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Crystalline silica in the Italian ceramic industry: workplace, finished product, and installation

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1. INTRODUCTION

Crystalline silica represents one of the most abundant families of minerals in Earth 's crust (59%) and it is contained in a wide variety of natural (main constituent of over 95% of rocks [1]) and artificial materials (ceramic, glass, bricks, concrete, asphalt and artificial stones [2]). The latter ones constitute the pillar of modern construction, playing a crucial role in the development of infrastructure and urban environments. In most of the raw materials used to develop materials of these industries, quartz is already inherently present and its eventual elimination or replacement with another material would be challenging and costly, with significant financial and environmental implications. Finally, within ceramic materials, quartz is used to reduce the dimensional shrinkage of the material during physical transformations and to increase its mechanical strength [3–5].

Despite its technical benefits, over the last few years, crystalline silica has been under observation by national, Union (European Commission) and international (IARC, International Agency for Research on Cancer and ACGIH, American Conference of Governmental Industrial Hygienists) authorities for safety and health concerns, as finely pulverized dust could be a threat to human health. For this reason, IARC has classified crystalline silica as a Group 1 carcinogen [6]; however, the danger of the respirable crystalline silica can be effectively and easily mitigated by implementing appropriate respiratory protective equipment [1].

This health issue is not exclusively related to crystalline silica dust, but also to other materials, such as hardwood, which in fact is classified by the IARC as a Group 1 carcinogen when pulverized [6]. Attention should therefore be focused on prevention and surveillance systems that can allow safe handling and processing of all these materials when dust is generated during processing.

Finally, despite the attention that has been given to the subject, there are no clear and precise regulations yet on respirable crystalline silica, especially regarding the use of protective systems that would drastically lower health risks, if properly employed. Due to this regulatory and informational uncertainty, individual countries feel free to implement local regulations aimed at "solving" the issue, potentially contributing to confuse the global trade landscape. One example is Australia, which have implemented from mid-2024 a trade ban to engineered stones and applied import policies for all the materials containing crystalline silica. Another example is represented by the U.S. state of California, which has implemented from December 2023 a specific temporary regulation on products containing silica.

Due to the complexity and controversy of the subject, this thesis aims at offering an overview on Italian ceramic tiles, particularly providing an in-depth focus on crystalline silica contained in ceramic products for flooring, wall coverings, kitchen and bathroom countertops, in order to increase knowledge and awareness about this industry. Several contexts will be considered: crystalline silica content in finished products, respirable crystalline silica generated during factory production, and respirable crystalline silica generated during dry cutting for installation purposes.

2. CRYSTALLINE SILICA: CHARACTERISTICS AND ANALYTICAL METHODOLOGIES

2.1. Crystalline vs. amorphous silica

Silica is the name given to silicon dioxide (SiO_2) and can be found in either crystalline or amorphous form. Silica tetrahedra serve as the fundamental structural units in both amorphous and crystalline phases. These units consist of a central silicon (Si) atom surrounded by four oxygen (O) atoms. Each oxygen atom is shared with an adjacent silicon atom, forming strong covalent bonds (Figure 1) [7].

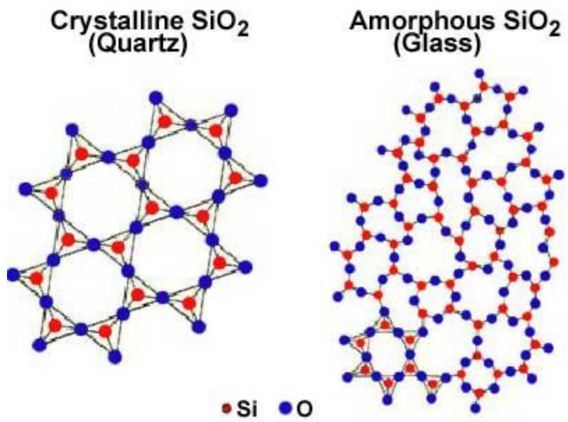

Figure 1. Crystalline and amorphous SiO_2 structure [8].

In its crystalline state, silica possesses a well-ordered structure that, depending on pressure and temperature conditions, can give rise to various crystal forms (e.g. α-quartz, β-quartz, α-tridymite, β-tridymite, α-cristobalite, β-cristobalite, keatite, coesite, stishovite, and moganite). The most common form is α-quartz, which is the thermodynamically stable form of crystalline silica in ambient conditions, and is the most abundant mineral in the Earth's crust [7]. It is a fundamental component of sedimentary, igneous and metamorphic rocks and other artificial materials used in construction and manufacturing [7,9]. In raw materials intended for the ceramic tile industry, quartz can be found within feldspars, clays and kaolins [9,10].

Amorphous silica, unlike crystalline one, lacks a defined three-dimensional periodic arrangement of atoms. Instead, it exhibits a disordered atomic structure, where silicon and oxygen atoms are again arranged into tetrahedra, but these are randomly distributed throughout the material and lacking a long-range order (Figure 1). This results in chemical and physical properties distinct from crystalline silica [7].

Unlike crystalline silica, no evidence has been found to classify amorphous silica as a cause of silicosis [11,12], in fact, IARC has classified this substance as non-carcinogenic [13].

2.2. Respirable crystalline silica

Silica dust can be generated and found in various situations. It can arise during manufacturing and construction processes where materials are cut, ground, or drilled. It can also be found in mining operations, waste treatment or disposal and sand-based product processing [14,15].

Recently, there has been significant focus on crystalline silica because its respirable fraction, when inhaled, could be harmful to human health. According to the European standard EN 481:1993 (Workplace atmospheres - Size fraction definitions for measurement of airborne particles), the respirable fraction has a median diameter equal to 4.25 μm and a maximum size of less than 10 μm. This particle size allows silica to stay suspended in the air for a long time and to reach the pulmonary alveoli, where the O_2 exchange in the blood occurs.

2.3. Analytical Methodologies

Crystalline silica can be measured both within a material and as airborne dust. Although the sampling methods differ, the analytical methodology is similar, using X-ray diffraction (XRD).

