer: Manning, Maxwell and Moore, Inc.
Model: Ashcroft Portable
Range: 10 to 2000 psig
Serial No.: 34740

4. Bits
Manufacturer: Timken Roller Bearing Co.
Type: Carbide insert
Size: 3 in.
Thread: Type H, 92 WJ

Manufacturer: Timken Roller Bearing Co.
Type: Carbide insert
Size: 1½ in.
Thread: Type H, MCB

5. Drills
Jackhammer
Manufacturer: Ingersoll-Rand Co.
Model: J-40
Weight: 53 lbs
Serial No.: 784060

Track-Mounted Drifter
Manufacturer: Gardner Denver Co.
Carrier model: AT
Drifter model: DH 123 J-1
Piston size: 4½ in.
Drifter weight: 154 lbs (without mounting bracket)
Serial No.: Unknown (data plate illegible)

6. Drill Steels
Manufacturer: Gardner Denver Co.
Size: 1½ in. diameter
Length: 10 ft.
Thread: Type H

Manufacturer: Gardner Denver Co.
Size: 7/8 in. hex.
Lengths: 2 and 4 ft.
Thread: Type H

7. Flexible Rubber Hose With Couplings
   Manufacturer: U.S. Rubber Co.
   Length: 22 ft. sections, each
   Size: 2 in. diameter
   Working pressure: 2000 psig

   Manufacturer: Unknown
   Length: 25 ft. sections, each
   Size: 1 in. diameter

   Manufacturer: Unknown
   Length: 50 ft.
   Size: 3/4 in. diameter

8. Miscellaneous Measuring Instruments
   Carpenters Level
   Manufacturer: Unknown
   Length: 2 ft.

   Inside Calipers
   Manufacturer: Nork
   Range: $\frac{1}{2}$ to 6$\frac{1}{2}$ in.

   Machinist's Rule
   Manufacturer: Pioneer
   Size: 12 in.
   Least subdivision: 1/100 in.

   Measuring Stand
   Manufacturer: Unknown
   Height: 9 1/8 in.
   Diameter: 3 1/8 in.

   Micrometer
   Manufacturer: Starrett Co.
   Model: Set A
   Range: 2 to 4 in.
   Least subdivision: 1/1000 in.

   Stop Watch
   Manufacturer: Zonex
   Range: 0 to 15 min.
   Least subdivision: 0.1 sec

Thermometer
Manufacturer: Unknown
Range: 14 to 400°F
Least subdivision: 1°F
Type: Liquid glass

6 Foot Measuring Tape Mounted on 3/4 Inch Square Rod
Manufacturer: Unknown
Least subdivision: 1/16 in.

9. Strain Measuring Apparatus
Beattie Oscillatron With Polaroid Camera
Manufacturer: Beattie Coleman Inc.
Model: K5
Type: 14594
Serial No.: 1333

Bridge Amplifier Meter
Manufacturer: Ellis Associates
Model: BAM-1
Serial No.: 2026

Oscilloscope
Manufacturer: Tektronix Inc.
Model: 502
Serial No. 006851

Polaroid Film
Manufacturer: Polaroid Corp.
Type: 3000 Type 47

Shielded Wire
Maufacturer: Beldon
Type: No. 8738, 2 strand braided
Size: No. 22, AWG

Strain Gages
Maufacturer: Baldwin-Lima-Hamilton
Type: SR-4, A-7
Resistance: 120.5±0.3 ohms
Gage factor: 1.91±2%
Lot No.: 516-A-66

10. Test Machines
Concrete Testing Machines
Manufacturer: Forney Inc.
Model: LT 700
Range: 0 to 350,000 lbs
Least subdivision: 200 lbs
Serial No.: 59156

Los Angeles Rattler Testing Machine
Manufacturer: Soil Test Inc.
Serial No.: M 501

APPENDIX B

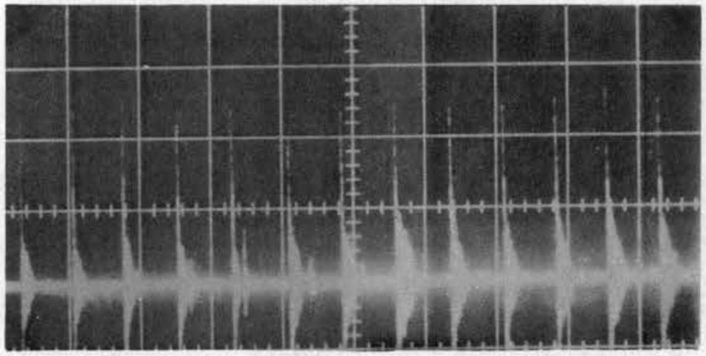
OBSERVED DATA

Run No.	Pres psig	Hole No.	Bit No.	Temp F	Hole Dia.	Depth (in.) Start	End 1	End 2	Time (min) One	Two
Empirical Test Track-Mounted Drill in Concrete										
48	55	K-5	D	34	3.04	13.875	55.062		3.500	
19	55	H-6	A	15	3.04	14.375	52.500		3.967	
12	55	C-7	C	16	3.04	14.875	55.250		4.000	
3	55	B-4	B	20	3.06	14.125	52.500		6.533	
44	60	K-7	C	26	3.02	14.375	55.375		3.570	
23	60	N-6	A	12	3.04	14.375	52.500		4.183	
11	60	A-1	A	16	3.04	20.562	53.375		2.550	
4	60	J-6	D	19	3.06	14.312	52.375		5.750	
1	65	L-4	B	24	3.08	16.625	52.250		4.767	
47	65	L-2	D	33	3.04	14.062	53.062		3.020	
6	65	M-5	A	22	3.06	14.500	53.750		4.317	
5	65	G-1	C	20	3.06	17.812	53.000		4.867	
34	70	I-3	B	30	3.04	14.500	57.250		3.150	
21	70	J-2	B	14	3.04	14.250	53.500		3.600	
20	70	C-5	C	16	3.04	14.500	52.750		3.500	
7	70	H-2	C	22	3.06	14.500	54.250		4.000	
2	70	B-2	D	24	3.06	14.187	55.187		5.600	
37	75	I-5	A	30	3.04	14.375	59.750		3.030	
22	75	K-3	B	12	3.04	14.500	53.250		3.500	
15	75	E-1	C	10	3.05	14.250	53.062		3.267	
10	75	M-7	D	18	3.06	14.375	54.500		4.017	
45	80	I-1	D	30	3.02	14.187	53.375		3.120	
43	80	C-3	A	27	3.04	13.500	53.937		2.870	
26	80	M-1	B	15	3.04	14.125	52.500		3.550	
38	85	F-6	D	31	3.04	13.562	57.437		2.970	
30	85	I-7	A	17	3.04	14.000	58.250		3.150	
28	85	N-4	B	18	3.04	13.500	54.687		3.167	
9	85	A-5	C	16	3.06	14.625	53.875		4.767	
36	90	D-6	D	32	3.04	14.500	57.562		2.820	
33	90	H-4	A	30	3.06	14.062	57.500		2.730	
32	90	G-5	C	30	3.04	14.187	58.000		2.833	
27	90	N-2	B	16	3.04	13.625	54.125		3.067	
18	95	J-4	A	12	3.06	14.250	53.250		3.000	
17	95	A-3	C	12	3.06	14.625	52.875		2.350	
14	95	E-5	D	16	3.06	14.437	53.687		3.950	
8	95	F-2	B	18	3.06	14.250	52.750		3.500	

