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Engineering Control for Respirable Crystalline Silica at Open-Air Asphalt Milling Operator Stations: Efficacy of an External Water Spray Barrier

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Featured Application

A standalone, retrofittable engineering control designed to suppress respirable crystalline silica dust on legacy open-air cold planers, offering a cost-effective compliance solution for road maintenance fleets lacking enclosed operator cabins.

Abstract

Open-air asphalt milling generates hazardous respirable crystalline silica (RCS), posing severe risks to operators of legacy machines lacking enclosed cabs. This study evaluates a novel, standalone retrofit water spray system designed to intercept fugitive dust. Field validation across 11 road maintenance sites involved particle characterization and paired system-off/on exposure monitoring. Results indicated a Mass Median Aerodynamic Diameter (MMAD) of 6.12 μm, confirming the efficacy of fine-atomizing nozzles (0.3 mm) for capturing respirable fractions. The system achieved RCS suppression efficiencies ranging from 60% to over 85% under low-to-moderate wind conditions (<2.5 m/s). A comparative analysis revealed no significant performance gain from larger 0.5 mm nozzles, supporting the use of smaller orifices for optimal water conservation. However, suppression efficacy degraded significantly when crosswinds exceeded 2.5 m/s, identifying a critical operational threshold. This retrofit solution provides a scientifically validated, cost-effective engineering control for reducing occupational silica exposure in aging road maintenance fleets.

Keywords: occupational hygiene; respirable crystalline silica; asphalt milling; engineering control; dust suppression; retrofit system

1. Introduction

Asphalt pavement milling is a fundamental process in road rehabilitation, essential for restoring pavement profiles and removing deteriorated surface layers. However, this mechanical fragmentation process is a significant source of occupational pollution, generating high concentrations of airborne particulate matter that frequently contain respirable crystalline silica (RCS) [1,2]. Chronic occupational exposure to RCS is causally linked to a spectrum of severe respiratory pathologies, including silicosis [3], chronic obstructive pulmonary disease (COPD) [4], pulmonary tuberculosis [5], and renal disease [6]. Furthermore, epidemiological evidence has established a strong association between silica exposure and lung cancer [7,8], leading the International Agency for Research on Cancer (IARC) to classify crystalline silica as a Group 1 human carcinogen [9].

The occupational health risks associated with road construction are well-documented. Field investigations indicate that workers involved in highway repair and pavement milling face some of the highest exposure levels in the construction sector [10,11]. Studies by Linch et al. (2002) and

Valiante et al. (2004) reported that milling machine operators often experience RCS exposures exceeding the recommended limits by several orders of magnitude [12,13]. Similarly, surveillance data from the U.S. construction industry identified milling operators as a high-risk group for silicosis due to the intensity of dust generation during the cutting of asphalt and concrete substrates [14,15]. In Taiwan, a recent exposure assessment by Yang et al. (2018) corroborated these findings, revealing that RCS concentrations in the breathing zone of milling operators consistently exceeded domestic and international regulatory standards [16].

In response to these pervasive hazards, regulatory bodies have tightened exposure limits. The U.S. Occupational Safety and Health Administration (OSHA) established a Permissible Exposure Limit (PEL) of 50 μg/m^3 for RCS [17], while the U.S. National Institute for Occupational Safety and Health (NIOSH) recommends a Recommended Exposure Limit (REL) of μg/m^3 [18]. To achieve compliance, NIOSH has published engineering control guidelines advocating for "source suppression" techniques [19]. Standard controls for cold planers typically involve internal water spray systems located within the cutter drum housing to suppress dust at the point of generation, often supplemented by local exhaust ventilation (LEV) systems [20–23].

Modern, large-scale milling machines are increasingly equipped with enclosed, pressurized cabins featuring high-efficiency particulate air (HEPA) filtration, which provides the most effective isolation for operators [19,24]. However, a significant operational gap remains. A vast proportion of road maintenance projects—particularly those executed by small-to-medium enterprises (SMEs) or in developing infrastructure markets—rely on legacy or compact milling machines that lack enclosed cabs [16]. For these "open-air" operator stations, relying solely on internal source suppression is often insufficient. Without the physical barrier of a cabin, operators are directly exposed to fugitive dust plumes that escape the cutter housing, especially under adverse environmental conditions such as strong crosswinds [25,26].

While retrofit solutions such as auxiliary LEV kits have been explored [27,28], they can be complex to install and maintain on aging machinery. Water spray systems, widely used in the mining industry for dust suppression [29,30], offer a potentially more adaptable solution. Research on other construction equipment, such as dowel drilling machines and cut-off saws, has demonstrated that well-designed external water sprays can significantly reduce respirable dust [31,32]. However, the application of a standalone, external water spray barrier specifically designed to protect the breathing zone of open-air milling operators has not been sufficiently evaluated in field settings.

This study aims to bridge this gap by developing and validating a retrofit engineering control: an External Water Spray Barrier System. Unlike internal suppression methods, this system creates an active water curtain between the emission source and the operator, utilizing mechanisms of inertial impaction and interception to capture fugitive dust. We conducted a field evaluation across 11 road maintenance sites to (1) characterize the particle size distribution of the milling dust, (2) quantify the suppression efficacy of the retrofit system for Total Dust, Respirable Dust, and RCS, and (3) investigate the influence of environmental wind speed on system performance. This research provides a scientifically grounded, cost-effective intervention strategy for legacy fleets to mitigate silica exposure risks.

2. Materials and Methods

2.1. System Architecture and Retrofit Configuration

To address the occupational hygiene challenges posed by legacy road maintenance equipment, a standalone, retrofittable external water spray system was developed. The system architecture, illustrated in Figure 1, was designed with a modular "plug-and-play" philosophy to ensure compatibility with various models of cold planers lacking enclosed cabs. The system comprises three independent sub-units: a supply unit, a control/power module, and a spray barrier effector.

