# Reducing risks from Occupational exposure to Coal Dust (ROCD)

## Deliverable D6.3:

## Publishable report

Research Fund for Coal and Steel

Grant Agreement number 754205

1st July, 2017 – 30th September, 2020

This project has received funding from the Research Fund for Coal and Steel under grant agreement No 754205

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| **Project:** | Reducing risks from Occupational exposure to Coal Dust (ROCD) |
| **Grant Agreement number:** | 754205 |
| **Funding Scheme:** | Research Fund for Coal and Steel |
| **Work Package:** | WP6 |
| **Start date:** | 1st July 2017 |
| **Due Date:** | 30th September 2020 |
| **Date of Delivery:** | 27th September 2020 |
| **Version:** | Revised – 16th June 2021 |
| **Project Website:** | www.exeter.ac.uk/csm/rocd |

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| Dissemination Level | |
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| **PU** | *Public* |

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Coal mining has long been associated with a variety of preventable coal mine dust lung diseases, the most common of which is pneumoconiosis, literally dusty lung, which includes a number of incurable and often fatal diseases such as coal workers' pneumoconiosis (CWP, or 'black lung') and silicosis[1]. Due to huge efforts in the USA to reduce incidences of CWP, the proportion of miners with more than 25 years' experience diagnosed with this dropped from approximately 33% in the early 1970s to less than 5% in the late 1990s. Since then, however, incidences of the disease have rebounded in the USA by over 10% for the longest serving miners[1], and a similar trend has been seen in Australia[2]. Most worrying is that less experienced US workers, who have spent their whole careers under modern mine regulations, show a higher prevalence of lung disease than miners who began work before 1970, when the regulations came into place[3].

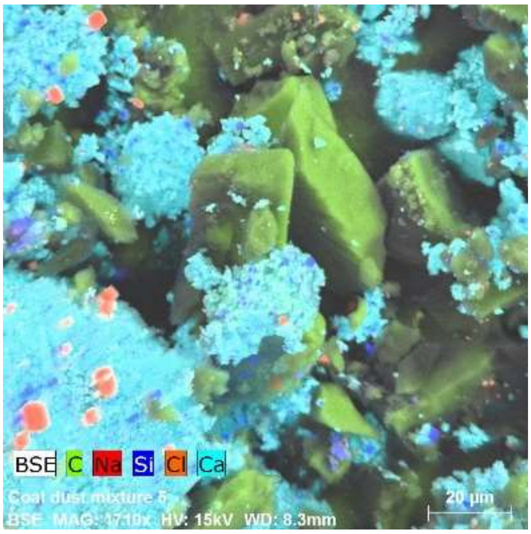

*Figure 1 False colour chemical map overlain on a scanning electron microscopy image showing limestone dust particle aggregates ('rock dust', light blue) attached to coal dust (green). Sample from a lignite mine in Slovenia.*

There is little modern data available for incidences of CWP in Europe. The reason for this is unclear and could be manifold, perhaps relating to a false perception that CWP is no longer an issue in modern coal mining, or because of the general decline in the industry and therefore tighter financial constraints. That there is a problem in certain European countries is indicated from a study of coal mine workers in Silesia, Poland, where 3,723 cases of CWP were diagnosed in the period 2003-2011[4].

There are numerous possible reasons for the apparent increase in CWP in at least some countries, the most likely being related to changes in mining practices underground. In Australian mines, it is blamed on a "potential decline in dust exposure control or a failure of health screening processes, or both"[5]. In the USA, it has been suggested that miners working in smaller mines and spending longer hours at the coalface are at greater risk of developing rapidly progressive CWP[6,7,8]. Another consideration is that modern, commonly diesel-powered mining equipment, whilst more efficient for coal production, may create toxic particulate

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[1] NIOSH, 2019. Mining Topic: Respiratory Diseases - What is the health and safety problem? https://www.cdc.gov/niosh/mining/topics/RespiratoryDiseases.html (viewed 17/2/2020).

[2] Perret, J. et al., 2017. Coal mine dust lung disease in the modern era. Respirology 22, 662-670. (and references therein)

[3] Graber, J.M. et al., 2017. Increasing severity of pneumoconiosis among younger former US coal miners working exclusively under modern dust-control regulations. J. Occup. Environ. Med. 59: 105-111.

[4] Zlotkowska, R. et al., 2013. Epidemiological analysis of the incidence and risk factors for coal-workers' pneumoconioses in the Silesia, Poland during period 2003-2011. European Respiratory Journal, 42: abs. P1001. Available at: https://erj.ersjournals.com/content/erj/42/Suppl_57/P1001.full.pdf [accessed May 2020].

[5] Zosky, G.R. et al., 2016. Coal workers' pneumoconiosis: an Australian perspective. Med. J. Aust. 204, 414-418.

[6] Seaton, A. et al., 1981. Quartz and pneumoconiosis in coalminers. Lancet 318, 1272-1275.

[7] Kenny, L.C. et al., 2002. Estimation of the risk of contracting pneumoconiosis in the UK coal mining industry. Ann. Occup. Hyg. 46, 257–260.

[8] Antao, V.C. et al., 2005. Rapidly progressive coal workers' pneumoconiosis in the United States: geographic clustering and other factors. Occup. Environ. Med. 62: 670–4.

underground[9]. *Worryingly, from visits to two European underground coal mines in 2017-18, many workers are simply not always wearing their dust masks.* The likely reasons for this, according to managerial staff, is that miners either find it uncomfortable to wear a mask, see it as a weakness, or say that it reduces their breathing capacity during hard work.

Of additional concern in the current study is that coal workers may be suffering unrecognised health impacts (possibly including cardiopulmonary diseases) from exposure to fine particulate matter ($PM_{2.5}$), in addition to occupational lung diseases such as CWP. $PM_{2.5}$ is dust particles nominally less than or equal to 2.5 µm in diameter which can be inhaled into the alveolar regions of the lungs[10]. In urban air pollution studies, increased atmospheric concentrations of $PM_{2.5}$ have been linked to higher rates of cardiovascular- and respiratory-related deaths[11,12]: "There is no evidence of a safe level of exposure or a threshold below which no adverse health effects occur"[11]. An assessment is therefore urgently required as to the levels and nature of $PM_{2.5}$ in underground coal dust, and whether this may contain higher concentrations of potentially toxic substances such as certain metals, e.g. Fe and Ni, minerals including quartz and organic-based toxins. Few previous studies have considered $PM_{2.5}$, mainly because of difficulties inherent in its collection, sample size separation from whole-dusts and physical and chemical characterisation. There are also few underground dust control devices and dust masks which have been tested for $PM_{2.5}$.

## 2. Background to the study and approach

The ROCD project was a 3-year EU Research Fund for Coal and Steel contract (No 754205) to address concerns about the occupational health impacts of dusts in coal mines. The project, which started in July 2017, was undertaken by a world-leading interdisciplinary consortium of 10 partners from 5 European countries (UK, Poland, Slovenia, Germany and Spain), including 3 coal mining companies, two from Poland and one from Slovenia.

The aims of the ROCD project were to address three main issues in the European coal mining industry:

1) Limited modern data on the concentrations, nature and possible toxicity of coal dust, particularly for $PM_{2.5}$;
2) The urgent need for better continuous dust concentration monitoring and control systems, modern quantitative physicochemical and toxicological assessment protocols for coal dust particles and predictive tools to assess dust hazards in different mining scenarios;
3) Whether dust control technologies and dust masks adequately protect workers.

Two case-study areas were selected which are representative of underground coal mining in Europe: the Upper Silesian Coal Basin of Poland and the Šaleška valley of Slovenia. The Polish mines work hard coal deposits using traditional longwall mining methods. The Slovenian coal mine works lignite from one of the thickest (average 60 m) known coal seams

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[9] Petsonk, E.L. et al., 2013. Coal mine dust lung disease: New lessons from an old exposure. Am. J. Respir. Crit. Care Med. 187, 1178-1185.

[10] Li, D. et al., 2019. Fluorescent reconstitution on deposition of $PM_{2.5}$ in lung and extrapulmonary organs. PNAS, 116 (7) 2488-2493.

[11] WHO, 2013. Health effects of particulate matter: Policy implications for countries in eastern Europe, Caucasus and central Asia (ISBN 978 92 890 0001 7). https://www.euro.who.int/__data/assets/pdf_file/0006/189051/Health-effects-of-particulate-matter-final-Eng.pdf (accessed: 11/6/2021)

[12] Liu, C. et al., 2019. Ambient particulate air pollution and daily mortality in 652 cities. N. Engl. J. Med., 381, 705-715.

in the world, which requires a specialised mining method, which produces particularly high concentrations of dust.

The main approaches used in the project were:

- Workers were asked to fill in questionnaires on their perceptions of the usefulness of current systems for controlling dusts underground and respiratory protective masks;
- Dust collection underground, including for deposited (time referenced), accumulated (long-term, non-time-referenced) and airborne dust (total particulate and $PM_{10}$);
- Coal dust particle size segregation into $PM_4$ (some samples were $PM_{10}$) and $PM_{2.5}$ using a recently patented device (Patent No. 201131895);
- Modern chemical, mineralogical and toxicological analysis of different size fractions of coal dust, including $PM_{2.5}$;
- Development of new devices for dust concentration measurements, monitoring and collection, and for dust control underground;
- Performance testing of currently used dust masks, particularly for $PM_{2.5}$;
- Development and testing of a range of new training and learning tools for underground coal workers, management and authorities, emphasising the importance of the proper use of dust control systems and respiratory protective masks;
- Design of outreach materials to optimise the dissemination of results from the ROCD project.

