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Aceh International Journal of Science and Technology
pISSN : 2088-9860 eISSN : 2503-2348

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AIJST
Aceh International Journal of Science and Technology
pISSN : 2088-9860 eISSN : 2503-2348

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AIJST
Aceh International Journal of Science and Technology
pISSN : 2088-9860 eISSN : 2503-2348

Vol 13, No 1 (2024)

April 2024 in press

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April 2024
doi: 10.13170/aijst.13.1.39211

Aceh International Journal of Science and Technology
ISSN: p-2088-9860; e-2503-2398
Journal homepage: http://jurnal.usk.ac.id/aijst

Variations in Site Conditions and Blast Geometry on The Formation of Toxic Gas (Fumes) in Open-Pit Coal Mining

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Received : June 09, 2024
Received in revised from: August 12, 2024
Accepted : August 12, 2024
Online : August 13, 2024

Abstract – The blasting activity generates one of the effects in the form of toxic gases (fumes) that can disturb living beings around them. Fumes formation is formed by the reaction of the explosive material not in a zero oxygen balance condition, and is influenced by several factors including the condition of the blast hole, rock moisture content, blast hole temperature and relative humidity, sleep blast, explosive material ratio, and poor confinement stemming. This study investigates the variations in site condition and blast geometry on the formation fumes in open-pit coal mining. This research was conducted at the coal mine of Kaltim Prima Coal (PT KPC) to quantitatively measure the levels of toxic gas (fumes) resulting from blasting activities. In-situ measurements were conducted using a gas detector suspended above a drone. From the measurement results, it was found that blasting activities at the PT KPC coal mine produce CO and NO_2 gases in toxic gas visual conditions at Levels 0 and 1A. The CO gas levels resulting from blasting activities ranged from 60.34 to 324.79 ppm, and the NO_2 gas levels ranged from 0.3 to 2.11 ppm. From the trial results, by altering the explosive material ratio, toxic gas visual conditions were observed at Level 2A with CO gas levels of 360.29 ppm and NO_2 gas levels of 3.16 ppm. The formation of CO and NO_2 gases from blasting is influenced by the blast hole temperature and humidity, as well as differences in explosive material ratios. Based on the gas CO and NO_2 level measurements, according to the threshold values with the maximum exposure level for humans over a 15-minute period for both gases, it was determined that workers could safely return to the blasting site in less than 1 minute.

Keywords: blasting, fumes, worker, mining, open-pit, coal, CO and NOx

Introduction

Blasting is one of the activities in the mining process aimed for breaking or fracturing large rocks into smaller sizes for easier material extraction. During the blasting process, rocks are fragmented due to high pressure and shock waves, which can affect the surrounding environment (Silva *et al.*, 2019; Das, 2022). During the blasting process, rocks are fragmented due to high pressure and shock waves, which can affect the surrounding environment (Tomberg and Toomik, 1999; Mikić *et al.*, 2017; Afum and Opoku, 2018).

As aforementioned, blasting activities can have direct effects on the environment (Bian *et al.*, 2010). The effects produced include ground vibration, airblast, flyrock, and blasting gases (Hartami *et al.*, 2023a; Hartami *et al.*, 2023b). Among the effects of blasting, blasting gases can be categorized into two types: smoke and fumes. Smoke generated from blasting is composed of gases that are not harmful, such as H_2O and CO_2, while fumes are gases produced from blasting that can be either non-toxic or toxic (Biessikirski *et al.*, 2023a; Yi *et al.*, 2023).

doi: 10.13170/aijst.13.1.39211

Several factors can cause the formation of fumes due to blasting, including explosives not being in Zero Oxygen Balance (ZOB) condition, influenced by water conditions in the blast holes, temperature and relative humidity of the blast holes, sleep blast, and explosive ratio (Hartami *et al*., 2023a). These factors can lead to the formation of hazardous gases such as NOx and CO (Attalla *et al*., 2008; Onederra *et al*., 2012). Which can be dangerous if inhaled by living beings around the blasting site (Oluwoye *et al*., 2017). Therefore, after blasting activities, workers wait until the blasting site is declared safe for a certain period of time.

The formation of blasting fumes has been traditionally identified solely based on physical appearance, derived from the observation of blasting results. Several countries, including Belgium, France, Spain, Russia, Slovakia, the USA, and Australia, have published standards to control fumes produced in mining activities, such as underground mining. In Australia, these standards not only regulate the gas content of fumes but also include visual assessments of the fumes visible after blasting (Hartami *et al*., 2023a)

PT Kaltim Prima Coal (PT KPC) uses emulsion explosives in its blasting activities, which are products of PT AEL Indonesia. Emulsion explosives are used due to the wet conditions of the blast holes at the site, requiring explosives with high water resistance properties (Ni *et al*., 2012; Lubis and Handayana, 2023; Skrlec *et al*., 2024). Wet blast hole conditions can disrupt explosive reactions, leading to non-zero oxygen balance conditions (Genetier *et al*., 2014). This condition is caused by water in the blast holes resulting from rain or groundwater. Explosive reactions not in Zero Oxygen Balance conditions lead to the formation of fumes that can disrupt workers' respiratory systems after blasting activities (Suceska *et al*., 2022).

Research on fumes from blasting in the present paper conducted at PT KPC pit locations operated by PT Thiess contractors. Some of the pits operated by PT Thiess include Melawan Pit, Mustahil Pit, Peri Pit, and Tania Pit. Field measurements are conducted using gas detectors flown by drones connected to GPS to fly accurately toward their destinations. This research aims to determine the concentration of blasting gases and identify the factors causing the formation of blasting fumes. Based on the obtained fume data, valuable insights can be provided to blasting operators before they re-enter the blasting area.

Materials and Methods

Research Site

This research was conducted at PT KPC, one of the mining areas in Kutai Timur Regency, East Kalimantan Province, Indonesia. In its mining process, PT KPC employs blasting activities to achieve coal production averaging 60 million tons per year. PT KPC operates several two mining blocks located located in Sangatta and Bengalon Blocks. This research was carried out in Sangatta Block, specifically in the Peri Pit, Tania Pit, Melawan Pit, and Mustahil Pit. Mining operational activities in this research area are carried out by mining contractors under PT THIESS, while drilling and blasting contractors are provided by PT AEL Indonesia. Gas measurements from blasting (fumes) were conducted 13 times, following the blasting schedule at the PT AEL site of PT KPC.

Blast Geometry

Actual field data collection of blast geometry must be recorded to compare the planned blast geometry from the company and serve as an evaluation material for identifying the causes of differences between the planned blast geometry and the actual blast geometry. Data collection for spacing, burden, and borehole diameter was carried out using a measuring tape.

Temperature and Relative Humidity in the Blast Hole

Temperature and humidity data collection in the blast holes was carried out when the holes have not been filled with explosive material yet. Temperature and humidity measurements in the blast holes were performed using a TSI 9545-A anemometer. Measurements were taken by inserting the probe into the blast hole to a minimum depth of 3 inches (7.5 cm) from the mouth of the hole to increase the accuracy of temperature and humidity measurements (TSI VelociCalc operation and service manual). Measurements were taken until the temperature and humidity stabilize, approximately 10 seconds after the probe is inserted into the hole.

Wind Direction and Speed

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Data collection for wind direction and speed was conducted prior to the blast. Determining wind direction can be done by observing the direction in which flags placed at the blast site flutter. Meanwhile, wind speed measurement can be carried out using the Krisbow KW06-653 anemometer. Speed measurements were taken at blast locations with higher elevations, such as blast site embankments. Measurements were taken for approximately ±10 minutes to ensure accurate wind speed measurements.

Wind direction and speed measurements serve as supportive data in creating fume dispersion maps and determining the rate of decrease in fume concentrations resulting from the blast over time during the measurements.

