Evaluation of Ventilation Network through Hybrid Analytical-Numerical Approach in Underground Working Block

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Abstract
The mine environment is complex and highly dynamic due to the developments over time and surrounding climatic changes. Heedlessness to supply adequate quantity and quality of air will catalyse short and long-term ailments to the workers. Therefore, this study emerges as the new research frontier in incorporating software-assisted numerical simulation with analytical computations. This investigation assesses the existing ventilation parameters at the Bogala underground graphite mine for the propriety of the working environment. The uttermost bottom block between 240 and 275 fathoms (FM) levels was examined. The parameters were obtained through the in-field ventilation survey. Measured air quantity, psychometry, and air quality values were analysed and fed to the computer-simulated model. Moreover, the re-entry time for a development drive at 275 FM level was estimated using the throwback method. Adequacy assessment unveils that all the parameters besides air quality are inadequate at most stations for optimal mine conditions to attain maximum efficiency. Furthermore, the re-entry time after the development blast at the selected drive is meager and necessitates re-calculation for each blast. Moreover, stale air mixing and air recirculation are extant at 240 FM and 275 FM levels, respectively. Thus, mine ventilation at Bogala needs to be optimised, admitting workers' health, safety and comfort, and productivity of the mine.

Keywords: Adequacy assessment, Mine safety, Mine ventilation, Re-entry time, Throwback method, Ventsim

1. Introduction

Mine ventilation, also described as the lifeblood of a mine, is the provision of sufficient quantity and quality of air to all the working places and travel ways to dilute the hazardous and unhealthy atmospheric contaminants to an acceptable level [1],[2]. Air quantity, velocity, humidity, effective temperature, dust, and contaminants concentration are the primary ventilation parameters. The threshold limits of these parameters are hinged on tolerance to provide a safe and comfortable working environment, and the standards have been raised substantially in recent years [3]. Different countries, territories, and regions adopt various standards according to their environment and human characteristics to regulate their mines. However, achieving a safe, effective, and efficient ventilation network is cost-effective and humanitarian.

Sufficient airflow is essential to satisfy the human respiratory needs and evacuate the strata gas, diesel exhaust fumes, dust, toxic fumes of explosives, and heat [3]. Nevertheless, these requirements depend on mine operating conditions and can be assessed individually or in combination. Psychometric properties have a significant role in providing reasonable comfort conditions in the work environment, which adversely affect the performance of workers and the productivity of the mine. Moreover, excessive temperature and humidity lead to loss of interest in the tasks, coordination, and dexterity, and in the worst-case fainting, exhaustion, cramps, rash, and stroke may result [1].

The ventilation network should be optimised to deplete the contaminant gases to yield a safer environment with good air quality. Means of contaminant addition to the working environment are personnel expiration, explosive blast fumes, and combustion engine emissions [3]. The primary gases of immediate concern to human lives are oxides of Nitrogen (NO_x, NO_2), Carbon monoxide (CO), and Ammonia (NH_3); exposure to these gases above the threshold limit would even cause fatalities [5]. Thus, re-entry to the workplaces after explosions should also be considered in ventilation planning to evacuate the toxic fumes.

This study mainly focuses on mine ventilation at Bogala graphite mine, one of the deepest narrow vein mines in Sri Lanka extending up to 500 meters, which adopts the cut and fill mining method. The exhaust ventilation system, which contains one upcast ventilation shaft with a vertically fixed fan, provides fresh air to this mine. Alfred shaft is the downcast primary shaft that extends up to 72 fathom (FM) level, and the blind shaft Gabriel carries the fresh air further to the deeper levels, as shown in Fig. 1. Besides, other downcast surface openings: Karadawatha shaft and Ravanamidulla adit contribute to the primary ventilation by a significant intake and act as maintenance and emergency routes. In addition, the installation of a booster fan at 275 FM level and three auxiliary fans at 142 FM, 240 FM, and 275 FM supports the ventilation system. However, a dynamic mine climate with an average temperature of 26° C and high humidity of 70 to 80 per cent [4] urge the necessity to evaluate the existing ventilation network at Bogala mines.

