THE EFFECT OF AIR PRESSURE ON ROCK DRILLING RATES

By

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ROCK DRILLING RATES

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PREFACE

Professor R. L. Peurifoy introduced the application of economics in the use of construction equipment to me and, therefore, sparked the interest which led to this research in rock drilling rates.

Indebtedness is acknowledged to Professor R. L. Peurifoy and Doctor R. L. Lowery for their valuable guidance, and for their assistance in the procurement of equipment; and to the following for the loan of equipment used in this research: G. L. James, Guy James Construction Company, Oklahoma City; V. L. Phillips Equipment Company, Oklahoma City; Lehland Equipment Company, Oklahoma City; Griffith Well Cementing Company, Cushing, Oklahoma; American Meter Company, Tulsa, Oklahoma; Central Propane Inc., Stillwater, Oklahoma; Oklahoma Natural Gas Company, Stillwater, Oklahoma; and Timken Roller Bearing Company.

I especially wish to express my gratitude to my wife for her understanding and patient assistance.

Finally, I wish to thank Miss Natalia Crenwelge for her excellent typing.

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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

Although it has been stated many times, the contribution the rock drill has made to the advance of civilization is so important that it cannot be over emphasized.

Many industries, including some of the largest ones, depend entirely upon the excavation of ore or rock for their raw materials. Our transportation systems - railroads, highways, canals, and ship channels - would inevitably follow longer and more circuitous routes had their builders been obligated to attack rock solely with the power of human muscles. Our great dams and hydroelectric plants, our deep-rooted skyscrapers, our water-supply and sewage systems, and numerous other physical works that affect our daily lives and well-being exist largely because of the rock drill (1).

In 1849 J. J. Couch of Philadelphia was granted a patent on a percussion drill mounted on a four-wheel carriage and actuated by steam. The mechanism, weighing several thousand pounds, drilled a hole by repeatedly hurling a drill bar at a rock face. It was the first machine capable of drilling other than vertical holes and was, therefore, the prototype of our present day percussive air drill. Between 1848 and 1866 there were several patents granted on rock drilling equipment, but there was no significant progress in the development of the percussion drill. However, in 1866 Charles Burleigh designed and built forty drills using a modification of patents previously granted to Couch and a J. W. Fowle. These drills were used on a railroad tunnel in Hoosac, Massachusetts, the first major use of mechanical rock drills for construction in the United States. In 1874 four hundred drills were used in the New Croton Aqueduct tunnels for New York City's water supply system. All of the aforementioned drills had the drill bar attached to the actuating piston so that the entire bar moved with the piston. It was not until around 1900 that a design, the hammer principle, was developed that allowed the piston to strike the drill steel, thereby, reducing the weight of the drill. In the same period John G. Leynor developed the hollow drill steel which allowed air to blow the cuttings out of the hole. Leynor is also credited with such improvements as automatic rifle bar rotation of the drill-steel chuck, automatic lubrication and the first successful application of the hammer principle to drills for horizontal and down hole work (2).

By 1900 industry had accepted the rock drill as a useful tool that was here to stay and began research on the factors affecting its operation. In 1917 B. F. Tillson (3) reported on a series of tests run by the New Jersey Zinc Company. The object of these tests was to develop a means of predicting the drilling rates for the different types of drills used in the Company. Tillson intended to accomplish this through a study of records kept on each type of drill but found that there were too many variables in everyday operations to yield conclusive results. In 1922 H. W. Seamon (4) reported on the results of fifteen hundred tests made by the United Verde Copper Company. His report represented a comprehensive series of tests in which he used selected types of rock drills to relate varied air pressures to blows per minute, energy per blow, drilling speed and air consumption. He concluded that: (a) there is little or no increase in efficiency above ninety pounds air pressure, (b) the average drill is made to operate at eighty pounds air pressure or less, (c) economics indicate that there is a reduction in the rate of returns above one hundred pounds air pressure, (d) the most economical operating pressure is around ninety-five pounds air pressure, at the drill. Seamon's work, done in 1920, was used as a reference as recently as 1941 by Robert Peele (5) in his Mining Engineers' Handbook.

Two English researchers, W. R. Cheetham and E. W. Inett (6), made an extremely thorough study of the factors affecting the performance of rock drills in 1954. They included, among other things, the effects of air pressure on drilling rates. Their results indicated that even though the drilling rate continued to increase with higher air pressures, there was a point, depending on the downward thrust of the operator, at which the rate of increase would diminish. E. W. Inett (7) continued the research he started with Cheetham and in 1958 published a paper which added little to the previous information.

The need for additional research in this area was pointed out by Professor R. L. Peurifoy to his class in

Construction Planning, Equipment, and Methods at Oklahoma State University, during the summer of 1963. He noted that in his experience he had seen several instances where the production rates for rock drills appeared to be less than those normally expected, apparently because of insufficient air pressure at the drill. Professor Peurifoy had made a preliminary search for literature or publications on this subject and found that if any tests had been conducted recently, the results had not been published.

The author felt that if rock drills were operated at other than optimum pressure, either maintenance costs would be greater or the production rates lower. Considering this and the highly competitive nature of the construction industry, the author felt that modern research into the effect of air pressures on drilling rates would be beneficial.

With the assistance of P. F. Kavanaugh and the advice of Professor R. L. Peurifoy the initial plans for the research were developed. As the planning continued, certain limitations tending to reduce the scope of the research became apparent. Both Mr. Kavanaugh and the author would be required to report back to active military duty in May of 1964, so the time frame of the work was limited to the winter of 1963-1964. Financial backing from industry did not develop as was expected; however, the School of Civil Engineering at Oklahoma State University provided funds to cover operating costs. Consequently, the major pieces of necessary equipment would have to be borrowed from local sources and, therefore, might not be in a new or like-new condition.

In spite of these restrictions the work does present a fairly complete coverage of the effect of air pressure on the drilling rates of common rock drills.

CHAPTER II

OBJECTIVES

Planning large operations using rock drills will involve, among other things, decisions as to the amount of air required and the pressure necessary at the compressor. To determine the required pressure the planner must either know or assume the pressure required at the drills and their air consumption. With this knowledge he can calculate the expected pressure losses due to friction in the lateral and header pipes of his distribution system. The friction losses and, therefore, the cost of production will decrease as the size of these pipes increases, but the cost of the larger pipes will also be greater. The planner must consider this in determining the optimum combination of the expected rock drilling rate and the cost of producing and delivering compressed air.

The literature made available by various rock drill manufacturers suggests an operating air pressure for each different type of drill and generally states that any increase in pressure will cause a corresponding increase in breakage and maintenance costs. Similarly reductions in air pressure cause corresponding reductions in drilling rates and, thus, production. This literature does not provide enough information on the relationship between air pressures and drilling rates to make even the simplest of economic studies. Consequently the user, be he a contractor, quarry operator, or mine owner, either must make a semi-educated guess or perform a costly and time consuming study on his own drills before purchasing the required equipment.

Therefore, the objective of this research was to develop the relationship between air pressure and drilling rates. This should provide the user with information on which to base comprehensive economic studies.

Two approaches, empirical and laboratory, were used to accomplish this objective. In the empirical method the changes in drilling rates were measured in a concrete block and natural limestone. The second approach involved the use of strain gages to measure the energy produced by the rock drills at different air pressures. The relationship between these values and their corresponding air pressures was studied to determine a means of predicting the change in drilling rates with respect to air pressure.

CHAPTER III

EXPERIMENTAL DESIGN

The first steps in any project are planning the work to be done and selecting the necessary equipment to satisfy the objectives. In planning this research, several external factors, considered to have potential effects on the results, were analyzed to determine the best way to measure and correct their effects. In most cases it was not possible to integrate a correction factor into the experimental design. Instead the external influence was measured, recorded and compared with the results to locate any existing correlation.

Test Media

The primary requisite of a test medium is that the property being used, in this case drillability, be homogenous. Batholithic granite and other massive formations are essentially homogeneous, but these are not found in north central Oklahoma. The predominant rocks in this area are sandstones and limestones, of which limestones are the least heterogeneous. However even limestone has sedimentary bedding planes and solution channels. The first series of the drilling test was performed on a concrete block located on the Oklahoma State University campus. This was followed by an identical series in a nearby limestone quarry.

The author recognized that despite every precaution the drillability of the test material might vary. Therefore it was decided to utilize the drilling pattern shown in Fig. 1 and to randomize the application of the treatment, air pressure. Each hole was assigned an identification number, and the one and one-half inch holes were alternated with the three inch holes to distribute any high stresses caused by the larger drill. Alternating the hole sizes actually created two patterns, one superimposed on the other. Each pattern was treated separately. The operating air pressures were assigned to the numbered holes using a random number process. This was done to insure that any grouping of the pressures was due only to chance. Also it was felt that concentrations of the higher pressures might cause cracking of the concrete, and randomization would spread the stresses over the entire pattern. The same process was used on both the one and one-half inch and the three inch holes.

A concrete block was poured for the work done on the campus. To maximize the homogeneity of the concrete it was well mixed in a transit mix truck and then vibrated, after pouring, only enough to remove air pockets without causing segregation of the aggregate. The governing criterion

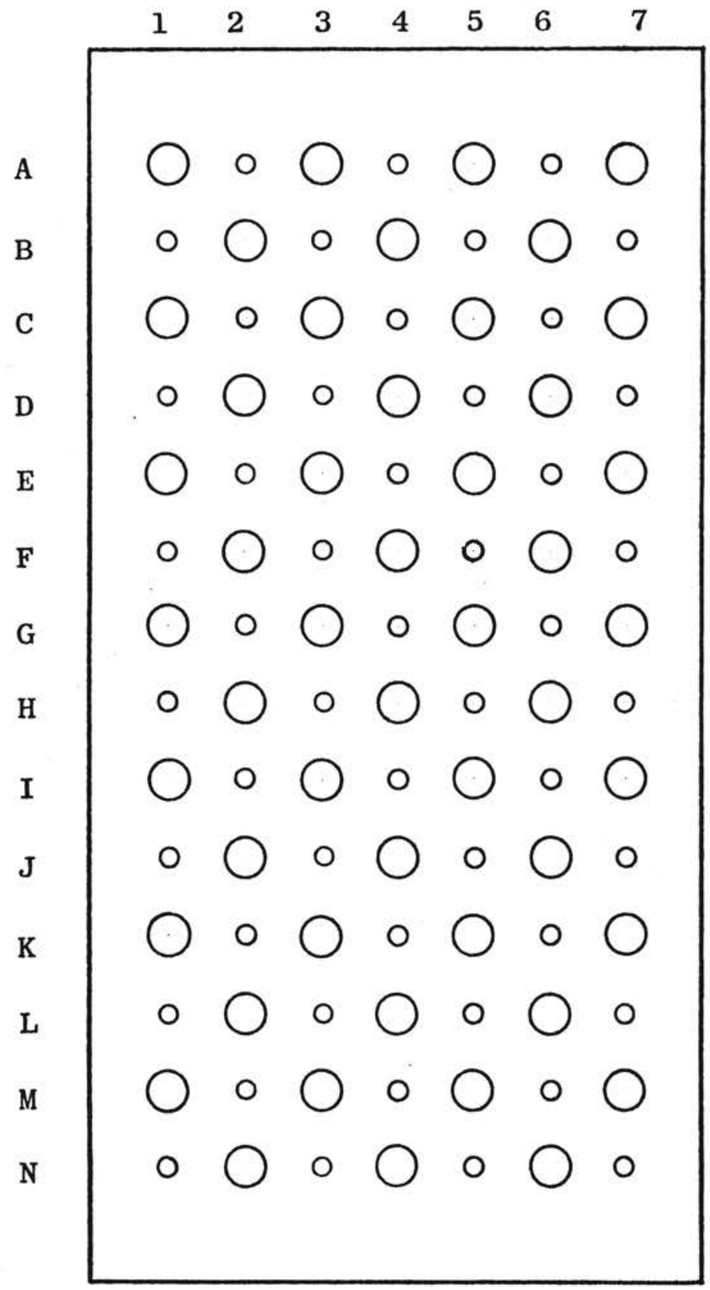

Fig. 1 Drilling Pattern

for the concrete was that it must have a compressive strength high enough to cause the mix to act as a unit. The concrete used had the mix proportions shown in Appendix E. The coarse aggregate was a limestone having a Los Angeles Abrasion Test (8) wear value of twenty-three per cent for gradation type B. The average slump was approximately one inch, and the average twenty-eight day compressive strength was 6,789 psi. (Appendix E).

The natural rock selected for the other test medium was a limestone deposit having horizontal beds. The limestone had a chemical composition of 78.75% calcium or magnesium carbonate plus impurities and a density of 162 pcf. (Appendix E). The deposit had some clay seams (Fig. 2), but an examination of the area indicated that the

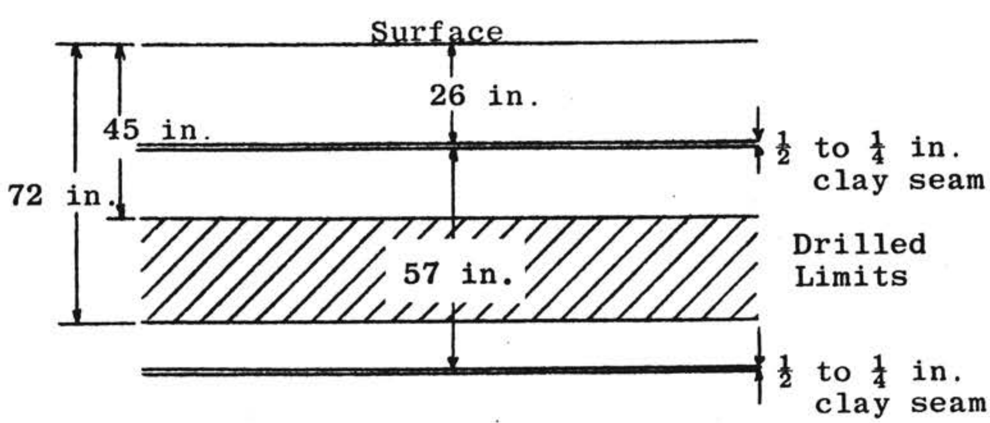

Fig. 2 Cross Section Through Limestone

bed and seam thicknesses were essentially uniform. The drilling reached a maximum depth of sixty-three inches so that each hole passed through two seams.

Operator Proficiency

Both Mr. Kavanaugh and the author were inexperienced rock drill operators. It was considered probable that each would become more proficient as he gained experience and became familiar with the bahavior of the individual drill. To compensate for this increase in proficiency the order of drilling the holes was randomized. Each hole was assigned a number from one to forty-nine through a random process. The numbers were arranged in increasing size to determine the order in which the holes would be drilled.

Air Compressor

The two basic air compressors are the reciprocating and the rotary types. The reciprocating compressor operates much the same as a two-cycle gasoline engine. The pistons may compress air while moving in only one or both directions. The pressure is regulated by a throttle control that opens the throttle when the receiver goes below a certain specified pressure and closes the throttle when a second and higher specified pressure is reached. This causes the engine to alternate between idle and full throttle. Fluctuations caused by the piston strokes and the alternating between idle and full throttle would create difficulty in stabilizing the regulator and reading pressures gages.

The rotary air compressor has an eccentric shaft rotating within a cylinder. Vanes radiating from the inner shaft form a seal against the cylinder wall. As the shaft rotates the volume enclosed by the shaft, the cylinder and the vanes become progressively smaller until the discharge port is reached. The pressure of the rotary compressor is regulated by the engine speed. As the pressure drops, a pressure-sensitive diaphragm increases the engine speed to compensate for the change. Therefore the rotary compressor will always try to reach an equilibrium speed that satisfies the demand.