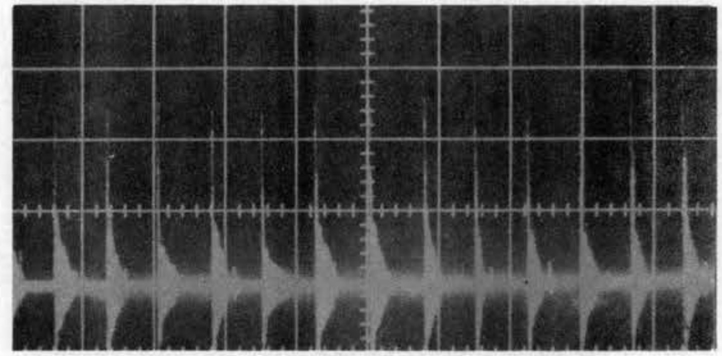
Run No.	Pres psig	Hole No.	Bit No.	Temp F	Hole Dia.	Depth (in.) Start	Depth (in.) End 1	Depth (in.) End 2	Time (min) One	Time (min) Two
42	100	A-7	A	29	3.04	13.500	52.750		2.770	
40	100	E-7	C	29	3.04	13.125	57.000		2.830	
29	100	M-3	D	16	3.04	13.312	54.750		2.467	
25	100	G-7	B	11	3.02	14.375	56.500		3.517	
49	105	K-1	C	36	3.04	14.250	52.750		2.420	
46	105	C-1	D	31	3.04	14.062	51.625		2.600	
35	105	G-3	B	31	3.04	14.125	58.250		2.700	
24	105	L-6	A	12	3.04	14.375	53.375		2.983	
Empirical Test Jackhammer in Concrete										
53	55	L-1	R	42	1.56	10.875	26.375	52.375	1.700	2.970
62	55	M-2	Q	65	1.56	11.625	27.312	52.437	1.480	2.520
69	55	H-5	P	39	1.56	11.625	27.562	52.562	1.630	2.680
98	55	D-3	P	46	1.56	12.062	27.375	53.250	1.420	2.580
54	60	J-1	R	42	1.56	10.687	27.437	52.750	1.720	2.950
61	60	M-4	P	66	1.56	11.562	27.812	52.687	1.420	2.420
71	60	J-7	R	40	1.57	12.062	27.750	53.500	1.470	2.650
94	60	C-2	Q	52	1.56	11.625	27.562	53.375	1.320	2.450
51	65	D-1	R	42	1.56	10.687	24.500	51.125	1.450	2.920
55	65	L-3	Q	67	1.58	11.500	26.937	52.562	1.320	2.470
56	65	B-1	T	67	1.57	11.375	27.187	52.312	1.430	2.600
97	65	N-1	R	48	1.57	11.625	27.375	53.062	1.300	2.720
52	70	N-3	R	42	1.56	10.750	24.750	52.375	1.470	2.780
70	70	K-4	Q	40	1.57	12.062	27.875	53.312	1.330	2.220
73	70	F-3	P	43	1.58	11.875	27.500	52.625	1.280	2.150
84	70	C-4	R	55	1.57	12.187	27.750	52.500	1.200	2.230
60	75	A-4	Q	66	1.55	12.500	26.562	52.625	1.200	2.200
65	75	F-1	Q	64	1.56	11.562	27.625	52.000	1.300	2.280
72	75	F-7	R	41	1.57	11.500	27.562	53.375	1.330	2.320
87	75	I-6	P	55	1.56	12.187	27.437	53.187	1.130	2.120
57	80	J-5	Q	67	1.56	12.000	27.125	52.625	1.080	2.070
76	80	M-6	R	50	1.56	11.250	27.625	52.625	1.300	2.150
93	80	H-7	P	52	1.56	12.375	27.500	53.187	1.120	2.200
95	80	L-5	R	50	1.56	12.500	27.312	53.312	1.080	2.220
59	85	L-7	Q	66	1.58	11.375	26.750	51.750	1.180	2.270
78	85	E-4	R	51	1.58	11.562	27.687	53.187	1.200	2.020
80	85	B-3	P	55	1.57	11.875	27.437	53.187	1.150	2.030
88	85	G-2	Q	55	1.56	12.000	27.687	53.062	1.000	2.020
63	90	A-6	P	44	1.57	12.187	27.500	53.437	1.030	2.020
77	90	E-2	R	50	1.57	12.312	27.375	53.000	1.170	2.000
82	90	D-7	Q	54	1.56	11.687	27.250	53.750	1.220	2.120
86	90	J-3	P	54	1.56	12.375	27.312	53.000	0.970	1.850
58	95	A-2	R	66	1.57	12.000	26.625	52.250	1.130	2.060
64	95	E-6	Q	64	1.58	12.125	27.312	53.250	1.050	1.930
67	95	H-1	Q	62	1.56	11.437	27.250	52.312	1.220	1.920
68	95	D-5	P	60	1.57	11.812	27.437	52.250	1.180	1.850
75	100	D-5	R	48	1.57	11.562	27.375	52.875	1.100	1.920
79	100	N-7	Q	52	1.58	12.125	27.437	52.500	1.150	1.970
90	100	F-5	Q	54	1.58	12.500	27.562	53.687	0.980	1.920

