An experimental investigation of jack hammer drill noise with special emphasis on drilling in rocks of different compressive strengths

Article *in* Noise Control Engineering Journal · May 2007

DOI: 10.3397/1.2737667

2 authors, including:

Harsha Vardhan
National Institute of Technology Karnataka

An experimental investigation of jack hammer drill noise with special emphasis on drilling in rocks of different compressive strengths

Harsha Vardhan[a] and Ch. S. N. Murthy[b]

(Received 2006 October 06; revised 2007 March 26; accepted 2007 April 11)

An attempt has been made in this paper to investigate the influence on sound level due to drilling in rocks of varying physical properties i.e. compressive strength and abrasivity using jackhammer drill. For this purpose, a jackhammer drill setup was fabricated wherein the thrust applied can be varied while drilling vertical holes. The compressive strength and the abrasivity of various rock samples collected from the field were determined in the laboratory. A set of test conditions were defined for measurement of sound level of the jackhammer drill. Also, with the help of the experimental setup, vertical drilling was carried out on the rock samples for varying thrust and air pressure values and the corresponding A-weighted equivalent continuous sound levels were measured. The results of this study indicate that, increase in thrust increases the sound level at higher midband frequencies in the noise spectrum. The study indicated the sound level near the drill rod to be 0.5 to 1.5 dB, 2.0 to 3.0 dB and 4.0 to 6.0 dB higher relative to that at the drill bit, the exhaust and the operator's position respectively at an air pressure of 5 kg/cm^2 and 160 N thrust for all the rock samples tested. Both the thrust and air pressure were found to have a significant effect on the sound level produced by jackhammer drill at all the measurement locations. The study further shows that an increase in sound level of the order of 1.5 to 2.5 dB at the operator's position can occur with an increase in air pressure by 2 kg/cm^2 at 160 N thrust and with an increase in compressive strength and decrease in abrasivity of rocks. Also, the increase in sound level at the operator's position with increase in compressive strength and decrease in abrasivity of rock is of the order of 1.0 to 2.0 dB. In order to maintain a constant penetration rate in the rocks, both the thrust and air pressure need to be increased with an increase in compressive strength and decrease in rock abrasivity. Therefore, increased compressive strength and lower abrasivity of rocks will require higher air pressure and thrusts to be applied to achieve an optimum penetration rate and therefore will result in higher sound level at the operator's position and at other measurement locations.

Primary subject classification: 12.2.1; Secondary subject classification: 12.2.1.2

1 INTRODUCTION

Pneumatic drills (jack hammer drill) are one of the most important sources of noise in mines. These machines are used frequently in underground hard rock mining. Large blasting operations in open pit mines produce huge boulders which cannot be loaded on to the dumpers until they are broken further. These boulders are drilled using pneumatic drills and blasted to reduce their sizes. Therefore, pneumatic drills also find utility in open pit mines for secondary breakage of rocks. A pneumatic drill is a hand held operated machine and therefore, the operator is located very close to the machine. This machine is known to produce A-weighted sound levels of the order of 110 to 120 dB at the operator's position.[1] Use of

[a] Department of Mining Engineering, National Institute of Technology Karnataka, Surathkal, P.O-Srinivasnagar, District-Mangalore (D.K.), Pin-575025 INDIA; email: har7323@rediffmail.com

[b] Department of Mining Engineering, National Institute of Technology Karnataka, Surathkal, P.O-Srinivasnagar, District-Mangalore (D.K.), Pin-575025 INDIA; email: chsn@nitk.ac.in

jackhammer drills in underground mines, increases the sound level further due to multiple reflections taking place in confined space. Walker[2] reported the A-weighted sound level of pneumatic drills as 5 to 6 dB higher underground than in open air. It was also said that the underground sound levels increase further with decrease in cross-sectional area of underground roadways. Since pneumatic drills are one of the most important sources of noise in mines, a considerable amount of work has been reported in literature regarding its noise assessment and control.[1–34] A few studies also indicated that sound levels of pneumatic drills decrease with increase in penetration of the drill rod into the rock.[2] However, assessment of sound pressure levels of pneumatic drills when drilling in rocks of varying physical properties like compressive strength and abrasivity has not been studied in detail. An attempt has been made in this paper to investigate the influence on sound level due to drilling in rocks of varying physical properties e.g. compressive strength and abrasivity using pneumatic drill.

2 SALIENT CONSTRUCTIONAL FEATURES OF PNEUMATIC DRILL

A jackhammer drill is a compressed air operated machine. Air at a pressure of approximately 6 kg/cm^2 is supplied from an external compressor using hose pipes. The drill weighs 10 to 30 kg and is hand held. It can drill holes with diameter varying from 25 to 40 mm. It can be used to drill both vertical and horizontal holes up to 3 m depth. Drilling with the pneumatic drill consists essentially in the drill delivering blows against the bottom of the holes and lifting the rock cuttings. The pneumatic drill basically consists of a hard-steel piston which delivers impacts to the shank of the drill rod. The piston comprises a head which slides in the cylinder and is smaller in diameter at its forward end to form the piston shaft. This shaft is cut externally by straight splines which fit inside similar grooves on the 'chuck' by means of which the hexagonal shaped drill rod is attached to the drill (Fig. 1). The rotating mechanism consists of a ratchet ring and pawls, a rifle bar with spiral fluting, and a rifle nut. The ratchet-and-pawl mechanism restricts the rotation of the rifle bar to one direction only. The piston cylinder having rifled splines internally, as shown in Fig. 2, houses the splined rifle bar. The system of ratchet and pawls allows the piston to travel forward without rotating on the forward stroke, while the fluted rifle bar is positioned for the next up-stroke. This causes, the drill rod and chuck to partially rotate on the back stroke of the piston, while the rifle bar rotates slightly on the forward stroke. These combined movements cause the drill bit to deliver successive impacts on the rock at

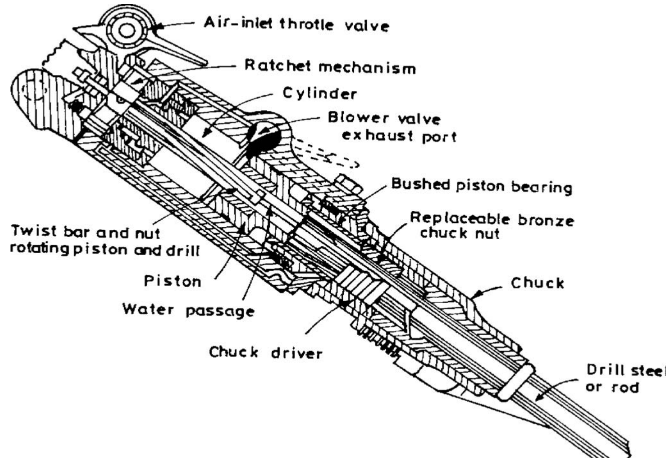

Fig. 1—Sketch showing the constructional features of jackhammer drill machine.

different places at the bottom of the hole, known as indexing.

