

# Engineered stone is now banned. How safe are new-generation low and no-silica stone materials?

## Final Report

*Prepared for the Mining and Quarrying Occupational Health and Safety Committee (MAQOHSC)*

### Research Team:

Dr Chandnee Ramkissoon, Prof Graeme Zosky, Assoc Prof Sharyn Gaskin

### Supported by

Dr Yong Song, Dr Lishi Cai, Dr Katherine Southam and Vibha Neupane

The University of Adelaide

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## Executive Summary

Engineered stone products containing >1% crystalline silica are now banned in Australia due to their link to rising cases of silicosis among stone benchtop industry workers. Although this ban at the highest level of the hierarchy of controls for occupational health and safety- ‘*elimination*’- in reality, these products have been rapidly substituted by stone benchtop alternatives in the form of no-silica engineered stone and low-silica products such as porcelain, ceramic, sintered stone, and natural stone. Currently, there is limited scientific evidence to confirm whether these substitute benchtop materials are actually safer than their high-silica predecessors.

This study aimed to evaluate the hazard potential of dust generated from mechanically processing new-generation low- to no-silica stone alternatives (n=10). Specifically, the objectives were to: (1) characterise the physical and chemical properties of dust emissions from active cutting of the slabs; (2) assess the inflammatory and cytotoxic effects of the new dusts on lung epithelial cells and macrophages using *in vitro* assays; and (3) develop an infographic that synthesises the research outcomes from the previous objectives to support health promotion efforts aimed at preventing occupational dust diseases in the stone benchtop industry.

Key findings indicated that processing high-silica stone products e.g. high-silica ES and quartzite, a natural stone, generated high levels of RCS (~75%). In comparison, low-silica alternatives e.g. porcelain (5%), ceramic (15%) and sintered stone (7-22%) generated dusts of lower RCS content, while no-silica ES emitted undetectable RCS levels. Dust from no-silica ES slabs contained an average of 12% resin, raising concerns about the potential release of volatile organic compounds (VOCs) during cutting, unlike non-ES (ceramic, porcelain, sintered or natural stone), which contained no resin. Particle size analysis showed that ES generated smaller, more homogenous dust particle distributions compared to non-ES materials, which could influence inhalation risks.

Toxicological testing demonstrated that although low- to no-silica stone dusts were less cytotoxic to lung macrophages, they induced significant inflammatory responses in epithelial lung cells. Particularly, no-silica ES stone and sintered stone triggered pro-inflammatory cytokine production, even more than pure (reference) silica dust in some cases.

These results highlight that despite lower crystalline silica content, new-generation stone products can still pose respiratory health risks through alternative mechanisms. It is crucial to continue monitoring and characterizing emissions from these materials and to maintain rigorous dust control measures in workplaces. This study underscores the importance of worker education about the persistent risks associated with dust exposure from all stone products, not just those high in crystalline silica.

## Introduction

Engineered stones (ES) are artificial stone products which are made by combining high levels of crystalline silica dust with polymer resins and pigments to create aesthetic slabs of various colours and textures. With advantages such as durability, customisation and low costs, they have become commercially popular among consumers wishing to renovate their kitchens and bathrooms. This is evidenced by the rapid growth in the ES industry, now a multibillion-dollar empire. In Australia, ES was used for 60% of the >200,000 residential kitchen and > 400,000-bathroom benchtops installed during the financial year 2021, alone [1]. Unfortunately, this rapid rise in popularity also saw a concurrent rise in occupational lung disease among stone benchtop industry (SBI) workers processing ES, which was attributed to their exposure to high levels of respirable crystalline silica (RCS) during mechanical fabrication of ES benchtops (Fig. 1). Given the aggressiveness of silicosis among SBI workers and rapid disease progression, it was suggested that ES exposures were uniquely toxic. Apart from high levels of RCS, hazards such as ultrafine particles of high surface area, metal ions, resin-associated VOCs have been identified during ES processing and hypothesized to contribute to the pathogenesis of disease in this occupational group [2-5].

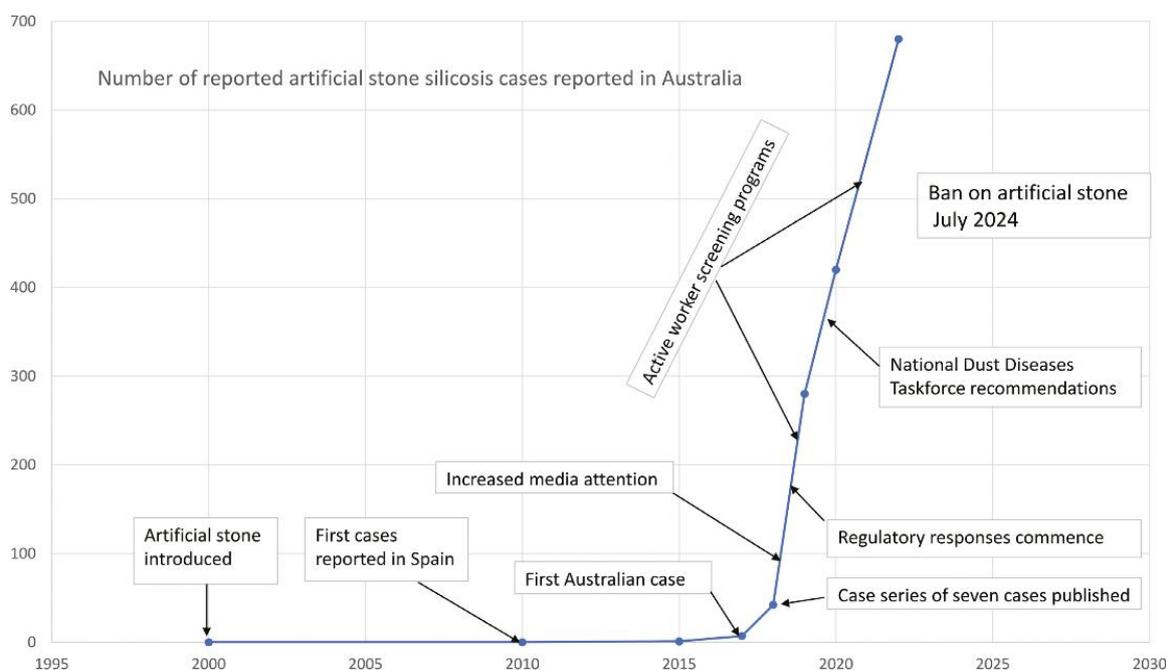


Fig. 1: The rise in occupational silicosis cases among engineered stone workers in Australia, according to Glass et al. (2024) [6].

