Discussion on Possible Approaches for the Management of Pollutants in Tunneling in Rock Formations Containing Asbestos Minerals

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Workers' exposure to asbestos minerals is a major factor in the Occupational Safety and Health risks typical of tunneling. For, as well as being a carcinogen, the distribution of asbestos minerals in rock formations is highly irregular since their possible formation during the metamorphic process depends on various parameters. This makes a special risk assessment and management necessary. Many case studies of specific risk assessment and management of pollutants applied in tunneling are available in literature, so the aim of this research study is to define which can be implemented in case of formations containing asbestos minerals, in combination also with other solutions, and organize them in hierarchical order. Initially, to achieve this goal, a literature review was carried out in accordance with the PRISMA statement, to select the current solutions used to manage possible workers' exposure to asbestos minerals. Subsequently, the various solutions selected (e.g., specific excavation techniques, catcher systems near the source, ventilation systems etc.) were given a hierarchy by order of priority and compared to each other. The selection of solutions and the priority order were achieved by taking into account the safety requirements for the construction of the base tunnel of the Turin-Lyon railway line. The study highlighted the fact that despite technological progress there are still some critical aspects in the management of pollutants and in particular of asbestos minerals.

Keywords: Occupational Safety and Health, tunneling, asbestos, risk assessment, risk management, literature review.

1. Introduction

In tunnel excavation a presence of high concentrations of dust is common (Padovese et al. 2017). Dust is the one of the main byproducts of tunnel construction sites (Liu et al. 2020a). With the rapid development of mechanization and intensified production in fully mechanized tunnels, the concentration level of dust has increased in the tunneling process (Hua et al. 2020; Yin et al. 2020). According to in-situ measurements, the average dust concentration in construction tunnels during the normal tunneling process is in the range of 10 mg/m^3 - 25 mg/m^3. However, when hard rock is being excavated, the average dust concentration is higher than 30 mg/m^3, which can be quite detrimental to workers' health (Liu et al. 2020a). What is more, some airborne pollutants such as asbestos, are carcinogenic for humans, (Bakke et al. 2014). Most of the world's asbestos was produced from ophiolite complexes, which are found in many parts of the world (Ross and Nolan 2003; Compagnoni et al. 1980). The distribution of asbestos minerals in rock formations is often highly irregular, since their possible formation during the metamorphic process, depends on pressure, temperature, host rock composition and the formation's structural framework (Labagnara et al. 2013b). Thus, exposure to a respirable dust in the underground works requires ever better and more advanced technological solutions to prevent it (Ulvestad et al. 2001) and special Risk Assessment and Management are also necessary. The tunnel face represents the main source of dust generation (Guglielmetti et al. 2008). At present, technical measures for dust prevention and dust suppression are extensively utilized in fully mechanized mining faces. This includes dust removal by wet process, dust removal through ventilation, airflow purification, utilizing a dry dust collector, application of chemical agents for dust removal, etc. (Xu et al. 2019; Yin et al. 2020). Since during the tunnel excavation it is not always possible to substitute materials that might emit pollutants, it is only possible to pretreat or change the tunnel route to avoid critical geological areas (an

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unacceptable solution in case of extensive presence of asbestos) (Labagnara et al. 2013a). It is essential to take into account the entire excavation system, starting from the choice of excavation techniques and technologies (Guglielmetti et al. 2008) which are least dusty. In some cases, however, airborne pollutants management starts from environmental treatment, that is, trying to purify polluted air locally and ensure recirculation, for example by using water curtains (Poma and Puma 2016). This pollutants management system does not provide high performance in the case of carcinogenic pollutants, because their efficiency cannot reach 100%. Thus, the aim of this research study is to propose a logical scheme in which pollutants management techniques and technologies (used in case of rock formations containing asbestos minerals) present in literature are illustrated and organized in a hierarchical order.

