CHAPTER 4

# MATERIAL AND METHODOLOGY

## 4.1 Introduction

All the experimental parameters, procedures, and data analysis, adopted in this laboratory-based

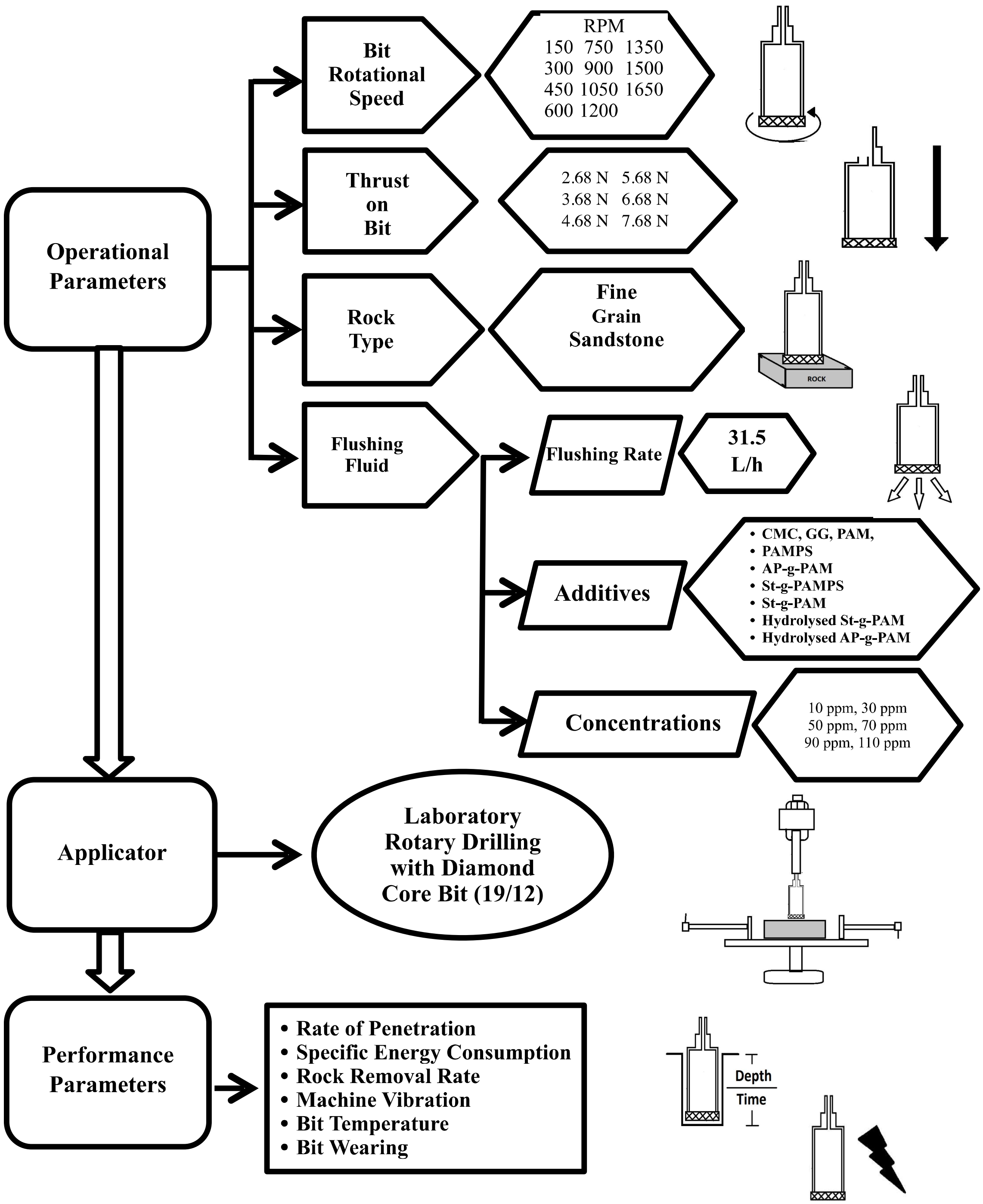



Fig. 4.1: Flow-chart of Experimental Parameters

research work, are discussed in this chapter. A detailed flow-chart is also presented covering all these aspects.

