PROHIBITION OF ENGINEERED STONE: LITERATURE REVIEW AND GAP ANALYSIS

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Prepared by
Dr Chandnee Ramkissoon
28 Anderson Street
Thebarton SA 5031
Adelaide Exposure Science and Health, School of Public Health
The University of Adelaide

T:0883134957
E.chandnee.ramkissoon@adelaide.edu.au

Supported by
Dr Yonatal Tefera
Assoc. Prof. Sharyn Gaskin MAIOH
Adj. Prof. Dino Pisaniello FAIOH FAIHS FRACI

Reviewed by
Associate Professor Deborah Glass, Monash University

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Overview

This Literature Review and Gap Analysis addresses a complex technical topic, involving the fields of material science, exposure science, epidemiology, risk assessment and hazard control. As such, a technical executive summary is provided. A glossary is also provided to aid reader understanding.

Executive Summary

In response to the epidemic of occupational lung disease including accelerated silicosis in the engineered stone industry, Work Health and Safety (WHS) ministers have recently agreed to consider a potential prohibition on the use of engineered stone in Australia. Safe Work Australia proposed three options for a prohibition on the use of engineered stone, as listed below, and sought stakeholder feedback through public consultation submissions.

- Option 1: a prohibition on the use of all engineered stone,
- Option 2: a prohibition on the use of engineered stone containing 40% or more crystalline silica, or
- Option 3: a prohibition on the use of engineered stone containing 40% or more crystalline silica and licensing of engineered stone containing less than 40% crystalline silica.

Purpose and Scope

In May 2023, Safe Work Australia commissioned the University of Adelaide to undertake a rapid literature review and gap analysis of the scientific evidence to inform recommendations related to the three options for prohibition on the use of engineered stone in Australia. The literature review was guided by 10 Research Questions and a definition of engineered stone, which were provided by Safe Work Australia. The answers to the research questions will assist Safe Work Australia in its recommendations to the WHS ministers on a prohibition on the use of engineered stone in Australia. WHS ministers have requested that the recommendations are provided to them by the end of August 2023.

The research questions are listed in Appendix 6.1. The **scope** of this Report does not address medical diagnosis, treatment or disease registries relating to engineered stone. It does not attempt to review the vast literature relating to crystalline silica exposures in mining, construction and other industries, where the materials are not specifically engineered stone. However, there is reference to relevant crystalline silica toxicology, and health effects that have been associated with selected engineered stone constituents. Finally, it does not offer advice on how to enforce a ban on certain engineered stones, or assess its economic impact, should a decision be made to prohibit their importation or use.

Safe Work Australia also provided the authors with the following definition of engineered stone in the recently amended (22 May 2023) model Work Health and Safety Regulations:

> ***engineered stone***:
> (a) means an artificial product that:
> (i) contains crystalline silica; and
> (ii) is created by combining natural stone materials with other chemical constituents such as water, resins or pigments; and
> (iii) undergoes a process to become hardened; but
> (b) does not include the following:
> (i) concrete and cement products;
> (ii) bricks, pavers and other similar blocks;
> (iii) ceramic and porcelain wall and floor tiles;
> (iv) roof tiles;

(v) grout, mortar and render;
(vi) plasterboard.

The questions were answered through a critical review of relevant published peer-reviewed scientific articles and grey literature. In addition, information was sought from key stakeholders and selected international organisations. The original research questions (see Appendix 6.1) were thematically grouped and addressed within themes as follows; *Material Science*, *Risk Profile*, *Engineered Stone Manufacturing and New Products*, and *Further Considerations*.

The key findings by theme were as follows:

Material science of engineered stone

> *Is there evidence that the level of respirable crystalline silica (RCS) generated when stone is processed is higher for engineered stone compared to natural stone, relative to silica content? Does the RCS generated differ in any other way?*
>
> *Do compounds in engineered stone other than crystalline silica (e.g. resin, pigments, amorphous silica, aluminium) present an additive risk, or exacerbate the risk, posed by RCS to workers?*
>
> *Are there other particles, such as nanoparticles, generated during processing of engineered and natural stones that are hazardous? If so, is there is any difference between particles generated from engineered and natural stones?*
>
> *Are there any other differences between engineered stone and natural stone that contribute to risk?*

The available scientific literature provides consistent evidence that the level of RCS generated from processing engineered stone products is higher compared to natural stone, relative to crystalline silica content.

Evidence also suggests that there are differences in particle surface area, morphology and surface charge of RCS particles generated from the processing of engineered stone compared to those from processing natural stone.

Nano-sized particles are generated during the mechanical processing of both natural stone and engineered stone. From currently available evidence, there does not appear to be significant differences between the levels of nanoparticles generated from engineered stone and those generated from natural stone. However, there are some differences in size distribution maxima. It should be noted that most experimental studies have not actively sampled for nanoparticles, which could explain the shortage of reported exposure data for this particle size range.

Besides RCS, there is evidence from scanning electron microscopy and other data sources that the original components of engineered stones, such as the binding resin (and their associated VOCs), pigments, amorphous silica, and minerals become airborne during stone processing. Fracturing, surface abrasion and lung deposition do not completely separate the solid mixture. Thus, a variable surface structure is presented to lung cells for attachment and internalisation by macrophages, which influence particle reactivity and cellular toxicity. Although non-crystalline silica components of emissions have individually been associated with health risks, there is insufficient evidence to identify whether they add to the risk from RCS, or interact with RCS to exacerbate or mitigate risks. Further toxicological investigation is necessary to validate the emerging experimental findings from laboratory studies.

There is insufficient evidence regarding both the dust characteristics and relative toxicity associated with newly introduced lower-silica engineered stone products, many of which may contain recycled inorganic materials. Relatedly, the toxicity of freshly ground amorphous silica remains uncertain. In addition to testing the agglomerated stone, research is needed that examines the individual constituents under controlled conditions.

Risk profile of engineered stone

> *Does the available evidence support a prohibition based on a threshold level of silica content? If so, what is the threshold? Does this threshold define the threshold between a high-risk and a low-risk product?*
>
> *What evidence is there to describe how risk differs between engineered stone with differing silica content (e.g. 95% vs 60% vs 40%)?*

Further research is needed to establish whether there is a threshold crystalline silica content of engineered stone, beyond which the risk of ill health is unacceptably increased. Engineered stone containing a high proportion (> 90% by weight) of crystalline silica has been the common factor in the Australian experience with engineered-stone related disease. There is some empirical evidence and a logical argument that reducing the crystalline silica content in the engineered stone slab will lead to reduced inhalation of crystalline silica, all other factors being equal. Even though there seems to be good correlation between the bulk proportion of crystalline silica and the RCS generated for given processing conditions, there is no epidemiological or laboratory toxicological evidence describing how risk of disease would differ for engineered stone over a range of crystalline silica concentrations. Recent Australian epidemiological research with Victorian engineered stone workers doesn't directly answer this question as the engineered stone used during the exposure period was the high crystalline silica version, rather than the new low crystalline silica products.

Notwithstanding the percentage of crystalline silica in the slab, the key risk factor is the exposure to airborne dust, which may exceed the RCS exposure standard by hundreds of times in the case of dry processing, and entail particle sizes that are efficient in causing lung disease and inflammation. The importance of high RCS levels from dry processing, also in the Victorian study, was evident.

Even though historically, natural stones have led to occupational lung disease, it is unclear whether crystalline silica from natural stone entails the same risk factor of silicosis (and other silica-related diseases) as crystalline silica from engineered stone. As mentioned above, there may be interacting toxicants in the composite material, which may explain the accelerated nature of silicosis among diagnosed engineered stone workers.

Engineered stone manufacturing and new products

> *Do different manufacturing methods for engineered stone affect the risk profile (e.g. heat curing vs sintering)?*
>
> *Are there other products in development that would not be captured by the definition of engineered stone, but which may pose risk to workers?*

Evidence suggests, but does not confirm, that different manufacturing methods can affect the risk profile arising from processing engineered stone. Heat curing is a common manufacturing method for resin-based engineered stones. Moderate heat cures the organic resin binder that holds the stone particles together, after vibro-compaction under vacuum. Sintering involves subjecting the stone particles to high temperatures and pressure, causing them to compact together, simulating the formation of natural granite. Hence, resin-based engineered stone comprise organic and inorganic constituents, whereas sintered stone and porcelain have only inorganic ingredients.

Evidence suggests that processing resin-based engineered stone at high temperatures can lead to more variable hazard emissions, and diverse health effects, compared to sintered stone and porcelain, which have already been subjected to high temperatures during manufacture. An example is the VOCs produced when processing resin-based engineered stone.

In the case of sintered engineered stone, which is harder than resin-based engineered stone, there is uncertainty as to whether the additional mechanical energy and different abrasive action required in processing sintered stone results in a different toxicity profile for the dust.

An area for consideration relates to emerging engineered stone products and/or benchtop materials containing inorganic waste, recycled glass and amorphous forms of silica, rather than crystalline silica, which may not be captured by the current definition of engineered stone but may still pose a risk to worker health. Similarly, porcelain-based benchtops contain crystalline silica, but may be ambiguous within Safe Work Australia's operational definition.

Further considerations

> *What is required to determine the silica content in engineered stone slabs? Are there technical limitations to the detection/analysis that may be relevant to the establishment of a silica content threshold?*
>
> *Is there any other evidence that would inform the impact analysis on a prohibition on the use of engineered stone?*

Understanding crystalline silica content in bulk (slab) engineered stone products currently relies on composition information provided by manufacturer Safety Data Sheets. These may not be accurate or

may relate to a group of stone materials, rather than a specific stone product or batch. There is currently no specific technique available to directly determine crystalline silica content in bulk stone materials (i.e. real-time, direct, non-destructive detection and quantification). To support the establishment of a crystalline silica content threshold in bulk engineered stone material, there is a need to investigate novel real-time, direct detection technologies to address some of the limitations. Some techniques have been explored for other industries such as mining and defence.