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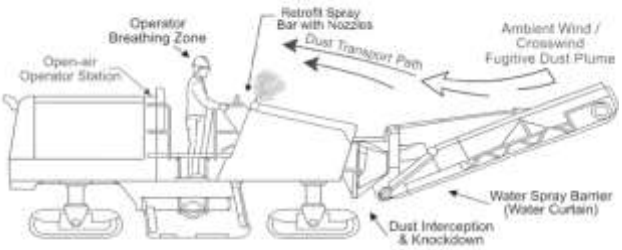

Figure 1. Schematic diagram of the standalone retrofit water spray system architecture.

A critical design feature is the independent fluid supply. Unlike traditional systems that tap into the milling machine's onboard water tank—which is often contaminated with sediment—this system utilizes a dedicated 30-liter polyethylene tank to ensure a consistent supply of clean water. This prevents nozzle clogging and maintains a stable spray pattern. Fluid delivery is driven by a high-pressure miniature diaphragm pump operating at a working pressure of 7 kg/cm^2 (approx. 100 psi) with a flow rate of 0.3 L/min. The system is powered by the host machine's DC 12V/24V electrical system via a regulated control box equipped with safety relays and a manual activation switch accessible to the operator.

The dust suppression mechanism relies on the "Exposure Pathway Interruption" strategy. A custom-fabricated spray bar is mounted horizontally on the operator's console, positioned anterior to the standing driver. The bar is fitted with an array of six (6) fine-atomizing brass nozzles (0.3 mm orifice diameter). As depicted in Figure 2, these nozzles are oriented to generate an overlapping, fan-shaped water curtain. This barrier is designed to intercept fugitive dust plumes driven by environmental crosswinds or machine turbulence before they enter the operator's breathing zone.

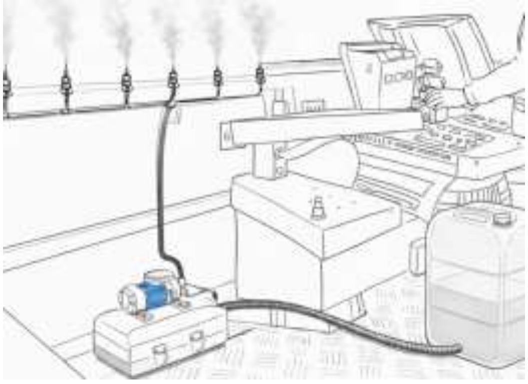

Figure 2. Schematic illustration of the external water spray barrier mechanism applied to an open-air operator station.

2.2. Field Site Characteristics

The field evaluation was conducted at 11 distinct asphalt pavement milling sites located in central and southern Taiwan. These sites represented typical road rehabilitation projects, characterized by varying pavement conditions, milling depths (ranging from 5 to 15 cm), and environmental terrains. The study specifically targeted older generation cold planers (drum widths ranging from 1.0 to 2.0 meters) that featured open-air operator stations. None of the machines in this study were equipped with enclosed pressurized cabs or manufacturer-installed high-efficiency filtration systems.

2.3. Experimental Design: Paired Comparison

Field conditions in road construction are highly variable, with changing wind speeds, pavement compositions, and machine operation modes. To control for these confounding variables, this study employed a paired comparison experimental design.

For each of the 11 field sites, personal exposure monitoring was conducted on the same driver, operating the same machine, during the same work shift. The sampling period was divided into two consecutive trials:

1. System-OFF (Baseline): The retrofit external spray system was deactivated. The machine's standard internal drum spray system remained active to represent the standard operating condition.
2. System-ON (Intervention): The retrofit external spray system was fully activated to generate the protective water barrier.

The sequence of ON/OFF trials was randomized where logistical constraints permitted, to minimize potential bias from temporal changes in environmental conditions. Each sampling trial lasted approximately 2 to 4 hours to ensure sufficient particulate mass loading for gravimetric and chemical analysis.

2.4. Sampling Methodology

Personal breathing zone (PBZ) samples were collected in accordance with standardized methodologies established by the U.S. National Institute for Occupational Safety and Health (NIOSH). Sampling trains were attached to the operator's collar, maintaining the inlet within a 30-cm radius of the nose and mouth.

- Respirable Dust and Crystalline Silica: Samples were collected using a 10-mm nylon Dorr-Oliver cyclone followed by a pre-weighed 37-mm, 5.0-µm pore size polyvinyl chloride (PVC) filter. The sampling pumps were calibrated to a flow rate of 1.7 L/min to achieve the requisite 50% cut-point (D_{50}) of 4 µm, following NIOSH Method 0600 [17].
- Total Dust: Parallel samples for total dust were collected using a 37-mm, 5.0-µm pore size PVC filter in a closed-face cassette (CFC) at a flow rate of 2.0 L/min, following NIOSH Method 0500 [18].
- Particle Size Distribution: To characterize the aerodynamic properties of the challenge aerosol, particle size distribution was measured at selected high-exposure sites using a Marple Series 290 Personal Cascade Impactor. This multi-stage impactor provided data on the Mass Median Aerodynamic Diameter (MMAD) and the Geometric Standard Deviation (GSD) of the dust reaching the operator.

Environmental parameters, including ambient wind speed and direction, were continuously monitored using a portable weather station positioned in the vicinity of the milling operation.

2.5. Laboratory Analysis

Post-sampling, all filters were transported to an accredited laboratory under temperature-controlled conditions.

Gravimetric Analysis: Total and respirable dust masses were determined by weighing the filters on a microbalance with a readability of 0.001 mg in an environmentally controlled weighing room, following the desiccation protocols specified in the respective NIOSH methods.

