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Predictive assessment of the asbestos content in the Western Italian Alps: an essential tool for an effective approach to Risk Analysis and Management in Tunneling operations and muck reuse.

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Abstract

The modern approach to the design and management of tunnel excavation, and muck reuse, can be influenced to a great extent by the possible presence of rock formations containing asbestos minerals. This situation creates problems concerning the protection of the workers' health and the expectable environmental criticalities, while a drastic re-consideration of the muck destination is necessary.

Since, in the case of carcinogens, corrective action following exposure or dispersion is not acceptable, detailed knowledge of the characteristics of the material to be excavated is all the more essential.

Only on this basis it is possible to design the tunneling operations in a Prevention through Design approach, so that the tunnel driving techniques, fittings and technologies, and special equipment and modus operandi, can grant, where necessary, minimized risk conditions, and make a correct decision on whether, how and when these measures must be fully activated, since such an approach involves a remarkable impact on costs and work organization.

In the western Alps a detailed identification and quantification of the asbestos content in rocks is a difficult task, due to the fact that the asbestos in the host rocks, mainly serpentinite, shows a highly variable distribution, typical of ophiolitic belts throughout the world, as it is mostly associated with joints and shear zones.

The possibilities of a predictive assessment of the asbestos content in the formations to be excavated are here discussed, with special reference to the reliability of the achievable results.

Keywords: Tunneling in rock formations containing asbestos, Risk Analysis and Management, Prevention through Design (PtD), Asbestos identification techniques, Reliability in the assessment of the asbestos content in rock.

Introduction: the target

Tunneling implies special Safety and Health risks which require a quite careful management (the risk analysis and management steps are listed in Table 1). In such situations the narrow working space, the high concentration of great power machines, the use of iterative work cycles and the limited times of execution of the excavation constitute elements of objective difficulty.

From the point of view of the protection of workers' safety these aspects make mandatory the accurate planning of the different tasks, in particular considering the interference between concurrent processes interacting in the same limited area. These issues are then interwoven with aspects of occupational health, becoming more critical in the case of excavation in the presence of hazardous minerals, such as asbestos, silica, radioactive substances, etc..

In these cases, a specific preliminary Risk Analysis is necessary, and mandatory (according to European Directives 89/391 and 92/57). The same approach is highly recommended in the Prevention through Design approach -PtD- introduced by the American Society of Safety Engineers (2009).

The Risk Analysis, which should be based on the collection of detailed information on the presence, the quality, the quantity and spatial pattern of the critical minerals, should lay at the base of the decision making process for an effective choice of the tunnelling techniques and

Tab. 1 Risk analysis and management steps

STEP 1	Definition of the Risk Analysis Strategy	Identification of the most suitable techniques usable for the risk analysis according to the context.
STEP 2	Identification of the Hazards	Pinpointing of material, system, process and/or plant characteristics that can produce undesirable consequences through the occurrence of an accident. Hazardous material means a substance or material capable of posing an unreasonable risk to health, safety, and property.
STEP 3	Risk Analysis	Process of identification of the most suitable exposure model and application of the analysis techniques in order to assess the risk.
STEP 4	Risk Assessment	Process by which the results of a risk analysis are used to make decisions, either through relative ranking of risk reduction strategies or through comparison with risk targets. The occupational exposure assessment is a formal process leading to the definition of the workers' professional exposure to the identified hazardous materials.
STEP 5	Risk Management	Systematic application of management policies, procedures and practices to the tasks of analyzing, assessing and controlling risk in order to protect employees, the general public, the environment and company assets.
STEP 6	R.A. Revision (quality management)	Improvement in the quality management of the residual risks.

technologies, aimed to minimize the associated risk, and to make correct decisions in the management of the excavated rock, which - apart from the impossibility of any reuse which could jeopardize the Safety and Health conditions of the workers involved- should now be considered a direct risk agent whose disposal becomes expensive.

In these situations, in order to make correct decisions during the preliminary design phases, an effective Risk Analysis requires reliable input data (technical, economical, environmental, etc.). In fact, a poor representativeness of these data can affect the results in many ways, and determine deviations from the expected goal.

The preliminary definition of the entity of the acceptable deviation of these data requires:

- ➢ the definition of the criticality of the various input parameters;
- ➢ the consequent adoption of suitable techniques to quantify each parameter;
- ➢ the recognition of the possible difficulties in the quantification of the aforementioned parameters.

The paper deals with the Safety and Health aspects of tunnelling in rocks containing asbestos minerals (known to be Class 1 carcinogenic by International Agency for Research on Cancer (IARC) since 1977) and in particular discusses how to obtain reliable input data on the presence and quantity of the asbestos potentially present in the rock mass, and the limits of representativeness of these data[1].

The views here expressed are the result of studies carried out, with different purposes and at various times, in the valleys of the Italian Western Alps, where important tunneling operations will shortly be started.

The problem: The case of tunneling operations in asbestos potentially containing rock formations

Asbestos toxicity

Industrial hygiene considers asbestos according to its ability to be airborne. The ability of asbestos contained in rocks to become airborne depends on the state of aggregation; the following terms can then be introduced:

- ✓ “total asbestos” indicates all asbestos present in a rock formation, whatever its state of aggregation,
- ✓ “friable asbestos” indicates the part formed by fibers that are not embedded in the rock and which are connected by such small cohesion forces that even weak mechanical action is sufficient to release them (Clerici et al. 1997).

The hazard degree of asbestos is therefore also a function of the mechanical actions applied to the asbestos-bearing rock and of the resulting granulometry: crushing causes an increase in the amount of friable asbestos, and the possible exposure of workers involved in excavation can result very different from the exposure of workers involved in the reuse plants.