Gas Concentrations of CO, NO_2, and H_2S After Blasting

The collection of toxic gas measurement data resulting from blasting must consider the direction of the prevailing wind. It is advisable to ensure that the prevailing wind direction is opposite to the direction of the free face to be blasted because this measurement uses a drone. The drone used is the DJI Phantom 4 Pro+, with a maximum speed of 45 m/h (S), a maximum altitude of 500 m, and a maximum remote-control range of 4 miles (6.4 km). The gas detector was tethered to the legs of the drone. The drone was flown shortly after the explosion has occurred. This is because PT AEL Indonesia uses electronic detonator products, so the drone signal frequency may interfere with the detonation. The gas detector used is the MSA Altair 5x, which can measure CO, O_2, H_2S, and NO_2 gases, with adjustable alarm limits for STEL, TWA, and high alarms. The MSA Altair 5x can measure CO gas up to 2000 ppm, NO_2 20 ppm, and H_2S 200 ppm.

Water Content of Rock

Data collection of rock moisture content serves as supporting data to identify the factors causing fumes from blasting. The moisture content of rocks can affect the reaction of the explosive materials used. Rock moisture content data was obtained by taking cutting samples from the blast holes. These samples were then tested in a geotechnical laboratory to determine the natural weight and dry weight of the rocks. From the test results, calculations are performed to determine the moisture content of the rocks at the blast site.

Results

Concentration of CO and NO_2

At the Mustahil 148 blasting location, a trial was conducted using different explosive ratios, specifically varying the proportions of emulsion and AN-prill. In this trial, a 50% emulsion and 50% AN-prill mixture was used. The change in the explosive ratio from the previous trial was implemented to assess the level of fumes produced, particularly in terms of visually observable toxic gas levels exceeding Level 0 and 1A. Figure 1 shows that the CO gas produced is below the STEL threshold value of 400 ppm, with a maximum of 360.29 ppm and a minimum of 60.34 ppm. Meanwhile, Figure 2 indicates that the NO2 content in the fumes ranges from 0.30 ppm to 3.16 ppm, which is still below the threshold value of 5 ppm. Therefore, it is evident that the toxic gases produced remain below the maximum exposure threshold for humans over a 15-minute period.

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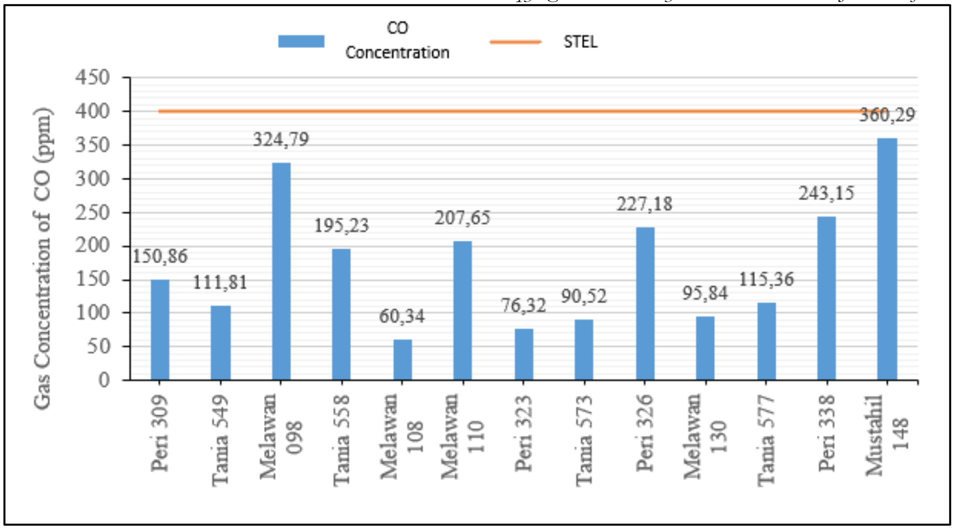

Figure 1. Comparison of CO Gas to Short-Term Exposure Limit (STEL) Threshold Values

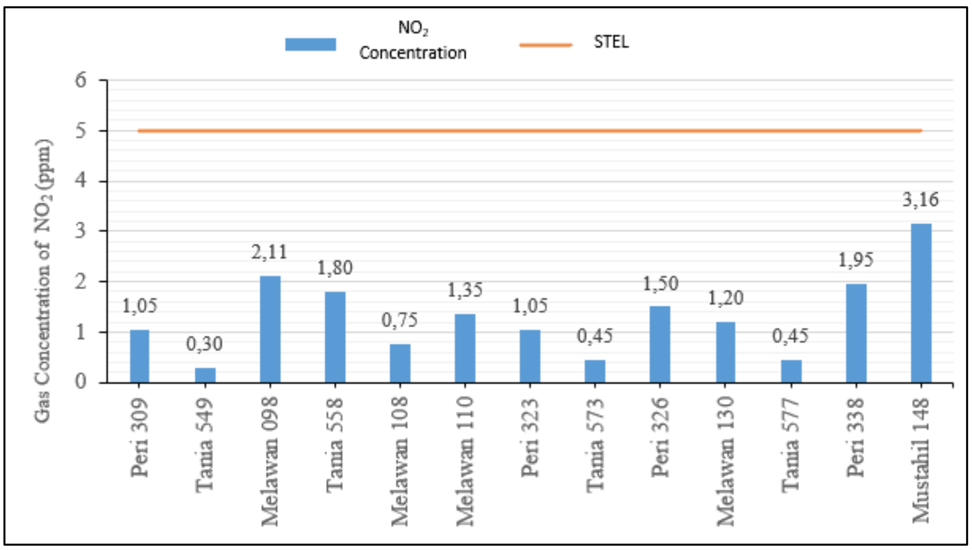

Figure 2. Comparison of NO_2 Gas to Short-Term Exposure Limit (STEL) Threshold Values

The Water's Condition in The Blast Holes

Based on Table 1, it can be seen that the average condition of blast holes at each blast site is wet, which is due to the presence of water in the blast holes. The use of S320 DRN 100 Eco emulsion with an 80% emulsion and 20% AN-prill percentage increases the resistance of the explosive material to water, so the wet condition of the blast holes due to the presence of water does not affect the formation of fumes.

Table 1. Condition of blast holes

Location	Number of Wet Holes	Percentage of Wet Holes (%)	Number of Dry Holes	Percentage of Dry Holes (%)
Peri 309	16	7	215	93
Tania 549	140	92	12	8
Melawan 098	48	40	71	60

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Location	Number of Wet Holes	Percentage of Wet Holes (%)	Number of Dry Holes	Percentage of Dry Holes (%)
Tania 558	0	0	151	100
Melawan 108	128	78	36	22
Melawan 110	80	67	40	33
Peri 323	0	0	162	100
Tania 573	32	23	108	77
Peri 326	97	78	28	22
Melawan 130	83	58	59	42
Tania 577	58	98	1	2
Peri 338	24	27	66	73
Mustahil 148	10	20	41	80

The high number of blast holes filled with water is due to weather conditions and the presence of groundwater in the rock. The high percentage of holes filled with water can affect the temperature and humidity of the blast holes because the increased amount of water in the blast holes increases the water content in the air.

Effect of The Temperature and Humidity

The temperature and humidity of blast holes are influenced by weather conditions and materials at the blast site. The humidity value in blast holes has an average value of 70% - 80%. The high humidity value in blast holes is caused by the presence of water in the holes due to the high groundwater level at the location and rainfall. The high-water content in blast holes reduces the temperature in the blast holes, thereby increasing the humidity value in the blast holes due to the formation of water vapor. In Figures 3 and 4, it can be observed that the higher the humidity value of the blast hole, the higher the fume concentration produced.

