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Effectiveness of half masks for respiratory health protection in coal mining

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Abstract:

An improved procedure is presented for testing the level of respiratory health protection and comfort of half masks currently used in coal mining and similar industries. This will allow companies to make the best choice of such equipment for their workers. Half masks used by one Slovenian (PV) and two Polish (JSW and PPG) coal mining companies were tested in terms of filtering efficiency, especially for $PM_{2.5}$, perceived effectiveness, comfort and ease of use.
Filtering efficiency was determined by analysing filters from masks used in underground operations for the levels and sizes of trapped coal dust particles and by carrying out experiments employing a specially developed laboratory test stand. The latter incorporated a replica human head and a climatic chamber to simulate the humidity of exhaled air during mining activities. To determine the comfort and utility of the half masks, selected miners were asked to fill in questionnaires. The main results of these studies were that, in the interest of miners' health, and for those working in other high dust environments, the quality of the half-mask should be assessed on the basis of workplace and stand tests. These are complementary and both should be included to ensure the correct assessment of the half masks. For the masks supplied by the mentioned mining companies, their filtering efficiency for $PM_{2.5}$, as determined using the test stand, was excellent at over 99%.

Keywords: RPE equipment, $PM_{2.5}$, half masks, testing stand

1. Introduction

The testing of half masks used to protect workers from potentially toxic coal dusts was one of the main objectives of the 3-year (2017-20) EU Research Fund for Coal and Steel project “Reducing risks from Occupational exposure to Coal Dust” (ROCD). This chiefly focussed on particulate matter in the size fraction $PM_{2.5}$ which has an aerodynamic diameter less than or equal to 2.5 µm and can therefore penetrate into the deepest, alveolar regions of the lung [1]. In urban air pollution studies, increased atmospheric concentrations of $PM_{2.5}$ have been linked to higher rates of cardiovascular and respiratory mortality [2,3]: “There is no evidence of a safe level of exposure or a threshold below which no adverse health effects occur”. Coal dust $PM_{2.5}$ assessed in the ROCD project was found to contain a range of potentially toxic metals and metalloids [4].

A common problem in mining and other sectors, e.g. the petrochemical industry [5], is the reluctance of workers to use respiratory protective equipment (RPE), even where dust concentrations are above maximum recommended values. Participants in the ROCD project included JSW and PGG from Poland, and PV from Slovenia, which are amongst the most important mining companies in the EU. The range of RPE they use is typical for the European mining industry but differs between companies. PV only uses FFP-1 half masks whereas JSW and PGG use either FFP-1, FFP-2 and FFP-3 masks, depending on the nature of the operation. FFP-1 are mainly used on surface, e.g. in coal processing plants.

The aim of the current study was to improve the testing procedures used for RPE which will allow mining and other companies to make the best choices of equipment for their workers. To begin with, their filtering efficiency was determined by analysing filters from masks used in underground operations for the levels and sizes of trapped coal dust particles. Next, KOMAG developed a laboratory test stand to assess the effectiveness of half masks to filter out dusts, particularly $PM_{2.5}$. To be as realistic as possible, this incorporated a replica human head and a climatic chamber, the latter to ensure the correct humidity of exhaled air during the tests. To determine the comfort and utility of the half masks, some miners were asked to fill in questionnaires.

In addition to providing test data for half masks, the study also gave recommendations for the appropriate selection of RPE for different types of operation and dust, the correct fit-to-face and best practice for its use. For example, facial hair can decrease the efficacy of the seal between the mask and face, and a tighter fit can reduce leaks. These aspects were pointed in the literature [6,7,8]. Breathing resistance is also important; if this is too high, requiring a lot of effort to breath, the user may suffer hypoxia [9]. It has a very significant influence on the rating of the mask.

This article addresses the above-mentioned issues and discusses the following:

- The design of the test stand,
- Results of half-mask tests in the aspect of breathing resistance and air filtering efficiency,
- Work place testing in the underground mines.

2. Methods of half mask testing

RPE in the EU is tested in accordance with standard EN 149 + A1: 2010 [10], which includes the following three types of test:

- Total internal leakage,
- CO_2 content in the inhaled air,
- Filter clogging by dolomite dust.

In addition, to be certified, tests are carried out on RPE to determine its level of protection. The issue with this is that most do not fully simulate workplace conditions [11]. Studies are therefore ongoing to develop more realistic and quantitative test methodologies. For example, a miniature, in-mask, sampling device has been designed to gain a better understanding of worker respiratory exposure to hazardous substances [12]. A new method has been proposed for evaluating the relative efficiency of commonly used respirators and surgical masks for airborne “vegetative cells”, e.g. bacteria and viruses [13]. In addition, the COVID 19 pandemic has prompted research into the effectiveness of masks for virus protection [14]. With regards to the ROCD project, the aim was to test the performance of half masks for dusts sampled in working coal mines.

The research process at KOMAG began with the microscopic analysis of filters from half masks to better understand how they work. FFP-3 masks usually consist of 3 layers: 1) the outer layer that consists of synthetic fibres, each with a thickness of 10-20 µm, which acts as a primary barrier to the largest particles; 2) the middle layer, the most important, that is made of densely pressed fibres each with a thickness of 2-3 µm; and 3) the inner layer which is usually similar to the outer layer but provides protection for the middle layer. Fig. 1 shows a fragment of used FFP-3 half mask with its 3 layers, and Fig. 2 a photomicrograph of each layer. The filters were from half masks used by miners during their shift. The main problem with this type of test for quantifying the effectiveness of masks is that different people's behaviour varies greatly, e.g. their working practices, rate of respiration etc., and levels and types of dust vary between mines and mining operations. It was therefore necessary to build a special test stand so that the filtering efficiency of masks could be determined under standard and controlled conditions. To complement this, questionnaires were given to selected miners of the PV, PGG and JSW companies to determine factors such as comfort and ease of use of different masks.