Run No.	Pres psig	Hole No.	Bit No.	Temp F	Hole Dia.	Depth (in.) Start	End 1	End 2	Time (min) One	Two
92	100	G-6	P	53	1.58	11.812	26.937	53.375	1.070	1.970
74	105	H-3	P	46	1.56	11.937	27.750	52.375	1.070	1.800
85	105	N-5	R	55	1.56	12.375	27.000	53.250	0.980	2.020
96	105	B-7	P	50	1.55	12.625	27.062	53.187	0.920	2.000
99	105	K-2	Q	45	1.56	12.750	27.250	53.625	0.870	1.860
				Empirical Test Jackhammer in Limestone						
P3	55	L-1	R	24	1.54	12.562	27.437	55.187	1.033	2.067
P12	55	M-2	Q	30	1.54	11.875	26.375	54.562	1.083	1.767
P19	55	H-5	P	38	1.56	11.625	26.750	54.687	1.300	2.300
P48	55	D-3	P	35	1.54	12.875	25.937	55.000	1.117	2.500
P4	60	J-1	R	25	1.55	12.062	27.625	55.125	1.067	2.033
P11	60	M-4	P	30	1.54	12.250	25.812	54.562	1.033	1.800
P21	60	J-7	R	35	1.54	12.937	26.250	54.000	1.100	2.300
P44	60	C-2	Q	35	1.54	12.375	26.500	53.812	1.217	2.183
P1	65	D-1	R	23	1.56	13.000	26.437	53.125	0.983	1.967
P5	65	L-3	Q	26	1.55	12.750	27.750	55.125	1.067	1.933
P6	65	B-1	P	27	1.55	12.312	27.312	54.937	1.067	1.983
P47	65	N-1	R	35	1.54	12.500	26.937	53.812	1.050	2.083
P2	70	N-3	R	24	1.56	12.750	27.500	53.500	1.000	1.833
P20	70	K-4	Q	36	1.56	12.375	26.250	54.000	1.133	1.850
P23	70	F-3	P	34	1.55	12.125	26.375	54.375	1.200	2.183
P34	70	C-4	R	35	1.54	12.500	26.000	54.062	1.100	1.983
P10	75	A-4	Q	30	1.54	11.937	25.687	54.312	0.767	1.667
P15	75	F-1	Q	34	1.54	12.500	27.250	54.125	0.883	1.617
P22	75	F-7	R	36	1.55	12.250	26.125	54.062	1.117	2.000
P37	75	I-6	P	35	1.54	12.000	25.875	53.750	1.067	1.950
P7	80	J-5	Q	28	1.55	12.187	25.937	54.678	0.833	1.700
P26	80	M-6	R	35	1.55	12.625	26.500	54.500	1.100	1.917
P43	80	H-7	P	35	1.54	12.000	26.187	52.625	1.083	1.850
P45	80	L-5	R	35	1.54	12.125	26.375	54.250	1.217	2.117
P9	85	L-7	Q	29	1.55	11.750	25.812	54.687	0.933	1.733
P28	85	N-7	R	34	1.53	12.000	26.187	53.562	1.117	1.817
P30	85	B-3	P	35	1.54	12.250	25.678	53.678	0.967	1.900
P38	85	G-2	Q	35	1.55	12.625	26.375	54.750	1.033	1.950
P27	90	E-2	R	35	1.53	12.875	27.125	54.000	1.150	1.867
P32	90	D-7	Q	35	1.55	13.187	26.312	53.937	0.883	1.783
P33	90	G-4	P	35	1.55	12.312	26.062	53.678	1.033	1.800
P36	90	J-3	P	35	1.54	12.062	26.125	53.750	1.017	1.767
P8	95	A-2	R	28	1.56	12.125	26.125	54.562	0.783	1.817
P14	95	E-6	Q	33	1.54	12.312	26.312	54.562	0.883	1.700
P17	95	H-1	Q	37	1.54	12.937	26.750	54.500	0.883	1.600
P18	95	D-5	P	37	1.55	12.500	26.125	53.625	0.967	1.717
P25	100	B-5	R	34	1.55	12.187	25.312	53.625	0.933	1.817
P29	100	E-4	Q	32	1.54	12.062	25.812	53.562	0.950	1.867
P40	100	F-5	Q	35	1.54	12.437	26.187	53.937	0.900	1.750
P42	100	G-6	P	35	1.54	12.625	26.687	53.500	0.967	1.683
P24	105	H-3	P	35	1.55	13.750	26.062	53.937	0.717	1.667
P35	105	N-5	R	35	1.54	13.750	26.000	53.437	0.800	1.733

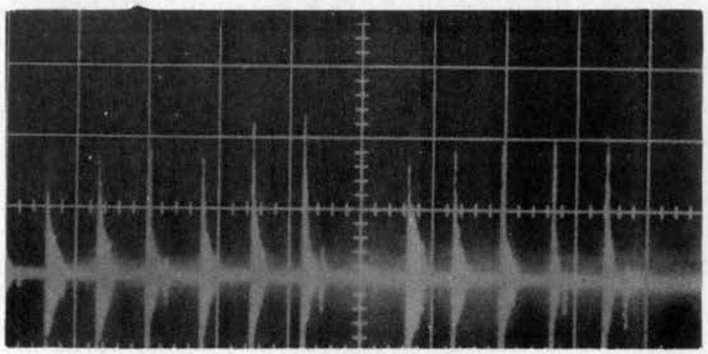
Run No.	Pres psig	Hole No.	Bit No.	Temp F	Hole Dia.	Depth (in.) Start	End 1	End 2	Time (min) One	Two
P46	105	B-7	P	35	1.54	12.500	26.250	53.437	0.967	1.767
P49	105	K-2	Q	35	1.54	12.375	26.812	54.750	1.000	1.750
Empirical Test Track-Mounted Drill in Limestone										
P53	55	B-4	B	35	3.06	13.062	69.250		4.367	
P62	55	C-7	C	35	3.06	14.062	70.937		4.067	
P98	55	K-5	D	59	3.06	13.187	70.812		4.717	
P54	60	J-6	D	35	3.06	14.062	70.000		4.133	
P61	60	A-1	A	35	3.06	13.687	70.625		4.183	
P71	60	J-2	B	43	3.06	14.750	69.875		3.967	
P94	60	K-7	C	64	3.07	14.000	70.875		3.833	
P51	65	L-4	B	35	3.05	13.312	69.062		3.700	
P55	65	G-1	C	35	3.06	13.250	70.000		3.500	
P56	65	M-5	A	35	3.08	13.750	71.062		3.033	
P97	65	L-2	D	59	3.06	14.437	70.625		4.083	
P52	70	B-2	D	35	3.06	13.000	68.625		3.717	
P57	70	H-2	C	35	3.07	14.000	71.375		3.833	
P70	70	C-5	C	41	3.06	13.750	70.875		3.583	
P73	70	N-6	A	44	3.08	13.562	70.625		3.783	
P84	70	I-3	B	57	3.06	14.125	71.125		3.667	
P60	75	M-7	D	35	3.06	13.125	70.250		3.833	
P65	75	E-1	C	35	3.06	13.375	71.312		4.617	
P72	75	K-3	B	43	3.06	13.750	71.750		3.883	
P87	75	I-5	A	63	3.07	14.187	71.687		3.600	
P76	80	M-1	B	50	3.06	13.750	71.187		3.550	
P93	80	C-3	A	64	3.07	14.562	71.062		3.500	
P95	80	I-1	D	63	3.07	14.750	71.562		3.567	
P59	85	A-5	C	35	3.08	13.875	71.750		3.350	
P78	85	F-4	B	51	3.06	13.687	71.875		3.267	
P80	85	I-7	A	53	3.08	13.937	71.500		3.167	
P88	85	F-6	D	63	3.06	14.062	72.000		3.400	
P77	90	N-2	B	49	3.08	14.125	71.750		3.017	
P82	90	G-5	C	55	3.06	13.437	71.625		2.950	
P83	90	H-4	A	56	3.06	14.125	71.062		3.017	
P86	90	D-6	D	63	3.08	14.062	71.625		3.150	
P58	95	F-2	B	35	3.08	14.500	71.000		2.833	
P64	95	E-5	D	35	3.06	14.125	71.125		3.317	
P67	95	A-3	C	37	3.07	13.687	71.312		3.133	
P68	95	J-4	A	39	3.05	13.687	70.625		3.283	
P75	100	G-7	B	47	3.07	14.437	71.250		2.900	
P79	100	M-3	D	51	3.07	13.312	71.375		2.883	
P90	100	E-7	C	63	3.07	14.100	71.312		2.817	
P92	100	D-4	A	63	3.08	14.500	71.750		2.917	
P74	105	L-6	A	45	3.07	13.250	71.312		3.167	
P85	105	G-3	B	57	3.06	14.375	71.312		2.817	
P96	105	C-1	D	63	3.07	13.750	71.250		2.983	
P99	105	K-1	C	36	3.07	14.312	72.000		3.083	