An Ingersoll-Rand "Gyro-Flo" 600 cfm portable type air compressor was used as the primary source of compressed air on the project. The "Gyro-Flo" was a rotary type so it did not have the fluctuations associated with the reciprocating type.

The medium class drifter requires less than three hundred sixty-five cfm at ninety psig (8). But since the drills would be operated at pressures as high as one hundred ten psig, a larger compressor was used to assure the availability of higher pressures.

The medium class jackhammer was supposed to use less than one hundred five cfm at ninety psig (8). Therefore, a Chicago Pneumatic, 125 RG-2, rotary air compressor was believed to be an adequate source of air for the jackhammer during strain measurements. This compressor was unable to operate the jackhammer at any pressure higher than ninety-four psig.

Air Pressure Range

The portable air compressor, common to the rock drilling field, was designed to produce one hundred pounds per square inch gage (psig) pressure under normal conditions. The safety valves were set to release around one hundred twenty-five psig. Assuming a ten per cent friction loss, the maximum pressure at which the drill would normally operate would be around ninety psig. The maximum pressure obtainable would be 112.5 psig under the same conditions. Therefore the top limit on the pressure range was established only by the compressor capabilities.

The Compressed Air and Gas Institute (8) recommended that eighty to ninety psig pressures be used in operating construction tools, hand held rock drills and small drifters. Drifters and blast hole drills with four inch cylinders or larger should have ninety to one hundred psig for the best performance. Also, increasing the air demand on an air compressor may reduce the air pressure available for operation to below the recommended pressures. With this in mind a lower limit of fifty-five psig was selected to represent a point well below the optimum and below the pressures expected after losses due to friction, air leaks and overloading.

An incremental change in pressure of five psig was arbitrarily selected as one small enough to cover fluctuations yet large enough to cause changes in drilling rates. A five psig change is equal to eight and one-half per cent of the range from fifty-five to one hundred ten psig.

Drills

Basically drills may be separated into two categories, the hand held drill and the mechanically mounted drill. It was desired to select a representative from each of these categories for testing. The medium class jackhammer seemed to be the most versatile and also the most common of the hand held drills. An Ingersoll-Rand J-40 (Fig. 3) was selected since it was in the forty-five pound class and seemed representative of the other drills.

Fig. 3 Jackhammer, Drill Steels and Bits

The medium class was also selected to represent the family of drifter drills. In this category a Gardner Denver DH 123-J drifter mounted on a Gardner Denver AT-1500 track mount (Fig. 4) was chosen. It had a four and one-half inch bore and was one of the larger drifters in the medium class. The track mounting was selected to facilitate moving the air compressor as well as the drill around the test area.

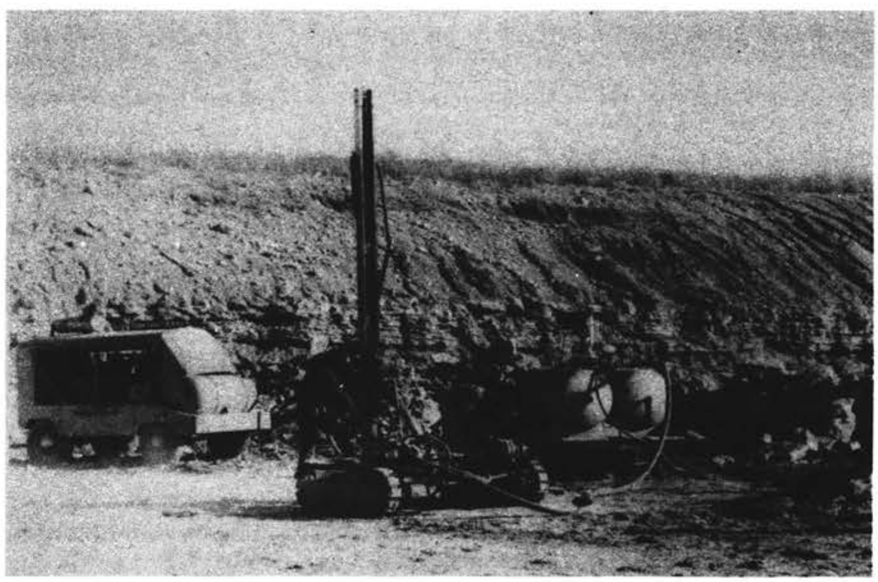

Fig. 4 Drilling in Limestone Quarry

Drill Steels

Material imperfections or dimensional variations could cause two drill steels having the same external appearance to transmit energy in a different manner and, therefore, yield a different drilling rate. To prevent this each steel was stamped with an identifying mark, and the same steels were used throughout the test. Because of wear against the sides of the hole the steel's behavior was expected to change. The effects of this change were assumed to be distributed in the same random pattern as the order of the drilling.

The shape of the steel remained constant throughout the drilling so no variation was expected. This was listed on the data sheets for information only.

Bits

It has been stated that a carbide bit will outlast a steel bit by at least thirty to one (2). With this in mind carbide bits were the only logical choice for research in rock drilling. The wear on these bits was assumed to be negligible for the short distances, approximately ninety feet, that they would drill. To confirm this assumption a record of the loss in gage was kept on the three inch bits. The average total loss in gage was 0.004 inches or approximately 0.00016 inches per hole.

Acknowledging the possibility that the carbide bits could have significant wear and also that the rate of wear could vary with the operating pressure, each bit was marked and exposed to identical conditions. Since there were four three inch bits and four holes drilled at each pressure, each bit was used only once at each pressure. Therefore any variation in rate of wear due to different pressures would be random since the order of drilling was randomized.

There were only three one and one-half inch bits so each bit was used once at each pressure. The fourth bit out was selected through a random process.

Air Holes

W. R. Cheetham and E. W. Inett had stated that

> ...in order to maintain good drilling performance it is essential that the rock debris formed at the bit edges be removed as soon as it is formed. Failure to do this causes clogging of the cutting edges with consequent loss of efficiency due to further pulverization of material already broken from the rock face, increased resistance to rotation and reduction in drill steel reaction (6).

Two of the factors affecting the removal of cuttings are the location and number of air holes in the bit. Variations in these may cause corresponding variations in drilling speeds. In order that these might be considered, the number and location of the air holes in the bits was recorded on each sheet.

Air Pressure Regulator

The regulator required for this work had to have a rapid response to pressure changes and be able to control the pressure to within two pounds of that desired. A Fisher "Wizard Pilot" (Fig. 5) differential pressure regulator was selected to control the pressure entering the auxiliary receiver tanks. This regulator had a bourdon tube with a range of zero to two hundred fifty psig. Its sensitivity was two per cent of the bourdon tube range or five psig. The inner valve was a double port throttle plug capable of passing up to one thousand three hundred cfm at a pressure differential of five psig and an inlet pressure of one hundred fifteen psig.

Fig. 5 Air Pressure Regulator

Air Pressure Recorder

Since the regulator required a five psig pressure change before responding and the air demand was expected to increase from zero to a maximum almost instantly, a pressure drop was expected each time a test was started. To determine the magnitude and the duration of that drop a pressure recorder was integrated into the system. An American Meter Co. recorder (Fig. 6) was connected to one of the auxiliary receivers. The recorder's range was zero to one hundred fifty psig with a sensitivity of one per cent of full scale deflection or one and one-half psig. It used twelve inch recording disks (Fig. 7) with two pound pressure increments and fifteen second time increments.

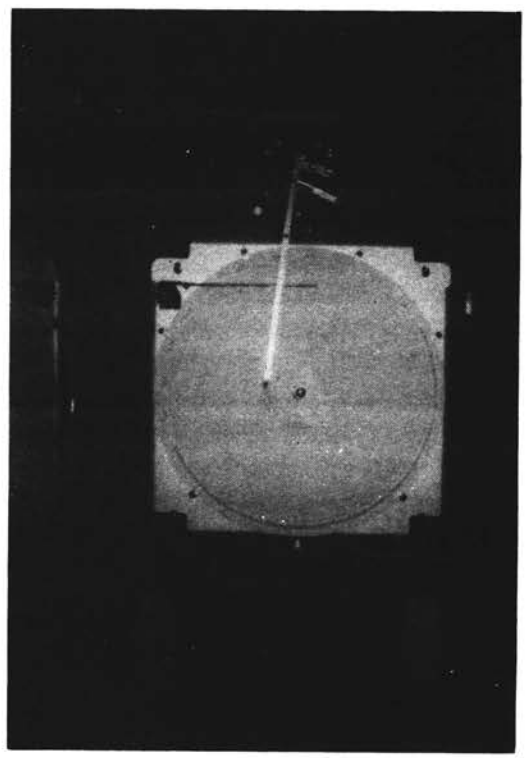

Fig. 6 Air Pressure Recorder

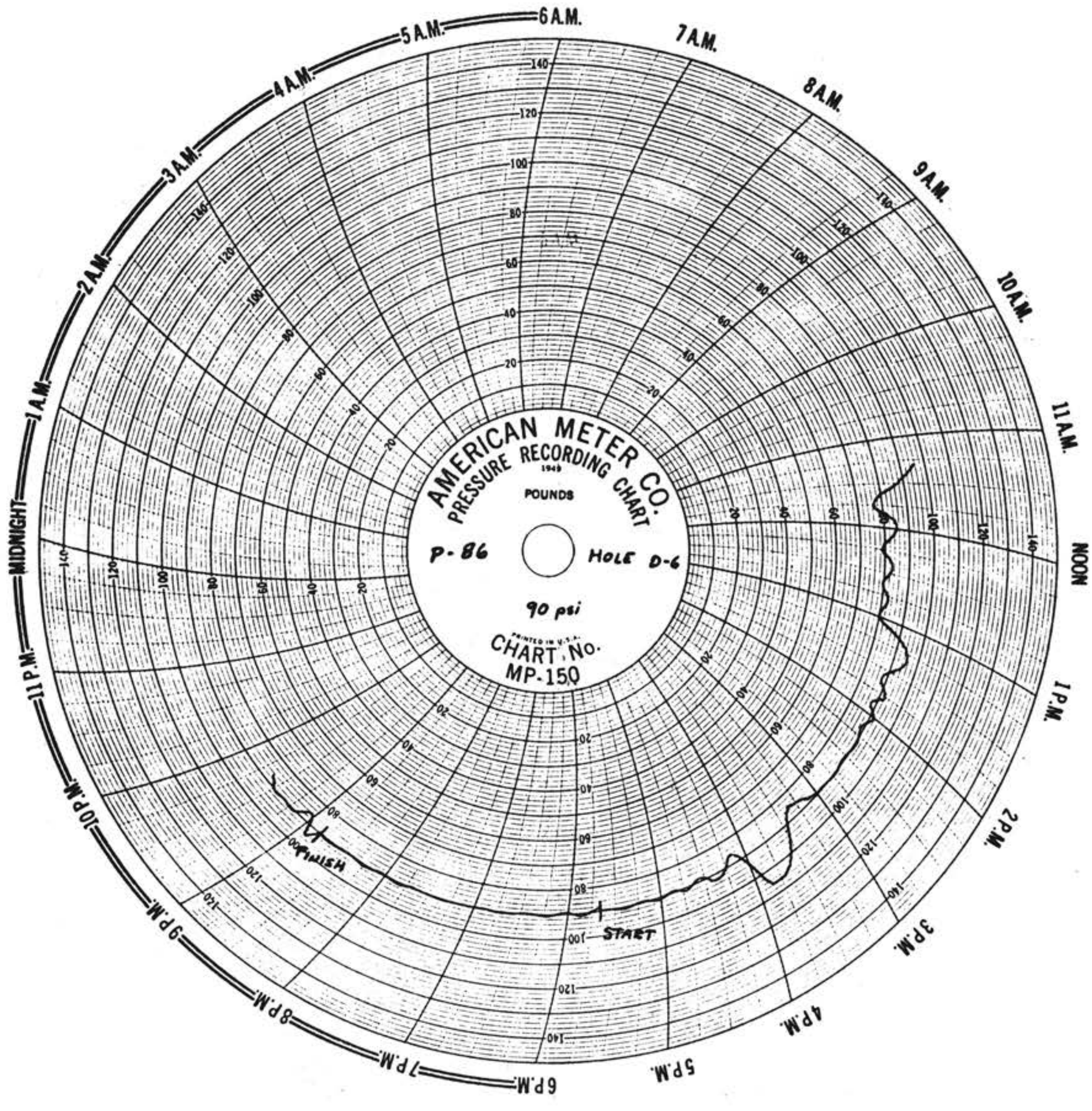

Fig. 7 Sample Air Pressure Recording Disk

Auxiliary Receivers

The 600 cfm air compressor had a receiver tank capacity estimated at twenty cubic feet. This was used to store air at high pressure behind the regulator. This storage served to reduce the effect on the regulator of the normal fluctuations in the air compressor output.

To dampen the rapid change in the air demand when the drills were started, two auxiliary air receivers were placed between the drills and the regulator. Each receiver had a capacity of fifty cubic feet, making a total capacity of one hundred cubic feet at the desired air pressure. These receivers reduced the vibrations transmitted from the drill piston and also removed additional water from the compressed air before it reached the drills.

Measurements

The linear rate of drilling was determined by measuring the start and finish depths of each test hole and the time required to drill the distance between these depths. This measurement technique was tested prior to the actual work, and the results were found to be easily reproduced to within one-sixteenth of an inch.

Several methods of determining the volume were considered before a final decision was made. The basic choice was between measuring the depth and diameter to compute the volume and using a direct measurement method like a fluid or

Ottawa sand. The direct method was expected to be the most accurate, but it required a quantity of materials and equipment. A three inch hole sixty-three inches deep required one-fourth of a cubic foot of sand or approximately two gallons of fluid. Removing the sand to allow for additional drilling would be difficult without wasting the entire lot. If fluid were used, a membrane would be required to prevent leakage into the limestone seams.

In view of these difficulties with the direct method of ascertaining the volume, the inside diameter was measured at the beginning of each hole. An assumption was made that the relationship between the hole diameter and the bit diameter would not change between the start and finish of each hole. Therefore the bit's gage was measured at the beginning and end of each hole to determine the amount of taper in the sides of the hole.

TABLE I

METHODS OF MEASUREMENTS

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 machinist's rule
Bit Diameter	In.	Micrometer

Reference Line

A reference line for measuring the depth of the holes was improvised by stretching a wire across the center of a three-legged ring stand. (Fig. 8). One side of the ring was marked, and all readings were taken from that side.

Fig. 8 Measuring Stand

Thrust

W. R. Cheetham and E. W. Inett (6) had established that the thrust had a definite effect on the drilling rate. In this work the only thrust was the actual weight of the drill. The operator kept the drill aligned with the hole and did not exert any downward force.

Operator

To reduce variations in proficiency and thrust the same operator was used for each complete phase of the test. That is, Mr. Kavanaugh operated the drifter, and the author operated the jackhammer for the drilling of all holes in the concrete block. This procedure was reversed when operations were moved to the limestone quarry. The initials of the operator, timer and recorder were indicated on each data sheet.

Temperature

Below freezing temperatures were expected during the time alloted for drilling, and the exact effects of the temperature on drilling rates were not known. Therefore a record of the temperature was kept for each hole. The recorded temperatures were averaged for each pressure and compared to the plotted data to detect any correlation between the temperature and drilling rates.

