Reduction of Respirable Silica Following the Introduction of Water Spray Applications in Indian Stone Crusher Mills

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Respirable crystalline silica dust generated during stone crushing operations has been linked to chronic lung disease and increased risk of tuberculosis. In India, most stone crushing mills operate without any dust control or containment systems. This investigation in the Khurda District of Orissa demonstrated a reduction in respirable particulate mass following the application of a fine mist of water. Average respirable quartz and cristobalite levels declined 82% and 69%, respectively, after water spray controls were installed. This finding suggests that relatively inexpensive modifications that are available in the local market can be effective at reducing silica exposures. Although average exposure levels, particularly during the dry season, may exceed the Permissible Exposure Limit for silica, the overall reductions observed were substantial. Widespread adoption of this simple control technology by stone crushers in India could have a positive public health impact. *Key words*: crystalline silica, silicosis, tuberculosis, lung cancer, stone crushers, water spray control, India, airborne dust.

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The stone crushing industry in India has been growing rapidly due to increasing demand from the construction industry and the present emphasis on developing the country's infrastructure (e.g., road building). Though reliable statistics are lacking for this industrial sector due to its informal nature, it is estimated that there are more than 12,000 stone crushing units in India, providing direct employment to 500,000.[1] Most of these operations are labor intensive, many involve child labor, and many are located in tight geographic clusters close to highways and residential dwellings. This industry has long been associated with exposure to respirable crystalline silica dust. Thousands of workers and those residing in close proximity to these operations are exposed to extremely high silica levels during stone crushing operations.

BACKGROUND

Health Effects

Occupational exposure to respirable crystalline silica causes silicosis, is associated with lung cancer and tuberculosis, and may be related to the development of chronic renal disease and autoimmune diseases such as rheumatoid arthritis. The primary factors determining the pathogenicity of crystalline silica, in addition to its structure, are particle size and concentration. Although respirable crystalline silica particulates are typically < 10 µm in diameter, studies with human subjects have shown the most fibrogenic particle size to be about 1 µm in diameter (range 0.5–3 µm).[2]

Silicosis, the most prominent of the silica-related diseases, is an interstitial lung disease caused primarily by the inhalation of free crystalline silica. Chronic silicosis has a latency period of 10-30 years of exposure to respirable crystalline silica dust at relatively low concentrations.[3] Acute silicosis, however, usually develops after exposures to very high levels of respirable crystalline silica resulting in onset of symptoms in as little as a few weeks to five years post exposure.[4] Studies have also shown a three-fold increased risk for developing tuberculosis (TB) in workers with silicosis compared to those without silicosis.[5]

Although there have been many epidemiologic cancer mortality and morbidity studies in silica-exposed workers, the issue of carcinogenicity was not resolved until the late 1990s. The International Agency for Research on Cancer (IARC) has classified inhaled crystalline silica in the form of quartz or cristobalite from occupational sources as carcinogenic to humans (Group 1).[6] Among a cohort of 3,246 U.S. workers in

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the crushed stone industry 1940-1980, there was a statistically-significant elevated risk for lung cancer among granite workers with at least a 20-year latency period and at least 10 years tenure (SMR: 3.35; 7 deaths observed; 95% CI = 1.24–6.90).[7]

A decrease in pulmonary function has also been observed among stone crushers. Fifty workers engaged in stone crushing outside Chennai, India were assessed for pulmonary function. Tests revealed significant decreases in forced vital capacity (FVC), forced expiratory volume in one second (FEV_1), and peak expiratory flow rate (PEF) for stone crusher workers compared to controls and normal populations.[8] Tiwari et al. (2007) conducted a cross-sectional study in India among slate pencil workers and quartz stone crushers to assess the prevalence of TB and some associated epidemiological factors. Their study found that among stone crushers, the prevalence of TB was 10.7%, and among slate pencil workers the prevalence of TB was as high as 22.5%. Tiwari et al. showed that the rate of TB observed in these workers was considerably more than the prevalence of radiologically active TB for the country as a whole (1.6%).[9]

Occupational Regulations

The United States Occupational Safety and Health Administration (OSHA) and the Indian Union Ministry of Labour have established a respirable dust exposure limit of 5.0 mg/m^3.[10] The permissible exposure limit (PEL) for respirable crystalline silica (regulated under both OSHA and India's 1948 Factories Act[11]) accounts for the variable toxicity of respirable dust proportional to the concentration of quartz and cristobalite present in the dust. The National Institute for Occupational Safety and Health (NIOSH) in the United States has a recommended exposure limit (REL) for respirable crystalline silica, quartz, and cristobalite of 0.05 mg/m^3 as a time weighted average (TWA) for up to a 10-hour workday during a 40-hour workweek.