To determine crystalline silica within a solid material, a sample is typically ground into a fine powder to ensure homogeneity, then subjected to XRD analysis. This method identifies and quantifies (if a specific technique is used) the various polymorphs of silica, such as quartz, tridymite, and cristobalite, by detecting the unique diffraction patterns of their crystal structures.

The sampling of the airborne respirable fraction is conducted using samplers, which can be worn by personnel or placed at a fixed station. These samplers use cyclone technology to draw air into the instrument, where dust is deposited onto a filter. The cyclone is selective and only samples the respirable fraction. ISO 7708:1995 (Air quality - Particle size fraction definitions for health-related sampling addresses this topic), specifically dealing with air quality and the definitions of particle size fractions for health-related sampling.

Mineralogical analysis of materials is performed using XRD and through appropriate methodologies (such as integrated intensities, the use of an internal standard, or the application of Rietveld refinement), allowing for quantitative analysis. XRD enables the determination of the amount of crystalline silica present in the material in its various polymorphic forms. Furthermore, it facilitates the distinction between the crystalline and amorphous fractions, allowing for precise identification of the fraction that poses potential health risks, if pulverized. There are specific technical standards for the analysis of crystalline silica using XRD. Internationally, ISO 16258-1:2015 (Workplace air - Analysis of respirable crystalline silica by X-ray diffraction - Part 1: Direct-on-filter method) and ISO 16258-2:2015 (Workplace air - Analysis of respirable crystalline silica by X-ray diffraction - Part 2: Method by indirect analysis) provide guidelines for the XRD analysis of respirable crystalline silica. In Italy, the UNI 11768 standard specifically addresses the analysis of free crystalline silica in conveyed gas streams using XRD.

3. PRODUCTS CONTAINING CRYSTALLINE SILICA

3.1. Ceramic tiles

Ceramic tiles represent construction materials that have historically been extensively used for flooring and wall cladding. In recent years, they have also found applications in the fabrication of furniture, kitchen countertops and bathroom countertops.

These products are manufactured from natural raw materials, following a carefully formulated mixture that enables the creation of a finished product with desired properties. The slurry primarily comprises three mineral components: feldspar, which acts as a flux to promote melting at low temperatures; clay, which acts as a plasticizer, making the raw pieces easier to manipulate; and silica sand, which serves as a filler to reduce shrinkage and increase the mechanical strength, improving dimensional stability and rigidity of the final product. Typically, a porcelain stoneware body contains the following fraction of raw materials: 20-45% clay, 40-50% feldspar, and 15-30% quartz [16,17].

In addition to these, kaolin is also used as a raw material and during firing step it undergoes a significant transformation converting into mullite. Mullite is a stable crystalline phase, typical for porcelain stoneware, that gives improved mechanical properties to the ceramic tile.

The raw materials are dosed and milled to ensure homogeneity and to achieve a suitable particle size for subsequent steps. After wet milling, the slurry undergoes atomization within a spray-dryer, producing a powder with approximately 6% water content. This powder is then pressed with a specific dimension in terms of size and thickness and the pressed semi-finished product is then dried. Before sintering, it is decorated, passing through the glazing line where engobe is applied, together with the digital printing decoration and the protective glaze. This stage is extremely variegated, as each company performs decoration differently, even in consideration that products can be glazed or unglazed. The tile is subsequently fired at temperatures around 1200°C, with firing cycles typically lasting between 40 and 90 minutes depending on the product dimension characteristics. After firing, the tile is treated mechanically to straighten the edges and to possibly lapping the surface. This phase is conducted within compartmentalized chambers, and suction systems are installed near the abrasion areas to ensure proper ventilation and avoid powders release.

Table 1. Classification of ceramic tiles according to ISO 13006:2018. Extruded tiles are obtained pushing the mixture through a rectangular die. Pressed tiles are obtained by pressing the atomized powder inside a mold.

Shaping	**Group I** $E_v \leq 3$ %	**Group II$_a$** 3 % $< E_v \leq 6$ %	**Group II$_b$** 6 % $< E_v \leq 10$ %	**Group III** $E_v > 10$ %
A **Extruded**	Group AI$_a$ $E_v \leq 0,5$ % (see Annex M)	Group AII$_{a-1}$[a] (see Annex B)	Group AII$_{b-1}$[a] (see Annex D)	Group AIII (see Annex F)
	Group AI$_b$ 0,5 % $< E_v \leq 3$ % (see Annex A)	Group AII$_{a-2}$[a] (see Annex C)	Group AII$_{b-2}$[a] (see Annex E)	
B **Dry pressed**	Group BI$_a$ $E_v \leq 0,5$ % (see Annex G)	Group BII$_a$ (see Annex J)	Group BII$_b$ (see Annex K)	Group BIII[b] (see Annex L)
	Group BI$_b$ 0,5 % $< E_v \leq 3$ % (see Annex H)			

[a] Groups AII$_a$ and AII$_b$ are divided into two subgroups (Parts 1 and 2) with different product specifications.

[b] Group BIII covers glazed tiles only. There is a low quantity of dry-pressed unglazed tiles produced with water absorption greater than 10 % mass fraction, which is not covered by this product group.

Depending on their water absorption and forming method, ceramic tiles are classified by ISO 13006 into different classes (Table 1).

Italy produces approximately 80% of porcelain stoneware (BIa according to ISO 13006), which has the lowest water absorption. Tiles come in various sizes, ranging from mosaics with dimensions smaller than 7x7 cm^2 to large slabs up to 320x160 cm^2, with thicknesses ranging from 2 to 20 mm. The porcelain stoneware exhibits exceptional mechanical, physical and chemical properties and possess a significant amount of amorphous phase content, ranging between 40% and 75%. This abundant amorphous phase results from the partial melting of the raw materials (mainly feldspar) during the sintering step and within this vitreous matrix, other minerals are dispersed: quartz 10–30%, mullite 4–10%, and unmolten feldspar 0–15% [16,17].

