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The Effectiveness of Rapid Stone Dust Compliance Testing in Underground Coal

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THE EFFECTIVENESS OF RAPID STONE DUST COMPLIANCE TESTING IN UNDERGROUND COAL

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ABSTRACT: The addition of stone (limestone) dust to roadway dust in an underground coal mine increases the Total Incombustible Content (TIC) to reduce the potential of the coal dust igniting and propagating an explosion. Coal dust explosions have been proven to be one of the most severe hazards in an underground coal mine hence as Queensland legislation requires the use of roadway stone dusting, the required levels of TIC are higher than other mining districts around the world which also employ other coal dust explosion barriers. Compliance testing currently involves Low Temperature Ashing (LTA) of representative samples with a turn around on results of up to two weeks. To minimise the time that the mine is potentially out of compliance and unsafe, the Coal Dust Explosibility Meter (CDEM) has been tested at a Queensland underground coal mine to determine its effectiveness, through 11 different calibration methods, in rapidly measuring the TIC of roadway dust samples. The key focus of the calibration methods was to explore the effectiveness of the CDEM at its designed threshold of 80% TIC, the use of an inbuilt methane content adjustment to replicate the Queensland legislative requirement of 85% TIC and the use of actual 85% TIC calibration samples. These calibration methods were replicated using both the manufacturer provided Pittsburgh coal dust and mine site specific coal dust for calibrating the CDEM. This paper provides the results of this investigation.

INTRODUCTION

Coal dust explosions present one of the most severe hazards in underground coal mining, however much has been learnt from past disasters, which has enabled the creation of the Department of Natural Resources and Mines, Queensland government Coal Mining Safety and Health Act (Qld,1999). Coal dust explosions are not as easily ignited as methane, however they are typically initiated by a methane explosion when dust is lifted into the air, increasing the strength of the explosion as it combusts. Stone dust in the form of limestone dust has been adopted globally as a means of increasing the incombustible content of roadway dust, rendering it inert to ignition and combustion if subject to a methane explosion. Frictional ignition has been identified as a potential means of coal dust ignition due to the increasing mechanisation in underground coal mines. This increased mechanisation has also resulted in a reduced coal particle size, which has been proven to require higher stone dusting quantities to render the roadway dust inert.

As the Coal Mining Safety and Health Regulation (DNRM, 2001) requires that incombustible contents of 70%, 80% and 85% are maintained in areas of the mine, compliance monitoring is part of an underground coal mine's legal obligation. Low Temperature Ashing (LTA) of roadway dust samples to determine the incombustible content, from the remains after combustion and the addition of the moisture content, has been accepted as the most accurate means of compliance testing. The colorimetric method involves human factor inaccuracies in sample preparation and visual competence during the comparison. The recently developed Coal Dust Explosibility Meter (CDEM), as detailed in Figure 1, exploits the different reflectance properties of coal and stone dust to compare dust samples to a reference sample of the desired incombustible content. Testing in USA underground coal mines has shown accuracies which challenge the colorimetric method and approach that of LTA (Harris *et al*., 2012).

Overview

In 1921, Queensland's worst mining disaster occurred at the Chillagoe Company's Mt Mulligan Mine in Far North Queensland, where 75 men were killed when a coal dust explosion engulfed the mine (QRC, 2007). A number of mine explosions have occurred since with varying degrees of coal dust ignition. Internationally, the increased number of casualties that are associated with coal dust explosions in

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comparison to a methane explosion are illustrated by 1527 lives lost in the Honkeiko Colliery, China in 1942 (Cybulska, 1988).

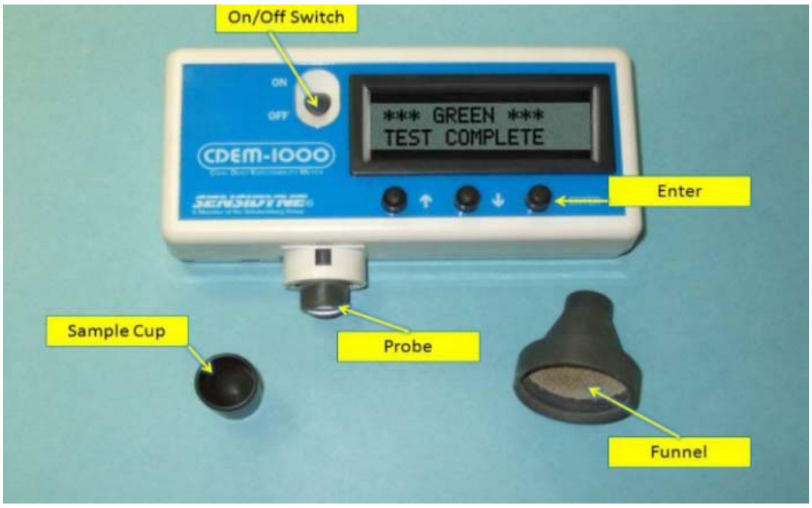

Figure 1: CDEM Components (Harris *et al*., 2012)

COAL DUST EXPLOSIONS

Harris *et al.,* (2009) explained the reduction in coal dust size over the century was due to the higher mechanisation of coal mines and the reduction in conventional blasting, with factors such as continuous miners, longwall shearers, cutting speed and cutting depth each having varying effects on the fineness. Sapko, Cashdollar and Green (2007) tested large scale mixtures of Pittsburgh high volatile bituminous coal and stone dust for the propagation of an explosion, demonstrating in Figure 2 that the finer the coal dust, the higher the amount of stone dust required to inert the mixture.