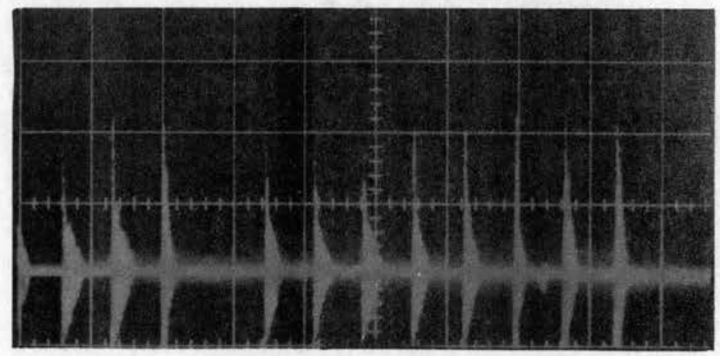
56 psig



60 psig

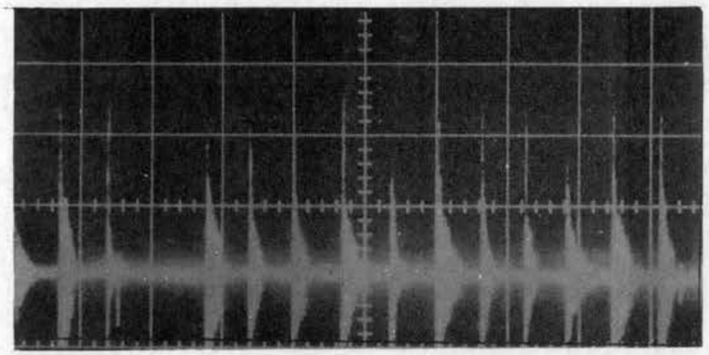


64 psig

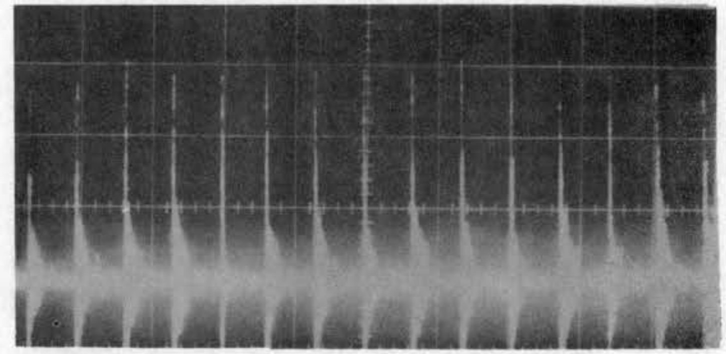


71 psig

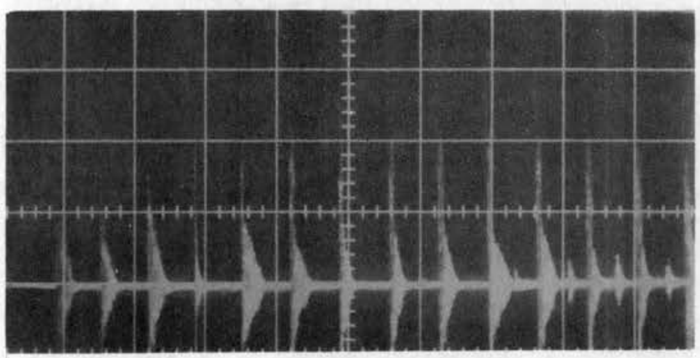
Fig. B-1 Sample Oscilloscope Display of Strain Gage Output



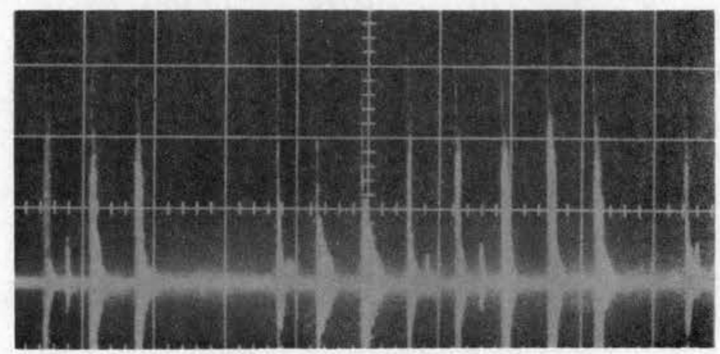
75 psig



79 psig

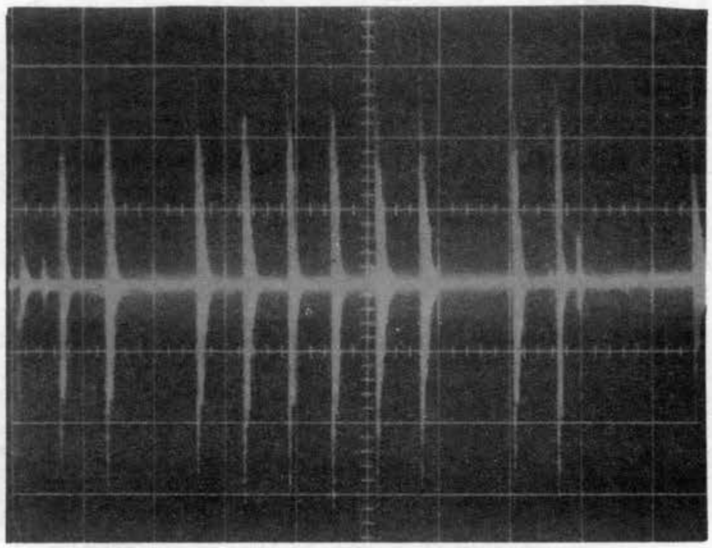


86 psig

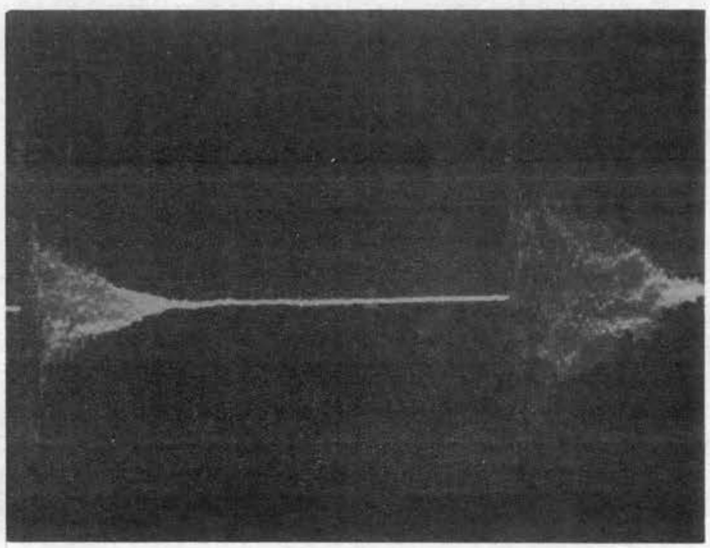


90 psig

Fig. B-2 Sample Oscilloscope Display of Strain Gage Output



94 psig



Strain Gage Output per Beat

Fig. B-3 Sample Oscilloscope Display of Strain Gage Output

LABORATORY TEST DATA

Run No.	Pressure psig	Avg. Peak Hgt mm	Max. Freq. cps	Act. Freq. cps
13	56	24.2	26.66	26.66
12	60	25.9	27.38	27.38
11	64	26.2	27.92	25.75
10	71	29.2	28.56	26.02
9	75	28.9	29.56	29.28
18	75	29.1	29.08	27.45
8	79	30.3	30.75	27.55
19	79	29.1	29.62	29.71
7	84	31.0	31.38	27.41
16	86	31.7	31.42	29.00
15	90	32.3	31.42	26.50
14	94	37.3	32.22	26.30