Dust Suppression

Dust suppression in stone crushing mills can be accomplished through containment measures, water spraying, and dust collectors. Most equipment and machinery at small-scale stone crushing mills in India are not enclosed with any rigid barrier. Dust generated from crushing, sieving, conveyor belts, and waste discharge are generally subject to wind and other weather conditions. In some cases, protective walls or "green belts" are used to limit off-site emissions, but do not address occupational exposures.

Dust collection from local exhaust ventilation would be effective only if applied to enclosed or partially-enclosed operations. Further, to efficiently trap both respirable-size and larger particles from the emission stream, costly filtration would be required. Therefore, dry methods for dust suppression are rarely employed in stone crushing operations.

Workers manually loading the crusher unit and hauling off fine materials accumulating under the rotary screen while continuously exposed to airborne silica.

Water spray equipment can be effective at controlling dust. Specially designed equipment removes respirable-size particles from the air, while general purpose sprinklers reduce the re-entrainment of settled dust on roadways and other areas. The proper design and placement of spray nozzles is key to effective dust suppression. Spray nozzles are characterized by pressure (high vs. low), spray patterns (circular cone vs. rectangular), and droplet size. Wet dust suppression spray nozzles are selected according to the size of the desired area to be covered and the particle size of interest. Atomizing nozzles provide water droplets that maintain a high velocity over some distance, are useful when spray nozzles must be placed away from the point of dust generation, and are considered the most effective at reducing dust.[12] These nozzles produce a fine mist in the range of 10 to 250 microns and are therefore useful for respirable dust control systems.[13]

The implementation of water spray dust control measures has been shown to reduce respirable crystalline silica dust during various construction and mining operations worldwide. Several studies of airborne crystalline silica in various occupations have shown dramatic reductions in airborne dust concentrations by either wetting or spraying. A recent review of the available studies on the use of wet methods showed overall reductions in silica dust of 86% in the construction industry and 80% in manufacturing.[14] Atomizing spray nozzles have been shown to reduce respirable particulate mass from brick cutting operations in the range of 63% to 79%.[15] Studies of respirable dust in

Typical stone crushing operation without containment. Large dust plumes are created during the crushing process.

underground coal mining operations showed reductions of approximately 60% with water spray controls.[16]

Study Population

In 2003, an international partnership was formed between Jeevan Rekha Parishad (JRP), an Indian non-governmental organization (NGO), and Occupational Knowledge International (OK International), a U.S.-based NGO, to investigate potential silica exposures among a cluster of 150 small stone crushing mills located in the Khurda District in the Indian State of Orissa. The partners initiated a study on measures to reduce respirable crystalline silica exposures in small-scale mechanized stone crusher mills in this area. The workforce consisted primarily of tribal women and adolescent girls. Housing was typically located near the stone crushing operations. Engineering controls to reduce silica exposures were generally not used by these mills. With a modest education and outreach effort, JRP engaged three stone crushing mill operators to test water-spray equipment to improve dust control in their operations. As word of the study spread throughout the cluster with the help of the local crusher owners' association, over 40 mill owners agreed to install water spray systems from an Indian supplier. This pilot study investigated the efficacy of the water spray system to reduce respirable crystalline silica dust levels.

METHODS

Samples of the crushed rock in the Khurda District were collected from fine dust deposited at three separate crusher units and placed into 50 ml sampling tubes for transport to an analytical laboratory in the United States. Personal and area air samples were collected inside mills in this cluster during three project phases. The initial phase (pre-implementation) was conducted in 2003 before any pollution control equipment was utilized to reduce dust exposures. Later phases (post-implementation) were conducted at three separate sites in the summer of 2006 and at four separate sites in the winter of 2007 to represent dry and monsoon season conditions. Each of the last two phases occurred three years after the water-spray systems were installed at the respective mills.