2. Methods

This study involved a systematic review conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Statement criteria (PRISMA) statement (Moher et al 2009). Both tunneling and underground mining environments were considered, as these environments have characteristics very similar to those relating to tunneling activities. Case studies regarding excavation techniques and technologies which are less dusty, dust suppression and control systems published in Italian or English were eligible for inclusion. Only documents from 1980 to the present were eligible for inclusion, as the literature search concerned pollutant management techniques for modern tunnel excavation. The literature search was performed on the Google Scholar database, which allows users to search for articles and other documents, whether online or in libraries. The search terms used included the following keywords: “dust suppression tunnel excavation”, “underground dust control”, “underground water-spray control system”, “dust suppression underground” and “asbestos control tunneling”. These keywords were applied anywhere in the documents to get as many results as possible. The search yielded 137,000 documents. The documents were sorted by relevance. Of the 137,000 documents identified, 90,000 were excluded by title. Of the remaining 47,000 documents, 45,005 were excluded because the abstracts were not relevant, 151 were excluded because no full text could be retrieved, 39 because they belong to the grey literature, such as theses, congress proceedings and papers not received peer review, and 1,761 because the full text was not relevant. Finally, 44 papers were included (Figure 1). Each of the papers included was searched for identification of the main techniques and technologies used, the context in which the study/research was performed, and the advantages and disadvantages/limitations that may influence their effectiveness.

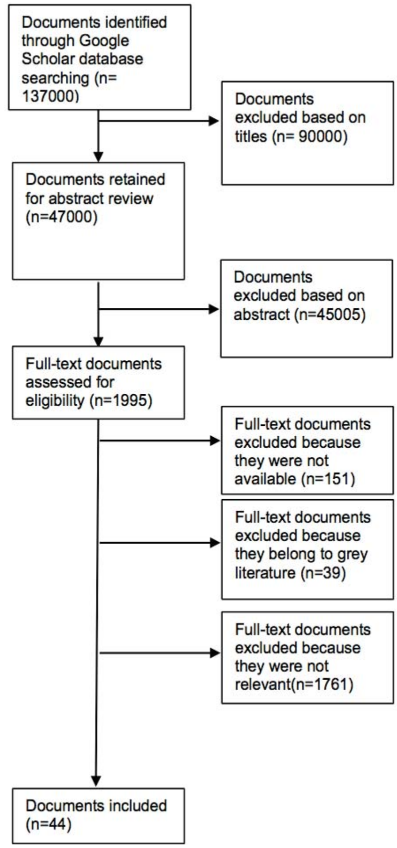

Fig. 1. Flow chart of the bibliographic search.

Finally, a hierarchy of engineering control measures (NIOSH 2015) was implemented to determine the most effective technologies to minimize exposure to carcinogenic airborne pollutants, such as asbestos, in tunneling. The hierarchy was derived from the general criterion for the hazard control measures selection, in order of decreasing effectiveness, based on 89/391/EEC Directive, Art.6.2.c “(c) combating the risks at source”, consistent with good engineering approaches that take into account elementary efficiency criteria (Patrucco 2002). The criterion was also confirmed by NIOSH (2015).

The hierarchy was established in a discussion held by a team of experts consisting of an occupational physician, a risk prevention technician and three engineers. The team also took into account the safety requirements of the construction of the base tunnel of the Turin-Lyon railway line in drafting the hierarchy. Afterward, the team set the following list of hazard control measures suitable for underground operations in rocks potentially containing asbestos layers:

- Control of the pollutant emission
- Control of the pollutant dispersion into the working environment
- Environmental pollution management (pollutant dilution and air substitution)
- Special working environments (remote control from a safe position)

In this case, hazard elimination and substitution (in this case, carcinogenic pollutants such as asbestos) which should be the first two sections above the engineering controls, were considered not fully feasible, since the pollutant can be naturally present in the rocks to be excavated and so difficult to eliminate and substitute.

3. Results and Discussion

As reported in the "Methods" section, a total of 44 documents were found. Of these 44 papers, 15 concern tunneling activities and 29 concern underground mining environments. Among them, Lunardi et al. (2017) is the sole case study that specifically regards the suppression of airborne asbestos fibers. The list is provided in Table 1, in which papers are classified by techniques and technologies used and context (tunneling/underground mining environments). The main results of the eligible studies are described and discussed below.