3 OBJECTIVE OF THE STUDY

A detailed literature search shows that a significant amount of work has been carried out by a number of investigators on the assessment of sound level of drills. Further, in-depth studies have been reported pertaining to the engineering noise control of pneumatic drills, either by retrofit treatments or by design modifications. However, detailed investigation on the sound level produced by pneumatic drills as influenced by drilling in rocks of different physical properties i.e. compressive strength and abrasivity has so far not been reported to the knowledge of the authors. It is anticipated that increases in compressive strength and decreases in abrasivity of rock will increase the noise level of the pneumatic drill. Therefore, the main objective of this study is to investigate of the sound level produced by jack hammer drill with drilling in rocks of different compressive strength and abrasivity.

4 EXPERIMENT

4.1 Design of Experimental Setup

In the laboratory, all the sound level measurements were conducted on jackhammer drill machine operated

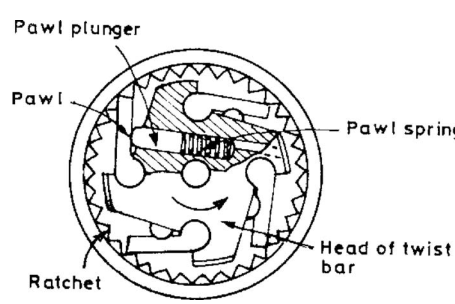

Fig. 2—Sketch showing the ratchet and pawl arrangement of jackhammer drill machine.

Fig. 3—Jackhammer drill setup for drilling vertical holes in rock samples.

by compressed air, as it is extensively used in underground hard rock excavation and quarries. The experimental setup was in a normal cement plastered room 5 m width, 9 m length and 5 m height. The important specifications of the jackhammer drill used were:
— Weight of the jackhammer drill machine (28 Kgs)
—Number of blows per minute—2200
—Type of drill rod—Integrated drill rod with tungsten carbide drill bit
—Recommended optimum air pressure—589.96 kPa
A lubricator of capacity 0.5 litre and a pressure gauge with a least count of 49 kPa were provided between the compressor and jackhammer drill machine to lubricate the various components and to regulate the air pressure supplied to the drill machine, respectively.

A percussive drill setup using the jackhammer to drill vertical holes was fabricated similarly to that given by Murthy[35] to carry out the drilling experiments for sound level measurement on a laboratory scale (Fig. 3). The base plate of the setup consists of two 12.5 mm thick I—sections (flange width—1 cm and height—30 cm) which are welded together all along the centre. They are firmly grouted to the concrete floor with the help of four 3.8 cm diameter anchored bolts. Two circular guiding columns of 60 mm diameter, 175 cm long, and 55 cm apart were secured firmly to the base plate. The vertical position of the two columns was maintained with the help of a top plate (3.8 cm thick, 13 cm width and 62.5 cm length). On the top of the base plate, 25.4 mm diameter holes were drilled at close intervals on two opposite sides for accommodating different sizes of rock blocks (up to 500 mm cube). The rock block was firmly held on the base plate with the help of two mild steel plates (1 cm thick, 7.5 cm width and 61 cm length) kept on the top of the rock block and four 25.4 mm bolts, placed at the four corners.

The jackhammer was firmly clamped at its top and bottom with the help of four semi-circular mild steel clamps, which were in turn bolted firmly to four mild steel bushes for frictionless vertical movement of the unit over the two guiding columns of the setup. In order that the top and bottom clamps work as one unit, they were firmly connected with the help of four vertical mild steel strips (1.3 cm thick, 5 cm width and 50 cm length) on each side of the jackhammer. For increasing the vertical thrust, two vertical mild steel strips (1.3 cm thick, 5 cm width and 32 cm length) were bolted to the top and bottom clamps. On this strip, dead weights made up of mild steel were fixed with the help of nut and bolt arrangements.

For conducting drilling experiments at low thrust level (less than the dead weight of drill machine assembly), a counter weight assembly was fabricated. For this purpose a steel wire rope (0.65 cm diameter) was clamped to the top of the jackhammer unit which in turn passed through the pulley arrangements located at the top plate of the setup. A rigid frame was firmly grouted to the shop floor at a distance of 86 cm from the experimental setup. The steel wire rope from the experimental setup was made to pass over the pulley mounted on the rigid frame. At the other end of the rope, a plate was fixed for holding the counter weights. The dead weight of jackhammer drill machine and accessories for vertical drilling was 637 N. With the help of counter weight arrangement, it was possible to achieve a desired thrust value as low as 100 N. Similarly, through the arrangement of increasing the thrust level, it was possible to achieve a thrust value as high as 900 N.

4.2 Rock Samples Used in the Investigation

Sound level measurement on jack hammer drill setup was carried out for five different rock samples obtained from the field. These rock samples were gabbros, granite, limestone, hematite and shale. The size of the rock blocks was approximately 30 cm $\times$20 cm$\times$20 cm.

4.3 Methodology

4.3.1 Instrumentation for noise measurement

Sound pressure levels were measured with a Larson-Davis model 814 integrating-averaging sound level meter. The instrument was equipped with a Larson Davis model 2540 condenser microphone mounted on a model PRM904 preamplifier. The microphone and

Fig. 4—Protodyakonov's apparatus for determination of compressive strength of rock samples.

preamplifier assembly were mounted directly on the sound level meter. The acoustical sensitivity of the sound level meter was checked once a year by the local manufacturer's representative. For all measurements, the sound level meter was hand held. To determine the noise spectrum, the instrument was set to measure A-weighted, time-averaged one-third-octave-band sound levels with nominal midband frequencies from 25 Hz to 20 kHz. The sound level meter was also set to measure A-weighted equivalent continuous sound levels. For each measurement, the sound level meter was set for an averaging time of 2 minutes.