## 4.2 Experimental Parameters

A detailed flow-chart presenting the various parameters considered in this experimentation, is given in Fig. 4.1.

### 4.2.1 Bit Rotational speed

In this experimentation, the effect of 12 variations in bit rotational speed have been identified on several performance parameters (shown in Fig 4.1).

### 4.2.2 Thrust on Bit

Six different types of weight bar combinations have been used in laboratory drilling experiments. These weight bars were used to apply constant load on bit-rock interaction surface via the bit - so this parameter can also be called as ‘Weight’ or ‘Load’ on bit and having  expressed in the unit of ‘N’.

### 4.2.3 Rock Type

The ‘Balua Patthar’ (sandstone) from the Chunar region (U.P., India) is having a Geographical Indication (GI) tag under the natural goods category. This stone is a reddish or buff-colored hard stone, which made it widely useful in architectural work. Also, ’The Pillars of Ashoka’, a notable monument of India, was carved from this stone. The raw rock slabs of this fine grain sandstone rock also known as ‘Chunar stone’, were brought from a sandstone quarry, situated near Chunar town in the Mirzapur district of Uttar Pradesh.

#### 4.2.4 Flushing Fluid

As drilling fluids, the aqueous solution of 5 different concentrations of 7 various polymeric additives, and tap water alone have been experimented with. The aforesaid combination of drilling fluids has facilitated to get a total of 36 different variations as shown in Fig. 4.1.

### 4.3 Experimental Procedures

In laboratory experiments, a sequential occurrence of various procedures bears a crucial role in the effectiveness of experiments. Salient procedures adopted in this research work can be divided into two categories, namely, (a) for operational parameters, and (b) for output parameters. The chronological order of procedures is listed for both types of procedures, as follows.

#### 4.3.1 Procedure for Applying Operational Parameters

- Rock sample preparation
- Preparation of additives
- Preparation of drilling fluid
- Flushing rate measurement
- Attaching drill bit
- Clamping and adjusting of sample
- Video recording process
- Applying drilling fluid
- Applying rotational force to the bit
- Applying weight on bit
- Implementing RPM feedback

All the above procedures are briefly discussed below.

#### *4.3.1.1 Rock Sample Preparation*

The sandstone slabs were resized into small cuboid-shaped samples with a disk saw cutter in the departmental workshop (Fig. 4.2).


Fig. 4.2: Picture of sandstone slab cutting on disk saw

As per the limitations of the laboratory setup, the critical dimensions of a rock sample that can be drilled with this setup ( i.e. 40 cm (W) × 23 cm (L) × 23 cm(H)), have to be kept in consideration as upper limit, while preparing the samples.

#### *4.3.1.2 Preparation of Additives*

The polymers are having many properties, like viscosity, shear stability, and temperature resistivity, etc., which made them advantageous for the improvement in the drilling performance in difficult situations. In this study, various types of polymeric additives namely, natural polymer, synthetic polymer, grafted polymer, and hydrolyzed polymers have been prepare in the chemistry laboratory and used in drilling. The 'carboxymethyl cellulose' (CMC) and 'guar gum' (GG) are natural polymers originated by plants, whereas 'polyacrylamide' (PAM) and 'poly-2-Acrylamido-2-methyl propane sulfonic acid' (PAMPS) are synthetic polymers, prepared by the polymerization process. The polymerisation process to prepare polyacrylamide (PAM), and the approach upto powder preparation are given in Fig.4.3. The same process was followed for PAMPS too.