*Figure 2 $PM_{10}$ sampling underground using a CIP-10 air pump-filter collection system.*

## 3. Concentrations of dusts in underground workings and new dust prediction algorithm

The demonstration mines were selected in consultation between GIG and the mining company partners JSWSA and PGG. Two were selected from JSWSA and five from PGG operations, which are located within different parts of the Upper Silesian Coal Basin (USCB). Each has at least two coal seams and different coal mining situations regarding mine architecture, ventilation and the nature of mining operations. The specific galleries to be used for tests in JSWSA and PGG mines, and approximate dates and locations for monitoring, were selected at the beginning of each quarter of the project. Longer planning was difficult considering mine operations (e.g. changes of mine plans, purchase of new equipment and possible malfunctions, different than planned advances of roadways or longwalls etc.). All activities within the Polish mines were conducted following local health and safety procedures. Most of the $PM_{10}$ dust concentration monitoring in Polish mines was carried out using a CIP-10 personal air sampling device.

Within the Slovenian mine, locations were selected to be representative of different coal mining situations regarding mine architecture and ventilation, nature of mining operations and dust concentrations. For this, preliminary measurements of dust concentrations in mine air were undertaken using a HUND TM Data, and dust moister, ash content and other important parameters were determined including temperature, relative humidity and air velocity, in a variety of mining scenarios. All activities within the Slovenian mine were conducted following health and safety guidelines and all instrumentation (CIP-10 and HUND TM Data) was checked for compliance with ATEX certification. PL-2 and IPS-Q systems were found to be unsuitable for use in the mine.

Dust monitoring was carried out in 16 different locations in the Polish (PGG and JSWSA) and Slovenian mines. This included roadways under development as well as longwall gate-roads. To ensure representativeness, monitoring was undertaken during a variety of mining operations including maintenance shifts, the regular advance of certain galleries, the use of different types of ventilation systems and dust suppression activities. The characterisation of dust levels in these environments provided a robust basis for the development of a predictive dust concentration algorithm (see below). The dust measurements were performed according to the AB – 005 credentials of the Polish Centre for Accreditation and EM Barbara internal procedures: KD-2.2/ZLGIG/PB-2207, KD-2.2/ZLGIG/PB-2208, KD-2.2/ZLGIG/PB-2209. A summary diagram of example results obtained with a CIP-10 monitoring instrument in the Polish and Slovenian mines is presented in Figure 3.

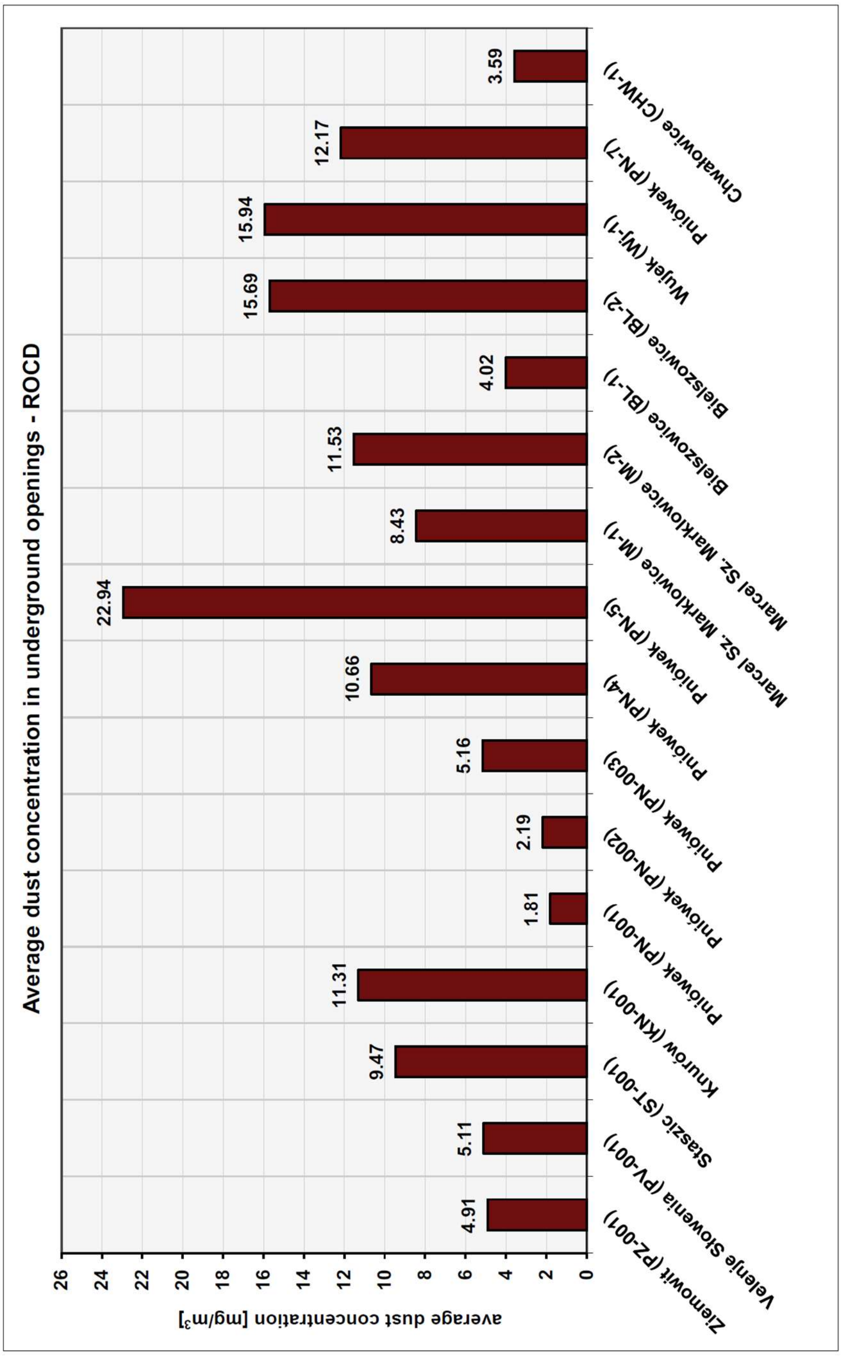


*Figure 3 Average dust concentrations based on CIP-10 measurements.*

The algorithm for predicting the concentrations of $PM_{10}$, $PM_{2.5}$ and $PM_4$ was developed based on the results of dust concentration measurements at different distances from the dust source and for different mining processes in several Polish operations and in the Slovenian mine. From plots of the results, curves were drawn and described using mathematical formulae, see example for longwall operations in Figure 4. The relationships between distance from dust source and dust concentrations obtained in this way were replaced with approximated dust concentration correlations which, to some extent, allows the determination of the concentration of a given fraction, for a given type of mine working, anywhere for a distance of up to 300 m from the dust emission source.