This could suggest that if the percentage of asbestos in the bearing rock is relatively small (few percent) the problem is not dramatic. A simple calculation shows the contrary. In fact, if during the excavation of a 100 m^2 cross section tunnel in serpentinite is crossed a 1 cm thick vein trending 90° to the tunnel and dipping 25° containing 100 kg of fibrous tremolite (2% of the total mass contained in the vein), simple calculations, even assuming that 10% (10 kg) of the tremolite is air dispersed as respirable fibers (e.g.: $L/\varnothing = 5$; $L = 10\ \mu m$; $\varnothing = 2\ \mu m$), would lead to a dispersion of $1 \cdot 10^{14}$ fibers!

Even the workers in reuse plants can be exposed to a high quantity of asbestos fibers, due to the increase in the free surface of the material that undergoes crushing, which is proportional to the reduction in the equivalent diameter to the power of 3 (Testut 1958). In a Risk Analysis that is also focused on muck reuse, it is necessary to measure the total asbestos present in the formations to be excavated which can be released during the reuse treatment.

Asbestos in nature

Of the six minerals recognized by the Italian law as asbestos (chrysotile, grunerite-amosite variety, crocidolite, tremolite, anthophyllite and actinolite), only chrysotile belongs to the serpentine family, while the others are part of the amphibole series (chrysotile is probably the most widespread fibrous mineral in nature and certainly the most commonly used).

The distribution of the different asbestos minerals is highly irregular, as their occurrence

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[1] Only asbestos minerals contained in natural rock formations are considered in the paper: in the case of tunneling in the cortical layers of heavily populated areas the possible presence of allochthonous asbestos and the widely different characteristics should be taken into account.

depends on the metamorphic conditions, the host-rock composition and the structural framework. Pressure and temperature are particularly important since asbestos are metamorphic minerals that are stable under different conditions: chrysotile forms during very low grade metamorphism, while tremolite-actinolite and crocidolite form during low grade metamorphism; amosite and anthophyllite instead occur at higher temperatures (mostly at medium grade metamorphic conditions). It is important also to underline the relationship with the host-rock composition: asbestos minerals are generally associated with specific rock-types (serpentinites: chrysotile, tremolite, anthophyllite; metabasites: tremolite-actinolite, crocidolite; BIF, ironstones: crocidolite, grunerite; impure, generally dolomitic, marble: tremolite-actinolite).

At a worldwide scale, most of the asbestos occurrences and concentrations are associated with ophiolite complexes of different ages and selected Precambrian rock-types: according to Ross and Nolan (2003), during its 5000 year-long history of use, ca. 85% of the world's asbestos has been produced (mostly as chrysotile) from ophiolites; grunerite and crocidolite occurrences are instead practically restricted to Precambrian iron-rich lithologies. The structural framework is also very important: most asbestos concentrations occur as "veins", related to ductile to (more often) brittle structures like shear zones, fault planes and fractures (Davis and Reynolds 1996; Perello and Venturini 2006).

Asbestos in the Western Alps

In the Western Alps, asbestos occurs mostly in the Piemonte Zone ("Calcescisti con Pietre Verdi" Zone in the old Italian Literature), an ophiolitic unit of the Jurassic age deriving from the lithosphere of the Ligurian-Piemontese Ocean. This unit crops out extensively for about 200 km from the Ossola Valley (in the North) to the Voltri Massif (in the hinterland of Genoa) (Fig. 1), and it is bordered on the west by the Briançonnais Zone (part of the thinned European paleomargin) and on the east by the Sesia Lanzo Zone (African paleomargin), the Inner Crystalline Massifs of Monte Rosa and Dora Maira (European paleomargin) and, in the southern sector, by the post-orogenic sediments of the Piemonte Tertiary Basin and the Po Plain. During the Alpine orogeny, the Piemonte Zone underwent a polyphase metamorphic evolution through a clockwise P-T path, which crossed the stability fields of various types of asbestos several times.

Of all the varieties of asbestos, only chrysotile, tremolite and actinolite occur in significant amount in the Western Alps. Chrysotile is a fibrous variety of serpentine, whose curved structure is responsible for its fibrous morphology; its occurrence is, therefore, strictly connected with the serpentinites. Tremolite and actinolite are instead part of the amphibole group and show very similar structures, belonging to the same isomorphic series (the tremolite-actinolite series): actinolite differs from tremolite because part of Mg (located in the M sites) is replaced by Fe. Such difference is important for their distribution. In fact, tremolite *sensu stricto* (i.e., Fe-free) mostly occurs in Fe-poor rocks, like serpentinites and related rocks (e.g., ophicarbonates); actinolite forms in rocks richer in Fe, like metabasites and mafic schists (actinolite schists). When the composition is intermediate between the two (e.g., in different types of mafic schists), the term tremolite-actinolite is used.

In general, the distribution of various types of asbestos in the Piemonte Zone is closely linked to areas where ophiolitic rocks occur. Ophiolites constitute a significant portion of the unit (the remaining part being represented by metasedimentary oceanic cover rocks); as can be seen in Fig. 1, these rocks (mainly serpentinized ultramafics and metabasalts) occur as up to km-sized bodies, especially in the north-western Alps (roughly north of Turin) and west of Genoa, in the innermost portion of the Zone (toward the Po Plain). Smaller bodies (the largest being represented by the Monviso ophiolites) also crop out in the outer portion of the Piemonte Zone, which is embedded by metasediments. Due to such a geographical distribution, most of the valleys in the western Alps intersect rocks that potentially contain asbestos. Among the ophiolitic rocks, serpentinites are certainly the rock type that potentially may contain more asbestos minerals, as chrysotile and tremolite. Other rock-types potentially containing fibrous minerals (as actinolite, tremolite-actinolite or tremolite) are represented by actinolite-, chlorite- talc-schists, metabasites and ophicarbonate rocks (Compagnoni and Groppo 2006).