Abbreviations and Glossary

Alveoli	Alveoli are tiny air sacs at the bottom of the respiratory tract, and allow for gas exchange in the lungs
Amorphous silica	Silica particles that do not have a crystalline structure. An example is glass.
CALD	Culturally and linguistically diverse. (CALD subpopulations are typically vulnerable minority groups, which may have their own subcultures)
Crystalline silica	Forms of silica that have a crystalline structure, i.e. a defined lattice arrangement. Examples are quartz and cristobalite.
Exposure	The interaction/contact between the person and the hazard. There are various routes of exposure, e.g. inhalation, skin contact and swallowing.
Hazard	This has the potential for illness and injury, if there is exposure. The health and safety risk arises from exposure to the hazard.
ISO	International Organization for Standardization (for the development and publication of international standards)
LEV	Local exhaust ventilation (typically used to capture air contaminants at their source)
mg/m^3	Milligrams per cubic metre
Lung macrophage	Specialised cells in the lungs for the detection, engulfment and destruction of bacteria and other harmful entities.
Nanoparticle	Particles less than 100 nm in size, often equated to ultrafine particles.
nm	Nanometre. An extremely small length, i.e. millionth of a millimetre.
PAH	Polycyclic aromatic hydrocarbons are organic compounds with fused ring structures that are produced during the incomplete burning of fuels. They are generally considered to be toxic pollutants.
Polymorph	Different forms of the same general thing. For example, quartz and cristobalite are polymorphs/forms of crystalline silica.
RCS	Respirable crystalline silica (The respirable size fraction represents airborne particles that are able to penetrate into the lowest part of the lungs, namely the alveolar region. These are typically less than 10 micrometers in size).
Redox	Reduction or oxidation. These are types of chemical reactions. For example, household bleach acts as an oxidiser.

RIS	Regulatory impact statement. This is typically used to determine if government intervention is necessary or desirable.
Risk	This is the probability of harm from the exposure. If the exposure can be controlled the risk is reduced. If the exposure can be eliminated by either removing the hazard or avoiding exposure then the risk is eliminated.
SEM	Scanning electron microscopy, typically used to determine size, shape, and texture of extremely small particles.
Silanols	Silanols (≡Si-OH; =Si $(OH)_2$) are chemical functional groups at the surface of fractured (crystalline and amorphous) silica. Their relative amount and spatial distribution influence the surface chemistry and reactivity of silica particles, which in turn drive cellular toxicity.
Silicosis	Lung scarring – manifested as damage to the alveoli in the lungs, reducing their ability to exchange oxygen. This can be a progressive disease even when the exposure is ceased. It greatly reduces quality of life and can be fatal. There are various forms of silicosis.
TC	Technical committee
Threshold	This is a term used in toxicology and in setting exposure standards. Exposures well below the threshold are considered safe. In the context of this Report, a threshold may also refer to the crystalline silica content of engineered stone, and this is meant to delineate high and low risk, under given exposure conditions.
TWA	Time weighted average. An example is the 8-hr TWA exposure standard for respirable crystalline silica, where measurements are averaged over an eight hour period, allowing for fluctuations during this period.
UFP	Ultrafine particles. These are extremely fine particles less than 100 nm in size. They are considered nanoparticles.
UK HSE	The United Kingdom Health and Safety Executive is the national regulator for workplace health and safety.
US NIOSH	The United States National Institute for Occupational Safety and Health is a research agency focused on the study of worker safety and health.
WHS	Work health and safety or workplace health and safety. Considered to be equivalent to occupational health and safety.
VOC	Volatile organic compound. This a class of organic chemical with a low boiling point. An example is benzene.
XRD	X-ray diffraction. Used to identify specific crystalline materials.

1 Introduction

In the last two decades, the world has witnessed the re-emergence of silicosis – a disease that should have been eliminated (Menéndez-Navarro et al., 2021; Pavan et al. 2016; Hoy et al. 2022). This phenomenon has been linked to the growing popularity of engineered stone, which is an artificial material made by binding finely crushed rocks of high crystalline silica content with polymer resin to make a composite material that is durable, easy to work with, aesthetically pleasing and cost-effective (Pavan et al., 2016; Leso et al., 2019). However, mechanically processing engineered stone generates high levels of respirable crystalline silica (RCS) and other potential hazards, for example organic and inorganic components of the binding agents and other constituents such as pigments. These are all potential risk factors for disease in those exposed (Leso et al., 2019; Ramkissoon et al., 2022; Mandler et al., 2023).

The association between the inhalation of RCS particles and silicosis has been known for hundreds of years. However, what was not appreciated when engineered stone was first introduced was the extremely high dust levels associated with dry processing (stone cutting, grinding, sanding and polishing), the cocktail of ingredients, and the extremely small dust particles that are efficient in causing lung scarring and other effects when inhaled. What has been seen is a high prevalence of *accelerated* silicosis rather than the traditional chronic silicosis, usually requiring decades of exposure. Some people may go on to develop other health outcomes such as progressive massive fibrosis (PMF - the most severe form of silicosis), respiratory failure, multiple comorbidities (such as autoimmune diseases including scleroderma, granulomatous lung infections, lung cancer and inflammatory kidney disease), severe disability and even death (Hoy 2021a; Hua et al., 2022). In NSW, health screening programs have revealed that the engineered stone industry is associated with an increase in annual cases of certified silicosis from 9 in 2015-2016 to 107 by 2019-2020 (Insurance and Care NSW, 2020). Similarly, in Victoria, of 587 stone bench top workers who had completed a primary screening of their lungs, 65 (11%) went on to be diagnosed with simple silicosis and 21 (4%) others were diagnosed with complicated silicosis (Hoy et al., 2021b). Further, health screening showed that as many as 20-30% of Australian workers in the engineered stone industry have radiological evidence of disease, making silicosis an occupational epidemic in Australia (Edwards & Knight, 2019).

Important exposure factors

Although the common engineered stone slabs had a very high proportion of crystalline silica by weight, the dominant risk factor is the actual airborne dust exposure, often hundreds of times greater than the exposure standard. Extremely fine dust is easily dispersed and difficult to control. It remains airborne for extended periods, and once settled on surfaces, it can be resuspended.

The primary exposures in the engineered stone fabrication workshops are:

- Short-range exposure close to the sources of dust generation (and where reactive particles are most likely). This is what is regulated in respect of the RCS exposure standard and is typically the predominant exposure mechanism, which needs to be controlled.
- Volatile organic compounds (VOCs) as resin decomposition products, become partially separated from the dust during engineered stone processing, and are inhaled, or may be adsorbed onto skin or clothing.

The secondary exposures include:

- Long-range exposures (greater than two metres), due to re-suspension of settled dust (possibly reduced particle reactivity), and long settling time for very small particles not captured at the source. This can affect nearby office staff and others not actively processing the stone.
- Dust inhaled from removing contaminated clothing, use of compressed air for clean-up, dumping of waste in bins etc.
- Dust-containing mist inhaled due to engineered stone particles suspended in the recycled water used for wet suppression of dust (usually for polishing activities).

Control of exposure

The so-called *hierarchy of control measures*, as described in Section 36 of the model WHS Regulations, can be applied to this occupational hygiene problem, and it has been argued that a suitable combination of control measures will mitigate exposures to the point of eliminating engineered stone disease. Current regulatory action in Australia typically entails the banning of dry abrasive processing, the use of integrated tool vacuum systems, wet methods and personal respiratory protection. The overall effectiveness of combined control measures is the subject of ongoing research and field investigation, and there are known inconsistencies of application across workshops. There are few data on exposures during installation, with potentially greater inconsistencies.

2 Methodology

A Rapid Review was undertaken to provide the scientific evidence underpinning the answers to the 10 Research Questions in this report. Rapid reviews are a form of knowledge synthesis in which components of a systematic review process are simplified to produce critical information in a short period of time (Khangura et al., 2012).

2.1 Literature search

A systematised approach for a structured literature review was used, which provided a rapid summary of the most impactful, innovative, and recent research on the specified topic using systematic procedures for identifying and synthesising studies (Grant & Booth, 2009). Search terms were identified in each Research Question and searched using a structured strategy and multiple databases, peer-reviewed and grey literature search tools. More detail (including PRISMA statement) is provided in Appendix 6.2. Thematic grouping of the Research Questions into research topics/themes helped further focus the literature search and output. This Report only includes published literature as of May 2023. However, after an external peer review of the Report (June 2023), an additional relevant study (Hoy et al., 2023) was identified and included. In addition, information was sought from key stakeholders, as well as relevant information from international technical committees, for example the International Organisation for Standardization (ISO).

2.2 Critical analysis (appraisal)

A critical appraisal tool, adopting the "Ten Key Questions" approach, was used to assess the relevance and validity of the research articles identified (Young & Salomon, 2009). Briefly, each question was given one mark if the answer was "yes" or a positive value. Based on the criteria, the quality of each paper was categorised as low (1-3 marks), medium (4-6 marks) or high (7-10 marks). In addition, expert judgement by the research team, as subject matter experts, was applied. An exemplar summary table of the results of this critical appraisal as it was applied to Research Question 4 is shown in Appendix 6.2. All screened articles relevant to this research question received high rankings, which denotes that the articles were relevant to identify and characterise risk factors.

