Monitoring of low, medium and high respirable dust concentrations using South African cyclones

*B.K. Belle, CSIR-Miningtek, Johannesburg, South Africa,
H.R. Phillips Head, School of Mining Engineering, University of Witwatersrand, South Africa*

Introduction

With the advent of newly available medical surveillance results on pneumoconiosis, worker exposure limits are being revised in many countries and new, more stringent dust standards are being recommended across the globe. It is, therefore, increasingly necessary to measure dust concentrations as accurately and in as practicable a way as possible to assess the dust exposure of workers. Trials involving underground dust measurements have been carried out using South African samplers positioned side-by-side on the continuous miner operator's cabin, in machine face areas and at intake and return locations. The performance of the South African cyclones is similar to that of the European Higgins-Dewell type cyclones at a flow rate of 2,2 L/min and they respond according to the CEN/ISO/ACGIH respirable curve. During the trials dust samples were collected for full production shifts, excluding travelling time. It was found that dust concentrations in the sample population ranged from 0,18 to 17,78 mg/m^3. The ratio of larger to smaller dust concentration values for pairs of samples at each location was determined.

The correlation coefficient between the pairs of samples for the intake, operator's cabin, face area and return positions were 0,98, 0,95, 0,88 and 0,95 respectively. The variations between the pair-wise samples were at their highest when sampled closest to the face area. This could be due to the various patterns of dust cloud around the face area and turbulent airflow patterns around the front portion of the continuous miner. The results also indicated that the use of a single dust measurement at high dust concentrations by itself sometimes underestimates the "true" dust concentration, depending on the position of the sampler. This paper recommends the cautious use and interpretation of single engineering dust concentration sample data collected for administrative dust control purposes.

Introduction

With the advent of new medical surveillance results on pneumoconiosis, worker exposure limits are being revised in many countries and more stringent dust standards are being recommended across the globe. It is therefore, increasingly necessary to measure the dust concentrations as accurately and practicably as possible to assess the dust exposure of workers. Currently, in South African mines, workers' exposure to dust is assessed by a gravimetric sampling technique using samplers such as the Higgins-Dewell type cyclone, Casella 10 mm cyclone, Gillian cyclone, MSA cyclone, and CIP10. All these units are designed for monitoring dust and are approved by the South African Government's Department of Minerals and Energy Affairs (DME). Samplers are operated at a conventional flow rate of 1,9 L/min, except for the CIP-10, where the flow rate is 10,0 L/min in agreement with the BMRC respirable convention (BMRC, 1952). However, Kenny, Baldwin and Maynand (1998) have suggested that SA samplers operated at 2,2 L/min would lead to better agreement with the new ISO/CEN/ACGIH respirable dust curve, with a 50 per cent cut-off point (d_{50}) of 4 μm. The new flow rate confers an immediate advantage in sensitivity since, presently, cyclones in South Africa sample 16 % less air per minute. Mines are obliged to submit "engineering samples" to the DME, where gravimetric samples are collected at pre-determined continuous mining machine operator positions. Apart from this, the DME separately collects bi-annual "personal samples" from each section of the South African coal mines for assessing personal exposure.

Previous research work

The measurement uncertainties while estimating true worker exposure are not new to the mining industry. The National Research Council in the USA (1980) concluded that uncertainties associated with spatial and temporal variation in dust estimates from machine mounted samplers precluded this method for estimating personal exposures. During the past three decades, researchers worldwide have been presenting and publishing research work in the area of dust measurement techniques and problems associated with its interpretation. Extensive work has been done to identify the factors associated with the variability of measured dust concentrations and the possible reasons identified for the variability. A Government Accounting Office report to the US Congress (1975) indicated that under certain conditions the error associated with the respirable mine dust samples could be as great as 50%. The US National Bureau of Standards (1975) submitted an investigation report to the senate committee studying respirable mine dust sampling and analysis and concluded that under tightly controlled conditions with a "well-trained" technician, the average standard deviation associated with the process was $\pm$ 0,39 mg/m^3 (at the 2,0 mg/m^3 standard). NIOSH (1976) found that in high-risk mine sections, which failed to comply with the 2,0 mg/m^3 standard, the coefficient of variation in dust measurements was 91,6 %. A study by Page and Jankowski (1984) attributed the sampling measurement variations to the differences in the aerosol cloud being sampled, air flow velocity at the face and cyclone orientation. In 1986, a study by Kissell, Ruggier and Jankowski reviewed several factors contributing to the measured dust concentration variability. They concluded that sampler position, geological variation in the composition of coal (for variability in measured free silica), production factors such as deep or continuous cutting and failure to control known sources, such as shuttle car loading, play a crucial role in dust concentration sample results. Another study on dust concentration levels and their variability indicated that in coalmines, sampler location made an important contribution to the variability (Hall, Corn and Zeger, 1997).