Fig. 1. Sample of filter from a half mask used during coal mining operations; the three layers have been partially separated, the outer layer in the foreground, then middle layer and finally inner layer

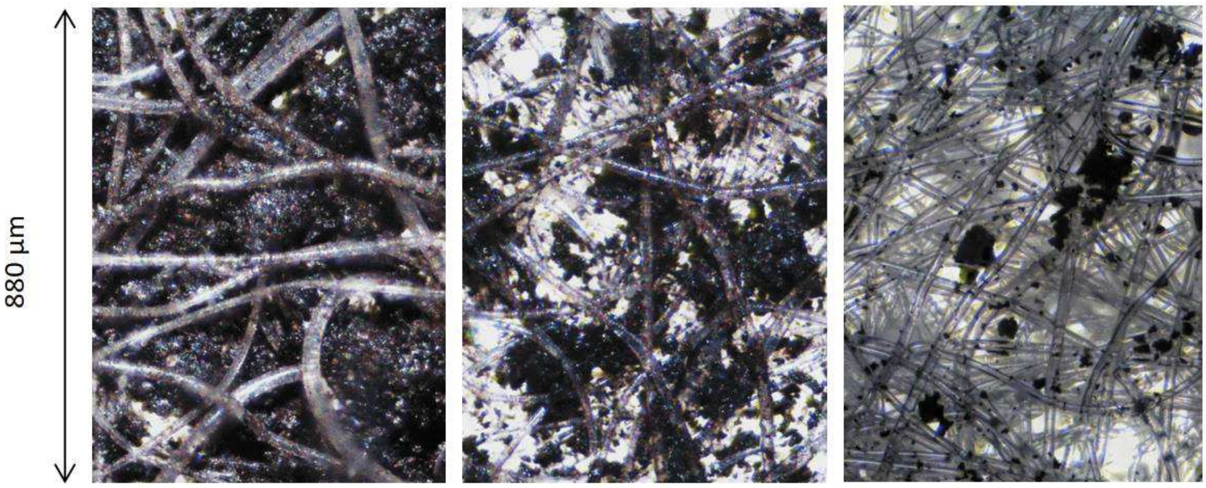

Fig. 2. Three layers of the FFP-3 mask visible at 50x magnification, from left to right: outer layer, middle layer, and inner layer; the black materials on and between the fibres are the particles of coal dust

2.1. Test stand, procedure of testing, half masks and filter materials testing

The new test stand designed under the ROCD project enabled the comprehensive assessment of different disposable and reusable half-masks, including breathing resistance which has a very significant influence on the rating of the mask [6,15], is shown in Fig.3. The schematic diagram of the test stand is shown in Fig. 4. The half-mask to be tested is strapped to the artificial head which is then placed in a dust chamber. The use of the artificial head does not eliminate leaks between the head and the mask, which is the same as for when a mask is fitted to a real human head. So that the masks could be tested without the effects of leakage, a comparative tests were also carried out, with the edges of the tested masks tightly glued to the artificial head.

The artificial head is joined to an artificial lung by two cylinders. The left (exhalation) cylinder is connected to the climatic chamber. Its task is to take air (with the required humidity) from the climatic chamber and to transmit this through the mask being tested and into the dust chamber. The right cylinder draws air through the half mask from the dust chamber and transfers it to the compensation tank. The measuring device measures the dust concentration in the air alternately, first in air from the dust chamber and then in air from the compensation tank. The artificial lung works in two operating modes: inhalation mode and exhalation mode.

Inhalation mode – when the piston rises, the dust-laden air from the dust chamber is sucked in (the right cylinder and red marked direction) through the half mask attached to the artificial head, using the inhalation cylinder. At the same time, the humid air from the climatic chamber is sucked in by the second cylinder (the left cylinder in Fig. 4 and red marked direction), which is called the exhalation cylinder.

Exhalation mode – when the piston descends, the air from the inhalation cylinder is directed into the compensation tank and (at the same time) the air from the exhalation cylinder is directed towards the dust chamber.

The dust concentration in the compensation tank (i.e. dust which passed through the mask) and in the dust chamber are measured alternately by the same dust monitoring unit.

Fig. 3. Test stand for RPE equipment with a view of its artificial lungs on the right

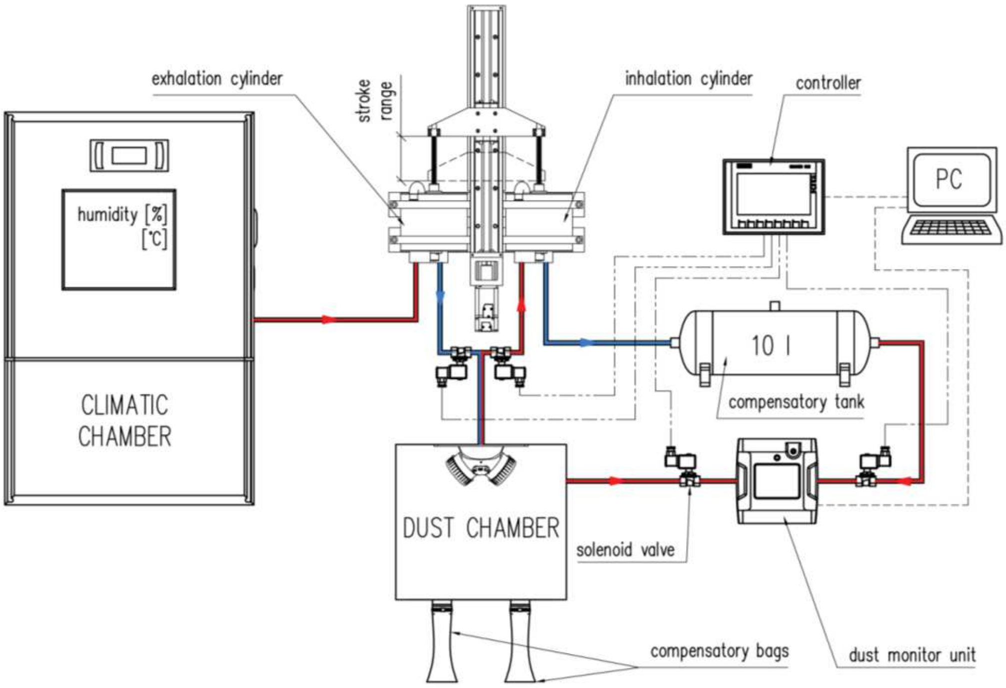

Fig. 4. Schematic diagram of the test stand used for assessing half masks

The auxiliary test stand for testing the filtration efficiency of filter materials and its breathing resistance is based on the main test stand. The auxiliary test stand enables comparative tests of mask filters through the elimination of the exhalation valve and mask-to-face leaks. To achieve this, an additional port was installed on the dust chamber which terminates in a threaded tip for attaching the filtration medium to the chamber. Only one cylinder, which sucks air from the dust chamber through the tested section of the filter material is used.

Schematic diagram of the auxiliary test stand is presented in Fig. 5.