APPENDIX C

COMPUTER ANALYSIS

```
C       ANALYSIS OF DATA FOR DRIFTER TYPE DRILL

C       M = NUMBER OF OPERATING PRESSURES
C       IP = OPERATING PRESSURE
C       N = NUMBER OF HOLES AT A GIVEN PRESSURE
C       DF = FINAL DEPTH
C       DS = STARTING DEPTH
C       DIA = DIAMETER
C       T(J) = DRILLING TIME (J TH RUN)
        DIMENSION T(8), D(8), R(8), V(8)
        PUNCH 10
10      FORMAT (28X, 34HDRILLING RATES WITH DRIFTER DRILL ,/)
        PUNCH 12
12      FORMAT (25X,8HPRESSURE,6X,11HLIN RATE,4X,15HVOL RATE)
        READ 14 , M
14      FORMAT (I3)
        DO 36 I = 1,M
        READ 16, IP
        READ 16, N
16      FORMAT(I3)
        DO 26 J = 1,N
        READ 18, DF
        READ 18, DS
        READ 18, DIA
        READ 18, T(J)
18      FORMAT (F7.3)
        D(J) = DF - DS
        R(J) = D(J)/T(J)
        V(J) = ((DIA**2)*3.142*D(J))/(4.0*T(J))
22      PUNCH 24, IP, R(J), V(J)
24      FORMAT (27X, I3, 10X, F8.3, 8X, F8.3)
26      CONTINUE
        AN = N
        DT = 0.0
        VT = 0.0
        DO 28 K = 1,N
        DT = DT +R(K)
28      VT = VT + V(K)
        RA = (DT)/(AN)
        VA = (VT)/(AN)
```

```
      ANALYSIS OF DATA FOR DRIFTER TYPE DRILL (CON'T)

      IF (SENSE SWITCH 1) 30,32
30    TYPE 34, RA, VA
32    PUNCH 34, RA, VA
34    FORMAT (25X, 7HAVERAGE, 8X, F8.3, 8X, F8.3)
36    CONTINUE
      END

C     ANALYSIS OF DATA FOR JACKHAMMER TYPE DRILL

C     M = NUMBER OF OPERATING PRESSURES
C     IP = OPERATING PRESSURE
C     N = NUMBER OF HOLES AT A GIVEN PRESSURE
C     DS = STARTING DEPTH
C     DFF = FINISH DEPTH 4 FT STEEL
C     DF = FINISH DEPTH 4 FT, STARTING DEPTH 2 FT
C     DIA = DIAMETER
C     T(J) = DRILLING TIME 2 FT STEEL (J-TH RUN)
C     TL(J) = DRILLING TIME 4 FT STEEL (J-TH RUN)
      DIMENSION D(8), DL(8), R(8), RL(8), V(8), VL(8),RT(8)
      DIMENSION VT(8), T(8), TL(8)
      PUNCH 10
10    FORMAT(25X,41HDRILLING RATES WITH JACKHAMMER DRILL,/)
      PUNCH 12
12    FORMAT(15X,4HPRES,8X,4HRATE,10X,4H2FT,9X,4H4FT,8X,6H2+4FT)
      READ 14, M
14    FORMAT (I3)
      DO 52 I = 1,M
      READ 16, IP
      READ 16, N
16    FORMAT (I3)
      DO 20 J =1,N
      READ 18, DS
      READ 18, DFF
      READ 18, DF
      READ 18, DIA
      READ 18, T(J)
      READ 18, TL(J)
18    FORMAT (F8.3)
      D(J) = DF -DS
      DL(J) = DFF - DF
      R(J) = D(J)/T(J)
      RL(J) = DL(J)/TL(J)
      V(J) = ((DIA**2)*3.142*D(J))/(4.0*T(J))
      VL(J) = ((DIA**2)*3.142*DL(J))/(4.0*TL(J))
      RT(J) = (D(J) + DL(J))/(T(J) + TL(J))
      VT(J) = ((DIA**2)*3.142*(D(J)+DL(J))) / (4.0*(T(J) + TL(J)))
20    CONTINUE
```

```
C       ANALYSIS OF DATA FOR JACKHAMMER TYPE DRILL (CONT'D)
        DT = 0.0
        DLT = 0.0
        DTT = 0.0
        VAT = 0.0
        VLT = 0.0
        VTT = 0.0
        AN = N
        DO 22 J = 1,N
        DT = DT + R(J)
        DLT = DLT + RL(J)
        DTT = DTT + RT(J)
        VAT = VAT +V(J)
        VLT = VLT + VL(J)
22      VTT = VTT + VT(J)
        RA = (DT)/(AN)
        RLA = (DLT)/(AN)
        RTA = (DTT)/(AN)
        VA = VAT/AN
        VLA = (VLT)/(AN)
        VTA = (VTT)/(AN)
        DO 30 J = 1,N
        IF (SENSE SWITCH 1) 24,26
24      TYPE 28, IP, R(J), RL(J), RT(J)
26      PUNCH 28, IP, R(J), RL(J), RT(J)
28      FORMAT(15X,I3,6X,9HLIN. RATE,5X,F8.3,5X,F8.3,5X,F8.3)
30      CONTINUE
        DO 38 J = 1,N
        IF (SENSE SWITCH 1) 32,34
32      TYPE 36, IP, V(J), VL(J), VT(J)
34      PUNCH 36, IP, V(J), VL(J), VT(J)
36      FORMAT(15X,I3,6X,9HVOL. RATE,5X,F8.3,5X,F8.3,5X,F8.3)
38      CONTINUE
        IF (SENSE SWITCH 1) 40,42
40      TYPE 44, IP, RA, RLA, RTA
42      PUNCH 44, IP, RA, RLA, RTA
44      FORMAT(15X,I3,6X,9HAVG. LIN.,5X,F8.3,5X,F8.3,5X,F8.3)
        IF (SENSE SWITCH 1) 46,48
46      TYPE 50, IP, VA, VLA, VTA
48      PUNCH 50, IP, VA, VLA, VTA
50      FORMAT(15X,I3,6X,9HAVG. VOL.,5X,F8.3,5X,F8.3,5X,F8.3,/)
52      CONTINUE
        END
```

DRILLING RATES WITH DRIFTER DRILL

CONCRETE BLOCK

PRESSURE	LINEAR RATE	VOLUMETRIC RATE
55	11.767	85.425
55	9.610	69.765
55	10.093	73.273
55	5.874	43.204
AVERAGE	9.336	67.917
60	11.484	82.276
60	9.114	66.163
60	12.867	93.411
60	6.619	48.688
AVERAGE	10.021	72.634
65	7.604	56.664
65	12.913	93.745
65	9.091	66.872
65	7.229	53.176
AVERAGE	9.210	67.614
70	13.571	98.518
70	10.902	79.146
70	10.928	79.333
70	9.937	73.091
70	7.321	53.849
AVERAGE	10.532	76.787
75	14.975	108.709
75	11.071	80.370
75	11.880	86.808
75	9.988	73.468
AVERAGE	11.978	87.339
80	12.560	89.982
80	14.089	102.279
80	10.809	78.471
AVERAGE	12.486	90.244
85	14.773	107.246
85	14.047	101.975
85	13.005	94.407
85	8.233	60.559
AVERAGE	12.515	91.047
90	15.270	110.850
90	15.911	117.029
90	15.463	112.254
90	13.205	95.859
AVERAGE	14.962	108.998