Crystalline Silica Analysis: Following gravimetric analysis, the respirable dust samples were analyzed for quartz content using X-ray Diffraction (XRD) in accordance with NIOSH Method 7500 [19]. The analysis utilized a high-power X-ray diffractometer with secondary target filtration to identify the primary quartz peak at $2\theta = 26.66^{o}$.

2.6. Data Analysis and Efficacy Calculation

The engineering control efficacy (E, %) for total dust, respirable dust, and respirable crystalline silica (RCS) was calculated for each paired trial using Equation (1):

$$E\ (\%) = \{(C_{OFF} - C_{ON})/C_{OFF}\} \times 100\%$$

Where C_{OFF} and C_{ON} represent the time-weighted average (TWA) concentrations (mg/m^3) measured during the System-OFF and System-ON periods, respectively.

Statistical analysis was performed to determine the significance of the concentration reductions. Given the paired nature of the data and the relatively small sample size (N=11), a Wilcoxon Signed-Rank Test (non-parametric) or a Paired Samples t-test (parametric) was employed, depending on the normality of the data distribution as verified by the Shapiro-Wilk test. A p-value of less than 0.05 was considered statistically significant. Additionally, the relationship between ambient wind speed and control efficacy was examined using regression analysis to assess the stability of the water barrier under varying meteorological conditions.

2.7. Quality Assurance and Quality Control (QA/QC)

To ensure data integrity and validity, a rigorous QA/QC protocol was implemented throughout the field and laboratory phases.

- Pump Calibration: All sampling pumps were calibrated before and after each sampling event using a primary flow standard (e.g., BIOS DryCal DC-Lite). Data from sampling trains where the post-sampling flow rate deviated by more than 5% from the pre-sampling rate were discarded.
- Field Blanks: Field blank filters were collected at a rate of 10% of the total sample volume (or at least one per sampling day) to account for potential contamination during handling and transport. These blanks were subjected to the same handling procedures as the field samples but were not exposed to air.
- Limit of Detection (LOD): For chemical analysis, the Limit of Detection (LOD) for crystalline silica (quartz) was established at 10 μg per filter. Analytical results falling below the LOD were treated using the method of LOD/√2 for statistical calculations.
- Informed Consent: Prior to field testing, the purpose and procedures of the study were explained to all participating machine operators, and informed consent was obtained. The study protocols adhered to ethical guidelines for occupational hygiene field research.

3. Results

3.1. Baseline Exposure Assessment and Site Conditions

Field evaluations were conducted across 11 distinct road milling sites in central and southern Taiwan to assess the occupational exposure risks under varying environmental conditions. The study sites comprised six expressway sections and five general surface roads, representing a comprehensive cross-section of typical road rehabilitation projects. As detailed in Table 1, environmental factors, particularly ambient crosswind speed, varied significantly during the sampling periods. Wind speeds ranged from negligible conditions of 0.15 m/s (Route 5) to a strong breeze of 4.11 m/s (Route 11). This variation provided a critical opportunity to evaluate the performance of engineering controls under different meteorological challenges. Notably, Routes 7 and 9 utilized smaller milling machines without conveyor systems, distinguishing them from the standard large cold planers used in other routes.

Table 1. Characteristics of field test sites and environmental conditions during sampling.

Route ID	Road Type	Milling Machine Type	Wind Speed (m/s)	Temperature (∘C)	Relative Humidity (%)
R1	Expressway	Large Cold Planer	0.29	27	85
R2	Expressway	Large Cold Planer	0.18	27.1	84
R3	Expressway	Large Cold Planer	0.25	27.1	85
R4	Surface Road	Large Cold Planer	0.17	29	83

R5	Expressway	Large Cold Planer	0.15	27	84
R6	Expressway	Large Cold Planer	0.2	26	90
R7	Surface Road	Small Cold Planer*	0.21	31.8	66
R8	Expressway	Large Cold Planer	0.45	26.2	59
R9	Surface Road	Small Cold Planer*	0.33	24	67
R10	Surface Road	Large Cold Planer	2.57	26	51
R11	Surface Road	Large Cold Planer	4.11	20	80

*Note: Small cold planers were operated without a conveyor belt system.

The baseline exposure assessment, conducted with the external suppression system deactivated (System-OFF), revealed that milling operators were consistently exposed to hazardous respiratory conditions . Gravimetric analysis results, summarized in Table 2, indicated that baseline concentrations of total dust and respirable dust were elevated across all sites. Specifically, total dust concentrations ranged from 1.53 mg/m^3 to a peak of 9.78 mg/m^3, while respirable dust levels reached as high as 4.92 mg/m^3 in Route 9.

Of particular concern were the levels of respirable crystalline silica (RCS), a confirmed human carcinogen. In the absence of supplementary engineering controls, baseline RCS concentrations frequently exceeded international occupational exposure limits. For instance, at the site designated as Route 7, where a smaller milling machine lacking a conveyor was utilized, the baseline RCS concentration peaked at 1.20 mg/m^3, a value 24 times higher than the NIOSH Recommended Exposure Limit (REL) of 0.05 mg/m^3. Similarly, Route 9 exhibited an exceptionally high RCS concentration of 1.67 mg/m^3. Even in larger milling operations such as Route 1 and Route 11, baseline RCS levels were recorded at 0.63 mg/m^3 and 0.80 mg/m^3, respectively. These findings underscore the inadequacy of standard onboard suppression systems in isolation and highlight the critical necessity for retrofitted engineering controls to mitigate these severe occupational health risks.

Table 2. Baseline personal breathing zone concentrations (System-OFF) for total dust, respirable dust, and respirable crystalline silica (RCS) across 11 test routes.