DATA COLLECTION

Dust Measurement

South African studies on systematic comparison of cyclones are limited to mechanized underground coal mining conditions. The dust samples during the study were collected replicating conditions encountered during the actual production section under various dynamic ventilation conditions. Dust samples were collected in a bord-and-pillar continuous mining machine (continuous miner or road header) sections. The samplers were positioned in the section intake (40m outbye of the face), in the operator's cabin position, face area position (on the machine) and in the section return airway (40m outbye of the face). The objectives of the study were to determine if the variance of samples collected at the identified sampling locations, are comparable with different sampling environments and also to investigate the effect of concentrations levels and dynamic airflow patterns on the variance of samples collected.

Test samplers

For all test purposes, the locally manufactured and DME-approved 10 mm cyclone (GME–G05) was used and is shown (operator's position) in Figure 1. The cyclone body is fabricated from plastic. The dust cup (grit pot) is also fabricated from plastic and is fitted to the cyclone body. Filtration is accomplished with a 37-mm filter holder, which is pressed on over an "O" ring seal. Measurement of the size-selection characteristics of this cyclone, as tested in the UK (Kenny, Baldwin and Maynand, 1998), confirmed that they are similar to those of the Higgins-Dewell (HD) designs commonly used in the UK and elsewhere in Europe.

The dust-monitoring set-up contained two HD type samplers, positioned side by side. The HD type samplers consist of an air pump, which draws 2,2 L/min of air through a cyclone, which in turn selectively collects the fraction of airborne respirable dust with particles less than 10 μm on a pre-weighed filter disc. Filters from the samplers were weighed on an analytical electronic balance capable of an accuracy of 0,0001 mg. The procedure for determining the particulate mass was followed as per the DME guidelines

(DME, 1997). Well-maintained pumps were used to avoid the effect of pump pulsations and fluctuations in the flow rate.

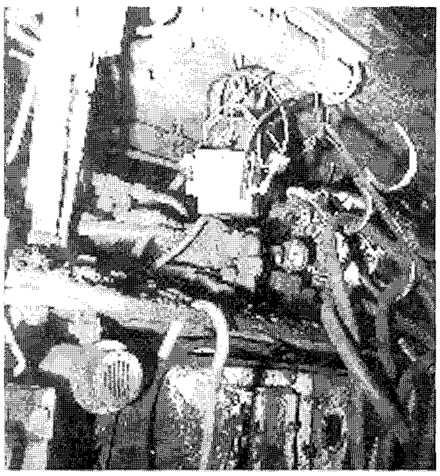

Figure 1. *Dust sampling train at the CM operator position.*

Data analysis

Paired samples were defined for this study as two HD type cyclones collecting the dust samples at the specified location for the same sampling period and positioned approximately 250mm apart. For the analysis, the ratios (larger to smaller) of airborne respirable dust (ARD) concentrations were used. A rejection protocol was applied to the sample data to maintain consistency. The criteria used to reject sample data pairs was failure of an individual pump in the sample pair during the sampling period. Rejection due to uncontrolled activity was a subjective call invoked on occasions such as when stone dusting took place in the section.

Results and Discussions

Summary of paired sample results

The statistical evaluation was carried out on the sample data collected from HD type sampler pairs at four positions. Descriptive statistics were calculated for the sampler concentration ratios including the mean, minimum, maximum, variance, median, standard deviation and standard error of the mean. Table 1 shows a summary statistic of respirable dust concentration values obtained by the HD samplers at different positions. The correlation coefficient (r) between all the HD type samplers is 0,95. The correlation coefficients (r) at the intake, operator's cabin, face area and return position are 0,98, 0,95, 0,88, and 0,95 respectively.