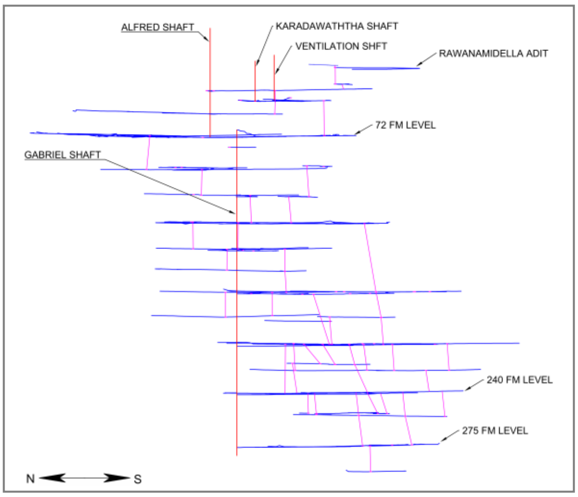

Figure 1: Ventilation Network of Bogala Mines.

2. Methodology

This assessment was performed to evaluate the adequacy of the ventilation network of a selected block between two primary levels of Bogala mines: 240 FM and 275 FM. These levels contain a higher number of workplaces and considerable air recirculation than other working levels. This study was performed through air quantity and quality survey, software-assisted numerical analysis, and analytical assessment of parameters.

2.1 Ventilation Survey

The required ventilation parameters: air quantity, psychometry, pressure, and air quality were measured through the surveys adhering to the standard practices in the selected ventilation stations during January 2019.

Cross-sectional areas of the airways were taken using the offset method. Meanwhile, the air velocity was measured using a vane anemometer (Testo 410-2) by a highly reliable fixed-point method and then validated through the traverse method. Moreover, minor airflows were measured using a low-range vane anemometer. The whirling hygrometer was utilised to obtain dry and wet bulb temperature. Further, barometric pressure at each station was recorded using a digital pressure meter (Testo 511). In addition, the concentrations of O_2, CO_2, and NH_3 were acquired using a multi-gas detector.

2.2 Air Flow Quantity Calculation

The existing airflows at the ventilation stations were calculated utilising the measurements from the survey using,

$$Q = A \times v \tag{1}$$

Where: Q = Volume flow rate (m^3/s), A = Cross-section area of the airway (m^2), v = Velocity of the air (m/s)

2.3 Numerical Simulation

The centerline model drawn using AutoCAD was imported as airways into the Ventsim software and simplified using the filter tool. The generated block model is illustrated in Fig. 2. The shape of the drives and crosscuts were set as irregular, and shaft and winzes as rectangular. Then the area measurements were fed with the calculated values and the perimeters with the standard values. Crosscuts and drives were deemed to have a rough blasted surface and shaft as average blasted surface. The Ventsim itself assigned frictional factors based on the characteristics of these surfaces.

This software model was simulated by allocating two-thirds of calculated airflow quantities as training samples. The model was executed with four iterations using the Hardy cross method [3] and validated by the rest of the calculated values. Finally, this model was utilised to obtain inaccessible and un-measurable airflow quantities for the adequacy assessment.

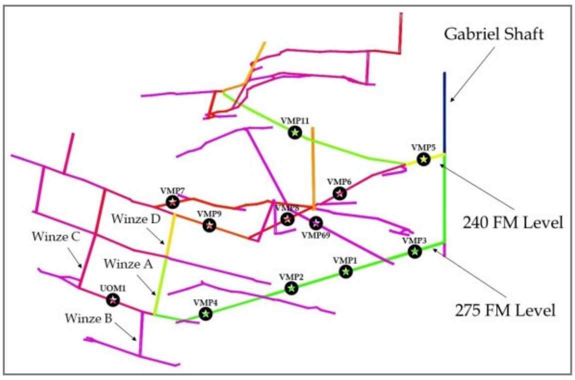

Figure 2: Ventsim model of the block between 240 FM and 275 FM.