Route ID	Total Dust (mg/m^3)	Respirable Dust (mg/m^3)	RCS (mg/m^3)
R1	2.68	1.31	0.63
R2	2.98	1.39	0.34
R3	1.53	0.87	0.28
R4	3.21	1.26	0.34
R5	2.01	1.18	0.35
R6	4.22	1.98	< LOD
R7	5.29	2.69	1.2
R8	2.07	0.82	0.3
R9	9.78	4.92	1.67
R10	2.56	1.21	0.42
R11	4.57	2.13	0.8

Note: LOD = Limit of Detection (0.03 mg/sample). Bold values indicate peak concentrations observed.

3.2. Particle Size Distribution Characterization

To characterize the aerodynamic properties of the fugitive dust and validate the nozzle selection strategy, the particle size distribution of the challenge aerosol was analyzed using a Marple Series 290 Personal Cascade Impactor. The cumulative mass distribution, as illustrated in Figure 3, reveals a unimodal distribution pattern typical of mechanically generated particulates .

The analysis yielded a Mass Median Aerodynamic Diameter (MMAD) of 6.12 μm with a Geometric Standard Deviation (GSD) of 2.51 . This distribution indicates that while the bulk of the particulate mass consists of coarser fractions (>10 μm), a substantial proportion of the aerosol mass lies within the respirable range (< 4 μm), which is capable of penetrating the deep lung.

These aerodynamic characteristics provide the physical basis for the retrofit system's design. Conventional low-pressure deluge systems often produce large water droplets (> 200 μm) that possess high inertia, causing them to bypass the smaller respirable dust particles due to the slip-stream effect. In contrast, the MMAD of 6.12 μm identified in this study supports the selection of fine-atomizing nozzles with a 0.3 mm orifice. This configuration generates a mist spectrum with a droplet size distribution aerodynamically tailored to intercept particles in the 1–10 μm range, thereby maximizing the collision efficiency for the specific dust profile generated during asphalt milling.

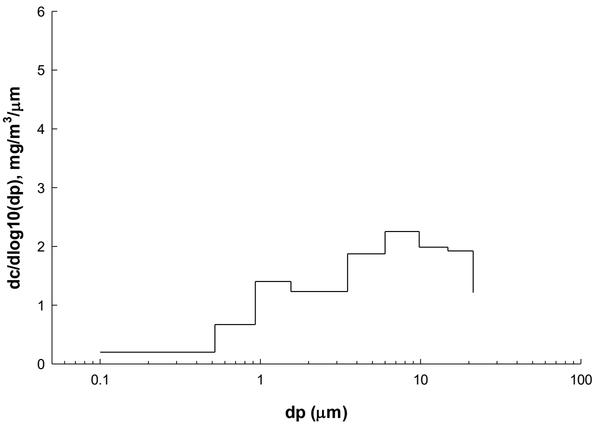

Figure 3. Cumulative particle size distribution of asphalt milling dust collected from the operator's breathing zone.

3.3. Efficacy of the Retrofit Water Spray System

The suppression efficacy of the retrofit external water spray system was evaluated by comparing the Time-Weighted Average (TWA) concentrations of particulate matter measured during paired System-OFF (baseline) and System-ON (intervention) trials. As presented in Table 3, the intervention demonstrated a consistent and robust reduction in dust exposures across the majority of test sites. Statistical analysis using the Wilcoxon Signed-Rank Test confirmed that the reductions in Total Dust, Respirable Dust, and Respirable Crystalline Silica (RCS) were statistically significant ($p < 0.05$) across the dataset .

For Total Dust, the engineering control achieved suppression efficiencies ranging from 54% to 84% High efficacy was observed even in high-load scenarios; for instance, in Route 9, where the baseline concentration was an extreme 9.78 mg/m^3, the system successfully reduced the concentration to 2.54 mg/m^3, representing a 74% reduction. Similarly, for Respirable Dust—the fraction most relevant to deep lung penetration—the system exhibited high performance, with reductions ranging between 57% and 80%. The highest efficiency was recorded in Route 5, where respirable dust levels dropped from 1.18 mg/m^3 to 0.24 mg/m^3(80% efficiency).

Crucially, the system proved highly effective in mitigating the most severe hazard: Respirable Crystalline Silica (RCS). In trials conducted under low-to-moderate wind conditions (Routes 1–9), RCS suppression efficiencies consistently exceeded 60, with several sites achieving reductions greater than 7%. A notable example is Route 2, where the baseline RCS concentration of 0.34 mg/m^3 was reduced to below the analytical limit of detection (< 0.05 mg/m^3) upon system activation, yielding an efficiency of >85%. Even in the challenging environment of Route 7, which utilized a smaller milling machine with a high baseline RCS of 1.20 mg/m^3, the system managed to reduce exposure by 62% to 0.46 mg/m ^{3}. However, it is noted that in Routes 10 and 11, the suppression efficiencies for RCS dropped to 50%$ a phenomenon attributed to environmental crosswinds which will be discussed in the subsequent section.

Table 3. Comparative efficacy of the retrofit water spray system on personal breathing zone concentrations of dust and crystalline silica.

Route ID	Total Dust (mg/m^3)			Respirable Dust (mg/m^3)			RCS (mg/m^3)		
	OFF	ON	Eff. (%)	OFF	ON	Eff. (%)	OFF	ON	Eff. (%)
R1	2.68	0.75	72	1.31	0.38	71	0.63	0.16	75
R2	2.98	0.81	72.8	1.39	0.35	74.8	0.34	< LOD	> 85.0
R3	1.53	0.3	80.4	0.87	0.22	74.7	0.28	< LOD	> 75.0
R4	3.21	0.52	83.8	1.26	0.31	75.4	0.34	0.12	64.7
R5	2.01	0.36	82.1	1.18	0.24	79.7	0.35	0.1	71.4
R6	4.22	0.82	80.6	1.98	0.56	71.7	< LOD	< LOD	N/A
R7	5.29	1.82	65.6	2.69	0.81	69.9	1.2	0.46	61.7
R8	2.07	0.54	73.9	0.82	0.23	72	0.3	< LOD	> 77.0
R9	9.78	2.54	74	4.92	1.02	79.3	1.67	0.37	77.8
R10	2.56	1.03	59.8	1.21	0.45	62.8	0.42	0.21	50
R11	4.57	2.12	53.6	2.13	0.91	57.3	0.8	0.4	50
Mean	3.72	1.06	72.6	1.8	0.49	71.7	0.63*	0.22*	68.8*