During all three phases, battery operated air sampling pumps (SKC and Gillian) were utilized with sampling cassettes attached to cyclones (SKC aluminum or 10-mm nylon Dorr-Oliver) with flow rates of 2.5 (SKC) and 1.7 liters per minute (Dorr-Oliver) to collect the respirable dust fraction. Sample calibration was done with a rotometer and a Gillibrator Flow Cell (Sensidyne, Inc.) using a film flow meter (MCS-102-A) meeting National Institute of Standards and Technology specifications, to set the desired flow rates. Samples were collected on a three-piece 37 mm air sampling filter cassette with a pre-weighed PVC membrane filter (pore size 5 μm) in an attached holder connected to the cyclone and plastic tubing.

Personal sampling was conducted by placing pumps on workers with the cyclone/cassette assembly attached in the breathing zone (approximately 30 cm from the worker's nose and mouth) pointing downward in accordance with NIOSH Method 7500. The NIOSH method consists of drawing air through a personal air monitoring pump, cyclone, and filter cassette, with a specified flow rate and a maximum sample volume of 1,000 liters. The sampling pump flow-rate was calibrated and checked at the beginning and end of each sampling period.

Workers were recruited to wear sampling pumps based on the tasks performed. In some cases where workers were reluctant to wear a sampling pump, the device was placed in a stationary location within the immediate work area at a height of approximately 1.0 to 1.5 meters above the ground.

A sample log was used to record the following information: name and location of the site, date, start time, stop time, work activity, air sample cassette number. Field blanks were collected by opening the cassette face to expose the filter during the sample collection period.

Sample Analysis

The three bulk material samples of crushed rock were analyzed by Clayton Group Services, Inc. (Novi, Michigan) with NIOSH Method 7500 using X-ray diffraction (XRD). The laboratory reporting limits were 2.0% by weight for cristobalite, and 1.0% for quartz.

A total of 54 air samples (including field blanks) were analyzed by Clayton Group Services, Inc., by XRD.

Samples were prepared and analyzed following NIOSH Method 7500 for the determination of crystalline silica on PVC filters. This method provides the concentration of each silica form (quartz, cristobalite, or tridymite, if present). We use the term crystalline silica to refer to the total of these three mineral components.

The instrument limit of detection (LOD) for the reporting of cristobalite was 20 µg per sample and 10 µg per sample for quartz. Spiked PVC media was used for the determination of the LOD for quartz. Laboratory results reported the concentration of respirable particulate mass, respirable cristobalite, and respirable quartz.

In 2003, Clayton Services, Inc. used NIOSH Analytical Method 0500 for respirable particulate analysis. Samples collected in 2006 and 2007 were first analyzed by Sri Ramachandra Medical College (Chennai, India) for respirable particulates before the cassettes were sent via air courier to Clayton Services, Inc. for XRD analysis.

We utilize the crystalline silica PEL, as specified in U.S. and Indian regulations to compare results over the three project phases. The PEL is calculated as:

$$\text{PEL (mg/m}^3\text{)} = \frac{10}{2 + (\%\text{Quartz}) + (2 \times \%\text{Cristobalite})}$$

For each sampling phase, the arithmetic mean respirable particulate mass, respirable quartz and respirable cristobalite exposures were calculated. The 95th percentile upper confidence limits (95% UCL) were also calculated using U.S. Environmental Protection Agency's (EPA) ProUCL statistical software with the assumption that these values are lognormally distributed.[17] Based on the quartz and cristobalite content of the dust on the filter, the appropriate PEL for respirable particulate mass was calculated with the formula above for each sample.

Percent reduction in the mean respirable particulate mass, respirable cristobalite and quartz concentrations were calculated by comparing pre-implementation results to post-implementation results:

$$\text{Percent Reduction} = \frac{(\text{Mean Pre-Implementation} - \text{Post-Implementation})}{(\text{Mean Pre-Implementation})} \times 100$$

RESULTS

Samples of settled dust (from the crushing of bulk rock) collected from stone crusher units in the study area showed levels of cristobalite and quartz of 3-6% and 4-27%, respectively (Table 1). No tridymite was detected in these samples.