Data Sheet

A sample data sheet is shown in Fig. 9. The heading and general information were placed at the top of the sheet. The actual data blanks were arranged on the bottom portion so as to facilitate the analysis of the raw information. One

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 ϕ　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

data sheet was used for each hole drilled.

Strain Gage Circuit

One method of determining the change in energy with respect to air pressure was measuring the total compressive stress at any given point in the drill steel. This value might not represent the maximum stress in the steel, but it would reflect the amount of change in stress due to a change in air pressure. Since the drill steel rotated during operation, the lead-in wire from the gages was shielded and allowed to wind onto the steel. The number of leads was reduced to two shielded strands to facilitate handling.

The strain gages were placed on the steel directly opposite each other and connected in series so that there were only two leads. (Fig. 10). This cancelled the effect of bending.

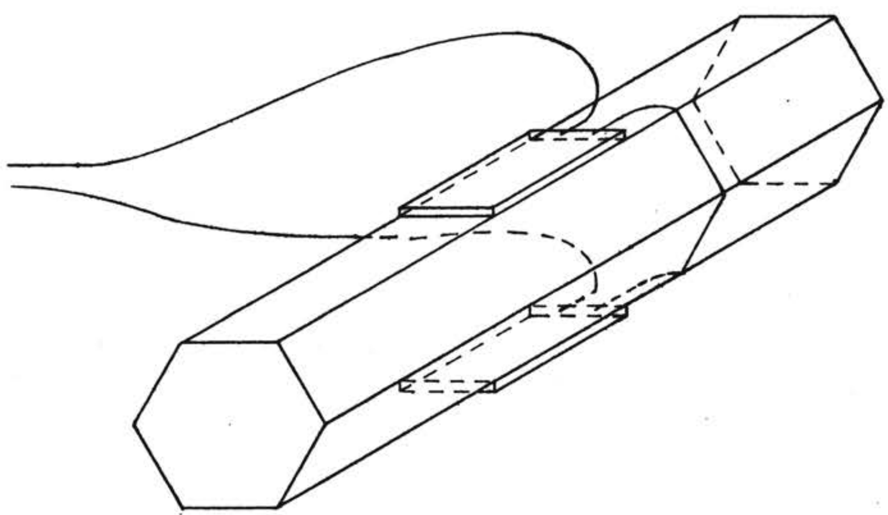

Fig. 10 Strain Gages Mounted on Drill Steel

The ballast circuit (Fig. 11) and the bridge circuit (Fig. 12) are the two basic circuits used in dynamic strain measurements. Since there were only two leads from the drill steel, only one leg of the bridge circuit could be used. This caused the bridge circuit to have the same sensitivity as the ballast circuit; thus, either circuit was acceptable. A bridge circuit was available in the form of a BAM-1 strain amplifier and was used in the research. The strain gages were connected in series and then placed in one leg of the bridge in the BAM-1. Two variable resistors were used in the temperature compensating leg of the BAM-1 bridge. This was possible because the dynamic strain levels were so short that temperature would not affect the results as in static strain measurements.

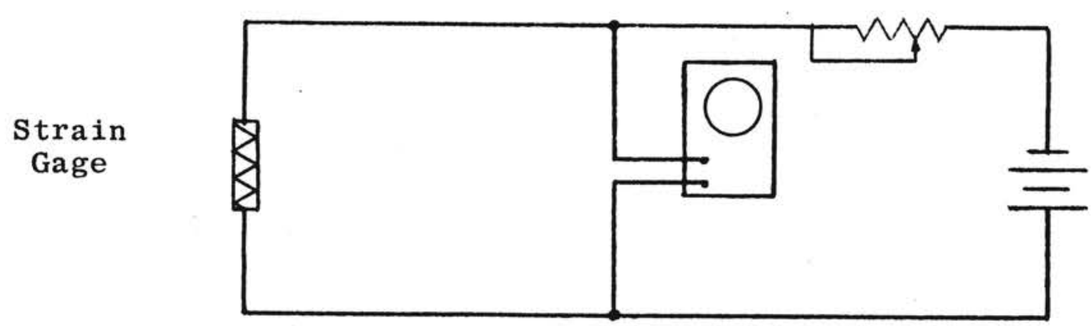

Fig. 11 Ballast Circuit

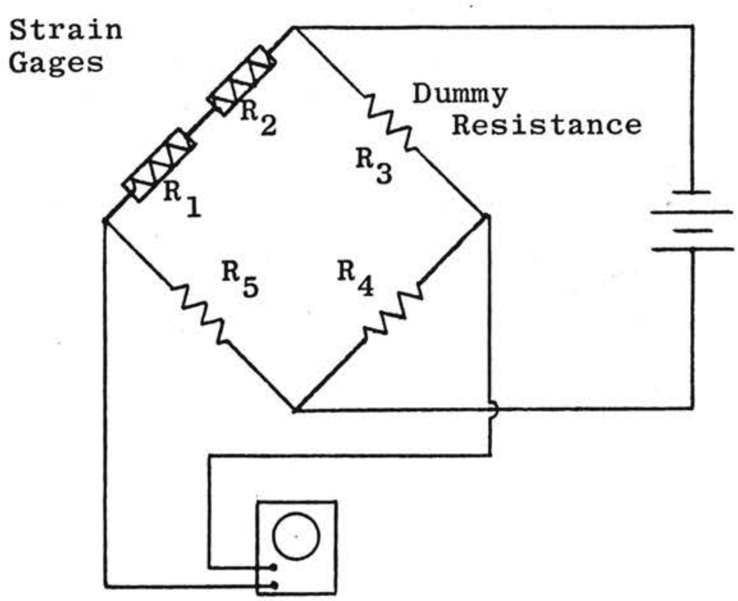

Fig. 12 Bridge Circuit

Strain Gages

Foil gages were attached to the drill steel for the initial investigation of the internal strain conditions. For some unknown reason these gages broke between the solder tab and the gage. In spite of decreasing the amount of solder and the size of the lead-in wire the gages continued to break. Wire wound gages were then tried and found to work satisfactorily. Therefore Baldwin-Lima-Hamilton SR-4 gages were used for the strain measurement.

Strain Measurements

Rock drills operate around two thousand blows per minute or thirty-three cycles per second (9). A twenty-four inch long drill steel has a natural frequency of around four thousand to five thousand cycles per second. (Appendix B). The author felt that it would be desirable to see the way these vibrations were damped within the steel.

For these measurements a heated-stylus oscillograph and a cathode ray oscilloscope capable of indicating the dynamic strain conditions were available. The inertia of the stylus limited the oscillograph to a maximum of one hundred cycles per second, and, therefore, the use of a Tektronix Model 502 dual beam oscilloscope was favored. A Polariod camera was attached to the scope to make pictorial recordings of the strain levels. (Fig. 13).

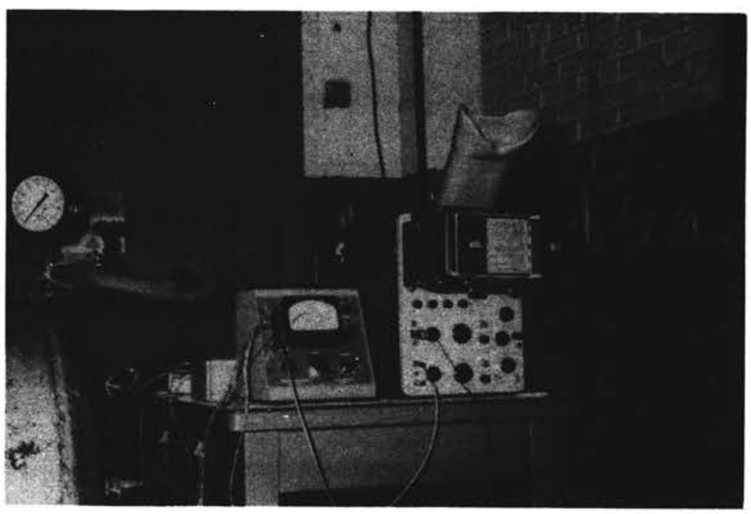

Fig. 13 BAM-1, and Oscilloscope With Polaroid Camera

The actual selection of equipment was a process of comparing the desired specifications to the available equipment and reaching a suitable compromise. In all but one case the resulting equipment, borrowed from industry, either reached or exceeded the requirements. The one exception was a track-mounted, medium sized drifter which had received more use than was desirable.

Fig. 14 shows a diagram of the pressure generating and regulating system used in the project. Compressed air was fed from the air compressor receiver through a pressure regulating device. The regulator reduced the high pressure from the air compressor to the desired pressure and fed it into the two auxiliary receivers. These receivers had outlets for both the two inch and the one inch air hoses. Air was sent through the minimum possible length of these hoses to the rock drills being tested.

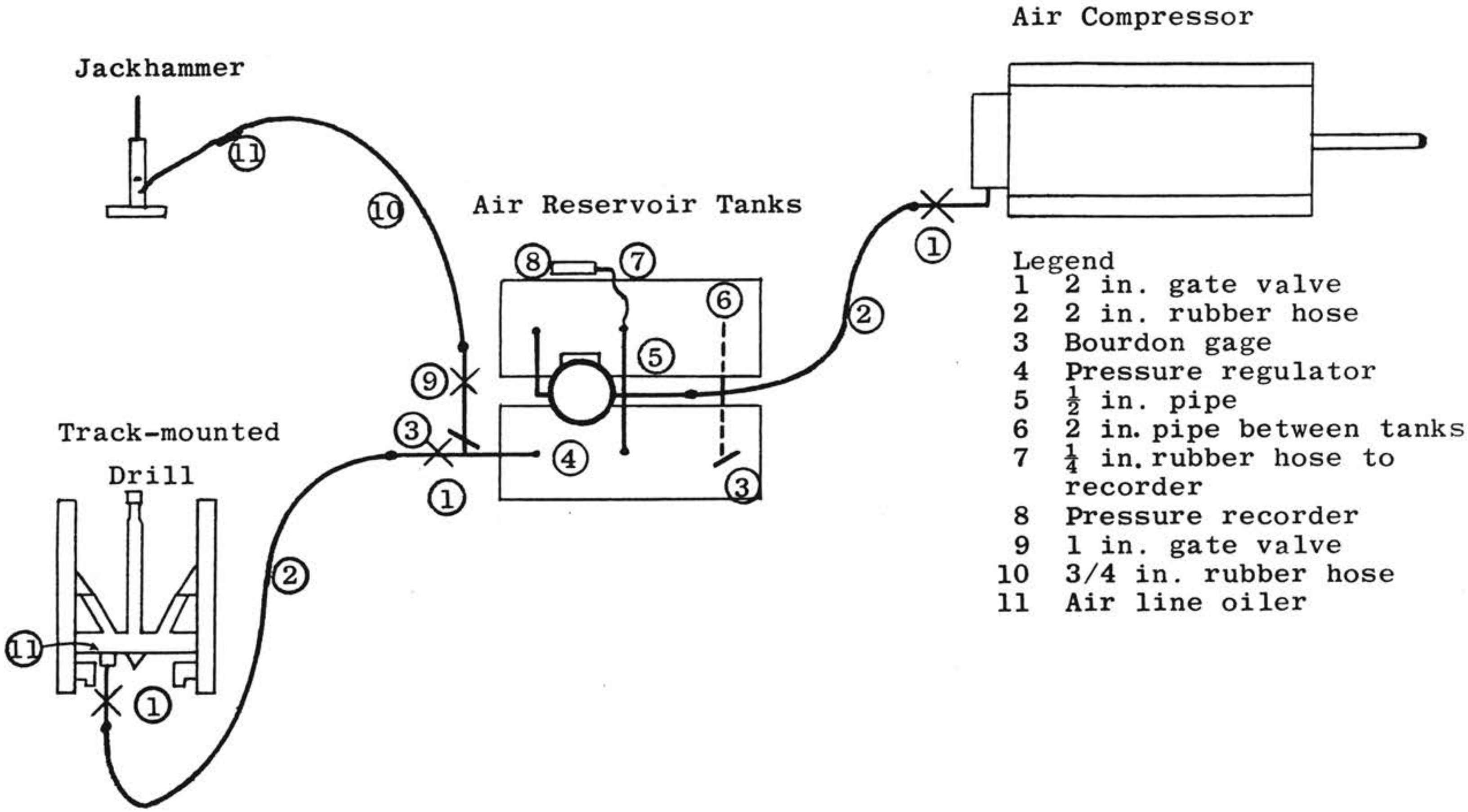

Fig. 14 Equipment Layout

CHAPTER IV

EXPERIMENTAL PROCEDURE

Before actually starting the drilling every piece of equipment was thoroughly checked and placed in the best possible operating condition. The pressure gages were calibrated using an Ashcroft Portable Type dead weight tester. Each bit and each drill steel was stamped with identifying marks. The hole numbers, order of drilling, bit numbers and operating pressures were placed on the data sheets. The hole pattern was layed out on the test block with two inch deep marking holes for every test hole. One and five-eighths inch steel bits were used for this.

Each day the pressure recorder was checked with the calibrated gage by filling the auxiliary receivers and, while slowly reducing the pressure, comparing the recorder with the gage. The water was drained out of each receiver daily.

Empirical Tests

A general procedure was established and followed during the drilling test with the drifter and the jackhammer. The following procedures for the drifter were enumerated for clarity although they were not used as a checklist:

1. One of the valves on the auxiliary receiver was opened to create enough demand to open the regulator valves.
2. The regulator was set at approximately the pressure desired and left to stabilize.
3. The bit gage was measured and recorded.
4. The bit and drill steel markings were checked against the data sheet.
5. The drill was plumbed and centered over the correct hole.
6. The bit was "collared" by operating the drill at one-half throttle and allowing the bit to drill five or six inches.
7. The bit was withdrawn and the cuttings blown away from the hole.
8. The ring stand was centered over the hole, the position of its legs marked and the depth of the hole measured. This was done by passing a steel tape, mounted on a wooden rod, through the ring stand so that the reference wire was across the face of the tape. The hole was measured at the center and both sides. The results were averaged and recorded.
9. The diameter of the collaring hole was measured near the bottom with inside calipers. The diameter was determined by placing one leg of the calipers against a positive stop on a machinest's rule and

reading the location of the other leg. This value was recorded on the data sheet.

10. While the measurements were being made, the man designated as recorder adjusted the regulator to the exact pressure desired.
11. The drill operator lowered the bit into the hole so that it supported the entire weight of the drifter. He then signaled the recorder that he was ready.
12. The recorder watched the air pressure rise and signaled the operator to start when it reached the desired level. Simultaneously he started the stop watch and immediately marked the position of the stylus on the pressure recording disk. He then recorded the time and temperature and adjusted the amount of air being bled from the receivers.
13. The operator controlled the drill to keep the entire weight of it on the bit at all times. (While working on the Oklahoma State University campus it was difficult to be certain that there was no positive downward pressure from the feed chain. Prior to drilling in the limestone the feed chain was disconnected from the bottom of the drifter so that it would be impossible for it to exert any additional downward force.)
14. While the drill was operating, the recorder noted the maximum and minimum gage pressures at the

auxiliary receivers.

15. As soon as the drill stopped, the recorder stopped the stop watch and marked the stylus position. The stop watch reading was recorded on the data sheet.
16. The operator measured and recorded the depth of the hole in the same manner as in 8. above.
17. The recorder measured and recorded the bit gage and determined the average pressure reading from the recording disk.