In the serpentinite bodies, the structural and petrographic studies show that the asbestos minerals – both chrysotile and tremolite - are related to fluids circulating along discontinuous, ductile to -more often- brittle deformation structures like shear planes, faults and fractures (Fig. 2a). This is a common feature of the

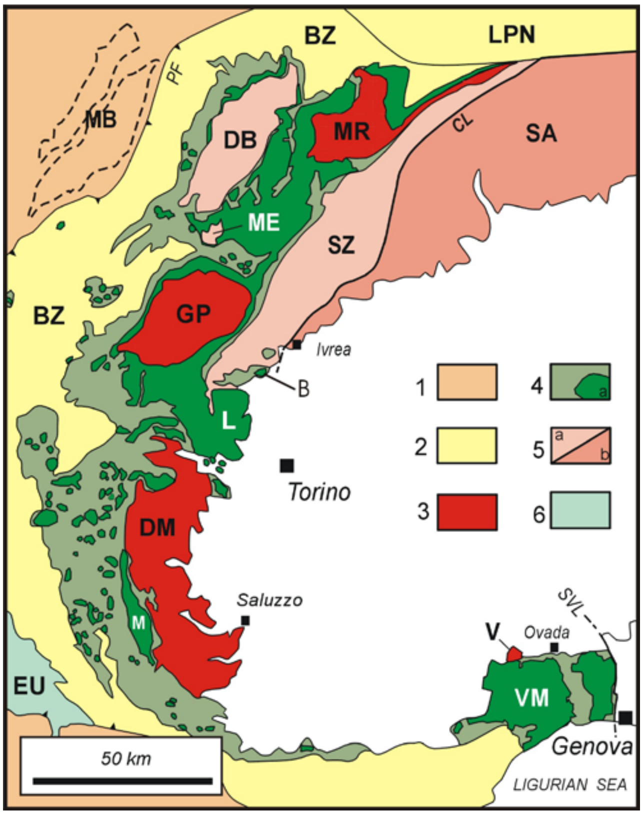

Fig. 1 Simplified tectonic sketch-map of the western Alps. 1: Helvetic Domain (MB: Mont Blanc – Aiguilles Rouges). 2-4: Penninic Domain, 2: Briançonnais Zone (BZ) and Lower Pennine Nappes (LPN); 3: Internal Crystalline Massifs of Monte Rosa (MR), Gran Paradiso (GP), Dora Maira (DM) and Valosio (V); 4: Piemonte Zone (a: main ophiolitic bodies), L: Lanzo Ultramafic Massif, M: Monviso ophiolites, VM: Voltri Massif. 5: Austro-alpine Domain: a: Dent-Blanche nappe (DB), Mt. Emilius nappe (ME) and Sesia Zone (SZ); b: undifferentiated Southalpine Domain (SA). 6: Embrunais-Ubaye Flysch Nappe (EU). CL: Canavese Line; SVL: Sestri-Voltaggio Line; PF: Penninic Thrust Front. B = Balangero chrysotile mine. Modified after Castelli et al. 2002.

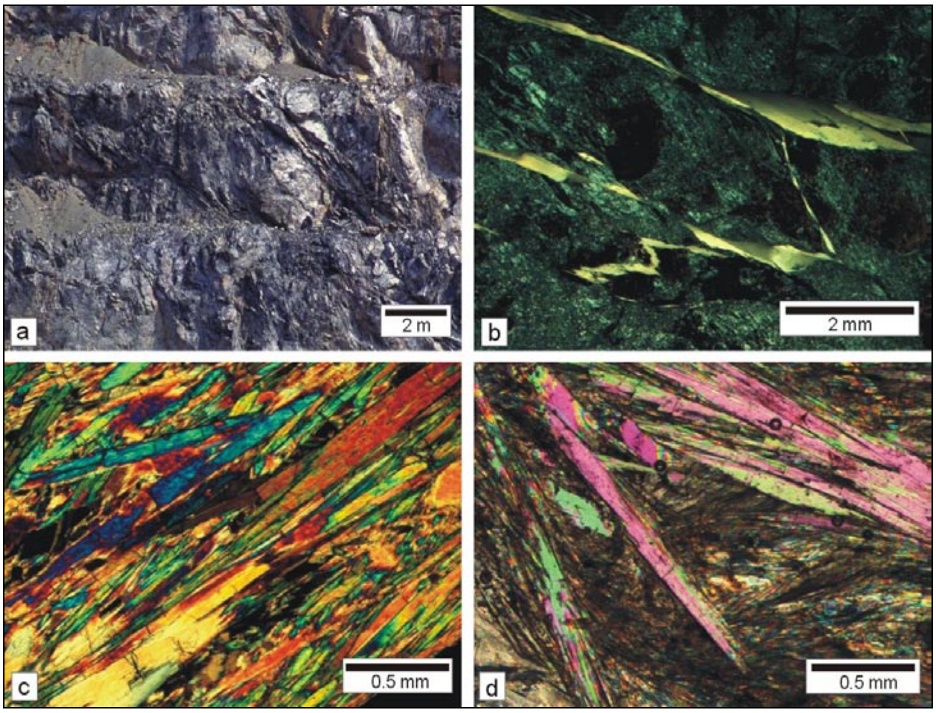

Fig. 2 Typical occurrences of asbestos, at the macro- and microscopic scale, in the serpentinites of the western Alps. a: serpentinite affected by strong shearing and fracturing: asbestos minerals (chrysotile and/or tremolite) often occur along the structural discontinuities. b, c, d: asbestos in serpentinite under the microscope (transmitted light, crossed polars). b: chrysotile veinlets (yellowish) crosscutting the antigorite matrix. Chrysotile fibers are broadly parallel to the veins walls ("sleep fibers"). c, d: detail of veins filled with fibrous tremolite, alone (c) and (d) associated with calcite (brown, lower left corner).

