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Estimating rock properties using sound levels produced during drilling

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ABSTRACT

An attempt has been made in this paper to experimentally investigate the estimation of rock properties like compressive strength and abrasivity using sound levels produced during drilling. The investigation was carried out on a laboratory scale using small portable pneumatic drilling equipment used in hard rock drilling. For this purpose, a pneumatic drill setup was fabricated for 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 pneumatic 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. Results of this study indicate that sound level can be a promising tool in estimating rock properties during drilling.

1. Introduction

For the purpose of effective design of blasts in mines, quarries and other construction projects, knowledge of rock properties such as compressive strength and density are extremely important. Without a proper knowledge of these properties, the energy released during blasting will be poorly utilized adversely affecting the environment and the cost.

The rock properties for the mining and construction sites are not readily available. Therefore, it is required to send rock blocks to an established national laboratory, which is time consuming. It also requires testing charges to be paid for their services. As the rock types and their properties may change as they are excavated, properties are again to be determined for those rocks. Testing on a continual basis may be difficult and the results may not be timely available.

There are various techniques for determination of rock properties in the laboratory and field. However, the concept of determination of rock property using sound levels produced during drilling have not been reported any where in the literature to the knowledge of the authors. Most of the works in the application of sound levels are in other branches of engineering [1–4]. A couple of studies in oil and gas industries have proposed a technique called "Seismic While Drilling" for estimating rock formations. For instance, few studies have proposed the use of noise produced by the bit during drilling as a seismic source for surveying the area around a well and also for formation characterization while drilling [5–14]. A recent study [15] has also reported a method of estimating formation properties by analyzing acoustic waves that are emitted from and received by a bottom hole assembly. It needs to be emphasized that "Seismic While Drilling" technique is different from the technique of estimating rock properties using sound levels produced during drilling.

For rock engineering purpose, very limited publications are available on this subject. The usefulness of sound level in determining rock or rock mass properties has been shown clearly only in two recent publications [16,17] and the need for further work in this area has been suggested.

It is anticipated that the sound level with drilling in rocks of different physico-mechanical properties will be different for the same type of drill machine. Keeping this point in mind, the present research work was undertaken.

2. Objectives of the study

The noise measurement for the same type of drill machine varies from strata to strata. Thus, the variations in the sound level can indicate the type of rock, which can be used to select suitable explosives and blast designs. Rock characterization while drilling is not a new idea. Devices for monitoring the drilling parameters such as thrust, rotation per minute, bailing velocity, drilling depth and penetration are available and the information obtained are used for blast designs. However, the concept of rock characterization using sound levels is new. Therefore, the objectives of this research work were investigation of the sound level produced while drilling in rocks having varying properties using small

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portable pneumatic drilling equipment and therefore estimation of rock property using sound levels. This can be used for the purpose of selecting optimum drilling parameters, designing blasthole patterns and selecting suitable explosives.

3. Experiment

3.1. Design of experimental setup

In the laboratory, all the sound level measurements were conducted on pneumatic drill machine operated by compressed air. The experimental set up was in a normal cement plastered room of 5 m width, 9 m length and 5 m height. The important specifications of the pneumatic drill used were as follows. The weight of the pneumatic drill machine is 28 kg. The number of blows per minute is 2200. The type of drill rod is an integrated drill rod with a tungsten carbide drill bit. The recommended optimum air pressure is 589.96 kPa.

A lubricator of capacity 0.5 l and a pressure gauge with a least count of 49 kPa were provided between the compressor and pneumatic drill machine to lubricate the various components and to regulate the air pressure supplied to the drill machine, respectively.

A percussive drill setup to drill vertical holes was fabricated to carry out the drilling experiments for sound level measurement on a laboratory scale (Fig. 1). 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 verticality 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.

