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Review

Silica Dust as an Additive in Concrete with Proven Impact on Human Health

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Abstract

Concrete is an extremely important factor for shaping today's infrastructure. However, it must be replaced or repaired over time. The various methods used to remove, repair or change existing concrete structures into new ones can globally release large amounts of dust into the air. Taking into account the fact that the crystalline silica in the form of quartz is the main component of silica fume added to concrete, dust in the air produced during construction, maintenance or renovation works may have properties that will increase not only the risk of morbidity of workers (e.g., silicosis), but also the risk of excessive contamination – by crystalline silica – of air and soils around areas where such work is carried out. This paper presents the properties of silica, which determine its presence and interactions in the environment. It has been shown that so far, the health exposure to silica was studied mainly in groups of miners. Most likely, the widespread use of silica in the construction industry and, above all, in the construction and renovation of the dynamically developing network of roads and motorways results in an increase in the amount of silica in fine particles of particulate matter. Therefore, it seems important to undertake new research to determine the amount of silica in the environment (mainly in fine particulate matter) in various areas and to link these data with industrial and construction activity in these areas.

Keywords: fine particles, crystalline silica exposure, road dust, elemental composition, road construction, road surface or pavement

Introduction

The negative effect of the industrialization of the economy is undoubtedly the increase in the production of industrial waste. The safe utilization of this waste is a major problem, both due to restrictions on storage locations and strict environmental standards related to the quantity and quality of generated waste. The growing demand for raw materials for the production of building materials led to the development of research on the possibility of using some industrial waste in the cement industry, e.g., blast furnace slag, fly ash and silica dust [1-2]. Due to increased environmental awareness and the potentially dangerous effects of industrial by-product storage, adding silica dust to concrete has become an attractive alternative to its storage [3-4].

Over the past two decades, silica fumes have gained acceptance as a pozzolan mineral admixture in concrete [5]. In the 1950s in northern European countries the first studies on the use of silica dust in concrete were

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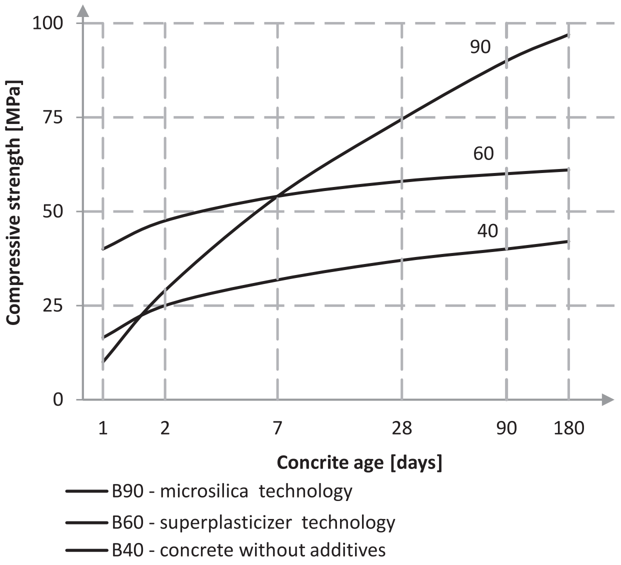

Fig. 1. Variation in time of concrete compressive strength for various concrete technologies (based on [9]).

carried out and they consisted of adding this material or by partially replacing Portland cement [6-7]. It was found that the compressive strength of concrete samples consisting of Portland cement with the addition of silica dust is significantly higher than the strength of samples without the addition of such dusts [8-10] (Fig. 1).

The proportion of microsilica in the concrete is determined individually, depending on what physical properties are critical (e.g., increased compression, bending and stretching strength) and what element will be made of it (e.g., bridges, tunnels, motorways, runways). The amount of binder (cement + k × additive) should not be less than the minimum cement content required due to the appropriate exposure class [11] (Table 1).

The concept of coefficient k is a recommended concept. It is based on a comparison of durability (or strength as a substitute for durability) of the reference concrete with cement "A" and concrete in which part of cement "A" has been replaced with an additive, taking into account the water/cement coefficient and additive content. In the case of type II additives, the PN-EN 13263-1: 2010 standard introduces the concept of coefficient k, which allows us to include additives in the composition of concretes by replacing the term "coefficient water/cement" with the term "coefficient water/(cement + k × additive)" [11, 13].

Due to its high silica content and very fine particle size, silica dust is a highly effective pozzolan. Amorphous silica reacts very rapidly with calcium hydroxide released in the hydration of silicates contained in Portland cement (so-called pozzolanic reaction), creating a homogeneous, durable product that acts as a binder in concrete. A compact and impermeable gel of hydrated calcium silicates (so-called C-S-H phase) is formed. The very fine grains of silica fill the spaces between the cement grains in the leaven/concrete and then the structure is sealed (concentrated). The matrix of hydration products closely adhering to the remains of unhydrated cement grains and showing negligible porosity is characterized by a rapid build-up of strength [14-15].

The obtained cement-silica mixture produces a bond matrix that has a dense microscopic pore structure, low permeability and is more resistant to degradation caused by acid rain, seawater, deicing salts of roads and pavements, and cycles of freezing and thawing [16]. Abrasion resistance is an important long-term requirement for all concrete surfaces exposed to pedestrian and vehicle traffic, or wind and water in hydraulic construction [5]. The abrasion of the surface layer has the components of materials and their proportions, design, performance, hardening and degree of exposure to devastating/unfavorable conditions [17].

In recent years, due to the development of high-performance concrete technology with a low water/binder coefficient (water/(cement + k × additive), as well as the emergence of a new generation of chemical admixtures, the ability to control the properties of a concrete mixture containing silica dust with the help of suitable superplasticizers have significantly expanded

Table 1. Rules for the use of silica dust in accordance with PN-EN 206:2014 [12].