2.4 Assessment of Parameters

Relative humidity was obtained from the psychrometric chart of 105 kPa, and the effective temperature was acquired from the effective temperature chart using wet and dry bulb temperature and air velocity. A reverse calculation was performed considering the maximum allowable effective temperature as 27° C to estimate the required air velocity. Furthermore, the required airflows for the workplaces and airways were calculated to maintain an adequate supply for persons considering the standard effective temperature.

2.5 Re-entry Time Calculation

Re-entry time after the blast in a development drive at 275 FM of 'Na' vein was ascertained by the throwback method amidst the following assumptions [1],[5],[6]:

1. Gases from explosives are evenly mixed within the throwback volume.
2. Gases are uniformly diluted over time with fresh air supply by evenly mixing in contaminated volume.
3. All the nitric oxides produced by the explosive are converted rapidly to nitrogen dioxide in the presence of air and water vapour.

Throwback distance of fume is estimated by:

$$L = \frac{KM}{FaD\sqrt{A}} \quad (2)$$

Where: L = Length of fume throw back (m), K = Constant (usually 25), M = Mass of explosives used (kg), Fa = Face advance (m), D = Density of rock (t/m^3), A = Area of face (m^2)

The time taken for the dispersion of gas to a threshold level is defined by:

$$t = \frac{V}{Q}\ln\left(\frac{G_c}{G_t}\right) \quad (3)$$

Where: t = Time to achieve target concentration (s), V = Volume of gas filled space (m^3), Q = Flow rate of fresh air (m^3/s), G_c = Initial gas concentration (ppm), G_t = Gas concentration at time t (ppm)

The explosive statistics of December 2018 were utilised to obtain the number of workplaces, explosive consumptions, and production quantities. Besides ANFO factor and water-gel factor were determined and tabulated in Table 1.

Table 1: Blast statistics of Bogala in December 2018.

Description	Value
ANFO factor (kg/m^3)	0.1707
Water-gel factor (kg/m^3)	0.4506

In addition, the required airflows for the production stopes were calculated from the reverse calculation of the throwback method.

2.6 Adequacy Assessment

Adequacy assessment was performed by correlating the measured, calculated, and simulated parameters with the standard provisions.

Table 2: Threshold limit values (TLV).

Description	TLV
NO_2 concentration (ppm)	3
CO concentration (ppm)	50

3. Results and Discussion

3.1 Ventsim Simulation

Gabriel shaft is the only intake airway to the considered block. The stale air exits to the upper levels through five winzes from 240 FM level. The model was generated considering the conservation of mass and simulated as compressible airflow, which resulted in the deviation between intake and exhaust airflow quantities. The summary of the simulated ventilation network is given in Table 3.

Table 3: Ventilation characteristics summary of simulated Ventsim model.

Description	Value
Total airflow intake (m^3/s)	15.4
Total airflow exhaust (m^3/s)	15.5
Total mass flow (kg/s)	24.3
Equivalent resistance for study area (Ns^2/m^8)	0.21886

3.2 Air Quantity

The adequacy of ventilation parameters was evaluated for each survey station located in the primary airways where the passage of men and haulage of materials occur. According to the standards emphasised in [3], the ventilation requirement for the sustenance of human life is a minimum of 0.01 m^3/s per person. It usually exceeds 0.1 m^3/s per person based on the entire mine network's functions and occasionally surpasses 1.0 m^3/s per person.

The required airflows in the working places are determined to satisfy the respiratory need of workers and maintain the maximum effective temperature, which is 0.1 m^3/s per person and 27° C, respectively. Besides, this study does not consider combustion engine emissions as mechanised equipment operates on compressed air at Bogala.

In light of this, it is found that only three stations: VMP11 at 240 FM level and VMP1 and VMP3 at 275 FM level meet the required quantity, and the rest have insufficient air supplies, as shown in Fig. 3. However, the primary ventilation system does not ventilate the production and development workplaces, resulting in no airflow; instead, compressed air is utilised.