Note: LOD = Limit of Detection (0.03 mg/sample). Eff. = Suppression Efficacy = $(C_{OFF} - C_{ON})/C_{OFF} \times 100$. *Mean calculation for RCS excludes R6 (below LOD) and treats "< LOD" values as LOD/√2 for calculation purposes. Bold values indicate peak concentrations or highest efficiencies.

3.4. Comparative Analysis of Nozzle Orifice Diameter

To optimize the trade-off between dust suppression efficiency and water consumption, a comparative analysis was conducted using two different nozzle orifice diameters: the standard 0.3 mm nozzles and larger 0.5 mm nozzles. While the majority of the field trials utilized the $0.3\ mm$ configuration to maximize the surface-area-to-volume ratio of the droplets, Routes 8 and 9 were specifically designated to evaluate the performance of the 0.5 mm$ nozzles.

Data from these trials indicate that increasing the nozzle diameter did not yield a statistically significant improvement in suppression efficacy. In Route 8 (Expressway), the system equipped with 0.5 mm nozzles achieved a Respirable Crystalline Silica (RCS) suppression efficiency of >77%. Similarly, in Route 9 (Surface Road), an efficiency of 78% was recorded. These performance metrics are comparable to those obtained with the 0.3 mm nozzles under similar environmental conditions, such as Route 3 (>75%) and Route 5 (71%).

The lack of significant disparity suggests that the finer mist generated by the 0.3 mm nozzles is sufficient to intercept the target aerosol fraction identified in the particle size analysis (MMAD = 6.12 µm). Consequently, the 0.3 mm configuration is deemed preferable for the final system design, as it maintains high suppression efficacy while significantly reducing water consumption rates, thereby extending the operational duration of the independent water supply unit.

3.5. Influence of Crosswind Speed on System Performance

While the retrofit system demonstrated high efficacy under stable atmospheric conditions, a distinct inverse relationship was observed between ambient crosswind speed and the suppression efficiency of respirable crystalline silica (RCS). To quantify this effect, a regression analysis was performed on the dataset, as illustrated in Figure 4.

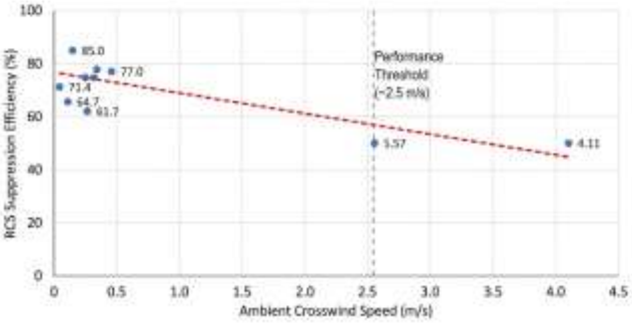

Figure 4. Scatter plot illustrating the relationship between ambient crosswind speed and the reduction efficiency of Respirable Crystalline Silica (RCS).

In trials conducted under low wind conditions (< 0.5 m/s), such as Routes 1 through 6, the system maintained a stable water curtain, achieving optimal performance with RCS reductions consistently ranging from 7% to over 85% . However, a marked degradation in suppression efficacy was identified when crosswind speeds exceeded a critical threshold. As evidenced by the data from Route 10, where the average wind speed reached 2.57 m/s, the RCS suppression efficiency declined significantly to 50%. This trend was further corroborated by Route 11, which was subjected to the highest recorded wind speed of 4.11 m/s; in this scenario, the efficiency for the driver remained at 50%, while the efficiency for the cutter operator—who is positioned closer to the turbulent generation source—dropped to 30%.

This performance decay suggests a physical limitation of the external spray barrier approach. When ambient crosswinds exceed approximately 2.5 m/s, the aerodynamic forces exerted by the wind can overcome the momentum of the fine mist droplets (0.3 mm nozzles), disrupting the integrity of the protective curtain. This disruption allows a fraction of the fugitive dust plume to bypass the interception zone and enter the operator's breathing zone. Consequently, while the system is highly effective for standard operations, supplementary wind shielding or increased droplet momentum may be required for operations in high-wind environments.

4. Discussion

4.1. Mechanistic Interpretation of Dust Suppression Efficacy

The field evaluation results demonstrate that the retrofit water spray system significantly mitigates occupational exposure to respirable crystalline silica (RCS), achieving suppression efficiencies exceeding 85% under optimal conditions. This high level of efficacy can be attributed to the scientifically grounded alignment between the spray droplet spectrum and the aerodynamic properties of the target aerosol.

As characterized in this study, the fugitive dust generated during milling exhibits a Mass Median Aerodynamic Diameter (MMAD) of 6.12 μm. From the perspective of aerosol mechanics, this particle size range presents a specific challenge for wet suppression. According to the theory of inertial impaction, the collection efficiency of a water droplet is a function of the Stokes number, which relates the stopping distance of a particle to the diameter of the obstacle (in this case, the water droplet). When conventional suppression systems utilize low-pressure, high-volume nozzles, they typically generate large droplets (>200 μm). As these large droplets move through the air, they create a significant bow wave or slip-stream around them. Small respirable particles (<10 μm), possessing low inertia, tend to follow these streamlines and flow around the large droplets rather than colliding with them—a phenomenon known as the "slip-stream effect."