Silica dust of class 1 $^{1)}$ according to PN-EN 13263-1:2010	
The maximum content of the additive in concrete $^{2)}$	Silica dust/cement ≤0.11
Value k $^{3)}$	For cement CEM I i CEM II/A: k $^{3)}$=2.0 for w/c ≤,45 k $^{3)}$=2.0 for w/c > 0,45 with the exception of exposure classes XC and XF, for which k = 1.0
The minimum cement content	min. cement content should not be reduced by more than 30 kg/m^3

1) In the case of class 2 silica dust, shall be applied the provisions in force at the place of concrete using.

2) In the case of a higher content of the additive in concrete, this excess should not be taken into account when calculating the coefficient w/(c + k x d).

3) With the exception of cements with addition of silica dust.

w – water
c – cement
XC – corrosion due to carbonisation
XF – aggressive impact of freezing / thawing (exposure class according to standard EN 206-1)

[18-19]. Technology of high value concretes determines the material with high mechanical strength ($R_c \geq 60$ MPa) and high durability. Microsilica is also a component of unconventional structural concretes with special mechanical properties. There is, e.g., concrete made with the addition of powders with high chemical reactivity in the leaven environment or fibre-reinforced concrete. These materials must contain a very finely dispersed component in order to seal the microstructure, and this property is characterized by microsilica [20-22].

Silica Dust

Silica dust is a very finely divided amorphous silicon oxide [16]. European Standard PN-EN 206:2014 defines a concrete additive as a finely divided material used to improve properties or achieve special properties, and distinguishes two types of additives:

- Type I – almost inert additives: fillers and pigments.
- Type II – pozzolanic or with poor hydraulic performance.

Only additives with a fixed suitability should be used for concrete. It is assumed as type II additives, fly ash, silica dust and ground granulated blast furnace slag [12]. Table 2 summarizes the chemical composition as well as physical and standard requirements for silica dust.

In the literature we can find different names for this material: silica fumes, silica dust, microsilica, condensed silica fume or silica powder [23]. The most suitable term is condensed silica dust. It is a byproduct in metallurgical processes and more specifically from the production of silicon metal and ferro-silicon alloys [10, 24]. Particles of partially reduced quartz evaporate as SiO and are oxidized to SiO_2 as a result of contact with oxygen in the cooler part of the furnace. There is formed an amorphous form of silicon, whose formation can be described by the following reactions [9]:

$$SiO_2 + C \rightarrow SiO + CO \quad (1)$$

$$2SiO \rightarrow Si + SiO_2 \quad (2)$$

$$3SiO + CO \rightarrow SiC + 2SiO_2 \quad (3)$$

Table 2. Requirements for the properties of silica dust (PN-EN-13263-1:2010) [10-11].

Property	Requirements	
SiO_2	cat. 1 ≥ 85.0%	cat. 2 ≥ 80.0%
Elemental silicon	≤0.4%	
Free CaO	≤1.0%	
Sulfur as SO_3	≤2.0%	
Total content of alcalis based on Na_2O	declared value	
Chlorides	≤0.3%	
Loss on ignition	≤4.0%	
Surface area	35.0 $m^2/g > x > 15.0$ m^2/g^{-1}	
Component content in suspension	± 2% the value declared by producer	
Activity index	100% up to 28 days	

During the production process at the exhaust of the flue-gases there are mounted filters catching solid particles, and with them also condensing pairs of silica. They have a high content of silicon dioxide SiO_2 (85-97%) and consist of very fine spherical, glassy particles with a specific surface area of about 20 000 m^2/kg [3, 16].

The amount of SiO_2 in dust increases proportionally with the increase of silicon in alloy and, e.g., for ferro-silicon alloy containing 50% or 75% of silicon – we have respectively 61÷77%, or 84÷88% silica in dusts, and for silicon metal up to 98% of silica in dust [9].

Silica dust is produced in many countries, including Canada, Egypt and Norway. In Poland, silica dust is produced only at Łaziska steelworks (85-95% SiO_2) as a by-product in the production of ferro-silicon. In the production of each ton of ferro-silicon alloy, about 300 kg of dust are produced simultaneously. The chemical composition of silica dust varies depending on the type of alloy or metal from which it was made [10, 25]. Table 3 summarizes the chemical composition of silica fume from silicon furnaces in Norway, Canada and Poland.

The basic forms of the available microsilica, which are adapted for transportation, storage and dosing to concrete:

a) Dry silica dust of an aerial colloid nature in which the silica particles are the dispersed phase and the air-dissipating phase; the electrostatic phenomena ensure the balance.
b) Dry silica dust – concentrated; character: as above with the difference that part of the disperse phase was removed by venting and pressing.
c) Aqueous suspension of silica (with or without additives) – similar to a solid phase colloidal suspension of silica particles and microparticles and a dispersion phase – water with optionally dissolved additives.

There are also other forms of microsilica that are not used in construction: silica granules, silica sludge and agglomerated silica dust [9].

Silica may be white or dark and when mixed with water gives a suspension that is black. The color of silica dust depends on the carbon content, the higher content, so the darker the color of the material [26]. The specific surface area of silica dust is usually measured by the method BET[1] and is within the limits of 13000 do 20000 m^2/kg; average grain sizes are on the level

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[1] The Brunauer-Emmett-Teller multi-layer adsorption isotherm (BET) describes a model in which a hypothetical but countable monomolecular layer of adsorbed gas is distinguished [27].

Table 3. Chemical composition of silica fumes from silicon ovens in Norway, North America and Poland [9, 25].