3 Findings

Available scientific evidence was gathered and synthesised to answer 10 Research Questions and provide a gap analysis. To improve the readability of this Report, evidence is thematically grouped and addressed across four themes: i) *Material Science of Engineered Stone* (section 3.1), ii) *Risk Profile of Engineered Stone* (section 3.2), iii*) Engineered Stone Manufacturing and New Products* (section 3.3), and iv) *Further Considerations* (section 3.4). Each outcome presents a 'Highlights and Research Gaps' summary box, followed by the full response.

3.1 Material Science of Engineered Stone

To understand the hazard of engineered stone, there is a need to first characterise the composition and material science and assess emissions generated during tasks associated with its use. Positioning this information in relation to natural stone products for comparative purposes will allow an understanding of any differences that may contribute to risk. This section covers research questions 3, 4, 6 and 7.

Research highlights

Overall, the evidence on comparative dust emission characteristics between engineered stone and natural stone is limited. The available scientific literature shows that processing high- crystalline silica engineered stone products generates much higher RCS compared to natural stone.

Besides the elevated RCS content (up to 90% by weight), there is some evidence indicating that the dust generated from engineered stone differs from that of natural stone in various aspects, including silica polymorphs, surface characteristics, resin and elemental composition and particle size distribution, all of which may influence its reactivity. The different polymorphs identified in engineered stone dust, primarily quartz and cristobalite, may influence their reactivity, compared to natural stone which contains mostly quartz. In particular, the presence of metal ions in open lattice structures like cristobalite may influence toxicity.

New-generation engineered stone products (with reduced crystalline silica content) can contain high (> 50%) levels of amorphous silica, a different non-crystalline silica polymorph. While previously thought to be not case harm, there is emerging evidence from laboratory studies that amorphous silica in the submicron size range may contribute to lung cell damage and inflammation.

The presence of resin in engineered stone may influence the risk associated with RCS exposure in two ways: (1) by generating resin decomposition products in the form of harmful VOCs; (2) by coating the reactive surface groups of RCS particles *in situ*, which initially may protect against inflammatory reactions but may eventually degrade in the lung fluid and initiate toxicity.

Natural stone contains a higher percentage of metal elements than engineered stone. Nevertheless, the presence of redox active species in engineered stone dust emissions as well as lung biopsies of silicotic patients, suggests the potential contribution of metal ions in engineered stone to disease risk.

There is evidence confirming the generation of ultrafine particles during the mechanical processing of both natural stone and engineered stone. However, the available evidence is insufficient to draw conclusions on any significant differences between the ultrafine particles generated from engineered stone and those generated from natural stone.

Although the combined toxicity of individual components identified in engineered stone dust emissions with RCS is unknown, there is ample evidence of their toxicity individually, consistent with the hypothesis that they may contribute to risk.

Research gaps

There is an urgent need to better understand the role of other components in engineered stone on the pathogenesis of disease in this occupational group. This can be achieved through interdisciplinary research linking exposure science to biomedical disciplines (e.g. controlled cell culture and animal studies). The lack of evidence regarding ultrafine particle emission rates from stone processing highlights the need for more specialised dust particle detection to determine the relative contribution of ultrafine particles to the total particle size distributions of dust from processing engineered and natural stone.

Respirable crystalline silica

Engineered stone can contain over 90% crystalline silica, significantly higher than the content found in most natural stone (up to 40%) (Mandler et al., 2023). Four recent studies were identified in this rapid review that compared silica dust emitted from engineered and natural stone under comparable conditions (Ramkissoon et al., 2022; Hall et al., 2022; Carrieri et al., 2020; Thompson & Qi, 2023). Three of these studies examined two to three samples of engineered stone (Hall et al., 2022; Carrieri et al., 2020; Thompson & Qi, 2023) and one study explored 12 different types of engineered stone (Ramkissoon et al., 2022). These studies also included one to three types of natural stone for comparison. For the purpose of this report, the stone materials tested in these studies were categorised into three groups: high-silica engineered stone (resin-based engineered stone with ≥ 80% crystalline silica by weight), low-silica engineered stone (sintered or resin-based engineered stone with ≤ 50% crystalline silica), and natural stone such as marble (< 10% crystalline silica), granite (40% crystalline silica), and sandstone (60-70% crystalline silica). In total, these four studies examined 17 types of high-silica engineered stone, three low-silica engineered stone products, and seven types of natural stone.

The stone samples underwent various mechanical processes, including cutting and/or grinding and polishing within controlled laboratory settings. The duration of these mechanical processes varied from 7 minutes to 60 minutes. Characterisation parameters included total dust, crystalline silica content in both the bulk dust and the respirable dust, dust generation rate (including RCS), and particle size distributions (Ramkissoon et al., 2022; Carrieri et al., 2020; Hall et al., 2022; Thompson & Qi, 2023). The total mass of dust generated during each process was similar for both artificial stone (resin or sintered-based) and natural stone. However, the dust generated had varying RCS contents depending on their bulk silica composition. The resin-based engineered stone (90% crystalline silica), generated significantly higher RCS (up to 80% of the total respirable dust by weight) compared to sintered-based engineered stone and natural stone where RCS was 3-6% of the total respirable dust (Hall et al., 2022; Thompson & Qi, 2023). In cases where natural stone products with high silica content, such as sandstone (62% silica), were processed, the dust was found to contain up to 55% RCS levels (Hall et al., 2022). The evidence also indicated that the low-silica engineered stone products generated comparable RCS percentages of the respirable dust (ranging from 2% to 20% of dust) to that of natural stone (Hall et al., 2022; Carrieri et al., 2020).

The findings regarding the total respirable dust generation rate have been inconsistent. Some studies indicated that natural stone generated 2 to 4 times more respirable dust compared to both high-silica and low-silica engineered stone products (Carrieri et al., 2020; Thompson & Qi, 2023), while others did not find a significant difference in the total respirable dust generated between different stone types (Hall et al., 2022). Nevertheless, all studies agreed that the generation rate (or concentration) of RCS was highest for high-silica engineered stone, followed by natural stone, and finally low-silica resin based engineered stone even in cases where a higher total respirable dust was generated from natural stone (Ramkissoon et al., 2022; Hall et al., 2022; Carrieri et al., 2020; Thompson & Qi, 2023).

Engineered stone workers are potentially exposed to freshly fractured silica, which occurs during the processing of engineered stone, as well as aged (settled) silica resulting from poor housekeeping practices. Studies conducted on animals (Porter et al., 2002) and *in vitro* (Thredgold et al., 2022) have demonstrated that exposure to freshly fractured silica leads to increased reactivity, heightened pulmonary inflammation, and greater damage when compared to aged silica. Furthermore, dust generated from engineered stone maintains its relatively high reactivity for extended periods of time, whereas reactivity in natural stone dust diminishes more rapidly.

Silica polymorphs

Crystalline silica

RCS particles generated from processing engineered stone have different physiochemical properties than dust from natural stone including variation in the form of crystalline silica present (Thompson & Qi, 2023). Crystalline silica exists in different mineral forms/polymorphs, but the most commonly occurring forms are quartz and cristobalite, which differ in their mineralogy, chemistry, surface characteristics, size distributions, and association with other elements (IARC, 2012; Thompson & Qi, 2023). Studies comparing dust emission characteristics between natural stone and engineered stone have reported the presence of both quartz and cristobalite forms of crystalline silica in 10 out of 20 types of engineered stone, whereas silica in natural stone was predominantly quartz (Ramkissoon et al., 2022; Thompson & Qi, 2023; Hall et al., 2022; Carrieri et al., 2020). The evidence linking cristobalite exposure, or combination of quartz and cristobalite, to toxicity is relatively inconclusive. Some early animal studies have suggested that cristobalite may exhibit a slightly faster toxic response compared to quartz (King et al., 1953), while others indicated that quartz and cristobalite may be comparably cytotoxic (Mossman and Glenn, 2013; Natrass et al., 2017). Some studies (Horwell et al., 2012) also showed that cristobalite-rich ash was less toxic than expected, potentially due to the substitution of silica by cations such as aluminium and sodium in the open cristobalite structure. The presence of cations on silica surfaces is also likely to interfere with the distribution and relative quantity of active silanol groups (see Glossary for term definition), which are the major determinant of silica particle toxicity (Pavan et al., 2020). Current evidence is, however, insufficient to link these toxicological effects to the pathogenesis of disease in silica dust-exposed workers. It is important to note that these studies separately compared the toxicological effects of cristobalite and quartz , hence, there may be additive or synergistic effects when workers are exposed to both forms which is currently unknown.

Amorphous silica

Silica is utilised in both its amorphous and crystalline forms in manufacturing and industrial applications. Amorphous silica refers to a non-crystalline form of silica with an irregular structure. Following recent diagnoses among engineered stone workers working with high silica content products, lower-silica engineered stone products have been introduced (e.g. Cosentino HybriQ, Smartstone Ibrido, Quantum Quartz Calacutta Roma) as potentially 'safer' alternatives due to their lower crystalline silica content, which ranges from 5 to 50% by weight of their total composition. Recent experimental work investigating the physico-chemical characteristics of the dust emitted from fracturing these materials has shown they typically contain high levels of amorphous silica and generate small particles, often as ultrafine particles (UFPs, < 100 nm in aerodynamic diameter). Amorphous silica is generally considered less toxic than crystalline silica, although available evidence remains inconclusive, particularly when emitted as UFPs (Dong et al., 2020; Marques da Silva, 2022). For example, certain animal and *in vitro* studies have found that synthetic amorphous silica exhibits less toxicity, with partially reversible effects and no potential for progressive lung inflammation than crystalline silica (Merget et al., 2002), while others have demonstrated comparable inflammation and cell damage between amorphous and crystalline silicas (Ghiazza et al., 2010; Porter et al. 2002). Pavan et al. (2020) have recently demonstrated that the presence of nearly free silanols found on the surface of both crystalline and amorphous silica particles plays a significant role in determining toxicity. Therefore, the presence of amorphous silica in engineered stone may still pose health risks, and should continue to be monitored using toxicity studies, given their increasing use in new-generation engineered stone products. Furthermore, the current Workplace Exposure Standard (WES) for amorphous silica may not be applicable to dust from recycled glass.