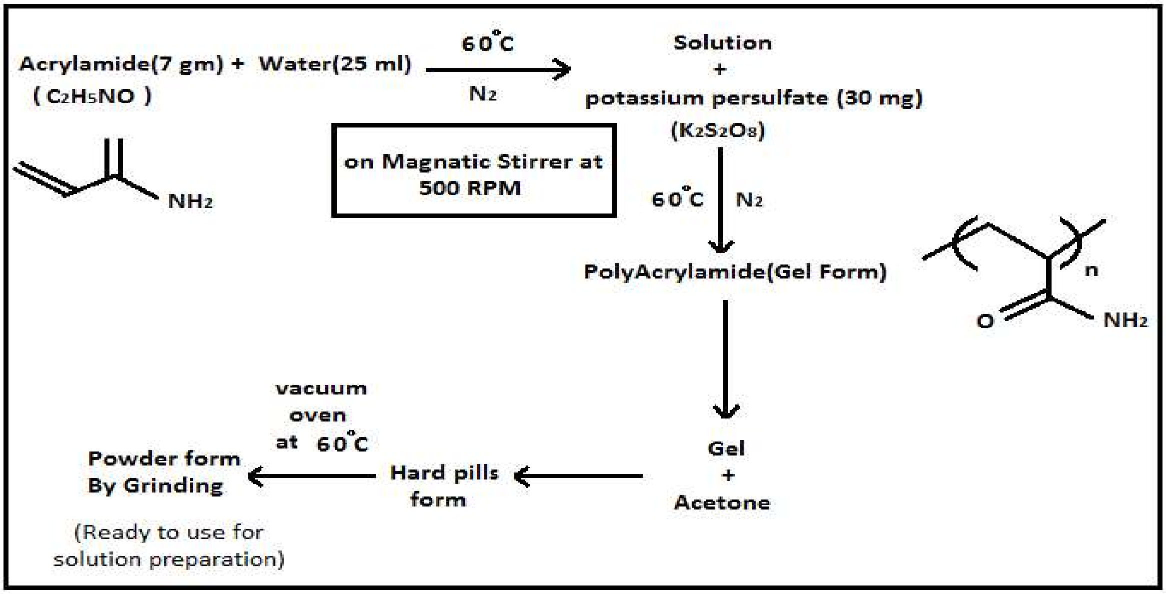



Fig. 4.3: Preparation of polyacrylamide additive

In polymer grafting process, the PAMPS was grafted on a starch (St) backbone to prepare 'St-g-PAMPS'. For grafting of 'St-g-PAM', and 'AP-g-PAM', the PAM was grafting on starch (St) and amylopectin (AP) backbone respectively. The process followed for the grafting of St-g-PAM is