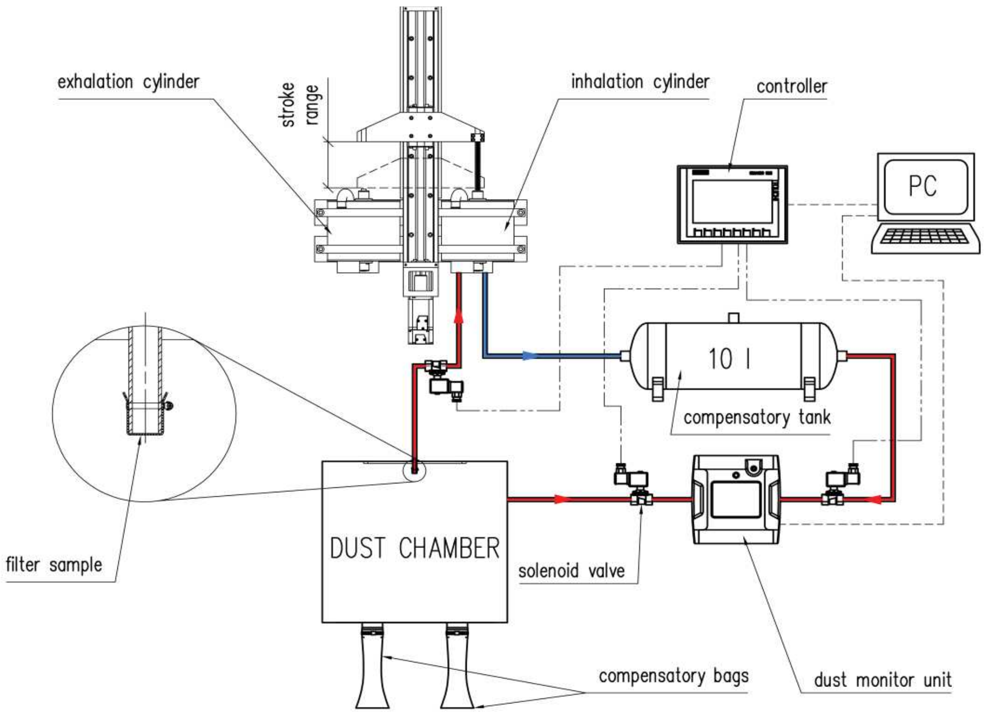

Fig. 5. Schematic diagram of the auxiliary version of the test stand

The test stand developed by KOMAG to determine the filtering efficiency of different types of half mask has three test modes:

- Testing of half masks fitted and strapped to the artificial head;
- Testing of half masks fitted and glued to the artificial head;
- Testing sections of filter material glued to the cover of the hermetic box (Fig.7) using the auxiliary test stand.

The test stand allows for determination of breathing resistance for a number of combinations of two breathing parameters - breathing volume and rate. The following three main combinations were used:

- 700 ml /12 breaths/min – simulating easy breathing (rest);
- 1000 ml / 25 breaths/min – simulating moderate effort (light work);
- 1500 ml / 60 breaths/min – simulating high effort (hard work).

Breathing resistance was measured four times, first at the beginning, when the mask is new and clean, and the three more times, when the following number of breathing cycles under light work rate were completed:

- after the first 1100 cycles;
- after the next 1100 cycles i.e. jointly after 2200 cycles;
- after the next 1100 cycles i.e. jointly after 3300 cycles.

For testing samples of mask filter, the following breathing volume and rate were used:

- 300 ml breaths with 12 breaths / min;
- 400 ml breaths with 12 breaths / min;
- 500 ml breaths with 12 breaths / min.

The dust for testing was prepared by the Główny Instytut Górnictwa from the dust samples taken from an underground mine. The dust was dosed into the air using a special pneumatic system, developed by KOMAG. During the tests of half-masks, dust was periodically replenished, while during the tests of the filter sections, one dust dose for a 20-minute test time was used. Due to a gravitational reduction in dust concentration in the chamber over 20 minutes (Fig. 6), dust concentrations in the chamber and in the passing air (air not drawn through the mask) were compared to calculate the effectiveness of the half mask or filter material.

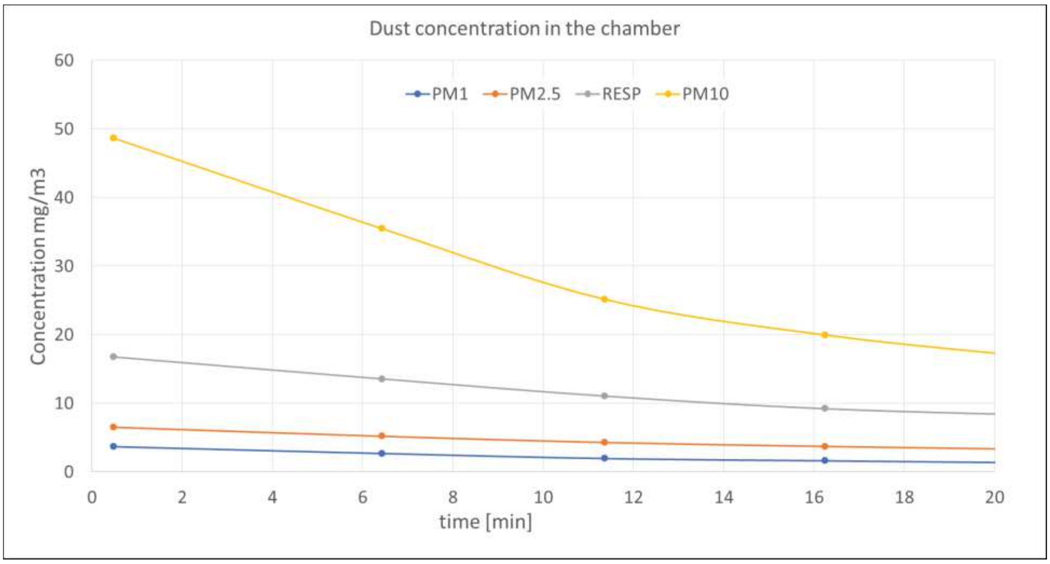

Fig. 6. Dust concentration as measured inside the dust chamber over a period of 20 minutes

The following procedure for half mask testing was developed:

a. a new mask is placed on the artificial head or sealed onto the artificial head (i.e. the mask rim is glued);

b. the breathing resistance is first tested for three levels of physical activity: rest, light work and hard work;
c. the dust chamber is closed, dust and humid air are introduced into the system;
d. when the dust concentration in the chamber reaches 30 mg/m^3, 1100 breathing cycles are started with light breathing rate (i.e. 1000 ml and 25 breaths per minute) and dosing dust and humid air;
e. the operation of artificial lungs is stopped, the chamber door opened and breathing resistance is tested, as in item "b";
f. the chamber is then closed again and the next 1100 (1100-2200) cycles are realized at the light work breathing rate, as in item "d", with dosing dust and humid air
g. the operation of the lungs is stopped, the chamber's door opened and, for the third time, breathing resistance is tested, as in item "b";
h. the chamber is then closed and the next 1100 (2200-3300) cycles at the light work breathing rate, same as in "d", are realized with dosing dust and humid air;
i. the lungs are stopped, the chamber's door opened and, for the last (fourth) time, breathing resistance is tested, as item in "b".