Surface characteristics

Other properties of RCS that may influence toxicity are related to its surface properties such as surface charge and morphology. Engineered stone products generate dust particles with more irregular shapes, sharp edges and fractures along the surface with higher surface areas than natural stone dust particles (Pavan et al., 2016; Ramkissoon et al., 2022). These surface irregularities are particularly noticeable in freshly cut engineered stone samples when compared to a reference quartz, because fracturing creates "surface defects" and a higher heterogeneity of silanol populations (≡Si-OH; =Si $(OH)_2$) and siloxane bridges (≡Si-O-Si≡), which lead to increased reactivity of the quartz surface (Turci et al., 2016). Furthermore, engineered stone dust particles tend to form agglomerates that consist of numerous smaller particles and a broader range of particle sizes compared to natural stone dust (Ramkissoon et al., 2022; Hall et al., 2022). Surface silanol groups can be detected by several methods, including zeta potential, which is a proxy for the surface charge and hence the reactivity and toxicity of RCS particles (Pavan et al., 2016). While there is currently no published evidence indicating differences in surface silanol groups between RCS generated from engineered and natural stone, many studies have reported a higher surface charge, hence possibly reactivity and higher pathogenicity associated with RCS particles emitted during processing engineered stone, compared to natural stone (Ramkissoon et al., 2022).

Resin

The presence of resin in engineered stone (which may be up to 20% of the bulk composition) can influence the reactivity of dust particles in two ways:

- By generating hazardous decomposition products during active processing of the slabs. Dry processing appears to generate more VOCs than wet process, perhaps as a result of the higher temperatures reached (Hall et al., 2022). Some of the VOCs liberated have been shown to be lung irritants and sensitizers (Ramkissoon et al., 2023).
- By acting as a resin coating for inhaled RCS particles, preventing their interaction with lung cells without affecting the reactive sites at the surface of the particle. This coating may eventually breakdown in in lysosomal fluid, and expose the reactive sites involved in free radical generation, thus restoring the cytotoxic potential of the RCS particle *in situ*.

In 2016, Pavan et al. reported that RCS particles generated by processing engineered stone dust can be resin-coated, which influence the reactive surfaces available for interaction with lung cells. They also inferred the role of resin-originated redox active species such as iron and copper on the reactivity of the particles. Using spectroscopic techniques, Di Benedetto et al. (2019) reported stable radicals at the surface of engineered stone dust particles, which they attributed to resin, coating the RCS particles

hence protecting the surface radicals from annihilation by clearance mechanisms for a limited time during their interaction with lung fluid, thus maintaining the cytotoxic activity of the crystalline silica dust. They reported that resin coating of RCS particles from engineered stone dust could explain their higher toxicity compared to other silica-containing dust, whose unprotected radicals could be “annihilated before reaching the lung tissues”. Maharjan et al. (2021) reported potential release of metal ions when engineered stone dusts were exposed to artificial lung fluid over time. No further evidence establishing the role of resin-coated RCS particles on the pathogenesis of disease has been identified so far.

Reporting on decomposition products from resin-based engineered stone, studies have demonstrated measurable concentrations of various volatile organic compounds (VOCs) when engineered stone products were pyrolysed at high temperatures (300°-650°C), with the most common compounds being styrene, phthalic anhydride and benzaldehyde (Hall et al., 2022; Ramkissoon et al., 2023). However, it is worth noting that such elevated temperatures are unlikely to occur during the processing of engineered stone, where temperatures typically reach approximately 35–40°C (Hall, Stacey et al. 2022). Similar VOCs, mainly styrene, were also detected during active cutting of engineered stone, highlighting the potential for workers to be exposed during stone fabrication work (Hall et al., 2022; Ramkissoon et al., 2023). Other frequently emitted VOCs during engineered stone processing include benzene, toluene, and m-xylene (Hall et al., 2022; Ramkissoon et al., 2023). Further discussion of VOCs from resin is provided in section 3.3.

Occupational exposure to styrene has been linked to a wide variety of respiratory diseases such as asthma, bronchitis and pneumonia as cited in recent studies (León-Jiménez et al., 2021; Ramkissoon et al., 2023), which may exacerbate the respiratory health risks associated with RCS exposure. Compounds such as phthalic anhydride, for example, are lung sensitisers (Venables, 1989), which can lead to further respiratory complications upon exposure. Moreover, polycyclic aromatic hydrocarbons (PAHs – see Glossary for term definition) such as phenanthrene and naphthalene have also been detected in engineered stone. PAHs exposure has been linked to oxidative stress and lung inflammation in toxicity studies using animal and human lung cells (León-Jiménez et al., 2021). Although the individual lung toxicity caused by either VOCs, PAHs or RCS is documented, the combined toxicity of these different components remains unknown. Further research is needed to elucidate the pathogenic mechanism of concurrent exposure to engineered stone-associated VOCs, PAHs and RCS.

Elemental composition

Several studies (Ramkissoon et al., 2022; León-Jiménez et al., 2021; Pavan et al., 2016; Di Benedetto et al., 2019) highlighted that engineered stone contains a variety of elements, the most abundant being silicon, aluminium, magnesium, sodium, potassium, and calcium. Elemental content of natural stone (29-37%) is much higher than engineered stone (<1–8%) (Ramkissoon et al, 2022). Engineered stone samples have been shown to contain trace amounts of some transition metals such as cobalt and titanium, which can enhance the production of free radicals and oxidative damage in lung tissues (Pavan et al., 2016; Fubini and Hubbard, 2003; Clouter et al., 2001).

Some elements such as silicon, iron, aluminium and titanium have also been detected in lung biopsy samples taken from silicosis patients who had been exposed to engineered stone dust for 10 to 23 years (León-Jiménez et al., 2021). Interestingly, aluminium was found at high concentration in the lung inflammations and highly correlated with silicon content. Several other studies cited therein (León-Jiménez et al., 2021) showed that aluminium was detected at high concentrations in lung biopsy samples of exposed workers in different occupations (e.g., miners, sandblasters) and that occupational exposure to aluminium has been associated with adverse lung outcomes. Although these studies suggest that aluminium may potentiate the lung toxicity of RCS, the presence of aluminium was shown to decrease reactivity and hence toxicity of crystalline silica in animal studies (Natrass et al., 2017), likely due to aluminium substituting and occluding the silica surface from producing an inflammatory response (Natrass et al., 2017; Horwell et al., 2012). Further studies are required to elucidate the role of the aluminium in engineered stone toxicity.

Particle size

The particle size distribution of dust generated from engineered stone and natural stone represents a potential point of difference between these two stone types, with implications for their exposure and toxicological profiles. Existing evidence suggests that the overall particle size distributions of natural stone dust tend to be comparable to engineered stone (Ramkissoon et al, 2022; Hall et al, 2022). However, some studies have shown that engineered stone samples may generate higher proportion of

exceptionally fine particles compared to both natural stone and other engineered stone samples, indicating variability within the engineered stone category (Ramkissoon et al, 2022). Moreover, the particle size distribution is dependent on the mechanical processes applied to the stone. Dust generated from polishing, for example, contains a higher proportion of smaller particles compared to that generated by cutting (Thompson and Qi, 2023; Hall et al, 2022).

Ultrafine particles (UFPs), are particles that have a diameter on the nanoscale, typically less than 100 nanometres (nm). UFPs were reportedly generated during the processing of both engineered stone (Carrieri et al, 2020; Noa et al, 2019) and natural stone (Kouam et al, 2022). However, the existing evidence regarding the difference in concentrations of UFPs between natural stone and engineered stone is inconclusive. Some studies indicated that engineered stone produced higher concentrations of UFPs compared to natural stone (Carrieri et al, 2020; Noa et al, 2019). For example, a comparative study between natural stone and engineered stone demonstrated a multimodal particle size distribution in which resin-based engineered stone samples containing high-silica exhibited a primary peak concentration in the nanometre range (< 100 nm), whereas natural stone and low-silica sintered stone exhibited similar particle size distributions with peak concentrations observed between 150 to 400 nm (Carrieri et al, 2020). Other studies reporting a multimodal distribution of dust particles did not find any difference between natural stone and engineered stone in terms of the peak concentration modes (Hall et al, 2022; Thompson and Qi, 2023). Real-time nanoparticle counters or cascade impactors capturing dust fractions to <100 nm size (e.g. Mini-MOUDI, 10-stage impactor 10 µm to 0.056 nm), may contribute to more accurate exposure monitoring.

3.2 Risk Profile of Engineered Stone

This section relates to research questions 1 and 2 and presents the available evidence outlining the risk of silica dust exposure and associated health risks depending on the silica content of bulk engineered stone material. It further discusses whether there is evidence to support a cut-off/threshold (see Glossary for term definition) level of crystalline silica in stone products at which risk is substantially changed between high-and low-risk.

Research highlights

The extent of health risks from crystalline silica dust exposure varies depending on the crystalline silica content of engineered stone. While research specifically comparing the risk associated with different silica content in engineered stone is limited, there is evidence to suggest that exposure to dust from a higher crystalline silica content product can increase the risk of silicosis. Epidemiological studies provide evidence of an exposure threshold “tipping point” for crystalline silica exposure, beyond which risk of developing and progressing disease is high. However, the actual precise exposure threshold is unknown.