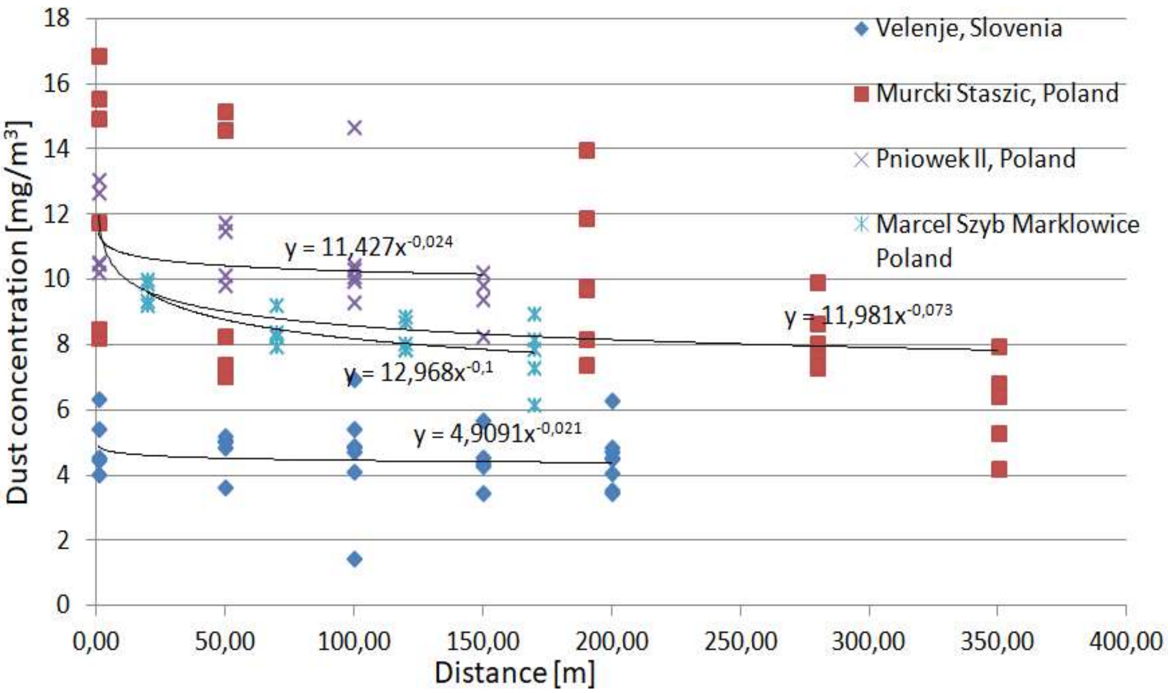
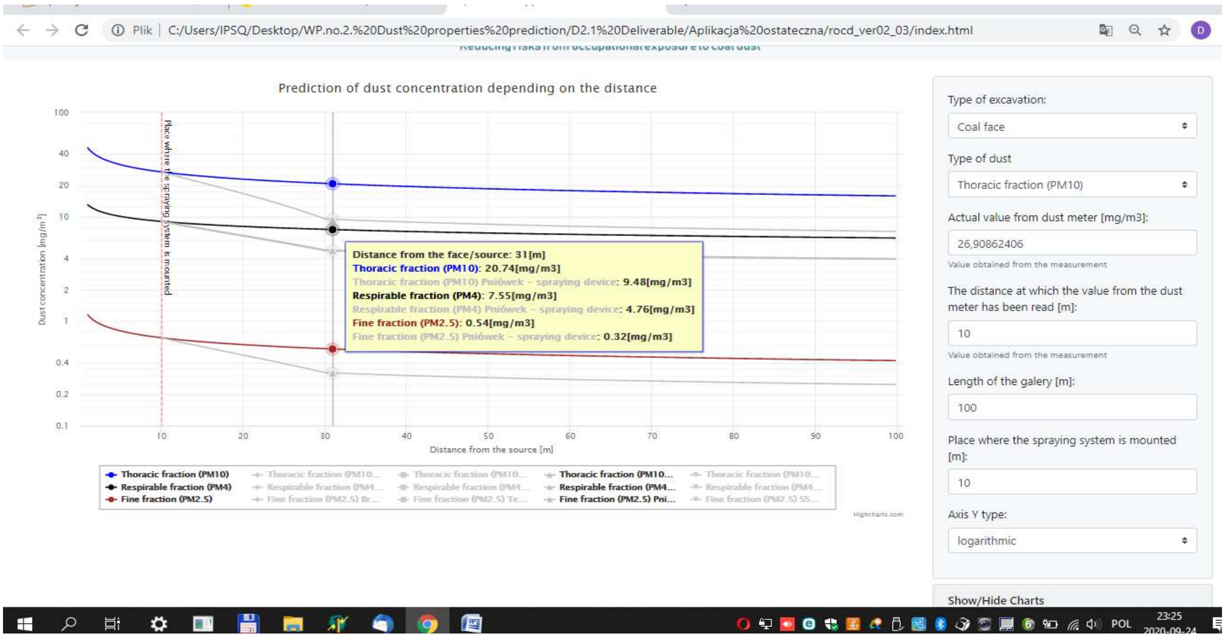


*Figure 4 Characteristics of the $PM_4$ dust concentration distribution in longwall panels which depends on the distance from the dust source (source at distance 0), based on dust concentration measurements using CIP-10R dust meters.*

The creation of such algorithms enabled the development of the predictive model (Figure 5) which can be viewed and interrogated via an interactive web application, available within the ROCD e-learning course https://elearning.komag.eu/course/index.php?categoryid=6, or via the ROCD website, Educational Resources page: http://emps.exeter.ac.uk/csm/rocd/educational/. The application enables the prediction of dust concentrations anywhere in mine workings. Predicted values for dust concentrations are calculated using values input into the table on the right-hand side of the web-tool shown in Figure 5. The application could also enable an assessment of the dust mitigation efficiency of spraying devices (including the SSD-1 device developed as part of the ROCD project), depending on its location.



Distance from the face/source: 31[m]
Thoracic fraction (PM10): 20.74[mg/m3]
Thoracic fraction (PM10) Pniówek – spraying device: 9.48[mg/m3]
Respirable fraction (PM4): 7.55[mg/m3]
Respirable fraction (PM4) Pniówek – spraying device: 4.76[mg/m3]
Fine fraction (PM2.5): 0.54[mg/m3]
Fine fraction (PM2.5) Pniówek – spraying device: 0.32[mg/m3]

Type of excavation: Coal face
Type of dust: Thoracic fraction (PM10)
Actual value from dust meter [mg/m3]: 26,90862406
Value obtained from the measurement
The distance at which the value from the dust meter has been read [m]: 10
Value obtained from the measurement
Length of the galery [m]: 100
Place where the spraying system is mounted [m]: 10
Axis Y type: logarithmic

*Figure 5 General view of the application for predicting dust concentrations, showing the dust concentration which depends on the distance from the dust source. Da*

Within the prediction algorithm, the database can be further developed which increases its predictive reliability. The algorithm could possibly be commercialised, aimed at mining companies, especially as it is easy to access via a web-based application. The solution can be used by mine ventilation departments which take care of de-dusting.

## 4. Current perceptions on the use of dust masks

Workers' perceptions on the use of dust masks in European coal mines were assessed from questionnaires returned by 137 underground manual workers from two Polish mining companies and 63 from a Slovenian mining company (results in Figure 6).

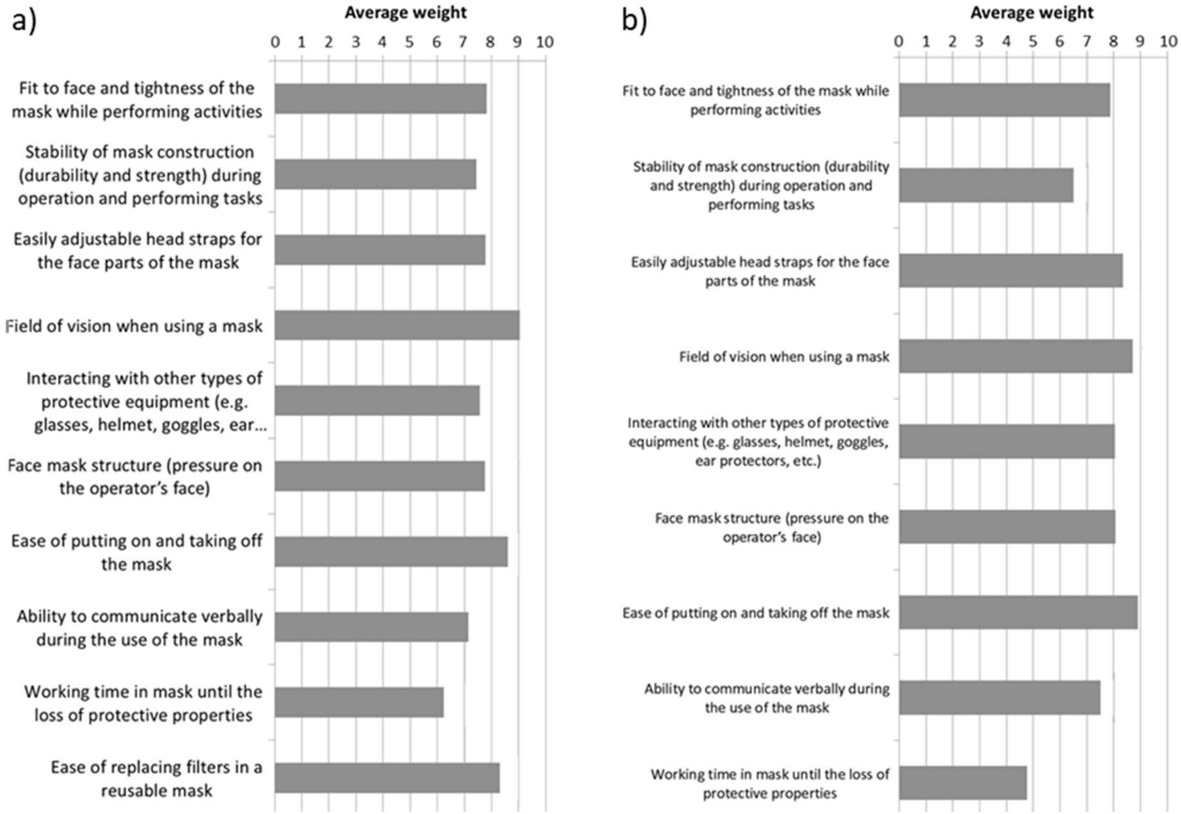


*Figure 6 a) Questionnaire responses from 137 underground workers from two Polish mining companies on the use of masks; b) Questionnaire responses from 63 underground manual workers from a Slovenian coal mining company on the use of masks. Average weight is out of 10: 0 indicates 'bad', and 10 is for 'perfect'.*

The Polish workers surveyed had worked underground for between 1 and 28 years, the average was 11 years. They gave the highest scores for the 'ease of putting on and taking off the mask' and 'field of vision when using a mask'. The lowest average score was for the 'working time in mask until the loss of protective properties'. Other parameters, such as fit to the face, tightness, stability of the material during work, and interface with other types of protective equipment, were thought to be moderately satisfactory.