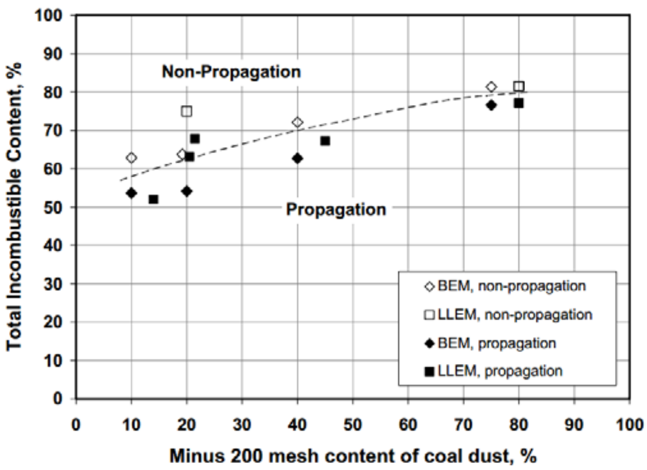

Figure 2: Effect of particle size of coal dust on the explosibility (Sapko, Cashdollar and Green, 2007)

Ignition Sources

Cybulska's (1988) study on major mine explosions concluded that the potential for a methane explosion is lower than a coal dust explosion due to the standards of ventilation and atmospheric sampling, minimising the accumulation of large pockets of methane. However, Cybulska (1988) points out that ignition of methane is easier than coal dust, hence it still provides a risk. Gillies and Jackson (1998) completed an analysis on the absolute flammability on a coal sample, as illustrated in Figure 3, demonstrating the impact that coal dust in the atmosphere has on the explosive limits of methane. The higher the coal dust concentration, the lower the explosive limit of the methane, promoting the importance of monitoring coal dust and methane concentrations together.

Du Plessis (1996) and Cain (2003) both describe that internationally, frictional ignition at the coal face has the highest potential for ignition of methane or coal dust. During Du Plessis' (1996) study of mine explosions, the increasing mechanisation of underground coal mining was responsible for 97% of explosions due to the resulting reduction in use of explosives for coal production.

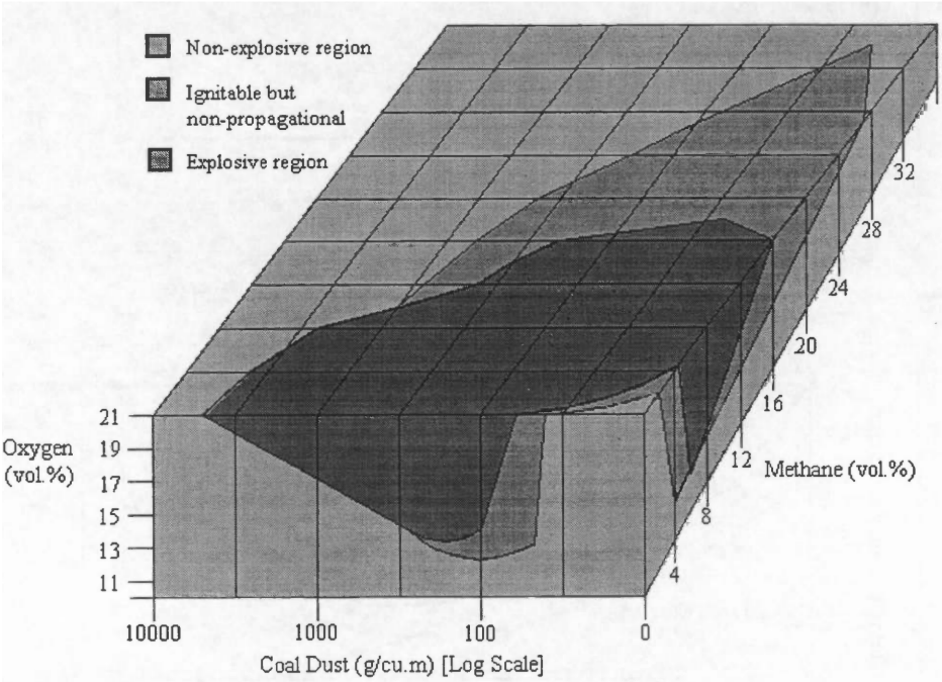

Figure 3: Absolute flammability limit surface for the coal sample (Gillies and Jackson, 1998)

Belle, Carey and Robertson (2012) describe that 70% of global frictional ignition events are initiated due to worn cutter picks and recommend a similar profile for pick replacement as Baker, Jones and Hardman (1981), as detailed in Figure 4.

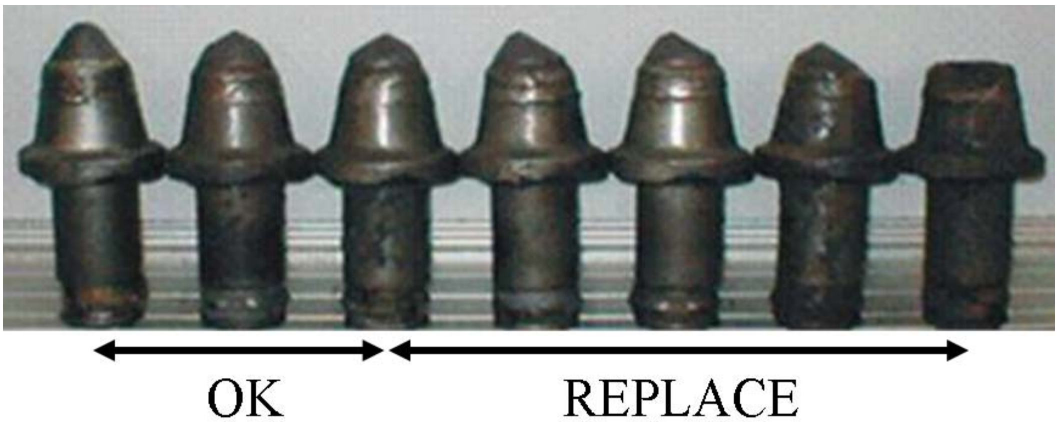

Figure 4: Cutting pick wear profiles (Belle, Carey and Robertson, 2012)