Health risks are associated with airborne silica dust exposure, not the silica content of the bulk material. Silica dust exposure is in turn determined by several factors such as bulk crystalline silica content, manufacturing processes and dust control measures in place that influence the overall exposure to respirable crystalline silica (RCS). It would be difficult to collect epidemiological evidence linking exposure to specific crystalline silica percentage in slabs and likelihood of health effects, partly because the percentage silica in the slab varies with manufacturer and from slab to slab for some products, and partly because the SDS statement of the percentage crystalline silica in the slab may not be accurate (Kumarasamy et al 2022).

Research gaps

Further research is needed to establish whether there is an exposure threshold to crystalline silica for which the risk of ill health is unacceptably increased. It is unclear whether the exposure should be measured as intensity or cumulative exposure to crystalline silica (or both). It is unclear whether crystalline silica from natural stone has the same risk of silicosis (and other silica-related diseases) as silica from engineered stone. It is possible that the binders/pigments potentiate disease, but data were not identified that established this.

Recent discussion on the ban of engineered stone has included discussion of a threshold level of crystalline silica content in the engineered stone slab that would differentiate between a 'high-risk' and a 'low-risk' material. *It is, however, too simplistic to directly link product composition (e.g. silica content) to health risk.* Health risks are more accurately associated with total airborne silica dust exposure, which are in turn determined by several factors such as bulk silica content, manufacturing processes and dust control measures in place that influence the overall exposure to respirable crystalline silica (RCS). These factors are discussed in further detail below, drawing particular attention to current gaps in knowledge.

Cumulative exposure (mg RCS/m^3 x years of exposure) to RCS is suggested to be the most important risk factor in the development of silicosis among exposed workers (Leso et al., 2019; Leung et al., 2012; Hedlund et al., 2008). Historically, miners, stonecutters, sandblasters, construction and quarry workers have been considered high-risk populations as they are frequently exposed to high levels of RCS for long periods of time, hence have high cumulative exposures (Poinen-Rughooputh et al., 2016). However, RCS exposure intensity can dramatically influence risks, even when average 8-hour cumulative exposures are comparable and below exposure limits. Some studies have shown that the health effects of short-term, very high concentration exposures to RCS are three times greater than long-term lower concentration exposure to similar amounts of RCS (Buchanan et al., 2003; Barnes et al. 2019). In occupations with high exposure intensities such as denim blasting and engineered stone fabrication, more severe and accelerated forms of silicosis have been diagnosed among workers (Akgun et al., 2006; Edwards and Knight, 2019). In a recent report to WorkSafe Victoria, researchers at Monash University (2021) showed that installers were among the workers in the engineered stone industry with the highest intensities of exposure to RCS, and highest prevalence of disease, suggesting that exposure intensity affects risk. In the engineered stone context, silica exposure intensities have been defined as the proportion of time using engineered stone and dry processing (without water suppression) (Glass et al., 2021).

Determinants of exposure to respirable crystalline silica

Several factors may influence the level and intensity of exposure to RCS in the workplace.

- Bulk composition of materials

As briefly outlined in Section 3.1, engineered stone typically contains high levels of crystalline silica, often > 90% by weight of their bulk composition (Mandler et al., 2023; Rose et al., 2019). More recently, 'low-crystalline silica' engineered stone has been marketed, containing between 5-50% crystalline silica by weight (Pisaniello & Ramkissoon, 2023). Building on this information, the peer reviewed literature points to a good agreement between the crystalline silica content of bulk stone and airborne RCS levels (Qi & Echt, 2016; Ramkissoon et al., 2022). For example, in a laboratory-controlled experiment, Thompson and Qi (2023) determined the silica content of different stone types, which had manufacturer-claimed 90% (Stone A), 50% (Stone B) and 72% crystalline silica by weight (natural stone, Granite). Bulk dust settled on the floor contained 60% (Stone A), 23% (Stone B) and 30% (Granite) crystalline silica by weight, and the RCS contents of emissions generated by processing the stones were proportionately comparable, at concentrations of 15.6 mg/m^3 (Stone A), 6.31 mg/m^3 (Stone B) and 10.8 mg/m^3 (Granite). Recently, a study has shown that low-silica engineered stone containing 10% and 50% crystalline silica emitted proportionately low RCS when processed, of 7% and 30% respectively (Pisaniello & Ramkissoon, 2023).

The above evidence suggests that high crystalline silica content engineered stone are associated with high levels of RCS, and the potential for increased risk of health problems. It is tempting to propose that lower-silica engineered stone products may to lead to lower RCS exposures, however, this is not clear, and the specific cut-off level of crystalline silica in the bulk engineered stone slab at which risk of ill health would be unacceptably increased is unknown.

Quartz and cristobalite are both found in engineered stone slabs, (see section 3.1 - Silica polymorphs) (Mandler et al., 2023; Ramkissoon et al., 2022; Hall et al., 2022). Both forms of silica may contribute to exposure during processing, and both should be included in the percentage of silica ascribed to the bulk engineered stone.

- Processing tasks

Apart from the type of material used, the abrasiveness of tasks has been shown to be a significant determinant of RCS exposure (Van Deurssen et al., 2014; Healy, 2014). In the engineered stone industry, cutting and grinding using hand-held power tools are reportedly the tasks that pose a greater

risk of exposure. Even when the hand tool work is wet, exposure can be high (Qi & Lo, 2016). Air sampling at a stone countertop fabrication workshop in 2015, measured average task-based RCS exposures of 0.062 mg/m^3 for workers involved in polishing, 0.091 mg/m^3 for workers involved in surface lamination, and 0.148 mg/m^3 for those involved in grinding of engineered stone (Qi and Echt, 2016). Healy (2014) reported similar results for workers processing naturally high-crystalline silica containing building materials such as sandstone, showing that fabrication tasks, particularly cutting and grinding, can be a determinant of overexposure to RCS.

Apart from the level of RCS emitted, size of particles emitted can also be influenced by active processing tasks. Studies have shown that polishing generated higher concentrations of airborne dust, with also a higher proportion of small particles, compared to cutting (Hall et al., 2022).

Although not considered a fabrication task, cleaning and housekeeping processes can also be a source of RCS exposure in engineered stone workshops, if appropriate control measures are not in place. Short-term high exposures to crystalline silica were observed when laminators used compressed air to clean engineered stone slabs among other tasks (Qi & Echt, 2016). Other potential sources of exposure are the re-suspension of dust from wet slurry and settled dust deposited on floors and equipment and the use of recycled water that is ineffectively filtered, leading to a build-up of silica dust in the water over time, and the mist arising from water suppression activities (WorkSafe NSW, 2022).

- Type of engineered stone

Variations in manufacturing processes give rise to different types of engineered stones. The main ones are resin-based engineered stone and sintered engineered stone – see Section 3.3. From a processing perspective, there is limited evidence on the relative RCS exposures comparing resin-based and sintered and porcelain based engineered stone. Hall et al. (2022) compared dust concentrations (not specifically RCS) arising from dry-cutting and polishing resin-based engineered stone with sintered engineered stone. They also contrasted inhalable, thoracic and respirable dust fractions. Focussing on respirable dust only, sintered engineered stone (n=1) concentrations (7.6 mg/m^3) were less than resin-based engineered stone concentrations (12.6 and 8.3 mg/m^3) during cutting but similar during polishing (0.5 mg/m^3). In this comparison, it should be noted that the crystalline silica content of the sintered engineered stone was low (6.9% by weight) versus 67% and 89% by weight for the two resin-based engineered stone. It may be considered that most of the dust from the sintered stone was not crystalline silica.

- Control measures

Engineering control measures commonly used in the engineered stone industry are on-tool water suppression of dust (wet processing) and/or dust extraction devices (on tool dust extraction, local exhaust ventilation, LEV). Water jet cutting *via* the use of CNC machines (computer numerical control) is suitable for the factory setting, but not for on-site installation. Automation is likely to result in lower exposure than hand tools due to the operator position being further from the cutting edge.

Beyond what is now being mandated by the model WHS Regulations, a combination of control measures is often advised for controlling RCS exposures to below the current Australian Workplace Exposure Standard (WES) of 0.05 mg/m^3 to prevent disease. A combination of wet methods and LEV, for example, can suppress dust more effectively, by a factor of 10 or more, compared to if a single control measure was applied (Cooper et al., 2015; Johnson et al., 2017). Cooper et al. (2015) reported short-term (30 minutes) RCS levels of 44 mg/m^3 for dry activities, which reduced to 4.9 mg/m^3 through the adoption of wet methods and further reduced to 0.6 mg/m^3 when the latter measure was combined with LEV. This is because workers using predominantly wet methods may still carry out brief dry operations, for example during finishing processes such as smoothing the edges or holes. Dry work is not uncommon during in-home installation of slabs, where water suppression methods may not be available, and finishing tasks end up being carried out manually (i.e. dry finishing). Wet dust suppression methods in combination with on-tool LEV may therefore be required to prevent overexposure to RCS while working with engineered stone (Qi & Echt, 2016; van Deurssen et al., 2014; Gaskin et al., 2018).

The continued use of multiple control measures when processing engineered stone to reduce exposure, e.g. wet-cutting and respiratory protection, will continue to be vital regardless of the silica content of the engineered stone product being processed.

- Organisational and psychosocial factors

Organisational and psychosocial factors have not generally been considered determinants of exposure in occupational hygiene (van Deurssen et al., 2014). However, they can add value to baseline

monitoring assessments to develop and implement targeted intervention strategies to reduce risks of overexposure to RCS. Van Deurssen et al. (2014) explored the effect of psychosocial factors in relation to occupational exposure to RCS in the construction industry. Their results showed that psychosocial factors such as knowledge, beliefs, risk perception and motivation played a role in the extent of RCS exposure in this industry. They suggest that the interplay between technical, organisational and psychosocial factors should be considered when developing intervention strategies.