3.2. Artificial stones

Artificial stones, also known as engineered, agglomerated or reconstituted stone and quartz conglomerate, are synthetic stone formed of finely crushed rocks mixed with a polymeric resin.

Quartz-based artificial stones are the most common, usually having crystalline silica content of about 90% [2], however, there are also marble-based ones, which naturally have crystalline silica contents significantly lower than 90%. However, these are softer, more prone to scratching, less resistant to acids, and defect removal is typically achieved through polishing.

Quartz-based artificial stones are widely used for the manufacturing of kitchen and bathroom countertops [2], although, their durability is lower than that of competing ceramic materials, as they are not very heat-resistant and the resin matrix may be subject to ageing. In fact, temperatures above 150 °C can damage the surface and compromise the physical and mechanical properties of the material [18].

3.3. Natural stones

Natural stones have historically been used in the construction sector and have always been used as flooring, cladding, or structural material. The mineral composition of natural stones heavily depends on their genesis and geological history, with quartz and feldspars being the most abundant minerals in the Earth's crust, as together comprising 63 vol% of the total crust [9].

Crystalline silica content within rocks varies depending on the nature of the material. It can be present in low concentrations, such as in marble and limestone, in intermediate concentrations, as seen in slates, shales, and granite rocks, or in very high concentrations, as in sandstones and quartzites. Table 2 displays the crystalline silica content in various natural stones.

Table 2. Crystalline silica content in various natural stones [19].

Stone type	Crystalline silica content [%]
Marble	< 2
Limestone	< 1
Basalt	< 5
Granite	< 30
Slate	< 40
Shale	40 - 60
Sandstone	> 80
Quartzite	> 95

4. EXPOSURE TO CRYSTALLINE SILICA: REGULATIONS AND HEALTH EFFECTS

4.1. An outline of health effects from exposure to crystalline silica

The cytotoxicity of respirable crystalline silica is associated with the reaction between free radicals (Si^- and SiO^-) present on freshly fractured surfaces and water, which generates hydroxyl radicals (OH^-) that cause tissue damage and leads to the silicosis disease. In fact, crystalline silica possesses piezoelectric properties, meaning that under pressure, the crystal acquires an electric polarity, leading to lipid peroxidation of cell membranes [1]. The potential for biological damage is proportional to the concentration of respirable crystalline silica in the air, and coating the surface of crystalline silica particles with other materials reduces the degree of toxicity. Currently, there are no effective treatments for silicosis; however, the issue is entirely preventable through the use of collective and individual protection systems [1], as silicosis is a disease typically linked to occupational exposure.

Moreover, the development of silicosis is associated with cumulative exposure to respirable crystalline silica, which is expressed as a time-weighted average (TWA) over an eight-hour working day. Regulatory limits are generally set based on TWA and are frequently between 0.05 and 0.1 mg/m^3; the risk of silicosis increases significantly with exposures above 0.2 mg/m^3 [1].

Respirable crystalline silica is under investigation by national, European, and international organizations such as IARC and ACGIH to assess its risks and potential carcinogenic effects. The IARC has classified crystalline silica as a

Group I carcinogen; however, its hazardousness varies depending on various physico-chemical factors that influence its interaction with cells and tissues in the human body. The main polymorphs of crystalline silica, such as quartz, tridymite, and cristobalite, exhibit different carcinogenic potentials, with quartz commonly considered the most harmful due to its sharp edges and its ability to generate free radicals after mechanical processes. Surface properties play a crucial role; particles with smooth surfaces tend to be less toxic as they have lower interaction with cell membranes; moreover, a lower cytotoxicity is observed when the hydrophilicity is lower. Additionally, impurities like aluminium and iron can significantly alter the toxicity of crystalline silica, reducing harmful effects through surface adsorption. Surface modifications, such as clay adsorption, can also change the reactivity of crystalline silica and thus its health impact. Particle size and surface area are also critical: smaller particles with a larger surface area tend to be more reactive and potentially more harmful [6].

Cytotoxicity therefore depends largely on the mechanical, thermal, and chemical history of the silica particles, which affects the particle surface and its reactivity [2,6]. Additionally, the age of the fracture impacts its aggressiveness, with older surfaces being less hazardous [6].

It is important to highlight that crystalline silica contained within a solid product is not harmful to health. It only becomes potentially dangerous when the product undergoes mechanical processes such as dry cutting, dry grinding, polishing, etc. [20–22], which cause potential exposure to inhalable dust. However, little information is currently available on the concentration of crystalline silica in work environments and relative to specific tasks [2,20,23,24].

Nonetheless, the use of protective measures and equipment mitigates the health risks associated with these activities [2]. In fact, scientific literature collects several studies on this topic, specifically on artificial stones, that report how the working environments are characterized by a wide use of dry cutting, improper protective measurements, no ventilation, low tools maintenance and no organized health surveillance. The use of protective measures and equipment is very limited and mainly applied inside the workshop; in-situ operations result the worst conditions [2,25–29].

No evidence has been found to classify amorphous silica as a cause of silicosis [11,12]; in fact, IARC has classified this substance as non-carcinogenic [13].

4.2. National, European and international regulatory frameworks

At the European level, Regulation (EC) 1272/2008 (CLP) governs the classification, labelling, and packaging of chemical substances and mixtures. This regulation aligns with the Globally Harmonized System of Classification and Labelling of Chemicals (GHS) and Regulation (EC) 1907/2006 (REACH), which addresses the registration, evaluation, authorization, and restriction of chemicals. The primary objective of the CLP Regulation is to ensure a high level of protection for human health and the environment, as well as to facilitate the free movement of substances and mixtures within the European Union. Annex VI, Part 3 of the CLP Regulation contains a list of hazardous substances with harmonized classification and labelling. However, crystalline silica is not included in this list and, therefore, a harmonized hazard classification is lacking.