Constituent, [%]	Norway[1)]	North America[2)]	Poland[3)]
SiO_2	90.0-96.0	93.7	86.93-97.60
Al_2O_3	0.5-3.0	0.3	0.55-3.61
Fe_2O_3	0.2-0.8	0.8	0.17-2.03
MgO	0.5-1.5	0.2	0.02-1.22
CaO	0.1-0.5	0.2	Traces – 0.89
Na_2O	0.2-0.7	0.2	0.11-0.37
K_2O	0.4-1.0	0.5	0.31-1.49

[1)] From brochure Elkem Silica, Elkem - Spigerverket A/S, Norway
[2)] From a plant in Eastern Canada
[3)] Łaziska steelworks.

0,02-0,45 μm, (on average, cement grains are 100 times larger) [26, 28]. The density of typical silica dust is low at about 2.2 g/cm^3; for comparison, the density of Portland cement is about 3.1g/cm^3. Unconcentrated dust unit mass is from 250 to 300 kg/m^3, while for cement this value is about 1200 kg/m^3 [9].

Silica dust was classified by The American Concrete Institute (ACI) as part of such cementitious materials as pozzolan [29]. ASTM C 618[2] recognizes three classes of pozzolan: N, F and C.

- Class N: Raw or calcined natural pozzolans that comply with the applicable requirements for the class as given herein, such as some diatomaceous earths; opaline cherts and shales; tuffs and volcanic ashes or pumicites, calcined or uncalcined; and various materials requiring calcination to induce satisfactory properties, such as some clays and shales.
- Class F: Fly ash normally produced from burning anthracite or bituminous coal that meets the applicable requirements for this class as given herein; this class of fly ash has pozzolanic properties.
- Class C: Fly ash normally produced from lignite or subbituminous coal that meets the applicable requirements for this class as given herein; this class of fly ash, in addition to having pozzolanic properties, also has some cementitious properties [30].

Silica dust is the closest to the N class. However, there are no detailed guidelines to allow unambiguous inclusion of silica dust in a given class [31].

Research of Concretes with Silica

Even small amounts of silica dust added to concrete mix improve its properties compared to concrete without additives [10, 32] (Fig. 2).

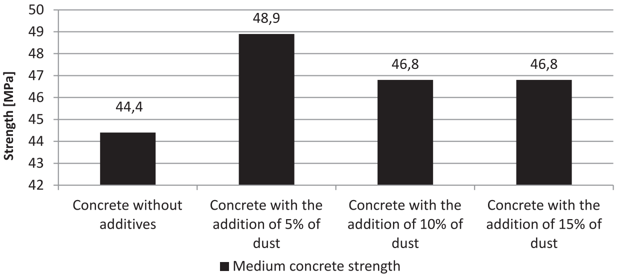

Fig. 2. Average of compressive strength concrete after 28 days (based on [10]).

The introduction of silica dust changes the physical properties of the fresh concrete mix, which has a significant impact on the way it is laid and compacted. With a low content of silica dust (less than 3% of the binder mass), liquefaction of the concrete mix is sometimes observed. It is connected with the fact that very small dust particles occupy the place of water displacing its apparent excess from between the cement grains. However, in general, the introduction of microsilica is accompanied by a completely opposite effect – the very large developed surface of the additive is the reason that it adsorbs water and the concrete mix with its content is faster gelling and it cannot be used without liquefying agents. Very small particles of this additive affect the cohesiveness and decrease the plasticity of the concrete mix, which results in increased water demand, but on the other hand it prevents the segregation of ingredients, especially the release of water [9, 33].

The addition of silica dust in the cement increases the density of the material (high SiO_2 content) and enhances the pozzolanic action in the concrete. However, significant dust fragmentation hinders the physical use of silica dust, among others, hindering the workability of the mixture. This was confirmed by the studies carried out using Portland cement containing from 10 to 30% of weight silica dust. It was found that the plasticity of mortars decreases with the increase in the amount of dust. Their addition of 10% results in a reduction of the plasticity by about 10% compared to the control mortar without addition. With the addition of 20%, the plasticity of the mortar is reduced by approximately 30%, while 30% of the dust reduces the plasticity by nearly 40% [9]. When using silica dust in concrete to improve the dispersion of this additive, plasticizers or superplasticizers are used [33-35].

According to the results of some studies, silica dust added to concrete has an impact on improving its mechanical properties and increasing resistance to freezing and thawing, vibration damping, tightness, abrasion resistance, corrosion of steel reinforcing bars and binder strength with steel reinforcing bars. Silica dust as an additive to concrete also reduces its alkali-silica reactivity, creep and shrinkage of concrete, permeability and thermal expansion [5, 22, 36-37]. Due

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[2] Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete [30].

to the increased resistance to abrasion of concrete with the addition of silica dust in relation to concrete without this additive, it is used in the construction of runways, structural elements of bridges and viaducts, as well as the surface of roads, bridges and parking lots. One of the most important features that concrete acquires thanks to silica dust is its resistance to the destructive effect of de-icing salts [38-39]. Typical concrete mixes contain added dust in the amount of 7.5-10%, which clearly improves the usable durability of the concrete, preventing its destruction. Silica dust affects the structure of the pores by reducing the capillary pores

Table 4. Occupational guidance values for quartz/crystalline silica [71].