Current evidence of a threshold silica exposure

When crystalline silica particles are inhaled, smaller particles can reach the lower respiratory tract and the gaseous exchange zones. After being phagocytosed by macrophages, they can persist and then cause an inflammatory process that is mediated by the production of reactive oxygen species (ROS). The inflammation caused by ROS generation damages the pulmonary parenchyma and subsequent repair/regeneration process leads to fibrogenesis and carcinogenesis (Leso et al., 2019; Leung et al., 2012; Mossman & Churg, 1998). In 2011, Cox (2011) suggested that an equilibrium exists between crystalline silica burden in the lungs and ROS production, implying a threshold "tipping point" for silica, which predicts that progression to disease will occur even after exposure cessation, due to continued ROS production. His model was supported by several animal studies which showed that relatively low exposures to RCS, probably < 0.1 mg/m^3 induced "largely self-limiting and reversible" effects in rats while higher exposures induced "self-sustaining escalation to a permanent high-ROS state", progressing to disease even after exposure cessation (Porter et al., 2002; 2004).

More recently, León-Jiménez et al. (2020) reported rapid disease progression among silicotic engineered stone workers, even after exposure had ceased. Crystalline silica remains in the lung after exposure to dust in air ceases. This explains why silicosis appears after retirement (Graham et al 2001) and in the Turkish denim blasters, years after the process was stopped (Akgun et al 2015).

Similarly, Velan et al. (1993) showed that low-intensity exposure to RCS led to reversible inflammatory reactions in mice, while higher intensity exposure elicited progressive pulmonary inflammation, suggesting a threshold of crystalline silica burden at which alveolar clearance mechanisms get overwhelmed. The link of particle burden to pathogenesis of disease has been documented for asbestosis and silicosis (Mossman & Churg, 1998). In the case of asbestosis, there is a clear relationship between high retained fibre concentration in the lung and the development of asbestosis. Similarly, a high pulmonary silica burden is associated to an increased risk of silicosis as well as increasing pathological grade of silicosis, although this relationship is complicated by many factors, including the properties of the silica particle (rather than mass or volume) (Nagelschmidt, 1960; Mossman & Churg, 1998). Studies by Pavan et al. (2019; 2020) have importantly shown how the pathogenicity of crystalline silica is highly dependent on the surface chemical properties of the particle, in particular the arrangement of silanol groups (see Glossary for term definition), which are formed upon fracture. The presence of impurities such as metal ions within the crystalline structure of silica can also influence particle reactivity and toxicity (further discussion in Section 3.1).

Overall, although there is evidence that a higher crystalline silica content confers a higher risk profile to a product, it is not possible to establish a specific crystalline silica content level that represents a demarcation of high and low risk product. It is also important to note that a threshold level of silica alone may not provide a complete picture of the risk associated with a product. Other factors contribute to the overall risk of the product, for example, the chemistry of the silica particles generated may also influence pathogenesis of disease.

3.3 Engineered Stone Manufacturing and New Products

In order to appreciate the residual hazard after manufacture, it is important to understand the original engineered stone components and whether they change during the manufacturing process or during machining due to variable tools/conditions. For example, sintered engineered stone is generally harder than resin-based engineered stone, and may involve higher temperatures for abrasive action. Furthermore, the engineered stone field is rapidly evolving with new products in development and consideration should be given regarding what risk they may pose to workers handling these materials. This section relates to research questions 5 and 8.

Research highlights

Resin-based engineered stone is comprised of organic and inorganic constituents, whereas sintered stone and porcelain have only inorganic ingredients. Hence, processing resin-based engineered stone can lead to more variable hazard emissions compared to sintered stone and porcelain, which have already been subjected to high temperatures during manufacture. On this basis there is potential for diverse health effects from resin-based engineered stone, which is consistent with the international engineered stone associated silicosis experience. That is, most of the cases of engineered stone related disease relate to older style engineered stone containing resin.

For resin-based engineered stone, the airborne dust may be partially or fully coated with organic resin, which may influence its electrical properties and modify the interaction with lung macrophages. There is little published evidence in that regard, although the resin may have an initial protective effect (Pavan et al, 2021). Furthermore, the charge on airborne crystalline silica particles has long been considered a factor in its toxicity (Bagchi, 1992). In addition, the airborne quartz aerodynamic behaviour is different from other industrial materials (Pensis et al, 2010).

Two areas of consideration relate to emerging engineered stone products containing inorganic waste. Emission profiles during processing tasks for these new-generation products has yet to be reported. In addition, some further consideration of emerging benchtop materials, such as porcelain products and the risks associated with their processing seems warranted.

Engineered stone components

To recap, in traditional resin-based engineered stone, the main ingredients are crystalline silica, inorganic fillers, inorganic pigments, organic resins and additives (e.g. polymerisation initiators and adhesion promoters), as discussed in section 3.1. The actual composition will be dependent on the manufacturer and product. Exact details are generally not provided in their Safety Data Sheets (SDS) (Kumarasamy et al, 2022). It should be noted that the composition has historically been set to achieve a technical specification (e.g. appearance and porosity), without occupational health consideration. The technical specifications apply to the final bulk product, and generally do not include information such as VOC off-gassing. However, these are important considerations, as shown by Hall et al. (2022) who investigated the VOCs emitted during resin-based engineered stone processing. As discussed in Section 3.1, as resin-based stone samples were heated from 20°-140°C, VOCs were emitted in variable amounts depending on the stone. Although the authors did not comment on how these VOCs arose, it can be surmised that the emissions reflect incomplete polymerisation, with release of solvent and monomers through residual pores in the stone.

For sintered stone and porcelain there can be many different inorganic constituents, but there is no organic resin. There is increasing use of recycled materials (Liu et al, 2023) for benchtop products. Due to the lack of information on materials used in engineered stone, there was initial concern about the potential for asbestos contamination. This has had limited investigation by Australian jurisdictions and there is no evidence for appreciable levels of asbestos.

Manufacturing methods

Resin-based engineered stone

In traditional resin-based engineered stone manufacture, there are multiple steps involving vibro-compaction under vacuum and moderate heating. The vibro-compaction under vacuum is a mild mixing process that should not alter the inorganic composition or size of inorganic particles, which are simply pressed together (*Pers. Comm.*, Mr Pierpaolo Tassone, Chair of the ISO Technical Committee 328, May 2023).

Sintered engineered stone

This is a high temperature (typically 1200°-1400°C) and high pressure process, mimicking the formation of natural stone such as granite. The crystalline silica already present is unlikely to change, but there is the possibility of the formation of crystalline silica from amorphous silica (Zhang et al, 2018). Dekton, manufactured by Cosentino, may be considered a sintered engineered stone product, with raw materials including a blend of glass, quartz and porcelain according to manufacturer details (Cosentino, 2023).

Porcelain

The process of making porcelain involves pressing the raw materials (clays, feldspar and silica) and firing at high temperatures (typically 1000°-1300°C) to achieve a hard external surface of low porosity. There is no use of high pressure. The crystalline silica already present is unlikely to change to different polymorphs. Porcelain is different from general ceramics which are fired at lower temperature which can be brittle and porous, and so may be unsuitable for kitchen benchtops.

Coated engineered stone

This involves an additional manufacturing step. Some engineered stone products have a fibreglass backing (Cosentino, 2023).

Coated natural stone

Sensa® by Cosentino® includes natural stone such as granite and quartzite, with a Senguard® anti-stain surface treatment

Health risk factors from processing or heating (20°-140°C) different types of engineered stone

Crystalline silica

As briefly explained in Section 3.1, the evidence on the relative RCS exposures comparing resin-based and sintered engineered stone is limited. Some studies have shown that cutting sintered engineered stone generated lower levels of respirable dust, compared to resin-based engineered stone. The proportion of RCS followed a similar pattern, although this may be a function of the bulk crystalline silica composition as sintered engineered stone contained < 10% crystalline silica compared to >75% in resin-based engineered stone. Studies comparing RCS emissions from processing sintered and resin-based engineered stones of comparable bulk crystalline silica contents have not been identified.

Resins

At least six different types of organic resin have been reported to be included in engineered stone in the peer-reviewed and grey literature. Several were identified by Hall et al. (2022), namely:

- Unsaturated polyester (polyester-styrene)

Organic emissions from processing these stone products included styrene and phthalic anhydride, similar to those reported by Ramkissoon et al. (2023). Curing of an unsaturated polyester resin often involves a radical initiated process involving styrene with peroxides mediated by a cobalt-based catalyst, especially cobalt octanoate. Cobalt has implications for lung toxicity (Stopford et al, 2003) and has been found in engineered stone samples following abrasion (Pavan et al, 2016). However, it appears that cobalt-free and styrene-free unsaturated polyesters are possible (Jansen et al, 2013).

- Polyethylene Terephthalate

Only trace levels of VOCs were detected.

- Epoxy resin

The main VOC emission was benzyl alcohol, which is considered to have low toxic properties.

- Acrylate resin

The main VOC emission was methyl methacrylate, which is a respiratory irritant and dermal sensitiser (Borak et al, 2011).

- Maleic anhydride and phthalic anhydride-based resins

This is reported to be a significant ingredient in new-generation low-silica engineered stone products such as the Quantum Quartz low silica engineered stone (Quantum Q., 2023). Organic anhydride emissions during processing or heating of this particular stone have not yet been explored, but if discovered, emissions could contribute to worker exposure.