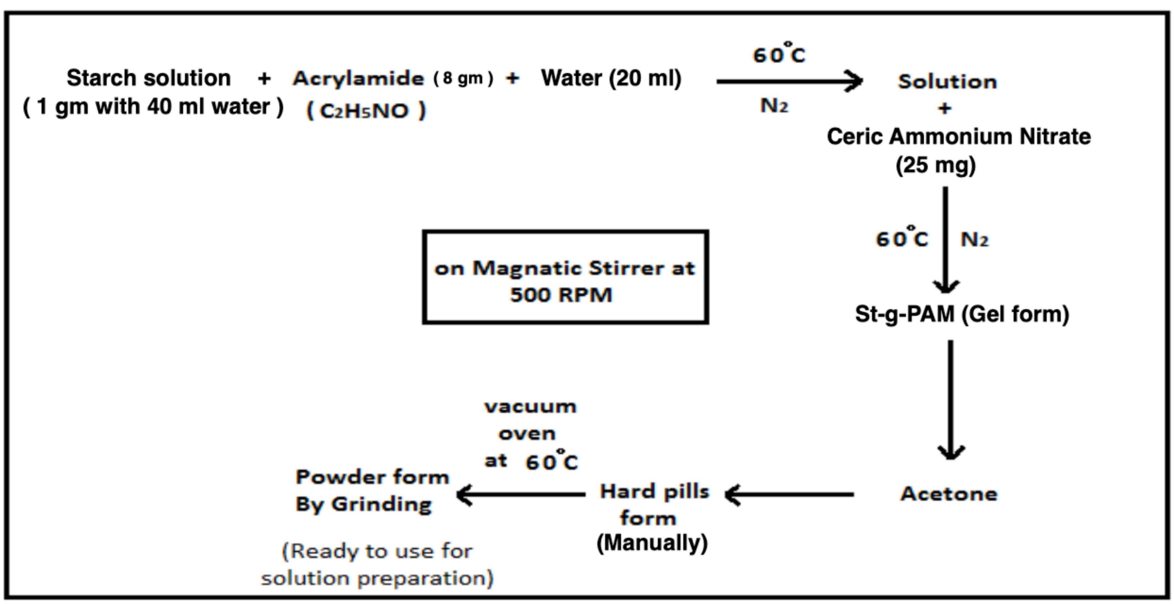



Fig. 4.4: Preparation of St-g-PAM additive

shown in Fig. 4.4, and the same process was followed for AP-g-PAM too. Further more, the St-g-

PAM', and 'AP-g-PAM' were hydrolyzed to prepare 'hydrolyzed St-g-PAM 'and 'hydrolyzed AP-g-PAM', as shown in Fig. 4.5. For better understanding, the molecular structure of aforesaid polymer additives is shown in Table 4.1.