Suppression Methods

Stone dust, which is derived from limestone, gypsum or marble dust, increases the TIC of the roadway dust to the point where it is no longer explosible if subject to a potential ignition source (Jensen and O'Beirne, 1997). The addition of stone dust to the fine coal dust acts as a dilutant, heat sink and oxygen/gas obstruction (DNRM, 2003). Limestone dust has a very limited pulmonary risk hence is the most widely used substance for stone dusting (Hartman *et al.*, 1997). Coal Mining Safety and Health Regulation 2001 (QLD) (and USA coal mines) requires only the use of roadway stone dusting for coal dust explosion suppression, however elsewhere require coal dust explosion barriers to be installed in underground coal mines (Cain, 2003). Queensland Coal Mining Safety and Health Regulation (DNRM, 2001) has a larger focus on roadway stone dusting with the highest legislative incombustible contents globally (DNRM, 2003).

Roadway dusting offers the advantages over other methods in that it does not affect ventilation resistance (like barriers hanging in the airstream), it provides protection throughout the mine (not just near the face like other barriers), is stirred up with the dust in the explosion front (does not require a pressure front to release it) and is simpler, safer and more cost effective to advance behind the production front than fixed barriers.

Passive stone dust barriers involve the placement of stone dust on lightweight boards which will be displaced by a pressure wave, allowing stone dust to fill the roadway (DME, 2002). This method engulfs the pressure front with stonedust, so any coal dust that is picked up is mixed with stone dust, inertising it prior to the flame front and effectively extinguishing the flame (Cain, 2003). These barriers require replacement of stone dust periodically as it is exposed to the atmosphere (coagulating and/or dispersing), they offer little protection for personnel inbye and require a specific range of conditions to deploy which are not always experienced during methane explosions and weak explosions. Triggered stone dust barriers are currently being developed so that the release of stone dust is determined by electrical sensors in the roadway or even integrated into continuous miners (Cain, 2003).

Bagged stone dust barriers, as shown in Figure 5, provide the same effect as stone dust being dispersed into the roadway upon impact of the pressure front (rupturing the bags).The key advantage of the bags is the longevity of the stone dust, as it is not exposed to the atmosphere, however if the explosion front lingers too far behind the triggering pressure front, there will not be stone dust in the airstream. Water barriers are closed troughs of up to 90 L which are suspended longways across the roadway and are composed of a material which is incombustible but will fail when subject to the pressure front, dumping a wall of water into the roadway, providing an alternative to stone dust barriers. Similarly, active on-board explosion suppression systems were tested in the Kloppersbos explosion tunnel (Belle and Du Plessis, 1999). These systems mounted on CM machines that detect the presence of a methane ignition by means of light sensors are employed in South African and Chinese coal mines. The electronic signals from the sensors trigger the suppression system which creates a barrier of flame-suppressing material, thus containing the flame in the immediate vicinity of the ignition and so preventing further development and propagation of a coal dust/methane explosion.

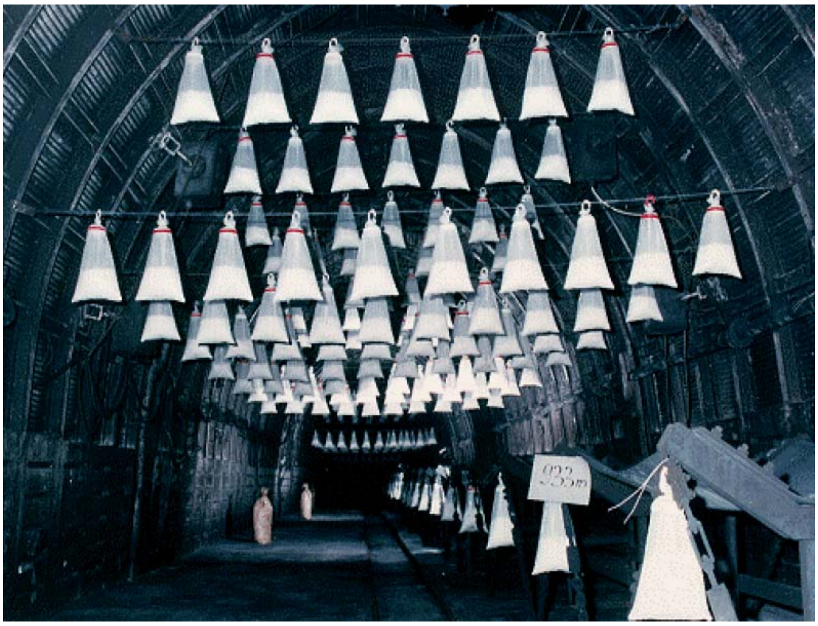

Figure 5: Bagged stone dust barrier (Belle and Du Plessis, 1999)