The retrofit design addresses this fundamental limitation by employing fine-atomizing nozzles with a 0.3 mm orifice operating at 7 kg/cm^2. This configuration generates a mist of much finer droplets. The reduced droplet size minimizes the slip-stream effect and increases the surface-area-to-volume ratio of the water, thereby significantly enhancing the collision efficiency for particles in the 1–10 μm range. The empirical success of the system validates the "Exposure Pathway Interruption" strategy; by creating a dense, fine-mist curtain directly between the generation source (the cutter housing) and the receptor (the operator), the system effectively intercepts the fugitive plume before it can enter the breathing zone, even without the complex enclosure required for local exhaust ventilation (LEV).

4.2. Operational Optimization: Balancing Efficacy and Resource Conservation

A critical constraint in designing retrofit engineering controls for mobile heavy machinery is the balance between performance and resource autonomy. Unlike integrated systems that may draw from large onboard reservoirs, the standalone unit developed in this study relies on a finite 30-liter independent water supply. Consequently, minimizing water consumption without compromising suppression efficacy is paramount for operational feasibility. The comparative analysis of nozzle orifice diameters provides essential data for this optimization.

Field trials comparing the standard 0.3 mmnozzles (Routes 1–7, 10–11) against the larger 0.5 mm nozzles (Routes 8–9) revealed no statistically significant difference in dust suppression performance. For instance, the system equipped with 0.5 mm nozzles achieved RCS suppression efficiencies of 77–78%, which is statistically comparable to the 75–85% efficiency range observed with the 0.3 mm configuration under similar wind conditions. This finding suggests that simply increasing the water flow rate or droplet diameter does not yield proportional gains in dust capture. It reinforces the mechanistic inference that the finer droplet spectrum generated by the 0.3 mm nozzles is already sufficient to saturate the interaction zone and effectively intercept the respirable dust fraction characterized by an MMAD of 6.12 μm.

From an engineering perspective, this "diminishing return" on larger nozzles validates the selection of the 0.3 mm configuration as the optimal design choice. By utilizing the smaller orifice, the system significantly reduces volumetric water consumption while maintaining peak suppression efficacy. This conservation strategy extends the operational runtime of the independent supply unit, thereby reducing the frequency of refill interruptions—a critical factor for ensuring operator acceptance and minimizing downtime in time-sensitive road maintenance projects.

4.3. Environmental Constraints and Operational Boundaries

While the retrofit system demonstrates high efficacy under stable atmospheric conditions, field validation has identified critical environmental constraints that define its operational envelope. Specifically, ambient crosswind speed acts as a primary limiting factor for external water spray barriers. The regression analysis of field data reveals a non-linear relationship between wind velocity and suppression performance, with a discernible performance inflection point at approximately 2.5 m/s.

In low-wind environments (< 2.5 m/s), the kinetic energy of the atomized droplets is sufficient to maintain the structural integrity of the water curtain, effectively intercepting the dust plume before it propagates to the operator's breathing zone. However, as crosswind speeds exceed this threshold—such as in Route 10 (2.57m/s) and Route 11 (4.11 m/s)—the aerodynamic drag forces exerted by the wind begin to dominate the momentum of the fine droplets (0.3 mm orifice). This aerodynamic disruption causes the spray curtain to drift or disperse, creating breaches through which fugitive dust can bypass the control mechanism. Consequently, the RCS suppression efficiency in these high-wind scenarios degrades significantly to approximately 30–50% .

This finding has significant practical implications for the deployment of retrofit controls. It establishes a clear operational boundary: the standalone spray system is most reliable when ambient wind speeds are low to moderate. For operations conducted in high-wind environments, reliance solely on the external spray bar may be insufficient. To extend the operational envelope, it is recommended that the system be augmented with physical wind shielding—such as installing partial side panels or wind deflectors around the cutter housing—to reduce local turbulence and protect the water curtain from direct crosswind shear. Alternatively, operational protocols could be adjusted to orient the machine heading relative to the wind direction to minimize crosswind exposure during milling.

4.4. Implications for Occupational Health in Retrofit Applications

The significance of this study extends beyond the technical validation of a spray system; it addresses a critical gap in occupational hygiene for legacy road maintenance equipment. As evidenced by the baseline exposure assessment, operators of older or smaller milling machines (e.g., Routes 7 and 9) are subject to extreme respiratory hazards, with RCS concentrations reaching up to 1.67 mg/m^3—more than 30 times the NIOSH REL. These smaller units often lack the integrated conveyor systems and enclosed cabs found in modern large-scale planers, leaving operators directly exposed to the dust plume. In such scenarios, where intrinsic engineering controls are absent, the risk of developing accelerated silicosis is profoundly elevated.

While advanced engineering controls such as Local Exhaust Ventilation (LEV) systems have been recommended by agencies like NIOSH , retrofitting complex vacuum and filtration systems onto aging machinery is often technically prohibitive and economically unfeasible for small and medium-sized enterprises (SMEs). The standalone water spray system developed in this study offers a viable alternative. By achieving RCS suppression efficiencies comparable to more complex systems (60–80%), this modular “plug-and-play” solution democratizes access to effective dust control. It provides a cost-effective, easily deployable intervention that does not require structural modification of the host machine.

This capability has broad implications for occupational health policy, particularly in developing regions or industries where fleet modernization is slow due to capital constraints. The demonstrated efficacy of this retrofit solution suggests that significant reductions in occupational disease burden can be achieved immediately through targeted retrofitting, without waiting for the natural turnover cycle of heavy machinery fleets. It validates a transitional strategy: deploying accessible external controls to mitigate immediate risks while longer-term fleet upgrades are planned.