To determine respirable particulate mass concentrations most representative of potential exposures in the work zone, we have considered all sample results regardless of whether crystalline silica was detected on the filter. For quartz and cristobalite samples reported below the analytical laboratory LOD, we used one-half the LOD as a proxy concentration.[18] Ratios for respirable particulate mass to the PEL, and ratios for the quartz and cristobalite fractions to the NIOSH REL were calculated using the following formula:

$$\text{Ratio} = \frac{\text{Exposure Concentration}}{\text{PEL (or REL)}}$$

Results for pre-implementation dust samples are summarized in Table 2. A total of five personal samples were collected. All respirable particulate mass samples exceeded the PEL, and all respirable quartz samples exceeded the REL for respirable quartz. Forty percent of the samples exceeded the REL for respirable cristobalite and all samples were above the LOD. Mean concentrations for respirable particulate mass, respirable cristobalite, and respirable quartz dust were 2.63, 0.09, and 0.25 mg/m^3, respectively. The 95% UCLs for respirable particulate mass, respirable cristobalite, and respirable

Spray nozzles strategically placed in the stone crushing unit help to significantly decrease the generation of respirable silica dust.

TABLE 1 Analytical Results of Bulk Material Samples, Khurda, India

Sample Number	Silica Type	Result (% wt.)
03030822-001A	Cristobalite	3.0
	Quartz	4.0
	Tridymite	ND
03030822-002A	Cristobalite	ND
	Quartz	ND
	Tridymite	ND
03030822-003	Cristobalite	6.0
	Quartz	27.0
	Tridymite	ND

Abbreviations: ND = None Detected; %wt = Percent Weight

TABLE 2 Exposure Levels of Respirable Dust at Stone Crushing Units Pre-Implementation, Khurda, India

Sample ID	Operation Unit	Sample Time (min)	Respirable Particulate Mass (mg/m^3)	Respirable Cristobalite (mg/m^3)	Respirable Quartz (mg/m^3)	PEL[a] (mg/m^3)	Respirable Particulate Mass/PEL	Cristobalite/ REL[b]	Quartz/ REL
34319	A	420	2.2	0.22	0.31	0.278	7.92	4.40	6.20
34229	A	420	1.4	0.05	0.21	0.431	3.25	0.90	4.20
34211	A	360	7.2	0.10	0.36	1.04	6.91	1.92	7.20
34224	B	390	0.67	0.04	0.06	0.426	1.57	0.80	1.26
34231	C	420	1.7	0.03	0.29	0.427	3.98	0.56	5.80
Mean:			2.63	0.09	0.25	0.52	4.73	1.72	4.93
Standard Deviation:			2.612	0.0785	0.117				
95% UCL[c]:			7.905	0.249	0.694				

Abbreviations: PEL = Permissible Exposure Limit; Min = Minutes; REL = Recommended Exposure Limit; 95%UCL = 95th percentile Upper Confidence Limit.

[a]PEL = 10/(2 + %Quartz + (2 × % Cristobalite))
[b]REL for Cristobalite and Quartz is 0.05 mg/m^3.
[c]95%UCL are maximum likelihood estimates assuming lognormal distribution. Calculations performed with ProUCL v. 4.0.

quartz were 7.9, 0.24, and 0.69 mg/m^3, respectively. Mean concentrations for respirable particulate mass exceeded the PEL by 4.73 times, while mean concentrations of respirable cristobalite and respirable quartz exceeded the REL by 1.72 and 4.93 times, respectively.

Following the implementation of dust control measures, air samples were collected from select crusher units in the same area during the monsoon season. A total of 18 samples (6 personal and 12 area samples) were collected. Results for these samples are summarized in Table 3. Mean concentrations for respirable particulate mass, respirable cristobalite, and respirable quartz are 0.19, 0.02, and 0.01 mg/m^3, respectively. The 95% UCL for respirable particulate mass, respirable cristobalite, and respirable quartz are 0.58, 0.04, and 0.03 mg/m^3, respectively. The cristobalite content of all samples taken during this phase was reported at or below the laboratory LOD. Eighty-three percent of the samples had levels of quartz below the LOD. As stated previously, one-half the LOD was used to quantify these samples. Mean concentrations of respirable particulate mass were less than the adjusted PEL and REL.