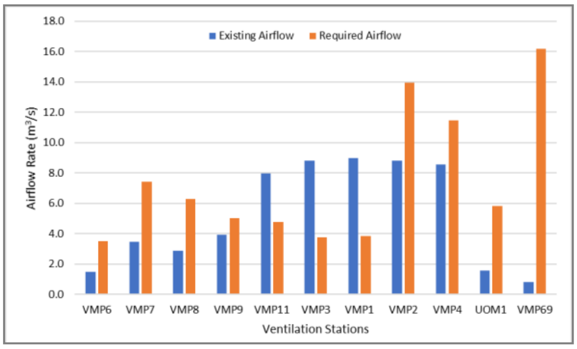

Figure 3: Existing and required airflows at ventilation stations.

Further, the required airflow for a working stope is calculated by considering the air quantity required to dilute the explosive fumes to a threshold value within 75 minutes, as shown in Table 4. In parallel, the sufficient airflow for three workers at a stope is estimated as 0.3 m^3/s, higher than the dilution requirements. Nevertheless, the effective temperature must be taken into account in further studies.

Table 4: Existing and required airflows at production stopes

Description	**Value**
Existing airflow (m^3)	0.0
Re-entry time between two shifts (min)	75.0
Time taken to fill the stope by the contaminants (min)	10.4
Time to dilute to limit (min)	64.6
Required airflow based on explosives consumption (m^3/s)	0.21
Required airflow based on number of workers (m^3/s)	0.30
Required airflow for a stope (m^3/s)	0.30

Utilising numerical simulation results of Ventsim software to obtain the existing airflow in inaccessible and unmeasurable locations is advantageous to this study. It reveals that airflows through winzes A, C, and D are adequate to supply fresh air to the adjacent stopes, as shown in Fig. 4. However, there is no proper mechanism in practice to make use of the airflows from the winzes.

The simulation unveils two potential threats of mixing fresh and stale air in the 240 FM and 275 FM levels. Stale air from the 275 FM level of the Kumbuk vein is directed to 240 FM level through winzes towards the 'Na' vein and mixes with the fresh air at the 'Na-Kumbuk' crosscut junction.

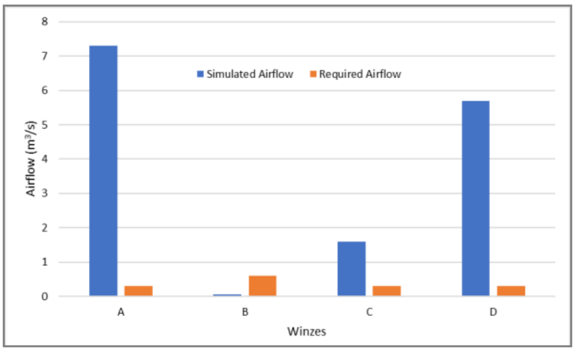

Figure 4: Simulated and required airflows at winzes.

Moreover, the axillary fan at 275 FM level of the 'Na' vein is installed incorrectly and causes recirculation in the same airway. As a result, this airway recorded the mine's highest wet and dry bulb temperature of 32° C and 100 per cent humidity, as shown in Fig. 5 and Fig. 8, respectively.

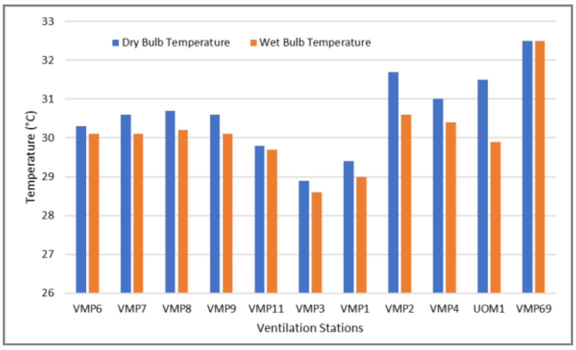

Figure 5: Dry and wet bulb temperatures at ventilation stations.

3.3 Air Velocity

The standards specified in [1] recommend maintaining the air velocity less than 4.0 m/s to avoid dust generation and provide comfort. In addition, the rule of thumb suggests maintaining the air velocity in the drift at 1.0 - 3.0 m/s and the stopes at

2.0 m/s unless it is affected by excessive cold or heat [3].