4.3.2 Determining the compressive strength and abrasivity of rock specimens

The compressive strength of rock samples was determined indirectly using Protodyakonov's Strength Index. In this method Protodyakonov's apparatus (Figs. 4 and 5) was used. Five samples weighing 50 gram each of a particular rock was separately taken in a Protodyakonov's apparatus (Fig. 4). Five blows (n) were given using a weight of 1.8 kg from a height of 0.6 m. This material ($5 \times 50 = 250$ gm) was then transferred to a 500-μm sieve (Fig. 5). The fines which pass through the sieve are taken in a volume meter (measuring cylinder) and the height of the column (h) is noted down. Protodyakanov's Strength Index (PSI) $= (20\ n)/h$, where, n=number of blows=5 and h =height in the volume meter (cm). Using this index, the compressive strength of a rock sample was determined using the relation: Compressive strength=100 $\times$ PSI (kg/cm^2)

Fig. 5—Test sieve and measuring cylinder used in Protodyaknov's test.

Abrasion test measures the resistance of rocks to wear. This test includes wear when subject to an abrasive material, wear in contact with metal and wear produced by contact between the rocks. The abrasivity of rock samples was determined in accordance with International Society of Rock Mechanics (ISRM) standards.[36] For this purpose, Los Angele's abrasion test apparatus (Fig. 6) was used. The abrasion test requires two different sizes of rock samples i.e., 19.0–13.2 mm and 13.2–9.5 mm. One set of test samples of (2500±10) grams was prepared so that they pass through a sieve of 19.0 mm and are retained on a sieve of 13.2 mm. Another set of test samples of (2500±10) grams was prepared so that they pass through a sieve of 13.2 mm and are retained on a

Fig. 6—Los Angele's abrasion test apparatus for determination of abrasivity of rock samples.

Table 1—Test conditions for determination of sound spectra.

Noise sources	Measured at operator position
Background	A1
Air only	A2
Air+drill with 100 N thrust	A3
Air+drill with 300 N thrust	A4

9.5 mm sieve. Both the test samples are placed in the Los Angle's abrasion testing machine. The abrasive charge consists of cast iron spheres approximately 48 mm in diameter and each weighing between 390−445 grams. The machine is rotated at a speed of 20–30 revolutions per minute for a period of 15 minutes. The material is then discharged from the machine and sieved on a 1.7 mm sieve. The material retained on the sieve is weighed. The abrasion resistance is calculated using the relation: Abrasion resistance or Abrasivity=(loss) in weight of the samples/original weight of the samples i.e. 5000±20 gm) ×100%.

4.3.3 Noise measurement

A set of four test conditions was defined for measurement of sound spectra which is given in Table 1. The measurement of sound spectra was carried out on pink granite. For the test conditions A2, A3 and A4 mentioned in Table 1, the air pressure was constant at 6 kg/cm^2. For test condition A1, the sound spectrum was measured at the operator's position and without actually operating the drill machine. This background noise was mainly due to the compressor operating near the pneumatic drill setup. Test condition A2 in the table refers to the measurement of sound spectra at the operator's position by opening the exhaust of the drill but without carrying out any drilling operation. Test condition A3 and A4 refers to measurement of noise spectra during drilling at the operator's position with 100 N and 300 N thrust respectively.

For measuring the variation in sound level while drilling in rocks of different compressive strength and abrasivity, the rock samples were kept beneath the integrated drill rod of the jack hammer drill. Sound level measurements were carried out for thrust values of 160, 200, 300 and 360 N on each rock sample. It is worth mentioning here that the realistic thrust values used by drill operators in the field vary based on the type of rock encountered at a particular site. Typical thrust values in the field may vary from 150 to beyond 500 N. For each thrust mentioned above, the A-weighted equivalent continuous sound level was measured by holding the sound level meter at 15 cm distance from the drill bit, drill rod and the exhaust for air pressure values of 5.0, 5.5, 6.0 and 7.0 kg/cm^2. Similarly, the A-weighted equivalent continuous sound level was measured at the operator's position for each thrust of 160 to 360 N and air pressures of 5 to 7 kg/cm^2 as mentioned above. The operator's position refers to the position of the operator's ear which was at a height of 1.7 m from the ground level and 0.75 m from the center of the experimental set-up. During measurement, all the doors and windows of the room were kept open so as to reduce the effect of reflected sound.

For a particular condition, at each microphone location and for the same rock sample, the sound level was determined five times in relatively rapid succession. The arithmetic average of the A-weighted sound levels from each set of five measurements was computed to yield an average A-weighted sound level for a particular condition.

Table 2—Compressive strength and abrasivity of different rock samples.

Sample No.	Rock Type	Compressive strength (kg/cm^2)	Abrasivity (%)
Sample-1	Shale	1051.35	23.70
Sample-2	Hematite	1262.33	21.50
Sample-3	Limestone	1542.57	20.30
Sample-4	Granite	1937.13	17.50
Sample-5	Gabros	2252.35	15.50

5 RESULTS AND DISCUSSION

5.1 Compressive Strength and Abrasivity of Rock Samples

The results of the experimental study for the compressive strength and the abrasivity of the rock samples are given in Table 2. It is seen that, with an increase in compressive strength of rock samples, the abrasivity decreases. This is due to an increase in the resistance of rocks to wear with increase in the compressive strength.