4.5. Study Limitations and Future Research Directions

While this study establishes the efficacy of the retrofit water spray system, several limitations warrant consideration. First, the field evaluations were cross-sectional in nature, focusing on the immediate suppression efficiency over sampling periods of 2 to 4 hours. The long-term durability of the system components—specifically the resilience of the miniature diaphragm pump against the high-frequency vibrations of road milling machinery and the susceptibility of the $0.3\ mm$ nozzle orifices to scaling or clogging over extended deployment—remains to be quantified in longitudinal studies. Although an inline mesh filter was incorporated to mitigate clogging risks, the use of industrial-grade water sources common in construction sites could still pose maintenance challenges.

Second, the system’s performance is intrinsically linked to meteorological conditions. As highlighted in the results, the “open-air” nature of the spray barrier renders it vulnerable to crosswinds exceeding 2.5 m/s. This physical limitation restricts the system’s standalone reliability in high-wind environments or coastal construction zones.

Future research should focus on enhancing the robustness of this control strategy through two primary avenues:

1. Hybridization with Physical Barriers: Investigating the synergistic effect of combining the water spray system with partial wind shrouds or flexible side-flaps installed around the cutter housing. Such physical barriers could reduce local turbulence and shield the water curtain, potentially extending the operational envelope to higher wind speeds.
2. Physicochemical Enhancement: Exploring the addition of surfactants or wetting agents to the water supply. Reducing the surface tension of the water droplets could theoretically enhance the capture efficiency for the finest silica fraction (< 1 μm) and reduce the total water volume required. However, such additives must be selected carefully to avoid excessive foaming, which could obscure the operator's vision or create slippery surfaces.

In conclusion, this study validates the standalone external water spray system as a scientifically sound, cost-effective, and highly deployable intervention for reducing silica exposure. While environmental constraints exist, the system offers a vital immediate solution for legacy fleet retrofit, bridging the gap between current hazardous practices and the eventual modernization of road maintenance equipment.

5. Conclusions

This study successfully developed and validated a standalone, retrofittable external water spray system designed to mitigate the high-risk exposure to respirable crystalline silica (RCS) associated with open-air road milling operations. By targeting the intersection of the fugitive dust plume and the operator's breathing zone, the system provides a scientifically grounded "Exposure Pathway Interruption" solution for legacy machinery that lacks intrinsic engineering controls.

The field evaluation across 11 diverse construction sites yields three primary conclusions. First, the retrofit system demonstrated robust suppression efficacy. Under standard operating conditions with low-to-moderate crosswinds (< 2.5 m/s), the system achieved consistent reductions in total dust and respirable dust ranging from 60% to 80%. Most critically, it effectively suppressed RCS concentrations by over 60%, with optimal scenarios exceeding 85%, thereby significantly reducing the inhalation risk for operators of older milling units.

Second, the characterization of the challenge aerosol (MMAD = 6.12 μm) validated the engineering selection of fine-atomizing nozzles (0.3 mm orifice). The comparative analysis confirmed that this configuration offers a suppression performance statistically equivalent to larger 0.5 mm nozzles but with superior water conservation. This finding establishes the 0.3 mm nozzle as the optimal design choice for standalone units where independent fluid autonomy is a critical operational constraint.

Third, while the system is highly effective, its performance is physically bounded by meteorological conditions. Ambient crosswind speed was identified as a governing factor, with a performance inflection point observed at approximately 2.5 m/s. Beyond this threshold, the aerodynamic disruption of the water curtain leads to a marked decline in suppression efficiency. Consequently, while this system offers a vital and cost-effective intervention for immediate risk reduction, operations in high-wind environments may require supplementary physical shielding to maintain the integrity of the spray barrier.

In summary, this research provides a verified, scalable, and economically feasible engineering control strategy. For the vast fleet of legacy cold planers currently in operation—particularly within small and medium-sized enterprises in developing infrastructure markets—this retrofit solution serves as a crucial transitional technology to bridge the gap in occupational health protection.

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References

1. Hammond, D.R.; Shulman, S.A.; Echt, A.S. Respirable crystalline silica exposures during asphalt pavement milling at eleven highway construction sites. J. Occup. Environ. Hyg. 2016, 13, 538–548.
2. Freund, A.; Zuckerman, N.; Baum, L.; Milek, D. Submicron particle monitoring of paving and related road construction operations. J. Occup. Environ. Hyg. 2012, 9, 298–307.
3. Leung, C.C.; Yu, I.T.; Chen, W. Silicosis. Lancet 2012, 379, 2008–2018.
4. Hnizdo, E.; Vallyathan, V. Chronic obstructive pulmonary disease due to occupational exposure to silica dust: A review of epidemiological and pathological evidence. Occup. Environ. Med. 2003, 60, 237–243.
5. Milovanović, A.; Nowak, D.; Milovanović, A.; Hering, K.G.; Kline, J.N.; Kovalevskiy, E. Silicotuberculosis and silicosis as occupational diseases: report of two cases. Srp. Arh. Celok. Lek. 2011, 139, 536–539.
6. Vupputuri, S.; Parks, C.G.; Nylander-French, L.A.; Owen-Smith, A.; Hogan, S.L.; Sandler, D.P. Occupational silica exposure and chronic kidney disease. Ren. Fail. 2012, 34, 40–46.
7. Liu, Y.; Steenland, K.; Rong, Y.; Hnizdo, E.; Huang, X.; Zhang, H.; Shi, T.; Sun, Y.; Wu, T.; Chen, W. Exposure-response analysis and risk assessment for lung cancer in relationship to silica exposure: A 44-year cohort study of 34,018 workers. Am. J. Epidemiol. 2013, 178, 1424–1433.
8. Soutar, C.A.; Robertson, A.; Miller, B.G.; Searl, A.; Borm, P.J.; Davidson, N. Epidemiological evidence on the carcinogenicity of silica: factors in scientific judgement. Ann. Occup. Hyg. 2000, 44, 3–14.
9. IARC. Silica dust, crystalline, in the form of quartz or cristobalite. In IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Volume 100C; International Agency for Research on Cancer: Lyon, France, 2012.
10. Rappaport, S.M.; Goldberg, M.; Susi, P.A.; Herrick, R.F. Excessive exposure to silica in the US construction industry. Ann. Occup. Hyg. 2003, 47, 111–122.
11. Beaudry, C.; Lavoué, J.; Sauvé, J.F.; Bégin, D.; Senhaji Rhazi, M.; Perrault, G. Occupational exposure to silica in construction workers: a literature-based exposure database. J. Occup. Environ. Hyg. 2013, 10, 71–77.
12. Linch, K.D. Respirable concrete dust—silicosis hazard in the construction industry. Appl. Occup. Environ. Hyg. 2002, 17, 209–221.
13. Valiante, D.J.; Schill, D.P.; Rosenman, K.D.; Socie, E. Highway repair: A new silicosis threat. Am. J. Public Health 2004, 94, 876–880.
14. NIOSH. Hazard Review: Health Effects of Occupational Exposure to Respirable Crystalline Silica; DHHS (NIOSH) Publication No. 2002-129; National Institute for Occupational Safety and Health: Cincinnati, OH, USA, 2002.