ophiolite complexes worldwide: high asbestos concentrations often occur when a serpentinite body is crosscut by shear zones (Hora 1997; Wrucke 1986). Along the deformation structures the asbestos minerals are concentrated within "veins" usually ranging in thickness from some microns to a few centimeters. Fibrous "veins" may form by two different mechanisms: mineral growth after the opening of a fracture ("crack-seal": Ramsay 1980), or development of the fibrous veins by replacement in the absence of fracturing ("dissolution-precipitation creep": Bons and Jessell 1997). Depending on the fluid conditions and their position in the P-T-t path, the veins can show different mineral assemblages and structural features. It is worth mentioning that chrysotile and tremolite are not the only fibrous phases in the serpentinites of the western Alps, where two new fibrous minerals have been discovered: balangeroite (a Mn-Mg-Fe hydrous silicate: Compagnoni et al. 1983) and carlosturanite (a Mg-Fe-Ti-Mn-Al silicate: Compagnoni et al. 1985). Moreover, fibrous varieties of antigorite and diopside also occur. However, all these fibrous phases/varieties are relatively rare and are not considered as asbestos by the current legislation.

The chrysotile-bearing veins inside the serpentinites of the western Alps formed late in the rock evolution, at low P-T conditions; the fibrous veins, mainly composed of chrysotile (± magnetite), crosscut the metamorphic foliation and show microstructural features typical of a crack-seal growth mechanism. Depending on the deformation regime, within the veins fibers can grow parallel ("slip-fibers": Fig. 2b) or at a high angle ("cross-fibers") to the vein walls. Some chrysotile has also been reported, associated with balangeroite and magnetite, within strongly folded veins related to an early veining event (Compagnoni et al. 1980). However, these early veins are very rare compared to the late chrysotile + magnetite veins.

Also tremolite formed late in the alpine evolution: it mainly occurs along post-metamorphic veins, alone (Fig. 2c) or associated with calcite (Fig. 2d). The latter occurrence seems restricted to small serpentinite bodies embedded by carbonate-bearing schists (Groppo, 2005).

Apart from the serpentinite bodies, asbestos minerals, particularly tremolite and actinolite, may also occur in different types of schist (the previously mentioned actinolite-, chlorite- and talc-schists), and this is often related to shearing and fluid infiltration in a ductile regime. However, these rocks are relatively rare and well localized; they in fact occur above all along shear zones inside serpentinites or, more often, at the contact between serpentinites and mafic rocks. Moreover, amphiboles generally are not concentrated along veins, but strongly intergrown with the other minerals. The same applies to ophicarbonate rocks and especially metabasites, which contain tremolite-actinolite that does not often have a fibrous habit and is not very friable.

When present, asbestos minerals occur in small amounts, well below 1%, with the exception of the area of the important asbestos mine in Balangero, near the southern edge of the Lanzo Ultramafic Massif (Fig. 1), which was mined for chrysotile from 1918 to 1990, and a few other areas that were mined in the past for asbestos.

The evaluation of the quality of the investigations results for an effective PtD approach

The techniques used to investigate on the content of the asbestos minerals in rock masses can be divided into two levels. The first level includes surface geological investigations, which are typically used to obtain detailed geological maps of the area, whereas the second level involves geognostic drilling, which is performed to provide information useful for the refinement of the geological modeling, to determine the possible critical factors in the material to be excavated, and to define the muck destination.

Investigations not involving drilling or significant excavation activities: a precious tool for preliminary information

The initial analyses mainly have two purposes: to draw a geological map of the area (possibly at least in 1:5000 scale), which will be the basis of the future drilling plan in areas worthy of further investigation, and will be validated and improved by the drill core analyses.

The first phase, in addition to the extensive collection of the documentation already available (literature, thematic and geological maps, etc.), is based on geologic mapping, focused to the recognition of lithologies (particularly, ophiolitic rocks) and brittle structures which are likely enriched in asbestos minerals. The occurrence of detrital material (e.g., gravel) containing ophiolitic pebbles must also be taken into account as a potential source of asbestos. Sampling of rocks and fracture/fault systems should also be carried out. The collected samples are useful not only for the identification of the asbestos types, but also for a first characterization of their distribution. The petrographic and mineralogic data on the samples, coupled with the field structural data, are essential for the recognition of the asbestos-bearing structures, and their first extrapolation at depth. During this stage, laboratory analysis procedures must therefore be set up. Petrographic and powder X-ray diffraction analyses are particularly suitable, although a number of different techniques are used (Environmental Protection Agency 1993). It should be important to consider that, during these early investigations, the microscopic relationships between the fibrous phases and other minerals are very important. MicroRaman spectroscopy on raw samples and/or thin sections (Rinaudo et al. 2005; Groppo et al. 2006) is at present considered a very promising technique for the identification of the fibrous phases in the field of earth sciences, since it is fast, non-destructive and without the need to prepare samples.