In the wake of such alarming rates of increase in silicosis in this industry, federal, state and territory governments agreed to ban the use, supply and manufacture (and later import) of ES containing >1% crystalline silica in Australia – first time worldwide. As this ban came into effect, the SBI quickly pivoted to stone benchtop alternatives to meet consumer demands. These alternatives came in the form of no-silica ES (also called zero-silica or silica-free ES), low-silica stone products such as sintered stone, porcelain and ceramic slabs, as well as natural stone [7, 8].

There is currently limited evidence of the risks that inhaling the dusts generated by fabricating these new-generation stone benchtop alternatives could pose to workers. This is particularly important because novel and emerging stone benchtop alternatives, while low in crystalline silica (0-40%), contain similar components as traditional high-silica ES, e.g., resin and metal oxides, together with various filler materials such as recycled glass (containing amorphous silica), feldspars, aluminium hydroxide, etc. – the health implications of which are still underexplored. This project was set up to directly address this knowledge gap. By adopting a multidisciplinary approach linking exposure science to biomedical research, it aimed to explore, for the first time, preliminary research about the types and toxicological implications of new hazards associated with novel low- to no-silica stone benchtop alternatives. Specifically, the objectives were to:

1. Characterise dusts emissions from low- to no-silica stone benchtop products for physical and chemical properties.
2. Assess the toxicological implications of low- to no-silica dusts on lung cells.
3. Create an educational tool (e.g. infographic) to help raise awareness about potential risks from low- to no-silica dust exposures.

The outcomes of this research are likely to contribute to an improved understanding of the hazards that ES workers still face while handling low- to no-silica stone products, thus challenging common (and unevidenced) perception that they are ‘safe’. This can, in turn, inform recommendations of control measures to best protect workers against risks to lung health.

## Methods

### Stage 1: Emissions characterisation

#### *Stone sample acquisition*

Novel stone benchtop alternatives available for kitchen benchtop fabrication (n=10) were sourced from a commercial supplier in Adelaide. They were selected to reflect a breadth in stone type and chemical composition, based on the information extracted from their Manufacturer’s Safety Data Sheets (MSDS). As such, stone samples, herein labelled MH1 – MH10 varied across ES (high and low-silica and no-silica), porcelain and ceramic surfaces, sintered stone and natural stone. Details about their composition is given below:

Table 1: Stone samples explored in this study (n=10, labelled MH1 -MH10). Samples have been grouped based on stone type: Engineered stone (ES; high- and low- silica and no-silica) and non-engineered stone (non-ES) such as porcelain, ceramic surfaces, sintered stone and; natural stone (quartzite). MSDS is Manufacturers’ Safety Data Sheet.

Stone type	Stone ID	Category	MSDS information		
			Bulk crystalline silica (%)	Resin (%)	Other*
ES	MH1	High-silica	70 – 90	5 – 15	Rutile (TiO <sub>2</sub> ) 0 – 2.5%
	MH2	Low-silica	<28	n.d <sup>†</sup>	Recycled materials 56%
	MH3	Silica-free	0 <sup>#</sup>	10	Silica, fused 89% TiO <sub>2</sub> 1%
	MH4	Silica-free	0	Not available <sup>§</sup>	Not available
	MH5	Silica-free	0	18 – 20	Aluminium hydroxide 78 - 80%
Non-ES	MH6	Porcelain	5 – 11	n.d	Silicoaluminates (clays, kaolins, feldspars) Amorphous silica Zircon (depending on the product) Inorganic or organic additives & pigments
	MH7	Ceramic	15 – 20	n.d	Amorphous phase 60 – 70% Silicoaluminates (feldspars) 5 – 10%
	MH8	Sintered stone	9 – 13	n.d	Kaolin 52% Talc 5% Feldspar minerals 40% Cornish stone 3%
	MH9		0 – 11	n.d	Silicoaluminates Amorphous silica Zirconium silicate Inorganic pigments
	MH10	Natural stone (quartzite)	>98	n.d	Not available

\*Where available, quantitative information of composition has been extracted from the MSDS.

<sup>#</sup>Below the practical limit of quantitation (PQL) of 0.1% for quartz, 0.3% for cristobalite.

<sup>†</sup>n.d: Not detected; stones do not contain resin.

<sup>§</sup>MSDS not supplied.

*Dust generation and collection*

Dust was generated by actively cutting MH1 – MH10 stone slabs, using an angle grinder (Metabo 720 W, 105 mm diamond blade, ~ 10,000 rpm) in a controlled test chamber, as described in Ramkissoon et al. (2022) [4]. Dust emissions were captured in two ways. Respirable dust fractions ( $\leq 4\mu\text{m}$ ) were collected using respirable cyclones such as Higgins-Dewell (Casella Solutions, Maryland, USA), fitted with pre-weighed 25-mm PVC membrane filter (GLA – 5000, SKC Inc., USA) and operating at a flow rate of 2.2 L/min or Particle Impactors (PPI) respirable samplers (No. 225 – 383, SKC Inc., Eighty-Four, PA, USA) fitted with 37-mm filters and operating at a flow rate of 8.0 L/min. Further, dusts that had settled on the bottom surface of the box – ‘settled dust’ fraction - were collected using a brush and transferred into glass vials. All dust samples were stored under cool, dry conditions until further characterization assays were performed.