Organization*	Chemical(s)	Name	Year	Guidance Value	Target Population
Mine Safety and Health Administration (MSHA)	Crystalline Silica, quartz	Permissible exposure limit (PEL)	2001	10mg/m^3 (%SiO$_2$+2) (respirable dust containing crystalline silica) 10 mg/m^3 (total dust)	Miners
Occupational Safety and Health Administration (OSHA)	Silica, Crystalline Quartz	PEL – current	1978	250 mppcf** %SiO$_2$+5 (TWA, respirable dust) 10 mg/m^3 %SiO$_2$+2 (TWA, respirable dust) 30 mg/m^3 %SiO$_2$+2 (TWA, total dust)	General Industry (also same for construction and shipyard employment)
Occupational Safety and Health Administration (OSHA)	Silica, Crystalline Quartz	PEL – proposed	2014	50 µg/m^3 (TWA, respirable)	General industry/ maritime; construction
National Institute for Occupational Safety and Health (NIOSH)	Crystalline Silica	Recommended Exposure Limit (REL)	1974, 2002 (update)	0.05 mg/m^3 (TWA, respirable dust) Cancer – Ca	General workers
American Conference of Governmental Industrial Hygienists (ACGIH)	Silica, Crystalline Quartz	Threshold Limit value (TLV)	2010	0.025 mg/m^3 (respirable aerosol fraction) Cancer – A2	General workers
California OSHA	Silica crystalline, quartz	PEL	2008	0.1 mg/m^3 (TWA, respirable dust) 0.3 mg/m^3 (TWA, total dust)	General workers
Scientific Committee on Occupational Exposure Limits (SCOEL)	Silica crystaline (Quartz)	Occupational Exposure Limit (OEL)	2003	<0.05 mg/m^3 (respirable dust)	General workers
Germany Deutsche Forschungsgemeinschaft (DFG)	Crystalline quartz	Maximale arbeitsplatzkonzentration (MAK): maximum workplace concentration	2000	Cancer Notation: 1	General workers
Safe Work Australia	Crystalline quartz	National Exposure Standard	2005	0.1 mg/m^3	General workers
Canada - Ontario	Silica, fused			0.1 mg/m^3 (respirable dust)	
New Zealand	Silica, fused			0.2 mg/m^3 (respirable dust)	
Switzerland	Silica, fused, respirable dust			0.3 mg/m^3 (respirable aerosol)	

TWA – 8 h, 40 h week weighted average concentration, which cannot be exceeded during an 8-hour work shift and 40-hour work week.

* Many individual countries (not listed here) also have published occupational exposure limits for silica, but they are duplicates of the values already listed in the table.

** Millions of particles per cubic foot of air (mppcf), based on impinger samples counted by light-field techniques. Conversion factors – 10 mppcf = 0.1 mg/m^3; mppcf x 35.3 = million particles per cubic meter = particles per c.c.

and by creating new structures of hydrated calcium silicates type C-S-H. This results in increased density of the cement stone matrix, manifesting itself, for example, in the reduction of water permeability of concrete as well as concrete permeability for other liquids and gases, which increase concrete resistance to corrosive agents [9, 40].

Many laboratory tests were carried out on concrete used for years in various environments. Finally, it was found that the test methods are effective in assessing the relative quality of the material and are not intended to measure the expected life of a particular surface. There is not one abrasion test that fits perfectly on all surfaces, but you can distinguish some that are more suitable for specific applications. Most testing methods, as described in the literature, use the technique of measuring wear depth at various exposure times as direct measures of abrasion resistant surface. There is also the technique of weighing samples at regular intervals [5, 39, 41].

ASTM short-term abrasion tests were normalized, including: sanding (ASTM C 418), rotary knife (ASTM C 994), revolving-disk machine (ASTM C 779, procedure A), dressing-wheel machine (ASTM C 779, procedure B) and ball bearing machine (ASTM C 779, procedure C). However, there is little available published data on the tests of concrete with silica wear, and almost all of the tests described have been based on silica dust technology replacing part of Portland cement [5].

Some of the more interesting results are described in the work of Linch [42]. It was found that during drilling in concrete road pavement concentrations of quartz particles in the air were in the range of 4,4 mg/m3 for a 358-minute sample, which gives an eight-hour weighted average of 3,3 mg/m$^{3.}$. However, during the milling of asphalt samples taken from concrete surface, there was a quartz concentration in the range of up to 0,34 mg/m^3 for a 504-minute sample, and as a result of an eight-hour weighted average was 0,36mg/m^3 [42]. It draws attention to the fact that global amounts of silica are likely to be released into the air during the wear of concrete surfaces with the addition of silica dust. However, so far no probable amounts have been estimated or measured that may be subject to these releases.

Effect of Silica Dust on Human Health

There is epidemiological and toxicological evidence for a clear relationship between the number (PNC) or mass concentration (PMC) of particulate matter (PM), in particular their ultrafine fraction (<100 μm) and human health [43-44]. It is very important for particle size that the finer the particles, the deeper they enter the respiratory system, increasing the risk of lung and cardiovascular diseases [45]. There are many PM particle sources in the urban environment. For the smallest particles (nano- and ultrafine particles), their number in the air volume (PNC) is usually determined, whereas for the PM10, PM2.5 or PM1 fraction (i.e., with the aerodynamic diameter ≤10, ≤2.5, ≤1 μm respectively) mass concentrations (PMC) are determined [46]. Emissions from vehicle engines are defined as a significant source of the finest particles [47-48], while road dust associated with abrasion of car body elements and resuspension of street dust/soil is the main source of thicker particles [49-50].

Many construction activities related to the creation and management of urban infrastructure are also the source of particles, especially those which belong to the PM10 fraction [51-52]. For example, Fuller and Green [53] showed that emission of PM10 during road works gives a trigger to concentrations exceeding the value established in the European Union as an acceptable daily concentration of PM10 (50 μg/m^3). There are also scientific reports suggesting that abrasion of road surfaces is the source of ultrafine particles [48, 54-55]. There is significantly less research devoted to concentrations and particle size distributions during the production, processing and use of various types of technical materials [44, 56]. There are several studies on PM emissions from drilling and cutting materials such as carbon nanofibers [57], as well as composite and silicon nanocomposites [58], construction demolitions [59-60], concrete recycling [46] and other construction and road works [53, 61]. The significance of particulate emissions from building sources is likely to increase as it is expected that the development of urban infrastructure around the world will reflect the increase in the world's population [62].