The air velocity assessment results show the stations: VMP11 at 240 FM level and VMP1 and VMP3 at 275 FM level have the adequate velocity to maintain the effective temperature within the boundary, and all other measured stations failed to satisfy the necessities as illustrated in Fig. 6. In addition, the air velocities at production stopes are nil. The required air velocities at all the stations were determined utilising analytical methods, and this revealed that none of them can re-entrain settled dust as it remains within the maximum limit.

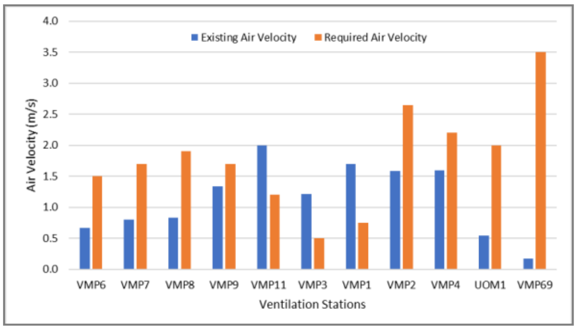

Figure 6: Existing and required air velocities at ventilation stations.

3.4 Effective Temperature

From the analytical calculations for the effective temperature, it is observed that VMP2, VMP4, VMP6, VMP8, VMP69, and UOM1 exceed the prescribed standard of 28° C, as shown in Fig. 7, which may adversely affect the duration of continuous work. Moreover, this study utilises 27° C as the reasonable threshold limit for the effective temperature.

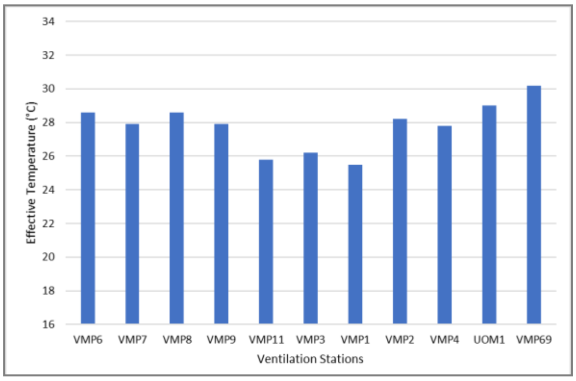

Figure 7: Effective temperatures at ventilation stations.

However, the stations VMP4, VMP7, and VMP9 surpass this limit. Moreover, according to [1], the effective temperature should be maintained lesser than 28° C for continuous work, and the work should be terminated as the temperature rises above 32° C. However, it is possible to lower the effective temperature by increasing the air velocity.

3.5 Humidity

Humidity around all the stations except UOM1 is witnessed higher than 90 per cent, as shown in Fig. 8, and it can cause fog even in the higher effective temperatures. High humidity can affect human comfort and may produce falls of roof and spalling of the sides of airways through physical and chemical reactions between the airborne water and hygroscopic minerals within the strata [1]. Moreover, high humid conditions may result in decay and corrosion as Bogala utilises timber and steel for primary supports. The natural wet condition of the mine and wet drilling practices exacerbate dust problems, though it is the main reason for the high humidity. However, a comprehensive study on dust must be carried out to ensure the quality of air.

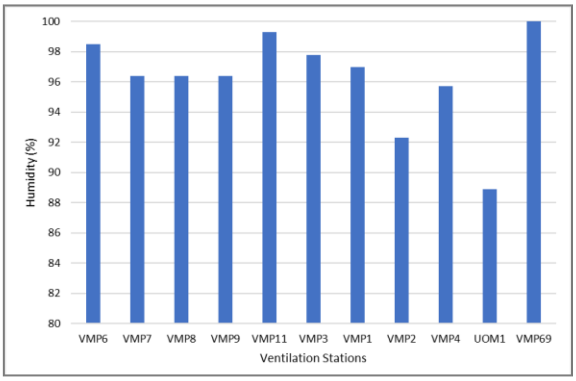

Figure 8: Humidity levels at ventilation stations.