### *Analyses*

#### Respirable crystalline silica

Quantitative analysis for the RCS content (i.e. quartz and cristobalite) of dust emissions from MH1 – MH10 was done by X-Ray Diffraction (XRD), based on the National Institute for Occupational Safety and Health (NIOSH) analytical 7500 thin film filter method. The detection limit for quartz and cristobalite was estimated to be 0.1% and 0.3 wt.%, respectively. Blank filters were measured with samples, and the difference of the average blank values were used for gravimetric correction [9].

#### Resin

The resin content of respirable dust samples was determined by thermogravimetric analysis (TGA) (Mettler-Toledo, Inc., TGA/DSC 2 STARe System, Columbus, Ohio, USA), using an ultra-microbalance to assess weight change upon pyrolysis. Samples (~10 mg) were heated from 50° to 1000 °C at a rate of 10 °C/minute under nitrogen atmosphere (Flow rate was 50 mL/min).

#### Morphology

The morphology of respirable dust particles was determined by Scanning Electron Microscopy (SEM) (FEI Helios Nanolab 600, USA), following loading of the sample (~1–2 mg) on double-sided adhesive tape and coating with carbon.

#### Particle size

Settled dust fractions<sup>1</sup> were analysed for particle size by laser diffractometry on a Mastersizer 2000 (Malvern Instruments, UK). Dry stone powder samples were dispersed in water until an obscuration level of ~15% was reached. Refraction indices ranged from 1.4 – 1.6, depending on the sample mineralogy.

#### Elemental composition

The settled dust fraction was also analysed for metal elemental content by X-Ray Fluorescence (XRF). No sample preparation was required; the stone dust samples were cast using a 12:22 lithium borate flux to form a glass bead. The content of Fe, Al<sub>2</sub>O<sub>3</sub>, MnO, TiO<sub>2</sub>, CaO, MgO, K<sub>2</sub>O, P, S, Na<sub>2</sub>O, Cu, Ni, Co,

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<sup>1</sup> Size analysis of the respirable dust fractions could not be performed at the time due to a breakdown of the particle size analyzer (Zetasizer Nano ZS, Malvern).

Cr, Pb, Zn, As, Sn, Sr, Zr, Ba, V, Cl was determined by XRF Spectrometry. Although measured, the Si content of the dust samples was not reported as part of the elemental composition.

### Stage 2: Lung cellular responses

#### *Cell culture*

Experiments were conducted at the Menzies Institute for Medical Research, University of Tasmania. Human alveolar epithelial cells (A549; ATCC) were grown in Ham's F-12 K medium (21127030; Gibco) with 10% fetal bovine serum (FBS) and 1% glutamine, while human macrophages (THP-1; ATCC) were cultured in growth medium (RPMI-1640; ATCC) with 10  $\mu$ M Phorbol 12-myristate 13-acetate (PMA, Sigma-Aldrich, UK) and 10% FBS, as described in our previous studies [10-12].

Cells were plated at  $1.05 \times 10^5/\text{cm}^2$  (A549) and  $2.1 \times 10^5/\text{cm}^2$  (THP-1) and exposed to 200  $\mu\text{g}/\text{mL}$  of dust particles, which had been sonicated 30 minutes to prepare dispersions, vehicle (negative control) or standard silica (positive control; respirable cristobalite, Merck, UK) for 24 h at 37°C. Each experiment was repeated eight times to allow for valid statistical comparisons between experimental groups.

#### *Cellular responses*

Two key cellular responses related to lung injury were measured, namely cytotoxicity (cell death) and inflammation. Cytotoxicity was quantified using lactate dehydrogenase (LDH) assay while inflammation was measured through the production of extracellular cytokines using the ELISA assays for interleukin (IL)-8, IL-6, tumour necrosis factor (TNF)- $\alpha$  and IL1- $\beta$ , according to the manufacturer's instructions.

#### *Statistical analysis*

Significant differences among groups were determined using one-way analysis of variance (ANOVA) followed by Dunn's post-hoc tests using SigmaPlot (v. 13; Systat Software, San Jose, CA) and GraphPad Prism (v. 9.0.0(121); GraphPad software, Boston, MA). Principal component analysis (PCA) (v. 20.0; SPSS Inc., Chicago, IL, USA). was performed to characterize the overall cellular response.

### Stage 3: Education tool (infographic) development

An infographic was created to detail the main findings and take-home messages from Stages 1 and 2. It served as a meaningful and easily disseminated tool to communicate scientific findings about the emissions characteristics and toxicological effects of new-generation low- to no-silica stone dusts. Graphical charts including statistical information were generated using GraphPad Prism (v. 9.0.0(121); GraphPad software, Boston, MA). The infographic was designed on Microsoft® PowerPoint® (2019, v. 1808 Build 10417.20007). This resource was developed in consultation with MAQOHSC staff for optimal pitch and messaging of scientific findings.

## Results

### Stage 1: Emissions characterisation

#### *Respirable crystalline silica content*

Unsurprisingly, high-silica ES MH1 generated a high level of RCS (73.5 wt. %) when cut and, low-silica ES MH2 generated low levels of RCS (23.0 wt. %). No-silica ES MH5 and MH6 showed undetectable RCS levels in their airborne fraction – in line with the manufacturers’ reported content for ‘crystalline silica-free’ stone slabs (Table 1). Trace levels of cristobalite were detected in one ES (MH1) and one sintered stone sample (MH9).

Table 2: Respirable crystalline silica (wt.%) and resin (wt.%) contents of airborne dusts generated by actively cutting engineered stone (ES, MH1-MH5) and non-engineered stone benchtop products, namely porcelain (MH6), ceramic (MH7), sintered stone (MH8-9) and natural stone (quartzite, MH10) slabs.

Stone type	Stone ID	Category	Respirable crystalline silica (quartz + cristobalite) (%)	Resin (%)
ES	MH1	High-silica	73.5 (72.5 + 1.00)	14.9
	MH2	Low-silica	23.0 (23.0 + 0.00 <sup>§</sup> )	NA
	MH3	No-silica	< LOD <sup>§</sup>	11.4
	MH4	No-silica	< LOD <sup>§</sup>	12.5
	MH5	No-silica	< LOD <sup>§</sup>	11.0
Non-ES	MH6	Porcelain	4.71 (4.71 + 0.00)	NA
	MH7	Ceramic	15.0 (15.0 + 0.00)	NA
	MH8	Sintered stone	7.32 (7.32 + 0.00)	NA
	MH9		21.9 (19.0 + 2.89)	NA
	MH10	Natural stone (quartzite)	74.9 (74.9 + 0.00)	NA

<sup>§</sup>: Below limits of detection of 0.1% for quartz and 0.3% for cristobalite.