With few exceptions the jackhammer procedures were the same as those listed for the track-mounted drill. The operator started with a two foot long drill steel and drilled to the maximum obtainable depth. Then the depth measurements and drilling time were recorded as with the drifter. The same bit was placed on the four foot steel, and the finish depth of the two foot steel was recorded as the starting depth for the four foot steel. When the four foot steel reached its maximum depth, the drill was stopped and the depth and drilling time were recorded.

Laboratory Tests

Before any drilling was done, the BAM-1 and the oscilloscope were turned on and allowed to warm up for at least one-half an hour. The scope was disconnected from the BAM-1, and the BAM-1's bridge power switch was turned off. The leads from the gages and the dummy resistors were connected to the BAM-1 completing the bridge circuit shown in Fig. 12. The balance control on the BAM-1 was adjusted until the meter needle remained at zero. The bridge power switch was then turned on and the BAM-1's balance control adjusted until the meter needle remained at zero. These steps were repeated until the meter needle remained on zero when the power switch was turned either on or off. The calibration button was pressed, and the calibration scales were changed until the meter showed a maximum reading. The meter reading and the calibration scale were recorded. The oscilloscope was connected to the BAM-1 and the horizontal axis on the oscilloscope screen adjusted to zero. The calibration button on the BAM-1 was pressed, and the displacement of the horizontal axis on the screen was measured and recorded.

The laboratory procedures for measuring the strains are enumerated below:

1. The drill operator adjusted the regulator to the desired pressure.
2. The drill was placed in the hole with the strain gage leads unwound from the drill steel.
3. The oscilloscope was placed on single-sweep manual control.
4. The BAM-1 bridge was checked for balance by temporarily disconnecting the oscilloscope and checking the meter needle for zero with the bridge power switch on and off.
5. A Polaroid camera was set to time exposure and the

shutter opened.

6. The recorder signaled the operator to start drilling and controlled the leads as they wound around the drill steel.
7. When the drill appeared to be operating smoothly, the recorder flipped the reset switch on the oscilloscope causing a single sweep to cross the screen.
8. The drilling was stopped, and the screen grid was momentarily illuminated.
9. The shutter was closed. Then the Polaroid picture was developed and marked.
10. The operating pressure, oscilloscope sensitivity and sweep time per centimeter were recorded.

CHAPTER V

EXPERIMENTAL RESULTS

After all of the observed data was collected it was consolidated into tables to facilitate computations. (Appendix B). The observed data was then analyzed and the results placed in tabular and/or graphical form to be interpreted.

Figures 15 through 25 present the results of the empirical testing along with Tables II through V. The laboratory results are presented in Figures 26 through 31 and Tables VI and VII.

TABLE II

ACTUAL DRILLING RATES

Pressure	Concrete		Limestone	
Psig	Linear in./min	Volumetric in.^{3}/min	Linear in./min	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

TABLE II (Continued)

Pressure Psig	Concrete Linear in./min	Concrete Volumetric $in.^3/min$	Limestone Linear in./min	Limestone Volumetric $in.^3/min$
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
	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	26.85
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	29.08
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