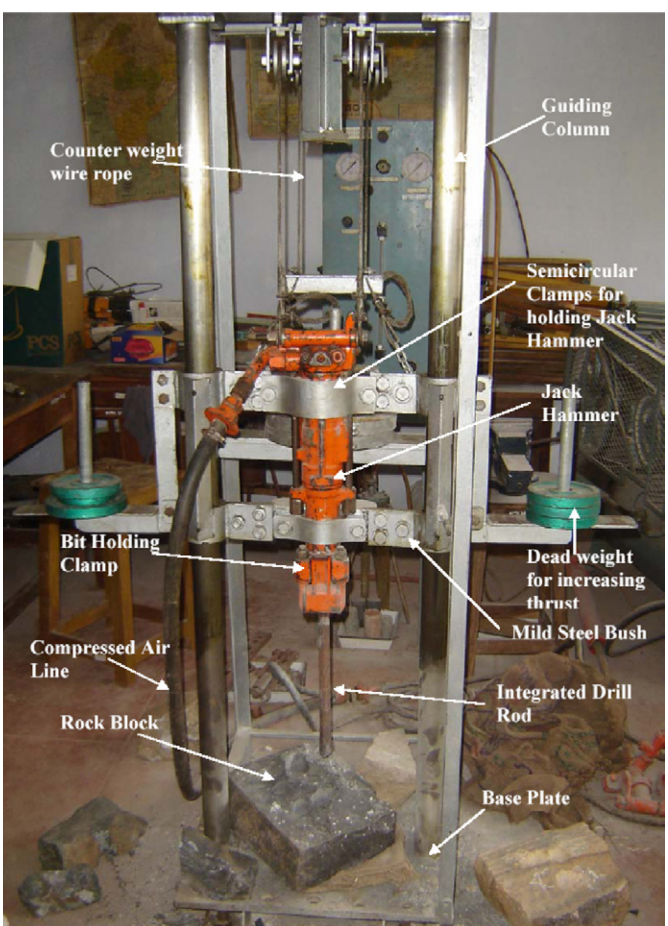

Fig. 1. Pneumatic drill setup for drilling vertical holes in rock blocks.

The pneumatic drill 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 pneumatic drill. 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 the 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 pneumatic drill 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 pneumatic 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 of 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.

3.2. Rock samples used in the investigation

Sound level measurement on pneumatic drill set up 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 × 20 cm × 20 cm.

3.3. Methodology

3.3.1. 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 preamplifier assembly were mounted directly on the sound level meter. The acoustical sensitivity of the sound level meter is 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 pressure 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 (L_{eq}). For each measurement, the sound level meter was set for an averaging time of 2 min.

3.3.2. Determining the compressive strength and abrasivity of rock specimens

The compressive strength of rock samples was determined indirectly using Protodyakonov's apparatus. Protodyakonov index for estimation of compressive strength of rock samples is an indirect and time-consuming method. However, it was chosen as rock samples of a particular type were limited in the laboratory. Therefore, first sound level measurement using drilling was carried out. Then the same drilled rock block was used for determining compressive strength and abrasivity. It was difficult to prepare samples for determining uniaxial compressive strength from these drilled rock blocks.

Five samples weighing 50 g each of a particular rock was separately taken in a Protodyakonov's apparatus. Five blows (n) were given using a weight of 1.8 kg from a height of 0.6 m. This material ($5 \times 50 = 250$ g) was then transferred to a 500 μm sieve. The fines which pass through the sieve were taken in a volume meter (measuring cylinder) and the height of the column (h) was noted down. Protodyakonov's strength index (PSI) $= (20n)/h$, where n is the number of blows $= 5$, and h is the 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).

Abrasion test measures the ability of rocks to wear the drill bit. 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 as per International Society of Rock Mechanics (ISRM) standards [18]. For this purpose, Los Angeles abrasion test apparatus was used. The abrasion test requires two different sizes of rock samples i.e., 19.0–13.2 and 13.2–9.5 mm. One set of test samples of (2500 ± 10) g 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) g was prepared so that they pass through a sieve of 13.2 mm and are retained on a 9.5 mm sieve. Both the test samples are placed in the Los Angeles abrasion testing machine. The abrasive charge consists of cast iron spheres approximately 48 mm in diameter and each weighing between 390–445 gm. The machine is rotated at a speed of 20–30 revolutions per minute for a period of 15 min. 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 g) $\times$ 100%.