5.2 Noise Assessment of Jackhammer Drill under Various Test Conditions at Operator's Position

The noise spectrum at the operator's position for test conditions A1 and A2 are shown in Fig. 7. It is seen that the background sound level at the measurement location due to the operation of the air compressor alone is below 82 dB with the nominal one-third-octave midband frequencies from 25 Hz to 20 kHz. Also, the increase in sound level with midband frequencies above 50 Hz is more than 10 dB for test

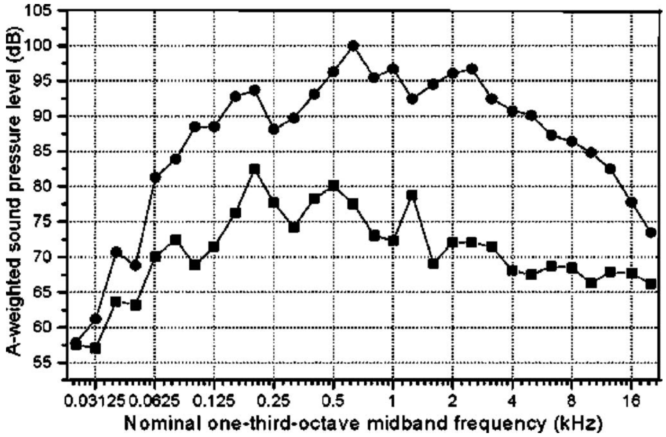

Fig. 7—Effect on A-weighted sound pressure level at operator's position for test conditions A1 and A2: ■ Background noise, Test condition A1; ● (Exhaust noise +background noise), Test condition A2.

conditions A2 relative to that of test condition A1. Therefore, the sound level in the frequency range of 63 Hz to 20 kHz for test conditions A2 is unlikely to be affected by the background noise due to the compressor. However, the sound level for test condition A2 may be affected due to test condition A1 with nominal midband frequencies from 25 to 50 Hz as the difference in sound level in this range of frequency is below 9 dB.

The noise spectrum at the operator's position for test conditions A2, A3 and A4 are shown in Fig. 8. It is seen that from 50 to 100 Hz, the increase in sound level for test conditions A3 relative to that of A2 is from 2.8 to 7.2 dB and that of A4 relative to that of A3 is from 3.2 to 5.9 dB. This shows that drilling operation has increased the sound level with midband frequencies from 50 to 100 Hz. The increase in sound level in this frequency range (50−100 Hz) is due to impact between the piston and the drill steel and that between the drill steel and the rock.[6,7,23,24] The increase in sound level for test condition A3 relative to that of A2 with midband frequencies from 125 Hz to 2 kHz is in the range of 1.0 to 11.7 dB and that of A4 relative to that of A3 is in the range of 1.6 to 6.0 dB. The noise in this frequency range (125 Hz−2 kHz) is due to the exhaust of the drill machine.[6,7,23,24] The combination of drilling noise and exhaust noise has resulted in an increase in the sound levels in this frequency range (125 Hz−2 kHz).

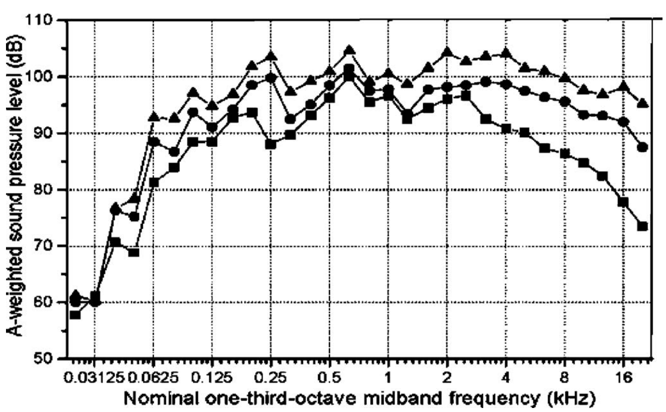

Fig. 8—Effect on A-weighted sound pressure level at operator's position for test condition A2, A3 and A4: ■ (Air only) Test condition A2; ● (Air+Drill with 100 N thrust), Test condition A3; ▲ (Air+Drill with 300 N thrust), Test condition A4.

There is a significant increase in sound level of the order of 6.6 to 14.2 dB from 2.5 to 20 kHz for test condition A3 relative to that of A2 and 4.0 to 7.7 dB for test condition A4 relative to that of A3. This increase in sound level is due to resonance of the steel parts of the drill steel and the drill due to drilling in rock.[6,7,23,24]

5.3 Assessment of Sound Level of Jackhammer Drill with Drilling in Rocks of Different Compressive Strength and Abrasivity

5.3.1 Effect of compressive strength and abrasivity of rock on sound level at operators position

The A-weighted equivalent continuous sound level at operator's position for rocks of different compressive strengths (Sample-1 to Sample-5 of Table 2) at various thrusts and air pressures are given in Table 3. In this table, the compressive strengths of rock samples are given in increasing order i.e., sample-1 having lowest compressive strength and highest abrasivity whereas sample-5 having highest compressive strength and lowest abrasivity. At an air pressure of 5 kg/cm^2 and thrust of 160 N, the difference in A-weighted sound level for sample-1 and sample-5 was of the order of 0.8 dB. This value varied from 0.8 to 1.4 dB with an increase in thrust from 160 to 360 N. At an air pressure of 5.5 kg/cm^2, and a thrust of 160 N, the difference in A-weighted sound level for sample-1 and sample-5 was 0.9 dB. At this air pressure (5.5 kg/cm^2), an increase in thrust from 160 to 360 N caused an increase in the sound level difference for sample-1 and sample-5 from 0.6 to 1.6 dB. Similar results i.e., increase in sound level difference from 1.1 to 1.5 dB and 1.6 to 2.2 dB, were observed at air pressure of 6 and 7 kg/cm^2 respectively for sample-1 and sample-5 with increase in thrust from 160 to 360 N.

Table 3—A-weighted equivalent continuous sound level at operator's position for rocks of different compressive strength and abrasivity at various thrust and air pressures.