Statistic	HD_{in}	Hd_{op}	Hd_{face}	HD_{ret}
Mean	1,116	1,151	1,253	1,121
Variance	0,016	0,011	0,065	0,019
Median	1,081	1,133	1,143	1,058
Std. Dev.	0,124	0,106	0,255	0,139
Std. Error	0,025	0,019	0,051	0,026
Minimum	1,000	1,002	1,006	1,004
Maximum	1,451	1,408	2,181	1,647
Size	25	30	25	29

Table 1. *Summary statistics of dust concentration ratios.*

Figures 2-5 display the plots of Airborne Respirable Dust (ARD) concentrations between pairs of dust samplers at various positions.

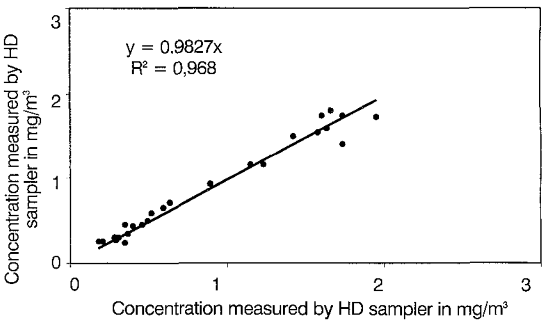

Figure 2. *ARD concentration data at the section intake.*

In addition, Figure 6 shows the cumulative frequency distribution of ARD ratios (larger to smaller) at various positions.

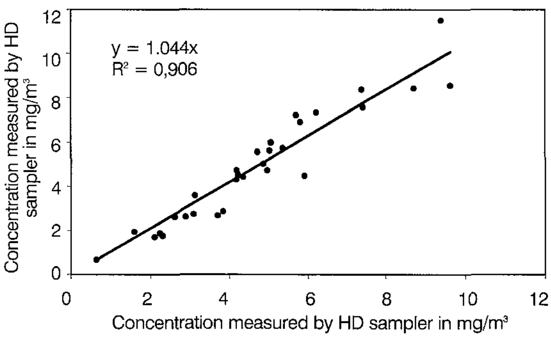

Figure 3. *Dust sampling train at the CM operator's cabin.*

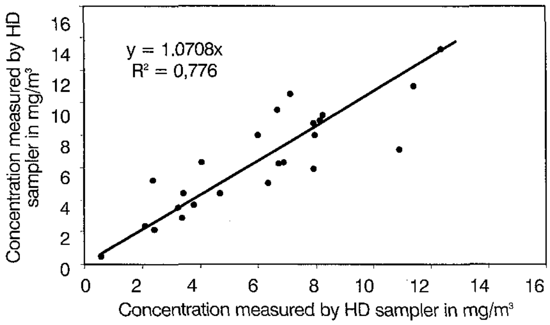

Figure 4. *ARD concentration data at the face area.*

The summary statistics of dust concentration ratios are briefly summarized as follows:

3.1.1 Section intake

- The ARD ratios (larger to smaller) values exceeded 1,1 in 40 % of the paired samples and 1,2 in 20 % of the pairs.
- The intake sample data had a standard deviation of 12,5 % with a maximum ARD ratio of 1,45.

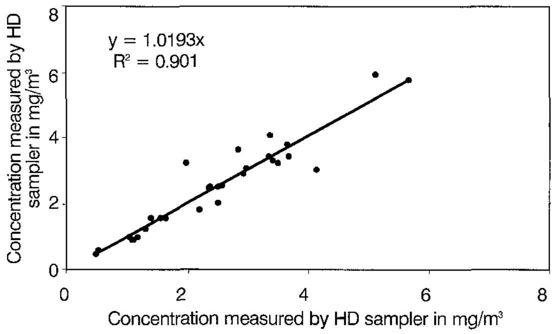

Figure 5. *ARD concentration data at the section return.*

CM operator position

- The ARD ratios (larger to smaller) values exceeded 1,13 in half of the paired samples and 1,2 in 25 % of the pairs.
- The standard deviation at the operator sample was 10,5 % with maximum ARD ratio of 1,407.