PRESSURE	LINEAR RATE	VOLUMETRIC RATE
95	13.000	95.616
95	16.276	119.716
95	9.936	73.085
95	10.694	78.658
AVERAGE	12.476	91.769
100	14.169	102.861
100	15.503	112.544
100	16.796	121.933
100	11.977	85.807
AVERAGE	14.611	105.786
105	15.909	115.488
105	14.447	104.877
105	16.342	118.635
105	13.074	94.908
AVERAGE	14.943	108.477

DRILLING RATES WITH DRIFTER DRILL

LIMESTONE QUARRY

PRESSURE	LINEAR RATE	VOLUMETRIC RATE
55	12.866	94.634
55	13.984	102.857
55	12.216	89.853
AVERAGE	13.022	95.781
60	13.534	99.547
60	13.611	100.115
60	13.895	102.205
60	14.838	109.851
AVERAGE	13.970	102.930
65	15.067	110.100
65	16.214	119.257
65	18.896	140.805
65	13.761	101.216
AVERAGE	15.984	117.845
70	14.965	110.069
70	14.968	110.817
70	15.943	117.265
70	15.084	112.399
70	15.544	114.328
AVERAGE	15.301	112.975

PRESSURE	LINEAR RATE	VOLUMETRIC RATE
75	14.903	109.616
75	12.548	92.296
75	14.936	109.862
75	15.972	118.246
AVERAGE	14.590	107.505
80	16.179	119.001
80	16.142	119.509
80	15.927	117.912
AVERAGE	16.083	118.807
85	17.276	128.734
85	17.810	131.000
85	18.175	135.438
85	17.040	125.335
AVERAGE	17.575	130.127
90	19.100	142.325
90	19.724	145.077
90	18.872	138.806
90	18.273	136.169
AVERAGE	18.992	140.594
95	19.943	148.610
95	17.184	126.391
95	18.392	136.167
95	17.343	126.729
AVERAGE	18.215	134.474
100	19.590	145.034
100	20.139	149.100
100	20.345	150.619
100	19.626	146.246
AVERAGE	19.925	147.750
105	18.333	135.727
105	20.211	148.660
105	19.275	142.704
105	18.711	138.527
AVERAGE	19.133	141.404

DRILLING RATES WITH JACKHAMMER TYPE DRILL

CONCRETE BLOCK

PRES	RATE	2 FT	4 FT	2+4 FT
55	LIN. RATE	9.117	8.754	8.886
55	LIN. RATE	10.599	9.970	10.203
55	LIN. RATE	9.777	9.328	9.498
55	LIN. RATE	10.783	10.029	10.297
55	VOL. RATE	17.429	16.734	16.987
55	VOL. RATE	20.261	19.059	19.503
55	VOL. RATE	18.690	17.832	18.156
55	VOL. RATE	20.614	19.171	19.683
55	AVG. LIN.	10.069	9.520	9.721
55	AVG. VOL.	19.248	18.199	18.582
60	LIN. RATE	9.411	8.771	9.007
60	LIN. RATE	10.739	10.692	10.709
60	LIN. RATE	10.672	9.716	10.057
60	LIN. RATE	12.073	10.535	11.074
60	VOL. RATE	17.991	16.766	17.217
60	VOL. RATE	20.529	20.439	20.472
60	VOL. RATE	20.663	18.813	19.473
60	VOL. RATE	23.079	20.140	21.169
60	AVG. LIN.	10.724	9.929	10.212
60	AVG. VOL.	20.565	19.040	19.583
65	LIN. RATE	9.526	9.118	9.253
65	LIN. RATE	11.694	10.374	10.834
65	LIN. RATE	11.057	9.663	10.158
65	LIN. RATE	12.115	9.443	10.307
65	VOL. RATE	18.210	17.430	17.689
65	VOL. RATE	22.932	20.343	21.245
65	VOL. RATE	21.408	18.710	19.667
65	VOL. RATE	23.457	18.284	19.957
65	AVG. LIN.	11.098	9.649	10.138
65	AVG. VOL.	21.502	18.692	19.639
70	LIN. RATE	9.523	9.937	9.794
70	LIN. RATE	11.889	11.458	11.619
70	LIN. RATE	12.207	11.686	11.880
70	LIN. RATE	12.969	11.098	11.753
70	VOL. RATE	18.205	18.995	18.722
70	VOL. RATE	23.020	22.184	22.497
70	VOL. RATE	23.937	22.915	23.296
70	VOL. RATE	25.110	21.488	22.756
70	AVG. LIN.	11.647	11.044	11.261
70	AVG. VOL.	22.568	21.396	21.818

PRES	RATE	2 FT	4 FT	2+4 FT
75	LIN. RATE	11.718	11.846	11.801
75	LIN. RATE	12.356	10.690	11.295
75	LIN. RATE	12.076	11.126	11.472
75	LIN. RATE	13.495	12.146	12.615
75	VOL. RATE	22.114	22.356	22.271
75	VOL. RATE	23.619	20.436	21.592
75	VOL. RATE	23.382	21.542	22.213
75	VOL. RATE	25.798	23.218	24.115
75	AVG. LIN.	12.411	11.452	11.796
75	AVG. VOL.	23.728	21.888	22.548
80	LIN. RATE	14.004	12.318	12.896
80	LIN. RATE	12.596	11.627	11.992
80	LIN. RATE	13.504	11.675	12.292
80	LIN. RATE	13.714	11.711	12.367
80	VOL. RATE	26.771	23.548	24.653
80	VOL. RATE	24.078	22.227	22.925
80	VOL. RATE	25.815	22.319	23.498
80	VOL. RATE	26.217	22.388	23.641
80	AVG. LIN.	13.455	11.833	12.387
80	AVG. VOL.	25.720	22.621	23.679
85	LIN. RATE	13.029	11.013	11.702
85	LIN. RATE	13.437	12.623	12.927
85	LIN. RATE	13.532	12.684	12.991
85	LIN. RATE	15.687	12.561	13.596
85	VOL. RATE	25.550	21.596	22.948
85	VOL. RATE	26.349	24.754	25.348
85	VOL. RATE	26.200	24.559	25.153
85	VOL. RATE	29.987	24.013	25.991
85	AVG. LIN.	13.921	12.220	12.804
85	AVG. VOL.	27.021	23.730	24.860
90	LIN. RATE	14.866	12.840	13.524
90	LIN. RATE	12.874	12.812	12.835
90	LIN. RATE	12.756	12.500	12.593
90	LIN. RATE	15.398	13.885	14.406
90	VOL. RATE	28.785	24.860	26.186
90	VOL. RATE	24.927	24.807	24.851
90	VOL. RATE	24.385	23.894	24.074
90	VOL. RATE	29.436	26.543	27.538
90	AVG. LIN.	13.974	13.009	13.339
90	AVG. VOL.	26.883	25.026	25.662