NA: Not Applicable as product contained no resin according to MSDS.

Among non-ES samples, RCS content ranged from ~5% - 22%. Porcelain slab generated the lowest RCS content (4.7%), followed by the ceramic MH7 slab (15.0%). Some variability in RCS content was observed in sintered stone, whereby MH9 generated ~3x as much RCS (21.9%) as MH8 (7.3%), highlighting variability in chemical composition within stone type. Among the non-ES dusts, quartz was the dominant crystalline silica form detected; a small portion (2.9%) of cristobalite was detected only in sintered stone MH9.

Cutting high-silica natural stone MH10, a quartzite, generated ~75% RCS.

Comparable levels of resin were detected in respirable dusts of all ES samples, ranging from 11.0% to 14.9% (average 12.4%, SE 0.68), suggesting that similar amounts of binders are used to manufacture ES slabs, irrespective of the bulk silica composition. Non-ES slabs contained no resin.

### Particle size

The size of the dust particles which *settled* at the bottom of the test chamber after the stone slabs MH1-MH10 were dry-cut was analysed by laser diffraction technology. Results are reported as mass median diameter (MMD) of dust particles, which indicates the size of the dust particles at which 50% of the sample by volume was smaller and 50% was larger.

Table 3: Mass Median Diameter (MMD) of dust particles generated by dry-cutting 10 stone slabs, MH1-MH10.

Stone type	Stone ID	Category	MMD ( $\mu\text{m}$ )
ES	MH1	High-silica	12.2
	MH2	Low-silica	15.0
	MH3	No-silica	19.0
	MH4	No-silica	18.4
	MH5	No-silica	22.2
Non-ES	MH6	Porcelain	34.8
	MH7	Ceramic	46.1
	MH8	Sintered stone	30.3
	MH9		70.7
	MH10	Natural stone (quartzite)	32.3

Particle size analysis showed high variation across stone types, suggesting that dust formation by mechanical processing is different depending on the source material. ES samples generated consistently smaller particles than non-ES samples, which tended to be larger and more heterogeneous as evidenced by their bimodal size distributions (Supp. Info. Fig. S1). The MMD of ES dust particles ranged from 12.2 – 22.2  $\mu\text{m}$  (average  $17.3 \pm 1.7 \mu\text{m}$ ), varying from smallest to largest as follows: High-Si ES MH1 < low-Si ES MH2 < No-Si ES MH4-6. In comparison, non-ES stone, specifically ceramic MH7 and sintered stone MH8 generated larger dust particles, with an average MMD of  $58.0 \pm 12 \mu\text{m}$ . Porcelain MH6, sintered stone MH8 and natural stone MH10 generated similar dust sizes (average  $32.5 \pm 1.3 \mu\text{m}$ ).

### Particle morphology

In comparison to high-Si ES dusts which have sharp edges and conchoidal fractures [2, 4], low-silica and silica-free ES samples such as MH2 and MH3, respectively, exhibited smoother surfaces and rounder edges (Fig. 2A-B).

The SEM images of non-ES dusts such as porcelain MH6 and sintered stone MH9 exhibited smooth edges and less angular features (Fig. 2 C-F), relative to quartzite (natural stone) MH10 particles, which showed conchoidal fractures and roughness typical of quartz obtained by grinding [2, 13].