The Slovenian miners gave the highest scores for the 'ease of putting on and taking off the mask' and the 'field of vision when using a mask' and had a relatively poor perception of the 'working time of masks until they lost their protective properties' (Figure 6b). Whether or not the poor scores for 'working time of masks until they lost their protective properties' is borne-out by laboratory tests, it is recommended that workers are always given spare masks or filter inserts in preparation for their shifts.

## 5. Geochemical composition of coal dust

The chemistry of inhaled coal dust, especially that of particle surfaces, is one of main controls on its toxicity. The metals identified to be of most concern in the studied coal mine dust are As, Cr, Cu, Fe, Mn, Ni, Pb, Se, Sb, Sn, Ti, V, Zn. The aim of the chemical studies was to compare the concentrations of these metals in $PM_{10}$ or $PM_4$ and $PM_{2.5}$ from a hard coal mine in Poland and a lignite mine in Slovenia, and from this to make a relative assessment of their toxicity. These mining scenarios were studied and compared as they were thought to be representative of the breadth of underground operations in Europe.

Coal dust deposition samples were size separated into $PM_4$ (some $PM_{10}$), and $PM_{2.5}$ fractions using a specially designed and patented particle size separation device. This consists of a rotating 17 cm diameter methacrylate cylinder attached at one end to a filter sampling head through which air is drawn by a pump[13]. The cylinder continuously rotates to mechanically resuspend dust which is then collected on to a 0.60 μm pore-size polycarbonate filter, at an air flow rate of $25\ l\ min^{-1}$ or $5\ l\ min^{-1}$ to collect $PM_4$ or $PM_{2.5}$, respectively. Two hundred grams of each bulk dust sample were loaded into the cylinder to obtain 1.5-2 g of $PM_{10}$ or $PM_4$ (after 8 h) and $PM_{2.5}$ (after 32 hr). Subsamples of the different size fractions of the coal dust samples were dissolved in acid and then analysed using inductively coupled plasma atomic emission spectroscopy (ICP-AES) and ICP-mass spectrometry (ICP-MS).

The $PM_4$/bulk dust ratios for different trace elements, i.e. the ratio of elements in $PM_4$ to those in the bulk dust, are shown for underground dust samples from Poland and Slovenia in Figure 7. The ratio for Mn is less than one, both in the Polish and Slovenian samples, indicating that Mn is relatively enriched in the bulk dust. This can be explained by Mn being bound to coal particles which are more prevalent in the coarser fraction. There was also a low ratio for As in the Polish sample (0.5±0.3), for which there is currently no explanation. There were higher ratios (>1.5) for the following metals in the Polish samples: Cu (1.5±1.8), Cs (1.5±0.4) and Sb (2.6±1.5); and those from Slovenia (Figure 7b): Ba (1.5±0.3), Zn (1.9 ±0.7), Pb (2.0±0.5), As (2.1±0.5), Sn (2.1±0.8), Cu (2.1±1.0) and Sb (3.5±1.4), indicating strong partitioning into the $PM_4$ fraction. This likely indicates that these metals originated from small (< 4 μm) particles, possibly liberated as a result of friction and wear in mine machinery, e.g. in transporter belts or moving parts in the mine ventilation system, the latter which could have helped spread these dusts[14].

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[13] Moreno, T., Trechera, P., Querol, X., Lah, R., Johnson, D., Wrana, A. and Williamson, B., 2019. Trace element fractionation between PM10 and PM2.5 in coal mine dust: implications for occupational respiratory health. Int. J. Coal Geol., 203: 52–59. (see references therein)

[14] Chen, X., Hu, H., Xu, Y., Zhang, Y. and Yang, G., 2015. Experimental investigation of foam dedusting agent in underground coal mine. Mater. Res. Innov. 19: 508–511.

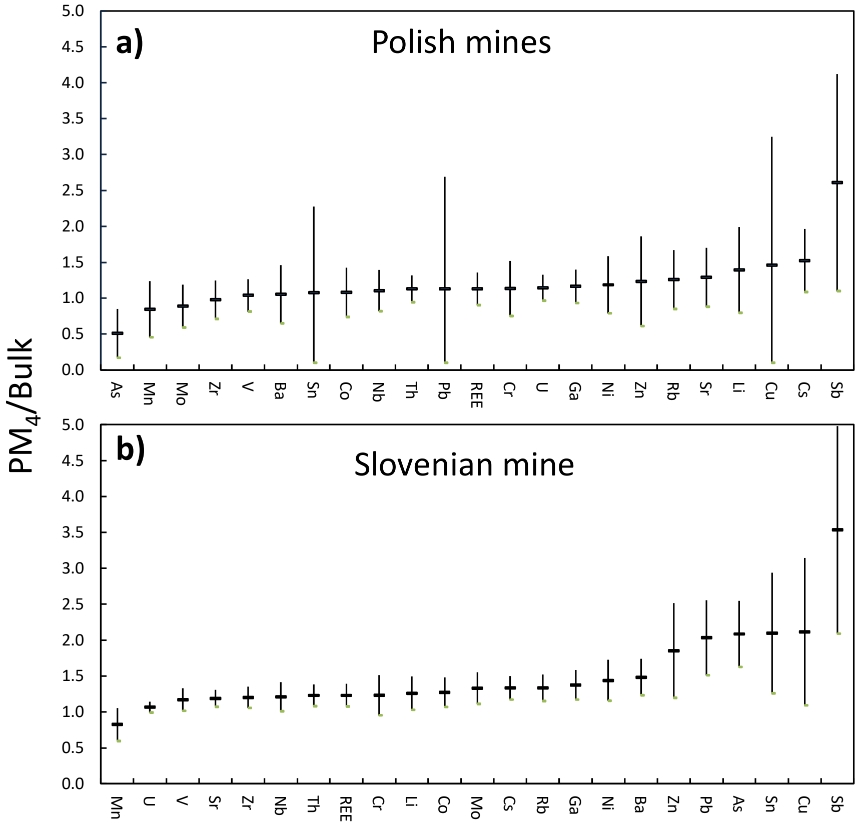

*Figure 7 Preliminary results (average +/- 1 s.d.) for the distribution of trace elements between $PM_4$ and bulk dust ($PM_4$/Bulk) for coal dust samples collected in the ROCD project: a) for the Polish underground coal mine (n=10); and b) for the Slovenian underground coal mine (n=12).*

From the distribution of different metals between $PM_{2.5}$ and $PM_4$ ($PM_{2.5}/PM_4$, Figure 8), the $PM_{2.5}$ fraction is slightly enriched in most metals and strongly enriched in Ni (1.3±0.5), Sn (1.5±0.4) and Cu (1.5±0.7). The latter is interpreted to be due to Ni, Sn and Cu being sourced from mine machinery. All are potentially toxic (largely depending on their concentration and form), which is worrying since $PM_{2.5}$ can penetrate into the deepest regions of the lung and possibly transfer directly into the bloodstream[15]. This may explain the results of toxicological assessments which showed that coal dust $PM_{2.5}$ from the Polish and Slovenian case study mines is relatively toxic compared with $PM_{10}$. In reality, it is likely to be far more complex than this, governed at least partly by the bioavailability of the different elements and the possible presence of a variety of other inorganic and organic species. Whatever the cause of the toxicity, these observations emphasise the need to monitor $PM_{2.5}$ in addition to $PM_4$ and $PM_{10}$. To re-emphasise, from urban air pollution studies, increased atmospheric concentrations of $PM_{2.5}$ have been linked to higher rates of cardiovascular and respiratory mortality; we do not yet know if coal dust $PM_{2.5}$ may have a similar effect.

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[15] Liu, C. et al., 2019. Ambient particulate air pollution and daily mortality in 652 cities. N. Engl. J. Med., 381, 705-715.

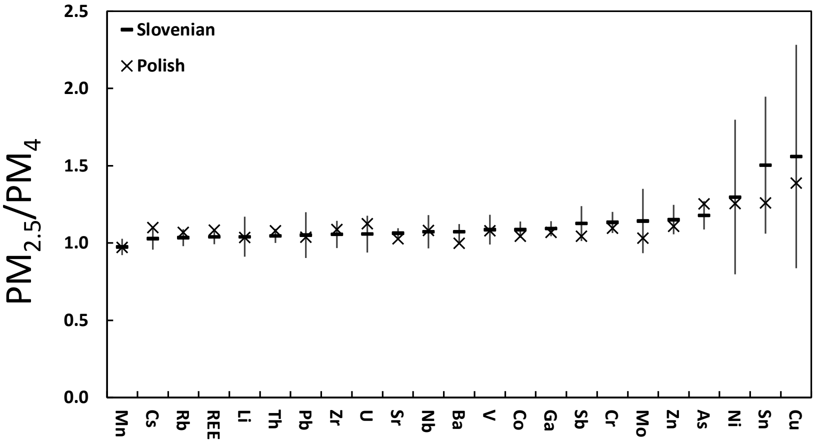

*Figure 8 Preliminary results (average +/-1 s.d.) for the distribution of trace elements between $PM_{2.5}$ and $PM_4$ ($PM_{2.5}/PM_4$) for coal dust samples from 7 Polish mines and one Slovenian mine.*

## 6. Mineralogical assessment of coal mine dust

The particle size and shape characteristics and mineralogical composition of coal dust $PM_4$ and $PM_{2.5}$ were determined using QEMSCAN® (Figure 9). This is an automated mineralogical analysis system which is based on a scanning electron microscope with energy dispersive X-ray detector(s). For QEMSCAN® to recognise coal particles, a new protocol was developed whereby samples were prepared as particle dispersions on polyethylene substrates. Polyethylene was used as particle demarcation requires a brighter backscattered electron signal (nominally a higher average atomic number) than their substrate. Once recognised, each particle was subject to elemental analysis in a grid pattern with an analytical point spacing of 0.5 µm. The energy dispersive spectra from each point of analysis was automatically compared with a database of mineral and phase spectra to assign a mineral name. The data was output as individual particle mineral maps, and for each sample, particle size and shape information, modal mineralogy, particle surface mineralogy and mineral associations data. For each sample, QEMSCAN® was configured to measure 100,000 particles which required approximately 10 hours of analysis time.