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

Table 2
Compressive strength and abrasivity of different rocks

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

3.3.3. Noise measurement

A set of four test conditions were 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–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

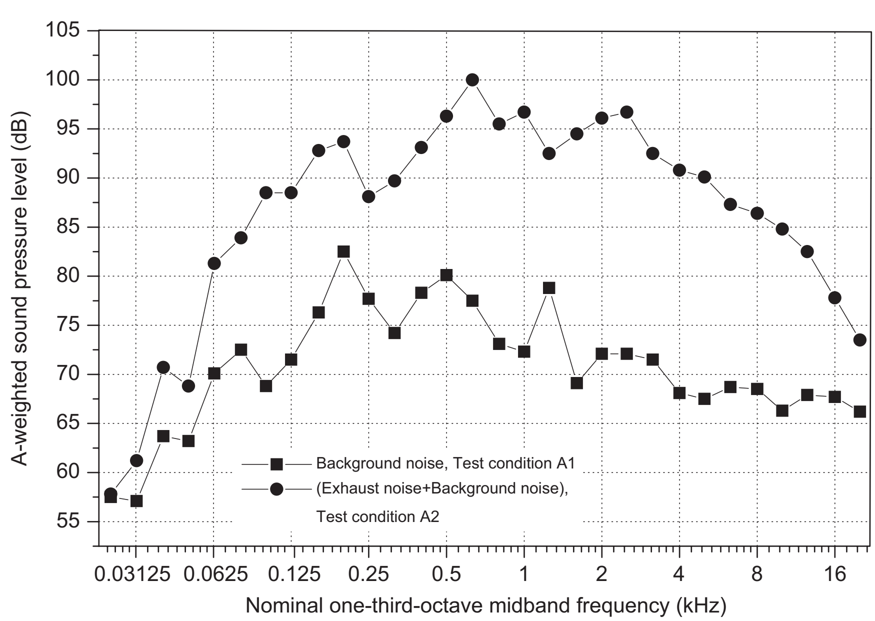

Fig. 2. Effect on L_{eq} levels at the operator's position for test conditions A1 and A2.

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 conditions A3 and A4 refersto measurement of noise spectra during drilling at the operator's position with 100 and 300 N thrust, respectively.

For measuring the variation in sound level while drilling in rocks of different compressive strength and abrasivity, the rock blocks were kept beneath the integrated drill rod of the pneumatic drill. Sound level measurements were carried out for thrust values of 160, 200, 300 and 360 N on each rock block. 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 (L_{eq}) 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 L_{eq} level was measured at the operator's position for each thrust of 160–360 N and air pressures of 5–7 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 block, the sound level was determined five times in relatively rapid succession. The arithmetic average of the A-weighted sound pressure levels from each set of five measurements was computed to yield an average A-weighted sound level for a particular condition.

4. Results and discussion

4.1. 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 increase in compressive strength of rock samples, the abrasivity decreases. This is due to increase in the resistance of rocks to wear with increase in the compressive strength.

4.2. Noise assessment of pneumatic 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. 2. 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 conditions A2 relative to that of test condition A1. Therefore, the sound level in the

Table 3
L_{eq} level at the operator's position for different rocks at various thrust and air pressures

Air pressure (kg/cm^2)	Thrust (N)	Shale	Hematite	Limestone	Granite	gabbros
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