Compliance Testing

DNRM (2003) recommends the stone dust compliance sample collection procedure of taking a uniform width and depth (not exceeding 5 mm) traverse strip sample from around the periphery of the roadway. Where spot samples are taken for weekly samples only, a representative area of the rib and floor should

be sampled to cover a total area greater than 0.1 m2 (DNRM, 2003). If there is any obstructions in the roadway such as conveyor belt structure, DNRM (2003) recommends sampling these surfaces as part of the strip or spot sample as they too have the potential to provide dust to propagate a coal dust explosion.
LTA is the analysis method which is employed in laboratories to accurately determine the TIC of the roadway dust sample (DNRM, 2003). Together the moisture content (through drying) and amount of incombustible material (through heating to burn off the coal) combines to give the incombustible content of the sample. The key advantage of the LTA method is the accuracy of the analysis, which far outweighs the accuracy of other testing methods as demonstrated by comparisons conducted by Harris *et al.,* (2008). Results from the laboratory are more costly than other methods and can take up to two weeks for quarterly stone dust samples to be returned, however weekly samples are turned around in a matter of days (Harris *et al.,* 2009).

The colorimetric method involves analysing the surface of a well-mixed homogenous sample of roadway dust, in comparison to predetermined reference samples at 70%, 80% and 85%, or compared to the greyscale of a digitally scanned sample. The digital colorimetric method involves sieving, drying and scanning reference samples of roadway dust with known TIC to established reference greyscales, then comparing those to scanned roadway dust samples (Kizil, Peterson and English, 2001; Peterson, 2001). The colorimetric method is a low cost (setup and ongoing testing) instant comparison of the roadway dust, albeit not required by Queensland Coal Mining Safety and Health Regulation 2001 (QLD, 2001) prior to sending for laboratory analysis, this practise offers the ability to enable immediate re-treatment of potentially non-compliant roadways. Peterson (2001) highlighted that sample discolouration; the visual ability of the tester to distinguish between the sample and reference colours; sufficient lightning, adequate drying to prepare the sample underground and consistency of the seam (relevance of reference samples) affect the accuracy of this method. In addition, supplied stone dust need not be typically 'white' in colour.

The CDEM, a hand held optical instrument for assessing coal dust incombustible content, has been created in collaboration between the Pittsburgh Research Laboratory of the National Institute for Occupation Safety and Health (NIOSH) and the Mine Safety and Health Administration (MSHA) (Sapko and Verakis, 2006). The CDEM produces either a green result which signifies the sample is compliant (lighter than the reference sample) or a red result which signifies a non-compliant sample (darker than the reference sample). In combination with a red result, it also estimates a range of the sample's TIC.

The CDEM employs an infrared light emitting diode, to focus a beam of infrared radiation onto the dust sample, with a silicon photodiode sensor, which measures the reflected light intensity. The reflected light intensity is then compared to the reference sample and the empirical normalised reflectance for Pittsburgh roadway dust samples, to determine if the sample is in compliance (Sapko and Verakis, 2006). Prior to the commercialisation of the product, Harris *et al.,* (2012) conducted a field study finding 75% of the 297 samples to pass and 25% to fail, the percentage of incorrect and correct readings are detailed in Table 1, with descriptions of the four criteria used to analyse CDEM effectiveness results.

Table 1: CDEM field study (after Harris *et al.,* 2012)

CDEM/LTA Comparison	*Percentage (%)*	*Description*
Disagreeing Red	9	Compliant samples that the CDEM falsely failed.
Disagreeing Green	1	Non-compliant samples that the CDEM falsely passed.
Agreeing Red	91	Non-compliant samples that the CDEM correctly failed.
Agreeing Green	99	Compliant samples that the CDEM correctly passed.

The two disagreeing values are low which proves this device to be promising, however the most concerning failure is the disagreeing green, which if the mine was to solely use the CDEM for compliance testing, these samples would have been considered compliant, even though they are actually non-compliant. Ideally this disagreeing value would be 0 with the optimum calibration standard, however there would not be a compliance issue if the disagreeing red was >0. The only issue with a disagreeing red sample would be that the cost and resource allocation employed to re-treat that roadway could be better utilised, saving costs and resource use.

CASE STUDY

Overview

Roadway dust samples were collected from a Queensland underground coal mine. The samples were well mixed, with a sieved sample taken from each for further testing using the LTA, CDEM and colorimetric methods. The results spanned 109 roadway dust samples, with each sample being tested with the CDEM three times for the 11 calibration methods to give 1199 averaged results. The colorimetric method and LTA results were a single result for each of the 109 samples. The 11 calibration methods include small variants on the seven detailed in the methodology due to variations in the reference samples' TIC and also due to the methane adjustment not equalling the desired 85%.

Calibration Methods

The calibration method detailed by the manufacturer is as follows (Sensidyne, 2013):

1. prepare a 50 mL sample of the provided Pittsburgh coal dust by passing through the molecular sieves (in the large tube) and sieve (in the funnel);
2. repeat step one with a 50 mL sample of stone dust from the mine;
3. repeat step one with a 50 mL mix of 20% Pittsburgh coal dust and 80% stone dust;
4. turn on CDEM;
5. attach reflectance calibration cup (standard cover) to base and follow prompts on screen to complete calibration;
6. fill the small thimble sized cup with a representative sample from the dried and sieved coal dust and insert into the CDEM to complete the coal dust calibration; and
7. repeat step six with the stone dust and, mix of 20% Pittsburgh coal dust and 80% stone dust, to complete the entire calibration.