Air pressure (kg/cm^2)	Thrust (N)	Sample-1	Sample-2	Sample-3	Sample-4	Sample-5
5	160	116.7	116.9	117.0	117.3	117.5
	200	116.9	117.3	117.3	117.5	117.8
	300	117.8	117.9	118.1	118.3	118.7
	360	118.2	118.3	118.5	118.8	119.6
5.5	160	116.9	117.1	117.2	117.4	117.8
	200	117.3	117.5	117.7	117.9	118.2
	300	118.3	118.9	119.1	119.5	119.7
	360	118.7	119.5	119.8	119.9	120.3
6	160	117.9	118.1	118.6	118.9	119.2
	200	118.4	118.5	118.9	119.3	119.5
	300	119.2	119.8	120.1	120.5	120.7
	360	119.8	120.2	120.5	120.8	121.3
7	160	118.3	118.8	119.1	119.5	119.9
	200	118.6	119.2	119.5	119.7	120.3
	300	119.5	120.3	120.7	121.1	121.7
	360	120.2	120.8	121.1	121.9	122.2

The effect of air pressure on sound level at constant thrust of 160 N for sample-1 to sample-5 at operator's position is shown in Fig. 9. An increase in sound level is observed with increasing air pressure values. With an increase in air pressure by 2 kg/cm^2, i.e., from 5 to 7 kg/cm^2 and at a thrust of 160 N, the sound level of sample-1 increased by 1.6 dB. Similar results were shown by other samples. The increase in sound level for sample-2, sample-3, sample-4 and sample-5 with an increase in air pressure by 2 kg/cm^2 at a thrust of 160 N is 1.9, 2.1, 2.2 and 2.4 dB respectively.

The above result shows that an increase in compressive strength and decrease in abrasivity of rock samples causes an increase in the sound level produced by jack hammer drill at the operator's position. It is worth mentioning that, to maintain optimum penetration rate, the thrust and air pressure must be increased in rocks of higher compressive strength and lower abrasivity. This in turn results in higher sound levels.

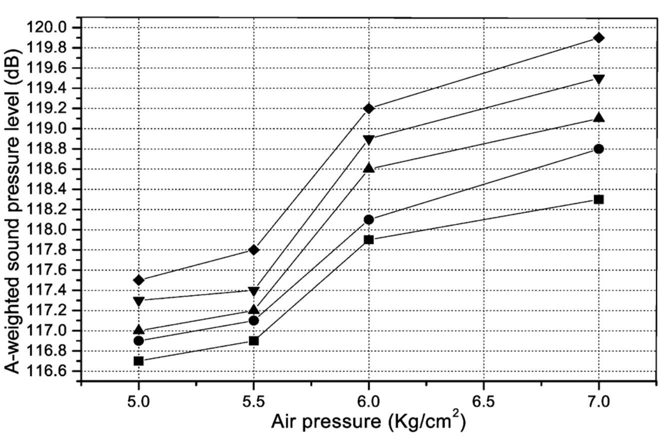

Fig. 9—Effect of air pressure on sound level at constant thrust of 160 N for sample-1 to sample-5 at operators position: ■ Sample-1; ● Sample-2; ▲ Sample-3; ▼ Sample-4; ♦ Sample-5.

5.3.2 Effect of compressive strength and abrasivity of rock on sound level at the exhaust

The effect of compressive strength and abrasivity of rock on sound level at the exhaust is given in Table 4. A significant increase in the sound level with increase in compressive strength and decrease in abrasivity is observed for the rock samples. For instance, the difference in A-weighted sound level for sample-1 and sample-5 is 2.2 dB at constant air pressure and thrust of 5 kg/cm^2 and 160 N respectively. The variation of sound level of all the five samples with different compressive strength and abrasivity at an air pressure of 5 kg/cm^2 and thrust varying from 160 to 360 N is shown in Fig. 10. It can be seen that, with an increase in compressive strength and decrease in abrasivity of rock samples i.e., from sample-1 to sample-5, the A-weighted sound level increased near the exhaust at each thrust level for a constant air pressure of 5 kg/cm^2. Similar results can be seen from Table 4, for air pressures of 5.5, 6.0 and 7.0 kg/cm^2.

At an air pressure of 5 kg/cm^2, an increase in thrust by 200 N (from 160 to 360 N) caused the sound level difference to vary from 1.4 to 1.8 dB for sample-1 to

Table 4—A-weighted equivalent continuous sound level at exhaust for rocks of different compressive strength and abrasivity at various thrust and air pressures.

Air pressure (kg/cm^2)	Thrust (N)	Sample-1	Sample-2	Sample-3	Sample-4	Sample-5
5	160	118.4	118.7	119.8	120.1	120.6
	200	118.8	119.2	120.6	120.9	121.5
	300	119.3	119.5	121.0	121.6	121.7
	360	119.9	120.5	121.5	121.9	122.2
5.5	160	119.9	120.1	120.2	120.7	120.8
	200	120.2	120.7	120.9	121.2	121.7
	300	120.9	121.3	121.7	121.9	122.3
	360	121.2	121.7	121.8	122.2	122.6
6	160	120.3	120.5	120.8	121.1	121.4
	200	120.6	121.2	121.8	122.2	122.5
	300	121.9	122.5	122.9	123.4	123.8
	360	121.8	122.8	123.2	123.7	124.2
7	160	120.8	120.9	121.2	121.5	121.8
	200	121.3	121.5	121.9	122.4	122.7
	300	122.0	122.7	123.2	123.7	123.9
	360	122.5	123.1	123.7	123.9	124.5

sample-5 at the exhaust. An increase in air pressure by 2 kg/cm^2 at a constant thrust of 160 N resulted in an increase in sound level at the exhaust of the drill. This increase in sound level varied from 1.2 to 2.4 dB for sample-1 to sample-5. This shows that, both thrust and air pressure have a significant effect on sound level produced by jack hammer drill at the exhaust.

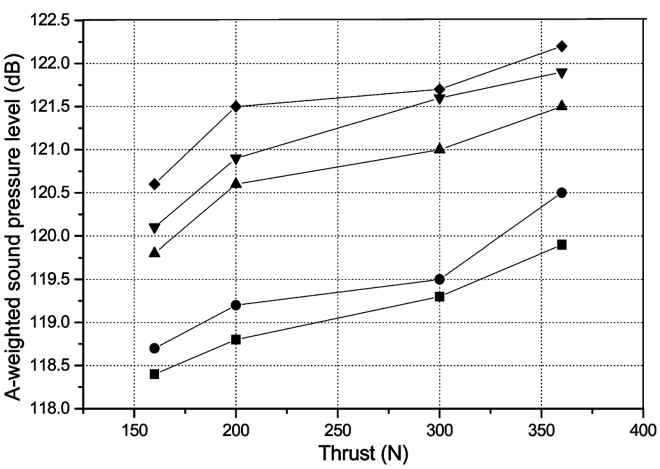

Fig. 10—Effect of thrust on sound level at constant air pressure of 5 kg/cm^2 *for sample-1 to sample-5 at exhaust: ■ Sample-1; ● Sample-2; ▲ Sample-3; ▼ Sample-4; ♦ Sample-5.*