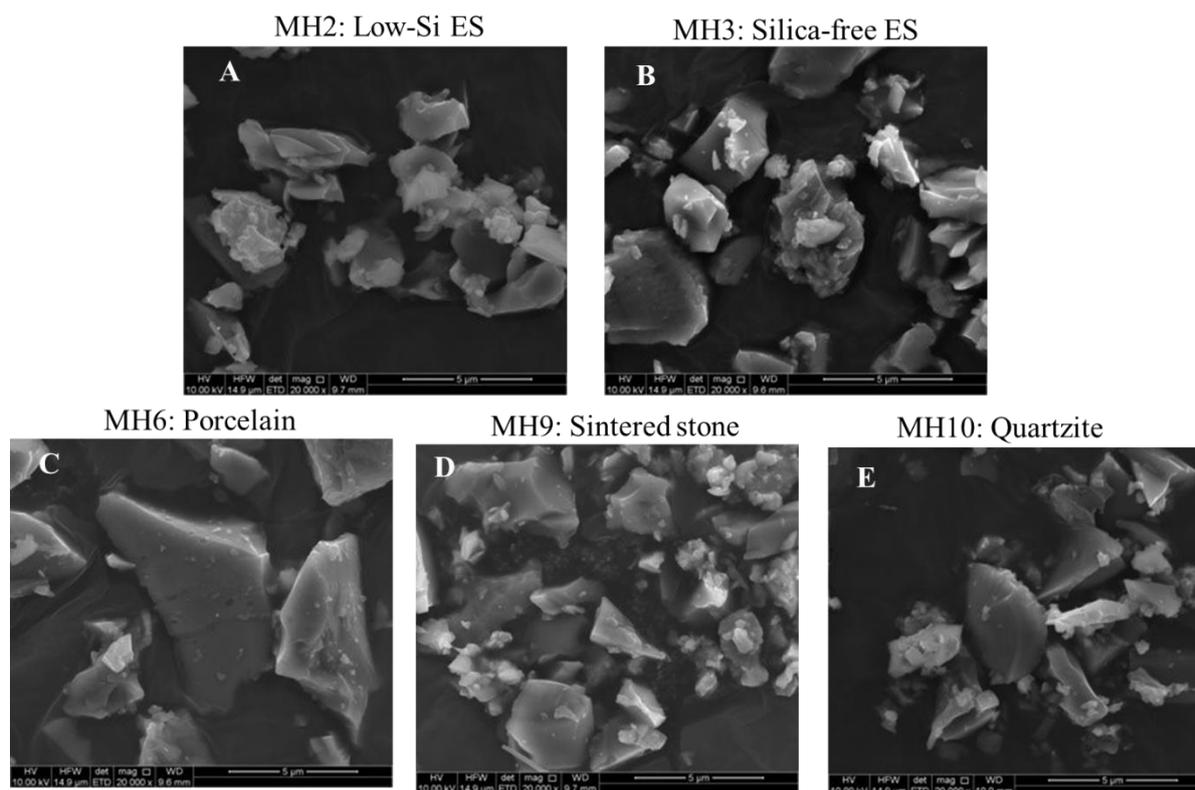


Fig. 2: Morphology of (A) low-Si engineered stone (ES) MH2, (B) no-silica (silica-free) engineered stone MH3, (C) porcelain stone MH6, (D) sintered stone MH9 and (E) natural stone quartzite MH10, analysed by SEM. Representative micrographs were taken at 20,000 $\times$  magnification.

### Elemental composition

The variability in elemental composition across stone types – ES, ceramic, sintered stone and natural stone quartzite, is shown in Fig. 3. The elemental composition of porcelain stone MH6 was not determined due to insufficient sample. Using the classification suggested by Di Benedetto et al. (2019) [3] to identify trace (<0.1%), minor (<1%) and major (>1%) elements, it was observed that the following elements were in trace amounts in stone types: Co, Cu, Ni, P, S, Sn (Fig. 3). Elements such as Al, Ca, K, Mg and Na had a range of distributions from minor to major fields for most stone types, suggesting that aluminosilicates made up a significant part of their composition, in line with their SDS information (Table 1).

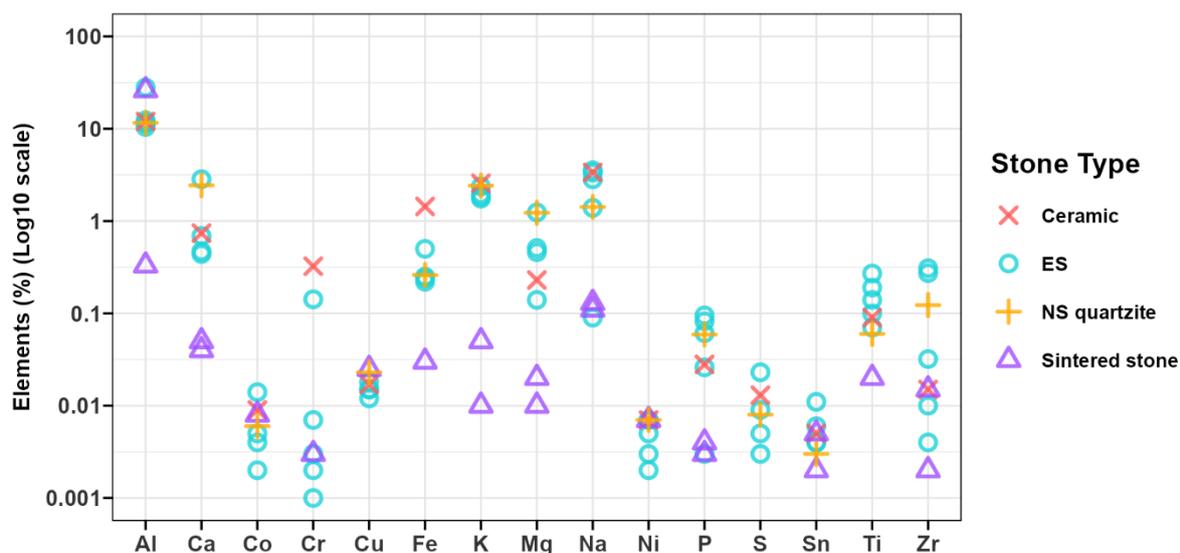


Fig. 3: Distribution of metal elements (excluding Si) of engineered stone (ES, MH1-MH5), ceramic (MH7), sintered stone (MH8-MH9) and natural stone (NS), quartzite (MH10).

## Stage 2: Lung cellular response

Two lung cell lines, namely epithelial cells (A549) and macrophages (THP-1) were exposed to 200  $\mu\text{g}/\text{mL}$  of low- to no-silica dust particles (MH1-10) and standard silica (positive control) as well as the vehicle (negative control) for 24 hours. Cytotoxicity (LDH assay) and inflammation (cytokine response) were analysed afterward.

In A549 cells, a consistent pattern was observed, in that IL-6 and IL-8 were significantly increased after exposure to a range of dusts, e.g. MH3, MH4, MH8, MH7, MH6, MH9 (Fig. 4B-C). In particular, no-silica ES MH3 and sintered stone MH9 induced the greatest cytokine response (5-fold increase in IL-6 and 3-fold increase in IL-8), which was even higher than those in standard/reference silica (~1.8 fold increase in IL-6 and IL-8 (Fig. 4B-C). No significant change of cytotoxicity in A549 cells after dust exposure was observed (overall  $p = 0.716$ ) (Fig. 4A).