Regarding the control of the pollutant emission, according to Cole (2017) Tunnel Boring Machines (TBM) result in the lowest overall exposures to pollutants, due to the many electrically powered and mechanized processes and the lower reliance on shotcrete for structural support. For example, the Drill & Blast method (D&B) is more prone to occupational disease, due to pollution caused by the explosives, exhaust fumes from lorries and dust from the sprayed concrete (Tender and Couto 2016; Tender et al. 2015). TBM Earth Pressure Balances (EPB) are widely used in rock masses when conditions require the control of polluting material, as they can prevent the dispersion of these substances in tunnel environment (Peila et al. 2013). With TBM EPB, the ground is extracted from the excavation chamber where is conditioned with water, polymers, and foams (having the function of transmitting supporting pressure to the face) to capture dust particles and stick them to the extracted material. The excavation chamber is insulated until the end point of the screw conveyor, and the presence of pollutants may be circumscribed and controlled (Labagnara et al 2013b; De Cillis et al. 2014). In TBM Hydro shield or Slurry Shield the mucking process is hydraulic, so the dust particles remain confined in the closed-circuit transport system (Labagnara et al. 2013a; Guglielmetti et al. 2008). These types of TBM are more efficient compared to EPB in terms of the smaller amount of dust generated and transportation of dust outside the tunnel (Guglielmetti et al. 2008).

Regarding the control of the pollutant dispersion into the working environment, the line brattice method is one of the most generally used to ventilate working faces. (U.S. National Research Council 1980). Brattice ventilation can provide good dust management in the underground tunnel as compared to blowing and/or suction ventilation configurations, effectively with no additional power source required to drive fans and a simpler design which make it suitable for application underground (Kurnia et al. 2014). The capital costs of line brattices are low in the short term, require no power and produce no noise (McPherson 1993). However, one of the major drawbacks is that the brattice installation limits the movement and flexibility of the operators and worker teams in excavating materials and transporting the materials, reducing space that is typically anyway limited in underground environments. Kurnia et al. (2015) propose a hybrid brattice system (air curtain in addition to physical brattice) which offers up to three times lower dust concentration than that of the physical brattice without air curtain. This hybrid method is not limited to dust control, but could also be applied for methane, temperature and humidity control in the mining face.

As to environment pollution management, an effective ventilation and dust removal system is vital to control the volume of dust produced during tunnel construction (Zhou et al 2019). The ventilated dust removal system behind the shield tunneling machine can provide sufficient fresh air in a tunnel, control the dust concentration and diffusion in a tunnel, and ensure the respiration of operators and normal operation of equipment (Zhou et al 2020; Liu et al. 2020a). A TBM-matched ventilation de-dusting system can effectively control the dust produced when a TBM is being used and can reduce the dust diffusion distance (Liu et al. 2020b). In addition, when an air curtain generator is used, the efficiency of ventilation system improves (Yu et al. 2017). The combination of forced and exhaust ventilation is one of the most common means of removing dust from workplace by ventilation in a reasonable timeframe, and should be considered as the correct ventilation layout in the case of possible presence of asbestos (Toraño et al. 2011; Yu et al. 2017; Labagnara et al. 2013a). The ventilation system and parts response should be analyzed by means of a combination of Hazard and Operability Analysis and Fault Tree Analysis, both in normal and emergency situations (Patrucco et al. 2018; Borchiellini et al. 2013). The ventilation layout parameters include: the fan model, the fan layout position, the length of the duct, and the diameter of the duct. The design process of the ventilation and dust removal system, and how reasonably to select the parameters to achieve the optimal dust removal effect is of great significance to the safe construction of the tunnel, and at the same time, it is of great significance also in improving energy efficiency and reducing energy costs. Generally, the first factor, that needs to be considered is changing the distance of the pressure tuyère to improve the dust control (Nie, et al. 2017a). However, ventilation only is not enough when dust concentration is high (Lu et al. 2015a; Guo et al. 2019). Water sprays are the simplest and most widely used of the dust suppression methods applied for example in underground mines (Xu et al. 2019). They are reliable to operate, have a low cost (compared to the other technologies) and are pollution-free (Tessum et al. 2014).

Table 1. Documents considered in the review.