5.3.3 Effect of compressive strength and abrasivity of rock on sound level near drill rod

The A-weighted equivalent continuous sound level near the drill rod for rocks of different compressive strength and abrasivity at various thrusts and air pressures is given in Table 5. Maximum increase in sound level with an increase in compressive strength and decrease in abrasivity was observed near the drill rod compared to that of operator's position, exhaust and drill bit. The sound level difference of sample-1 and sample-5 at an air pressure of 5 kg/cm^2 with an increase in thrust from 160 to 360 N varied from 2.2 to 2.8 dB. At air pressures of 5.5, 6.0 and 7.0 kg/cm^2, this sound level difference of sample-1 and sample-5 varied from 2.2 to 2.4 dB, 2.1 to 2.5 dB and 1.7 to 2.2 dB respectively. From the above discussion it is clearly seen that increase in compressive strength and decrease in abrasivity of rock produces a significant increase in sound level near the drill rod. A possible reason for the higher sound level near the drill rod with an increase in compressive strength of rock is the increased vibration of the drill rod with drilling in rocks of higher compressive strengths.

Both the air pressure and thrust were observed to have a significant effect on the sound level produced near the drill rod. As for instance, an increase in air pressure by 2 kg/cm^2, at a constant thrust of 160 N caused an increase in sound level of sample-1, sample-2, sample-3, sample-4 and sample-5 by 2.6 dB,

Table 5—A-weighted equivalent continuous sound level near drill rod for rocks of different compressive strength and abrasivity at various thrust and air pressures.

Air pressure (kg/cm^2)	Thrust (N)	Sample-1	Sample-2	Sample-3	Sample-4	Sample-5
5	160	120.5	121.9	122.3	122.8	123.3
	200	121.2	122.4	123.0	123.4	123.9
	300	122.0	122.7	123.4	124.1	124.2
	360	122.7	123.3	123.7	124.4	125.0
5.5	160	121.1	122.2	122.7	123.1	123.4
	200	121.9	122.8	123.5	123.9	124.1
	300	122.4	123.5	124.2	124.5	124.7
	360	122.9	123.9	124.5	124.8	125.3
6	160	121.7	122.8	123.1	123.5	123.8
	200	122.3	123.1	123.8	124.2	124.5
	300	122.8	123.9	124.6	124.9	125.3
	360	123.2	124.2	124.9	125.3	125.7
7	160	123.1	123.7	123.9	124.2	124.8
	200	123.7	124.2	124.9	125.0	125.5
	300	124.5	125.5	125.2	126.2	126.7
	360	124.9	125.7	125.8	126.7	126.9

1.8 dB, 1.6 dB, 1.4 dB and 1.5 dB respectively. Similarly, an increase in sound level with an increase in thrust of 200 N at an air pressure of 5 kg/cm^2 was 2.2 dB for sample-1, 1.4 dB for sample-2 and sample-3, 1.6 dB for sample-4 and 1.7 dB for sample-5.

5.3.4 Effect of compressive strength and abrasivity of rock on sound level near drill bit

The effect of compressive strength and abrasivity of rock on the sound level near drill bit at various thrust and air pressure is given in Table 6. An increase in sound level is observed at each thrust and air pressure

Table 6—A-weighted equivalent continuous sound level near drill bit for rocks of different compressive strength and abrasivity at various thrust and air pressures.

Air pressure (kg/cm^2)	Thrust (N)	Sample-1	Sample-2	Sample-3	Sample-4	Sample-5
5	160	120.0	121.0	121.2	121.6	121.9
	200	120.8	121.5	121.7	122.0	122.3
	300	121.5	122.0	122.1	122.3	122.5
	360	121.8	122.1	122.3	122.5	122.7
5.5	160	120.8	121.2	121.6	121.8	122.2
	200	121.3	121.7	122.2	122.5	122.7
	300	121.6	122.3	122.7	122.9	122.9
	360	121.9	122.6	122.9	123.3	123.7
6	160	121.5	121.7	122.0	122.4	122.7
	200	121.8	121.9	122.3	122.7	122.9
	300	122.3	122.6	122.9	123.2	123.6
	360	122.7	122.8	123.2	123.7	123.9
7	160	121.7	122.0	122.2	122.5	122.9
	200	121.9	122.4	122.7	122.9	123.1
	300	122.7	123.1	123.6	123.9	124.8
	360	122.9	123.5	123.8	124.0	124.9

with an increase in compressive strength and decrease in abrasivity of the rock samples. The sound level difference of sample-1 and sample-5 at an air pressure of 5 kg/cm^2 and with an increase in thrust from 160 to 360 N varied from 0.9 to 1.9 dB. At air pressures of 5.5, 6.0 and 7.0 kg/cm^2, this sound level difference of sample-1 and sample-5 varied from 1.3 to 1.8 dB, 1.1 to 1.3 dB and 1.2 to 2.1 dB respectively. This shows that an increase in compressive strength and decrease in abrasivity of rock causes a significant increase in sound level near the drill bit.

Again as in the earlier cases, both the air pressure and thrust were observed to have a significant effect on the sound level produced near the drill bit. For example, an increase in air pressure by 2 kg/cm^2, at a constant thrust of 160 N indicated an increase in sound level of 1.7 dB for sample-1 and 1.0 dB for sample-2 to sample-5. Increases in sound level with an increase in thrust of 200 N at an air pressure of 5 kg/cm^2 were 1.8 dB for sample-1, 1.1 dB for sample-2 and sample-3, 0.9 dB for sample-4 and 0.8 dB for sample-5.

6 ENGINEERING NOISE CONTROL OF THE PNEUMATIC DRILL

It is well known that the risk of noise induced hearing loss (NIHL) begins at 83 dB and above. The legal 'safe limit' for an 8 hour day is considered to be 85 dB in most countries. In India, to regulate and control noise pollution for mining occupations, the Directorate General of Mines Safety (DGMS) in its Circular No. DGMS Cir.Tech./18 of 1975[37] and DGMS Cir.Tech./5 of 1990[38] suggests a warning limit of 85 dB and a danger limit of 90 dB for the 8-hour average A-weighted sound level. DGMS also recommends A-weighted sound level of 115 dB at and above which the unprotected ear may run a risk of hearing impairment and therefore appropriate ear protective devices should be used; and 140 dB where no worker should enter even with ear protection.