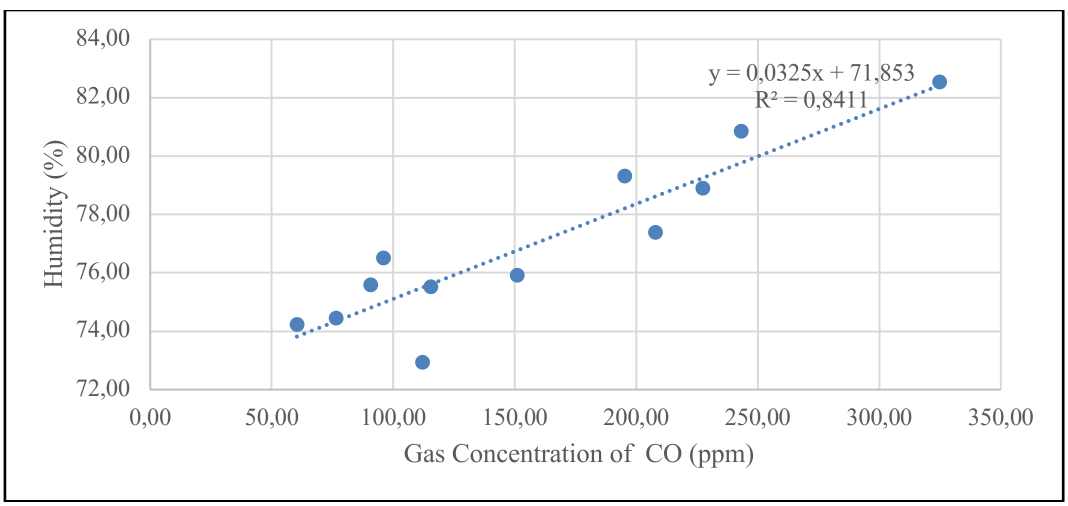

Figure 3. Blast holes humidity's effect on CO gas

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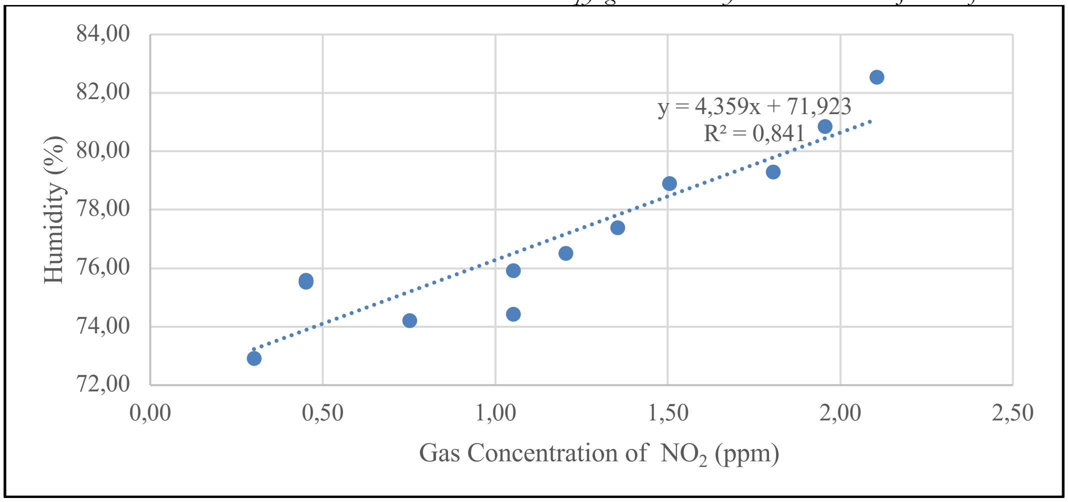

Figure 4. Blast holes humidity's effect on NO_2 gas

Based on the linear regression values, a hypothesis can be drawn that the humidity of the blast hole affects the Zero Oxygen Balance condition of the explosive material, resulting in Negative Oxygen Balance or a mixture of explosive materials lacking oxygen value, thus producing CO gas. Further analysis is required regarding the influence of blast hole humidity on chemical mixtures and chemical reactions of explosive materials, so that the hypothesis about blast hole humidity reducing the oxygen content in explosive materials and the reaction of explosive materials can be substantiated. Blast hole humidity needs to be studied at other mine sites because the conditions vary from one mining location to another. The differences in mining locations result in each mining site having different valuable materials and minerals.

Effect of Stemming Length

Poor confinement of explosive materials results in suboptimal energy output from the explosive materials. Excessive use of explosive materials filled in a blast hole leads to a reduction in the stemming length to be used. The gassing property of emulsion explosive materials causes a further reduction in stemming length. The suboptimal energy output from the explosive materials results in the explosion reaction to the material to be blasted not being adequate. Loss of energy from the explosive materials produced can lead to the formation of fumes from the blast. As depicted in Figures 5 and 6, it illustrates the influence of gas levels on stemming length.

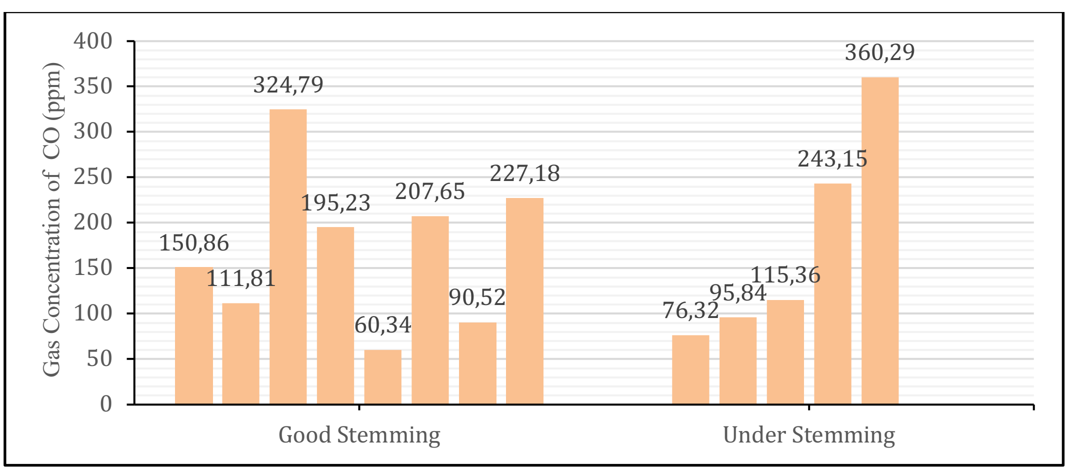

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Figure 5. Stemming length's Effect on CO Gas Levels

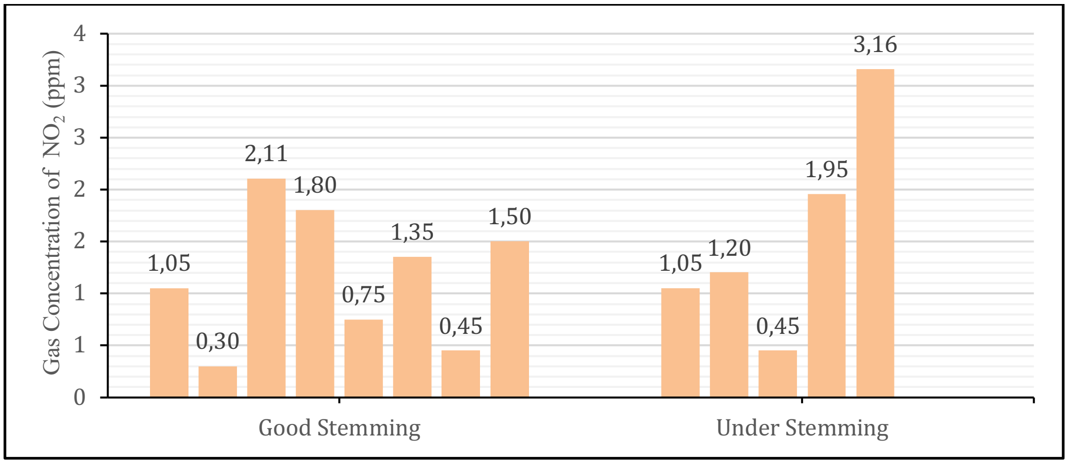

Figure 6. Stemming length's Effect on NO_2 Gas Levels

Effect of Sleep Blast

The limitation of the number and capacity of MMUs (mobile manufacturing units) used in charging at the blast site results in the need for sleep blasting to meet production demands. The conducted sleep blasting has been in accordance with the established production plan and complies with the explosive material specifications for the duration of the blasting. Sleep blasting can cause the explosive material that has been charged to be contaminated with water in the blast holes. As shown in Figures 7 and 8, it depicts the influence of the duration of sleep blasting on the concentration of fumes formed.