In general, it can be briefly summarized that many PM studies were carried out in urban areas, but few of them focused on PM in construction works [34, 63], or PM from road surfaces abrasion [64]; the minimum amount of data in this range can be found for the smallest PM particles below 100 μm [48].

Currently, there are no legal provisions or guidelines for controlling human exposure to ultrafine particles in the urban environment, including their impact on construction sites or areas adjoining busy roads [46, 65-66]. Meanwhile, construction activities, such as mixing, drilling and cutting concrete, as well as concrete abrasion (e.g., of concrete road surface by moving vehicles) have the potential to generate PM particles from any size range [67-68].

It was proved that professional exposure to dust containing crystalline silica occurs in mining industries, metal foundries, construction, manufacture of glass, ceramics, concrete and granite and stonework industries [69]. Production of concrete products such as brick, tile and sewer drains, as well as some materials for the production or repair of road surfaces, require the use of silica, sand and cement. Quartz, tridymite and cristobalite are the three important crystalline forms of crystalline silica, for which the values of permissible concentrations in the working environment were determined [70-72].

A thorough search was conducted to identify all existing occupational exposure guidance values applicable to crystalline silica/quartz. These values are

Table 5. Occurrence of silicosis in exposed to respirable crystalline silica (RCS) based on epidemiological results [70]

Examined group	Observed effects of exposure (changes connected with silicosis along with their classification according to the International Labor Organization (ILO) (2002) or deaths)	Exposure level; exposure time	Dose-effect research results	Authors' comments
Research relating to exposure to quartz				
Miners (2109) of gold and uranium mines in Ontario (Canada); exposed > 5 years, examined after 2342 years from the beginning of exposure	32 cases of round opacities cat. ≥ 1/1	average exposure time - about 20 years	Risk of silicosis estimaed after 40 years of exposure: 0.4% (0.2÷0.8) (95 – percentage confidence interval) with exposure 0.05 mg/m^3 1.2% (0,7÷2,1) with exposure 0.1 mg/m^3 2.4% (1,4÷3,9) with exposure 0.15 mg/m^3 3.8% (2,2÷6,5) with exposure 0.20 mg/m^3	-
Workers (972) of granite industries in Vermont (USA); exposed from several to about forty years	7 cases of category changes ≥ 1/0; 21 cases of irregular opacities in the X-ray of the lungs	average concentration: 0.06 mg/m^3 ± 0037 mg/m^3 (standard deviation)	as a result of exposure to concentrations < 0.1 mg/m^3 there were found no silica changes	few observed changes can be a result of elderly age and smoking cigarettes
Retired workers (600) of granite industries in Vermont (USA); 408 of them were subjected to radiological examinations of the lungs	Changes in radiological lung image were found in general in 7.1% of respondents: changes of cat. ≥ 1/0 for 15 people among 58 exposed> 0.1 mg/m^3 and for 20 people in the group of 350 exposed to lower concentrations, but sporadically exceeding mg/m^3; latency period - over 40 years (counting from the beginning of employment)	initially > 0.1 mg/m^3, in the years 1940-1945 a decrease to 0.05÷0,06 mg/m^3, but for 10÷15% of samples > 0.1 mg/m^3,	Exposure for about 40 years for concentrations < 0.1 mg/m^3 was the source of lung changes cat. ≥1/0 for 5.7 % of examined; with concentrations > 0.1 mg/m^3 risk of silicosis cat. ≥ 1/0 was 25.9 %	It found that development of silicosis progress after stop of exposure
Workers (2539) of granite industries in Vermont (USA), they died to the end 1996 year		the estimated level of exposure before 1995 r.: 0.2÷0.6 mg/m^3, after 1955 year: 0.05÷0.06 mg/m^3,	SMR (Standardized Mortality Ratio) was 20.55 (15.39 ÷ 26.87) (95- percentage confidence interval)	-
Miners (2235) of gold mines (RPA), examined at the age 45÷, then observed for following 20 years	313 cases of changes in cat. ≥ 1/1; in 57% of cases the changes occurred on average after 7.4 years from the end exposure	0.2% risk of changes cat. ≥ 1/1 related to a dose of 0.9 mg/m^3·years and exposure for 24 years, 5% risk after a 40-year exposure to a concentration of 0.05 mg/m^3; the risk increases exponentially with the cumulative dose of dust; accelerated increase from the dose of 7 mg/m^3·years after the highest cumulative exposure – 15 mg/m^3·years (0.4 mg/m^3 for 37 years) risk reaches 77%		the risk of silicosis is strongly dependent on cumulative crystalline silica dose while the period latency does not depend on the dose

Table 5. Continued.