In absence of a harmonized classification, suppliers or those responsible for placing a substance on the market, must self-classify and notify their substance or mixture to the European Chemicals Agency (ECHA). This classification must be based on available toxicological data, as well as structural, morphological, and crystallographic knowledge. If such information is not available, the classification should follow the bridging principles outlined in Section 1.1.3 of the CLP Regulation. These details, which are present in the Safety Data Sheet, must be carefully evaluated to determine the most appropriate usage methods.

Within this regulatory framework, the European Directive 2017/2398 updates the Carcinogens and Mutagens Directive (CMD) 2004/37/EC, which aims at protecting workers from risks arising from exposure to carcinogenic, mutagenic or toxic substances produced during occupational activities by establishing minimum requirements to minimise exposure. This amendment did not introduce the chemical substance "Crystalline Silica" into its scope but identified " work involving exposure to respirable crystalline silica dust generated by a work process ". The same Directive also set an occupational exposure limit value of 0.1 mg/m^3, referred to TWA.

Individual European member states have transposed the directives, introducing specific exposure limits, typically ranging between 0.05 and 0.15 mg/m^3. Italy applies a limit value of 0.1 mg/m^3, i.e., the same limit applied by the European Directive 2017/2398.

At the international level, the scenario is broader, and in this landscape, Australia and California set an exposure limit of 0.05 mg/m^3, referred to TWA. As summarized in a document by Confindustria Ceramica [30], the ACGIH identifies quartz and cristobalite as suspected human carcinogens and sets a threshold limit value for respirable dust at 0.025 mg/m^3, referred to the TWA. The Occupational Safety and Health Administration (OSHA) lists respirable crystalline silica among carcinogenic or potentially carcinogenic substances, establishing an action level at 0.025 mg/m^3 and a permissible exposure limit at 0.5 mg/m^3. Finally, the National Institute for Occupational Safety and Health (NIOSH) considers crystalline silica a potential carcinogenic substance and sets an exposure limit at 0.5 mg/m^3. Table 3 provides the permissible exposure limits and threshold limit values according to the EU, ACGIH, OSHA, NIOSH, Australia and California.

Table 3. Permissible exposure limits and threshold limit values set by EU, ACGIH, OSHA, NIOSH, Australia and California, expressed as TWA.

	EU Directive 2017/2398	**ACGIH**	**OSHA**	**NIOSH**	**Australia**	**California**
Permissible exposure limit [mg/m^3]	0.1	-	0.05	0.05	0.05	0.05
Threshold limit value/action level [mg/m^3]	-	0.025	0.025	-	-	0.025

As stated by ACGIH and OSHA, the threshold limit value, set at 0.025 mg/m^3, represents the level below which a worker can be repeatedly exposed throughout his/her working life without adverse health effects.

4.3. Australia: the ban on artificial stone

On December 13, 2023, the Australian Ministry of Health and Safety, representing the Commonwealth, States, and Territories, approved Safe Work

Australia, which bans the use of artificial stone nationwide. These provisions have been implemented starting from July 1, 2024.

The regulation exclusively involves artificial stones, excluding other sintered materials containing crystalline silica such as ceramic tiles, bricks, and roofing tiles from its scope.

Nonetheless, products containing crystalline silica are under the attention of policy makers. Designers, manufacturers, importers, and suppliers must ensure that marketed products have undergone necessary testing to ensure the absence of health and safety risks. Crystalline silica-based products, containing more than 1% of crystalline silica, must therefore be accompanied by a sheet indicating:

- the quantity of crystalline silica in the product;
- hazards and health risks;
- precautions to be taken during manufacturing, installation, maintenance, and removal.

Finally, Australian Ministry of Health and Safety have agreed that Safe Work Australia will complete a review of the prohibition by July 31, 2025, to ensure it is effectively protecting workers from exposure to respirable crystalline silica and to identify and assess any unintended consequences.

4.4. California (USA): temporary standard addressing RSC

Even though California state fixes an exposure limit of 0.05 mg/m^3 based on TWA, it has experienced an increase in the cases of silicosis for workers who operate in the field of engineered stones countertop, i.e., 100 cases since 2019

[31]. This scenario led to the adoption of emergency measures, including the implementation of wet cutting techniques, the use of protective respirators, and the prohibition of dry dust sweeping.

Great attention is given to the use of appropriate preventive measures and respiratory protection devices that shield workers from exposure to respirable crystalline silica dust. In fact, the state of California has declared that if companies fail to reduce cases of silicosis, it will possibly consider a ban on engineered stone.

On December 14, 2023, the Occupational Safety and Health Standards Board officially approved Cal/OSHA's emergency temporary standard (ETS) addressing respirable crystalline silica, which went into effect on December 29, 2023. This newly approved emergency temporary standard introduces significant updates aimed at safeguarding workers involved in high-exposure activities such as cutting, grinding, polishing, and cleanup, when working with artificial material that contain more than 0.1% crystalline silica and natural stone that contains more that 10% crystalline silica.

According to emergency temporary standard, employers must:

- ensure that wet methods are consistently used;
- conduct air monitoring to verify that respirable crystalline silica levels remain below the action level of 0.025 mg/m^3;
- provide workers with full-face, tightly fitting powered air-purifying respirators or an equally effective alternative;

- offer training and information on the ETS in languages and at literacy levels that workers understand.

The ETS also mandates guidelines on housekeeping, exposure assessments, regulated areas, and reporting confirmed cases of silicosis.

4.5. Veneto (Italy): the prevention plan

Regarding artificial stones, the Italian region of Veneto has implemented in 2024 a Prevention Plan (Piano Mirato di Prevenzione, PMP) to assess and mitigate exposure to crystalline silica in the engineered stone sector. Companies producing and utilizing these materials are required to adhere to best practices outlined in the PMP and conduct a self-assessment. This self-assessment aims at identifying the phases with the highest risk of exposure, enabling the implementation of possible corrective actions.

5. CRYSTALLINE SILICA IN THE ITALIAN CERAMIC PROCESS

Due to the international regulatory complexity regarding crystalline silica-containing products and the different exposure limits set by different countries, representative data from the Italian ceramic industry referring to potential exposure to crystalline silica within the production process and during cutting operations are here presented. Finally, the following chapter (Chapter 6) will report instead the mineralogical composition of the Italian ceramic product, representative of the current state of the art.