From initial analyses (results in Figure 10), the $PM_4$ and $PM_{2.5}$ samples from a Polish hard coal mine contained higher concentrations of quartz and Ti-phases compared with those from the Slovenian lignite mine, but lower sulphide/sulphates, Fe-phases, gypsum/anhydrite, salts and fly-ash. How this may related to the relative toxicity of the PM and risk to mine workers will require further studies, however, the mere presence of fly ash and minerals such as quartz, particularly in the $PM_{2.5}$ fraction, is cause for concern. The higher concentrations of quartz in the Polish vs Slovenian $PM_{2.5}$ may, at least partly, explain their higher toxicity in some of the toxicological tests. The developed QEMSCAN® method has excellent potential for the quantitative mineralogical assessment of coal and other mixed dusts in studies of their toxicity. It also has applications in the efficiency testing of new dust control systems and dust masks.

*Figure 9 QEMSCAN® automated mineralogical analysis system which can determine the size, shape and mineral associations of up to 100,000 dust particles in 10 hours.*

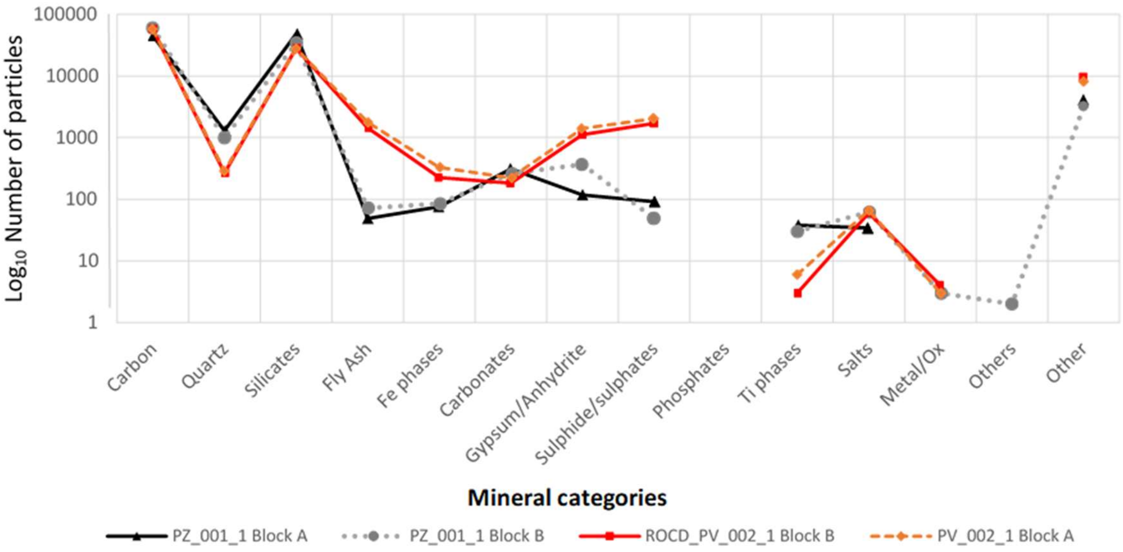

*Figure 10 Plot of QEMSCAN® data comparing particle numbers ($\log_{10}$ scale), out of 100,000 particles analysed (i.e. representing relative concentration by particle number), of mineral categories in coal dust $PM_{2.5}$ from Poland (sample PZ_001_1) and Slovenia (sample PV_002_1). Repeated analyses were undertaken of the same sample preparation (Block A and B) to give an indication of inter-sample variability.*

## 7. Toxicological assessment of coal dust

Tests were undertaken to determine the damage caused by $PM_{10}$ and $PM_{2.5}$ to human lung cells cultured in the lab. In general, both coal dust $PM_{10}$ and $PM_{2.5}$ from the Polish and Slovenian mines were found to be toxic and increasingly so at higher concentrations. As an example, Figure 11 shows the results of a toxicological experiment to determine the impact of $PM_{10}$ and $PM_{2.5}$ on the 'health' of a certain type of cultured human cell. With increasing concentrations of $PM_{10}$ and $PM_{2.5}$ there was a decrease in cell viability ('health'), in much the same way as for quartz mineral dust and coal fly ash which are known to be toxic to humans. In addition, for both the Polish (PZ_) and Slovenian (PV_) samples, coal dust $PM_{2.5}$ caused a stronger decrease in cell viability than the corresponding $PM_{10}$ fraction. In most tests, the Polish coal $PM_{10}$ and $PM_{2.5}$ caused a greater decrease in cell viability than Slovenian equivalents, however this was not always the case. This is surprising as, from the mineralogical assessment, the Slovenian coal dust $PM_{2.5}$ contained a higher proportion of fly ash, which has relatively elevated levels of potentially toxic metals. However, the Polish samples contained a higher proportion of quartz which is a known toxin. The variability in results from the different tests is probably due to some tests being more sensitive to certain toxins than others, and the chemically and mineralogically complex nature of the $PM_{10}$ and $PM_{2.5}$, with the presence of multiple toxins including certain transition metals, e.g. Fe, As, Cr, Cu, Fe, Mn, Ni, Pb, Se, Sb, Sn, Ti, V and/or Zn, minerals such as quartz and organic-based substances. The exact reasons for the differences in toxicity between the Polish and Slovenian samples therefore remains unclear.

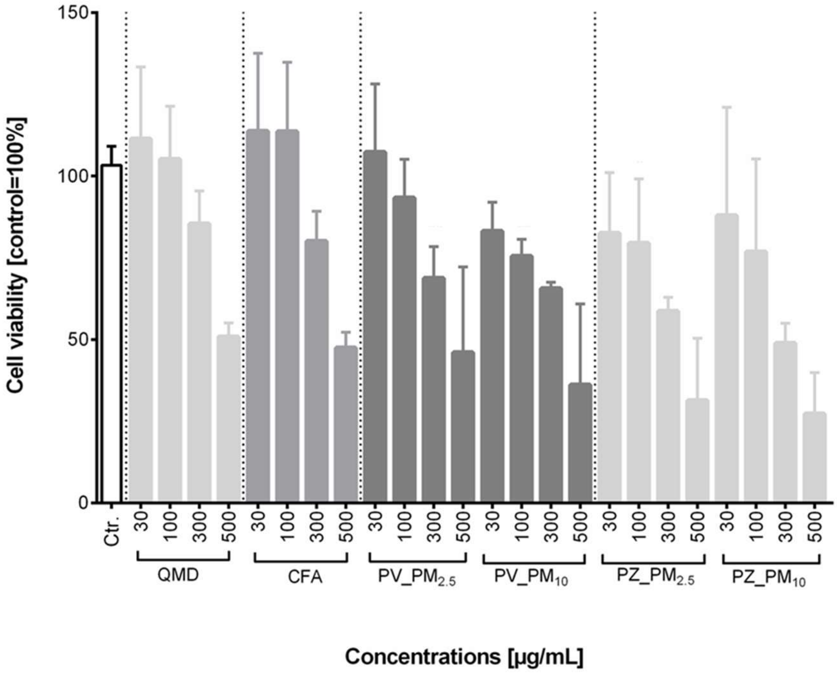

*Figure 11 Results of tests (WST-1 assay) on human monocytic cells to determine the acute toxicity of different concentrations (30, 100, 300, 500 mg/mL; 24 h exposure) of coal dust $PM_{10}$ and $PM_{2.5}$ from the Polish (PZ_) and Slovenian (PV_) mines. The negative control (Ctr.), with no exposure to toxins, gave a value for cell viability of approximately 100%. At increasing concentrations of the positive (toxic) control substances QMD (quartz mineral dust) and CFA (coal fly ash), and the coal dust $PM_{10}$ and $PM_{2.5}$ from Poland and Slovenia, there was a substantial reduction in cell viability. Each bar represents the data for the mean (±SD) of three independent experiments performed in triplicate.*

## 8. Development of new dust monitoring devices

Two new devices for monitoring dusts underground were developed to prototype stage, the EMIDUST continuous dust monitor and the DMIex continuous monitoring and integrated gravimetric dust sampling device. Both have been ATEX-certified which means they can be operated in potentially explosive environments underground.