The testing of fragments of mask filters on the auxiliary test stand eliminates the impact of leaks between the mask and face and from the exhalation valve. It allows the most accurate assessment of filter quality, regardless of the shape and size of the mask. Filter materials from masks were tested in the following procedure. A piece of filter material was glued onto the cover (Fig. 7) of a hermetic box. The box with cover is placed on the dust chamber and connected by a pipe to the measuring equipment in the test stand.

Fig. 7. A fragment of mask filter glued to the cover of the hermetic box before its testing

For each filter, 240 breathing cycles of 12 breaths/min for each of the three selected volumes i.e. of 300 ml, 400 ml and 500 ml was carried out. Seven types of half masks were tested during the ROCD project; two from JSW, two from PGG and one from PV. Additionally, 2 masks used by KOMAG's (KOM) workers were also tested to gain more data. The tested half-masks are listed in Table 1 and examples of tested disposable and reusable half masks are shown in Fig. 8 and Fig. 9.

Table 1. Masks tested with the newly developed test stand.

Item	Mining co.	Designation only for the article purpose	Mask type
1.	JSW	1J FFP2	bowl type disposable, exhal. valve
2.	JSW	1J FFP3	bowl type disposable, exhal. valve
3.	PGG	2P FFP3	foldable disposable, exhal. valve
4.	PGG	3P FFP2	foldable disposable, exhal. valve
5.	PV	1V FFP1	bowl type disposable, exhal. valve
6.	KOM	4K FFP2	foldable disposable, no exhal. valve
7.	KOM	5K FFP2	reusable, exhal. valve

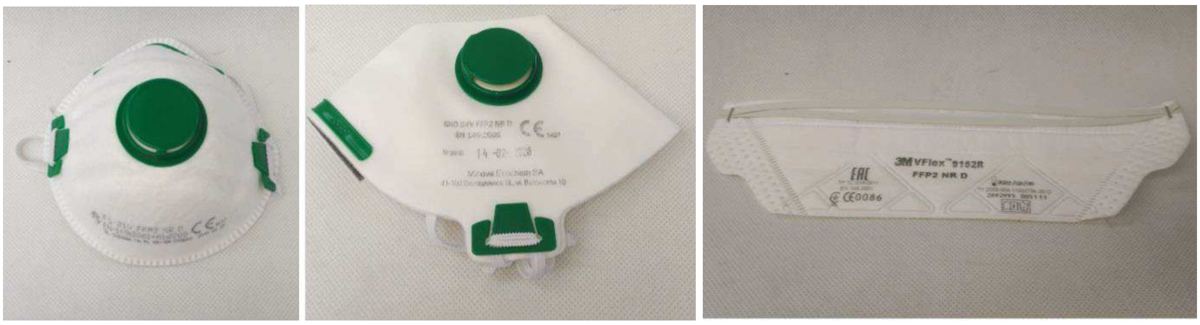

Fig. 8. Examples of disposable masks: bowl type (on the left) and two types of foldable masks (on the right)

Fig. 9. Example of the reusable mask SECURA 2000

Reusable masks have two replaceable filters which makes the active filtering area larger than for a disposable mask, which may affect the test results. Reusable masks were therefore also tested for comparison with disposable masks.

2.2. Workplace testing

Providing workers with RPE is not enough to protect them. RPE should be selected correctly, worn properly and fitted adequately [7,8,9]. The lifetime of masks before their efficiency drops below acceptable levels depends on the breathing rate and the concentration of airborne dust. During intensive work in dusty conditions, the filter material quickly becomes wet, due to the passage of humid exhaled air, and clogged with deposited dusts which increases breathing resistance. Use of an exhalation valve in the mask is advantageous as it reduces exhalation resistance and the wetting of the filter. Only one valve is usually necessary (rather than one per filter) as the second valve will normally remain idle, except for situations of very high physical activity. Moreover, it should be remembered that the second valve unnecessarily reduces the active area of the filter for dust capture as it replaces a portion of the filter area. The effective lifetime of a half-mask or a set of replaceable filters in dusty conditions may be from 30 minutes to several hours. Mine employees have indicated a practical working life of between 2 and 6 hours. It is obvious that a higher density of fibres in the mask filter (giving greater filtration efficiency) will cause an increase in breathing resistance (i.e. greater difficulty breathing) and therefore the choice of mask should be a compromise between these features. The type of mask to be used should be carefully selected according to the dust-related health hazards which is reflected in the literature [16,17]. The workplace method of research using questionnaires is important for verifying RPE utility [18], however it has been noticed that the questionnaires used in some mining companies promote masks with a long lifetime. These tend to have a low breathing resistance and immediate breathing comfort but may not offer the best filtering efficiency. This aspect was also taken into consideration when planning the underground RPE test program in the ROCD project, which involved PGG, JSW and PV. The agreed questions in the questionnaire are presented in Table 2 of section 3.3.

3. Results

The results of the half-mask testing are discussed below in the following order:

- Results from the testing of breathing resistance;
- Results of filtering efficiency tests;
- Results from workplace testing.

3.1. Half mask breathing resistance test results

With regards to points a-i of the testing procedure, the breathing resistance tests for half masks were conducted for all three breathing parameters. An example of the results from these breathing resistance tests are shown on Fig. 10 and 11. It was observed that during the hard work mode (i.e. 1500 ml and 60 breaths/min), the under-pressure was high. As expected, the resistance of reusable masks (dark blue and brown bars in the graphs) was the lowest.

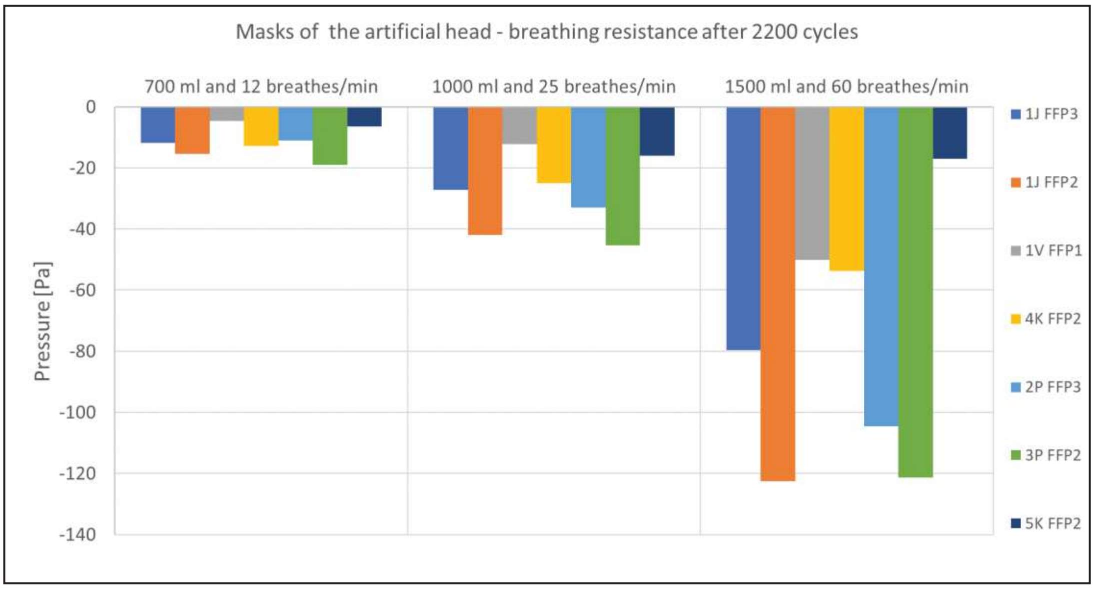

Fig. 10. Graph comparing the breathing resistance of different half masks attached to the artificial head, after 2200 cycles