Geophysics, in this case, cannot provide suitable information: techniques, such as tomography and induced polarization, are useless in the case of the presence of a dry filler in the joints. Tests for the identification of changes in the geomechanical features, which are potentially useful to identify asbestos serpentinites or crosscutting planes containing fibrous minerals, do not offer the precision and spatial resolution necessary to identify small and often sudden changes.

Geognostic drilling and core analysis, and achievable results

As a first approach to the analysis, it is possible to obtain information on the presence of asbestos in the rock from the analysis of the drilling fluid recovered during the geotechnical investigation, since the asbestos fibers present in the joints can be easily removed with the pressurized fluid. However, this method cannot be used to determine the concentration of asbestos in the rock, due to the possibility of over-flushing of the mineralized fractures by the pressurized fluid.

For the quantification of asbestos concentration, we then decided to divide the drill core in tracts (less than 5 meters in length, a measure that can be taken as the minimum necessary detail) and for each tract to calculate the average asbestos concentration on the basis of the concentration values of samples collected from the tract. The average value is then compared with the values calculated for the adjacent tracts, so that information will be available on the evolution of the concentration of asbestos all along the core.

The division of the drill core in tracts and the samples collection can be performed with statistical or judgmental methods:

- ✓ when a statistical approach is adopted, the core is divided into tracts of non-variable length and the samples are collected with a pre-defined interval. This approach involves the possibility of a concerning underestimation of the asbestos concentration if joints with asbestos are not intercepted.
- ✓ in the judgmental approach, instead, the analyst defines homogeneous tracts (of variable length; based on the occurrence, or not, of fibers, elements or structures certainly, or potentially, connected with asbestos) and decides where to collect samples from each tract. This method can also lead to uncertainties: it depends completely on the analyst’s capabilities (and it is certainly not an easy task: see Fig. 3).

Tab. 2 shows a real case of measurement of the concentration of asbestos in a drill core that crosscuts a serpentinite body from the Piemonte Zone. It is evident from Table 2 that the definition of “homogeneous tracts” was here based on the degree of fracturing, as (even if asbestos was not visible on hand samples) the previous geologic and mineralogic surface studies had clearly stressed the relationship between brittle structures and asbestos occurrence. In this specific case, the Phase Contrast Optical Microscopy + image analysis technique (PCOM: see Table 3) has been adopted for the determination of the asbestos content (and asbestos typology, not shown in Table 2).

Uncertainties in the Geognostic drilling and core analysis results

The result of a measurement is only an approximation or estimate of the real value of the measurand (the quantity intended to be measured), and thus is only complete when accompanied by a statement of the uncertainty of that estimate.

In order to obtain a correct measurement of the uncertainty, according with the official standards (Bureau International des Poids et Mesures (2008)) it is possible to use A Type uncertainty evaluation methods, based on the statistical analysis of the results of a series of observations, or B Type methods, based on approaches other than the A Type evaluation approach.

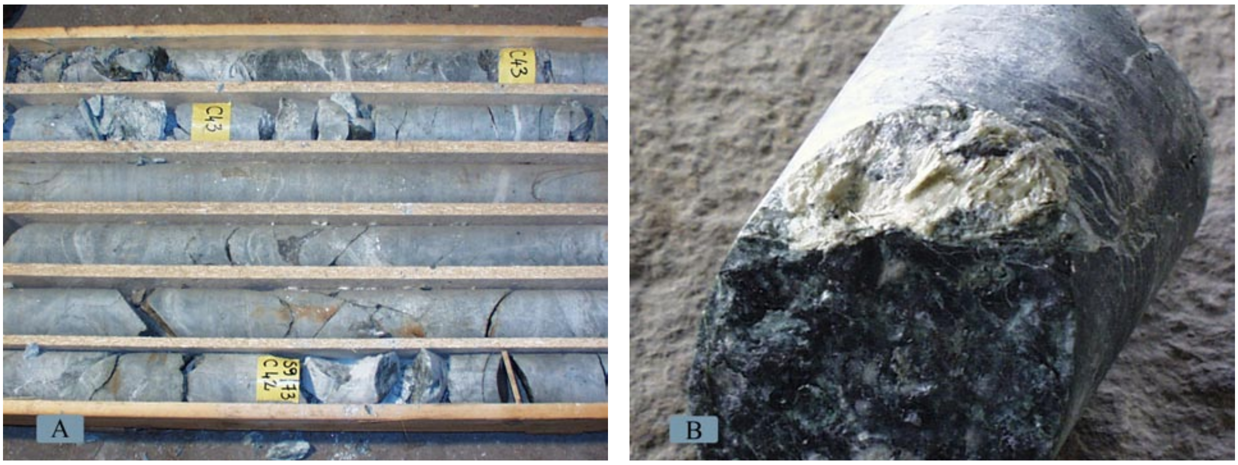

Fig. 3 Drill cores from serpentinite bodies of the western Alps (a), with portions (b) strongly enriched in asbestos. Definition of homogeneous tracts and sampling are clearly difficult tasks.