The experiments on this drill were performed using ear muffs. However, it is seen that some of the measured sound levels in the experiments exceeded 126 dB. This is tremendously high—41 dB above the legal limit and 43 dB above the limit for risk of NIHL. Therefore no personal protective device would adequately protect against NIHL. Therefore, the drill is basically unacceptable and therefore engineering noise control for this drill should be carried out for noise reduction.

The major noise source in pneumatic drill is the driving unit which emits high intensity low frequency noise due to compressed air.[3] Of the total noise energy of pneumatic drill, 87.5% is contributed by the exhaust and the next largest component is the impact between the piston and the drill steel.[2,4,6] It was suggested by Miller[6] that efforts should be made to attenuate the sound levels in the frequency range of 500 to 600 Hz and 1500 to 7000 Hz, as most of the sound power is concentrated in these frequency ranges. Some studies in the past attempted to reduce the high frequency noise due to vibration of the drill steel using rubber collars on the drill rod.[8] However, at that time this method was not successful as the heat generated due to internal friction deteriorated both the material in the collar and the bonding in the rod.

Significant sound level reduction in pneumatic drills could be achieved by eliminating two large exhaust openings and substituting rows of holes around the circumference of the cylinder. A 75% reduction in the total noise energy has been reported by incorporating the above design modifications.[2,11] The low frequency noise of pneumatic drill can be effectively reduced using exhaust muffler.[2,9,19,22–24]

Use of exhaust hose with two or more bends which are extended away from the immediate working place for noise reduction in pneumatic drills can also be a solution.[10,19,22] Some studies indicate use of sound suppression hose with spiral square ribs which are specially designed to trap sound, moisture and oil from the exhaust air of pneumatic drill.[13] However, for adequate protection of drilling crews against noise, mufflers should be used for reduction of the low frequency exhaust noise along with suitable ear protectors to guard against high frequency mechanical noise.

A simple damping sleeve of rubber hose clipped over the drill steel can also reduce the drill noise.[5] Further, a closed case fitted with a muffler around the drill body can also be designed for the purpose of noise reduction.[17] Replacement of normal steel collared rod by a plastic collared rod in pneumatic drills has also been reported to reduce the sound level of drills.[18] Attempts can also be made to reduce the drill rod noise by muffling the hammer using telescopic tube for the rods and using borehole mouth seal. Noise control using concentric drill steels may also be tried.[1] Trials can also be made for reducing the noise radiated from the drill rod and the rock face using rubber damping bushes mounted near the drill chuck.[21]

7 CONCLUSIONS

The sound levels in the low frequency range of 50 to 100 Hz are due to impact between the piston and the drill steel and that between the drill steel and the rock whereas the sound levels in the frequency range of 125 Hz to 2 kHz are due to the exhaust of the drill machine. The sound level from 2.5 to 20 kHz is due to resonance of the steel parts of the drill steel and the drill due to drilling in rock. An increase in thrust level increased the sound level at higher midband frequencies in the noise spectrum.

The study indicated the sound level near the drill rod to be higher than that near the exhaust, the drill bit and the operator's position for all the rock samples tested. It was of the order of 0.5 to 1.5 dB higher relative to that of drill bit, 2.0 to 3.0 dB higher relative to that at the exhaust and 4.0 to 6.0 dB higher relative to that at the operator's position at an air pressure of 5 kg/cm^2 and 160 N thrust. This increase in sound level near the drill rod is due to its higher vibration while drilling in rocks with a higher compressive strength.

Both the thrust and air pressure were found to have a significant effect on the sound level produced by jackhammer drill at all the measurement locations i.e., at operator's position, exhaust, drill rod and the drill bit. An increase in sound level of the order of 1.5 to 2.5 dB at the operator's position can result from an increase in air pressure by 2 kg/cm^2 at 160 N thrust and with an increase in compressive strength and decrease in abrasivity of rocks from shale to gabbros. Similarly, an increase in thrust by 200 N at a constant air pressure of 5 kg/cm^2 can result in an increase in the sound level at the operator's position by 1.5 to 2.0 dB with an increase in compressive strength and decrease in abrasivity of rocks from shale to gabbros.

The increase in sound level at the operator's position with an increase in compressive strength and decrease in abrasivity of rock from shale to gabbros is of the order of 1.0 to 2.0 dB at constant thrust and air pressure. It needs to be emphasized that to maintain a constant penetration rate in the rocks, both the thrust and air pressure need to be increased with an increase in compressive strength and decrease in abrasivity of rocks. In other words, for a fixed penetration rate, the thrust and air pressure values will be lower in a rock of lesser compressive strength than that of a rock with higher compressive strengths. Therefore, increased compressive strength and lower abrasivity of rocks will require higher air pressure and thrusts to be applied to achieve an optimum penetration rate which will result in higher sound levels at the operator's position.

8 ACKNOWLEDGMENTS

The principal author sincerely thanks the Ministry of Science and Technology, Government of India for the "Young Scientist Award" under Science and Engineering Research Council Fast Track Proposals for Young Scientists Scheme entitled "Investigation of the sound level produced by jack hammer drill with drilling in rocks of different compressive strength." All the necessary equipment and fabrication was carried out from this award. The authors sincerely thank the reviewers who went through the paper in depth and provided valuable comments. They also thank Sri D. Chandrahasa Rai, Technical Staff in the Department of Mining Engineering, N.I.T.K, Surathkal for his help in taking laboratory measurements.