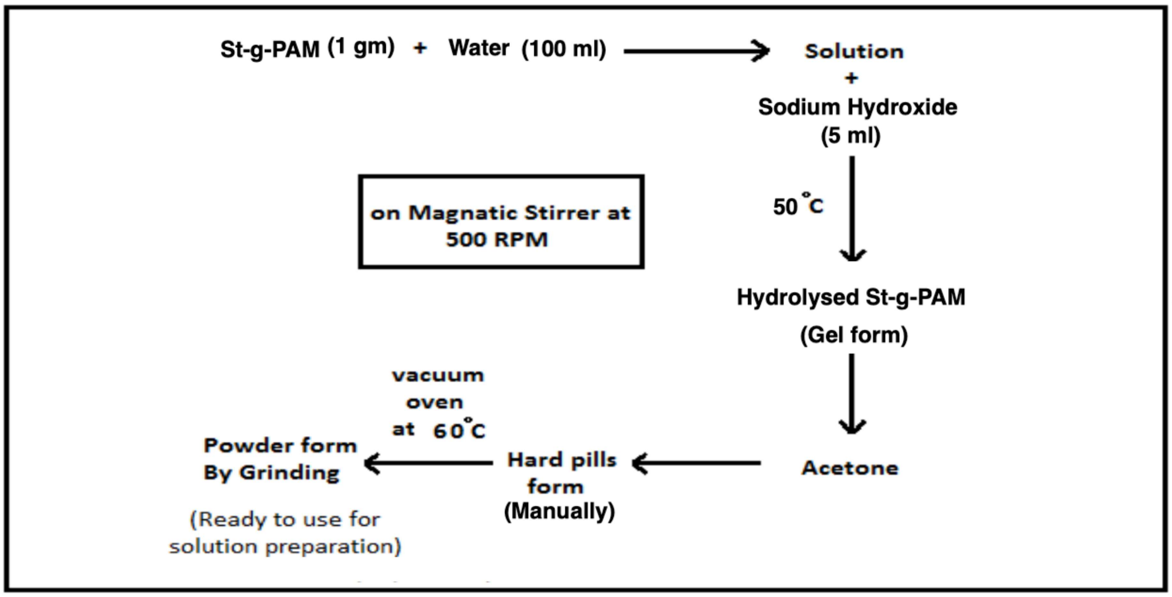



Fig. 4.5: Preparation of hydrolysed St-g-PAM additive

Table 4.1: Chemical structures and parameters of drilling fluid additives

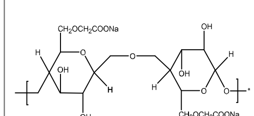
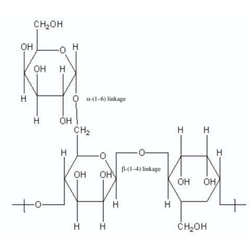
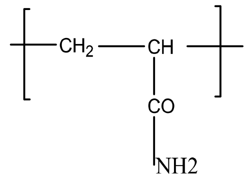
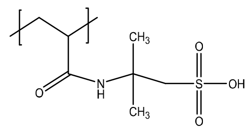
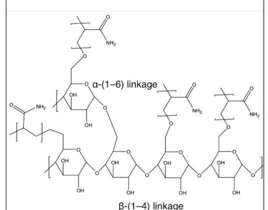
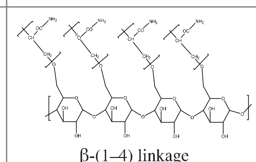
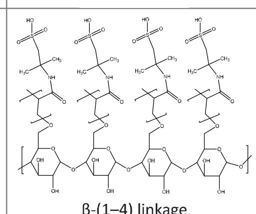
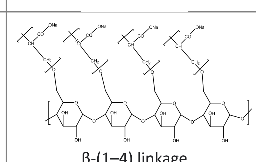
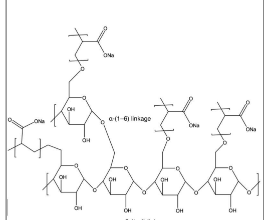
| Sr. | Additive | Type | Chemical Structure | Con$^{n}$. | Shear Rate Viscosity at 100/s (pascal) | Reference. |
|---|---|---|---|---|---|---|
| 1 | Water | - | - | - | 0.001 | Shin et al 2001 |
| 2 | Carboxy Methyl Cellulose (CMC) | Modified Poly-saccharide |  β-(1, 4) glycosidic linkages | 1% | 0.985 | Tatsawan et al 2008 |
| 3 | Guar Gum (GG) | Natural Poly-saccharide |  | 1% | 0.578 | Tatsawan et al 2008 |

Table 4.1: Chemical structures and parameters of drilling fluid additives

| | | | | | | |
|---|---|---|---|---|---|---|
| 4 | Polyacrylamide (PAM) | Synthetic Polymer |  | 1.5% | 0.91 | Bird et al. 1977 |
| 5 | PAMPS | Synthetic Polymer |  | 0.5% | 0.6 | Jingyuan et al. 2020 |
| 6 | AP-g-PAM | Grafted Polymer |  | 0.5% | 0.025 | Singh et al. 2009 |
| 7 | St-g-PAM | Grafted Polymer |  | 1% | 0.067 | Eutamene et al. 2009 |
| 8 | St-g-PAMPS | Grafted Polymer |  | 1.2% | 0.450 | Yifei 2018 |
| 9 | Hydrolysed St-g-PAM | Hydrolysed polymer |  | 2% | 0.63 | Soleeimani et al. 2013 |
| 10 | Hydrolysed AP-g-PAM | Hydrolysed polymer |  | 0.2% | 0.07 | Singh et al. 2009 |

#### *4.3.1.3 Preparation of Drilling Fluid*

The various additives prepared by different chemical processes were in powder form. To utilize them as fluid in drilling operations, aqueous solutions have been prepared in two steps. Initially, a master or stock solution was prepared, having a concentration of 1000 ppm, by making a homogeneous mixture of 100 mg additive with 100 ml distilled water. The mixture was prepared by stirring the solution for 48 hours at 500 RPM, as shown in Fig. 4.6.

According to the desired concentration of drilling fluid (i.e. 10 ppm, 50 ppm, 50 ppm, 70 ppm, and 90 ppm, etc.) required in experimentation, the master solution is diluted with tap water. For example, to prepare a drilling fluid of 10 ppm concentration, 10 ml of master solution is diluted with 990 ml water.