The EMIDUST device (Figure 12) was designed for continuous measurement and recording of rapid changes in concentrations of dust ($PM_{2.5}$ and $PM_{10}$) in air during the operation of mining machines, at transfer points, on the routes of transport of extracted materials and in dust-generating processes in general. It was specifically developed for use in methane and/or coal dust explosion hazard areas. It is portable and can be suspended in any safe place in an underground mine where it is possible to supervise its operation. EMIDUST should be mounted within the current of the air carrying the dust (the axis of the chamber parallel to the direction of the flowing air) in places indicated by the Ventilation Department Manager.

The advantage of EMIDUST over similar devices is the real-time measurement of dust concentrations and its use with other mine monitoring or dust suppression systems, e.g. the SSD-1 dust control spraying device developed within the ROCD project.

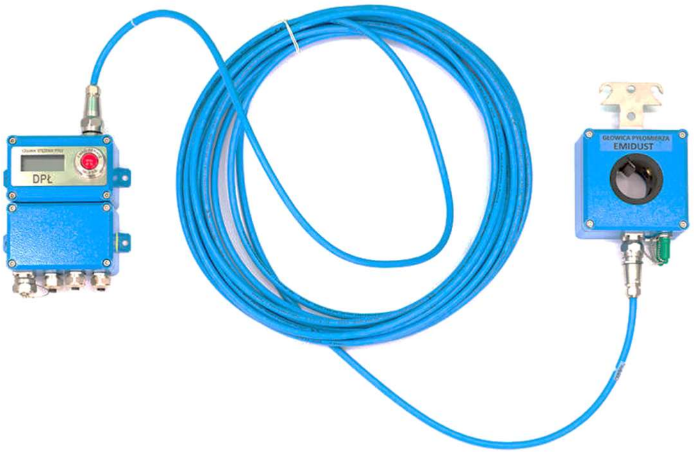

*Figure 12 EMIDUST continuous dust monitoring device.*

The DMIex dust monitoring and collection device (Figure 13) combines a commercially available dust sensor with a cascade-impactor for gravimetric measurement of dust concentrations ($PM_{10}$ (Stage 1) and $PM_4$ or $PM_{2.5}$ (Stage 2)) and dust collection for physicochemical characterisation. For continuous measurement, a portion of the dust is diverted into the dust sensors via adjustable air adaptation chambers. The measuring, processing, storage and transmission electronics ensure the appropriate treatment of dust concentration, temperature and humidity data from the respective adaptation-chambers.

*Figure 13 Prototype of new dust-meter DMIex.*

Benefits of the DMIex device over previously available systems:

- Time-accurate and continuous measurement of dust, temperature and humidity.
- The measurement accuracy of the inexpensive commercially available dust sensors is enhanced by regular comparison with gravimetric (involving physical weighing) measurements of dust collected in the impactor.
- The impactor is designed in such a way that even in harsh underground conditions the impactor collection medium can be exchanged cleanly (i.e. with little chance of contamination).
- With a high impactor throughput of 50 l/min, it is possible to collect particles in the fractions $PM_4$ and $PM_{2.5}$ in a relatively short time.

## 9. Development of new dust control devices

The most common way to control airborne dust in underground coal mines is to use water spraying systems and dust collectors. In the case of spraying systems, these can be placed where dusts are generated or where their concentrations are high, such as at conveyor transfer points or close to longwalls. Their current shortcomings are that water flow rates cannot be adjusted to specific dust concentrations and the use of standard spray nozzles, at recommended flow rates, does not efficiently remove particles <25 µm in diameter, let alone $PM_{2.5}$. To address this, a new 'smart' dust spraying device, the SSD-1, has been developed for coal dust $PM_{10}$ and $PM_{2.5}$ (Figure 14). This can use information from simultaneous dust concentration measurements (e.g. using the EMIDUST device) to set 9 combinations of water and compressed air pressures to create suitable amounts and sizes of water droplets to optimise the capture of airborne $PM_{10}$ and $PM_{2.5}$.

The prototype SSD-1 spraying device has been shown to be around 10% more effective in reducing respirable and inhalable dust concentrations and it consumed less water than currently used devices. An additional advantage is its adaptability in being able to automatically adjust its spraying intensity to the current level of $PM_{10}$ and $PM_{2.5}$. This allows optimal spraying conditions to be achieved in terms of reducing dust and minimising water consumption. The SSD-1 system underwent a successful trial in the "Pniówek" mine, Poland, receiving very positive feedback from mine workers. There was a significant improvement in air quality in the area where the device was installed. This capability was confirmed by additional tests carried out after the completion of the ROCD project.

Other commonly used dust control systems are dust collectors. These are mainly used for dedusting air behind the roadheader during its operation, as illustrated in Figure 15. They work by pressing or sucking dust-laden air into an inlet unit, spraying droplets of water to capture dust particles, allowing the water-dust droplets to deposit out, and returning cleaned water to the spraying system of the dust collector. In most current systems, water droplets are created by water being introduced into a spinning rotor driven by an electric motor. The water is expelled radially through the holes in the rotor's flange by the action of centrifugal force which creates a water curtain for dust capture. In the new collector system, the rotor has been replaced by a dispersion section which is made of intersecting metal sheets which creates square inlet openings with rectangular outlets. The inlet stream containing airborne dust, which is initially dispersed, reaches the square-shaped inlet openings forming its own partial stream. Each opening has converging walls in which the partial streams are accelerated due to a gradual narrowing of cross-sectional flow. The exit rectangles of neighbouring sections are perpendicular to each other so that the partial streams mix turbulently which causes water droplets to collide with and capture dust particles. From laboratory tests, the new system had a dust removal efficiency of up to 99.7%[16]. From this, we can conclude that the use of dispersion sections will allow more efficient dust collection than in systems based on rotating nozzles.

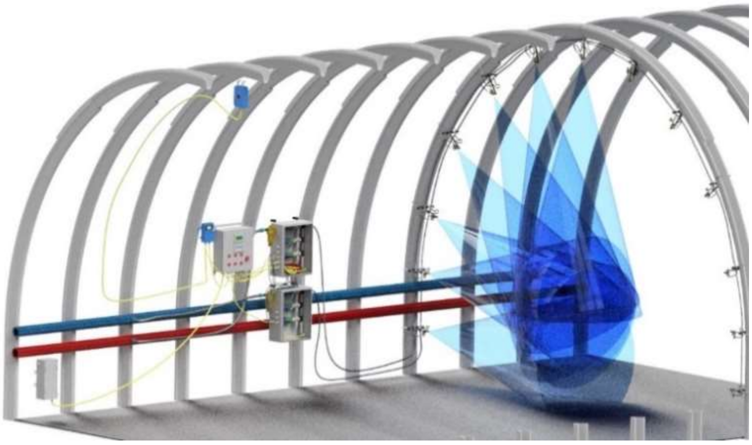

*Figure 14 Illustration of the SSD-1 underground mine spraying installation for dust control.*

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[16] Jedziniak, M., 2013. "Badania procesu mokrego odpylania powietrza z kopalnianego wyrobiska chodnikowego za pomocą odpylacza dyspersyjnego", praca doktorska, Politechnika Śląska, wrzesień 2013, ("Research of wet dedusting of mine workings using a dispersive dust collector", doctoral dissertation, The Silesian Technical University, September 2013).Kenny, L.C., Hurley, F., Warren, N.D., 2002. Estimation of the risk of contracting pneumoconiosis in the UK coal mining industry. Ann. Occup.

*Figure 15 Dust collector OD-1000/1000 in the Knurów underground mine.*

## 10. Experimental work to improve the testing of dust masks

Experiments were carried out to improve the performance testing of currently available dust masks to allow mining companies to make the best choice of equipment for their workers. Masks for use in underground coal mines are divided into three basic categories, based on their efficiency: FFP1 which captures about 80% of particles that are not smaller than 2 µm, FFP2 which captures about 94% of particles that are not smaller than 0.5 µm, and FFP3 which captures about 99% of particles that are not smaller than 0.5 µm. Testing was carried out on the FFP2 and FFP3 class of dust masks, from a number of different suppliers, which are officially approved for use (having appropriate certificates) in areas of underground mines with high dust concentrations. Respiratory protective masks placed on the market are tested in accordance with standard EN 149 + A1: 2010 [1].

An experimental test stand constructed as part of the ROCD project (Figure 16) allowed an assessment of the filtration efficiency of different types of half mask. It is equipped with a dust chamber, artificial head inside the chamber, artificial lung, climatic chamber, and DustTrak™ unit for the measurement of dust concentrations inside the chamber and in inhaled air.
The masks were assessed using three types of test:

- Testing of masks strapped to the artificial head.
- Testing of masks sealed onto a special suction base.
- Testing of pieces of filter material glued onto the special suction base.

*Figure 16  Test stand for assessing the performance of dust masks and filters. Note the test dummy head which is wearing a mask in the experimental chamber. The artificial lungs are shown on the right.*

Different rates of breathing were assessed which relate to different levels of physical activity: **rest** (12 breaths per minute), **effort** (25 breaths per minute), and **hard work** (60 breaths per minute).