15. Steenland, K.; Goldsmith, D.F. Silica exposure and autoimmune diseases. Am. J. Ind. Med. 1995, 28, 603–608.
16. Yang, S.; Chen, K.H.; Huang, H.L.; Hung, P.C.; Huang, H.C.; Hsu, Y.F.; Chuang, C.Y. The Investigation on Exposure Characteristics of Crystalline Free Silica of Pavement Milling Operator. *Taiwan J. Public Health* **2020**, *39*, 441–452.
17. Occupational Safety and Health Administration (OSHA). Occupational Exposure to Respirable Crystalline Silica; Final Rule. Fed. Regist. 2016, 81, 16285–16890.
18. NIOSH. NIOSH Pocket Guide to Chemical Hazards; DHHS (NIOSH) Publication No. 2005-149; National Institute for Occupational Safety and Health: Cincinnati, OH, USA, 2007.
19. Hammond, D.R.; Cecala, A.B.; Colinet, J.F.; Garcia, A.; Mead, K.R.; Echt, A.; Zimmer, J.A. Best Practice Engineering Control Guidelines to Control Worker Exposure to Respirable Crystalline Silica during Asphalt Pavement Milling; DHHS (NIOSH) Publication No. 2015-105; National Institute for Occupational Safety and Health: Cincinnati, OH, USA, 2015.
20. NIOSH. Control Technology for Crystalline Silica Exposure During Pavement Milling Using a Roadtec Milling Machine Equipped with a Local Exhaust Ventilation System; EPHB Report No. 282-25a; NIOSH: Cincinnati, OH, USA, 2013.
21. NIOSH. Control Technology for Crystalline Silica Exposure During Pavement Milling Using a Wirtgen Milling Machine Equipped with a Vacuum Cutting System; EPHB Report No. 282-23a; NIOSH: Cincinnati, OH, USA, 2013.
22. NIOSH. Evaluation of a Volvo Milling Machine Equipped with a Wet Drum Designed to Reduce Respirable Crystalline Silica Exposure During Pavement Milling; EPHB Report No. 282-24a; NIOSH: Cincinnati, OH, USA, 2013.
23. NIOSH. Dust-Control Technology for Asphalt-Pavement Milling Controlled-Site Testing at State Highway 47, Bonduel, Wisconsin; EPHB Report No. 282-18a; NIOSH: Cincinnati, OH, USA, 2011.
24. NIOSH. A Laboratory Evaluation of a Local Exhaust Ventilation System on a Caterpillar Cold Milling Machine at Caterpillar, Minnesota; EPHB Report No. 282-22a; NIOSH: Cincinnati, OH, USA, 2012.
25. Woskie, S.R.; Kalil, A.; Bello, D.; Virji, M.A. Exposures to quartz, diesel, dust, and welding fumes during heavy and highway construction. AIHA J. 2002, 63, 447–457.
26. Blute, N.A.; Woskie, S.R.; Greenspan, C.A. Exposure characterization for highway construction Part I: Cut and cover and tunnel finish stages. Appl. Occup. Environ. Hyg. 1999, 14, 632–641.
27. NIOSH. In-Depth Survey Report: Dust-Control Technology for Asphalt Pavement Milling; EPHB Report No. 282-17a; NIOSH: Cincinnati, OH, USA, 2011.
28. NIOSH. In-Depth Field Evaluation: Dust-Control Technology for Asphalt Pavement Milling at South Dakota Highway 79; EPHB Report No. 282-14a; NIOSH: Cincinnati, OH, USA, 2009.
29. Colinet, J.F.; Cecala, A.B.; Chekan, G.J. Best Practices for Dust Control in Metal/Nonmetal Mining; DHHS (NIOSH) Publication No. 2010-132; National Institute for Occupational Safety and Health: Pittsburgh, PA, USA, 2010.
30. Kissell, F.N. Handbook for Dust Control in Mining; DHHS (NIOSH) Publication No. 2003-147; National Institute for Occupational Safety and Health: Pittsburgh, PA, USA, 2003.
31. Echt, A.S.; Sanderson, W.T.; Mead, K.R. Effective dust control systems on concrete dowel drilling machinery. J. Occup. Environ. Hyg. 2016, 13, 718–724.
32. Middaugh, B.; Hubbard, B.; Zimmerman, N.; McGlothlin, J. Evaluation of cut-off saw exposure control methods for respirable dust and crystalline silica in roadway construction. J. Occup. Environ. Hyg. 2012, 9, 157–165.