5.1. Work Environment

Between 2016 and 2019, Confindustria Ceramica (the national ceramic Association) together with Regione Emilia-Romagna, ACIMAC, CGIL, CISL e UIL conducted an analysis on the presence of crystalline silica in proximity to workstations within company boundaries [32]. A total of 585 personal samples were collected across 14 different workstations.

Figure 2 shows the exposure values relative to the different workstations. It can be observed that the average exposure for individual tasks never exceeds 0.038 mg/m3, a value corresponding to the atomization/milling workstation. The lowest exposure values are associated with laboratory tasks, with an average exposure of 0.007 mg/m^3. It is important to highlight that these averages values are below both the regulatory exposure limits mainly adopted (0.05 and 0.1 mg/m^3). For ATM/Milling, Milling, and Glaze Milling phases, the maximum individual values can rarely exceed 0.05 mg/m^3. However, considering the upper reference value, consisting of the sum between the average and the standard deviation, the recorded value remains well below the European limit of 0.1 mg/m^3. Finally, the overall average value for all 585 samples is 0.024 mg/m^3.

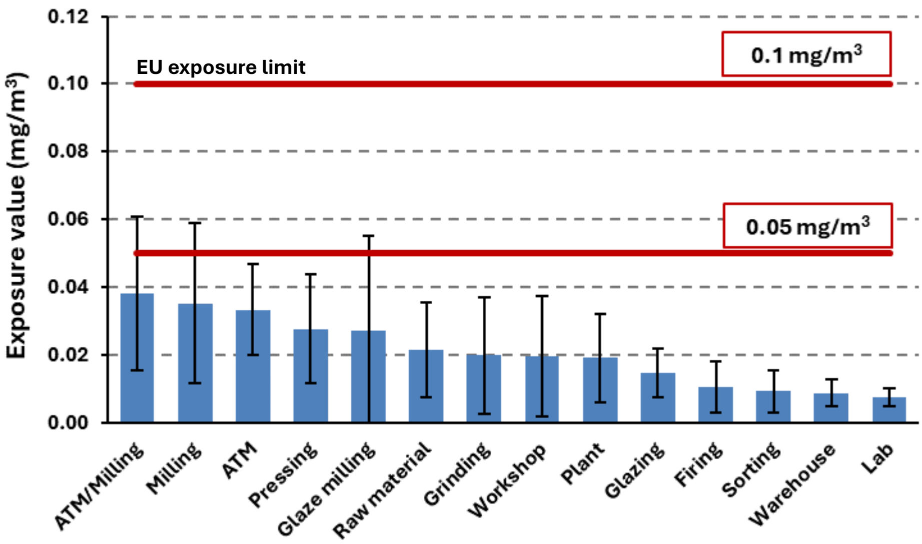

Figure 2. *Exposure values recorded from personal sampling at 14 workstations. The red lines represent the exposure limits of 0.1 and 0.05 mg/m³. ATM = atomisation.*

To better understand the statistical distribution of the data, Figure 3 shows the cumulative and relative frequencies of exposure classes with intervals of 0.002 mg/m^3. The data indicate that 94% of the values are below 0.05 mg/m^3, 5.2% are between 0.05 and 0.1 mg/m3, and only 0.8% exceed the European threshold value of 0.1 mg/m^3. It is also highlighted that 60% of the data is below the 0.025 mg/m^3 value, limit below which there is no health risk even for prolonged periods of exposure.

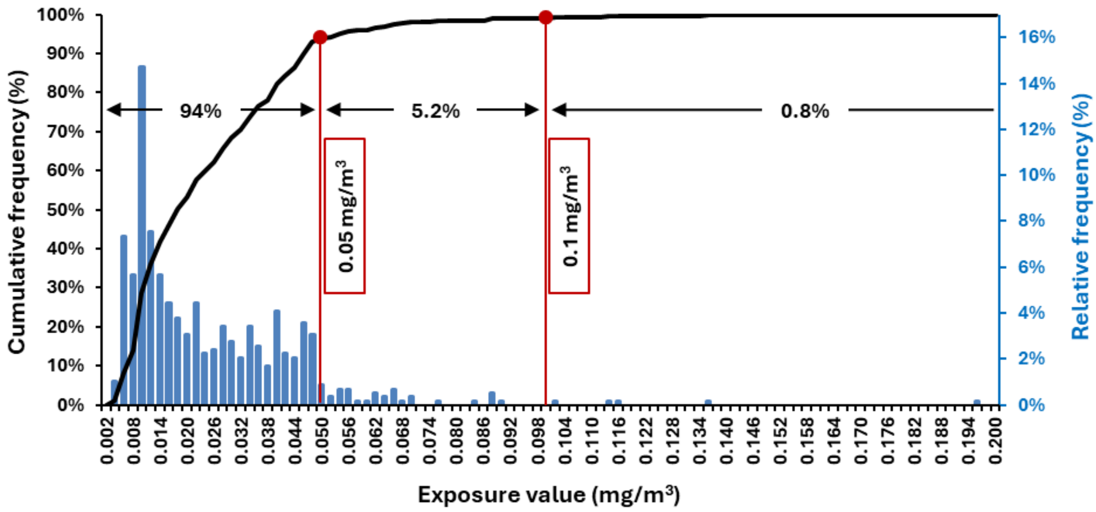

Figure 3. *Exposure values recorded as a function of their cumulative frequency (in black) and relative frequency (in blue). The red lines indicate the exposure limits of 0.1 and 0.05 mg/m³.*

These data highlight that proper ventilation and cleaning of the work environment can successfully prevent exposure to respirable crystalline silica. In fact, Italian companies are committed to the continuous improvement of their production facilities, paying close attention to health-related issues, such as the adoption of an informative technical data sheet accompanying the Italian product that also lists the crystalline silica content among the various characteristics.