Breathing resistance was measured four times, firstly at the beginning, when the mask was new and clean, and then at:

- 1100 cycles at **rest** breathing rate
- 1100 cycles with **effort** breathing rate
- 1100 cycles with **hard work** breathing rate

Additional tests on the efficiency of the filter material used in masks (i.e. removing the effects of leaks around the mask) were carried out using an auxiliary test stand. For this, pieces of the filter material were glued over a hole in a special suction box. The box was situated on the dust chamber and connected by a pipe to the measuring equipment on the main stand. Only one cylinder of the artificial lungs was used for sucking air from the chamber through the piece of filter. For each filter, 240 cycles were undertaken using 500 ml for each ‘breath’ and 12 breaths/min. (**rest mode**).

Eight types of half masks were tested during the ROCD project (Table 1), two from the mining company JSW, two from PGG and one from PV. Additionally, 3 masks used by KOMAG’s workers (KOM) were tested to gain more data.

*Table 1  Masks and filters tested with the newly developed test stand.*

| | Mining co. | Mark of the mask containing filter type mark | Mask type |
|---|---|---|---|
| 1. | JSW | FS-21V FFP2  NR D | Bowl type disposable |

| | | | |
|---|---|---|---|
| 2. | JSW | X310SV FFP3 NR D | Bowl type disposable |
| 3. | PGG | ZF 0/27z FFP3 NR D | Foldable disposable |
| 4. | PGG | EKO 54V FFP2 NR D | Foldable disposable |
| 5. | PV | MOLDEX 2365 P1 NR D | Bowl type disposable |
| 6. | KOM | 3M Vflex 9152R FFP2 NR D | Foldable disposable |
| 7. | KOM | SECURA 3000 / filter SECAIR 2000.03 P2 R | Reusable |
| 8. | KOM | SECURA 2000 / filter SECAIR 2000.03 P2 R | Reusable |

Example results from the breathing resistance tests are shown on Figure 17. The magnitude of the under-pressure (negative pressure, Pa) was relatively low for **rest** and **effort** breathing rates and therefore, in general, the breathing resistance of the masks can be said to be satisfactory in most circumstances. Worryingly, the breathing resistance for the '**hard work**' rate was considerably higher for some types of masks. This should be taken into account during the selection of dust masks for hard work activities.

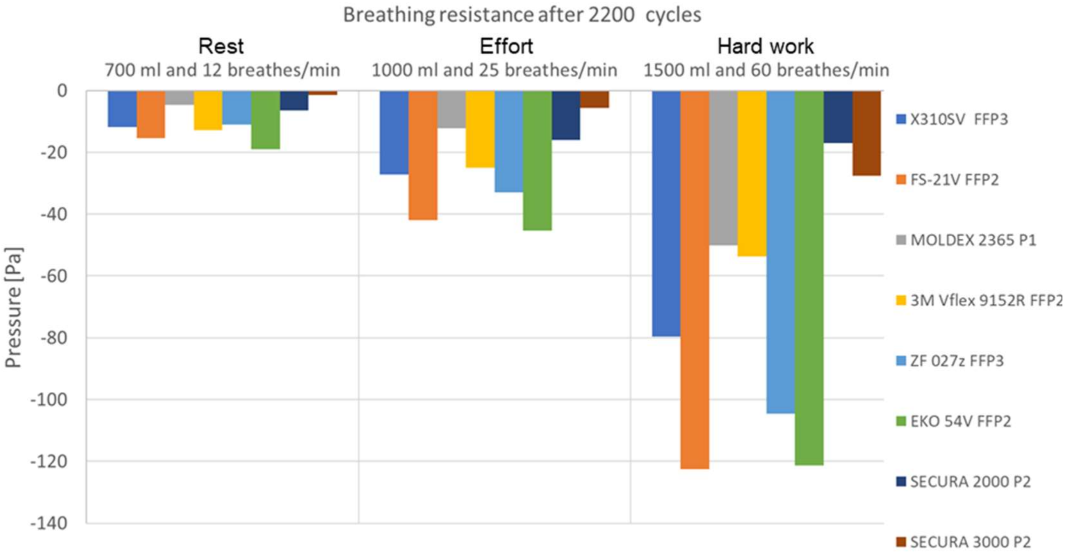

*Figure 17 Graph comparing breathing resistance (negative pressure) after 2200 cycles for the three breathing rates.*

The next parameter to be assessed was filtration efficiency, see results in Figure 18. It can be observed that for each type of filter, filtration efficiency did not decrease noticeably when the number of breathing cycles increased up to 3300. There were, however, substantial differences between the efficiencies of the different masks. The reusable mask filter FFP2 had a much lower efficiency compared with the FFP1 which is used in the Slovenian mine (PV, MOLDEX 2365 P1 NR D); this was surprising. The lower graph in Figure 18 shows the average filtering efficiency of different masks for different dust size fractions. The efficiency of the masks for PM$_1$ and PM$_{2.5}$ was always a little bit lower than for PM$_4$ and PM$_{10}$. In conclusion, it is clear from the data in Figures 17 and 18 that a good knowledge of the particle size range of the coal dust and the nature of the work to be performed in a particular operation is needed in order to choose the most appropriate types of dust masks. A guide to the selection of masks is available at: http://emps.exeter.ac.uk/csm/rocd/educational/

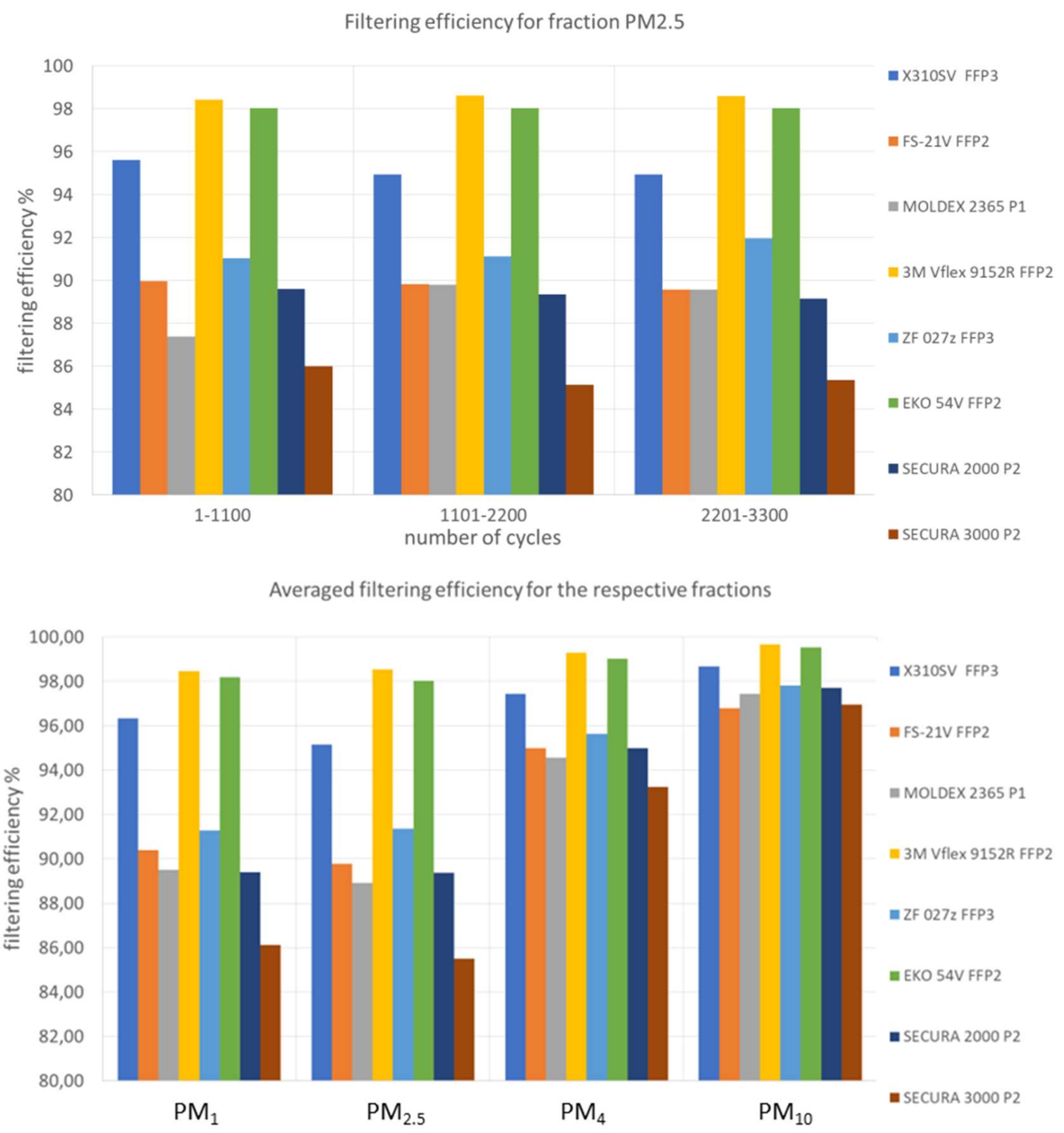

*Figure 18 Graph comparing the filtration efficiency of the tested masks, upper graph for $PM_{2.5}$ (for different masks and different numbers of cycles in the procedure) and lower graph for the filtering efficiently of the different masks for the different size fractions.*

## 11. Training and outreach activities to reduce worker exposure to coal dusts

The use of masks is vital for reducing worker exposure to coal dusts. In theory, they should work well for most types of dust, including $PM_{2.5}$. Their performance in the workplace, however, is generally much poorer than suggested by manufacturers' literature. This is because their effectiveness depends on whether they are fitted and worn correctly which can be compromised if the worker adjusts the mask to make it more comfortable, to fit it around other equipment such as glasses, or does not replace their mask or mask filter regularly. Another important aspect is that workers may sometimes only wear their masks when they visually or otherwise sense high dust concentrations, which will be mainly due to the presence of relatively coarse particles, and less so when there are imperceptibly high levels of invisible $PM_{2.5}$.