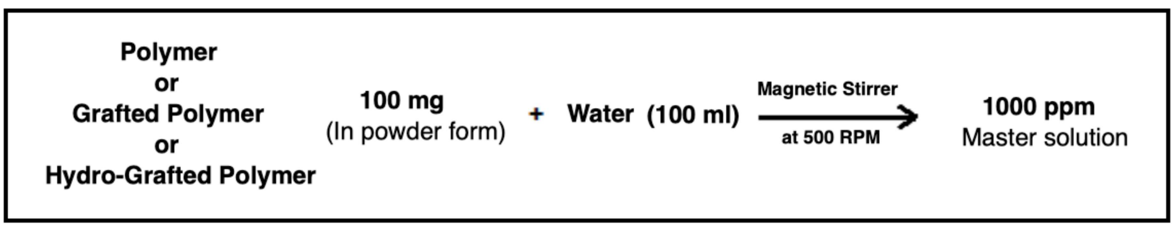



Fig. 4.6: Preparation of master solution

#### *4.3.1.4 Flushing Rate Measurement*

The flushing rate can be defined as the quantity of fluid circulated during the drilling operation in unit time, expressed in litre per minute (l/min). It was identified by collecting the fluid flow from the bit in the defined time interval. A measuring cylinder (Fig. 4.7) is put just below the drill bit in such a way that the total amount of fluid passing through the bit is directly collected in the cylinder. The flow can be control with a pump switch and flow rate adjuster (‘**P**’ in Fig. 3.2).


Fig. 4.7: Picture of Fluid Flow Rate Measurement Arrangement

#### *4.3.1.5 Attaching Drill Bit*

The drill bit is attached to the bit holder (‘**e**’ in Fig 3.2) with “T-key” manually and tightened it properly.

#### *4.3.1.6 Clamping and Adjusting of Rock Sample*

The rock sample was placed on the platform and manually clamped between screw jaws by adjusting individual jaw plates. With the help of the height adjuster handles (‘**q**’ in Fig 3.2), the height and position of the drill plate were set as required.

#### *4.3.1.7 Video Recording Process*

The video recording of the whole setup was started just prior to the initialization of the power source for the drilling setup and stopped after the completion of the drilling process. Afterward, the recorded video has been analyzed to collect the data regarding the depth of the hole, time-interval, power fluctuation, energy consumption, volt & ammeter readings. These values were collected against the three different stages of operation namely the initial, intermediate, and final stages. In the intermediate stage of the drilling operation, there may be multiple segments as per the requirements like, based on unit time, depth, and energy. This has supported the intra-hole drilling study.

#### *4.3.1.8 Applying Drilling Fluid*

The flushing pump was started with a switch attached to the control panel, just after the power initiation of the drilling setup. The predefined optimum flow rate was set prior to the operation. The fluid flows from the tank to the bit-rock interface and cleans the drill cuttings. It should be taken care that the pump remains completely submerged in the drilling fluid.

#### *4.3.1.9 Applying Rotational Force to the Bit*

To achieve the required RPM of the bit, the rotational force is applied with the help of an RPM controller ('**T**' in Fig 3.2) and an electric motor ('**t**' in Fig 3.2).

#### *4.3.1.10 Applying Weight on Bit*

To apply constant load on the bit, weight bars were placed into the bucket hanging at the free end of the pulley loading mechanism. The depth limiting assembly was used to hold this load until the operation starts, by sliding the 'limiting bolt' nearest to the 'base bolt', as described in sub-heading 3.3.6, This situation can be defined as 'zero position' of the bit. On the commencement of operation, the limiting bolt was released by up-lifting the handle ('**b**' in Fig 3.2). Thereafter, the bit rotating at pre-defined RPM was lowered down by releasing the handle 'b' gently, to avoid any jerk on the rock sample.

A precaution needed to be taken care about the swinging of the cage while drilling operation is in progress. The weight of the bit, spindle, and loading bucket constitute the dead load i.e. 2.68 kg (as discussed in sub-chapter 3.2.1), which constantly acts applying force on the bit-rock interface along with the weight bars. So, while calculating the thrust on bit, the dead load was added to the load exerted by weight bars in the bucket.

#### *4.3.1.11 Implementing RPM Feedback*

As the drill bit reaches the desired depth in the rock strata, the frictional force is exerted on the side walls of the bit by the surrounding rock, which causes reduction in the bit rotational speed. The drop was sensed by the RPM sensor (tagged ‘s’ in Fig 3.2) and displayed on the digital RPM meter as feedback. Afterward, the RPM controller was manually adjusted to maintain the desired constant RPM of the drill bit.