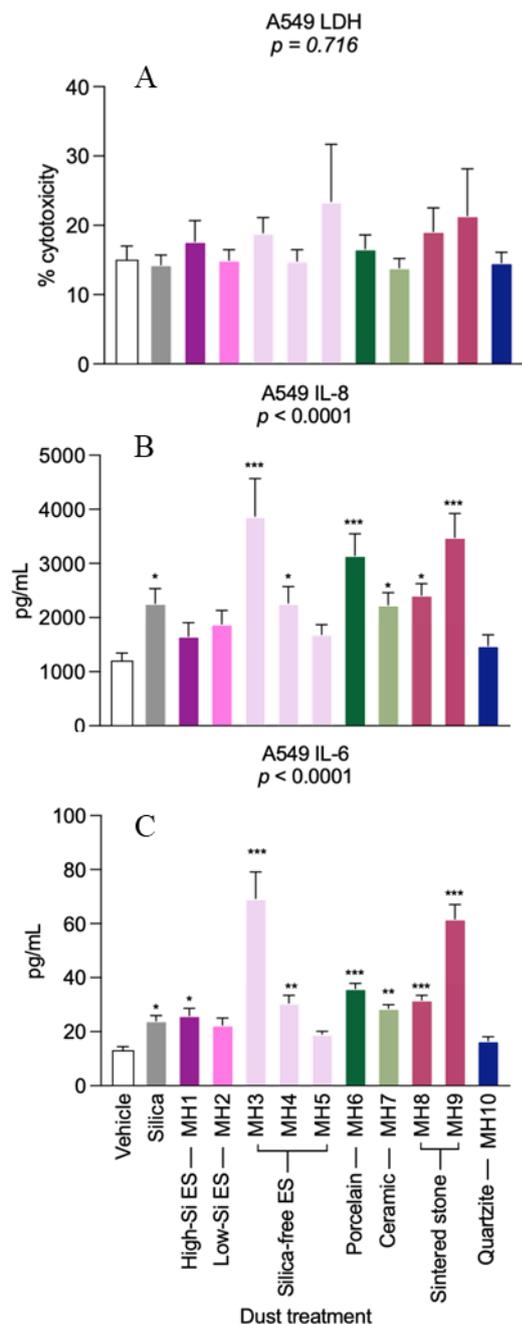


Fig. 4: Cellular response in epithelial cells including cytotoxicity (A), IL-8 (B) and IL-6 (C) production assessed in A549 in response to 10 stone dusts, across engineered stone (MH1-MH5) and non-engineered stone materials (MH6-MH10), reference silica (silica) and the vehicle control (vehicle). Significant differences are indicated by ‘\*’ ( $p < 0.05$ ), ‘\*\*’ ( $p < 0.01$ ) and ‘\*\*\*’ ( $p < 0.001$ ), compared to the control. Values are mean (SD) with  $n = 8$  per group. LDH, lactate dehydrogenase.

In lung macrophage THP-1 cells, the low-to no-silica stone dusts did not cause significant effects on cytotoxicity, IL-1 $\beta$  and IL-8 response (overall  $p > 0.05$ ) (Fig. 5A-C). However, there was a significant

increase in TNF- $\alpha$  after exposing to no-silica ES MH5 ( $p = 0.012$ ), and marginal increase in response to exposure of no-silica ES MH3 ( $p = 0.066$ ) and MH4 ( $p = 0.069$ ), as well as high-Si ES MH1 ( $p = 0.057$ ) (Fig. 5D).

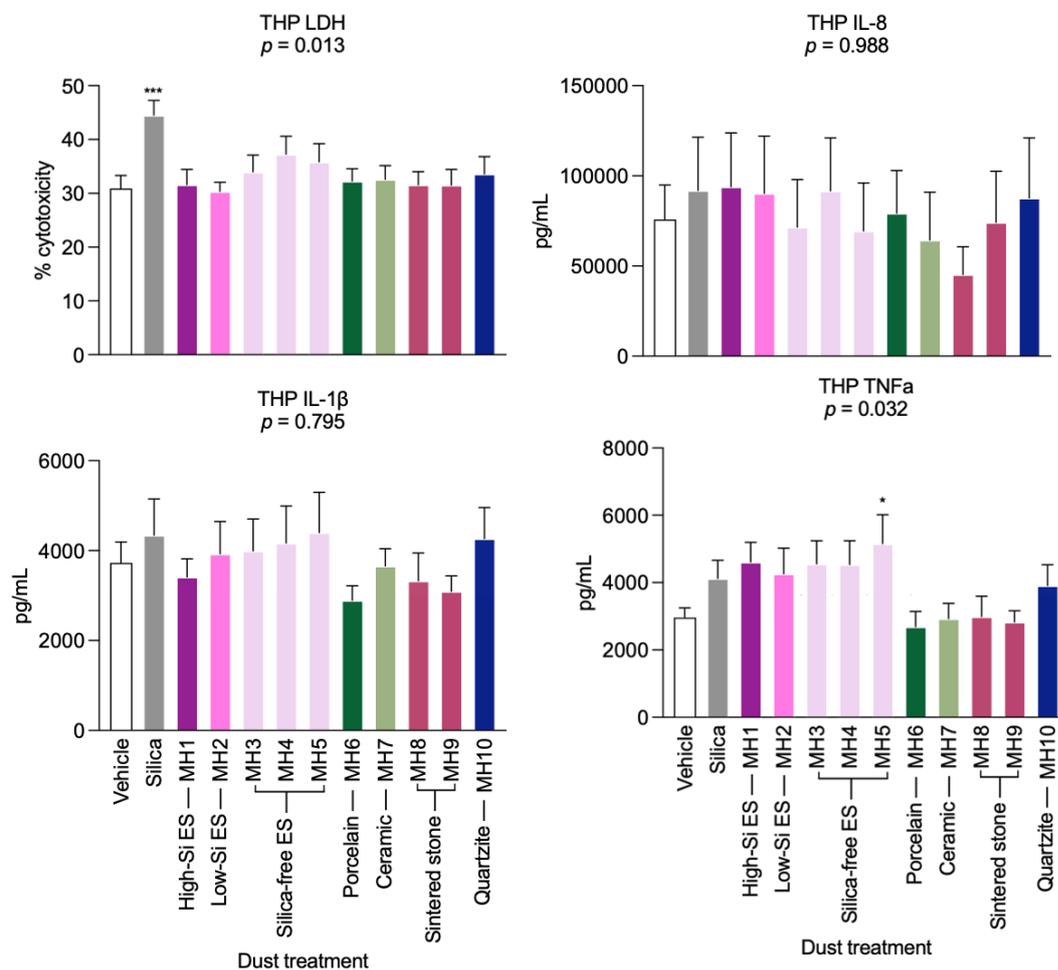


Fig. 5: Cellular response in macrophages including cytotoxicity (A), IL-8 (B), IL-1 $\beta$  (C) and TNF- $\alpha$  (D) production assessed in THP-1 cells in response to 10 stone dusts across engineered stones (MH1-MH5), non-engineered stone (MH6-MH10), standard silica (Silica) and the vehicle control (Vehicle). ‘\*’ indicates significant differences ( $p < 0.05$ ) compared to the vehicle control. Values are mean (SD) with  $n = 8$  per group. LDH, lactate dehydrogenase.