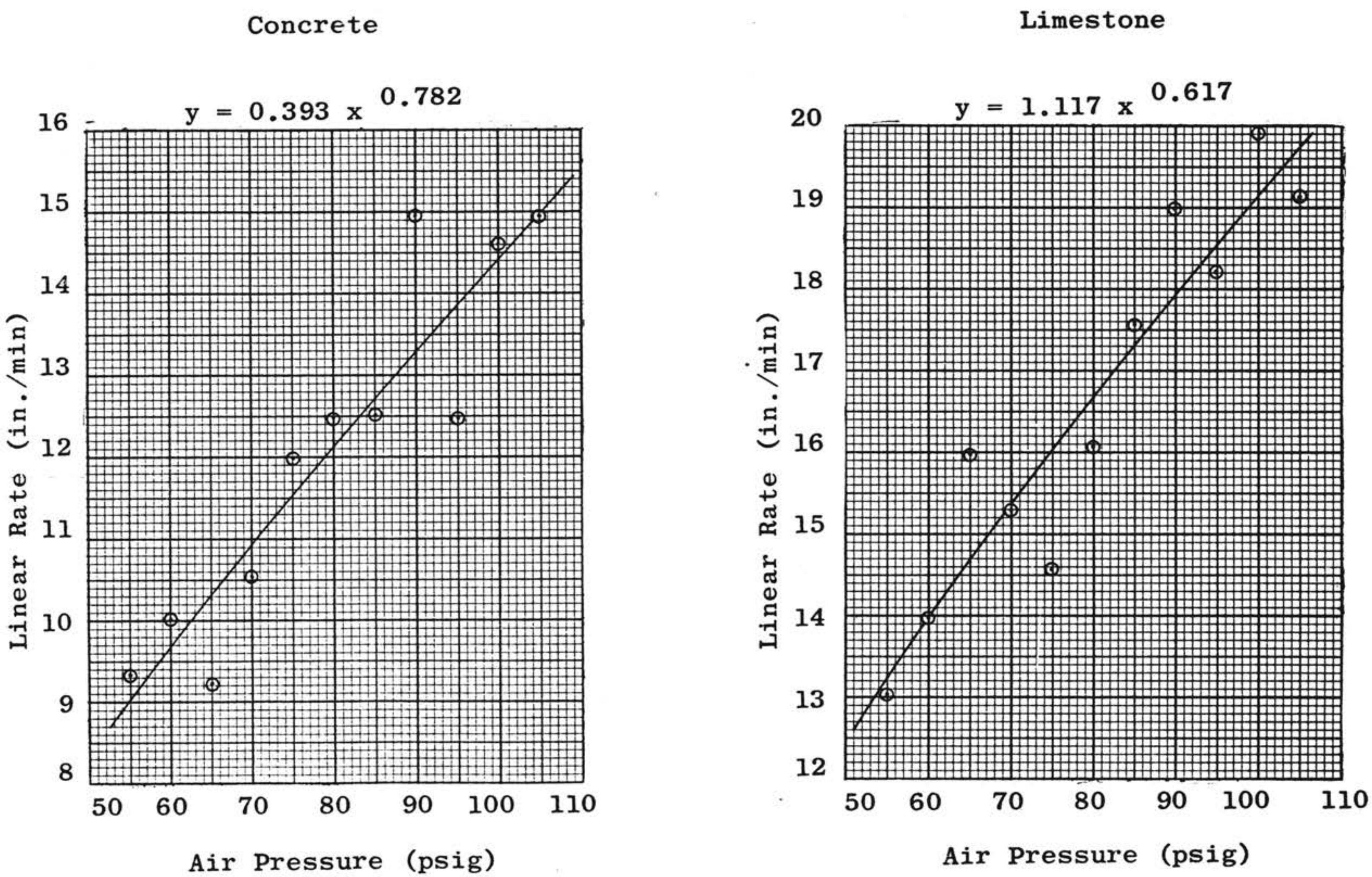

Fig. 15 Linear Drilling Rates for Track-Mounted Drill

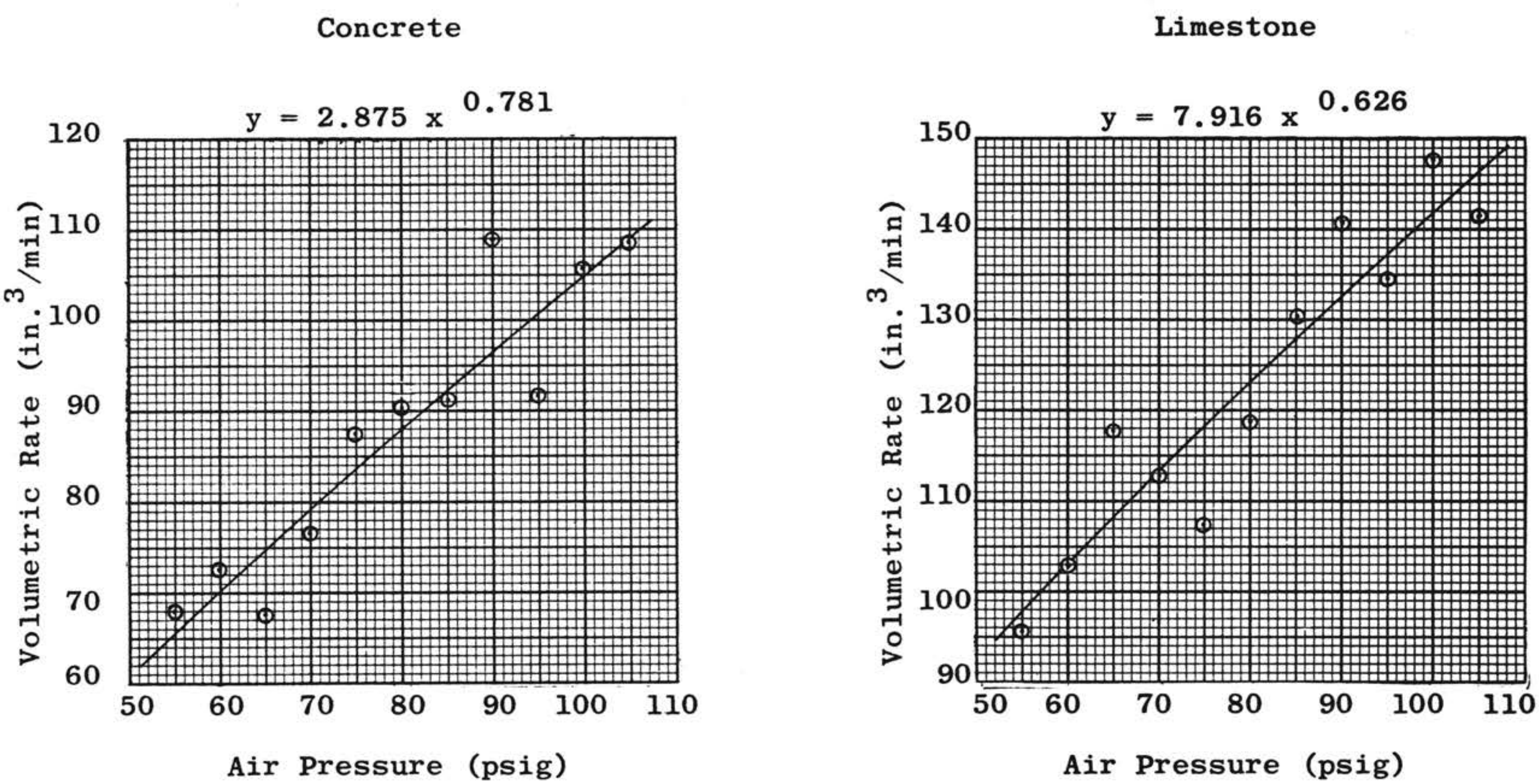

Fig. 16 Volumetric Drilling Rates for Track-Mounted Drill

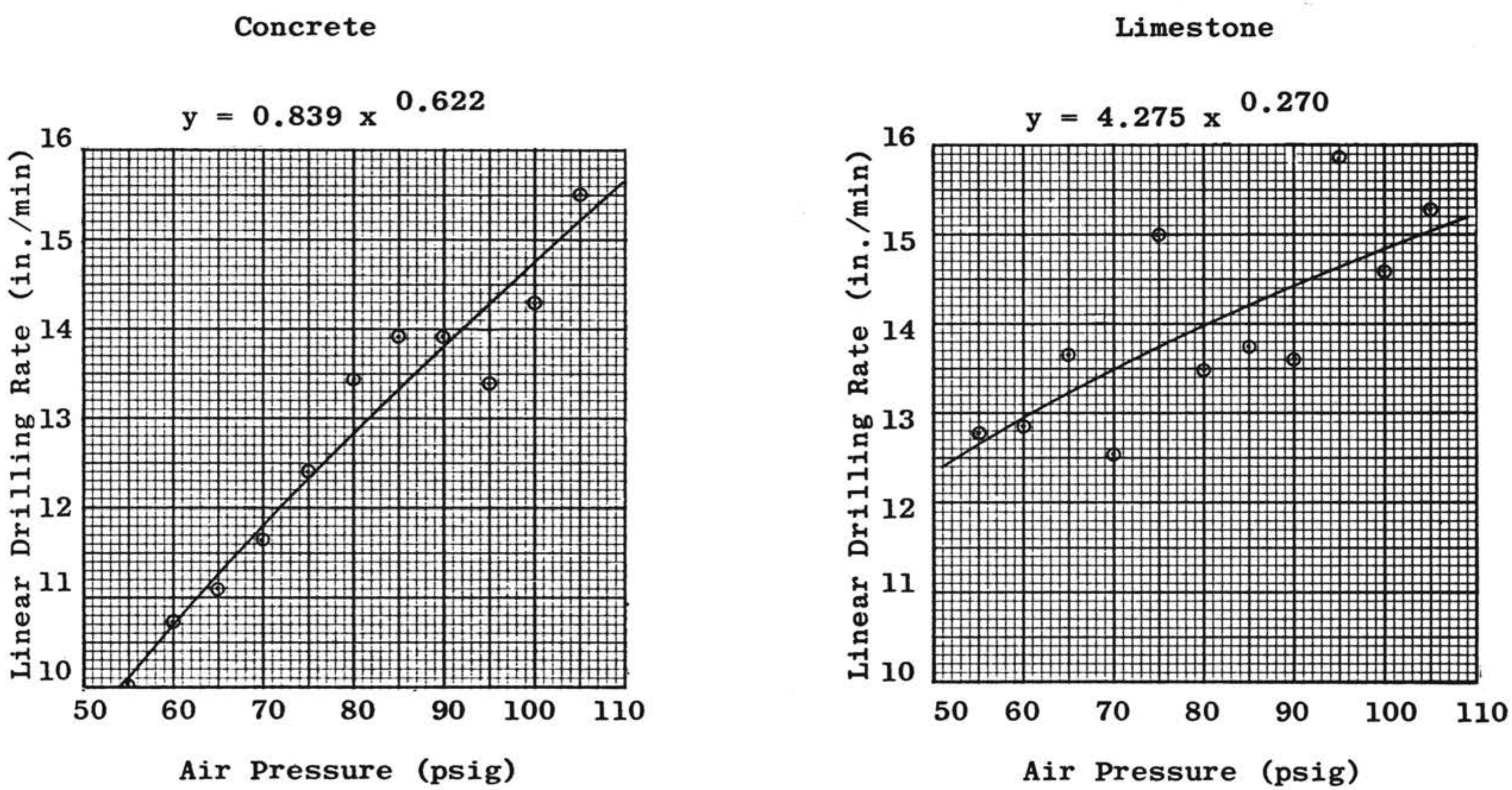

Fig. 17 Linear Drilling Rates for Jackhammer - 2 Foot Drill Steel

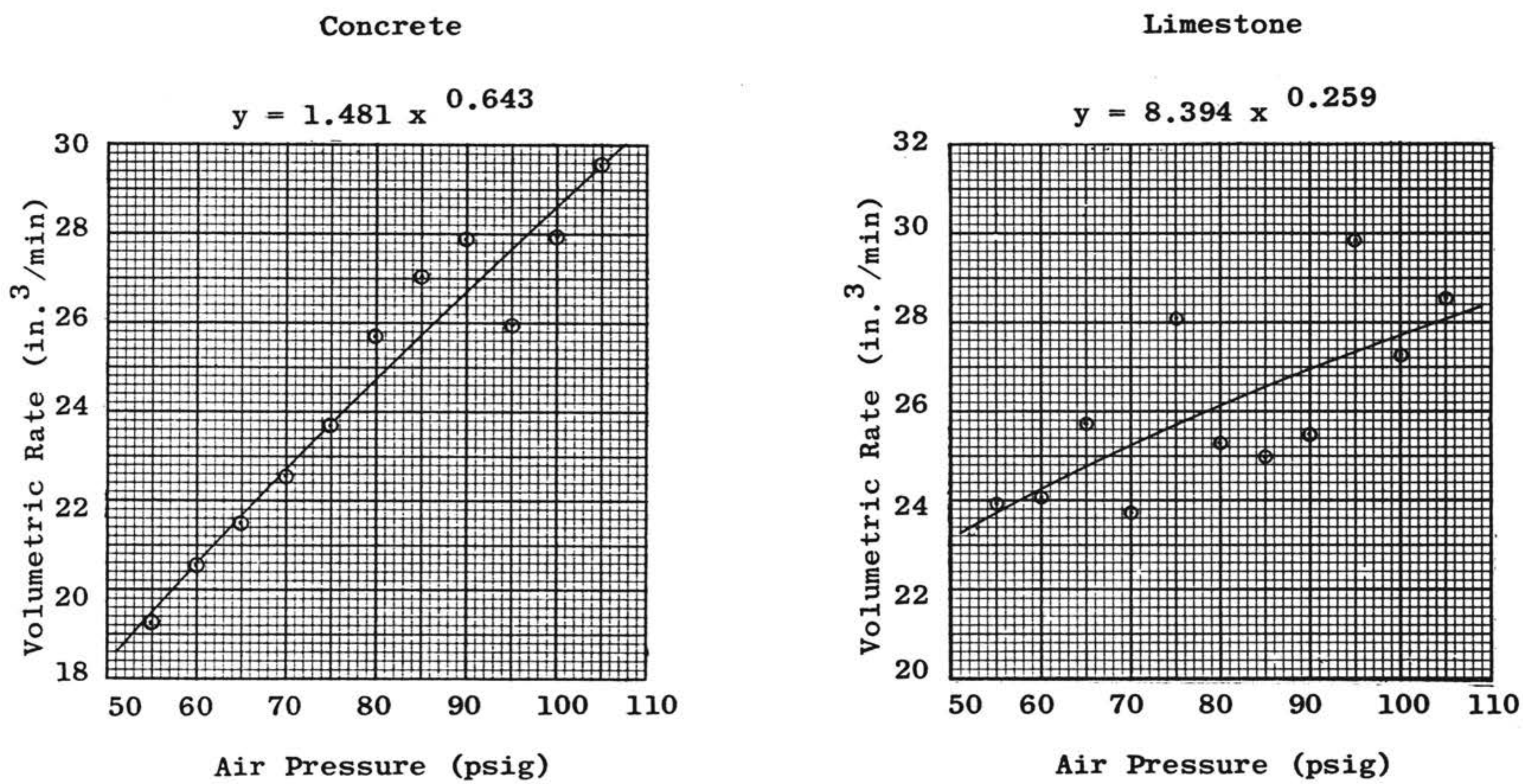

Fig. 18 Volumetric Drilling Rates for Jackhammer - 2 Foot Drill Steel

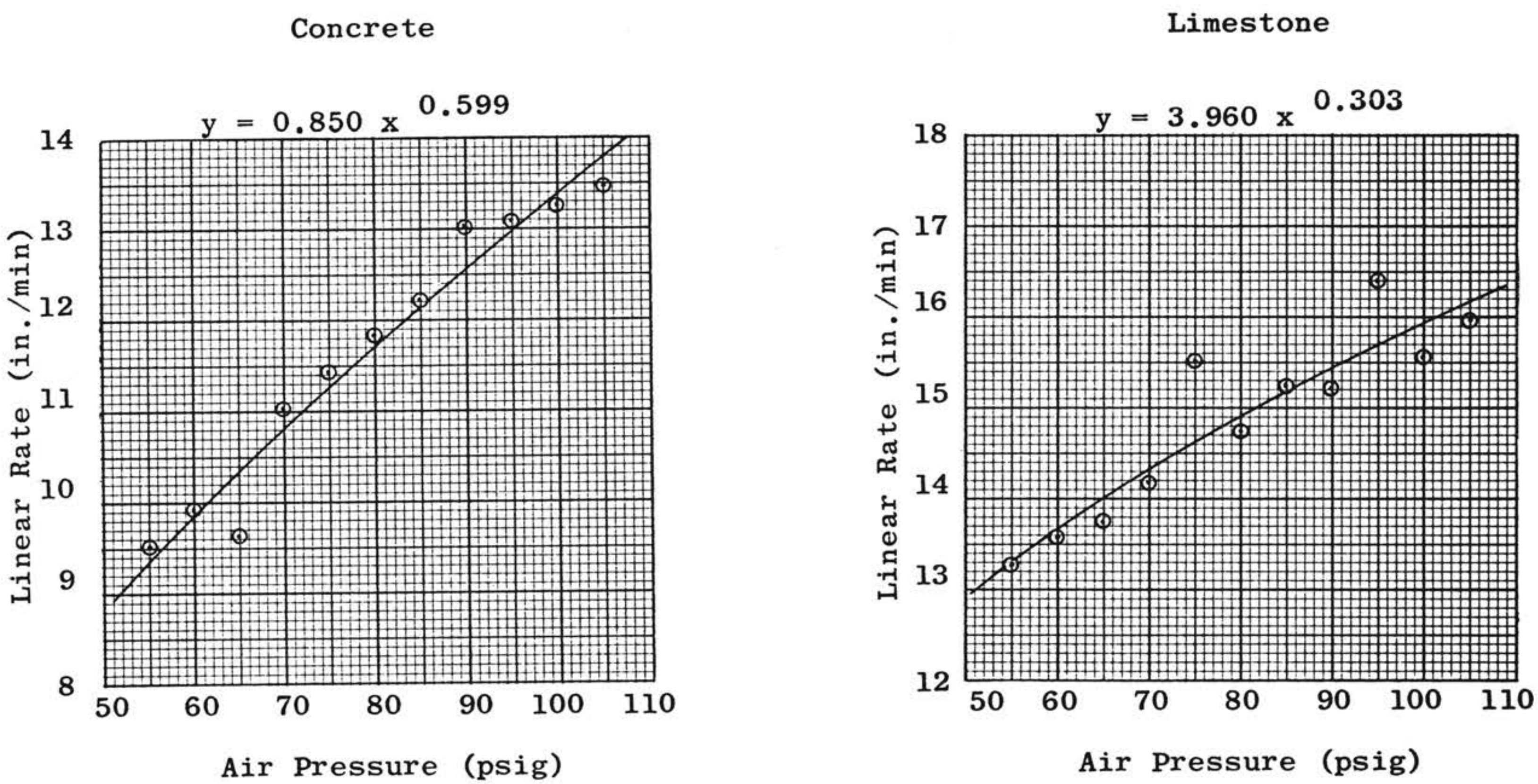

Fig. 19 Linear Drilling Rates for Jackhammer - 4 Foot Drill Steel

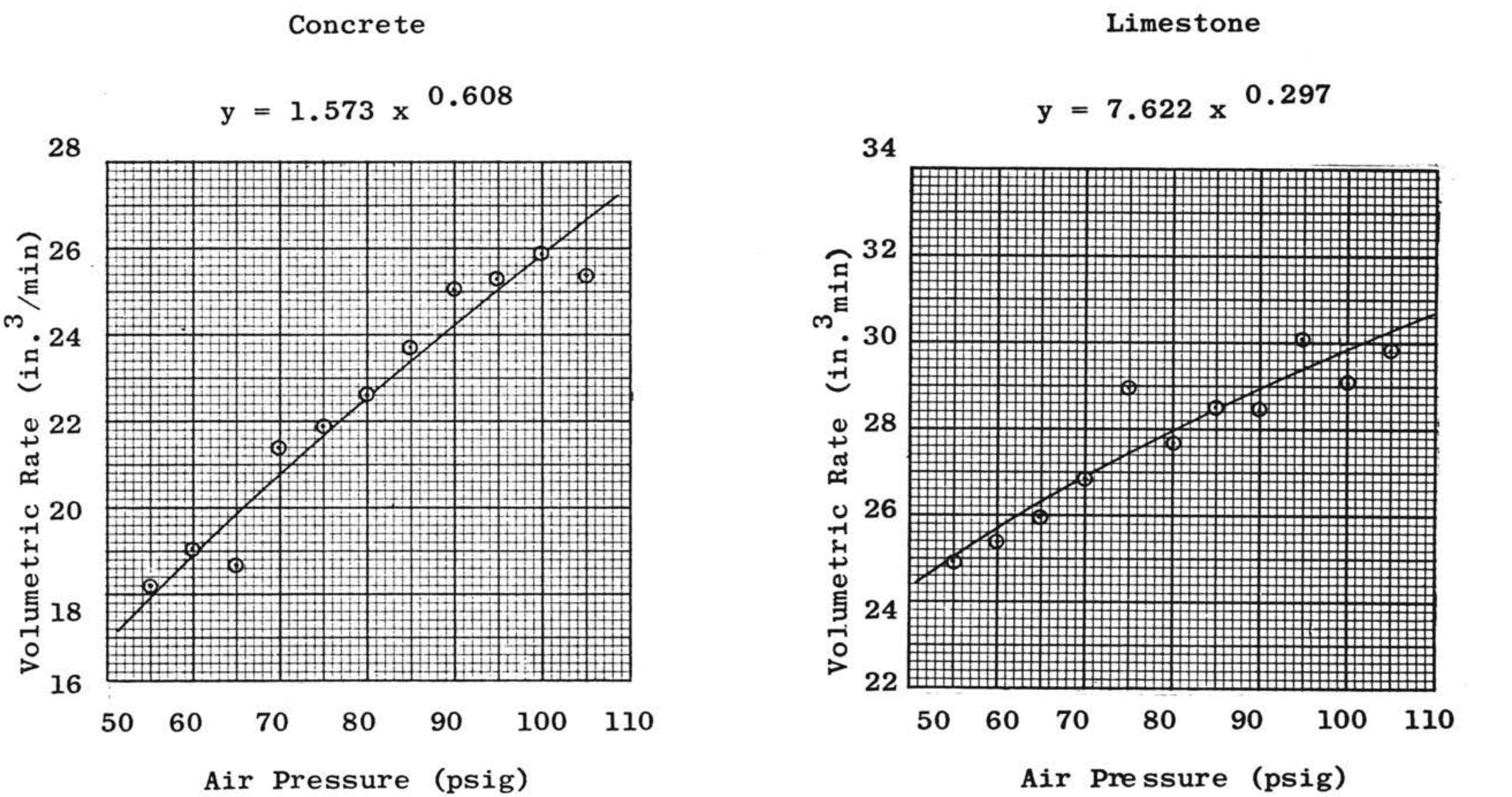