### 4.3.2 Procedure to Measure Output Parameters

- Hole dimensions measurement
- Time measurement
- Energy, power, ampere, and voltage measurement
- Machine vibration measurement
- Bit temperature measurement
- Bit weight measurement

All the above procedures are discussed below.

#### *4.3.2.1 Hole Dimension Measurement*

The depth and diameter of the drilled hole are measured by a mechanical vernier caliper scale having least count of 0.01cm. Every hole is measured 3 times at different positions, so the possibility of manual error in measurement could be minimised by taking the average value of depth into consideration. Also, the recorded video was used to collect intra-hole readings.

#### *4.3.2.2 Time Measurement*

The time taken for drilling in rock was measured with the help of recorded video.

#### *4.3.2.3 Energy, Power, Ampere, and Voltage Measurement*

The readings of the energy meter, wattmeter, ampere, and voltmeter were collected from the recorded video, as discussed in the video recording process of sub-heading 4.3.2.

#### *4.3.2.4 Machine Vibration Measurement*

The vibration acceleration of the drill spindle for the duration of the complete drilling operation was recorded by the readout unit and displayed as root mean square (RMS) values and vibration total values (VTV). The detailed per second data on vibration were also collected from the excel file imported from the internal storage of the readout unit.

#### *4.3.2.5 Bit Temperature Measurement*

The temperature of the drill bit's cutting edge has been recorded prior to starting drilling operation with the help of a K-type thermocouple. Then after the completion of drilling for predefined depth of hole i.e. 5 cm (as per the limitation of setup), the machine was shut down manually. And, immediately within 5 seconds of shut-down, the temperature of the bit was measured again from the surface of the cutting edge. This 5 second time was required to pull out the bit from the hole and to re-clamp it at zero position, as described in sub-heading 4.3.1.

#### *4.3.2.6 Bit Weight Measurement*

The weight of bit was measured prior to the starting of drilling process. And, after drilling up to the cumulative total depth of 500 mm, the drill bit was detached from the machine assembly for further processing. It has been washed under pressurized water flush and cleaned thoroughly from outside and inside, using a cotton cloth. Afterward, the bit was heated in a hot air oven at 100 $^{0}$C for 2 min to make it dry and weighted on digital sensitive balance, which was capable of providing accuracy up to 4 decimal points.

### 4.3.3 Instruments Used for Data Collection

The instruments used for the measurement of various parameters are given in Table 4.2, along with their least count.

Table 4.2: Instruments Used for the Measurement of Parameters

| Sr. | PARAMETER | INSTRUMENT | Least Count |
|---|---|---|---|
| 1 | Time | Stop watch | 1 s |
| 2 | Bit Rotation speed | RPM Sensor | 1 RPM |
| 3 | Energy | Milli ampere energy meter | 0.001 kWh |
| 4 | Fluid Flow Speed | Measuring cylinder and stop watch | 1 ml/s |
| 5 | Bit Length | Vernier Caliper | 0.002 mm |
| 6 | Hole Dia | Vernier Caliper | 0.002 mm |
| 7 | Depth | Vernier caliper | 0.002 mm |
| | | Machine mounted scale | 1 mm |
| 8 | Video* | 4k video recorder | 1/8 s |
| 9 | Vibration | Vibration analyser | $ms^{-2}$ |
| 10 | Bit Temperature | K- type Thermocouple | 0.1 °C |
| 11 | Bit Weight | Digital weighing machine | 0.001 g |

*The recorded video can be used to measure all the parameters for Sr. nos. 1-7, shown in Table 4.2.

## 4.4 Data Analysis

The output data generated by the implementation of operational parameters were used to calculate the performance of drilling operation in the form of the following factors namely, rate of penetration (ROP), specific energy consumption (SEC), Rock removal rate (RRR), bit vibration, bit wearing, and bit temperature. Calculation of drilling performance parameters are described hereunder.