The key difference between calibration of the meter for use in United States of America (USA) and Australia is the TIC required by legislation being 80% and 85% respectively, providing the motivation for the analysis of these seven different calibration methods:

1. the manufacturer's standard (calibrated to Pittsburgh coal at 80% TIC with mine site specific stone dust) (Sensidyne, 2013);
2. the manufacturer's standard for Queensland (higher methane level to mimic the 85% TIC required by legislation) (Sensidyne, 2013);
3. the manufacturer's standard, air drying samples first (removing the use of the provided molecular sieves) (Wu, 2013);
4. calibrated to Pittsburgh coal at 85% TIC with mine site specific stone dust, using manufacturer's standard for sample drying;
5. calibrated to mine site specific coal at 80% TIC with mine site specific stone dust, using manufacturer's standard for sample drying;
6. calibrated to mine site specific coal at 80% TIC with mine site specific stone dust, using manufacturer's standard for sample drying and higher methane level to mimic the 85% TIC required by legislation; and
7. calibrated to mine site specific coal at 85% TIC with mine site specific stone dust, using manufacturer's standard for sample drying.

Results

Analysis of the CDEM data showed promising results with the CQ underground coal dust calibrations showing the lowest disagreements out of all the calibrations, as detailed in Table 2. Table 2 also includes the values derived from the two colorimetric tests which were conducted using the mine's colour templates for roadway dust samples with a known TIC of 80% and 85%. The two colorimetric methods both had low and no green disagreements, however there were many samples which were considered red disagreements.

Table 2: Percentage based on red and green result totals of CDEM and colorimetric calibration methods

Calibration Method (LTA %TIC)	Disagreement		Agreement	
	Red	Green	Red	Green
1 (80%)	85	2	15	98
2a (85.2%)	65	4	35	96
2b (84.8%)	65	4	35	96
3 (80%)	87	0	13	100
4 (85%)	67	2	33	98
5 (80%)	58	3	42	97
6a (84.8%)	38	8	63	92
6b (85.2%)	38	8	63	92
7a (89.7%)	61	3	39	97
7b (86%)	55	6	45	94
7c (85.1%)	25	11	75	89
Colorimetric (80%)	82	1	18	99
Colorimetric (85%)	60	0	40	100
Harris *et al.,* (2012) (80%)	9	1	91	99

The CDEM sample which provides the lowest disagreements is calibration method five (preference on lowest disagreeing green, then lowest disagreeing red) which is the calibration of the system to 80% using all mine site related references. Calibration method #3 offers no disagreeing green values, however this was a much smaller sample size due to the undried and dried samples showing a definitive result to begin with, hence further testing of the calibration method was discontinued. The CDEM and colorimetric method offer similar amounts of red disagreements, however both colorimetric methods have lower green disagreements. The all-important green disagreements are on average lower for the 80% calibration methods, potentially due to this being the upper limit the CDEM was designed for.

A comparison between the LTA and CDEM TIC results is displayed in Figure 6, however as the CDEM only displays TIC estimates between 70% and 80%, the data is situated within this zone. The green disagreements are those samples which lie to the left of the 1:1 line and the CDEM estimates them as 80% (top left quadrant). The red disagreements are highlighted in the bottom quadrant of Figure 6 as this is where the TIC determined by the CDEM is less than the LTA (which found the samples TIC >80%). The results where both are in agreement are the blue points lying in the remaining two quadrants. Figure 6 shows that the CDEM does not rank the TIC for the majority of samples higher than the LTA, hence providing an additional safety factor in the test results. Being too safe however is costly, in terms of re-treating roadways which may not require re-treatment following the return of LTA results.

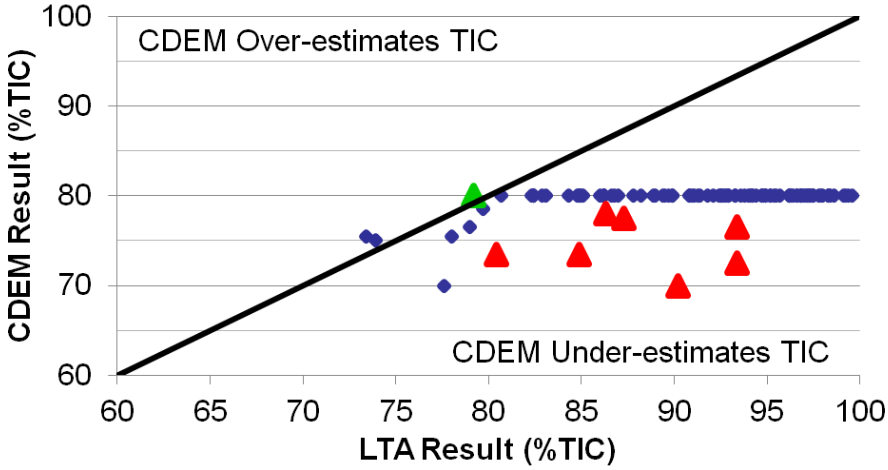

Figure 6: TIC correlation between averaged CDEM estimate and LTA result for calibration method five samples

To highlight the inability to replicate the results from Harris *et al*., (2012) field study of the CDEM, Figure 7 demonstrates the average results of testing at 80% TIC. The proportion of disagreements is substantially higher than the CDEM pre-commercialisation field study, disproving the effectiveness of the CDEM for rapid compliance testing for this particular mine site and set of samples.

The colorimetric methods offer little difference between the two reference levels in Table 2, however in comparison to the CDEM results in Figure 7, the average disagreements are slightly higher. The lower all-important green disagreements for the colorimetric method suggests the method may offer the potential of a higher accuracy (with minor adjustments), than the current CDEM calibration methods.