Fig. 20 Volumetric Drilling Rates for Jackhammer - 4 Foot Drill Steel

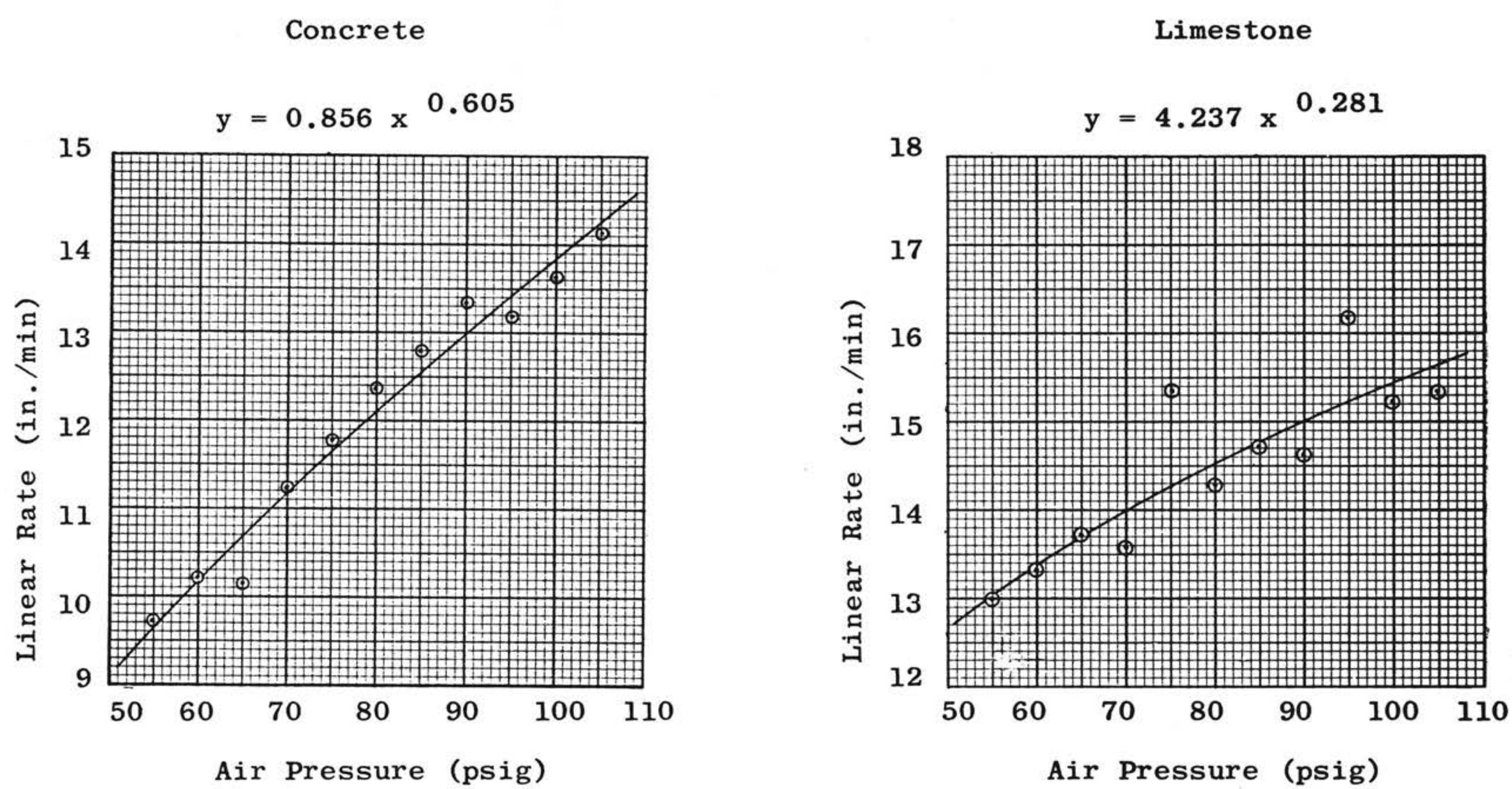

Fig. 21 Linear Drilling Rates for Jackhammer - 2 and 4 Foot Drill Steels

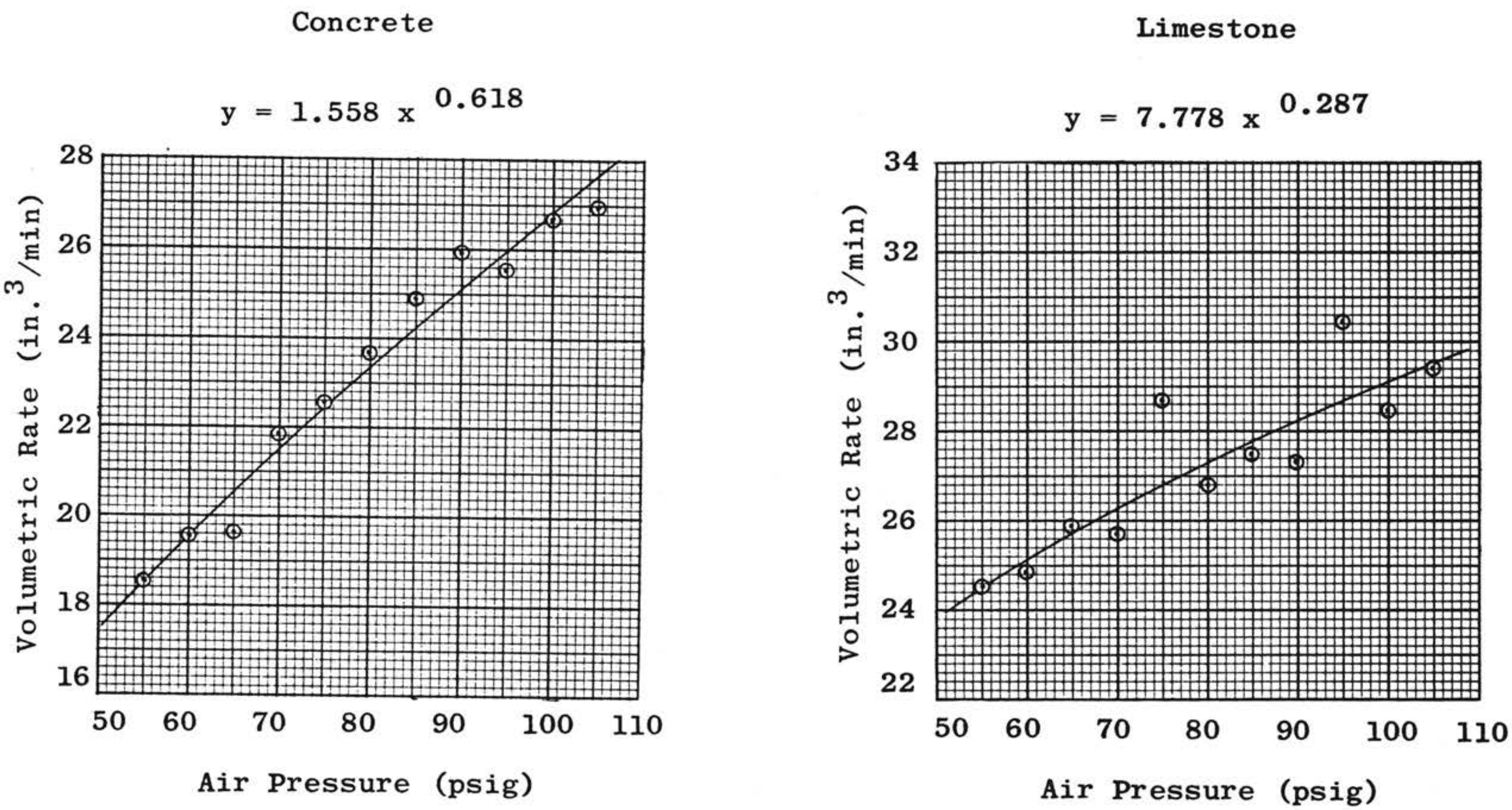

Fig. 22 Volumetric Drilling Rates for Jackhammer - 2 and 4 Foot Drill Steels

TABLE III

DRILLING RATES FROM CURVE OF BEST FIT

Pres psig	Concrete: Linear in./min	Concrete: Per Cent of 80	Concrete: Volumetric in.^{3}/min	Concrete: Per Cent of 80	Limestone: Linear in./min	Limestone: Per Cent of 80	Limestone: Volumetric in.^{3}/min	Limestone: 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