Tab. 2 Example of statistical analysis carried out to determine the presence and quantity of asbestos minerals in the core. Legend:

🟩	No asbestos detected
🟨	Small concentration values (< $1\cdot10^{-2}$ %)
🟪	Intermediate concentration values ($1\cdot10^{-2}$ % ÷$5\cdot10^{-1}$ %)
🟥	Remarkable concentration values (≥ $5\cdot10^{-1}$ %)

Chainage [m]	Zone and sample type	Approximate average grade of the “total” asbestos content in the sample
64.00 –71.15	Massive zone, 3 massive samples	$4\cdot10^{-3}$ %
71.15 – 74.90	Massive zone, 2 massive samples, 1 fractured sample	$1\cdot10^{-4}$ %
74.90 – 78.20	Massive zone, 2 massive samples	🟩
78.20 – 82.10	Strongly fractured zone, 3 fractured samples	2 %
82.10 – 87.00	Fractured zone, 2 fractured samples	$2\cdot10^{-2}$ %
87.00 – 91.20	Strongly fractured zone, 3 fractured samples	$5\cdot10^{-1}$ %
91.20 – 100.30	Fractured zone, 2 fractured samples	$2\cdot10^{-2}$ %
100.30 – 105.10	Massive zone, 1 massive sample, 2 fractured samples	$5\cdot10^{-3}$ %
105.10 – 110.60	Massive zone, 2 massive samples	🟩
110.60 – 125.50	Massive zone, 3 massive samples	🟩
125.50 – 140.30	Massive zone, 2 massive samples	🟩
140.30 -142.50	Massive zone, 2 massive samples, 1 fractured sample	$2\cdot10^{-3}$ %

In the present case the measurand is the average concentration of asbestos in a tract of the drill core. Its total uncertainty is related to the sampling and sample preparation uncertainty, and to the measurement method uncertainty:

- ✓ the sampling uncertainty comprises the *fundamental uncertainty*, associated with short distance fluctuations of the concentration of asbestos in the core, the *drilling uncertainty,* mainly due to the possible mixing of materials from different positions, and the *sample collection uncertainty*, connected to material dispersion during the collection of the samples from the core (the fibrous material dispersion is unavoidable even if a sampling technique involving minimized energy is adopted, since the asbestos is often very weakly bound to the rock) fig. 4.
- ✓ the sample preparation uncertainty is connected to *contamination, loss, physical and chemical changes, human errors, etc*. In rock analysis, uncertainties may arise since the analytical methods, of whatever kind, can be applied only on a very limited amount of sample (few grams). Each sample collected from the core usually ranging from 100 to 200 grams, an alternation of reductions in size (by comminution) and reductions in mass (by quartering) is necessary to obtain a test sample suitable for the analysis.
- ✓ the measurement method uncertainty is associated with the used technique. All potentially usable techniques are affected by uncertainty (see Table 3).

The different types of uncertainty are discussed and evaluated in the following sections. It is assumed that i) the uncertainties due to losses in material at the various sampling and analysis stages, which lead only to underestimation of the value of asbestos concentration, decrease the measurement accuracy (i.e. the closeness of the agreement between the result of a measurement and a true value of the measurand), and ii) the other uncertainties (e.g. due to the instruments characteristics), which may lead to an underestimation or overestimation of the value of the asbestos concentration, modify the repeatability of the measurement (i.e. the agreement between the results of successive measurements of the same measurand carried out under the same measurement conditions).

The various uncertainties are analyzed separately below, and methods to limit and measure the respective variances (the mathematical tool used in statistics to quantify the uncertainties) are proposed.

Evaluation of the sampling uncertainties

The sampling variance is a function of the drilling, sample collection and fundamental variances. The first two are due to the possible loss of material during the operations. In order to mathematically relate the amount of the lost material to the variation in the calculated concentration, it is essential to know the composition of the lost material. If this information is not available, it is still useful to estimate the amount of the lost part: it is possible -on a non-statistical basis- to assume that the lost part consists of asbestos fibers, as previously discussed.

With special reference to the losses in material, it is important to take into account that in the drilling step it is possible to determine the amount of lost material only through subjective evaluations so that the concept of quality in the various drilling steps becomes very important (U.S. Army Corps of Engineers 2001).

During the collection of the sample, instead, the amount of lost material and its composition is, to some extent, identifiable. At the purpose, a suitable method is to carry out the various operations in presence of a suction hood with a filtered flow, and measure the concentration of asbestos on the filter.

A Type uncertainty evaluation regarding the collection step are therefore possible, whilst only B Type uncertainty evaluations can be made with reference to drilling operations.

Finally, the A Type evaluation of the fundamental uncertainty is not possible, and only B Type uncertainty evaluations can be made with reference to the different sampling methods.

With the statistical sampling method the choice of the length of the single tract of the core is critical: often the samples collected from the same tract show poor homogenization. In order to obtain similar concentration values in the samples collected from the tract, the length of the tract itself (and consequently the sampling interval) should be limited, the problem being that this length cannot be a priori defined.

This method, in an inhomogeneous core such as those taken into consideration, can therefore lead to values that are affected to a great extent by the fundamental uncertainty.

Fig. 4 Drill core sampling operation (a). Due to the possible dispersion of asbestos fibers during the operations, effective measures are necessary to prevent the laboratory pollution and the risk of exposure of the operators (b).

Tab. 3 Main asbestos measurement methods and related uncertainties

Analysis method	Minimum detectable amount	Uncertainty	Analysis Time
XRD	1 ÷ 0.5%	10-50%; possible interference with non fibrous varieties	0.5 – 2 h
SEM – EDS	0.001% with counting	1-5% with a low number of fibers, high on the bulk material	0.5 – 2 h
TEM	0.001%	1-5% with a low number of fibers, high on the bulk material	2-3 h
PCOM + image analysis	0.001%	2-5%	depending on the sample and the analyst
IR	0.01%	1-5%; possible interference with non fibrous varieties	1 h
FTIR	0.01%	1-5%; possible interference with non fibrous varieties	0.5 h
µ-Raman* + BSE image analysis	0.001% with counting	1-5% with a low number of fiber, high on the bulk material	depending on the sample and the analyst

Data from Cazzola et al. 2005, Compagnoni et al. 2007. * Groppo et al. 2005.