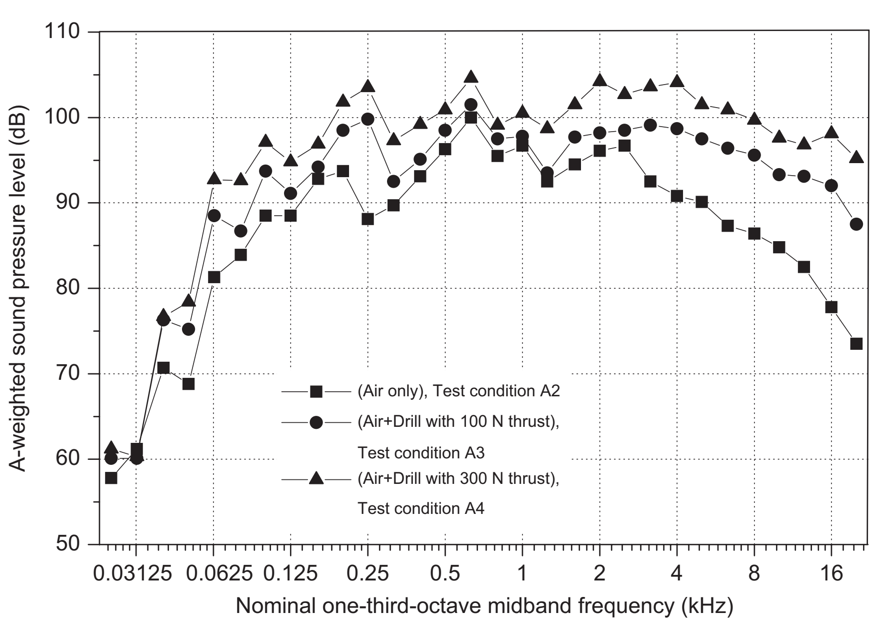

Fig. 3. Effect on L_{eq} levels at the operator's position for test conditions A2–A4.

frequency range of 63 Hz–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–A4 are shown in Fig. 3. 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 [19–22]. 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 1.0–11.7 dB and that of A4 relative to that of A3 is in the range of 1.6–6.0 dB. The noise in this frequency range 125 Hz–2 kHz is due to the exhaust of the drill machine [19–22]. The combination of drilling noise and exhaust noise has resulted in increase of sound level in this frequency range 125 Hz–2 kHz.

There is significant increase in sound level of the order of 6.6–14.2 dB from 2.5 to 20 kHz for test condition A3 relative to that of A2 and 4.0–7.7 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 due to rock drilling [19–22].

4.3. *Effect of rock properties on sound level of pneumatic drill*

4.3.1. *At operators position*

The L_{eq} level at the operator's position for different rocks of varying strength at various thrusts and air pressures are given in

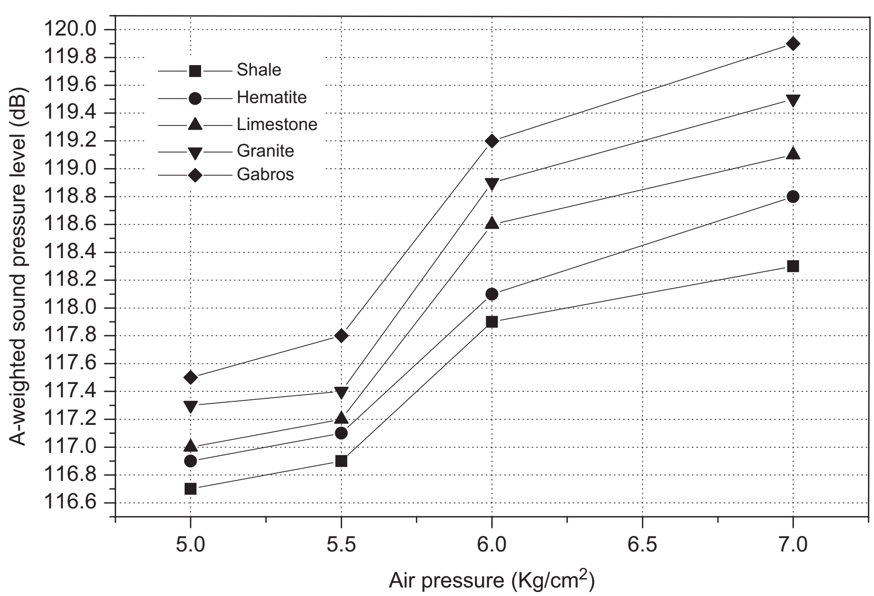

Fig. 4. Effect of air pressure on sound level at the operator's position at a constant thrust of 160 N for different rock blocks.