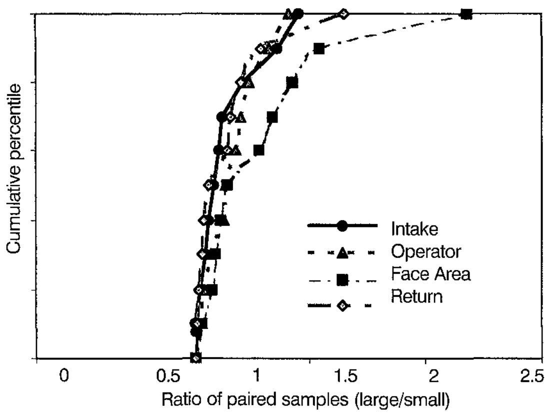

Figure 6. *Cumulative frequency distribution of ARD ratios.*

Face area

- The ARD ratios (larger to smaller) values exceeded 1,10 in 60 % of the paired samples and 1,4 in 20 % of the pairs.
- The variability was highest of all the sample positions (25 %) with a maximum ARD ratio of 2,181.

Section return

- The ARD ratios (larger to smaller) values exceeded 1,06 in 50 % of the paired samples and 1,2 in 19 % of the pairs.
- The standard deviation in the return air samples was 13,9 % with a maximum ARD ratio of 1,647.

Statistical Analyses

Preliminary data analysis indicated that $\log_e$ –transformed data was an improved fit of the normal distribution. Therefore, for the statistical analysis, $\mathrm{Log_e}(H_a)$ and $\mathrm{Log_e}(H_b)$ at each sampling position were compared (paired t-test). The subscripts, Ha and Hb are the sample concentration values in the sample pair (random) at various positions. Hypothesis tests were carried out at each of the sampling locations as the sampling environment varies in terms of air flow pattern, degree of turbulence, dust concentration profiles and fixed-point (intake position and return position) or moving (operator cabin and face area) type of sampling. The null and alternative hypothesis for the tested sample pairs were:

H_0: μmdiff = 0

H_a: μmdiff $\neq 0$

In the paired t-test, hypothesis H_0 states that the mean difference in concentration values (transformed values) between side-by-side sample pairs is equal to zero. On the other hand, the alternative hypothesis states that the two samplers positioned side-by-side in fact measured different mean concentration levels or the difference was not equal to zero. For this research work, a standard 95% confidence level was chosen. Results of the paired t-test statistical analyses are given in Table 2.

Statistic	Sample pair concentration difference				
	Hd_{in}	HD_{op}	Hd_{face}	HD_{ret}	Hd_{all}
95 % LCL	-0,09	-0,06	-0,17	-0,07	-0,06
95 % UCL	0,03	0,06	0,05	0,05	0,01
Size	25	30	25	29	109
t-Statistic	-1,01	-0,07	-1,15	-0,22	-1,30
p-value	0,32	0,94	0,26	0,83	0,19
Hypothesis (accept/reject)	accept	Accept	accept	accept	accept

Table 2. *Results of paired t – test (on transformed values).*

From Table 2, it is observed that, at all sampling positions, the measured mean dust concentration level from each pair of HD samplers are not significantly different and the null hypothesis is accepted.

A paired t-test was performed on the combined data of all four sampling positions (Figure 7) to determine if there was a statistical difference in the results obtained between two samplers at all locations.

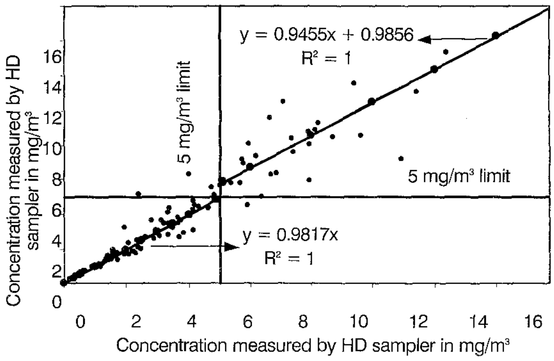

Figure 7. *Combined ARD concentration data.*

The result of the paired t-test was a test statistic with 107 degrees of freedom, p = 0,197, indicating no significant difference between measured mean concentration levels using two side-by-side HD samplers. Therefore, hypothesis H_0 was accepted. In other words, dust readings measured by the two samplers side-by-side are not affected at the 95 % level of confidence.

The data was further separated in order to determine if there was any difference between the side-by-side sampler pairs at measured concentrations greater than 5 mg/m³ for the sampling period. The correlation coefficient (r) between all the HD type sampler pairs where one of the sample pair concentrations was greater than 5 mg/m³ is 0,79. The comparison of the paired sample data (greater than 5 mg/m³) was a test statistic with 30 degrees of freedom, p=0,05. This indicates that at higher dust concentrations (above the DME directive maximum), there appears to be a minor difference (due to low p-value of 0,05) between measured mean concentration levels using two side-by-side HD samplers.