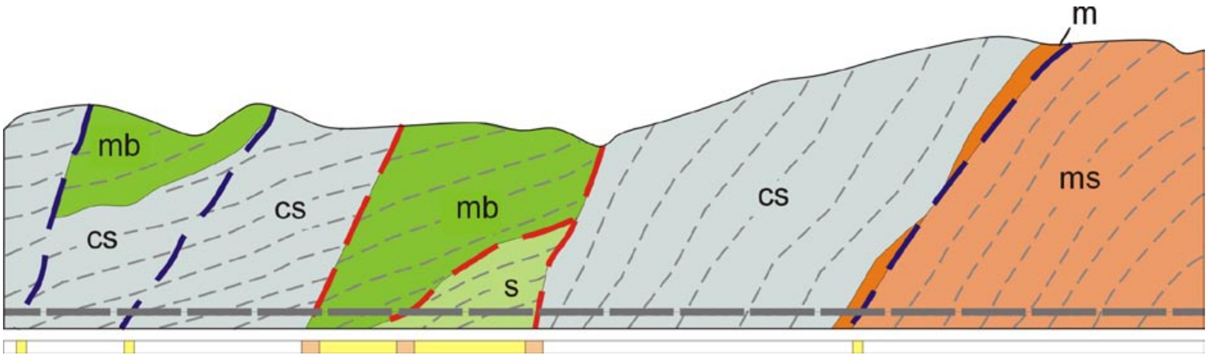

Fig. 5 Cross-section from a (highly schematic, hypothetical) geological-structural model that highlights, based on all the surface and drilling data, the main lithologic and structural features connected with potential asbestos occurrence. A distinction is made between faults/deformation zones which are likely (red), or not (blue), to contain asbestos. The bar at bottom highlights sectors of the tunnel with different probability of encountering rocks containing asbestos (white: null to very low; yellow: low to medium; orange: high to very high probability, respectively). ms: micaschist, m: marble, cs: calcschist, mb: metabasite, s: serpentinite).

<u>With the judgmental sampling method,</u> instead, the homogenization of samples correlated to the reduction of the fundamental uncertainty is based on a subjective approach for the selection of the collection positions of the samples along the core tract. Even though good results can be achieved in some cases, this method is devoid of scientific significance, since it is totally dependent on the analyst's capability.

Evaluation of the sample preparation uncertainties

The sample preparation variance is related to the variances of the uncertainties due to the possible loss in material during comminution steps (comminution variance) and the possible inhomogeneity due to the quartering phases (quartering variance), taking into account that the loss in material is a direct function of the comminution degree.

The A Type evaluation of the comminution variance can be achieved by means of analyses of the collected and filtered material, during a series of repeated comminution phases under a suction hood. This leads to an estimate of the asbestos percentage in the lost material, cross-controlled with a series of mass measurements of samples collected before and after each comminution phase. A simplified approach, leading to a B Type evaluation, can be based on the assumption that the whole lost part -basically the finer-grained portion- consists of asbestos fibers.

The quartering variance can be calculated on the basis of the variance of the asbestos concentration in a series of samples taken from different quartered areas. In this case also, it is possible to consider the particle size range of the material as a variable, and the variance calculation should be performed for each quartered stage.

This procedure, which leads to a A Type evaluation of the uncertainty, is conditioned by the fact that the variance calculation also includes the uncertainties of subsequent operations, such as those of additional reductions in mass and size carried out to obtain the final test sample.

In order to evaluate the variance of all the quartering steps in a single procedure, an unprocessed sample of sufficient size (e.g. 1 kg), can be divided into several similar sub-samples, which will be subjected to the same comminution and quartering procedures. The resulting variance, which is the sum of quartering and measurement variances, can be calculated by means of a series of measured concentration values obtained from the resulting test samples: the quartering variance can then be determined.

It should be underlined that the quartering step variance is not related to a specific substance, but only to the degree of accuracy of the laboratory operations, and can be evaluated using similar sub-samples (with a void sampling variance). Very heterogeneously distributed materials, such as asbestos, have no such features, and the quartering step variance should therefore preferably be calculated by performing the sample preparation procedure, in the same laboratory, on a different (and more homogeneous) material: fine-grained hypo-abyssal igneous rocks, which are often characterized by a good homogeneity in composition, could be used.

Evaluation of the measurement uncertainties

The variance due to the measurement uncertainty can be calculated with a A Type evaluation, through the concentration values measured on a series of test samples collected after size and mass reduction processes. It should be noted that, in this case, the sampling uncertainty is not considered, since the comminuted and quartered material can be considered homogenous.

An estimate of the measurement variance values for the main analytical methods is provided in Table 3. An example of the complete procedure for the determination of the amount of asbestos in a rock mass is suggested by Clerici et al. (1997), from a study we performed within a serpentinite quarry. Such study included first of all the detailed structural mapping and sampling of the quarry area. Two types of sampling techniques have been adopted: random sampling following a grid (to obtain a representative sampling) and vein sampling (for the characterization of the asbestos types and for the analysis of the microstructures, performed through a petrographic study). The random samples have than been crushed, milled (the degree of milling, important for the fibers liberation, has been decided based on preliminary tests) and quartered. Finally the quantitative analysis has been performed, by counting the fibers and transforming the data into mass values. The analyses were performed (see also Table 2) adopting the Phase Contrast Optical Microscopy + image analysis technique (PCOM in Table 3), which easily allows the unambiguous recognition of the different types of fibrous phases. In our study, the subsequent quartering and verification revealed a measurement uncertainty of ±3%. Our choice was also due to the availability, at Politecnico di Torino, of a PCOM laboratory where a specific procedure for the asbestos determination had been developed (Clerici et al. 1997).