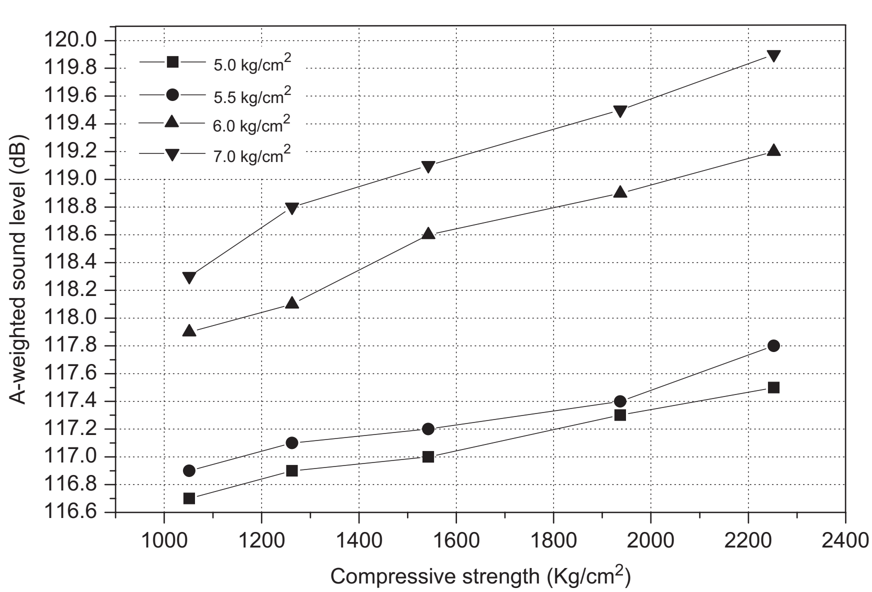

Fig. 5. Effect of compressive strength of rock on sound levels at the operator's position for a constant thrust of 160 N and different air pressures.

Table 3. In this table, the compressive strengths of rocks are given in increasing order i.e., shale has the lowest compressive strength and the highest abrasivity whereas gabbro has the highest compressive strength and the lowest abrasivity. At an air pressure of 5 kg/cm^2 and thrust of 160 N, the difference in A-weighted sound level for different rocks was of the order of 0.8 dB, which varied from 0.8 to 1.4 dB with an increase in the 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 different rocks was 0.9 dB. At this air pressure (5.5 kg/cm^2), an increase in the thrust from 160 to 360 N caused an increase in the sound level by 1.6 dB. Similar results were observed at air pressure of 6 and 7 kg/cm^2, respectively, with an increase in the thrust from 160 to 360 N.

The effect of air pressure on sound levels at constant thrust of 160 N for different rock samples at operator's position is shown in Fig. 4. 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 Block-1 increased by 1.6 dB. Similar results were shown by other rock samples too. The increase in sound level for different rocks (Block-1 to Block-5) with an increase in the 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 effect of compressive strength of rock on sound level at operator's position for a constant thrust of 160 N and for different air pressure values is shown in Fig. 5.

The above result shows that an increase in the compressive strength and a decrease in the abrasivity of rocks increase the sound level. It is worth mentioning that, to maintain optimum penetration rate, the thrust and air pressure must be increased in rocks having higher compressive strength and lower abrasivity, which in turn results in higher sound levels.