<table>
<tr><th>Examined group</th><th>Observed effects of exposure (changes connected with silicosis along with their classification according to the International Labor Organization (ILO) (2002) or deaths)</th><th>Exposure level; exposure time</th><th colspan="2">Dose-effect research results</th><th>Authors' comments</th></tr>
<tr><td rowspan="2">Miners (3330) of gold mines in South Dakota (USA), at least working for 1 year (average for 9 years) under ground</td><td rowspan="2">170 cases of silicosis recognized sequentially or radiologically – cat. ≥1 / 1; average time from the beginning of exposure to finding silicosis 37 years old</td><td colspan="3">Median concentration of 0.05 mg/m^3, before 1930 year concentration 0.15 mg/m^3;
the risk of silicosis in people exposed for 45 years to 0.09 mg/m^3 is 35 ÷ 47% (taking into account other deaths)</td><td rowspan="2">-</td></tr>
<tr><td>cumulative exposure (mg/m^3·years)
0 ÷ 0.2
0.2 ÷ 0.5
0.5 ÷1.0
1.0 ÷ 2.0
2.0 ÷ 3.0
3.0 ÷ 4.0
> 4.0</td><td>Risk
0.002
0.005
0.022
0.064
0.245
0.534
0.844</td><td>Age-adjusted risk
0.002
0.005
0.017
0.060
0.167
0.403
0.678</td></tr>
<tr><td>Men (134) from the mining town of Leadville in Colorado (USA); of which 100 were exposed to crystalline silica</td><td>32 cases of changes cat. ≥1/0 according to ILO (2002) among exposed; average exposure time - 27.6 years; average time from the beginning of exposure to diagnose 33.5 years</td><td colspan="3">frequency of changes cat. ≥1/0:
13% when exposed to concentrations 0.025 ÷ 0.05 mg/m^3
34% when exposed 0.05 ÷ 0.1 mg/m^3
75% when exposed above 0.1 mg/m^3.
20% with cumulative exposure < 2 mg/m^3·years
and 63% after dose > 2 mg/m^3·years</td><td>The significance of risk of silicosis is dependent on the dose and time from the beginning of exposure</td></tr>
<tr><td rowspan="2">Men (1080) employed in: ceramics, refractory material plants and sandstone dressing plats (United Kingdom)</td><td rowspan="2">Changes cat. ≥ 1/0 for 64 persons (5.9%), in which 21 persons had changes cat. ≥ 2/1 after exposure for at leats 10 years</td><td rowspan="2">accumulated exposure (mg/m^3 ·years)
<2 000
2.000÷3.999
4.000÷5.999
≥ 6.000

total</td><td colspan="2">Frequency of changes (%) kat. ≥1/0</td><td rowspan="2">-</td></tr>
<tr><td>Non-smoker
0
0.9
2.9
9.3

2.7</td><td>smoker
0
1.8
6.3
16.3

6.0</td></tr>
<tr><td>Workrs (547) in coal mine is Scoland (United Kingdom), employed in the 1970s</td><td>158 cases (29%) of changes cat. ≥1/0, in which 21 cat. ≥2/1</td><td colspan="3">Risk of silicosis cat. ≥ 2/1 after 15 years of exposure was:
– 5% with concentration 0.1 mg/m^3,
– 0,5% with concentration 0.04 mg/m^3,
– 0,26% with concentration 0.02 mg/^{3}</td><td>coal dust may modify the fibrosing effect of quartz dust</td></tr>
<tr><td>People (2670) working in sand mines and in the production of quartz flour (USA), employed at least 3 years before 1980.</td><td>37 deaths because of silicosis and silicotuberculosis</td><td colspan="3">odds ratio (OR) of death from silicosis after 15 years of exposure was:
– 2.1 with concentration ≤ 100 µg/m^3
– 2.4 with concentration > 100 µg/m^3</td><td>the risk of death was relevantly dependent on cumulative dose, while there were no significant dependence on exposure time</td></tr>
</table>

Table 5. Continued.

<table>
<tr><th>Examined group</th><th>Observed effects of exposure (changes connected with silicosis along with their classification according to the International Labor Organization (ILO) (2002) or deaths)</th><th>Exposure level; exposure time</th><th colspan="4">Dose-effect research results</th><th>Authors' comments</th></tr>
<tr><td rowspan="4">Workers (547) in coal mine in Scotland (United Kingdom), employed in the 1970s.</td><td rowspan="4">111 people with changes cat. $\geq 1/0$ and 47 people with changes cat.$\geq 2/1$ in a group of 371 miners
aged 50 ÷ 74 years, exposed in various periods of time to high
crystalline silica concentration
(> 1 mg/m^3)</td><td colspan="5">Expected risk (%) changes cat. $\geq 2/1+$ according to ILO, 15 years after ending exposure for low concentrations during 15 years and additionally for high concentrations for several months (> 2 mg/m^3)</td><td rowspan="4">short exposure (for several months) to high concentrations is the cause of significant
increase in the risk of silicosis</td></tr>
<tr><td rowspan="2">level of exposure (mg/m^3)</td><td colspan="4">Additional exposure > 2 mg/m^3 (time in months)</td></tr>
<tr><td>0</td><td>4</td><td>8</td><td>12</td></tr>
<tr><td>0.30
0.20
0.10
0.08
0.06
0.04
0.02
< 0.02</td><td>20.52
7.50
2.49
1.98
1.58
1.26
1.00
0.80</td><td>54.51
27.36
10.58
8.59
6.93
5.58
4.48
3.59</td><td>84.76
63.61
35.46
30.36
25.70
21.53
17.88
14.73</td><td>96.27
89.03
71.84
66.93
61.62
56.02
50.26
44.50</td></tr>
<tr><td>Collective analysis of 6 exposed cohorts for which exposure levels were documented: 2342 employees of the diatomite mine (USA),
1026 workers of granite quarry (Finland), 5480 employees of the granite industry (USA), 4027 employees of the sand mine (US), 3348 miners of the gold mine (US), 2213 gold mine miners (Australia)
The total of 18364 people</td><td>170 deaths because of silicosis or undefined pneumoconiosis</td><td>Median concentration 0.26 mg/m^3; median cumulative dose of dust – 7.15 mg/m^3 ·years; median time of exposure of persons with silicosis – 28 years</td><td colspan="4">relative risk of death due to silicosis at the age of 65, after 45 years of exposure to silica with concentration 0.05 mg/m^3 or dose 2.25 mg/m^3·years is 6/1000, and with concentration 0.1 mg/m^3 or dose 4.5 mg/m^3·years – 12/1000</td><td>-</td></tr>
<tr><td>Persons (1786) employed in 18 English and Scottish factories producing: ceramic bricks, pipes and tiles; average age 40, 42% were smokers</td><td>For 25 people occures changes cat. $\geq 1/0$, in which for 7 people changes cat. $\geq 2/1$</td><td>Level of exposure: 0.04 ÷0.62 mg/m^3 (average 0.11 mg/m^3); 97% measurement results were lower than 0.4 mg/m^3</td><td colspan="4">Silicosis cat. 1/0 was assumed for 1.4 % exposed, and cat. 2/1 for 0.4 %</td><td>for 14% examined was observed chronic bronchitis</td></tr>
<tr><td>Miners (4028) of tin ore mines, miners (14,427) of tungsten ore mines, workers (4547) of the ceramic industry (China), employed in 1950. and working for at least a year
in the years 1960-1974, then examined until 1994.</td><td>recognition of silicosis according to local criteria,
similar to classification
according to ILO 2002 - cat. 1</td><td>Average dose (mg/m^3·years): workers of ceramics – 6.37, miners of tin ore mines – 2.43, miners of tungsten ore mines – 3.25</td><td colspan="4">After 45 years of beginning of employment silicosis was observed for:
17.3% ceramics workers,
21.2% miners of of tin ore mines,
1.,5% miners of tungsten ore mines;
Silicosis latency period was respectively: 29.4, 20.2 and 19.0 years</td><td>Crystalline silica present in mines has stronger fibrogenic properties than silica
in ceramics; the cause can be occlusion of silica particles by clay minerals</td></tr>
</table>