5.2. Installation

In 2017, the research centre dedicated to ceramic material, Centro Ceramico (University of Bologna), conducted a comprehensive study on exposure to respirable crystalline silica during the tile cutting phase [33]. The study focused on the most severe condition, specifically dry cutting using a motorized grinder. The study examined four different ceramic products, categorized as BIa and BIIIb, from four distinct manufacturers. Sampling was performed by positioning the vacuum device near the operator's respiratory tract and was conducted under two different conditions: sampling "as is" and sampling using a FFP1 respiratory protection mask.

As stated by Centro Ceramico, sampling was conducted over 30-40 minutes, and the data obtained were subsequently normalized to an 8-hour work shift, considering that cutting activities occupy approximately 10-20% of the shift duration.

Table 4 presents the main results of the study concerning respirable crystalline silica. Ceramic tiles tested contained a quartz content ranging from 20.8% to 26.8%, and the airborne dust generated from their cutting exhibited respirable crystalline silica concentrations between 0.59 and 2.58 mg/m^3. Interestingly, no clear correlation was observed between the quartz content and the respirable crystalline silica production. In fact, the tile with the highest quartz content (26.8%) produced a respirable crystalline silica concentration of 1.38 mg/m^3 during cut. These exposure values should not be considered as-is but require normalization; thus, when extended to a full work shift, the exposure significantly decreases, yielding values between 0.07 and 0.27 mg/m^3. It is important to note that these values are referred to dry cutting without the use of any personal protective equipment (PPE).

When respiratory protection (an FFP1 mask) is used, crystalline silica dust potentially inhalable by the operator decreases from 2.58 mg/m^3 to 0.28 mg/m^3, representing an approximate ninefold reduction in as-is exposure. When this value is normalized over an 8-hour work shift, the exposure level is 0.03 mg/m^3, which is well below the limit established by European regulations. It should also be noted that the test with the protective device was conducted for the measurement with the highest respirable crystalline silica levels. It can be observed that if the test would have been performed on the other samplings as well, the exposure value would have likely been below 0.025 mg/m^3, the action level set by International Health Organizations.

Table 4. Respirable crystalline silica generated from dry cutting of ceramic tiles as a function of PPE usage.

Product classification	Quartz in the tile [%]	RCS dry cutting [mg/m^3]	RCS dry cutting over shift1 [mg/m^3]	RCS dry cutting + FPP1 [mg/m^3]	RCS dry cutting + FPP1 over shift1 [mg/m^3]
BIa	26.8	1.38	0.17	-	-
BIa	21.4	2.58	0.27	0.28	0.03
BIIIb	22.7	0.59	0.07	-	-
BIIIb	20.8	1.67	0.19	-	-

[1] Calculated in relation to a reference period of eight hours (TWA)

The use of an FFP1 mask significantly reduces the potentially respirable fraction of airborne dust. However, there are various other respiratory protective equipment options that might prove even more efficient, such as FFP2, FFP3 masks, or masks with filters designed for specific substances.

Regarding the cutting method, wet cutting is always preferable to dry cutting as it can reduce exposure to respirable crystalline silica by nine times [29]. A study on quartz-based engineered stones measured an exposure of 44 mg/m^3 over a 30-minute sampling period when dry cutting with a hand-operated circular saw. This value was reduced by approximately nine times (to 4.9 mg/m^3) when the same material was cut wet and further reduced by eight times when local exhaust ventilation was also used [29]. Applying these reduction values to the previously mentioned ceramic products, the results are shown in Table 5. For ceramic tiles, the limit of 0.05 mg/m^3 proposed by some countries is met using wet cutting alone. Combining wet cutting with PPE devices could lead to dramatically low exposure levels, below 0.003 mg/m^3 over an 8-hour work shift, which is 85 times lower than the value obtained from dry cutting.

Table 5. Estimated respirable crystalline silica generated based on the type of cutting (dry or wet) and the use of PPE.

Product classification	Quartz in the tile [%]	RCS dry cutting [mg/m^3]	RCS dry cutting over shift[1] [mg/m^3]	Estimated RCS wet cutting per shift[1 2] [mg/m^3]	Estimated RCS wet cutting + PPE over shift[1 2] [mg/m^3]
BIa	26.8	1.38	0.17	0.02	0.002
BIa	21.4	2.58	0.27	0.03	0.003
BIIIb	22.7	0.59	0.07	0.01	0.001
BIIIb	20.8	1.67	0.19	0.02	0.002

[1] Calculated in relation to a reference period of eight hours (TWA)
[2] Estimated according to scientific literature data [29]

Comparing the values of respirable crystalline silica generated from the dry cutting of engineered stone and ceramic tiles, it is observed that ceramic tiles produce significantly less dust than engineered stones, approximately 17 to 75 times less [29].

Finally, although these results are derived from empirical tests and are not based on ISO or CEN technical standards, they still provide a good representation of the exposure levels to which ceramic tile installers are potentially subjected. Future studies can certainly investigate this context by basing sampling on standardised methods developed by international and European technical committees.

6. DETERMINATION OF CRYSTALLINE SILICA IN THE CERAMIC TILE

6.1. Data collection

In 2024, Confindustria Ceramica, the Italian ceramic association, collected data on the mineralogical composition of ceramic tiles produced by some of its member companies. These data reflect the current state of the art, considering the restructuring of the raw material supply chain, which, until 2021, accounted 80-90% of clay and kaolin coming from Ukraine. Currently, as a result of the war conflict, raw materials from Ukraine have been almost entirely replaced by those from other countries.

The data were collected through a voluntary questionnaire that, for each substrate produced, have requested the mineralogical composition, the analytical technique, the analytical instrument, the quantitative determination technique, and the formats and thicknesses produced by pressing (excluding those obtained by splitting or cutting).