Table 4
L_{eq} level at exhaust for different rocks at various thrust and air pressures

Air pressure (kg/cm^2)	Thrust (N)	Shale	Hematite	Limestone	Granite	gabbros
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

4.3.2. At exhaust

The effect of compressive strength and abrasivity of rocks on sound levels at exhaust is given in Table 4. A significant increase in the sound level with an increase in the compressive strength and a decrease in the abrasivity is observed for different rocks. For instance, the difference in A-weighted sound level for Block-1 and Block-5 is 2.2 dB at constant air pressure and thrust of 5 kg/cm^2 and 160 N, respectively. The variation of sound levels in all the five rocks 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. 6. It can be seen that, with an increase in the compressive strength and a decrease in the abrasivity of rocks, the L_{eq} 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 different rocks at the exhaust. The effect of compressive strength of rock on sound level at exhaust for a constant thrust of 160 N for different air pressure values is shown in Fig. 7. An increase in the air pressure by 2 kg/cm^2 at a constant thrust of 160 N resulted in an increase in the sound level, varying

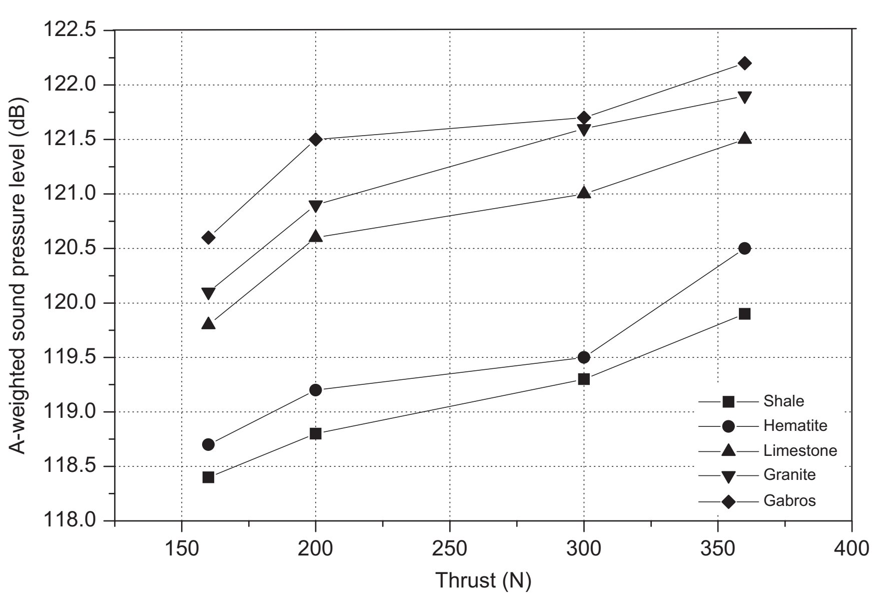

Fig. 6. Effect of thrust on sound level at the exhaust at constant air pressure of 5 kg/cm^2 for different rock blocks.

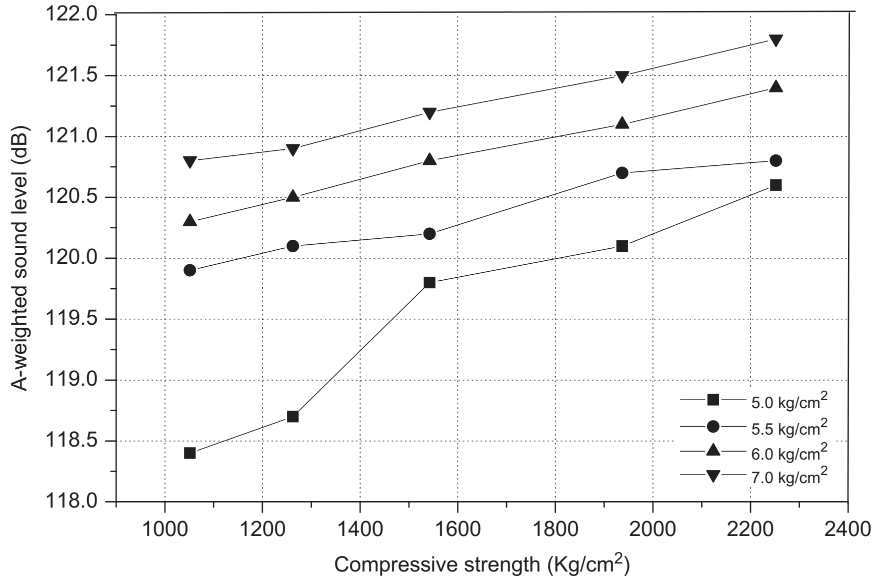

Fig. 7. Effect of compressive strength of rock on sound levels at exhaust at a constant thrust of 160 N and varying air pressure.