3.6 Air Quality

Gas concentration measurements tabulated in Table 5 imply that the occupational level of O_2, CO_2, and NH_3 are within the acceptable limits in the primary airways.

Table 5: Presence of O_2, CO_2, and NH_3 levels at ventilation stations.

Ventilation Stations	O_2 (%)	CO_2 (ppm)	NH_3 (ppm)
VMP6	20.9	250	0
VMP7	20.9	2050	0
VMP8	20.9	250	0
VMP9	20.9	2050	0
VMP11	20.9	2050	0
VMP3	21.2	250	0
VMP1	20.9	150	0
VMP2	20.9	150	0
VMP4	20.9	150	0
UOM1	20.9	150	0
VMP69	20.9	1350	0

3.7 Re-entry Time

The usage of ANFO and Water-gel as explosives liberates toxic gases into the airways. Therefore, the re-entry time is evaluated using the throwback method at a development drive in a dead-end, and the results are tabulated in Table 6. Accordingly, the available time duration of 75 minutes between two shifts is inadequate to dilute the contaminants to their threshold limits in that drive. Habitually, CO and NO_2 gases are treated separately in calculating the threshold limit of the gas mixture [1]. In light of this, 116 minutes is required to provide a safer environment utilising the existing auxiliary ventilation.

Table 6: Concentration of contaminants after blast and re-entry time.

Description	NO_2	CO
Concentration of contaminant after blast (ppm)	4012.0	3884.9
Concentration of contaminant when filled the airway (ppm)	89.4	86.6
Time to fill the airway (min)	21.3	21.3
Time to dilute to limit (min)	73.8	94.6
Re-entry time (min)	95.1	115.9

5. Conclusion

From the assessment through the analytical and numerical approaches, it can be concluded that the parameters including air quantity, velocity, wet and dry bulb temperature, effective temperature, and humidity in the block between 240 FM and 275 FM levels of Bogala mines are inadequate for optimal mine conditions in most occasions. It may lead to loss of productivity of the workplaces as it has an adverse effect on the health, safety, and comfort of workers and the physical conditions of the mine. Nevertheless, the gas concentrations of O_2, CO_2, and NH_3 in the primary airways meet the regulatory requirements. It has been calculated that the airflow needed for three workers in the stopes is 0.3 m/s. Although winzes carry adequate air quantity, the appropriate mechanism is absent in practice to deliver it into the workplaces. Re-entry time after the blast was calculated as 116 minutes in a development drive at a dead end, and it is higher than the existing time gap between two shifts of 75 minutes. Exposure to these toxic fumes may cause severe illnesses, which is a major concern regarding workers' health. Moreover, a simulated Ventsim model reveals the stale air mixing at the 240 FM level. In addition, it exhibits an air recirculation at 275 FM level as the installed auxiliary ventilation in the dead-end is not exposed to the fresh air intake.

6. Recommendations

Optimising the ventilation network by installing auxiliary fans and dehumidifiers is recommended to provide a comfortable working environment in production stopes and development areas. In addition, automating the mine ventilation through real-time monitoring sensors and three-dimensional (3D) simulations would optimise the dynamically changing mine environment with developments by reducing cost and energy consumption. Moreover, re-entry time after explosions should be accounted for each ventilation design occasion to provide workers with a safe atmosphere.

Acknowledgement

The authors thank Eng. Saliya Gunasekara, Eng. Chaminda Ekanayake, Mr. Kithsiri Palandagama, Eng. Likitha Lasantha and Eng. Lahiru Sandaruwan and other staff of Bogala Graphite Lanka PLC for providing facilities and extending their support. Further, the authors extend their gratitude to Eng. P.V.A. Hemalal and Dr. S.P. Chaminda from Department of Earth Resources Engineering, University of Moratuwa for the guidance, and Dr. Rick Brake of Mine Ventilation Australia for sharing the knowledge. Moreover, the authors thank Mr. S.L.I.K. Liyanage and Mr. S.A.D.K. Chameera for the support during the field survey.

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