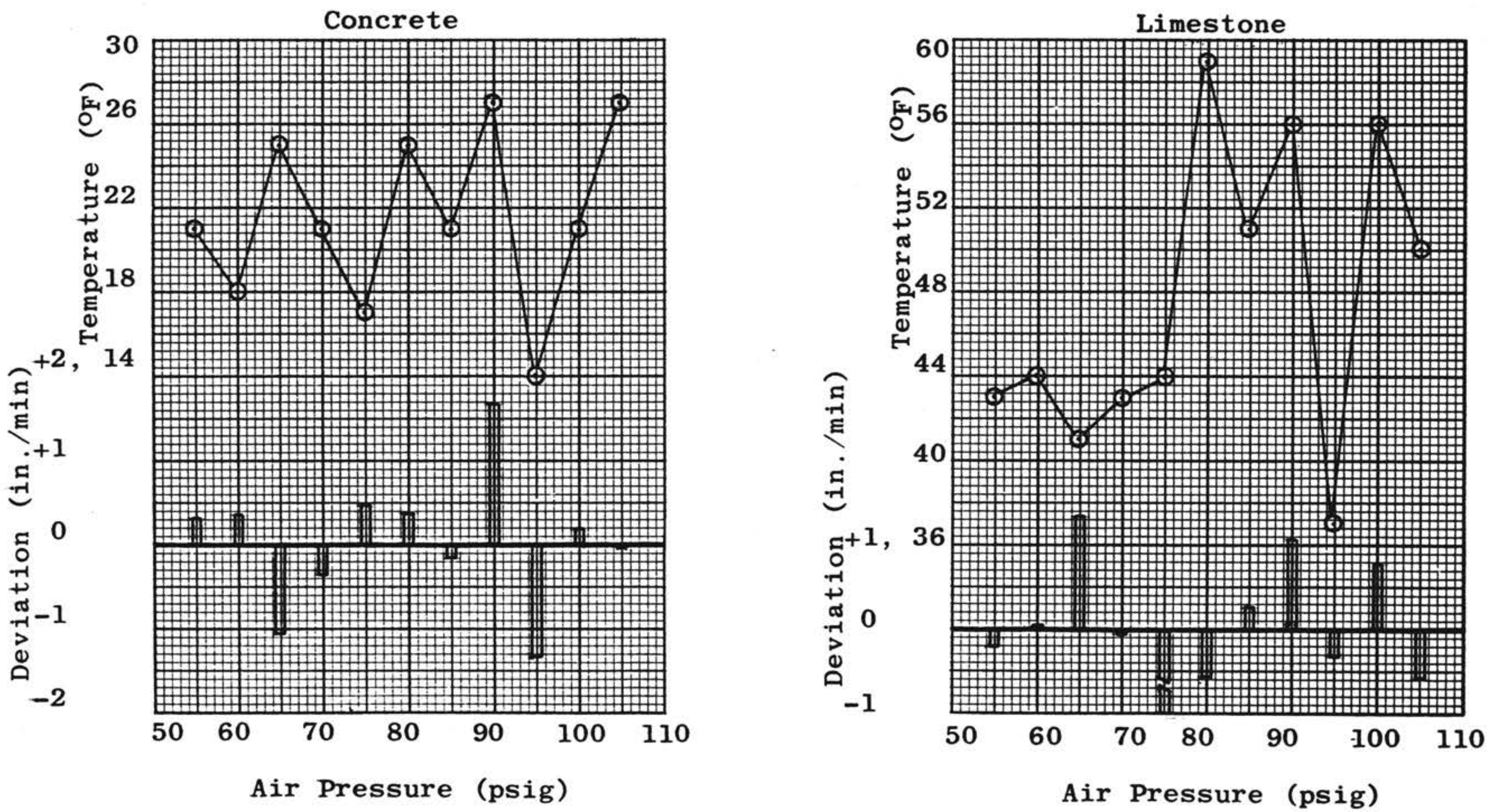

Fig. 23 Correlation Between Temperature and Air Pressure for Track-Mounted Drill

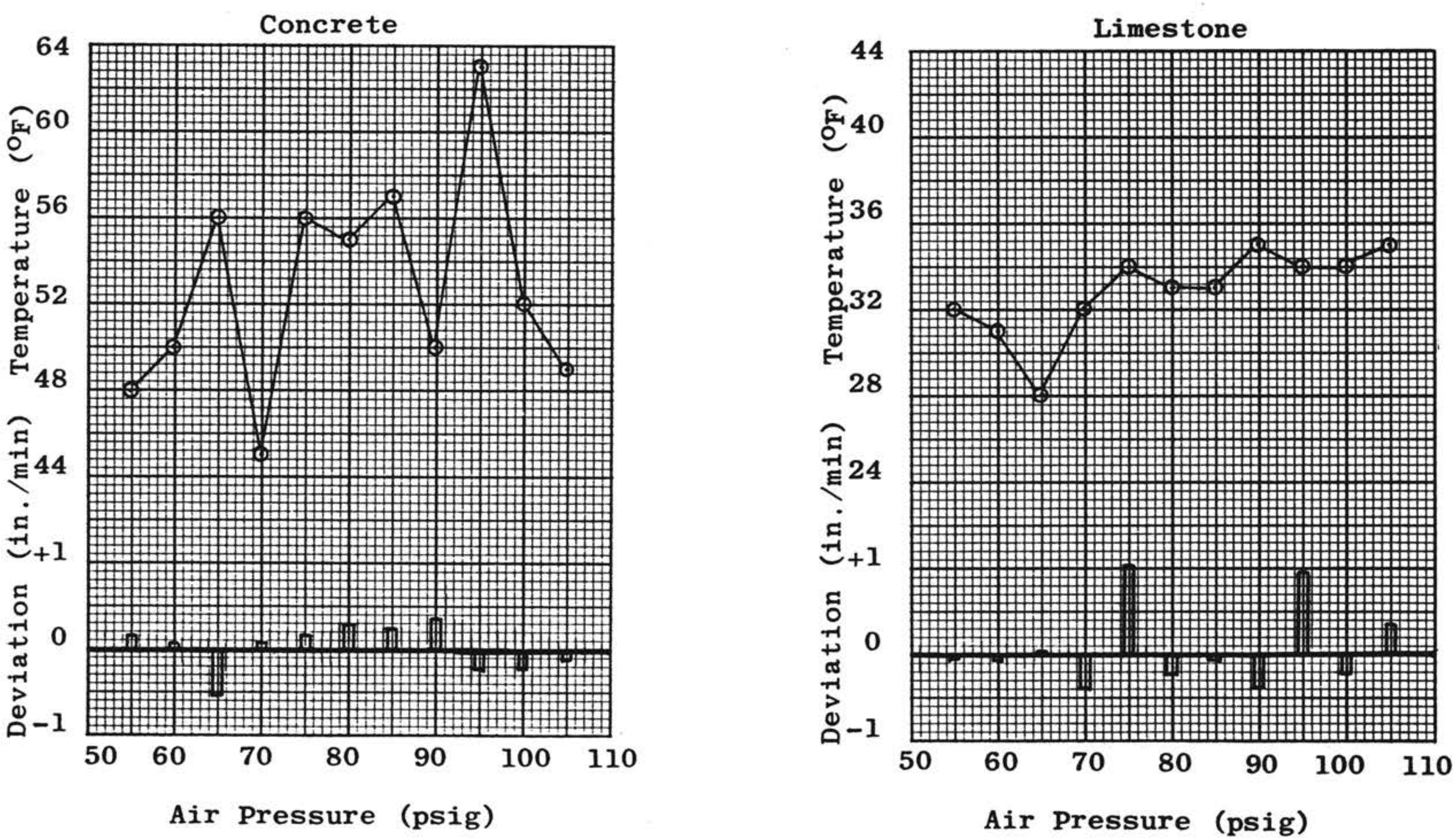

Fig. 24 Correlation Between Temperature and Air Pressure for Jackhammer

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

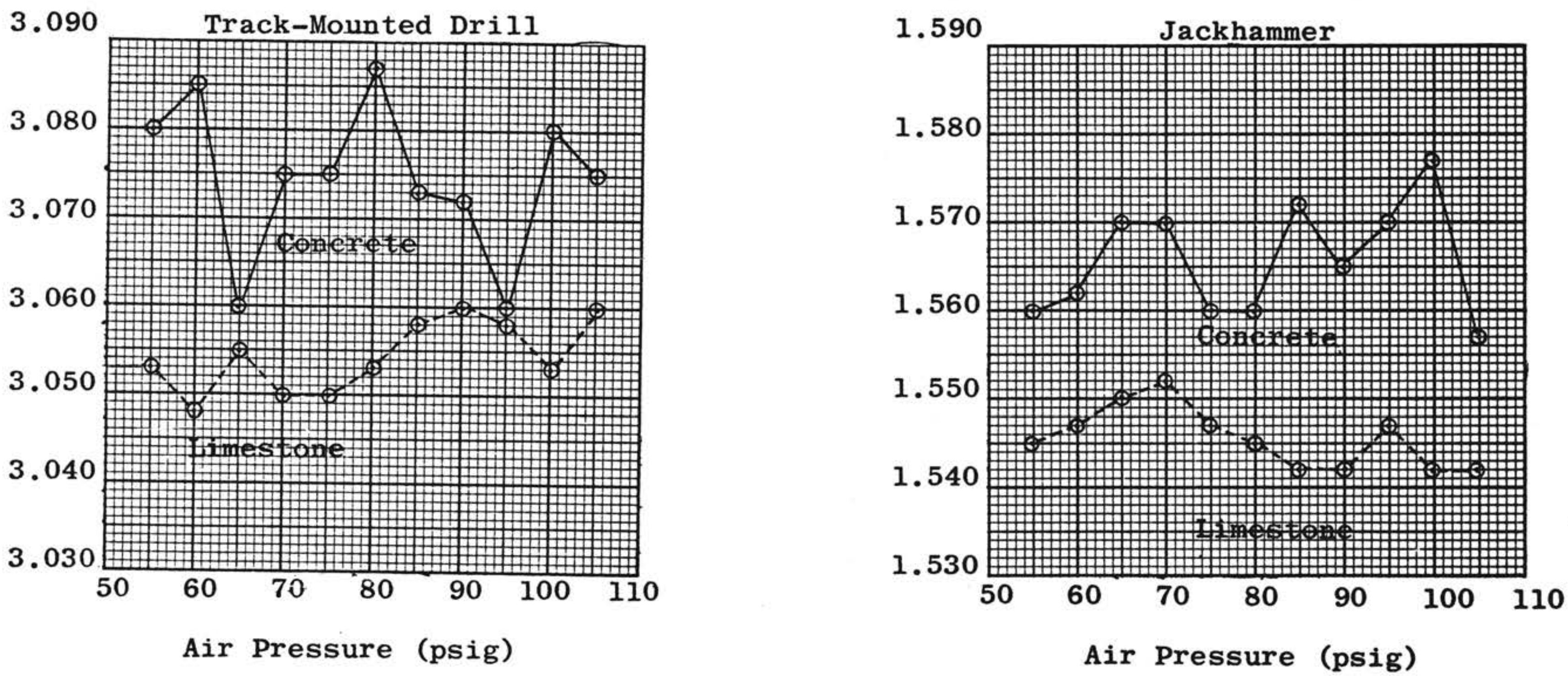

Fig. 25 Correlation Between Hole Diameters and Air Pressure

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

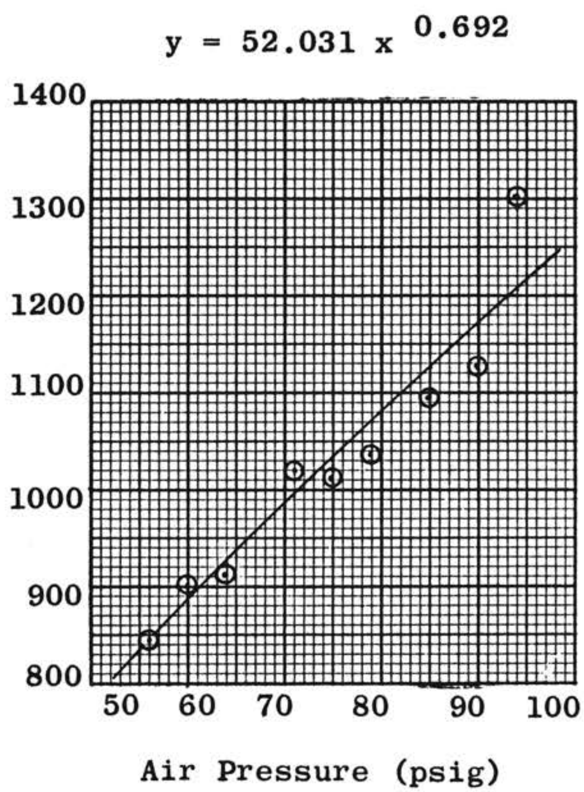

Fig. 26 Strain

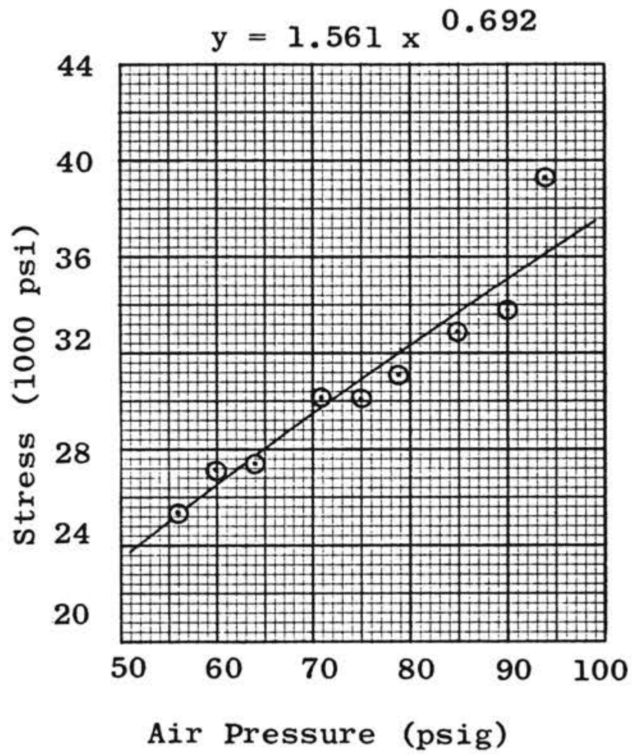

Fig. 27 Stress

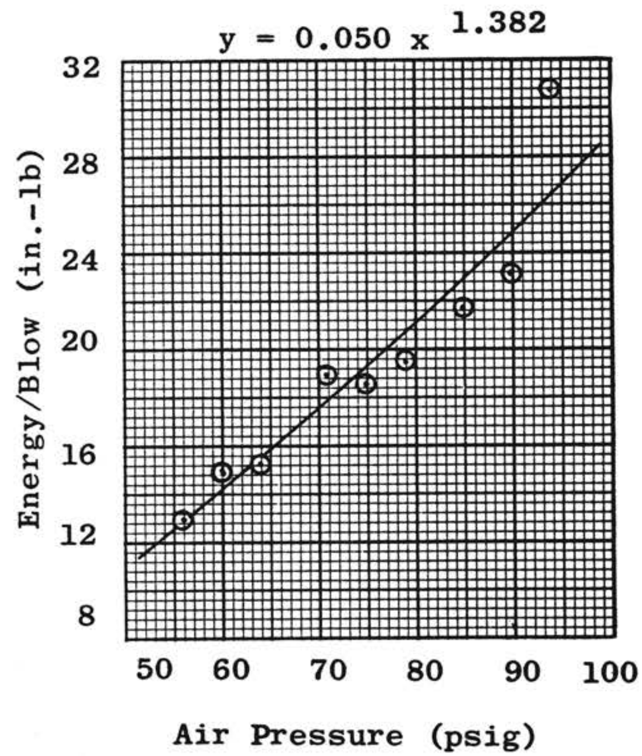

Fig. 28 Energy per Blow

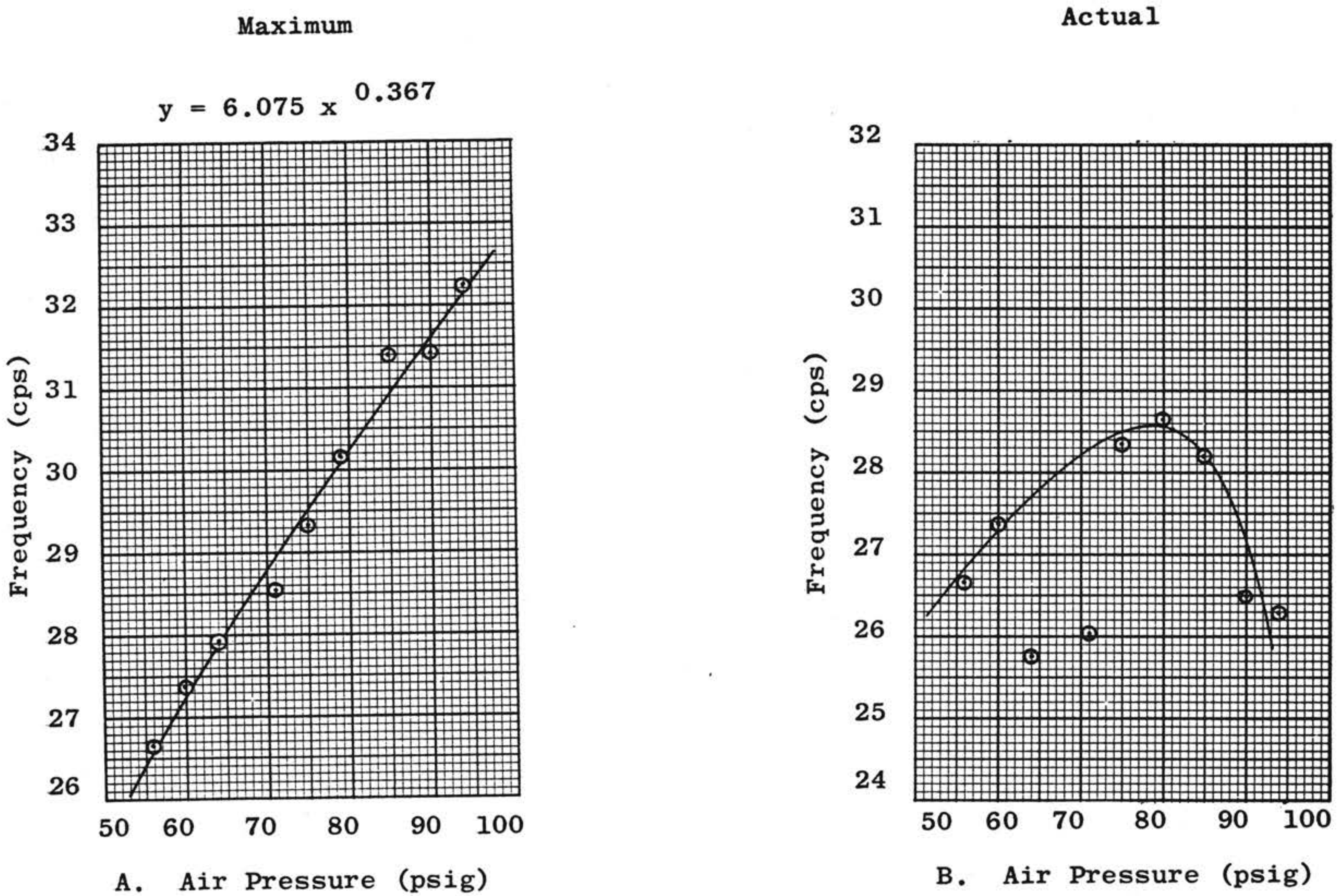

Fig. 29 Operating Frequencies of Jackhammer

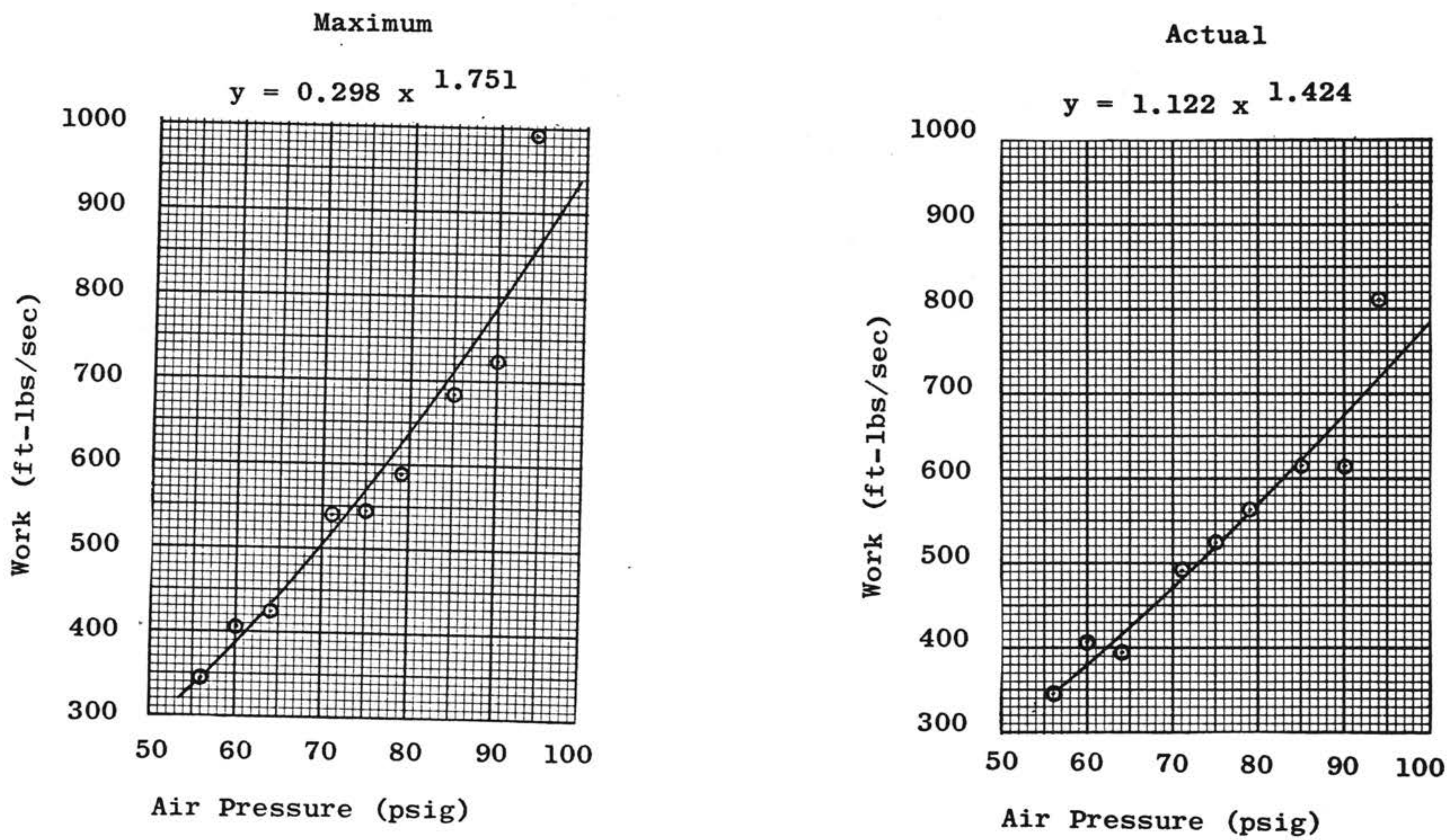

Fig. 30 Work Output From Jackhammer

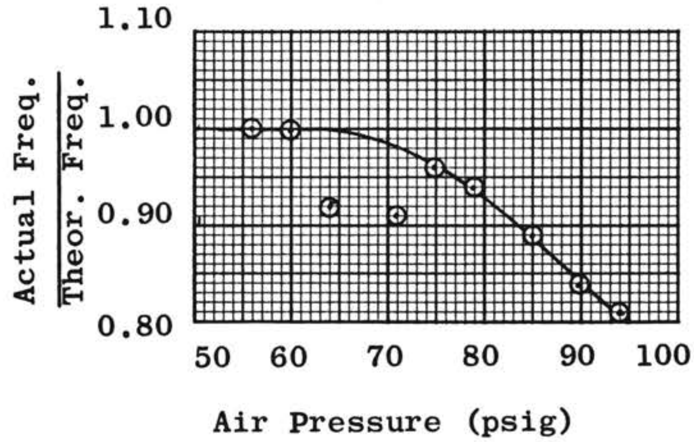

Fig. 31 Ratio of the Actual to the Theoretical Frequencies

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 AND DISCUSSION OF THE RESULTS

The main emphasis of the analysis portion of this research was on the results and their relation to the objectives.

Empirical Results

A computer program to analyze the observed data was written by the author. (Appendix C). It was designed to compute the individual drilling rates for each test hole and then determine the average drilling rate for the four holes drilled at each pressure.

Since each hole was not the same depth, the author considered the possibility of the weighted averages being significantly different from the arithmetic means. Study showed this difference to be consistently less than one-tenth of an inch per minute in the linear drilling rate and, therefore, not significant.

Each set of drilling rates was studied to find the line or curve that best represented the plotted data. An exponential curve was selected as best fitting the individual points. Therefore a computer program was written to determine the exponential equation for the curve of best fit for all of the data. (Appendix C). These equations are entered beside each curve. (Figs. 15-22).

Using the new drilling rates obtained from the curve of best fit the per cent of change from the drilling rate at eighty psig air pressure was determined. (Table III). Eighty psig was selected as a standard since it represented a probable operating air pressure encountered in actual work. Comparing with an arbitrary standard provided a means of visualizing the actual effect on the drilling rates of a five psig change in air pressure. In Table III the per cent of change in drilling rate is almost constant within the material, but there is a difference between per cent of change in the concrete and the limestone.

Earlier, below freezing temperatures were mentioned as possible influences on the drilling rates. To determine if they did have any effect a record of the temperatures was kept for each hole. These temperatures were averaged and plotted for each air pressure. (Figs. 23 and 24). On the same graph the deviation of each drilling rate from the curve of best fit was plotted as a vertical bar at its corresponding pressure. The low temperatures, especially those below freezing, were compared to the deviation at the same pressure. There was not a consistent relationship between low temperatures and either plus or minus deviations. Neither was there any obvious correlation between high temperatures and deviations.

A similar type of study was made on the relationship between hole diameters and operating pressures. The average hole diameters were plotted against their corresponding air pressures, Fig. 25, and a visual check was made to see if the plotted points showed tendencies to either rise or fall. The points did not exhibit any trends that appeared likely to influence the results of the research; therefore, the writer assumed that there was no correlation between the hole diameter and air pressure.

Laboratory Results

The basic data from the laboratory work was recorded in Polaroid pictures showing the oscilloscope display of the strain output. (Appendix B). Each picture was considered to be a complete set of data for a given air pressure. The distances from the zero axis of the oscilloscope screen to the strain peaks were measured and averaged by Mr. Kavanaugh and the author. The averages were compared and recomputed if they were not equal.

The term "maximum frequency" was used by the writer to identify the maximum blows per minute possible if none were skipped. The term "actual frequency" included the skipped blows. Both frequencies were obtained by measuring the distance covered by the base of a number of peaks, subtacting one peak and determining the number of peaks per centimeter. This was multiplied by the sweep speed of the oscilloscope in centimeters per second to yield the frequencies in peaks or blows per second.