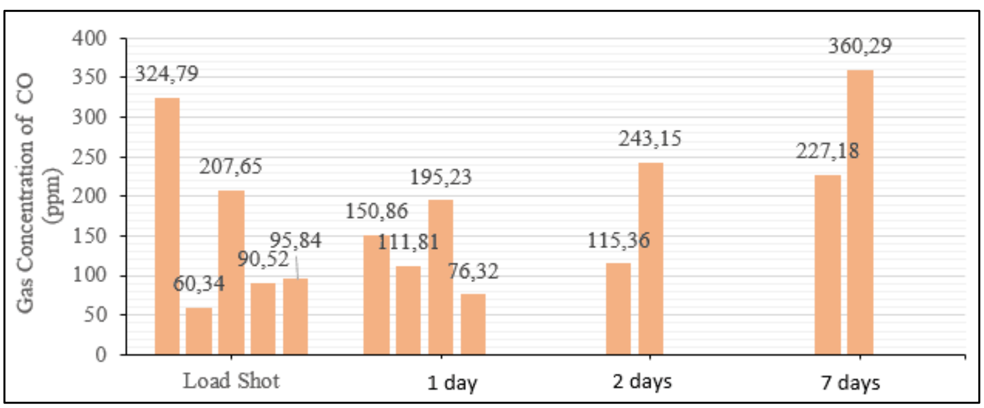

Figure 7. Sleep Blast's Effect on CO Gas Levels

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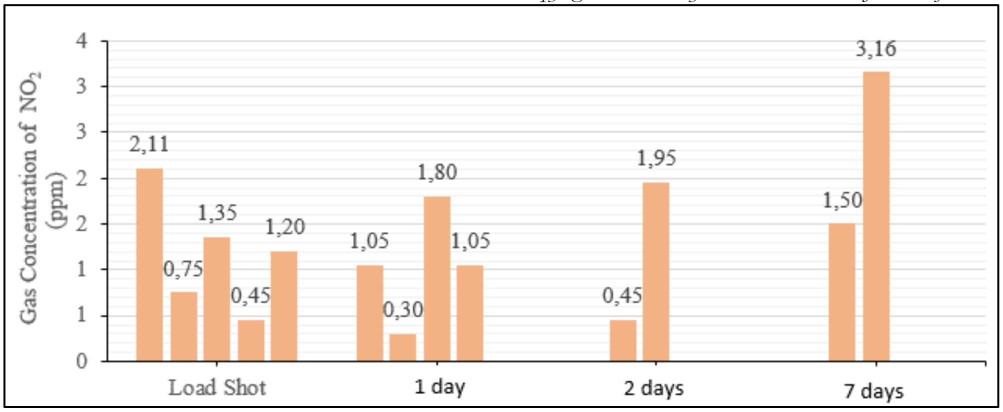

Figure 8. Sleep Blast's Effect on NO_2 Gas Levels

Explosive Material Ratio's Effect

In this study, a trial was conducted at location Mustahil 148 by changing the explosive material ratio from 80% emulsion and 20% AN-prill to 50% emulsion and 50% AN-prill, as shown in Figure 9. The experiment of changing the explosive material ratio was carried out to determine the gas concentration values formed with the visual fume condition classification at Level 2. From the measurement results of toxic gases at the trial blast site, there was an increase in the concentration values of CO and NO_2 gases resulting from the blast. This is due to the high percentage of AN-prill used, resulting in a decrease in the explosive material's resistance to water. By changing the explosive material ratio, it can be indicated that the explosive material used is not in a zero-oxygen balance condition, thus forming fumes. Therefore, it can be indicated that changing the explosive material ratio can affect the formation of fumes resulting from the blast.

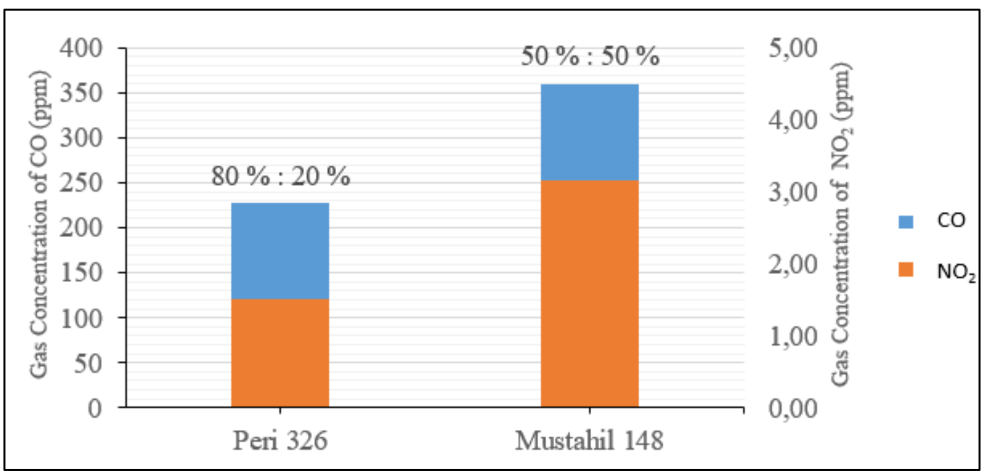

Figure 9. Comparison of explosive material ratios

Discussion

The nature of a gas filling a space is the primary factor in reducing fume levels; in a room, a gas will spread and attempt to fill that space. The characteristics of this gas cause gas measurements to be expressed in ppm (parts per million). Blasting in open-pit mines causes gas to spread and attempt to fill the unlimited space of the environment (Abbaspour *et al*., 2018). The decrease in gas levels is also accelerated by the wind speed at the blast site. Based on the measured fume levels measured using drones and conventional methods post-blast, the duration of the decrease in measured gas levels can

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be determined (Bamford *et al.*, 2020). Blast crews who will check the post-blast location must wait until the location is free from fumes. The decrease in fume levels at the blast site is influenced by the presence of wind blowing at the blast site. This can expedite blast crews' post-blast location checks.

Weighting or classification of fumes based on visual inspection is the standard used because there is currently no standard for classifying blast fumes in open-pit or underground mines based on the concentration of fumes formed (Biessikirski *et al.*, 2023b). The classification of fumes based on visual inspection is determined by the color of the gases formed, where the color indications provide the level of danger of the fumes formed. The classification of fume types based on visual inspection was issued by the Australian Explosives Industry Safety Group (AEISG) in 2011. AEISG is a community aimed at improving safety and security levels in all aspects of explosive material manufacturing, transportation, storage, handling, and use throughout Australia (AEISG 2011).

Classifying fumes based on visual inspection results in many biased perceptions of the fumes formed from blasting, as each individual has a different opinion on the type and danger of fumes based on color. Many workers do not recognize the danger of fumes and assume that the gases formed from blasting are just ordinary smoke. This research will attempt to classify the types and dangers of blast fumes based on visual inspection using blast photo data collected during the research.

Classifying blast fumes based solely on visual inspection cannot be used as a standard for representing the level of danger of the fumes. Based on measurements using gas detectors, it was found that white-colored fumes still contain levels of CO, H_2S, and NO_2, making them very dangerous for mine workers, especially blasting crews conducting post-blast checks. The color of blast fumes cannot be classified accurately due to the presence of dust particles originating from cutting materials during blast hole drilling, making it difficult to distinguish between gases and dust. Therefore, a clear standard is needed for weighting the fumes formed in open-pit mines and for measuring blast fume levels safely, quickly, and accurately.

Based on the visualization results from field photography, it is shown that, on average, all research locations are at level 0, except for measurement locations Tania 577 at level 1A and Mustahil 148 at level 2A. Further details can be seen in Table 2.