	Tunnelling	**Mining**
Excavation techniques and technologies choice	1. Labagnara et al. (2013a) 2. Tender and Couto (2016) 3. Tender et al. (2015) 4. Cole (2017) 5. Peila et al. (2013) 6. Labagnara et al (2013b) 7. De Cillis et al. (2014) 8. Guglielmetti et al. (2008)	
Area's separation	1. Lunardi et al. (2017)	1. U.S. National Research Council (1980) 2. Kurnia et al. (2015) 3. Kurnia et al. (2014) 4. McPherson (1993)
Ventilation	1. Zhou et al (2019) 2. Zhou et al (2020) 3. Liu et al. (2020a) 4. Patrucco et al. (2018) 5. Lunardi et al. (2017) 6. Liu et al. (2020b)	1. Yin et al. (2020) 2. Yu et al. (2017) 3. Toraño et al. (2011) 4. Nie, et al. (2017a) 5. Borchiellini et al. (2013) 6. Colinet et al. (2010) 7. WHO (1999)
Spray dust suppression water systems	1. Lunardi et al. (2017)	1. Ren et al. (2020) 2. Xu et al. (2019) 3. Tessum et al. (2014) 4. Nie et al (2017b) 5. NIOSH (2012) 6. WHO (1999) 7. XIE et al. (2007) 8. USBM (1987) 9. Pollock and Organiscak. (2007) 10. Seaman et al. (2020) 11. Peng et al. (2020) 12. Colinet et al. (2010)
Spray dust suppression system with chemical suppressants added	1. Lu et al. (2015a)	1. Guo et al. (2019) 2. Wang et al. (2013) 3. Ren et al (2012) 4. Lu et al. (2015b) 5. Kilau et al. (1996) 6. Wang et al. (2015)
Ultrasonic dust suppression systems		1. Okawa et al. (2015) 2. Okawa et al. (2017) 3. XIE et al. (2007)
Enclosed cab filtration systems		1. Colinet et al. (2010)

Seaman et al. (2020) and Peng et al. (2020) measured dust spray capture efficiencies on respirable dust but not for asbestos. These systems have certain disadvantages, especially during tunneling operations; if the droplet diameter is much greater than the dust particles, the latter simply follows the air streamlines around the droplets, and little or no contact occurs. Only if the diameters are comparable (roughly equivalent), may the droplet and dust particle collide. Thus, the probability of particle to droplet contact increases as the size of water droplets decreases (XIE et al. 2007). However, voids always exist between the water droplets regardless of the fineness of the droplets. Thus, Ren et al (2012) developed a foam (using three suitable surfactants along with a certain amount of auxiliary agent) which reduces the surface tension and improves dust wettability. Compared with simple water spraying, high-expansion foam covers much more space with the same amount of water, and so increases the probability of collision between foam and dust. Despite chemical additives increasing the system efficiency, they have several limitations: they are more expensive compared to just water; they can alter the properties of the minerals to be excavated or extracted; they may damage some equipment (e.g. conveyor belts); they require higher maintenance respect to typical water systems; they are closely linked to the hydrophobic nature of the material to be treated. Another and more serious problem is that chemical reagents are not "green" or environmentally friendly (Nie et al 2017b).

The probability of collision between a droplet and particle can be also increased using ultrasonic dust suppression systems, which are able to produce micron-sized droplets of a 10 μm average size (XIE et al. 2007). Okawa et al. (2017) examined dust suppression using water particles generated by ultrasonic atomization (2.4 MHz) at low temperature (10°C) and found that water particles remained stable even with low relative air humidity.

Regarding the last hazard control (remote control from a safe position) enclosed cab filtration systems are one of the mainstay engineering controls for reducing mobile equipment operators' exposure to airborne dust during excavation. Enclosed cabs with heating, ventilation, and air conditioning systems are typically integrated into the drills and mobile equipment to separate and protect the operator from the outside polluted environment. Key performance factors for enclosed cab filtration systems are: ensure good cab enclosure integrity to achieve positive pressurization against wind penetration into the enclosure, use high-efficiency respirable dust filters on the air intake supply into the cab; use an efficient respirable dust recirculation filter; minimize dust sources in the cab and keep doors closed during equipment operation.