To assess the possible impact of leakage between the mask and the face of the artificial head, similar tests were carried out on masks glued to the artificial head, see results in Fig. 11.

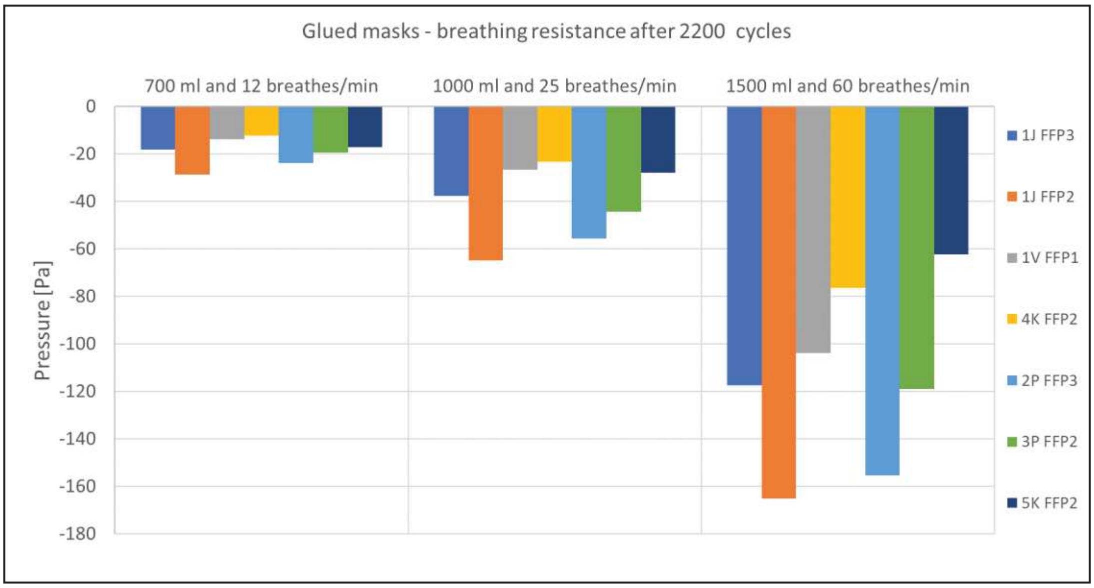

Fig. 11. Graph comparing breathing resistance of different glued masks after 2200 cycles

When comparing the graphs in Fig. 10 and 11, it is clear that there is a significant impact of leaks on breathing resistance. Reusable masks (dark blue) had the lowest resistance and the disposable masks (brown) the highest. The mask type represented by the yellow data bar (3M Vflex 9152R FFP-2) gave good results even without an exhalation valve. This result is similar to that of the reusable masks shown in dark blue, with a centrally located exhalation valve.

After analysing the resistance data for the masks, it was interesting to compare them with the results from the testing of filter sections, see Fig. 12.

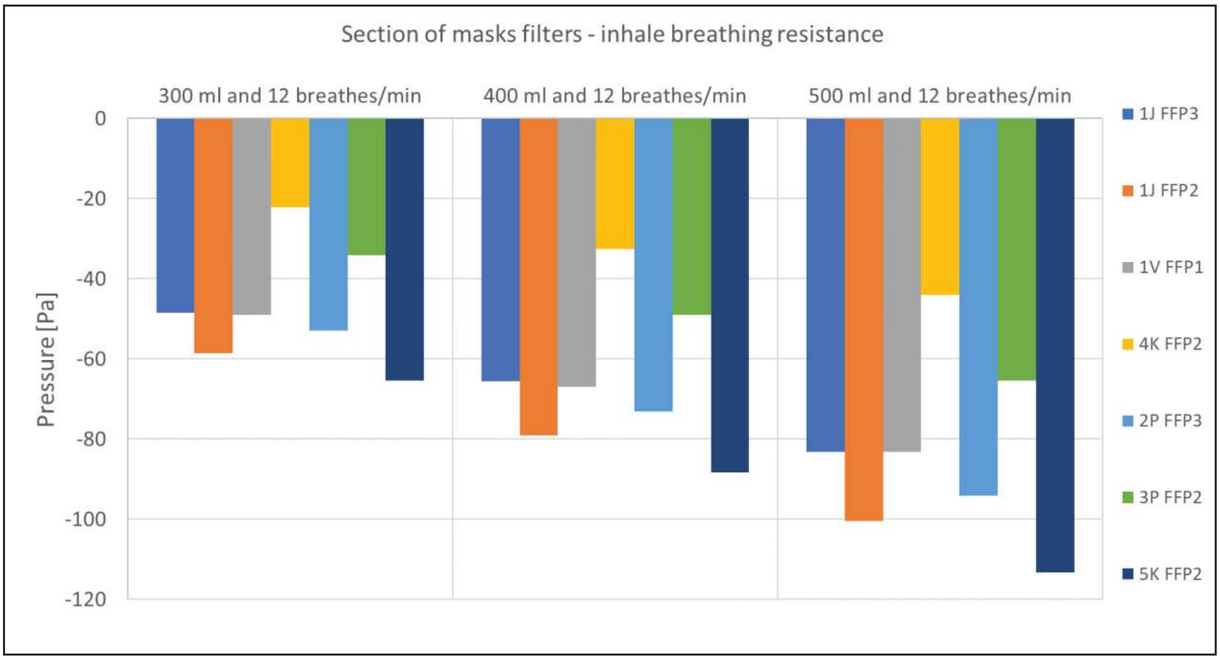

Fig. 12. Graph comparing the inhalation resistance of filter sections from different masks

Reusable masks, which have two filters and therefore a combined active filter surface of 300 cm^2, have a lower resistance than disposable masks with an area of up to 240 cm^2. However, when testing a defined area of the filtering material (the same as that for the disposable masks), their inhalation resistance is higher (Fig. 12). This emphasises the importance, better comparability, of testing filter sections rather than whole filters when assessing the filtration efficiency of mask filters. The same is true for the results of testing the exhalation resistance of filter sections (Fig. 13).