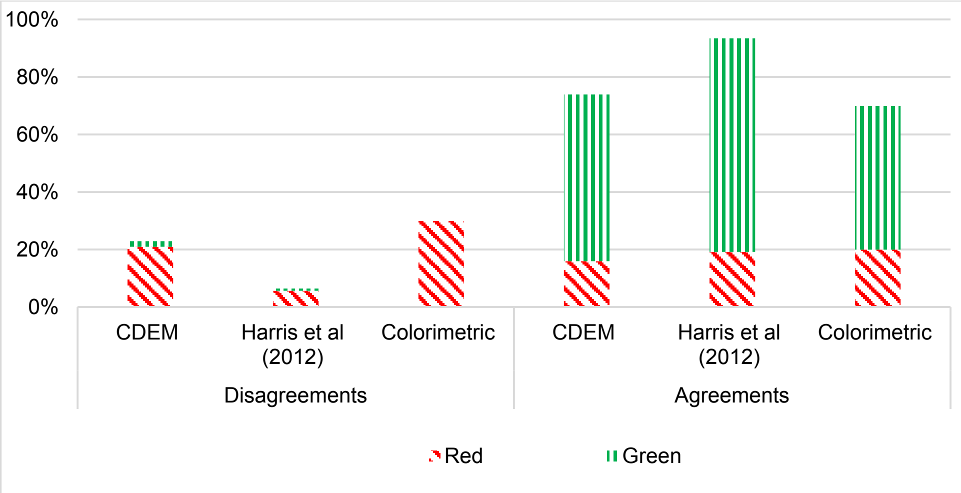

Figure 7: Average disagreements and agreements between CDEM, Harris *et al*., (2012) and colorimetric results with LTA for 80% TIC

ANALYSIS AND DISCUSSIONS

Calibration

The three calibration samples (80/85% TIC reference, coal and stone dusts) in combination with the initial reflectance calibration are the most critical variables in the process, as these define the accuracy of the CDEM in estimating TIC. The reference sample required by the manufacturer involves mixing the provided Pittsburgh coal dust with site specific stone dust. It can be seen in Table 2 that the calibration methods where the Pittsburgh coal dust was used as the reference sample (1, 2 and 4) experienced the highest number of disagreeing greens. As disagreeing greens are those which the CDEM would pass, even though they are non-compliant, this quite clearly disproves the effectiveness of the CDEM when used in CQ coals in accordance to the manufacturer's calibration methodology.

The TIC of the three reference samples developed for calibration method seven varied with 85.1%, 86% and 89.7%, and the effect this had on the accuracy of the CDEM is exemplified with the increasing number of green disagreements with the decreasing TIC. The green disagreements increase with decreasing TIC because the reference is becoming darker, but the samples are still not in compliance. It is of interest that the TIC of 89.7% offered the highest amount of red disagreements in calibration method seven, with 85.1% featuring the lowest number. The converse relationship between the red and green disagreements throughout the varying TICs in calibration method seven clearly demonstrates the fine line between what the CDEM estimates as compliant or non-compliant, hence the creation of a reference sample has a major impact on the CDEM effectiveness.

The 85% TIC reference sample should be prepared using coal dust and stone dust representative of the roadways that the CDEM is intended on being employed within for compliance testing. These samples should also follow the particle size distribution exemplified by the supplied Pittsburgh coal dust and be thoroughly mixed to ensure that the sample provides the appropriate surface area of 85% stone dust and 15% coal dust, when pressed against the CDEM probe. To further investigate the effectiveness of the device in its current state, if the initial reflectance calibration is replaced with an accurate site specific reference sample (the same used in the fourth calibration step), this would potentially align the CDEM with site specific parameters, potentially improving the effectiveness. This hypothesis is based on the assumption that the reflectance calibration cup replicates the manufacturer's empirical reflectance for the 80% TIC sample using Pittsburgh coal dust.

Testing Methodology

Sapko and Verakis (2006) identified the impact that the moisture content of a sample has on the effectiveness of the CDEM in estimating TIC as detailed in Figure 8, however Wu (2013) recommended removing the use of the molecular sieves from the testing methodology, by leaving the 50 mL sample to dry overnight in an air conditioned room. This recommendation was tested in calibration method three with a small group of roadway dust samples finding that of the 48 samples, calibration method one and three agreed on 43 of the samples.

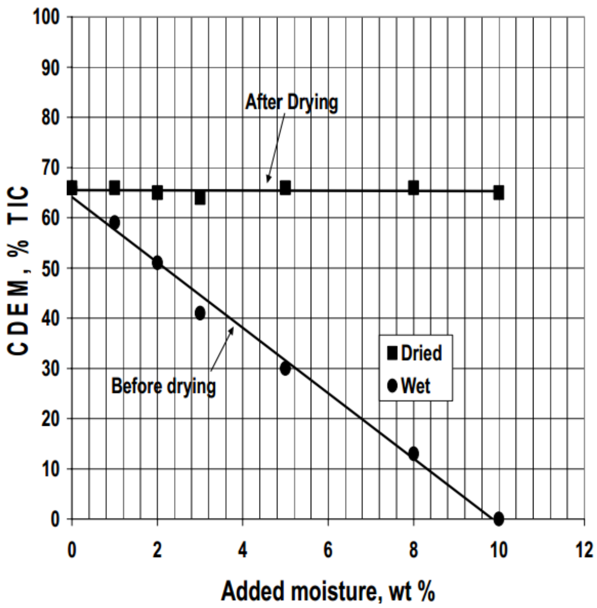

Figure 8: Effect of moisture on CDEM reading (Sapko and Verakis, 2006)

These results support molecular sieves being used on all samples to remove as much moisture as possible. The American Society for Testing and Materials (2008) has developed ASTM D4643 – 08 Standard Test Method for Determination of Water (Moisture) Content of Soil by Microwave Oven Heating which involves heating a small sample of a moist soil in the microwave for 3 minutes to remove all water. This method could be trialled for drying roadway dust samples prior to testing with the CDEM, more efficiently and less costly than molecular sieves.