Table 2. Visual Classification of Fumes

Location	Level	Actual Figures
Tania 549	*Level 0*	
Melawan 098	*Level 0*	

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Location	Level	Actual Figures
Tania 558	*Level 0*	
Melawan 108	*Level 0*	
Melawan 110	*Level 0*	
Peri 323	*Level 0*	
Tania 573	*Level 0*	
Peri 326	*Level 0*	
Melawan 130	*Level 0*	

doi: 10.13170/aijst.13.1.39211

Location	Level	Actual Figures
Tania 577	*Level 1A*	
Peri 338	*Level 0*	
Mustahil 148 (*Trial*)	*Level 2A*	

Conclusion

The gases formed from the explosion activities at PT KPC are CO gas and NO_2 gas. The maximum CO gas concentration formed due to the blasting activities is 360.29 ppm, and the maximum NO_2 gas concentration formed due to the blasting activities is 3.16 ppm. Stemming length, conditions of blast hole water, and sleep blast do not significantly affect the formation of fumes, but the relative humidity of the blast hole and the difference in explosive material ratios affect the formation of fumes resulting from the explosion. Based on the Short-Term Exposure Limit (STEL), with the maximum gas concentration workers are exposed to within a 15-minute period, workers are declared safe to enter the blast site less than 1 minute after the explosion is carried out.

Acknowledgment

Thanks are extended to Universitas Trisakti for funding the research through the Faculty's Outstanding Research Scheme, to PT AEL for collaborating on field data collection, and also to the management of PT Kaltim Prima Coal for granting permission to conduct this research.

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Variations in Site Conditions and Blast Geometry on The Formation of Toxic Gas (Fumes) in Open-Pit Coal Mining

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Submission date: 09-Sep-2024 06:25PM (UTC+0700)
Submission ID: 2205697732
File name: 39211-139724-1-PB_2.pdf (6.06M)
Word count: 4891
Character count: 24838

Aceh Int. J. Sci. Technol., 13(1) 79-91
April 2024
doi: 10.13170/aijst.13.1.39211

Aceh International Journal of Science and Technology
ISSN: p-2088-9860; e-2503-2398
Journal homepage: http://jurnal.usk.ac.id/aijst

Variations in Site Conditions and Blast Geometry on The Formation of Toxic Gas (Fumes) in Open-Pit Coal Mining

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Received : June 09, 2024
Received in revised from: August 12, 2024
Accepted : August 12, 2024
Online : August 13, 2024

Abstract – The blasting activity generates one of the effects in the form of toxic gases (fumes) that can disturb living beings around them. Fumes formation is formed by the reaction of the explosive material not in a zero oxygen balance condition, and is influenced by several factors including the condition of the blast hole, rock moisture content, blast hole temperature and relative humidity, sleep blast, explosive material ratio, and poor confinement stemming. This study investigates the variations in site condition and blast geometry on the formation fumes in open-pit coal mining. This research was conducted at the coal mine of Kaltim Prima Coal (PT KPC) to quantitatively measure the levels of toxic gas (fumes) resulting from blasting activities. In-situ measurements were conducted using a gas detector suspended above a drone. From the measurement results, it was found that blasting activities at the PT KPC coal mine produce CO and NO_2 gases in toxic gas visual conditions at Levels 0 and 1A. The CO gas levels resulting from blasting activities ranged from 60.34 to 324.79 ppm, and the NO_2 gas levels ranged from 0.3 to 2.11 ppm. From the trial results, by altering the explosive material ratio, toxic gas visual conditions were observed at Level 2A with CO gas levels of 360.29 ppm and NO_2 gas levels of 3.16 ppm. The formation of CO and NO_2 gases from blasting is influenced by the blast hole temperature and humidity, as well as differences in explosive material ratios. Based on the gas CO and NO_2 level measurements, according to the threshold values with the maximum exposure level for humans over a 15-minute period for both gases, it was determined that workers could safely return to the blasting site in less than 1 minute.

Keywords: blasting, fumes, worker, mining, open-pit, coal, CO and NOx

Introduction

Blasting is one of the activities in the mining process aimed for breaking or fracturing large rocks into smaller sizes for easier material extraction. During the blasting process, rocks are fragmented due to high pressure and shock waves, which can affect the surrounding environment (Silva *et al.*, 2019; Das, 2022). During the blasting process, rocks are fragmented due to high pressure and shock waves, which can affect the surrounding environment (Tomberg and Toomik, 1999; Mikić *et al.*, 2017; Afum and Opoku, 2018).

As aforementioned, blasting activities can have direct effects on the environment (Bian *et al.*, 2010). The effects produced include ground vibration, airblast, flyrock, and blasting gases (Hartami *et al.*, 2023a; Hartami *et al.*, 2023b). Among the effects of blasting, blasting gases can be categorized into two types: smoke and fumes. Smoke generated from blasting is composed of gases that are not harmful, such as H_2O and CO_2, while fumes are gases produced from blasting that can be either non-toxic or toxic (Biessikirski *et al.*, 2023a; Yi *et al.*, 2023).

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doi: 10.13170/aijst.13.1.39211

Several factors can cause the formation of fumes due to blasting, including explosives not being in Zero Oxygen Balance (ZOB) condition, influenced by water conditions in the blast holes, temperature and relative humidity of the blast holes, sleep blast, and explosive ratio (Hartami *et al.*, 2023a). These factors can lead to the formation of hazardous gases such as NOx and CO (Attalla *et al.*, 2008; Onederra *et al.*, 2012). Which can be dangerous if inhaled by living beings around the blasting site (Oluwoye *et al.*, 2017). Therefore, after blasting activities, workers wait until the blasting site is declared safe for a certain period of time.

The formation of blasting fumes has been traditionally identified solely based on physical appearance, derived from the observation of blasting results. Several countries, including Belgium, France, Spain, Russia, Slovakia, the USA, and Australia, have published standards to control fumes produced in mining activities, such as underground mining. In Australia, these standards not only regulate the gas content of fumes but also include visual assessments of the fumes visible after blasting (Hartami *et al.*, 2023a)

PT Kaltim Prima Coal (PT KPC) uses emulsion explosives in its blasting activities, which are products of PT AEL Indonesia. Emulsion explosives are used due to the wet conditions of the blast holes at the site, requiring explosives with high water resistance properties (Ni *et al.*, 2012; Lubis and Handayana, 2023; Skrlec *et al.*, 2024). Wet blast hole conditions can disrupt explosive reactions, leading to non-zero oxygen balance conditions (Genetier *et al.*, 2014). This condition is caused by water in the blast holes resulting from rain or groundwater. Explosive reactions not in Zero Oxygen Balance conditions lead to the formation of fumes that can disrupt workers' respiratory systems after blasting activities (Suceska *et al.*, 2022).

Research on fumes from blasting in the present paper conducted at PT KPC pit locations operated by PT Thiess contractors. Some of the pits operated by PT Thiess include Melawan Pit, Mustahil Pit, Peri Pit, and Tania Pit. Field measurements are conducted using gas detectors flown by drones connected to GPS to fly accurately toward their destinations. This research aims to determine the concentration of blasting gases and identify the factors causing the formation of blasting fumes. Based on the obtained fume data, valuable insights can be provided to blasting operators before they re-enter the blasting area.

Materials and Methods

Research Site

This research was conducted at PT KPC, one of the mining areas in Kutai Timur Regency, East Kalimantan Province, Indonesia. In its mining process, PT KPC employs blasting activities to achieve coal production averaging 60 million tons per year. PT KPC operates several two mining blocks located located in Sangatta and Bengalon Blocks. This research was carried out in Sangatta Block, specifically in the Peri Pit, Tania Pit, Melawan Pit, and Mustahil Pit. Mining operational activities in this research area are carried out by mining contractors under PT THIESS, while drilling and blasting contractors are provided by PT AEL Indonesia. Gas measurements from blasting (fumes) were conducted 13 times, following the blasting schedule at the PT AEL site of PT KPC.