PRES	RATE	2 FT	4 FT	2+4 FT
95	LIN. RATE	12.942	12.439	12.617
95	LIN. RATE	14.463	13.439	13.800
95	LIN. RATE	12.961	13.053	13.017
95	LIN. RATE	13.241	13.412	13.345
95	VOL. RATE	25.058	24.084	24.429
95	VOL. RATE	28.362	26.353	27.061
95	VOL. RATE	24.777	24.952	24.884
95	VOL. RATE	25.637	25.968	25.840
95	AVG. LIN.	13.402	13.086	13.195
95	AVG. VOL.	25.959	25.339	25.553
100	LIN. RATE	14.375	13.281	13.679
100	LIN. RATE	13.314	12.722	12.940
100	LIN. RATE	15.369	13.606	14.202
100	LIN. RATE	14.135	13.420	13.672
100	VOL. RATE	27.833	25.714	26.486
100	VOL. RATE	26.109	24.947	25.375
100	VOL. RATE	30.138	26.681	27.849
100	VOL. RATE	27.718	26.316	26.809
100	AVG. LIN.	14.298	13.257	13.623
100	AVG. VOL.	27.949	25.915	26.630
105	LIN. RATE	14.778	13.680	14.089
105	LIN. RATE	14.923	12.995	13.625
105	LIN. RATE	15.692	13.062	13.891
105	LIN. RATE	16.666	14.180	14.972
105	VOL. RATE	28.250	26.151	26.934
105	VOL. RATE	28.527	24.841	26.045
105	VOL. RATE	29.614	24.651	26.214
105	VOL. RATE	31.859	27.106	28.621
105	AVG. LIN.	15.515	13.479	14.144
105	AVG. VOL.	29.563	25.687	26.953

DRILLING RATES WITH JACKHAMMER TYPE DRILL

LIMESTONE QUARRY

PRES	RATE	2 FT	4 FT	2+4 FT
55	LIN. RATE	14.399	13.425	13.750
55	LIN. RATE	13.388	15.951	14.977
55	LIN. RATE	11.634	12.146	11.961
55	LIN. RATE	11.693	11.625	11.646
55	VOL. RATE	26.825	25.009	25.614
55	VOL. RATE	24.941	29.716	27.902
55	VOL. RATE	22.240	23.219	22.865
55	VOL. RATE	21.784	21.656	21.695
55	AVG. LIN.	12.779	13.287	13.083
55	AVG. VOL.	23.948	24.900	24.519

PRES	RATE	2 FT	4 FT	2+4 FT
60	LIN. RATE	14.585	13.526	13.891
60	LIN. RATE	13.128	15.972	14.935
60	LIN. RATE	12.102	12.065	12.077
60	LIN. RATE	11.606	12.804	12.369
60	VOL. RATE	27.525	25.527	26.215
60	VOL. RATE	24.457	29.754	27.823
60	VOL. RATE	22.546	22.476	22.498
60	VOL. RATE	21.621	23.853	23.042
60	AVG. LIN.	12.855	13.592	13.318
60	AVG. VOL.	24.037	25.402	24.894
65	LIN. RATE	13.669	13.567	13.601
65	LIN. RATE	13.120	14.679	14.125
65	LIN. RATE	14.058	13.930	13.975
65	LIN. RATE	13.749	12.902	13.186
65	VOL. RATE	26.130	25.936	26.000
65	VOL. RATE	24.761	27.702	26.656
65	VOL. RATE	26.529	26.289	26.373
65	VOL. RATE	25.613	24.035	24.564
65	AVG. LIN.	13.649	13.770	13.722
65	AVG. VOL.	25.758	25.990	25.898
70	LIN. RATE	13.750	14.729	14.384
70	LIN. RATE	12.246	15.000	13.954
70	LIN. RATE	11.875	12.826	12.488
70	LIN. RATE	12.272	14.151	13.481
70	VOL. RATE	26.284	28.157	27.496
70	VOL. RATE	23.409	28.673	26.674
70	VOL. RATE	22.410	24.205	23.568
70	VOL. RATE	22.862	26.362	25.113
70	AVG. LIN.	12.535	14.176	13.577
70	AVG. VOL.	23.741	26.849	25.713
75	LIN. RATE	17.926	17.171	17.409
75	LIN. RATE	16.704	16.620	16.650
75	LIN. RATE	12.421	13.968	13.414
75	LIN. RATE	13.003	14.294	13.838
75	VOL. RATE	33.396	31.988	32.432
75	VOL. RATE	31.118	30.961	31.017
75	VOL. RATE	23.441	26.360	25.314
75	VOL. RATE	24.224	26.629	25.779
75	AVG. LIN.	15.014	15.513	15.328
75	AVG. VOL.	28.045	28.985	28.635

PRES	RATE	2 FT	4 FT	2+4 FT
80	LIN. RATE	16.506	16.911	16.778
80	LIN. RATE	12.613	14.606	13.879
80	LIN. RATE	13.099	14.290	13.851
80	LIN. RATE	11.709	13.167	12.634
80	VOL. RATE	31.150	31.915	31.663
80	VOL. RATE	23.803	27.564	26.193
80	VOL. RATE	24.403	26.622	25.802
80	VOL. RATE	21.812	24.529	23.537
80	AVG. LIN.	13.482	14.743	14.286
80	AVG. VOL.	25.292	27.657	26.799
85	LIN. RATE	15.071	16.661	16.105
85	LIN. RATE	12.700	15.066	14.165
85	LIN. RATE	13.895	14.736	14.453
85	LIN. RATE	13.310	14.551	14.121
85	VOL. RATE	28.442	31.443	30.393
85	VOL. RATE	23.354	27.703	26.047
85	VOL. RATE	25.885	27.453	26.924
85	VOL. RATE	25.119	27.460	26.649
85	AVG. LIN.	13.744	15.254	14.711
85	AVG. VOL.	25.700	28.515	27.503
90	LIN. RATE	12.391	14.394	13.631
90	LIN. RATE	14.864	15.493	15.285
90	LIN. RATE	13.310	15.347	14.604
90	LIN. RATE	13.827	15.633	14.974
90	VOL. RATE	22.784	26.468	25.064
90	VOL. RATE	28.050	29.238	28.845
90	VOL. RATE	25.119	28.962	27.561
90	VOL. RATE	25.759	29.124	27.895
90	AVG. LIN.	13.598	15.217	14.623
90	AVG. VOL.	25.428	28.448	27.341
95	LIN. RATE	17.879	15.650	16.321
95	LIN. RATE	15.855	16.617	16.356
95	LIN. RATE	15.643	17.343	16.739
95	LIN. RATE	14.089	16.016	15.322
95	VOL. RATE	34.179	29.917	31.200
95	VOL. RATE	29.536	30.956	30.471
95	VOL. RATE	29.141	32.309	31.182
95	VOL. RATE	26.590	30.225	28.915
95	AVG. LIN.	15.867	16.407	16.185
95	AVG. VOL.	29.861	30.852	30.442