Methane content adjustments used in calibration methods two and six can be compared to the actual 85% TIC calibration methods four and seven respectively. The actual 85% TIC reduces the disagreements, hence the methane content adjustments should not be used to mimic a TIC higher than 80% where there is the ability to mix an actual reference sample for the specific TIC.

Reflectance Algorithm

The CDEM calculates the normalised reflectance relative to the reference sample that is used to calibrate the meter, however the unit only accepts reference samples within a certain range of normalised reflectance either side of the empirical value found for the Pittsburgh coal dust. It would be of value to test the normalised reflectance from a series of samples which are close to the extinction limit (minimum TIC to prevent explosion) for the CQ underground mine, then having the value input as a single averaged value, rather than calibrating with a single sample, to potentially improve the CDEM effectiveness.

Intrinsic Safety

The CDEM has not been recognised in Queensland as intrinsically safe, as such the CDEM would need to be certified against International Electrotechnical Commission System for Certification to Standards Relating to Equipment for Use in Explosive Atmospheres (IECEx System) before being able to be used in an underground coal mine (DNRM, 2014). Once certified, the CDEM would offer a less subjective means of preliminary testing in the low light conditions of an underground coal mine, as the colorimetric method requires good light for distinguishing between colours and the CDEM just displays the word green or red on the screen. This would allow for real time feedback during stone dusting.

Colorimetric Method

The data on a whole shows that similar accuracies are achievable from both the colorimetric and CDEM testing methods. Due to the lower cost and time involved with the colorimetric method, it is recommended that the CQ mine continues using the colorimetric method for preliminary testing (prior to LTA). To lower the number of disagreements, darker reference samples should be adopted for the colorimetric reference template. A safety factor should still be applied during colorimetric testing in the form of some compliant samples being slightly darker than the reference sample, to minimise the potential for any incompliant roadways being deemed safe. Adopting these actions will reduce time spent on using the CDEM with practically no change in accuracy and changing the colorimetric reference template will save large costs by reducing excessive stone dusting.

CONCLUSIONS

Testing in an underground coal mine has shown that the CDEM is not supported for use in its current equipment format in favour of the colorimetric method for preliminary compliance testing, as the accuracies achieved are lower than the manufacturer found during their testing. Adjustments of the reference samples of the colorimetric method to darker than they are currently, will allow the mine to achieve similar accuracies to the CDEM for a lower labour cost and adopting darker reference samples, the re-treatment of already compliant roadways will be reduced, hence reducing costs.

The CDEM proved to be more effective when calibrated using all mine site specific samples (coal dust, stone dust and 80%/85% reference sample) with the 80% TIC calibration offering the best results. The manufacturer's calibration method resulted in slightly lower green disagreements, than the mine site specific calibration methods, however it had significantly higher red disagreements, resulting in a higher cost for re-treatments. The single worst calibration method was one where the methane content was adjusted to mimic 85% TIC. The methane adjustment was found to be less effective than an actual TIC reference sample, hence when possible the methane adjustment should be avoided.

The air drying of samples was investigated as a cost reduction exercise by not using the manufacturer's molecular sieves for drying. The results however highlighted that this method is less effective than the molecular sieves. The effect of the reference sample for calibration on the accuracy of the results was found to be a result of the particle sizes of the coal dust featuring in the roadway dust samples. As the stone dust is typically regular in size throughout the mine, the resulting reflectance of roadway dust samples where different coal dust particle sizes is present, results in varied reflectance for the same TIC. It should be noted that the CDEM was only used on the surface for this study and not underground.

RECOMMENDATIONS

There are six key recommendations that have been derived from the findings of this study:

1. it is not recommended for immediate use of the CDEM as a preliminary testing method;
2. investigate improvement options for the current colorimetric method by updating the reference samples and developing different sets of reference samples for different operational zones of the mine (dependant of coal dust size) to reduce the additional costs of re-treating roadways that are actually compliant;
3. investigate the effectiveness of the CDEM in compliance testing in non-operational zones of the underground mine by developing different sets of reference samples for different operational zones of the mine (dependant of coal dust size) and replicating the testing that has been completed in this study to determine if the CDEM is more effective when calibrated with samples which are similar in composition to those being tested;
4. determine the normalised reflectance of the roadway dust at the extinction limit from a series of samples, so as to determine an average value that could be input into the CDEM as a reference rather than basing the calibration on a single reference sample or roadway dust;

5. adjust the programming of the CDEM to allow "developers or evaluators" to finely adjust calibration settings in an aim to improve the effectiveness of the meter;
6. complete the intrinsic safety certification on the CDEM upon fine tuning; and
7. investigate the use of the ASTM microwave drying method as an alternative to the use of the manufacturer's molecular sieves.

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REFERENCES

American Society for Testing and Materials. 2008, ASTM D4643 – 08 Standard Test Method for Determination of Water (Moisture) Content of Soil by Microwave [online], Available from: < http://www.dot.nd.gov/manuals/materials/testingmanual/d4643.pdf > [Accessed: 29 August 2014].

Baker, R H, Jones, G J and Hardman, D R. 1981, An assessment of pick wear and its effect on continuous miner performance, *South African Chamber of Mines Res Org Report No 10/81*, 28 p (South African Chamber of Mines: Johannesburg).