Blast Geometry

Actual field data collection of blast geometry must be recorded to compare the planned blast geometry from the company and serve as an evaluation material for identifying the causes of differences between the planned blast geometry and the actual blast geometry. Data collection for spacing, burden, and borehole diameter was carried out using a measuring tape.

Temperature and Relative Humidity in the Blast Hole

Temperature and humidity data collection in the blast holes was carried out when the holes have not been filled with explosive material yet. Temperature and humidity measurements in the blast holes were performed using a TSI 9545-A anemometer. Measurements were taken by inserting the probe into the blast hole to a minimum depth of 3 inches (7.5 cm) from the mouth of the hole to increase the accuracy of temperature and humidity measurements (TSI VelociCalc operation and service manual). Measurements were taken until the temperature and humidity stabilize, approximately 10 seconds after the probe is inserted into the hole.

Wind Direction and Speed

doi: 10.13170/aijst.13.1.39211

Data collection for wind direction and speed was conducted prior to the blast. Determining wind direction can be done by observing the direction in which flags placed at the blast site flutter. Meanwhile, wind speed measurement can be carried out using the Krisbow KW06-653 anemometer. Speed measurements were taken at blast locations with higher elevations, such as blast site embankments. Measurements were taken for approximately ±10 minutes to ensure accurate wind speed measurements.

Wind direction and speed measurements serve as supportive data in creating fume dispersion maps and determining the rate of decrease in fume concentrations resulting from the blast over time during the measurements.

Gas Concentrations of CO, NO_2, and H_2S After Blasting

The collection of toxic gas measurement data resulting from blasting must consider the direction of the prevailing wind. It is advisable to ensure that the prevailing wind direction is opposite to the direction of the free face to be blasted because this measurement uses a drone. The drone used is the DJI Phantom 4 Pro+, with a maximum speed of 45 m/h (S), a maximum altitude of 500 m, and a maximum remote-control range of 4 miles (6.4 km). The gas detector was tethered to the legs of the drone. The drone was flown shortly after the explosion has occurred. This is because PT AEL Indonesia uses electronic detonator products, so the drone signal frequency may interfere with the detonation. The gas detector used is the MSA Altair 5x, which can measure CO, O_2, H_2S, and NO_2 gases, with adjustable alarm limits for STEL, TWA, and high alarms. The MSA Altair 5x can measure CO gas up to 2000 ppm, NO_2 20 ppm, and H_2S 200 ppm.

Water Content of Rock

Data collection of rock moisture content serves as supporting data to identify the factors causing fumes from blasting. The moisture content of rocks can affect the reaction of the explosive materials used. Rock moisture content data was obtained by taking cutting samples from the blast holes. These samples were then tested in a geotechnical laboratory to determine the natural weight and dry weight of the rocks. From the test results, calculations are performed to determine the moisture content of the rocks at the blast site.

Results

Concentration of CO and NO_2

At the Mustahil 148 blasting location, a trial was conducted using different explosive ratios, specifically varying the proportions of emulsion and AN-prill. In this trial, a 50% emulsion and 50% AN-prill mixture was used. The change in the explosive ratio from the previous trial was implemented to assess the level of fumes produced, particularly in terms of visually observable toxic gas levels exceeding Level 0 and 1A. Figure 1 shows that the CO gas produced is below the STEL threshold value of 400 ppm, with a maximum of 360.29 ppm and a minimum of 60.34 ppm. Meanwhile, Figure 2 indicates that the NO2 content in the fumes ranges from 0.30 ppm to 3.16 ppm, which is still below the threshold value of 5 ppm. Therefore, it is evident that the toxic gases produced remain below the maximum exposure threshold for humans over a 15-minute period.

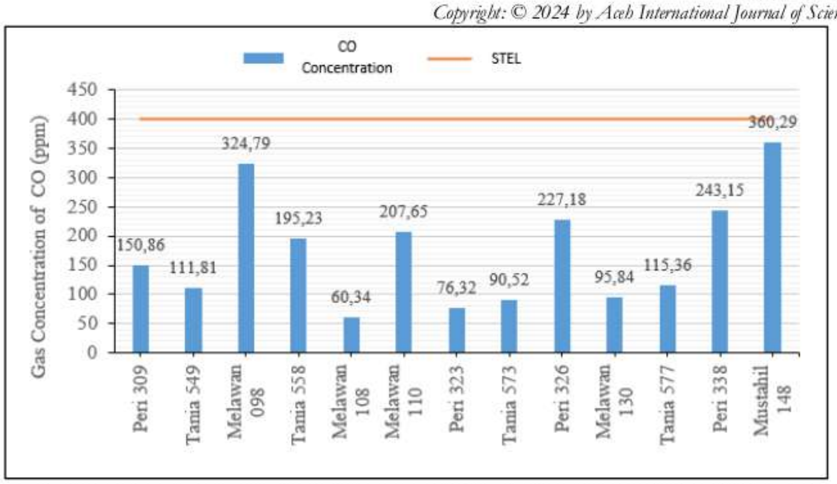

Figure 1. Comparison of CO Gas to Short-Term Exposure Limit (STEL) Threshold Values

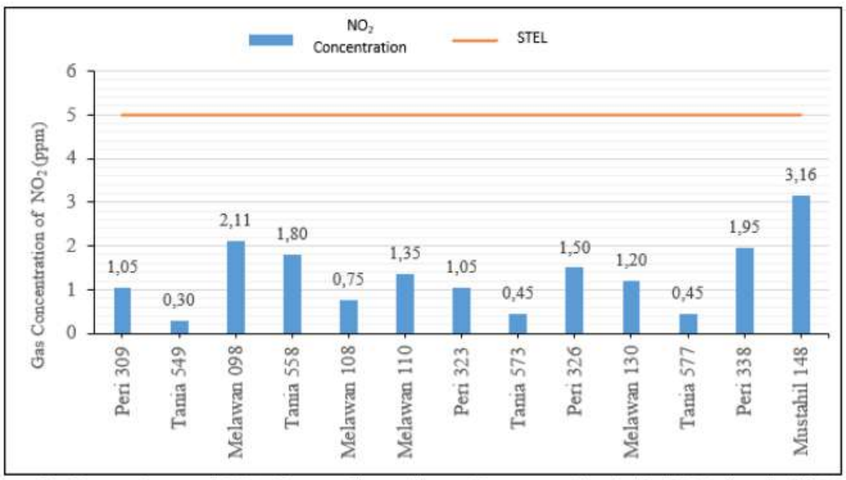

Figure 2. Comparison of NO_2 Gas to Short-Term Exposure Limit (STEL) Threshold Values

The Water's Condition in The Blast Holes

Based on Table 1, it can be seen that the average condition of blast holes at each blast site is wet, which is due to the presence of water in the blast holes. The use of S320 DRN 100 Eco emulsion with an 80% emulsion and 20% AN-prill percentage increases the resistance of the explosive material to water, so the wet condition of the blast holes due to the presence of water does not affect the formation of fumes.

Table 1. Condition of blast holes

Location	Number of Wet Holes	Percentage of Wet Holes (%)	Number of Dry Holes	Percentage of Dry Holes (%)
Peri 309	16	7	215	93
Tania 549	140	92	12	8
Melawan 098	48	40	71	60

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doi: 10.13170/aijst.13.1.39211

Location	Number of Wet Holes	Percentage of Wet Holes (%)	Number of Dry Holes	Percentage of Dry Holes (%)
Tania 558	0	0	151	100
Melawan 108	128	78	36	22
Melawan 110	80	67	40	33
Peri 323	0	0	162	100
Tania 573	32	23	108	77
Peri 326	97	78	28	22
Melawan 130	83	58	59	42
Tania 577	58	98	1	2
Peri 338	24	27	66	73
Mustahil 148	10	20	41	80

The high number of blast holes filled with water is due to weather conditions and the presence of groundwater in the rock. The high percentage of holes filled with water can affect the temperature and humidity of the blast holes because the increased amount of water in the blast holes increases the water content in the air.