The strain, stress and work were determined by using the equations suggested by Ellis Associates (10) and listed below:

$$\text{Calibration Factor} = \frac{400}{\text{Gage Factor}} \times \frac{\text{Calibration Scale}}{\text{Number Active Arms}}$$

$$\text{Strain } (\epsilon) \text{ per mm on Oscilloscope} = \frac{104.71 \text{ u in./in.}}{3 \text{ mm displacement}}$$

$$= 34.9 \text{ u in./in.}$$

$$\text{Stress } (\sigma) = \epsilon E$$

$$\text{Work} = \frac{A}{2} El\epsilon^2 \text{ (f)}$$

The strain, stress, energy per blow and work were plotted against air pressure and the exponential curve of best fit determined. (Figs. 26, 27, 28, 30). Using the values obtained from the curves the per cent of change from eighty psig air pressure was determined. (Table VII).

The maximum possible and the actual frequencies were plotted against air pressure and examined for correlation between points. The correlation within the maximum possible frequency was obvious, and an exponential curve was fitted to the data. (Fig. 29A). There was no obvious relationship between the points for the actual frequency; however, the writer assumed that the points at sixty-four and seventy-one psig air pressure were not representative of the data and drew the approximate curve in Fig. 29B.

Professor R. L. Peurifoy suggested a comparison of the ratio between the actual and the maximum frequencies to air pressure. (Fig. 31). Again the author assumed that the points at sixty-four and seventy-one psig air pressure were not representative and drew the approximate curve shown. One possible explanation for the lower frequency at the higher air pressures is that the exhaust air valve in the jackhammer may not always operate at higher speeds. This seemed plausible because the photographs depicting the strain intensities did not indicate that the steel was ever struck by the piston when blows were missed. Also the preceding and the following strains were normal. This situation could happen if the exhaust valve remained closed and the falling piston formed its own cushion of air.

CHAPTER VII

CONCLUSIONS

The data obtained in this research indicates that the performance of a rock drill is rational and predictable and that, within the air pressure range from fifty-five to one hundred five psig, the changes in the drilling rates are essentially linear. Using five psig incremental changes in air pressure the per cent of change in drilling did not vary more than one per cent within the same material.

However, the results also showed that the type of material being drilled greatly influenced the drilling rates and, therefore, the effect of air pressure. The incremental change in air pressure caused a four per cent change in the jackhammer drilling rate in concrete and only a two per cent change in the relatively soft limestone. Since the drifter had a five per cent change in drilling rate in concrete and only a four per cent change while in limestone, it was obvious that the two drills were influenced to a different degree by the two materials.

The strain and energy measurements indicated a definite correlation between the per cent of change in strain and the drilling rates with incremental changes in air pressure.

The per cent of change in the strain level was essentially the same as the changes of the jackhammer's drilling rate in concrete. Further research in this area may formulate a method of measuring rock drill performance in a laboratory rather than in the field. This should be considered for further study using a wider and higher range of air pressures and a broader scope of drilling media.

The problems encountered in designing and performing this research have pointed out several areas where further research would be beneficial. Some of these have been studied, but the information is sparse.

Early researchers in rock drilling spoke of a need to classify rock as to its drillability. The author feels that this is still of paramount importance, especially to the construction industry where a slight miscalculation can result in considerable loss of time and money.

Finally, if, as this research indicates, the increase in drilling rate is essentially linear, why are the operating pressures and the drilling rates confined to one hundred psig? With the metallurgy and the machine design knowledge available the drill manufacturers must be able to design a drill and drill steel that will be economical to operate at higher air pressures. With this in mind the writer suggests research into drilling rates obtainable above one hundred psig and up to one hundred fifty psig air pressure.

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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	End 1	End 2	Time (min) One	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

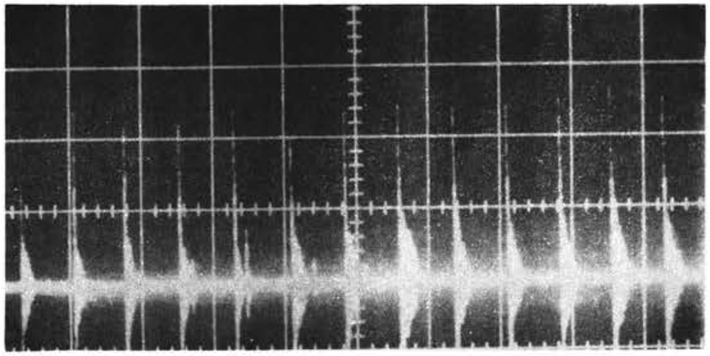
53	55	L-1	R	42	1.56	10.875	26.375	52.375	1.700	2.970
62	55	M-2	Q	65	1.56	11.625	27.312	52.437	1.480	2.520
69	55	H-5	P	39	1.56	11.625	27.562	52.562	1.630	2.680
98	55	D-3	P	46	1.56	12.062	27.375	53.250	1.420	2.580
54	60	J-1	R	42	1.56	10.687	27.437	52.750	1.720	2.950
61	60	M-4	P	66	1.56	11.562	27.812	52.687	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	2.180
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	52.376	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

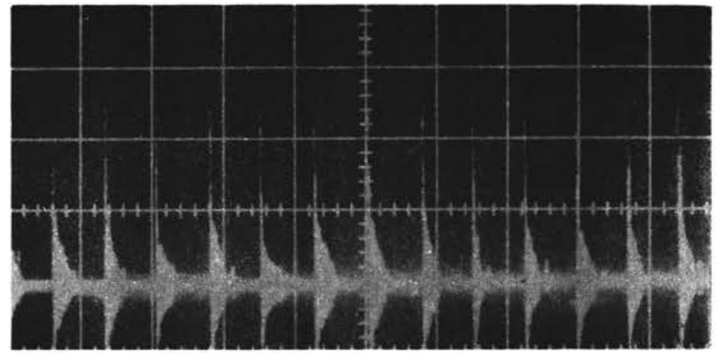
Empirical Test Jackhammer in Limestone

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

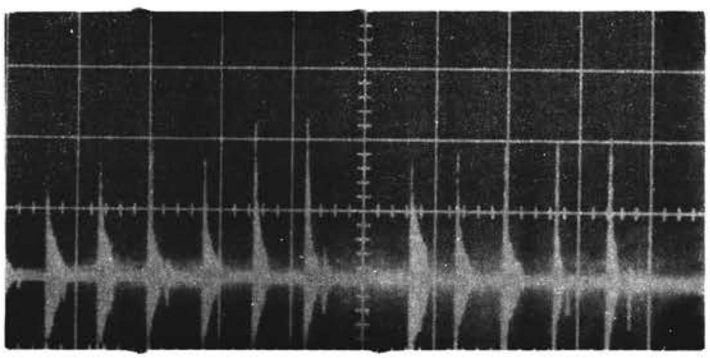
Run No.	Pres psig	Hole No.	Bit No.	Temp F	Hole Dia.	Depth (in.) Start	End 1	End 2	Time (min) One	Two
P46	105	B-7	P	35	1.54	12.500	26.250	53.437	0.967	1.767
P49	105	K-2	Q	35	1.54	12.375	26.812	54.750	1,000	1.750
Empirical Test Track-Mounted Drill in Limestone										
P53	55	B-4	B	35	3.06	13.062	69.250		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	



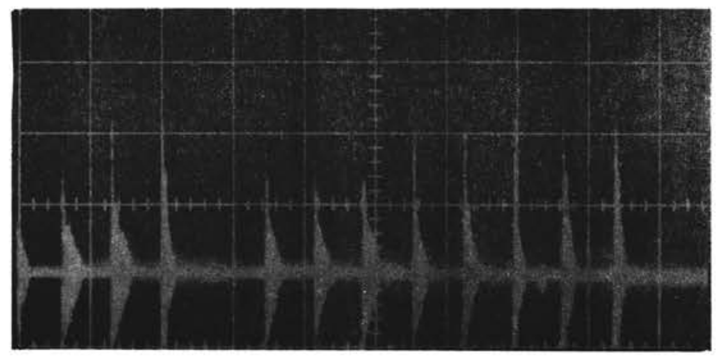
56 psig



60 psig

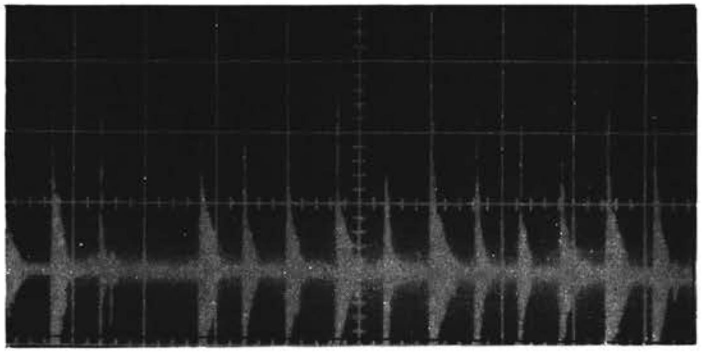


64 psig

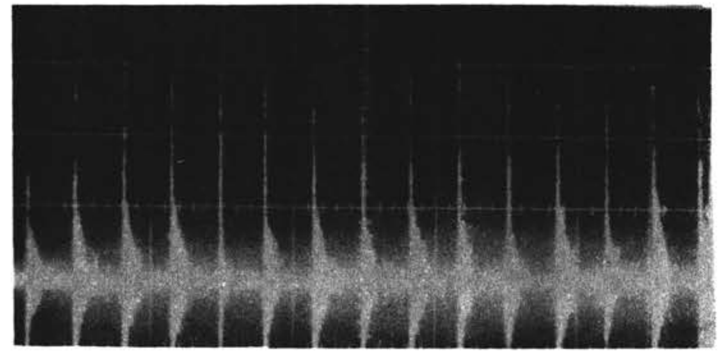


71 psig

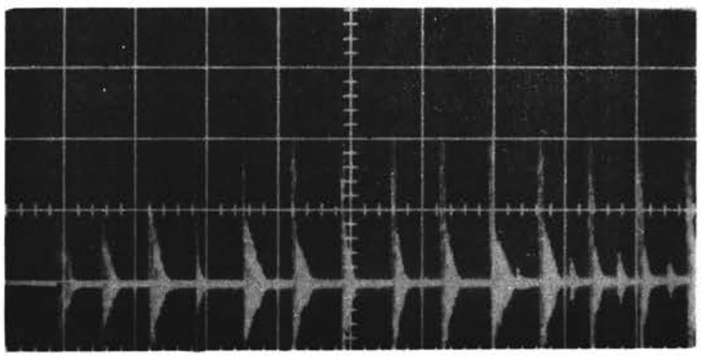
Fig. B-1 Sample Oscilloscope Display of Strain Gage Output



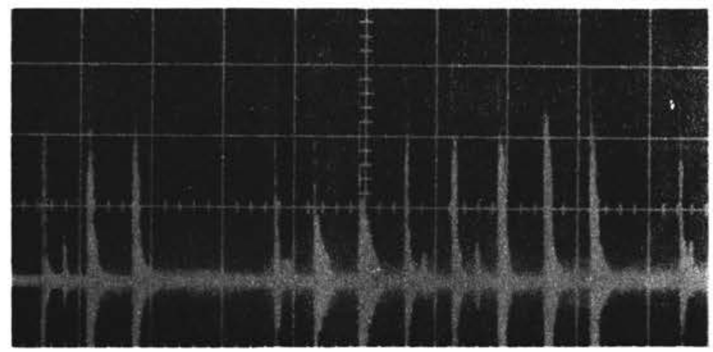
75 psig



79 psig

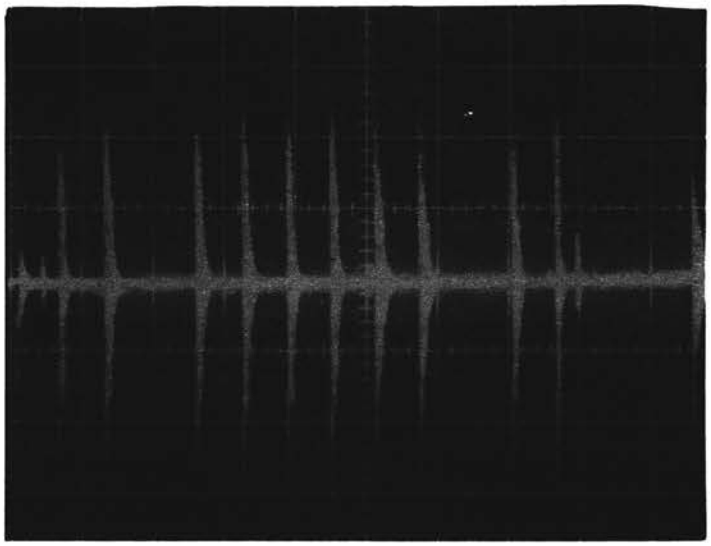


86 psig

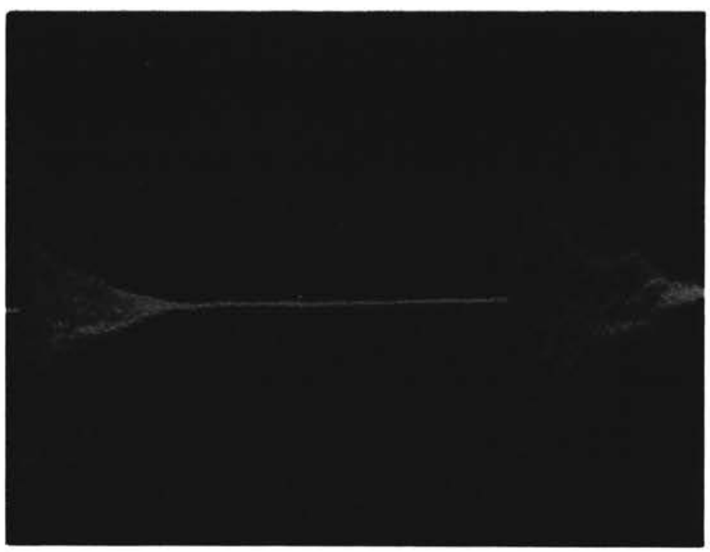


90 psig

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

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

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

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

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

$$= 32.3 \text{ mm}$$

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

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

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

$$= 31.42 \text{ cps}$$

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

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

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

$$= 26.50 \text{ cps}$$

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

$= 23.1 \times 31.42$

$= 727.0$ ft-lbs/sec

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

$= 23.1 \times 26.50$

$= 613$ 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

Robert Houston Reinen

Candidate for the Degree of

Master of Science

Thesis: THE EFFECT OF AIR PRESSURE ON ROCK DRILLING RATES

Major Field: Civil Engineering

Biographical:

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Education: Attended grade school in Schofield Barracks, Hawaii, Carmel, Pasadena, and Monrovia, California, Oatman, Arizona, Silver City, New Mexico, and Spokane, Washington; attended junior high school in Cheyenne, Wyoming; attended high school in Denver, Colorado, Tokyo, Japan, and Arlington, Virginia; graduated from Narimasu High School, Tokyo, Japan in 1953; attended George Washington University, Washington, D.C. from September, 1953 until August, 1953; attended Virginia Polytechnic Institute, Blacksburg, Virginia, from September, 1954 until June, 1958; completed the requirements for and received the Degree of Bachelor of Science in Civil Engineering at Virginia Polytechnic Institute in June, 1958; completed the requirements for the Master of Science degree in Civil Engineering at Oklahoma State University in May, 1964.

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