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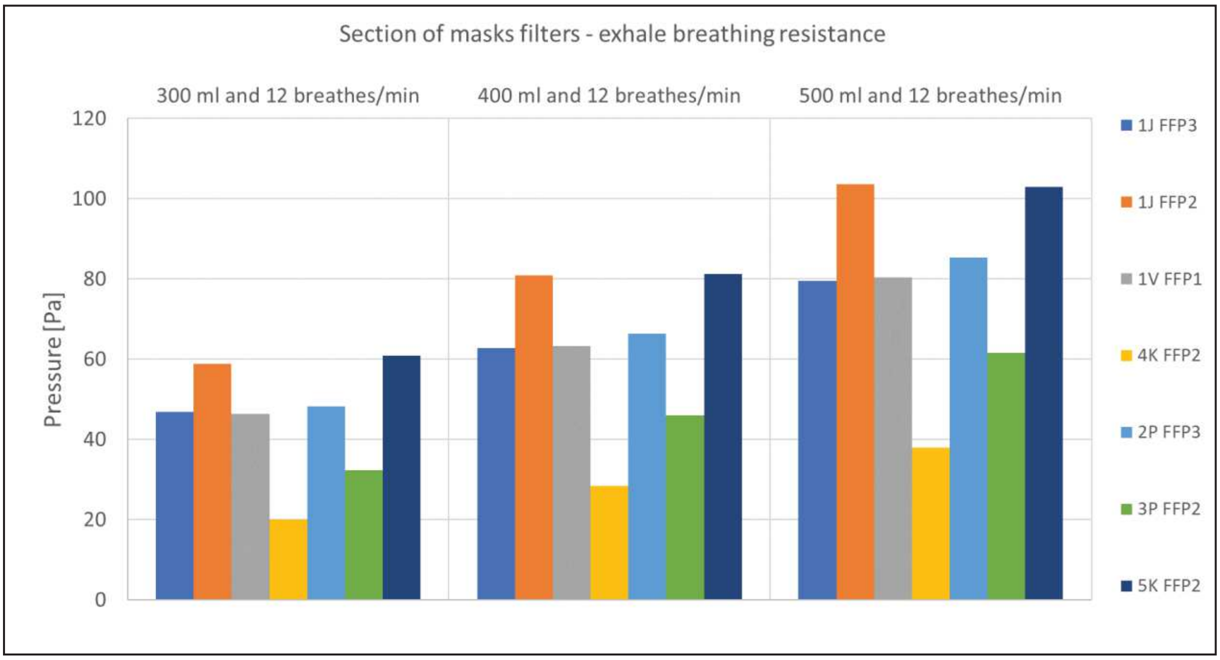

Fig. 13. Graph comparing the exhalation breathing resistance of filter sections from different masks

3.2. Results of filter efficiency tests

The tests undertaken to determine the filtering efficiency for $PM_{2.5}$ of different masks were carried out using the test stand with the artificial head, see results in Fig. 14. It can be observed that filtration efficiency did not decrease noticeably when the number of breathing cycles increased up to 3300, however, there were differences between each mask. The reusable masks (FFP-2 filters) showed a relatively low efficiency comparable with FFP-1 masks (provided by PV), which was a bit surprising. In Fig. 15, similar results are presented for $PM_{2.5}$, for masks glued to the artificial head, i.e. where there is no possibility of leakage. The glued masks showed a much higher filtering efficiency (>99%) than for the masks fitted to the artificial head (>87%).

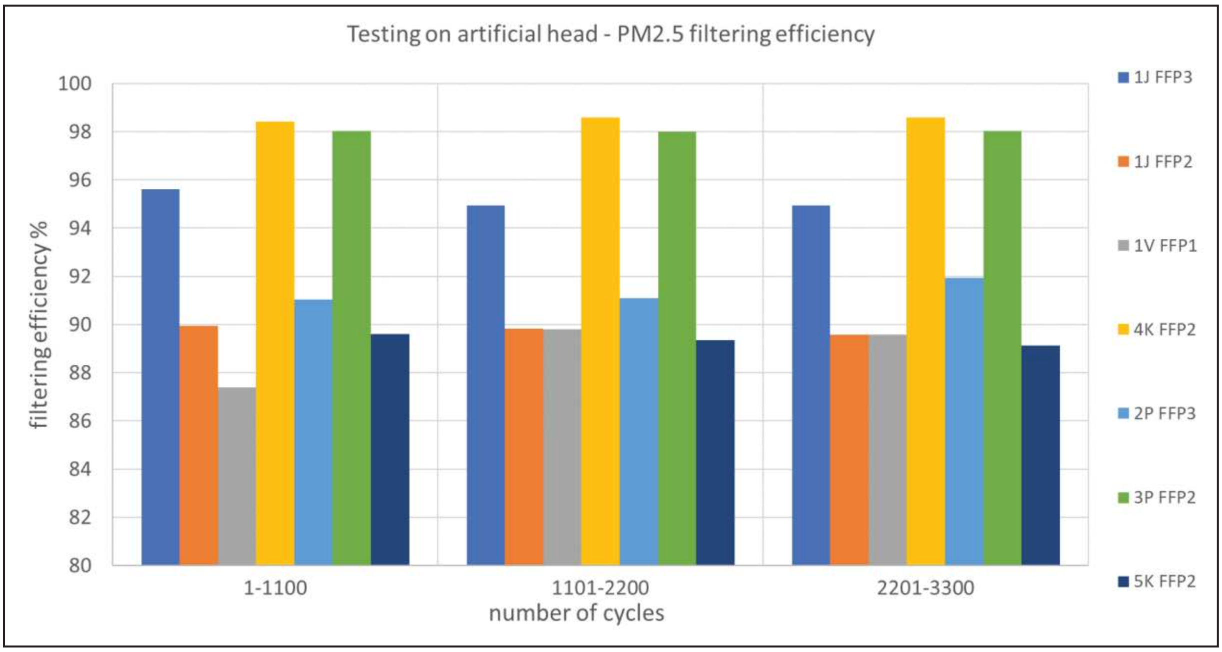

Fig. 14. Filtering efficiency for $PM_{2.5}$ of masks fitted to the artificial head