Effect of The Temperature and Humidity

The temperature and humidity of blast holes are influenced by weather conditions and materials at the blast site. The humidity value in blast holes has an average value of 70% - 80%. The high humidity value in blast holes is caused by the presence of water in the holes due to the high groundwater level at the location and rainfall. The high-water content in blast holes reduces the temperature in the blast holes, thereby increasing the humidity value in the blast holes due to the formation of water vapor. In Figures 3 and 4, it can be observed that the higher the humidity value of the blast hole, the higher the fume concentration produced.

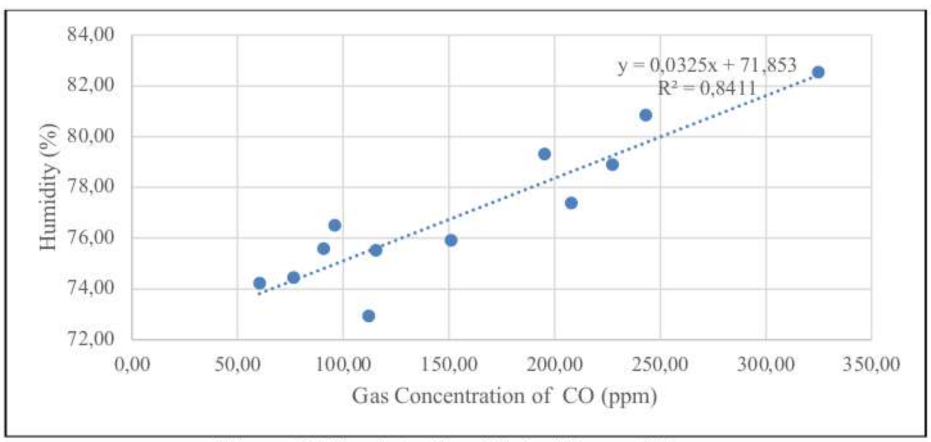

Figure 3. Blast holes humidity's effect on CO gas

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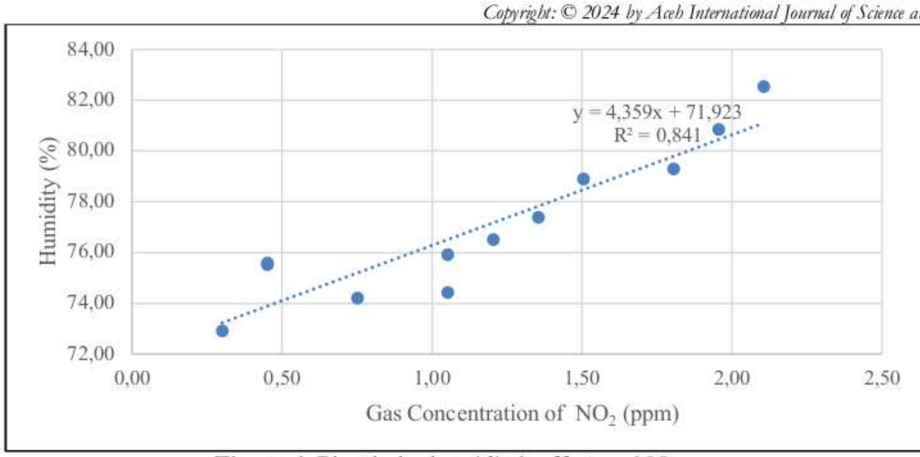

Figure 4. Blast holes humidity's effect on NO_2 gas

Based on the linear regression values, a hypothesis can be drawn that the humidity of the blast hole affects the Zero Oxygen Balance condition of the explosive material, resulting in Negative Oxygen Balance or a mixture of explosive materials lacking oxygen value, thus producing CO gas. Further analysis is required regarding the influence of blast hole humidity on chemical mixtures and chemical reactions of explosive materials, so that the hypothesis about blast hole humidity reducing the oxygen content in explosive materials and the reaction of explosive materials can be substantiated. Blast hole humidity needs to be studied at other mine sites because the conditions vary from one mining location to another. The differences in mining locations result in each mining site having different valuable materials and minerals.

Effect of Stemming Length

Poor confinement of explosive materials results in suboptimal energy output from the explosive materials. Excessive use of explosive materials filled in a blast hole leads to a reduction in the stemming length to be used. The gassing property of emulsion explosive materials causes a further reduction in stemming length. The suboptimal energy output from the explosive materials results in the explosion reaction to the material to be blasted not being adequate. Loss of energy from the explosive materials produced can lead to the formation of fumes from the blast. As depicted in Figures 5 and 6, it illustrates the influence of gas levels on stemming length.

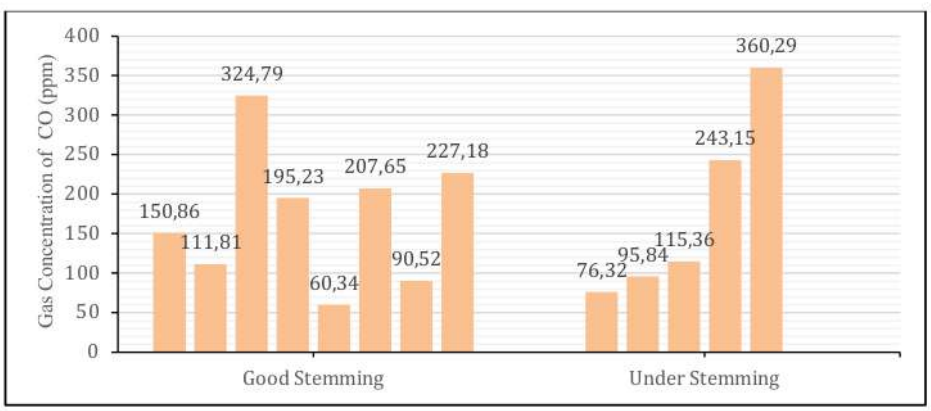

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Figure 5. Stemming length's Effect on CO Gas Levels

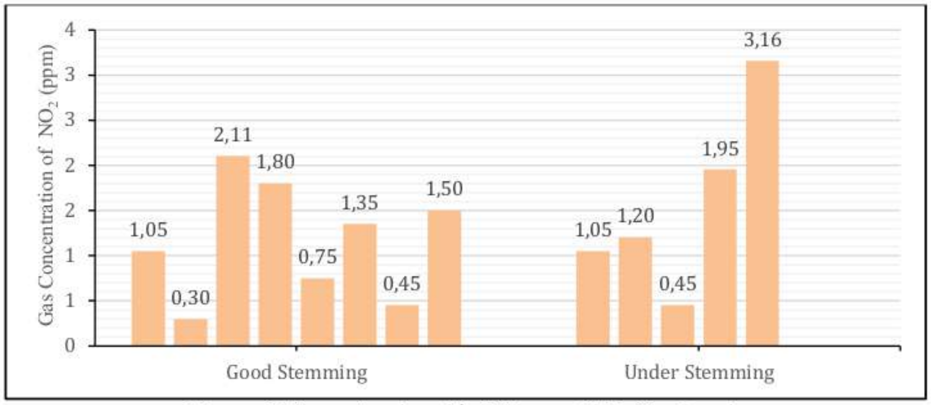

Figure 6. Stemming length's Effect on NO_2 Gas Levels

Effect of Sleep Blast

The limitation of the number and capacity of MMUs (mobile manufacturing units) used in charging at the blast site results in the need for sleep blasting to meet production demands. The conducted sleep blasting has been in accordance with the established production plan and complies with the explosive material specifications for the duration of the blasting. Sleep blasting can cause the explosive material that has been charged to be contaminated with water in the blast holes. As shown in Figures 7 and 8, it depicts the influence of the duration of sleep blasting on the concentration of fumes formed.