### 4.4.1 Rate of Penetration (ROP)

The ROP can be defined as the rate at which the drilling bit penetrates the rock. It can be calculated as the ratio of the depth of hole achieved to the time taken in drilling, as shown in Eq. (4.1). Also, the ROP at intermediate stages can be calculated to understand the fluctuations in it.

$$ROP = \frac{Depth\ of\ hole\ (mm)}{Time\ Taken\ in\ Drilling\ (sec)}$$

**… Eq. (4.1)**

### 4.4.2 Specific Energy Consumption (SEC)

It can be defined as the rate at which the energy is consumed in drilling unit volume of the rock mass. To calculate the SEC, a ratio of total energy consumed in drilling to the volume of the hole drilled, can be used, as shown in Eq. (4.2).

$$SEC = \frac{Energy\ Consumption\ in\ Drilling\ (kWh)}{Volume\ of\ hole\ (mm^3)}$$ **… Eq. (4.2)**

Here, the volume of the hole can be calculated by the following formula:

$$\text{Volume of hole (V)} = \frac{\pi l(D^2 - d^2)}{4},$$

where,

'$l$' = Depth of hole (mm)

'D'= Outer dia. of hole = 19 mm

'd'= Inner dia. of hole = 12 mm

So, V = $170.345 \times l$ $mm^3$

***Energy Consumption in Drilling***

The energy meter shows the cumulative sum of electrical energy ($E_T$) consumed consisting of two-component - constant energy consumed by the whole setup, and energy required to drill the hole ($E_D$). Energy consumed by the setup is due to motor consumption ($E_{RPM}$) at no-load condition (when no drilling takes place), this value has a constant rate of energy consumption for individual RPM.

To identify the energy consumption in drilling operation, the difference of initial and final reading of energy meter was considered as total consumption. Thereafter, the energy consumption in no-load condition for drilling time was subtracted from the total consumption. For better understanding, the aforesaid methodology is shown below as formula in Eq. (4.3) and Eq. (4.4).

*Formulation*:

$$Total\ electrical\ energy\ consumption\ (ET) = Final\ energy\ reading\ (E2) - Initial\ energy\ reading\ (E1) \ldots Eq.(4.3)$$

$$Energy\ consumption\ in\ drilling\ (ED) = ET - (ERPM * t)\ \ldots\ldots\ldots Eq.(4.4)$$

Where;

$E_T$: Total energy consumption

$E_1$: Initial energy meter reading at first interaction of bit and rock

$E_2$: Final energy reading at the completion of drilling a hole

$E_D$: Energy consumption due to drilling only

$E_{RPM}$: Constant energy consumption at a particular RPM by machine

t: Time to drill a hole

### 4.4.3 Rock Removal Rate (RRR)

It can be defined as the rate at which a unit volume of drill cuttings is removed from the hole by the bit, and the unit is ‘$mm^3$/min’. It was measured from the product of cross-section of bit (mm²) and rate of penetration (mm/min), so the unit of RRR is mm³/min. This value is most useful when various drill bits of different shapes and sizes are under consideration for the study.

### 4.4.4 Bit Vibration

The vibration analyzing instrument was started prior to the initiation of the power source for setup and used to sense the vibration flections for the complete drilling operation with a sensor installed on the drill spindle and recorded in the internal memory of the vibration read-out unit.

### 4.4.5 Bit Temperature

The temperature probe of the thermocouple was touched to the cutting edge of the bit after pulling it out of the hole and the current temperature was noted from the read-out unit.

### 4.4.6 Bit Wearing

The bit weight was measured prior to the drilling operation and again after drilling of 500 mm depth. The bit was properly washed, cleaned, and dried before taking its weighting. The formula used to calculate bit weight is given in Eq. (4.5).

$$Bit\ Weight\ Loss\ = (Initial\ Weight\ Prior\ to\ Drilling) - (Final\ Weight\ after\ Drilling\ of\ FixedDepth) \ldots\ldots Eq.(4.5)$$