Table 5. Continued.

<table>
<tr><th>Examined group</th><th>Observed effects of exposure (changes connected with silicosis along with their classification according to the International Labor Organization (ILO) (2002) or deaths)</th><th>Exposure level; exposure time</th><th colspan="4">Dose-effect research results</th><th>Authors’ comments</th></tr>
<tr><td rowspan="3">Miners (7729) from the central professional register (Sweden) who worked for at least a year between 1923 and 1996 and died between 1952 and 2001.</td><td rowspan="3">58 deaths because of silicosis; median exposure time of the deceased 25 years, median time from the beginning of exposure to death 49 years</td><td rowspan="3">median cumulative silica doses estimated for the dead with silicosis – 4.8 mg/m^3·years</td><td colspan="4">Dependence of mortality rate on cumulative exposure</td><td rowspan="3">Limit exposure to level 0.05 ÷ 0.1 mg/m^3 during 45 years do not protect the exposed from silicosis</td></tr>
<tr><td>exposure level by 45 years</td><td>Cumulative exposure (mg/m^3·years)</td><td>Death rate because of silicosis</td><td>Death rate adjusted to year of birth and the age reached</td></tr>
<tr><td>0 ÷ 0.02
0.02 ÷ 0.07
0.07 ÷ 0.11
0.11÷ 0.16
> 0.16</td><td>0 ÷ 0.9 (0.4)*
1 ÷ 2.9 (1.8)
3 ÷ 4.9 (3.9)
5 ÷ 6 .9 (5.9)
> 7 (8.3)
*average value</td><td>9.71
24.6
117
154
224</td><td>18.7
32.8
117
129
140</td></tr>
<tr><td>Miners (520) from gold mine (RPA) at age > 37 years</td><td>Asumed about 100 cases (19%) of changes cat. ≥ 1/1</td><td>Average time of exposure 21.8 cat; median exposure 0.051 mg/m^3, median dose 1.15 mg/m^3·years</td><td colspan="4">Odds ratio (OR) of silicosis development after 20 years of exposure and after taking into account cigarette smoking and race, it was 1.18 (1.02 ÷ 1.37) (95- percentage confidence interval)</td><td>Exposure at level 0.1 mg/m^3 does not prevent from silicosis development</td></tr>
<tr><td rowspan="2">Workers (952) automotive foundry (US)</td><td rowspan="2">36 people with changes cat. ≥ 1/0 (3.8%), average age 58.9 years</td><td rowspan="2">Average exposure (mg/m^3):
0.01
0.05
0.10
0.15
0.20
0.25
0.30</td><td colspan="4">Odds ratio (OR) of silicosis including smoking cigarettes and race</td><td rowspan="2">-</td></tr>
<tr><td colspan="2">After 20 years of exposure:
1.04 (1.02 ÷ 1.15)*
1.20 (1.12 ÷ 1.30)
1.45 (1.25 ÷ 1.68)
1.74 (1.40 ÷ 2.17)
2.10 (1.56 ÷ 2.82)
2.53 (1.75 ÷ 3.65)
3.04 (1.96 ÷ 4.72)
*95- percentage confidence interval</td><td colspan="2">After 40 years of exposure:
1.08 (1.05 ÷ 1.11)*
1.45 (1.25 ÷ 1.68)
2.10 (1.56 ÷ 2.82)
3.04 (1.96 ÷ 4.72)
4.40 (2.45 ÷ 7.93)
6.38 (3.06 ÷ 13.30)
9.24 (3.83 ÷ 22.31)
*95- percentage confidence interval</td></tr>
</table>

Table 5. Continued.