- Polyurethane resins

Agrizzi et al. (2022) and Gomes et al. (2021) reported on the use of polyurethanes resin. High temperature degradation of polyurethanes have the potential to release isocyanates, linked to occupational asthma (Boutin et al, 2006).

New-generation and other products

In this section, publicly available grey literature (e.g. SDS) for products described as engineered stone across 10 manufacturers/suppliers was reviewed. These were Caesarstone, Cosentino, Laminex/Essastone, Smartstone, Quantum Quartz/WK Stone, Neolith, Stone Ambassador, Aurea stone/Zenstone, RHF Quartz and YDL stone. In fact, new products are only likely to be identifiable from the grey literature and may require a watching brief to identify new products in the future.

The products can be classified as high-crystalline silica resin-based engineered stone, low-crystalline silica resin-based engineered stone, sintered stone, and other products e.g. porcelain and ceramics. The sintered stone and porcelain material do not contain organic resin, and the hardening entails high temperatures and pressure in the case of sintered stone, and high temperature in the case of porcelain, as described earlier. Porcelain is being used for benchtops (e.g. Neolith) and therefore present a potential risk for worker in terms of dust exposure from processing. There is not currently enough known about the composition of this product to determine if it would meet the definition of engineered stone in the model WHS Regulations, and further work is required to understand any risks it may pose to workers during processing.

All of the products contain crystalline silica in variable amounts, and many entail the use of recycled materials such as glass (amorphous silica) and ceramic waste. Products used for benchtops with predominantly amorphous silica (e.g. Betta Stone) may be problematic in the future as the hazards from processing recycled glass do not seem to be acknowledged. For example, Betta Stone is an Australian product made with recycled glass that is reported to contain <1% crystalline silica according to its SDS. A report on the safety of recycled glass does not discuss the risks to workers from processing emissions from bulk materials containing recycled glass (Winder 2011). This product may not be captured by the current definition of engineered stone (may not contain crystalline silica or natural stone materials), but the emissions produced from processing the recycled glass content may pose a health hazard to workers. Further work to understand the properties of dust produced from recycled glass is required.

Some manufacturers of engineered stone may incorporate feldspars in the production of new low-silica products. Feldspars are minerals containing aluminium and varying amounts of potassium, sodium, and calcium. Previous research has reported contradictory findings regarding the potential risk of exposure to feldspar. While some studies have indicated that samples with a high feldspar content were the least toxic (Becher, et al. 2001), other studies suggest that feldspar dust particles (< 10 µm) may induce cytotoxicity and acute pro-inflammatory responses to a similar or greater degree than quartz (Grytting et al. 2021). A more recent *in vitro* study has provided further insight by demonstrating that the conflicting results can be attributed to the presence of different varieties of feldspar minerals highlighting certain feldspars, such as Ca-feldspar (99% anorthite) and Na-feldspar (69% albite), exhibit greater toxicity than K-feldspar (71% microcline) (Grytting et al. 2022).

3.4 Further Considerations

Further considerations and gap analysis in the context of establishing a silica content threshold relates to understanding the technical limitations in detection of silica content in *bulk* material. Of additional consideration is the investigation of any other evidence that would inform the impact analysis on a prohibition on the use of engineered stone. This section relates to research questions 9 and 10.

Research highlights

Understanding the crystalline silica content in bulk (slab) engineered stone products currently relies on information provided by manufacturer Safety Data Sheet (SDS). There is not currently available a non-destructive, direct, real-time detector technique to screen and quantify/verify the crystalline silica content in bulk engineered stone material.

Research gap

In order to support the establishment of a crystalline silica content threshold in bulk engineered stone material, there is a need to investigate novel real-time, direct detection technologies to address some of the limitations.

Understanding the crystalline silica content in bulk (slab) engineered stone products currently relies on information provided by manufacturers' Safety Data Sheet (SDS). Some studies have reported testing composition of bulk engineered stone products for crystalline silica content using manual crushing or abrasion techniques followed by analysis using X-Ray Diffraction (XRD) and other spectroscopic techniques (Ramkissoon et al, 2022; Carrieri et al, 2020; Kumarasamy et al, 2022; Ichikawa et al, 2022). There is increasing interest and exploration of technology advances related to real-time detection of crystalline silica, although these have focussed on dust rather than bulk (slab) materials. The question remains, how to meet the challenge to detect crystalline silica content accurately and rapidly in bulk products? And, given the popularity of emerging low crystalline silica (high amorphous silica) engineered stone products, is there a need to accurately detect their amorphous silica content as well? To the authors' knowledge, there is not currently available a non-destructive, direct real-time detection technique available to screen and quantify the crystalline or amorphous silica content in bulk engineered stone slabs (e.g. at border control, or when working with engineered stone that has previously been installed).

To support the establishment of a silica content threshold, investigating novel real-time, direct detection technologies may be required to address some of the current limitations. Technology already developed for other purposes may represent value for money if explored.

4. Concluding remarks

This review gave irrefutable evidence of the variability of hazards associated with engineered stone fabrication, which would impact on a complete or partial prohibition of the use of engineered stone in Australia. Evidence supports that factors such as higher crystalline silica content, resin decomposition products and potentially small sized-particles generated during engineered stone processing may be contributing to the increased pathogenesis of severe disease in engineered stone workers compared to other silica-exposed workers. While there is ample evidence linking respirable crystalline silica exposure frequency and intensity to the pathogenesis of accelerated silicosis, the toxicological mechanisms by which other exposure hazards present in engineered stone emissions impact risk are unclear.

New-generation low-crystalline silica engineered stone products are already on the market and commercially popular due to their marketing as 'safer' alternatives to high-crystalline silica containing engineered stone. From the evidence presented in this report, it seems reasonable to associate lower-crystalline silica containing engineered stone to lower risk, compared to currently used engineered stone, however there are several caveats to this statement. Firstly, while lowering the crystalline silica content of bulk engineered stone may result in lower exposure to respirable crystalline silica there is no evidence of a threshold level of crystalline silica in the bulk composition that would differentiate a 'high-risk' and a 'low-risk' product. Secondly, lower-crystalline silica engineered stone products contain a similar resin content to high-crystalline silica engineered stone, which may be of toxicological importance. Other emerging benchtop products containing materials such as recycled glass

(amorphous silica) should also be considered in toxicological assessment. Given the enormous harm that engineered stone has caused, and continues to cause even after exposure cessation, it is crucial if low-crystalline silica engineered stone replaces currently used ones, the risk to workers is understood. It is also crucial to identify the components of engineered stone that pose the greatest risk to health, and regulate the products, to prevent further disease. This is a key research priority. Thirdly, the key determinant of silica-related lung disease risk is how much crystalline silica is inhaled and one factor in this may be the bulk crystalline silica percentage of stone materials. But, as discussed in this report, the level and intensity of airborne silica dust exposure is dependent on many factors such as the fabrication tasks and control measures employed. This suggests that a cut-off/threshold for crystalline silica should be based on airborne RCS exposure data, not the crystalline silica content of the bulk material.

Finally, the evidence suggests that there are artificial silica-containing materials on the market which may warrant further consideration by Safe Work Australia despite not meeting the current Safe Work Australia definition of engineered stone.

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6. Appendices

6.1 Research Questions

The objectives of the research were to provide scientific evidence to support responses to the 10 Research Questions provided by Safe Work Australia, as listed in Table A1.

Table A1: Research Questions provided by Safe Work Australia to inform recommendations for the prohibition of engineered stone in Australia.

Question number	Research Question
1	Does the available evidence support a prohibition based on a threshold level of silica content? If so, what is the threshold? Does this threshold define the threshold between a high-risk and a low-risk product?
2	What evidence is there to describe how risk differs between engineered stone with differing silica content (e.g. 95% vs 60% vs 40%)?
3	Is there evidence that the level of respirable crystalline silica (RCS) generated when stone is processed is higher for engineered stone compared to natural stone, relative to silica content? Does the RCS generated differ in any other way?
4	Do compounds in engineered stone other than crystalline silica (e.g. resin, pigments, amorphous silica, aluminium) present an additive risk, or exacerbate the risk, posed by RCS to workers?
5	Do different manufacturing methods for engineered stone affect the risk profile (e.g. heat curing vs sintering)?
6	Are there other particles, such as nanoparticles, generated during processing of engineered and natural stones that are hazardous? If so, is there is any difference between particles generated from engineered and natural stones?
7	Are there any other differences between engineered stone and natural stone that contribute to risk?
8	Are there other products in development that would not be captured by the definition of engineered stone, but which may pose risk to workers?
9	What is required to determine the silica content in engineered stone slabs? Are there technical limitations to the detection/analysis that may be relevant to the establishment of a silica content threshold?
10	Is there any other evidence that would inform the impact analysis on a prohibition on the use of engineered stone?

6.2 Additional Methods information

A systematized literature review was undertaken to address ten specific research questions. In order to streamline the search process, the research questions were grouped under three main topic areas: “Material Science”, “Risk profile” and “Manufacturing and new products”. Additionally, the topics of "Silica Detection and Analysis" and "Other Considerations" were also explored. A systematized approach was undertaken to identify relevant peer-reviewed research articles and national and international agency documents on each topic. Search terms based on keywords and phrases associated with each topic area were constructed and utilized across various databases (as shown in Table A2). Major scientific databases namely, PubMed, Web of Science and Scopus, were searched to identify papers addressing the research questions. The search terms employed and the total number of articles and reports retrieved are presented in Table A2. Grey literature search was conducted using CDC WONDER, Grey Literature Report, Open Knowledge Repository (World Bank) and MedNar.