Belle, B and Du Plessis J. 1999, Kloppersbos health and safety research in the South African coal industry, in *Proceedings International Conference on Mining - Challenges of the 21st Century*, New Delhi, pp 1-8 (CSIR Division of Mining Technology: Johannesburg).

Belle, B, Carey, D and Robertson, B. 2012, Prevention of frictional ignition in coal mines using chilled water sprays, in *Proceedings 12th Coal Operators' Conference*, Wollongong, pp 175-184 (University of Wollongong, Australasian Institute of Mining and Metallurgy and the Mine Managers Association of Australia: Wollongong).

Cain, P. 2003, The Use of Stone Dust to Control Coal Dust Explosions: A Review of International Practice, 100 p (rokdok: Lethbridge).

Cybulska, R. 1988, Propagation and Suppression of Colliery Explosions-with Particular Reference to Polish Conditions, *The AusIMM Bulletin and Proceedings*, 293(7):61-66.

DME. 2002, Department of Minerals and Energy, Republic of South Africa, Guideline for the Compilation of a Mandatory Code of Practice for the Prevention of Flammable Gas and Coal Dust Explosions in Collieries, 30 p (Department of Minerals and Energy: Sunnyside).

DNRM. 1999, Department of Natural Resources and Mines, Queensland Government, *Coal Mining Safety and Health Act 1999*, 2 March 2001.

DNRM. 2001, Department of Natural Resources and Mines, Queensland Government. *Coal Mining Safety and Health Regulation 2001*, 2 March 2001.

DNRM. 2003, Department of Natural Resources and Mines, Queensland Government. Quality of incombustible dust, sampling and analysis of roadway dust in underground coal mines, Coal Mining Safety and Health Act 1999, Recognised Standard – 05 [online]. Available from: < http://mines.industry.qld.gov.au/assets/inspectorate/recog_standard05.pdf > [Accessed: 30 December 2013].

DNRM. 2014, Department of Natural Resources and Mines, Queensland Government. Simtars: Testing, certification and calibration services [online]. Available from: < http://www.dnrm.qld.gov.au/mining/simtars/testing-cert-calibration-services > [Accessed: 29 August 2014].

Du Plessis, M. 1996, South African coal mine explosions, *in Proceedings QCO/DME Coal Industry Conference in Conjunction with Hazcoal Management*, Yeppoon, pp 127-134 (QCO/DME Coal Industry Safety Conference: Yeppoon).

Gillies, A D S and Jackson, S. 1998, Some investigations into the explosibility of mine dust laden atmospheres, *in Proceedings coal 98*, Wollongong, pp 626-640 (Australasian Institute of Mining and Metallurgy: Melbourne).

Harris, M L, Cashdollar, K L, Man, C and Thimons, E. 2009, *Mitigating coal dust explosions in modern underground coal mines*, 7 p (The National Institute for Occupational Safety and Health: Pittsburgh).

Harris, M L, Sapko, M J, Cashdollar, K L and Verakis, H C. 2008, Field evaluation of the Coal Dust Explosibility Meter (CDEM), *in Proceedings SME Annual Meeting*, Salt Lake City, pp 1-5 (Society for Mining, Metallurgy and Exploration: Eaglewood).

Harris, M L, Sapko, M J, Varley, F D and Weiss, E S. 2012, Coal Dust Explosibility Meter evaluation and recommendations for application [online], Available from: < http://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/ic9529.pdf > [Accessed: 25 March 2014].

Hartman, H L, Mutmansky, J M, Ramani, R V and Wang, Y J. 1997, *Mine Ventilation and Air Conditioning (3rd Edition),* pp 95-101 (John Wiley & Sons, Inc.: New York).

Jensen, B and O'Beirne, T. 1997, The design and performance of underground explosion barriers – a review, *The AusIMM Proceedings*, 302(1):71-76.

Kizil, M S, Peterson, J and English, W. 2001, The effect of coal particle size on colorimetric analysis of roadway dust. Journal of Loss Prevention in the Process Industries, 14 5: 387-394.

Peterson, J. 2001, Colorimetric and density analysis of roadway dust, Bachelor of Engineering Undergraduate Thesis (unpublished), University of Queensland, Brisbane.

Peterson, J and Kizil, M S. 2001, Colorimetric and density analysis of roadway dust. In: , AusIMM Youth Congress. AusIMM Youth Congress, Brisbane, (21-26). 2-6 May 2001.

QRC. 2007, Make Safety their Monument, documentary, Queensland Resources Council, Brisbane, 19 January.

Sapko, M J, Cashdollar, K L and Green, G M. 2007, Coal Dust Particle Size Survey of U.S. Mines, *Journal of Loss Prevention in the Process Industries*, 20:616-620.

Sapko, M J and Verakis, H C. 2006, Technical development of the Coal Dust Explosibility Meter, in *Proceedings SME Annual Meeting*, St. Louis, USA, pp 1-5 (Society for Mining, Metallurgy and Exploration: Eaglewood).

Sapko, M J, Weiss, E S and Watson, R W. 1987, Explosibility of float coal dust distributed over a coal-rock dust substratum, *in Proceedings of the 22nd International Conference of Safety in Mines Research Institutes* (ed: D Guoquan), pp 459-468, (China Coal Industry Publishing House: Beijing).

Sensidyne. 2013, Coal Dust Explosibility Meter calibration and use, pp 1-4 (Sensidyne: St Petersburg).

Wu, H W. 2013, Personal communication, Mining Engineering and Mine Ventilation Consultant, Gillies Wu Mining Technolog.