Table 5
L_{eq} level near the drill rod for different rocks at various thrust and air pressures

Air pressure (kg/cm^2)	Thrust (N)	Shale	Hematite	Limestone	Granite	gabbros
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

from 1.2 to 2.4 dB for different rock properties. This shows that, both thrust and air pressure has a significant effect on sound level produced by pneumatic drill at the exhaust.

4.3.3. *Near drill rod*

The L_{eq} level near the drill rod for rocks having varying compressive strength and abrasivity at various thrusts and air pressures is given in Table 5. Maximum increase in the sound level with an increase in the compressive strength and a decrease in the abrasivity was observed near the drill rod compared to that of other positions. The sound level difference at an air pressure of 5 kg/cm^2 with 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 shale and gabbro varied from 2.2 to 2.4, 2.1 to 2.5 and 1.7 to 2.2 dB, respectively. The above discussion clearly indicate that the variation in the compressive strength and abrasivity of rock has a significant increase in the sound level near the drill rod, which could be higher sound level near the drill rod as the compressive strength increases.

Both the air pressure and thrust were observed to have a significant effect on the sound level produced near the drill rod. For instance, an increase in the air pressure by 2 kg/cm^2, at a constant thrust of 160 N caused an increase in the sound level varying from 1.4 to 2.6 dB. Similarly, an increase in the sound level with an increase in the thrust of 200 N at an air pressure of 5 kg/cm^2 varied from 1.4 to 2.2 dB for rocks having varying properties.

The effect of the compressive strength of rock on the sound level near the drill rod at a constant thrust of 160 N and varying air pressure is shown in Fig. 8.

4.3.4. *Near the drill bit*

The effect of compressive strength and abrasivity of rock on the sound level near the drill bit at various thrust and air pressure is given in Table 6. In general, an increase in the sound level is observed at each thrust and air pressure with an increase in the compressive strength and a decrease in the abrasivity of the rocks. The difference in the sound level at an air pressure of 5 kg/cm^2 and with an increase in the 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 in different rocks varied from 1.2 to 2.1 dB, respectively. This shows that an increase in the compressive strength and a decrease in the abrasivity of rock increase the sound level significantly.

In this case also, both air pressure and thrust were observed to have a significant effect on the sound level. For example, an increase in the air pressure by 2 kg/cm^2 at a constant thrust of 160 N indicated an increase in the sound level of 1.7 dB for Block-1 and 1.0 dB for Block-2 to Block-5. An increase in the sound level with an increase in the thrust of 200 N at an air pressure of 5 kg/cm^2 was 1.8 dB for shale, 1.1 dB for hematite and limestone, 0.9 dB for granite and 0.8 dB for gabbro. The effect of compressive