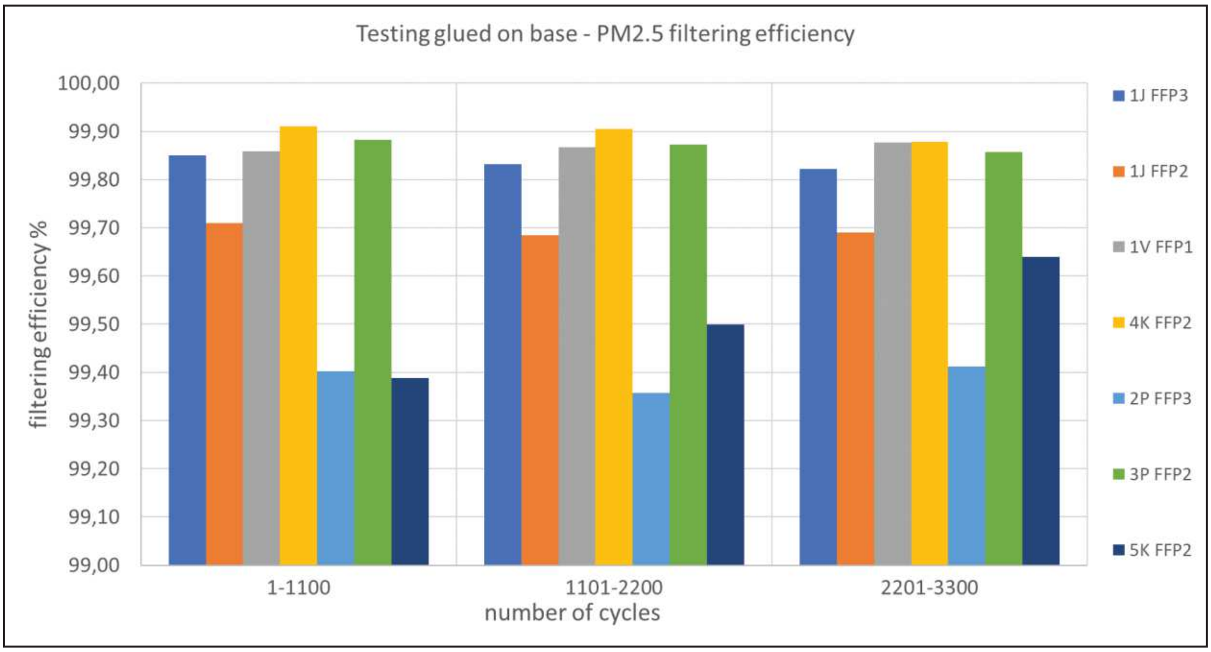

Fig. 15. Filtering efficiency for $PM_{2.5}$ of masks glued to the base of the auxiliary test stand

Fig. 16 shows the filtering efficiency of the masks tested on the artificial head for the full range of dust sizes, i.e. PM_1, $PM_{2.5}$, PM_{10}, and respirable dust. For comparison, the same tests were carried out for masks glued to the base (Fig. 17). By comparing these graphs, the impact of leakage can be seen, i.e. where dust filtration efficiency is always above 85% in Fig. 16 and above 99.2% in Fig. 17. The filtering efficiency of some fitted and glued masks was extremely impressive reaching >99.8% for PM_1.

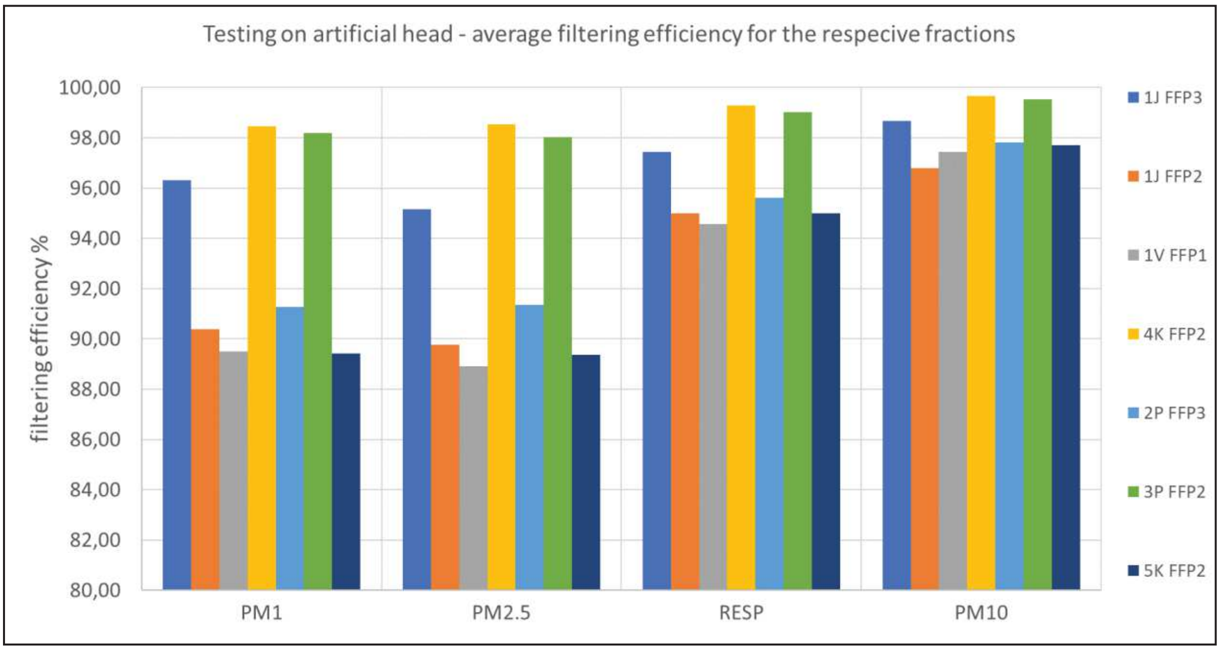

Fig. 16. Average filtering efficiency, for different dust particle size fractions, of masks fitted to the artificial head