Conclusions

Trials involving underground dust measurements were carried out using South African samplers positioned side-by-side at low, medium and high concentration positions. During the trials dust samples were collected for full production shifts, excluding traveling time. It was found that dust concentrations in the sample population ranged from 0,18 to 17,78 mg/m³. The ratio of larger to smaller dust concentration values for a pair of samples at each location was determined. The variation in the sample dust concentration between the pair wise samplers is at its highest when sampled closest to the face area. This could be due to various patterns of sample cloud around the face area and operator's cabin and turbulent airflow patterns around the machine. In general, test data have indicated that there are a variety of factors that bring into question the validity of samples collected underground for exposure assessment.

The perception of significant difference between pair of side-by-side samplers at the operator's position (engineering sample) seems to be persistent. The bias between the sample pairs was determined using the concentration ratio (larger to smaller) data. The analysis indicate that the sampler biases the measurement by 11,6 %, 15,1 %, 25,3 % and 12 % for the dust samples collected at section intake, operator's cabin, face area position and section return respectively. The bias is at its highest for the samplers located at the face area position. The results also indicate that the use of a single dust sampler may not by itself either underestimate or overestimate the actual dust concentration for engineering control purposes. The results also indicated that the use of a single dust measurement value at very high dust concentrations (face area) sometimes underestimates the "true" dust concentration for near-accurate exposure assessment. This paper therefore, recommends the cautious use and interpretation of single engineering dust concentration sample data collected daily for administrative dust control purposes. However, the question of greater bias for dust sample concentration values greater than 5 mg/m^3 is not an immediate matter of concern as it fails to meet the DME directive. Therefore, mine management should continue to channel efforts into greater dust control measures in the face area. Finally, at the operator's cabin position, use of a single dust sampler would suffice for near-accurate exposure assessment of the face condition under correct sampling and sample handling procedures.

Acknowledgements

The authors would like to acknowledge the financial support of the Safety In Mines Research Advisory Committee. Gratitude is also expressed to Dr. Brian Williams, formerly of CSIR-Miningtek for the advice in data handling during initial stages of the research work. The support of CSIR-Miningtek and many of its employees is also appreciated.

References

- American Conference of Governmental Industrial Hygienists (ACGIH). 1998. Threshold Limit Values for chemical substances and physical agents and biological exposure indices. USA.
- British Medical Research Council. 1952. Recommendations of the BMRC panels relating to selective sampling. 1952. From the minutes of a joint meeting of panels 1, 2 and 3 held on 4th March.
- Comite European de Normalization. 1991. Size fraction definitions for measurement of airborne particles in the workplace. Pr EN 481.
- DME. 1997. Guidelines for the gravimetric sampling of airborne particulate for risk assessment in terms of the occupational diseases in mines and works act # 78 of 1978, Parent Doc. 3rd Ed. SA.
- Hall, T. A., Corn, M., Zeger, S., 1997: Respirable dust and free Silica variation in mine environments, Strategies for mine dust measurement.
- Kissell, F. N. Ruggier, S. K. and Jankowski, R.A. 1986. How to improve the accuracy of coal mine dust sampling. Am. Ind. Hyg. Assoc. J. 47 (10): 602-606.
- International Standards Organization: Air Quality, 1993. Size fraction definitions for measurement of airborne particles. CD 7708.
- Kenny, L. Baldwin, P.E.J. and Maynard, A. D. 1998. Respirable dust sampling at very high concentrations, HSL, UK.
- National Resource Council. 1980.Measurement and control of respirable dust in mines, Washington D.C. USA.
- National Bureau of Standards. 1975. An evaluation of the accuracy of the coal mine dust sampling program administrated by the Department of Interior. Final report to the senate committee on labor and public welfare, Washington, D.C. USA.
- NIOSH, CDC. 1976. Statistical analysis of (Mining Enforcement Safety Administration) respirable dust data, Pittsburgh. USA.
- Page, S. & Jankowski, R. 1984. Correlations between measurements with RAM-1 and gravimetric samplers on longwall shearer faces. Am. Ind. Hyg. Assoc. J. 45(9): 610-616.