The mineralogical analysis was conducted solely on the substrate, thus excluding the potential influence of the glaze and surface decoration. This approach was chosen because the substrate is representative of the entire tile. In fact, 80% of the substrates receive 0.10-0.22 kg/m^2 (dry weight) application of glaze containing 10-20% frit, 20% receive 0.10-0.60 kg/m^2 (dry weight) application of granules (100% frit), and 70% receive 0.15-0.25 kg/m^2 (dry weight) application of engobe (0-5% frit). These application quantities are very modest compared to the mass of the substrate, which weighs approximately 21 kg/m^2 for a thickness of 10 mm. Additionally, the intrinsic error in compositional determination via quantitative XRD (Rietveld internal standard refinement method) could be greater than the contribution of individual minerals constituting the glaze.

6.2. Data processing

The mineralogical analyses were conducted mainly by certified external laboratories using XRD analysis, and in most cases, an internal standard was used, processing the XRD spectra with a Rietveld refinement. The compositional data were collected from 11 companies, which produce a total of 23 different substrates (Table 6). Based on the formats and thicknesses, a database was created, resulting in 257 distinct data points.

Table 6. Information regarding the samples collected.

Companies	Substrates	Laboratories	Quantitative XRD methods used
11	23	5	2 (mainly Rietveld Refinement)

Statistical analyses regarding the crystalline silica content in the finished product were calculated based on the individual substrates to avoid biases related to the number of formats and thicknesses. This latter information were instead used to understand potential correlations between thickness or surface area and the amount of crystalline silica contained in the tile.

6.3. Results

Table 7 presents the quartz content within the 23 sampled supports. The quartz content averages 23±5%, with a maximum value of 30% and a minimum value of 8.3%. The 8.3% value is notably low compared to the overall data distribution, which ranges from 16% to 30%, and is representative of only one sampled support, and is probably associated to a specific technological necessity.

Table 7. Average, maximum and minimum quartz content within sampled ceramic tiles product.

	Quartz [%]	**Amorphous phase [%]**
Average content	23 ± 5	63 ± 6
Maximum content	30	70.3
Minimum content	8.3	54

A quartz content of 23% is significantly lower than that found in engineered stones (approximately 90%), and also lower than the one in many natural stones such as sandstones, granites, and quartzites. Consequently, any cutting of ceramic tiles would result in a lower airborne dispersion of respirable crystalline silica compared to quartz-based engineered stone, as highlighted in the previous chapter.

Moreover, the cytotoxicity of the respirable crystalline silica originate from ceramic tiles is mitigated by the presence of a substantial amount of amorphous phase that encapsulates the mineral phases (with a 73:27 ratio of amorphous to quartz) [6]. This results in respirable dust that is not entirely composed of crystalline silica. Additionally, the presence of aluminium, originally included in the aluminosilicates constituting the raw materials (clays, kaolins, and feldspars), further reduces the risk. This is however an empirical conclusion and should be validated with scanning electron microscopy (SEM) analysis to observe the composition and morphology of individual particles at the microscopic scale.

Observing the relationship between the mineralogical phase content and the thickness of the sampled products, it can be noticed that an increase in thickness is accompanied by a slight increase in quartz content. Specifically, the quartz content averages 21% for products with a thickness of 2-3 mm and rises to an average of 24% for products with a thickness of 20-21 mm (Figure 4). This behaviour is linked to greater sintering heterogeneity in thicker products, where the core of the ceramic body reaches a lower temperature during firing (due to thermal inertia and the fast-firing cycles of the kilns). As a result, quartz, despite being an inert phase, undergoes less fusion. Additionally, a slight increase in the amorphous phase is also observed with greater thickness. These variations are, however, within the range of one sigma so they are not statistically validated.

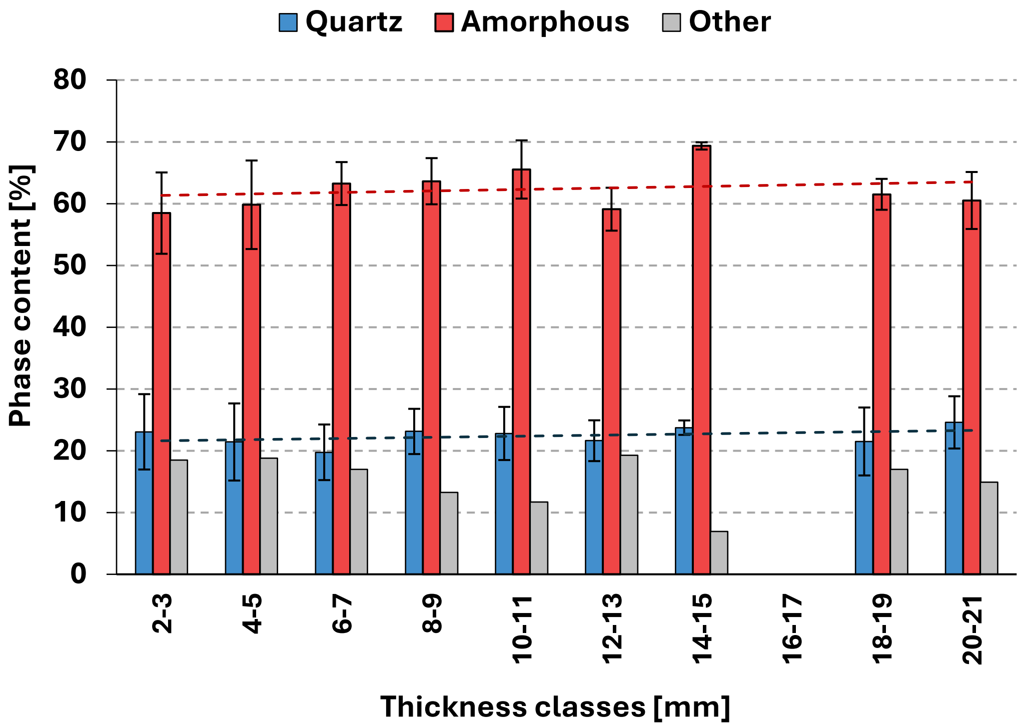

Figure 4. Quartz, amorphous, and other minerals content within the sampled ceramic tiles, related to the thickness of the products.