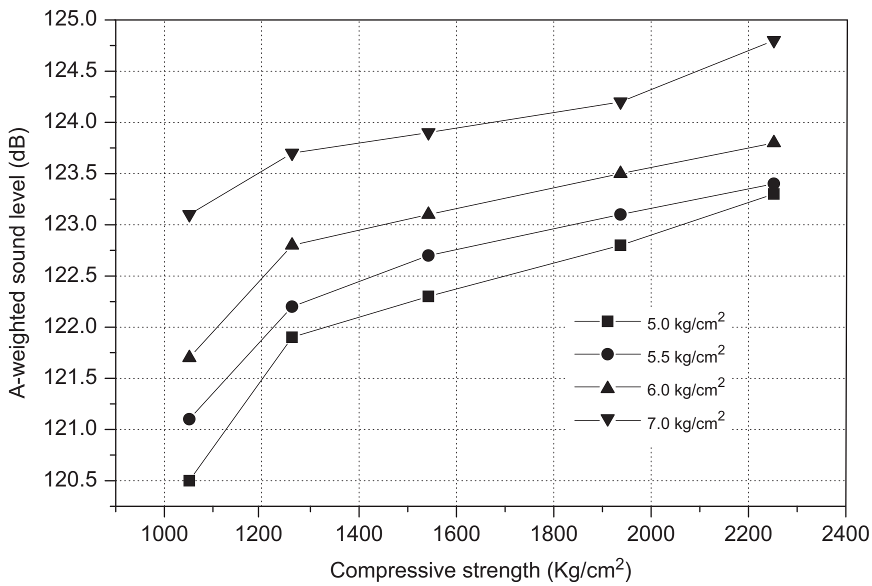

Fig. 8. Effect of compressive strength of rock on sound level near drill rod for a constant thrust of 160 N and varying air pressure.

Table 6
L_{eq} level near drill bit for different rocks at various thrust and air pressures

Air pressure (kg/cm^2)	Thrust (N)	Shale	Hematite	Limestone	Granite	gabbros
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

strength of rock on the sound level near the drill bit for a constant thrust of 160 N for different air pressure values is shown in Fig. 9.

5. Conclusions

The sound level in the low frequency range of 50–100 Hz is due to impact between the piston and the drill steel and also between the drill steel and the rock. Sound level in the frequency range of 125 Hz–2 kHz is 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. 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 relatively 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 0.5–1.5 dB higher relative to that at drill bit, 2.0–3.0 dB higher relative to that at the exhaust and 4.0–6.0 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 with drilling in rocks of higher compressive strength.

Both the thrust and air pressure were found to have a significant effect on the sound level produced by pneumatic 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 1.5–2.5 dB at the operator's position can result with increase in air pressure by 2 kg/cm^2 at 160 N thrust and with 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 1.5–2.0 dB with 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 increase in compressive strength and decrease in abrasivity of rock from shale to gabbros is of the order of 1.0–2.0 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 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 and therefore will result in higher sound level at the operator's position.

The study shows that, estimation of rock properties using sound levels produced during drilling can be a very useful technique for the purpose of selecting suitable explosives and designing blast hole patterns. The laboratory testing will give the rock properties. Similar study in the field will indicate rock mass properties, which are essential for rock excavation planning and

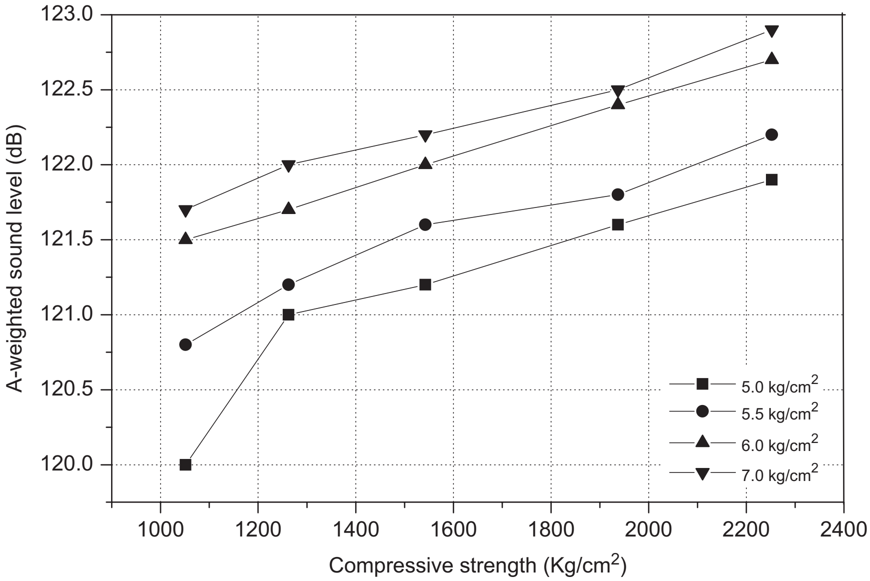

Fig. 9. Effect of compressive strength of rock on sound levels near the drill bit for a constant thrust of 160 N and varying air pressure.

design. The present investigation is a new attempt for further research in this direction.

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