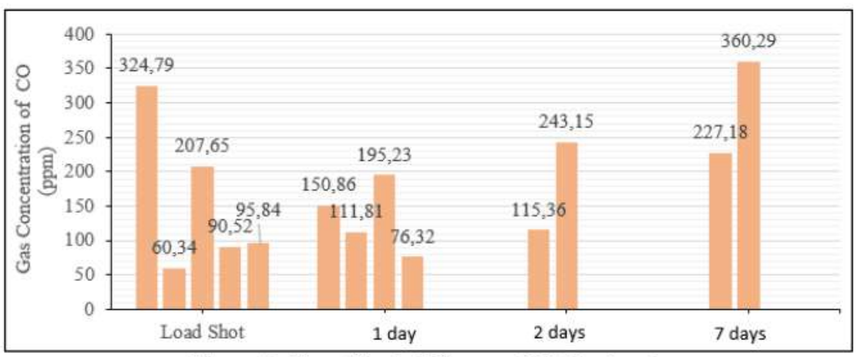

Figure 7. Sleep Blast's Effect on CO Gas Levels

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doi: 10.13170/aijst.13.1.39211

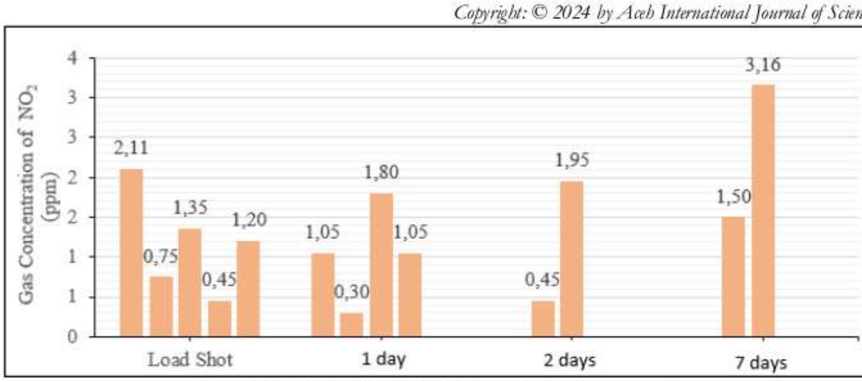

Figure 8. Sleep Blast's Effect on NO_2 Gas Levels

Explosive Material Ratio's Effect

In this study, a trial was conducted at location Mustahil 148 by changing the explosive material ratio from 80% emulsion and 20% AN-prill to 50% emulsion and 50% AN-prill, as shown in Figure 9. The experiment of changing the explosive material ratio was carried out to determine the gas concentration values formed with the visual fume condition classification at Level 2. From the measurement results of toxic gases at the trial blast site, there was an increase in the concentration values of CO and NO_2 gases resulting from the blast. This is due to the high percentage of AN-prill used, resulting in a decrease in the explosive material's resistance to water. By changing the explosive material ratio, it can be indicated that the explosive material used is not in a zero-oxygen balance condition, thus forming fumes. Therefore, it can be indicated that changing the explosive material ratio can affect the formation of fumes resulting from the blast.

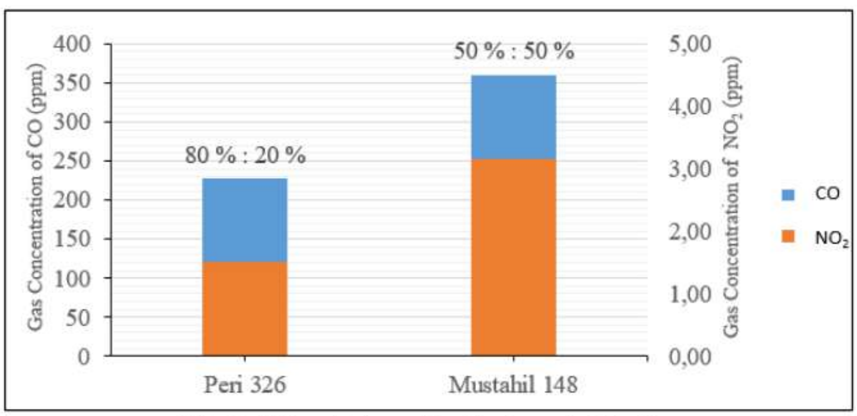

Figure 9. Comparison of explosive material ratios

Discussion

The nature of a gas filling a space is the primary factor in reducing fume levels; in a room, a gas will spread and attempt to fill that space. The characteristics of this gas cause gas measurements to be expressed in ppm (parts per million). Blasting in open-pit mines causes gas to spread and attempt to fill the unlimited space of the environment (Abbaspour *et al.*, 2018). The decrease in gas levels is also accelerated by the wind speed at the blast site. Based on the measured fume levels measured using drones and conventional methods post-blast, the duration of the decrease in measured gas levels can

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be determined (Bamford *et al.*, 2020). Blast crews who will check the post-blast location must wait until the location is free from fumes. The decrease in fume levels at the blast site is influenced by the presence of wind blowing at the blast site. This can expedite blast crews' post-blast location checks.

Weighting or classification of fumes based on visual inspection is the standard used because there is currently no standard for classifying blast fumes in open-pit or underground mines based on the concentration of fumes formed (Biessikirski *et al.*, 2023b). The classification of fumes based on visual inspection is determined by the color of the gases formed, where the color indications provide the level of danger of the fumes formed. The classification of fume types based on visual inspection was issued by the Australian Explosives Industry Safety Group (AEISG) in 2011. AEISG is a community aimed at improving safety and security levels in all aspects of explosive material manufacturing, transportation, storage, handling, and use throughout Australia (AEISG 2011).

Classifying fumes based on visual inspection results in many biased perceptions of the fumes formed from blasting, as each individual has a different opinion on the type and danger of fumes based on color. Many workers do not recognize the danger of fumes and assume that the gases formed from blasting are just ordinary smoke. This research will attempt to classify the types and dangers of blast fumes based on visual inspection using blast photo data collected during the research.

Classifying blast fumes based solely on visual inspection cannot be used as a standard for representing the level of danger of the fumes. Based on measurements using gas detectors, it was found that white-colored fumes still contain levels of CO, H_2S, and NO_2, making them very dangerous for mine workers, especially blasting crews conducting post-blast checks. The color of blast fumes cannot be classified accurately due to the presence of dust particles originating from cutting materials during blast hole drilling, making it difficult to distinguish between gases and dust. Therefore, a clear standard is needed for weighting the fumes formed in open-pit mines and for measuring blast fume levels safely, quickly, and accurately.

Based on the visualization results from field photography, it is shown that, on average, all research locations are at level 0, except for measurement locations Tania 577 at level 1A and Mustahil 148 at level 2A. Further details can be seen in Table 2.

Table 2. Visual Classification of Fumes

Location	Level	Actual Figures
Tania 549	*Level 0*	
Melawan 098	*Level 0*	

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Location	Level	Actual Figures
Tania 558	*Level 0*	
Melawan 108	*Level 0*	
Melawan 110	*Level 0*	
Peri 323	*Level 0*	
Tania 573	*Level 0*	
Peri 326	*Level 0*	
Melawan 130	*Level 0*	

Location	Level	Actual Figures
Tania 577	*Level 1A*	
Peri 338	*Level 0*	
Mustahil 148 (*Trial*)	*Level 2A*	

Conclusion

The gases formed from the explosion activities at PT KPC are CO gas and NO_2 gas. The maximum CO gas concentration formed due to the blasting activities is 360.29 ppm, and the maximum NO_2 gas concentration formed due to the blasting activities is 3.16 ppm. Stemming length, conditions of blast hole water, and sleep blast do not significantly affect the formation of fumes, but the relative humidity of the blast hole and the difference in explosive material ratios affect the formation of fumes resulting from the explosion. Based on the Short-Term Exposure Limit (STEL), with the maximum gas concentration workers are exposed to within a 15-minute period, workers are declared safe to enter the blast site less than 1 minute after the explosion is carried out.

Acknowledgment

Thanks are extended to Universitas Trisakti for funding the research through the Faculty's Outstanding Research Scheme, to PT AEL for collaborating on field data collection, and also to the management of PT Kaltim Prima Coal for granting permission to conduct this research.

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