Figure 5 shows the content of various phases as a function of the ceramic tile surface area. The quartz content slightly decreases as the tile size increases, reaching an average of 21% when the surface area is higher than 40,000 cm^2.

Similarly, the amorphous phase also decreases with increasing surface area, from approximately 64% for smaller sizes to around 58% for larger sizes. Finally, the content of the other mineralogical phases (mullite, unmolten feldspar, etc.) increases as the surface area increases.

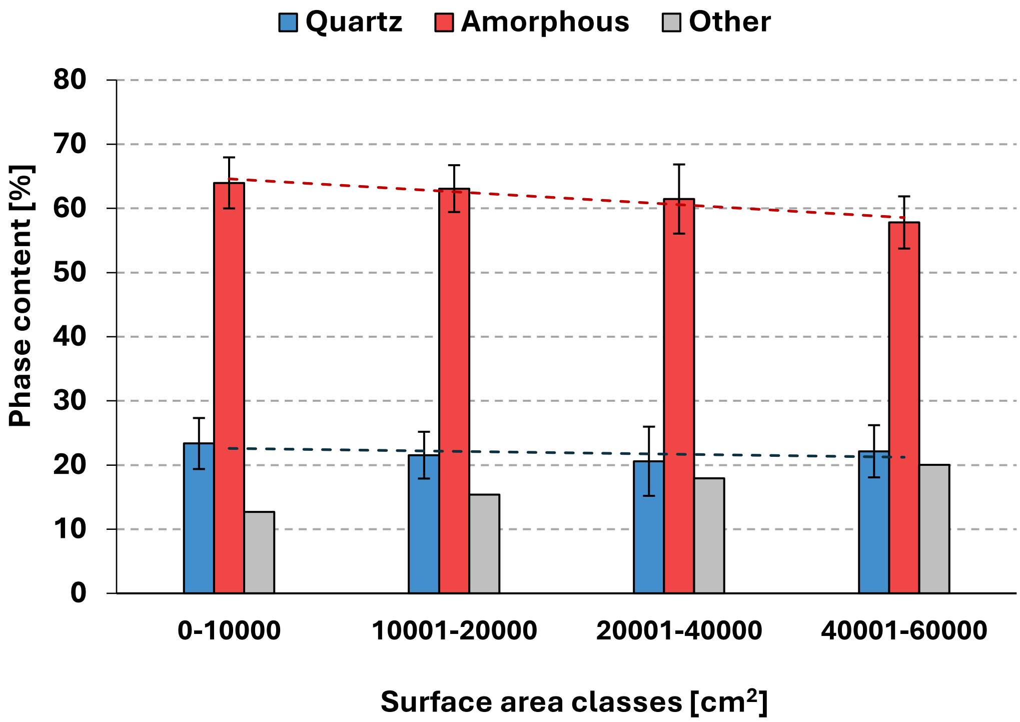

Figure 5. Quartz, amorphous, and other minerals content within the sampled ceramic tiles, related to the surface areas of the products.

It is important to highlight that these graphs do not independently analyse the variation of the single dimensions (thickness or surface area), e.g., the variation of quartz as a function of thickness is not performed while keeping the surface area fixed. This is related to the wide variety of data available and the impossibility to fix a representative thickness or surface area. Although enough data have been collected to define the silica content in the finished product, more data could better highlight the correlation between quartz content and dimensional properties.

7. CONCLUSIONS

Although there is debate about the carcinogenicity of crystalline silica and the correlation with the development of silicosis and cancer, to ensure the health and safety of workers, international, European and national legislations are paying increasing attention to both products containing silica and the factories where such products are produced.

In this context, Confindustria Ceramica pays much attention to sustainability issues (health, safety and environment), promoting transparent studies that inform all stakeholders about the characteristics of Italian products. In 2024, a study conducted on Italian ceramic tiles showed an average quartz content of 23±5%, slightly dependent on the thickness and the surface area of the tile. The distribution spread between 16 and 30% with an outline of 8.3%, probably associated to a specific technological necessity. The predominant phase within the ceramic tiles is the amorphous phase, with a content of 63±6%, which has been classified by the IARC as non-cancerous. These quartz contents are well below engineered stones that contain up to 90% of this phase and below some natural stones such as granites, sandstone, shales, slates, quartzites.

In addition, Confindustria Ceramica together with Regione Emilia-Romagna, ACIMAC, CGIL, CISL e UIL conducted a study regarding to dispersed crystalline silica in the workplace. From this study emerges that during the production of Italian ceramic tiles, much attention is paid to the proper cleaning and suction of the dust generated. In fact, from 585 personal samplings, performed at different workstations, an average exposure of 0.024 mg/m^3 was found, a value that is below the action limit identified by International Health Organisations. Moreover, 60% of the measurements are below 0.025 mg/m^3, 94% are below 0.05 mg/m^3, and 99.2% are below 0.1 mg/m^3.

Finally, a 2017 study conducted by Centro Ceramico (University of Bologna) investigating the dry cutting of ceramic tiles found that using a basic FFP1 mask reduces exposure to respirable crystalline silica by a factor of 9, achieving an exposure level during the dry cut of 0.03 mg/m^3. Comparing values obtained from ceramic tile with those from dry cutting the engineered stone, exposure values to respirable crystalline silica are observed to be 17 to 75 times lower. Additionally, wet cutting of ceramic tiles would result in an airborne respirable crystalline silica concentration 9 times lower than dry cutting. With the combined use of wet cutting and an FFP1 mask, exposure levels are estimated to range between 0.001 and 0.003 mg/m^3, values that are definitely below the threshold limit and the action level defined by ACGIH and OSHA.

Despite the generation of dust containing crystalline silica when the ceramic tile is subjected to cutting, the hazard of airborne dust should be reduced by the fact that the quartz is immersed in a glassy matrix and the generated micronized particles may consist mainly of other phases; in addition, the presence of aluminium, as reported in the scientific literature also lowers the health hazard.

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