Within the topic of "Material Science," articles were carefully reviewed to identify studies conducted in laboratories and field settings that focused on the characterization of physico-chemical properties of engineered stone and natural stone and their dust emissions. Similarly, articles falling under the "Risk Profile" category were analyzed to explore a dose-response relationship between adverse health effects caused by respirable crystalline silica (RCS) in engineered stone, considering short- and long-term exposures at varying concentrations, along with other hazards associated with engineered stone, using human and animal data. The remaining articles were scrutinized for specific inquiries related to that particular topic. The entire process of article identification and screening is depicted in the PRISMA flow diagram (Figure A1).

Table A2: Search terms and the number of articles retrieved from different databases.

Topic	Search terms	Databases		
		Pubmed	Web of Science	Scopus
Material science	((Engineered stone) OR (Artificial stone) OR (Sintered stone)) AND ((Natural stone) OR (Granite) OR (Sand stone) OR (Marble)) AND ((Ultrafine particles) OR (Nano) OR (dust) OR (Resin) OR (Amorphous silica) OR (Metal) OR (Trace Metal) OR (Volatile organic compounds) OR (Particle size) OR (Pigment) OR (Aluminium) OR (QUARTZ) OR (Cristobalite))	309	476	255
Risk profile	((Engineered stone) OR (Artificial stone) OR (Sintered stone)) AND ((dust) OR (Silica) OR (Quartz) OR (Cristobalite) OR (Silica threshold) OR (RCS)) AND ((Silicosis) OR (Accelerated silicosis) OR (risk) OR (Exposure) OR (Toxicity))	128	126	104
Manufacturing and new products	((Engineered stone) OR (Artificial stone) OR (Sintered stone) OR (Porcelain) OR (Feldspar)) AND ((new products) OR (Manufacturing) OR (next generation) OR (Recycled glass) OR (Amorphous) OR (Sintering) OR (Heat curing)) AND ((Silicosis) OR (Accelerated	248	222	220

	silicosis) OR (risk) OR (Exposure) OR (Toxicity))			
Detection and analysis	((Engineered stone) OR (Artificial stone) OR (Sintered stone)) AND ((detection) OR (chemical analysis) OR (sample) OR (quantification) OR (pyrolysis) OR (XRD)) AND ((dust) OR (Silica) OR (Quartz) OR (Cristobalite))	153	137	90

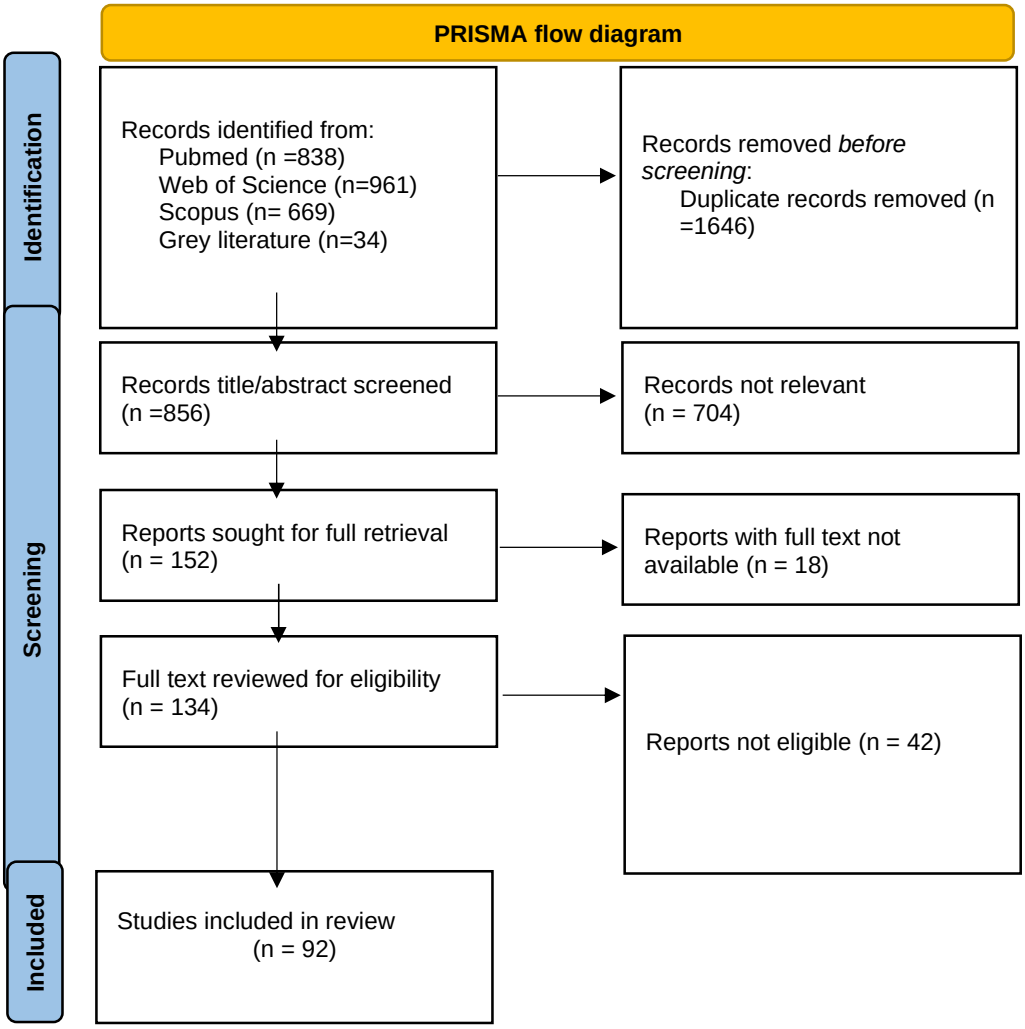

Figure A1: PRISMA flow diagram for literature review and gap analysis.

An exemplar of critical appraisal outcomes (applying the Ten Key Questions tool) (Young and Solomon, 2009) for literature relevant to Research Question 4 is presented in Table A2. This relates to the research question: *Do compounds in engineered stone other than crystalline silica (e.g. resin, pigments, amorphous silica, aluminium) present an additive risk, or exacerbate the risk, posed by RCS to workers?*

Table A2: Exemplar of critical appraisal outcomes (applying the Ten Key Questions tool) (Young and Solomon, 2009) for literature relevant to Research Question 4 (presented alphabetically).

Article	Is the study question relevant?	Does the study add anything new?	What type of research question is being asked?	Was the study design appropriate for the research question?	Did the study methods address the most important potential sources of bias?	Was the study performed according to the original protocol?	Does the study test a stated hypothesis?	Were the statistical analyses performed correctly?	Do the data justify the conclusion?	Are there any conflicts of interest?	Total mark	Ranking
Clouter et al. 2001	Yes	Yes	Comparative. Workplace samples differed in toxicity from standard quartz.	Yes	Yes	Yes	Yes	Yes	Yes	No	**10**	**High**
Di Benedetto et al. 2019	Yes	Yes	Comparative. ES dust composition from different processing technique.	Yes	Yes	Yes	Yes	Yes	Yes	No	**10**	**High**
Fubini and Hubbard 2003	Yes	Yes	Exploratory review; Ralationship/Causal. ES ROS and inflammation/fibrosis.	Yes	No	Yes	No	N/A	Yes	No	**7**	**High**
Ghiazza et al. 2010	Yes	Yes	Comparative. Silica form and surface reactivity/cellular responses.	Yes	Yes	Yes	Yes	Yes	Yes	No	**10**	**High**
Hall et al. 2022	Yes	Yes	Comparative. Variability in emissions between natural and ES stones.	Yes	Yes	Yes	No	N/A	Yes	No	**8**	**High**
Horwell et al. 2012	Yes	Yes	Relationship/Causal. Volcanic RCS characteristics and pathogenicity.	Yes	Yes	Yes	Yes	N/A	Yes	No	**9**	**High**
León-Jiménez et al. 2021	Yes	Yes	Relationship/Causal. ES composition and disease development.	Yes	Yes	Yes	No	Yes	Yes	No	**9**	**High**
Maharjan et al. 2021	Yes	Yes	Comparative. Variability in metal ion release across ES types.	Yes	Yes	Yes	No	Yes	Yes	No	**9**	**High**
Merget et al. 2002	Yes	Yes	Exploratory review; Relationship/Casual. Health effects of non-crystalline forms of silica.	Yes	No	Yes	No	N/A	Yes	No	**7**	**High**
Nattrass et al. 2017	Yes	Yes	Relationship/Causal. Cristobalite impurities and toxicity effects.	Yes	Yes	Yes	Yes	Yes	Yes	No	**10**	**High**
Pavan et al. 2016	Yes	Yes	Relationship/Causal. ES composition and cellular response.	Yes	Yes	Yes	No	Yes	Yes	No	**9**	**High**
Pavan et al. 2019	Yes	Yes	Explatory review.	Yes	No	Yes	No	N/A	Yes	No	**7**	**High**
Pavan et al. 2020	Yes	Yes	Relationship/Causal. Silanols and silica particle toxicity.	Yes	Yes	Yes	Yes	Yes	Yes	No	**10**	**High**
Porter et al. 2002a	Yes	Yes	Comparative; Relationship. Pulmonary toxicity differences from blasting different abrasive materials.	Yes	No	Yes	No	Yes	Yes	No	**8**	**High**
Ramkissoon et al. 2022	Yes	Yes	Comparative. Variability in physical & chemical emissions among stone types.	Yes	Yes	Yes	No	Yes	Yes	No	**9**	**High**
Ramkissoon et al. 2023	Yes	Yes	Descriptive. VOC release from ES cutting.	Yes	Yes	Yes	No	N/A	Yes	No	**8**	**High**
Thompson and Qi 2023	Yes	Yes	Comparative. Natural vs ES emissions.	Yes	No	Yes	Yes	Yes	Yes	No	**9**	**High**