As a result of the ROCD project, an online e-training course (available from http://emps.exeter.ac.uk/csm/rocd/educational/, in English and Polish) and other materials have been developed to promote a greater awareness of coal dust hazards and how to deal with them, including how to wear masks properly and the importance of their constant use underground. The main target audiences are those involved in the control of dusts in coal mines, mine workers exposed to dusts and mining authorities and legislators.

The ROCD course ‘Dust hazards in mines and ways to reduce their impact’ incorporates learning materials of various kinds including PowerPoint presentations, software tools, quizzes, a glossary of terms, films and downloadable pamphlets and instructional materials. Most of these have been made available through a Moodle platform which is ideal for the creation of quizzes. The films are available freely via a YouTube channel at https://www.youtube.com/channel/UCTGT6uTLCjiOYa2mSTSVNSA which is linked from the ROCD website. The structure of the ROCD course is presented in Figure 19.

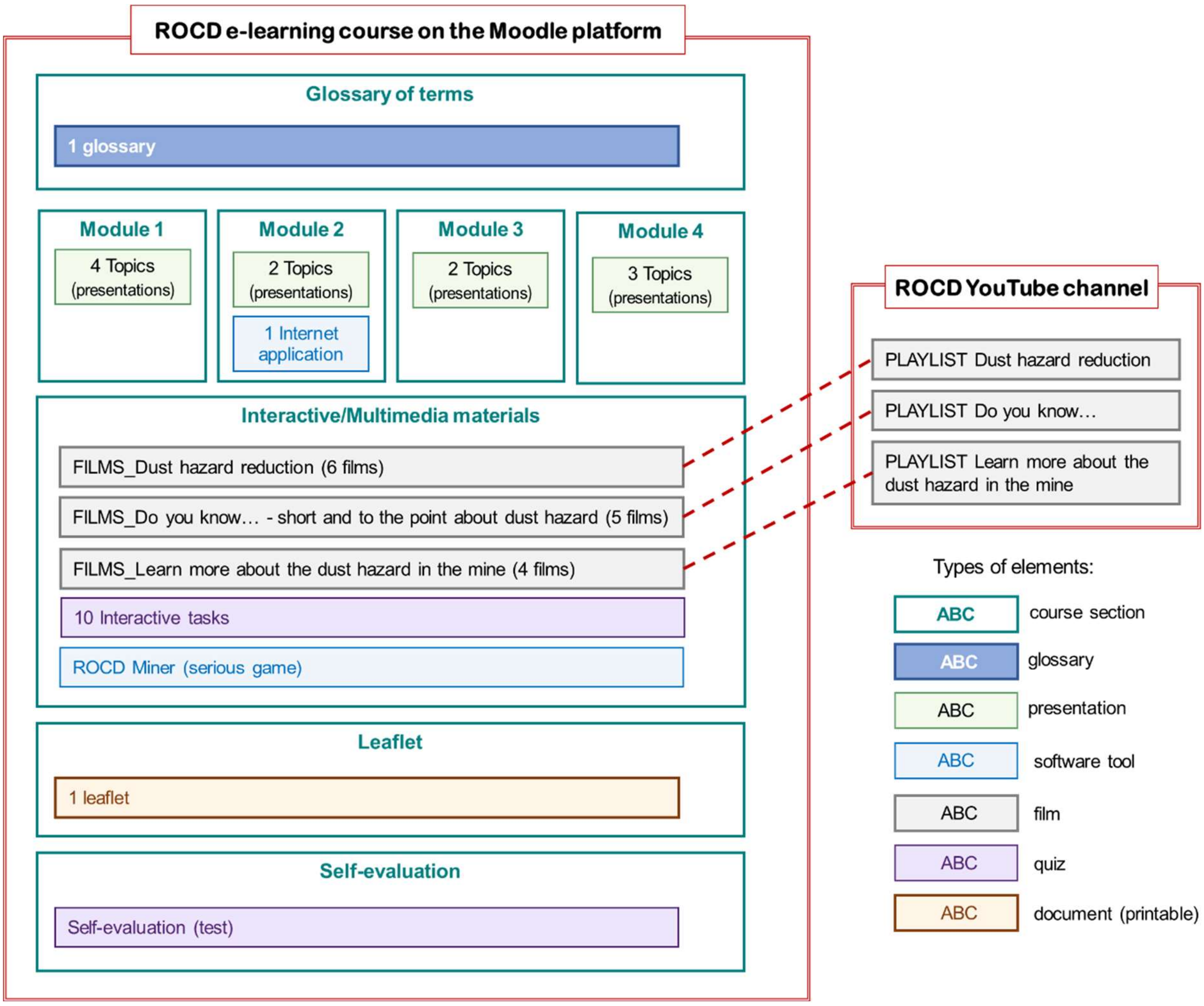

*Figure 19 Structure of the ROCD training materials hosted on Moodle.*

The glossary within the course covers more than 50 terms regarding dust hazards which are in accordance with relevant standards, regulations and other considered sources. Module 1 ‘Introduction to dust hazards’ provides fundamental knowledge regarding dusts (not only coal dusts) including where within mines dusts are “produced”, how coal dust enters and affects the human respiratory system, and pneumoconiosis as the most common of the serious diseases associated with coal dust. Module 2 ‘Dust hazards prediction’ provides knowledge about sample devices used for measuring dust levels, and gives access to an online application that describes the distribution of dust concentrations which depends on: i) the distance from the source and ii) the use of spraying systems. Module 3 'Dust hazards prevention' focuses on the types of solutions that can be used to reduce dust concentrations in different areas of coal mines. Module 4 'Dust hazards protection' provides comprehensive information about half-masks and their correct use.

Following the completion of the modules, the user moves on to work with interactive and multimedia materials which are designed to reinforce their knowledge and understanding. These include: i) 3 playlists of films hosted on the ROCD YouTube channel, ii) interactive Moodle 'quizzes', and iii) a serious game app called ROCD Miner which can be downloaded and played on Android devices.

The most notable features of the ROCD e-training course are: 1) access to the course and to the YouTube channel is unlimited and free; 2) there is no compulsory order of learning, i.e. any content can be accessed at any time – the learner controls the process, they can work at their own pace, skip content if they are comfortable to do so and recap whenever they choose; and 3) individual components of the programme can be used as part of organised workshops or training events.

Apart from training materials, a number of awareness raising and outreach tools have been developed under the ROCD project. One example is the set of four posters shown in Figure 20, which can be placed in different areas of mines (canteens, toilets, changing rooms, elevators, rest areas etc.) to remind workers to always wear their masks. Some of these were designed to be 'hard hitting', similar to infographics used on cigarette packets, i.e. as is appropriate for the terrible potential consequences of not correctly wearing a dust mask underground. Materials designed to raise awareness amongst school children and teenagers were also designed to more gently embed understanding of the risks at an early age; these can be downloaded from http://emps.exeter.ac.uk/csm/rocd/educational/

*Figure 20 Workplace posters created during the ROCD project to encourage workers to wear their dust masks. The posters have been translated into Polish and Slovenian and made available to mining companies.*

## 12. Concluding remarks

The ROCD project has provided a modern reassessment of the nature and toxicity of coal dust $PM_{10}$, $PM_4$ and, for the first time in a major European study, $PM_{2.5}$ which may be contributing to cardiovascular as well as respiratory diseases in miners. This has included the development of a particle size separation device for the study of different fractions of inhalable coal dusts, and a new methodology for assessing their mineralogical composition. In addition, two new monitoring and two new dust control devices, and a new protocol for the testing of dust masks have been developed to prototype stage. The results of the ROCD project are being disseminated globally via its dedicated website http://emps.exeter.ac.uk/csm/rocd/, including a list of publications from the work and links to e-training materials for best practice in the use of dust control systems and respiratory protective masks. It is hoped that these resources will help reduce worldwide incidences of coal mine dust-related diseases.

## Acknowledgements

This work was supported by the ‘Reducing risks from Occupational exposure to Coal Dust” (ROCD) project funded by the European Commission Research Fund for Coal and Steel, Grant Agreement Number - 754205 - ROCD - RFCS-2016. Thanks to all partners in the ROCD project for their assistance in this study, see partner list at: http://emps.exeter.ac.uk/csm/rocd/