The sole case study that regards specifically the suppression of airborne asbestos fibers (Lunardi et al. 2017) focused on the Cravasco tunnel, which was excavated through rock masses containing asbestos minerals. Excavation was carried out with conventional methods. The tunnel was divided into three physically separate areas, each one associated with a specific risk related to the potential exposure to airborne asbestos fibers during excavation. The areas were: A zone (contaminated area), B zone (decontamination area) and C zone (clean area). The physical separation of the three areas was achieved by the realization of two physical compartments, made of metal; these were removable and covered with PVC waterproofing. Automated gates were set up between one area and another, with a series of nozzles to create an effective water curtain for the entire opening time. Moreover, an exhaust ventilation system was set, to catch the highest number of asbestos fibers released during excavation directly and quickly at source. Upstream of the ventilation system, three de-dusting units were installed to return clean air to the outside environment. In the contaminated zone (A), together with the exhaust ventilation system, an intense system of sprayed water abatement was adopted, installed on the hydraulic hammer, and a nebulizer arc a few meters from the excavation face, covering the entire section of excavation. Moreover, in zone A, two fog cannons were placed aimed at the heap of spoil. An SEM (Scanning Electron Microscope) was used to determine asbestos fiber concentration and it was shown that, during all excavation stages (74 excavation face cycles - approx. 500 data points) the fiber spread was almost completely confined to the "contaminated" A Zone.

Even if for this review only one documented case study, supported by measurements, was found on the airborne asbestos fibers' suppression efficiency, it was possible to set a preliminary qualitative hierarchy of engineering controls, which is illustrated in Figure 2. For each hazard control (Fig. 2 on the left), a hierarchy of the less dusty technique and technologies or that with a supposed major efficiency, was established (Fig. 2 on the right). This is a first result based on a literature review and the judgments of a team of experts, so it needs to be implemented in future research with more asbestos specific case studies.

As demonstrated in Lunardi et al. (2017) a good risk management strategy involves the implementation of more than one engineering solution of the hierarchy, starting always from the control of the pollutant emission.

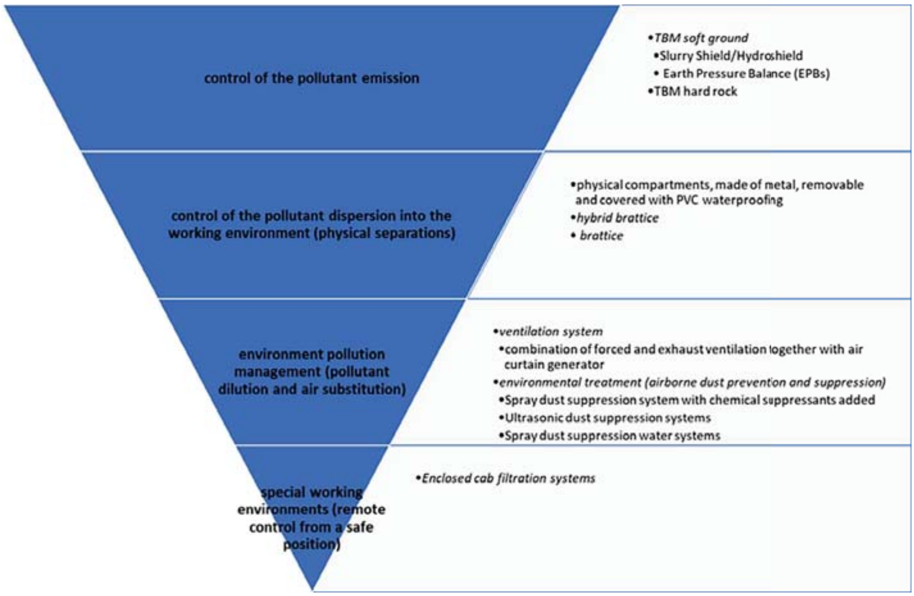

Fig. 2. Hierarchy of engineering controls proposed for tunnelling through rock masses that may contain asbestos minerals and other pollutants

Conclusion

The study brought into evidence the fact that, despite technological progress, there are still few case studies for the management of pollutants, and in particular of asbestos minerals, available and visible on the internet. This research study highlights this gap and may be considered as a first step for future case studies in the field of tunneling through rock masses containing asbestos minerals.

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