9 REFERENCES

1. W. W. Aljoe, "Quieted percussion drills," Proceedings: Bureau of Mines Technology Transfer Seminars, Pittsburgh, PA, July 24 and Denver, Co, July 26, U.S. Bureau of Mines—Information Circular No. 8986, 75–89, (1984).
2. A. Walker, "Noise—its effect and control in mining operations," *The Canadian Mining and Metallurgical Bulletin*, November, 820–834, (1963).
3. W. H. Powell, "The assessment of noise at collieries," *Transactions of the Institution of Mining Engineers*, **116**, 22–42, (1956).
4. J. Holdo, "Energy consumed by rock drill noise," Mining Magazine, (1958).
5. A. H. Barker and W. F. Gill, "Noise," Symposium on Environmental Engineering in Coal Mining," organised by the Institution of Mining Engineers 3, Grosvenor Crescent, London, 31st October to 2nd November, 191–199, (1972).
6. W. C. Miller, "Noise from pneumatic rock drills—measurement and significance," U.S. Bureau of Mines—Report of Investigation No. 6165, 1–30, (1963).
7. M. U. Savich and J. Wylie, "Noise attenuation in rock drills," *Canadian Mining Journal*, **96**, 39–42, (1975).
8. J. E. Gordon, "Noise suppression on rock drills," *Canadian Mining and Metallurgical Bulletin*, **56**, 835–838, (1963).
9. A. W. Wallace, "Rock drill noise—an approach," *Canadian Mining and Metallurgical Bulletin*, **57**, 1038–1041, (1964).
10. J. W. Reynolds, "Noise control at the Sullivan Mine," *The Canadian Mining and Metallurgical Bulletin*, **LXVII**, 13–16, (1964).
11. J. W. Chester, R. T. Dewoody and W. C. Miller, "Noise from pneumatic rock drills-shape and exit noise of an exhaust muffler," U. S. Bureau of Mines—Report of Investigation No. 6450, 1–12, (1964).
12. H. C. Fischer, "Noise control of pneumatic mining equipment," *Canadian Mining Journal*, **83**, 75–85, (1972).
13. G. Lemay, "Campaign quiets worst noise offenders," *Canadian Mining Journal*, **93**, 59–60, (1972).
14. B. H. Weber, "Noise suppression on rock drills," *Canadian Mining Journal*, **93**, 63–64, (1972).
15. J. F. Higginson, "A study of the effect of underground environments on the noise produced by percussive drills," Department of Mineral Engineering, University of British Columbia, Internal Report, (1973).
16. C. L. Workman and Workman-Davies, "Noise and hearing in a trackless mining environment," *Journal of the South African Institute of Mining and Metallurgy*, 211–217, (1989).
17. A. Visnapuu and J. W. Jensen, "Noise reduction of a pneumatic rock drill," U. S. Bureau of Mines—Report of Investigation No. 8082, 1–23, (1975).
18. Schliesing, "Noise reduction in roadway drivage," *Gluckauf*, **114**, 524–525, (1978).
19. M. U. Savich, "Abatement of noise and vibration in the Canadian mining industry," *Canadian Mining Journal*, 103, 31–38, (1982).
20. J. Das and R. S. Deshbhratar, "Noise- a source of environmental pollution in mines," *The Indian Mining and Engineering Journal*, 11–15, (1982).
21. J. C. Leahy and B. Mawson, "Control of noise in UK coal mines," 21st International Conference on Safety in Mines Research Institutes, Sydney, 413–420, (1985).

22. S. K. Turner, "Noise control in South Midlands Area," The Mining Engineer, Paper No. 5030, 289–294, (1986).
23. W. W. Aljoe, R. R. Stein and R. C. Bartholomae, "Test apparatus for measuring sound power level of drills," U. S. Bureau of Mines—Information Circular No. 9166, 1–35, (1987).
24. R. R. Stein and W. W. Aljoe, "Noise test report-hand held pneumatic rotary drill," U. S. Bureau of Mines-Report of Investigation No. 9269, 1–11, (1989).
25. NPC Resources: Report on Construction noise from British Columbia's Workers Compensation Board of BC Engineering Section Report; http://www.nonoise.org/resource/construc/bc.htm, (2000).
26. Renzo Tonin and Associates Pty Ltd, "Managing noise and vibration on construction sites," http://www.rtagroup.com.au, (2003).
27. J. I. Philips, G. Nelson and M. H. Ross, "Noise and Vibration in South African Mining Industry" IOHA; Pilanesberg; Paper F4–3, 1–7; www.saioh.org/ioha2005/proceedings/papers/SSF/paperF4_3, (2005).
28. J. I. Philips, G. Nelson, and M. H. Ross, "Preventing adverse effects of noise and vibration in South African mining industry," *African Newsletter on Occupational Health and Safety*, **16**(2), 33–35, (2006).
29. R. W. Otterman, A. J. Von Wieligh, N. D. L. Burger and P. R. DeWet, "Design and development of a quiet, self-thrusting blast hole drilling system," Mine Health and Safety Council: Johannesburg; http://www.simrac.co.za, (2001).
30. J. L. VanNiekerk, P. S. Heyns, M. Heyns and J. R. Hassall, "The measurement of vibration characteristics of mining equipment and impact percussion machines and tools," Mine Health and Safety Council: Johannesburg; http://www.simrac.co.za, (1998).
31. J. L. VanNiekerk and J. R. Hassall, "A practical guide to noise and vibration control in the South African mining industry," Johannesburg: Mine Health and Safety Council, (2005).
32. T. T. Chew and W. C. Keung, "Noise surveys of hand-held pneumatic rock drills in HongKong," *Environmental Monitoring and Assessment*, **19**(1–3), 519–523, (2004).
33. E. R. Reeves, "Assessment of noise controls commonly used on jumbo drills and bolters in Western United States underground metal mines," Mining Engineering; A publication of Society of Mining Engineers (SME), 41–47, (2005).
34. G. S. Harper and T. M. O'Brien, "The prediction of underground drilling noise," *Journal of the South African Institute of Mining and Metallurgy*, **106**, 533–543, (2005).
35. Ch. S. N. Murthy, "Experimental and theoretical investigations of some aspects of percussive drilling," PhD Thesis submitted to Indian Institute of Technology, Kharagpur-Unpublished, (1998).
36. E. T. Brown, "Rock characterization testing and monitoring, International Society of Rock Mechanics (ISRM) suggested methods," Published for the Commission on Testing Methods, International Society of Rock Methanics by Pergamon Press, (1981).
37. DGMS Circular No. DGMS (Tech)/18, Directorate General of Mines Safety, Dhanbad, India, (1975).
38. DGMS Circular No. DGMS (Tech)/5, Directorate General of Mines Safety, Dhanbad, India, (1990).