### Stage 3: Educational tool development

In consultation with MAQOHSC, an infographic was created as a visual educational tool to raise awareness about the potential risks that processing novel stone benchtop alternatives could pose to worker lung health. Evidence was synthesized from research findings obtained across Stage 1 (emissions characterisation) and Stage 2 (toxicological evaluation) of the study and selected for presentation based on stone products that are legally commercially-available as alternatives in Australia, namely no-silica ES, porcelain, ceramic, sintered stone and natural stone. Principal component analysis

(PCA) was used to group inflammatory cellular responses. The infographic is attached to the end of this Report (Appendix A).

## Discussion

This study aimed to explore the material science of dust emissions from cutting novel unprohibited stone benchtop alternatives typically of low or no silica content, with the view to identifying potential hazards that processing replacement products for high-silica ES stone may involve. Stone materials studied were generally grouped as ES, ranking from high silica (MH1) to low silica (MH2) and zero/no silica content (no-silica MH3-5) and non-ES materials, namely porcelain (MH6), ceramic (MH7), sintered stone (MH8-9) and natural stone, quartzite (MH10). Under current Australian WHS Regulations, MH1 and MH2 are banned for use, supply and manufacture due to their associated risk of high silica exposure, and high disease incidence [14]. Therefore, from 1 July 2024, alternative products such as MH3 – MH10 are commercially available as replacement stone benchtop products.

As observed in several previous studies characterising emissions from engineered and natural stone [4, 5, 15], the level of RCS generated during mechanical grinding of stone slabs reflected the bulk silica composition of the materials (reported in their MSDS). Generally, the higher the silica content in the bulk material, the higher the crystalline silica content of dust emissions [15]. For example, in comparison with high-Si ES and high-Si natural stone (>70% RCS), low-silica products generated much lower RCS levels, e.g. <25% for porcelain, ceramic and sintered stone. The RCS content of silica-free ES dusts (MH3-5) was below analytical detection limits, thus supporting their ‘crystalline silica-free’ composition statements in their safety data sheets. Although lacking a standard format, the MSDS of the stone products studied herein generally gave reliable information about their silica composition. Safety data sheets play an important role in providing information on composition of bulk stone products, from which potential health risks can be inferred [16]. To this effect, it is advised that MSDS be standardised across suppliers and/or countries to facilitate more accurate risk assessment and management.

Particle size distribution and morphology results showed that mechanically processing non-ES slabs such as ceramic and sintered stone generated much larger and more heterogeneous particles than ES (Table 3). Apart from their different manufacturing process, non-ES slabs were generally also harder to cut compared to ES, according to the operator’s anecdotal experience. This could result in more force being applied to the non-ES slab, which can lead to brittleness and consequently coarser dust particles, relative to ES. Hall et al. (2022) [15] discussed the likelihood that operators move their tools “more quickly across softer stones” e.g. sandstone, compared to harder ones e.g. granite, which can affect the emissions characteristics. However, this was not investigated within the scope of the current study.

Among the stones studied, only ES samples generated ~12 wt.% resin during mechanical processing, which was consistent in all ES, irrespective of bulk silica composition. This has implications for hazard exposures as previous studies have shown that resin-based high-silica ES emit a suite of volatile organic compounds (VOCs), including lung irritants and sensitisers such as styrene and phthalic anhydride, respectively, when processed [15, 17], which could be contributing to the pathogenesis of disease in this occupational group. Further research should therefore test the presence and composition of VOCs

emitted when novel silica-free ES stone benchtops are processed, for a more complete assessment of airborne hazards.

The *in vitro* cell responses for the different stone categories revealed interesting patterns. Firstly, low-silica and silica-free dusts were not particularly toxic or inflammatory to macrophages. However, in epithelial cells, significant pro-inflammatory responses were recorded for silica-free ES MH3, sintered stone MH9, and porcelain stone MH6. Common to these stone samples were non-crystalline silica phases such as amorphous and fused silica (Table 1). Amorphous silica has previously been linked to human pulmonary inflammation in toxicological studies, particularly when inhaled as ultrafine particles [18, 19], although its role in inducing fibrosis and silicosis is still unclear. For example O'Reilly et al. (2023) showed that being more soluble and easily cleared from the lungs, amorphous silica leads to more transient inflammatory response compared to crystalline silica [19]. Further, a recent review of epidemiological studies on synthetic amorphous silica and respiratory health showed no evidence to support a causal relationship between the two [20]. On the other hand, one clinical case of amorphous silica-associated incidental silicosis was reported in 2023, linked to exposure during the purification of silica gel daily for 4 years in a chemistry lab [21]. Further research is therefore needed to clarify the effect, especially long-term, of amorphous silica-laden occupational dusts on lung cellular response. This is particularly important because amorphous silica exposures can be expected to rise in the stone benchtop industry, given their presence in various stone benchtop alternatives [6, 7].

Apart from silica, SBI workers are likely to be exposed to other airborne hazards during the processing of stone alternatives. Our results showed that novel low-silica and silica-free stone dusts contain a range of metal elements, including Al and Co (Fig. 3), which according to our recent study can also contribute to particle toxicity and pathogenesis of disease [12]. Silica-free ES dusts also contained on average ~12% by wt. resin (Table 1), which suggest they can emit VOCs during active fabrication, which are currently not actively controlled for in the SBI industry, and therefore can potentiate harm [17].