Examined group	Observed effects of exposure (changes connected with silicosis along with their classification according to the International Labor Organization (ILO) (2002) or deaths)	Exposure level; exposure time	Dose-effect research results			Authors' comments
Research relating to exposure to cristobalite						
Workers (1809) in mine and diatomite processing plant in California (USA)	81 people (4.5% of examined) with changes cat. $\geq 1/0$	Average concentration ≤ 0.5 mg/m^3 and dose ≤ 2.0 mg/m$^3\cdot$years; Average concentration > 0.5 mg/m^3 and dose > 2.0 mg/m$^3\cdot$years;	Risk of changes cat. $\geq 1/0$ is: – 1.1% – 3.7%			Strong statistical reliance ($\alpha < 0.001$) Between cumulative exposure and risk of changes cat. $\geq 1/0$
		Cumulative exposure (mg/m$^3\cdot$years) ≤ 1 $> 1, \leq 3$ $> 3, \leq 6$ >6	relative risk (RR) of changes cat. $\geq 1/0$ in relation to those exposed to the smallest doses and taking into account the age of the examined: 1.00 4.35 (1.7 ÷ 11.06)* 20.16 (98.2 ÷ 49.7) 40.37 (916.1 ÷ 101.3) *95- percentage confidence interval			
Workers (2342) in mine and diatomite processing plant in California (USA), employed for at least a year in the years 1942- 1994	67 deathsbecause of lung diseases other than cancer, 70 people with changes cat. $\geq 1/0$; average exposure time 7.4 years	Average concentration 0.29 mg/m^3, average dose 2.16 mg/m^3 $\cdot$years	Relative risk of death because of lung diseases other than cancer related to a dose of 5.79 mg/m^3 $\cdot$ years and after taking into account cigarette smoking was 4.2, and for the maximum dose – 31.8 mg/m^3 $\cdot$ years were 18.4			-
			Relative risk of death because of lung diseases other than cancer (excluding coniosis)) and silicosis estimated up to age 85 years, after 45 years of exposure, converted to 1000 employees (the observations were limited to people exposed to doses lower than 10 mg/m$^3\cdot$years:			
			Average exposure, (mg/m^3): 0.001 0.005 0.010 0.020 0.050 0.100 0.200	Lung diseases other than cancer: 1.1 5.6 11.0 22.0 54.0 100.0 190.0	Silicosis cat.$\geq 1/0$: 1.6 7.8 16.0 31.0 75.0 140.0 260.0	

listed in Table 4 and include the year of assessment, chemical type, guidance value, target population, and the source of this information.

Diseases caused by the inhalation of free crystalline silica are silicosis, pulmonary tuberculosis, lung cancer, chronic obstructive pulmonary disease (COPD) and several extra pulmonary diseases [70, 73]. It is assumed that pulmonary silicosis requires exposure to high levels of dust for a long time. Many studies describe the quantitative relationship between silica exposure and pneumonia, emphysema, and obstruction as aspects of silicosis [66, 74-75]. There was also evaluated a correlation between cumulative dust exposure and an increased risk of deaths due to COPD in combination with smoking [76]. In South African studies, chronic bronchitis associated with loss of lung function was found among gold miners. These results were strongly related to exposure to dust containing silica and not depending on silicosis [74].

Exposure to crystalline silica can cause both respiratory and non-respiratory effects. It was found that silicosis among the diseases of the respiratory system is one of the best-documented occupational diseases [77]. Every year, about 100 workers in the U.S. die from silicosis, while hundreds of people suffer from breathing difficulties such as bronchitis. Over 2 milion U.S. workers are exposed to high risks associated with silica as a result of construction and mining activities [75, 78]. There is a connection between exposure to crystalline silica and other health problems, including rheumatoid arthritis, scleroderma, Sjogren's syndrome, lupus and kidney disease [71]. NIOSH believes that more attention should be paid to these atypical health effects [76].

Based on epidemiological studies, crystalline silica dust was classified as a known carcinogen for humans [70, 79-80]. The study of mortality among industrial workers confirmed the causal link between lung cancer and crystalline silica exposure [75, 81-82].

It can be concluded that exposure to silica is clearly greater for people working in the construction industry than for other professions. Exposure to silica at a construction site is much more common than in any other industry, so there is increased mortality due to silicosis among construction workers, as well as increased risk associated with lung cancer through contact with silica. It was reported that people exposed to concrete containing silica dust suffer from reduced lung function [75, 83].

Although workers exposed to silica are at the same time exposed to a mix of other pollutants, including nitrogen gases and diesel exhaust emissions, research suggests that lung diseases can be largely caused by the inhalation of silica dust [84]. Epidemiological studies on occupational exposure to crystalline silica are carried out for decades; the list of selected ones are prepared in Table 5 [70].

Conclusions

Many organizations have focused recently on environmental protection research in the construction industry. One of the pro-ecological activities is using less energy-consuming cement materials such as fly ash, slag and pozzolan. It was also pointed out that condensed silica has the possibility of wide use as a partial substitute for cement (concrete additive). Currently, high-quality concrete for road and highway construction is increasingly used, and it is also used for road renovation/repair. It seems that all this causes silica, in a much larger quantity than is generally estimated, to be introduced into the environment, especially to the atmosphere and the ground environment. The problem of excessive inhalation of silica may be important due to health exposure, not only in groups of people professionally exposed to its inhalation such as construction industry workers and miners, but also commonly in humans and everywhere where there is a lot of silica in the atmosphere. So far, the problem of silica pollution was important only from the point of view of the working environment, so it was associated with occupational exposure. In the case of environmental research, silicon or silica in the samples are treated as indicators of the impact of natural sources in a given area, and therefore their occurrence is associated with the composition of soils or upper continental crust [88, 89].

Efforts have been made to collect and summarize information on exposure to silicon dust in the mining and construction industries [70, 75, 82, 85-87]. However, the exposure levels during specific construction work – or the indication of silica concentrations in the air during such work – are insufficiently characterized. This particularly applies to work related to the performance and repair of concrete road surfaces, which, as shown in this paper, are probably related to the increase in the concentration of silica in the air. Sampling of silica dust under its natural emission conditions (e.g., road surface abrasion) may create many problems due to dynamically changing environmental conditions as well as many sources of dust in urban areas. Another problem in this area is the use of specific and sensitive analytical methods for determining small amounts of silica in environmental samples. Therefore, the attempt to determine the emission trigger of road surface abrasion to the total balance of crystalline silica in the air seems to be an essential element of research that should be developed in coming years.

Conflict of Interest

The authors declare no conflict of interest.

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