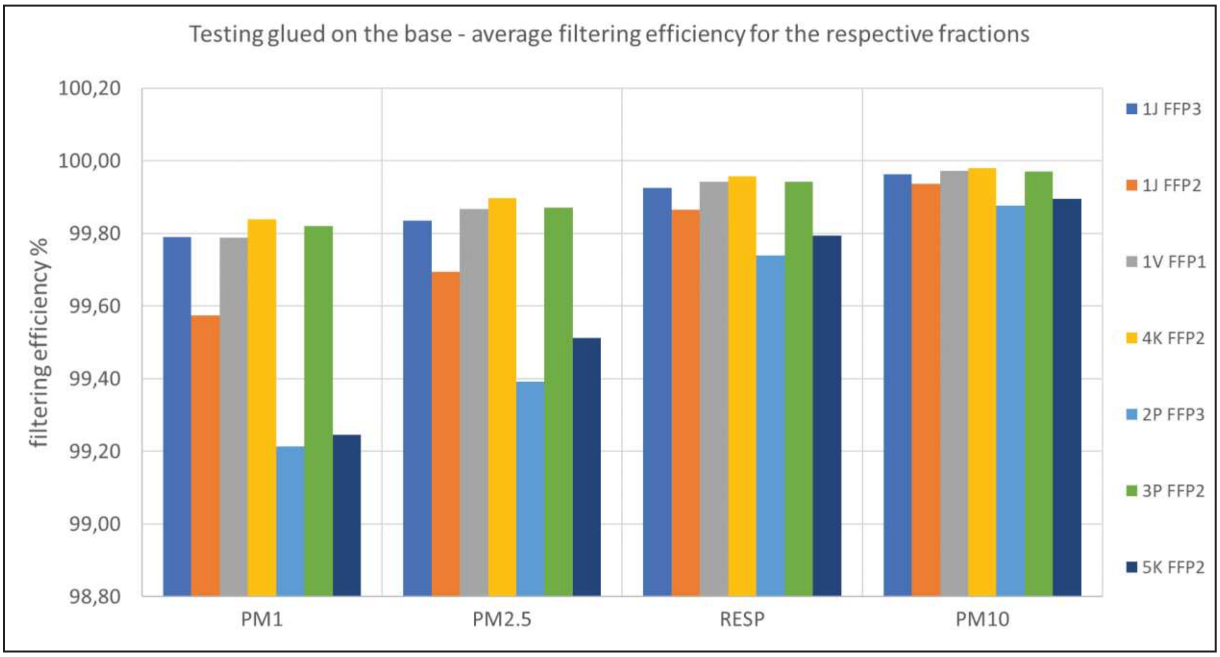

Fig. 17. Average filtering efficiency, for different dust particle size fractions, of masks fitted and glued to the artificial head

It was observed that:

- All masks have a good filtering effectiveness, over 99.2% but they must be tightly fitted, as observed in Fig. 17.
- Comparing Fig.16 and Fig.17, it can be concluded that poor fitting can cause reducing of filtering efficiency by a few percent.
- The masks represented by the yellow and green bars in Fig. 17 had the best results regarding filtering efficiency. It is worth noting that these are FFP2 masks, rather than FFP3 which, in theory, should be the best.
- In the tests of masks glued to the base of the auxiliary test stand, the FFP3 mask represented by the blue bar in Fig. 17 has the lowest efficiency, while the FFP1 mask marked grey has very high efficiency; this was a bit unexpected.

3.3. Workplace testing results

Table 2 shows examples of results from questionnaires completed by 61 miners from PGG mines. The question which is related to problems with sputum has never been the subject of an inquiry before but was considered very important for the correct assessment of mask effectiveness.

Table 2. Example results from questionnaires from 61 miners in PGG mines on the use of disposable half mask, type FFP3

Item	Tested parameter of useful feature		Number of results / % Score 0	Number of results / % Score 1	Number of results / % Score 2
1.	Face fit and tightness of the mask during the operation / tightness of filter on the reusable mask (rating: 0=bad : 1=moderate; 2 =very good)		**1** 1,64%	**34** 55,74	**26** 42,62%
2.	Stability of the mask structure (susceptibility to collapse, laxity) during work (rating: 0=bad : 1=moderate ; 2 =very good)		**3** 4,92%	**25** 40,98%	**33** 54,10%
3.	Interaction of mask with other types of protective equipment (e.g. glasses, helmet, goggles, earmuffs, etc.) (rating: 0=bad : 1=moderate ; 2 =very good)		**5** 8,20%	**24** 39,34%	**32** 55,46%
4.	Did you have to remove the mask due to too much breathing resistance? (rating: 0 = yes 1= rather rarely , 2 = did not happen)		**17** 27,87%	**4** 6,56%	**40** 65,57%
5.	Did you need to spit out sputum despite using the mask? (rating: 0 = yes ; 1= rather rarely 2 = no)		**12** 19,67%	**2** 3,28%	**47** 77,05%
	If yes, is your sputum dark? (rating: 0 = yes; 2 = no)		**6** 9,84%	**0**	**6** 9,84%
6.	Usable working time up to (hours)	2h	4h	6h	over 6h
	number of results / %	**24** 39,35%	**14** 22,95%	**21** 34,42%	**2** 3.28%

From Table 2, most miners i.e. 55.74 %, indicated that the mask tested offered a good fit-to-face and tightness. Most miners reported good structural stability of the masks, and 65.57 % good breathing resistance. 77.05% of miners did not feel the need to spit out sputum however 9.84 % gave an affirmative answer regarding its dark colour. The latter is worrying and shows that there is still room for improvement in the field of miners' health protection, especially for miners on the front line of dust exposure. The usable working time in a purchasing analysis should be treated wisely as longer working time could be the result of poor filtering efficiency. Such a new approach can have positive results for miners' health provided that it will be implemented in practice.

4. Discussion

From the results of tests using the artificial head, mask tightness on the face is crucial. As it turned out, testing of fitted and glued masks is valuable in assessing mask's quality as glued masks can be compared with masks which are well fitted on the head.

The auxiliary test stand enabled testing of sections of filter material and the gaining of additional information regarding filtering parameters, excluding the impact of other factors e.g. exhalative valves and mask-face seal leaks. All tested masks meet the filtering efficiency requirements.

Breathing resistance, especially inhalation resistance varies significantly and heavily depends on the intensity of breathing so this parameter should be taken into account when selecting a mask.

In situ tests allow for checking the masks functionality that cannot be sufficiently checked in a laboratory. In the interests of miners' health, the quality of the half-mask should be assessed on the basis of workplace and test stand tests.

The knowledge gained from research should contribute to best practice in the use of masks in areas exposed to dust. Researchers emphasize the need for a wide range of incentives and to provide the necessary knowledge to employees [19,20,21] to encourage the use of RPE because, according to their opinion, the use of masks, even where there are high dust concentrations, is often ignored.

The main cause, according to the authors, is breathing resistance which causes accelerated fatigue of the body.

5. Conclusions

As a result of the ROCD project, KOMAG designed and built a test stand to assess the quality of RPE equipment used in mines. From this they have created a database to compare the attributes of half-masks and their filters. The new test stand has provided invaluable information regarding breathing resistance and filter effectiveness. However, using the artificial head is problematic because the quality of the seal between the mask and artificial head is different in each test and depends on many factors.

The filtering efficiency of the different masks tested, which were either strapped or glued to the head, was always excellent, at over 99%. Taking into account that mask fitting is crucial in the aspect of filtering efficiency, the assessment and choice of mask should be based mainly on tests where inhalation resistance is measured, i.e. by incorporating a measurement of under-pressure.

In the interest of miners' health, and for those working in other high dust environments, the quality of the half-mask should be assessed on the basis of workplace and stand tests. The tests are complementary and both should be included to ensure the correct assessment of RPE.

Acknowledgements

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