Resulting modeling

The target is to obtain data useful for modeling of the rock formation before the excavation. The first step of the modeling is the geological analysis, which is fundamental to develop the geological-structural model of the rock mass (lithostratigraphic setting, localization of various types of ophiolitic bodies, structural framework, with particular attention to the identification of deformation zones and veins), and to analyze the fracture situation (Fig. 5). The geological model can be further refined and modified with the results of analyses of samples collected from outcrops, and, in particular with regards to a 3D structural model of the drill cores.

A geostatistical approach contributes to the model since it makes possible to infer suggestions on the characteristics of the portions of the rock mass not directly reached by exploratory drillings. This analysis technique, however, encounters serious problems when applied to asbestos minerals, since it refers to a regionalized concentration of the studied substances, whilst asbestos show a typical “nugget” semivariogram (as mentioned above, the stockwork veins are here not considered). As a consequence, geostatistics, based on surface drills is unusable in our case.

The need to develop a direct and detailed analysis of the part of the rock mass that has to be excavated is therefore clear. Such a goal can be reached by means of progressive drillings from the tunnel face, which should be carried out in a sufficient number to ensure that all the possible structures containing fibrous minerals are intercepted. The problem due to the possible presence of layers sub parallel to the tunnel route, which are not detectable through parallel drillings from the face, can be solved by adopting inclined drill holes and carrying out back analysis on the previously excavated tracts.

Discussion and conclusion

It is clear, from the considerations listed above, that the problem of quantifying the asbestos content in rocks, which is fundamental for risk analysis, tunneling management operations and muck reuse, is far from being resolved. This may seem surprising: apparently, such problem should not differ from that of mineral resource/ore reserve estimation and grade calculation, which is routinely addressed in mineral exploration. However, the comparison does not work, for several reasons.

As already mentioned, the asbestos distribution in the rock mass can be (and mostly is) highly erratic: from the geostatistical point of view, asbestos commonly shows a typical “nugget” effect. In theory, this should not preclude the possibility of an accurate estimate: gold deposits often show, by definition, a nugget effect, but can – and actually are – evaluated in detail, in terms of grade and tonnage distribution. A thorough gold reserve estimation, however, can be very demanding and expensive, as it may require, depending on the deposit type, a drill spacing of 50 m, often followed by 25 m drill infill for a certified resource estimate. If the same approach is applied to tunneling operations, the costs would be extremely high. But even not considering costs, the analogy with the mining industry methods fails. In fact gold -as all metals- can be easily detected, even at the ppb level, by the geochemical analyses, which are actually carried out routinely (the common procedure is to perform one analysis for each meter of drill core samples). Such procedure cannot be used for asbestos, whose identification requires a mineralogical (i.e., not chemical) analysis.

In the mining industry mineralogical analyses for ore reserve estimation and grade calculations are carried out for industrial minerals. The typical abundance, required “detection limits” and acceptable uncertainty are, however, orders of magnitude higher than for asbestos; actually, a method for routinely performing mineralogical analyses with the required accuracy and detection limits is so far not available. An additional problem is, of course, the fact that the available methods cannot discriminate between fibrous and non fibrous varieties of asbestos, which is fundamental.

The problem of quantifying the asbestos content in rocks, which is fundamental for risk analysis, tunneling management operations and muck reuse, is still far from being resolved. Based on our experience in the Italian Western Alps, taking into account all the considerations on the sampling techniques, and technologies and the reliability of different quantification approaches provided, the following conclusions can be drawn:

a. surface core drills, realized according to a quality approach, even though essential for the characterization of large scale rock formations in terms of the geological and geo-mechanic aspects, and the rock quality index, cannot be considered exhaustive for an evaluation of the asbestos content. However, they play a fundamental role for refining the geological model, provided that the drill cores are studied in detail: in strongly deformed areas like the western Alps, the recognition of the structural features (faults, shear zones etc.) associated to asbestos, when coupled with a well focused petrographic study, is of paramount importance for forecasting, in a 3D model, sectors of the tunnel with different probability of encountering rocks containing asbestos. In sectors where such probability exists, progressive core drillings from the tunnel face are always necessary, to obtain information at a local scale on the expectable presence of asbestos along the tunnel route;

b. furthermore, a common problem of core drilling technologies concerns the possibility of underestimating the asbestos content during drilling and analysis operations. Further studies are still necessary to improve the possibility of quantifying the asbestos content on the basis of the analysis of the circulating fluid, since this methodology, potentially the best in terms of reliability and cost efficiency [?effectiveness?] in the case of pollutant searches, is still not completely reliable when applied to asbestos;

c. finally, the direct measurement of airborne fibers in tunnel air, in exhaust ventilation and in excavated rock can be considered the only way of making a detailed judgment on the presence of asbestos, but, unfortunately, no technology at present available can provide immediate results.

Decision making processes aimed at reducing occupational and environmental risks, and at evaluating the possibilities of reusing muck should therefore be analyzed on this basis in order to correctly identify the suitable operational scenarios, taking into account that, in such situations, the specific layout for asbestos excavation should always be ready to be activated, a fact that certainly conditions the very first steps concerning the choice of techniques and technologies.

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