It was interesting to note that despite containing >75% RCS and clearly no resin, quartzite (natural stone) dusts induced no significant inflammatory or cytotoxic responses in lung cells. The underlying reasons for this absence of effect compared to other natural high crystalline silica dusts e.g. reference silica [22] are unclear; we hypothesize that it could be due to the concomitant effect of large NS dust particle size and its surface chemistry. For example, previous literature has shown that the occurrence of carbonaceous material such as carbon soot, on the surface of natural quartz particles reduces surface reactivity [18]. However further research is needed to explore the underlying mechanisms by which this occurs.

Some limitations in the design of this study must also be considered when drawing general conclusions. Firstly, only ten stone samples were investigated and although they were carefully selected to reflect a breadth in their composition, a larger sample size is needed to capture a more general vision of the potential hazards that emerging low-silica and no-silica stone composites may pose to workers during mechanical processing. Secondly, toxicological evaluation of stone dusts *via in vitro* tests was determined after a short exposure (24 h) to stone dusts. While this showed early signs of toxicity in response to dust exposure, longer term effects need to be investigated to confirm that the association is causal and identify components that drive cellular response, with the view to regulating them out of the

stone materials and/or identifying ways of controlling them in the workplace – key for disease prevention.

## Conclusions

Taken together, the outcomes of this study showed that low-silica and silica-free stone materials emitted a variety of airborne hazards when processed. Low-silica stones emitted up to 20% RCS as well as metal ions when processed, while silica-free ES – although free of crystalline silica – likely contained other forms of silica (e.g. amorphous silica) or aluminium trihydrate and resin, which have independently been linked to adverse health effects previously. Toxicological data showed that low- to no-silica dust particles were able to elicit potent cellular response, which was particularly obvious in epithelial cells. This has implications for understanding the pathogenesis of low/no silica dust-related lung injury. There remains an urgent need to continue to educate workers and employers that dust remains a health concern and must be controlled even when using low- to no-silica stone materials.

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## Supplementary Information

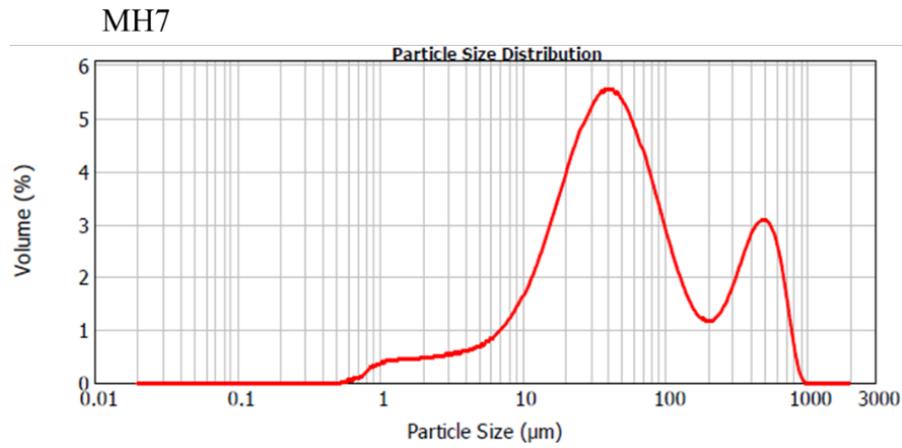


Fig. S1: Bimodal volume-weighted particle size distribution of dust generated during cutting of the ceramic stone slab MH7.

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# Appendix

Appendix A: Infographic showing the physico-chemical characteristics and toxicological effects of dusts emitted by processing engineered stone (ES) alternatives such as no-silica (silica-free) engineered stone, porcelain, ceramic, sintered stone and natural stone (NS).

## Beyond Engineered Stone : Are Alternatives Safe?

Exploring the emissions characterisation and health risks of new-generation stone benchtop products.

Chandnee Ramkissoon<sup>1</sup>, Graeme Zosky<sup>2</sup>, Sharyn Gaskin<sup>1</sup>

<sup>1</sup>Adelaide Exposure Science and Health, School of Public Health, University of Adelaide.

<sup>2</sup>Menzies Institute for Medical Research, University of Tasmania.

### Introduction

With engineered stone (ES) now prohibited for use in Australia due to high silica dust exposure risks, alternatives like natural stone (NS), sintered stone, porcelain, ceramic or 'silica-free' ES are being adopted.

This research aimed to study the risk profiles by characterising dust emissions and assessing the toxicological implications in lung cells of some *unprohibited* alternative benchtop materials.

Dust remains a health concern and must be controlled even when using low-silica or 'silica-free' materials.

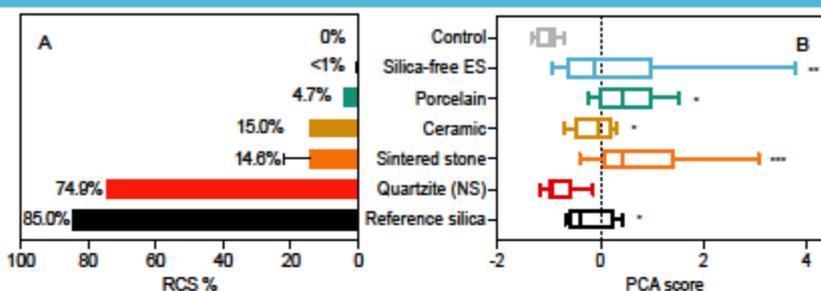


Figure: Respirable crystalline silica (RCS) content (A) and comparative lung cell inflammatory response (B) of stone benchtop alternatives, reference silica and control. NS, natural stone. Significant differences are indicated by \* $p < 0.05$ , \*\*\* $p < 0.001$ .

### Results

- ❖ Low-silica or 'silica-free' stones emitted lower respirable crystalline silica dust compared to high-silica materials e.g. quartzite (natural stone).
- ❖ Only 'silica-free' ES generated resin (~12%) among the stone alternatives studied.
- ❖ Importantly, low-silica and 'silica-free' materials elicited a significant inflammatory response in lung cells, compared to the control group.
- ❖ Despite high RCS levels, natural stone dust did not cause significant inflammation.
- ❖ Research outcomes suggest that novel stone benchtop alternatives could pose a risk to worker lung health. Appropriate dust control measures are advised to mitigate risks.