PRES	RATE	2 FT	4 FT	2+4 FT
100	LIN. RATE	14.067	15.582	15.068
100	LIN. RATE	14.473	14.863	14.731
100	LIN. RATE	15.277	15.857	15.660
100	LIN. RATE	14.541	15.931	15.424
100	VOL. RATE	26.547	29.406	28.436
100	VOL. RATE	26.962	27.688	27.444
100	VOL. RATE	28.460	29.540	29.173
100	VOL. RATE	27.089	29.678	28.734
100	AVG. LIN.	14.590	15.558	15.221
100	AVG. VOL.	27.265	29.078	28.447
105	LIN. RATE	17.171	16.721	16.856
105	LIN. RATE	15.312	15.832	15.667
105	LIN. RATE	14.219	15.385	14.973
105	LIN. RATE	14.437	15.964	15.409
105	VOL. RATE	32.405	31.556	31.811
105	VOL. RATE	28.525	29.493	29.187
105	VOL. RATE	26.488	28.662	27.893
105	VOL. RATE	26.894	29.740	28.705
105	AVG. LIN.	15.285	15.976	15.726
105	AVG. VOL.	28.578	29.863	29.399

```
C      DETERMINING EXPONENTIAL CURVE OF BEST FIT

C      N = NUMBER OF PAIRS OF POINTS
C      X(I) = X VALUE (I TH PAIR)
C      Y(I) = Y VALUE (I TH PAIR)
       DIMENSION X(100), Y(100), XL(100), YL(100), Z(100)
8      READ 10, N
10     FORMAT (I3)
       DO 12 I = 1,N
       READ 11, X(I)
11     FORMAT (F7.2)
12     CONTINUE
       DO 14 I = 1,N
       READ 13, Y(I)
13     FORMAT (F7.2)
14     CONTINUE
       AN = N
       IF (SENSE SWITCH 1) 16,19
16     DO 18 I = 1,N
       TYPE 17, X(I), Y(I), N
17     FORMAT (F7.2, F7.2, I3)
18     CONTINUE
19     I = 0
       DO 20 J = 1,N
       I=I+1
       XL(I) = LOG(X(I))
20     YL(I) = LOG(Y(I))
       I = 0
       TLX = 0.0
       TLY = 0.0
       SLX = 0.0
       PLXY = 0.0
       DO 22 J = 1,N
       I = I+1
       TLX = TLX +XL(I)
       TLY = TLY + YL(I)
       SLX =((XL(I))**2.0) + SLX
22     PLXY = ((XL(I))*(YL(I))) + PLXY
       C = ((PLXY)/(TLX))-((TLY)/(AN))
       D = ((SLX)/(TLX))-((TLX)/(AN))
       A = C/D
       V = ((TLY)/AN) - (((TLX)/AN)*A)
       I = 0
       DO 24 J = 1,N
       I = I+1
24     Z(I) = (A*XL(I))+V
       P = EXP(V)
       IF (SENSE SWITCH 2) 26,28
26     TYPE 30, P,A
       TYPE 32
28     PUNCH 30, P,A
       PUNCH 32
```

```
C       DETERMINING EXPONENTIAL CURVE OF BEST FIT (CONT'D)

30      FORMAT (39X, 4HY = , F10.5, 6H X ** , F10.5,/)
32      FORMAT (44X, 3H X , 13X, 3H Y , /)
        I = 0
        DO 40 J = 1,N
        I = I+1
        W = EXP(Z(I))
        IF (SENSE SWITCH 2) 34,36
34      TYPE 38, X(J), W
36      PUNCH 38, X(J), W
38      FORMAT (40X, F8.2, 9X, F8.2)
40      CONTINUE
        PAUSE
        GO TO 8
        END
```

SAMPLE CURVE

INPUT DATA

X	Y
55.00	9.52
60.00	9.93
65.00	9.65
70.00	11.04
75.00	11.45
80.00	11.83
85.00	12.22
90.00	13.01
95.00	13.08
100.00	13.26
105.00	13.48

OUTPUT DATA

Y = 0.85028 X ** 0.59892

X	Y
55.00	9.37
60.00	9.87
65.00	10.35
70.00	10.83
75.00	11.28
80.00	11.73
85.00	12.16
90.00	13.00
95.00	13.00
100.00	13.40
105.00	13.80

APPENDIX D

SAMPLE LABORATORY ANALYSIS CALCULATIONS

Laboratory Test Data (Appendix B)

Air pressure: 90 psi

$$\text{Average peak height} = \frac{\text{peak heights in mm}}{\text{no. of peaks}}$$

$$= \frac{36.0 + 30.0 + 35.0 + 37.0 + 20.0 + 30.0}{12}$$

$$+ \frac{32.0 + 31.0 + 30.5 + 40.0 + 33.5 + 32.0}{12}$$

$$= \frac{387.0 \text{ mm}}{12}$$

$$= 32.3 \text{ mm}$$

$$\text{Maximum Frequency} = \frac{\text{no. of adjacent peaks} - 1}{\text{length of base}}$$

$$\times \text{ oscilloscope sweep time}$$

$$= \frac{8 - 1}{4.45 \text{ cm}} \times 20 \frac{\text{cm}}{\text{sec}}$$

$$= 31.42 \text{ cps}$$

$$\text{Actual Frequency} = \frac{\text{no. of peaks} - 1}{\text{length of base}}$$

$$\times \text{ oscilloscope sweep time}$$

$$= \frac{12-1}{8.30 \text{ cm}} \times 20 \frac{\text{cm}}{\text{sec}}$$

$$= 26.50 \text{ cps}$$

Results of Laboratory Measurements (Table VI)

Formula:

Energy = $\frac{1}{2}$ AELϵ^2

Where:

A = cross-section area of drill steel in in.^{2}

E = modulus of elasticity in psi

L = length of drill steel in in.

ϵ = strain in in./in.

$$E = \frac{0.606}{2} \times 30 \times 10^6 \times 24 \times \epsilon^2$$

$$= 218.2 \times 10^6 \epsilon^2$$

Calibration factor: Both the meter on the BAM-1 and the oscilloscope give arbitrary readings. To obtain reading in micro inches per inch (u in./in.), Ellis Associates, manufacturers of the BAM-1 suggest that the following formula be used to compute the calibration factor.

For power switch at 2

$$\frac{400}{\text{gage factor}} \times \frac{\text{calibration setting}}{\text{no. active arms}} = \text{u in./in.}$$

$$\frac{400}{1.91} \times \frac{0.5}{1} = 104.71 \text{ u in./in.}$$

Then:

3 mm on scope = 104.71 u in./in.

1 mm on scope = 34.9 u in./in.

Air pressure: 90 psi

Strain = avg hgt of peaks x 34.9

= 32.3 x 34.9

= 1128 u in./in.

Stress = strain x modules of elasticity

$= 1128 \times 10^{-6} \times 30 \times 10^{6}$

= 33,840 psi

Energy/Blow = $218.2 \times 10^{6} \times \epsilon^{2}$

$= 218.2 \times 10^{6} \times (1128 \times 10^{-6})^{2}$

= 277.9 in.-lb or 23.1 ft-lb

Maximum work = energy/blow x No. of blows/sec

= 23.1 x 31.42

= 727.0 ft-lbs/sec

Actual work = energy/blow x no. of blow/sec

= 23.1 x 26.50

= 613 ft-lbs/sec

APPENDIX E

CHARACTERISTICS OF TEST MEDIA

Concrete

Aggregate sieve analysis:

Sieve Size	Per Cent Passing
3/4 in.	88.18
1/2 in.	51.58
#4	38.87
#10	32.51
#30	16.35
#100	0.41

Los Angeles Abrasion Test results:

Gradation type: B

Wear value: 23%

Concrete mix proportions per cubic yard:

Cement: 710 lbs

Fine aggregate: 1250 lbs

Coarse aggregate: 1882 lbs

Water: 308 lbs

Slump: 1"

Compressive strength at 28 days:

Test No.	Max. Load (lbs)	Compressive Strength (psi)
1	195,000	6920
2	189,000	6752
3	186,000	6579
Average		6750

Limestone

Spectrographic analysis:

Calcium and magnesium carbonate: 78.75%

Impurities: 21.25%

Density:

Sample weight in air 2083.5 gm

Sample weight in water 1280.5 gm

Loss of weight in water 803.0 gm

$$\text{Density} = \frac{2083.5 \text{ gm}}{803.0 \text{ gm}} \times 62.4 \text{ pcf} = 162 \text{ pcf}$$

VITA

Paul Frederick Kavanaugh

Candidate for the Degree of

Master of Science

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