Stone crushing units are labor intensive. These units are often located in tight clusters and dust drifts from neighboring operations.

During the 2007 dry season, another set of post-implementation samples were collected from select mills in the area. A total of 27 samples were collected (15 personal and 12 area samples). Results for these samples are summarized in Table 4. Mean concentrations for respirable particulate mass, respirable cristobalite, and respirable quartz are 0.96, 0.03, and 0.06 mg/m^3, respectively. The 95% UCL for respirable particulate mass, respirable cristobalite, and respirable quartz are 2.5, 0.05, and 0.19 mg/m^3, respectively. Eighty-nine percent of the samples had levels of cristobalite below the LOD and 48% had quartz below the LOD. The mean respirable particulate mass concentration exceeded the adjusted PEL by 1.29 times, and the mean concentration for respirable quartz exceeded the REL for respirable quartz by 1.23 times. Mean respirable cristobalite concentrations, however, were below the REL for respirable cristobalite. When combined, the monsoon and dry season mean respirable particulate mass concentrations are below the corresponding PEL and REL.

As shown in Table 5, the mean concentrations of respirable particulate mass in the monsoon season and the dry season were reduced by 92.6% and 63.7% respectively, compared to pre-implementation mean concentrations. Combined results from both seasons show a 75.2% reduction in mean respirable particulate mass concentrations compared to pre-implementation mean concentrations.

DISCUSSION

In this study, respirable crystalline silica monitoring was conducted in stone crushing mills in the Khurda Dis-

TABLE 3 Exposure Levels of Respirable Dust at Stone Crushing Units Post-Implementation—Monsoon Season, Khurda, India

Sample ID	Operation Unit	Respirable Particulate Mass (mg/m^3)	Respirable Cristobalite (mg/m^3)	Respirable Quartz (mg/m^3)	PEL[a] (mg/m^3)	Respirable Particulate Mass/PEL	Cristobalite/ REL[b]	Quartz/ REL
Res-001	D	0.069	**0.033***	**0.016***	0.083	0.83	0.66	0.33
Res-002	D	0.035	**0.029***	**0.015***	0.048	0.73	0.59	0.29
Res-003	D	0.359	**0.032***	**0.016***	0.415	0.87	0.64	0.32
Res-004	D	0.063	**0.045***	**0.022***	0.055	1.14	0.90	0.45
Res-005	D	0.257	**0.036***	**0.018***	0.272	0.94	0.71	0.36
Res-006	E	0.085	**0.017***	**0.008***	0.833	0.10	0.34	0.17
Res-007	E	0.177	**0.017***	**0.008***	1.489	0.12	0.33	0.17
Res-008	E	0.113	**0.018***	**0.009***	1.006	0.11	0.36	0.18
Res-009	E	0.225	**0.019***	**0.010***	0.425	0.53	0.39	0.19
Res-021	E	0.065	**0.027***	**0.013***	0.094	0.69	0.54	0.27
Res-022	E	0.454	**0.020***	0.055	0.432	1.05	0.41	1.10
Res-012	F	0.806	**0.011***	0.011	1.637	0.49	0.22	0.22
Res-013	F	0.309	**0.012***	0.023	0.569	0.54	0.25	0.5
Res-014	F	0.104	**0.011***	**0.005***	0.360	0.29	0.21	0.11
Res-015	F	0.077	**0.011***	**0.005***	0.272	0.28	0.21	0.11
Res-023	F	0.146	**0.012***	**0.006***	0.428	0.34	0.25	0.12
Res-016	F	0.132	**0.011***	**0.006***	0.438	0.30	0.22	0.11
SJ-05	F	0.027	**0.011***	**0.005***	0.098	0.28	0.22	0.11
Mean:		0.190	0.020	0.0100	0.497	0.54	0.41	0.28
Standard Deviation:		0.194	0.0105	0.0117				
95% UCL[c]:		0.580	0.040	0.0300				

Abbreviations: PEL = Permissible Exposure Limit; REL = Recommended Exposure Limit; 95%UCL = 95th percentile Upper Confidence Limit.

*Concentration calculated using 1/2 the reported limit of detection.

[a]PEL = 10/(2+% Quartz + (2 × % Cristobalite))

[b]REL for Cristobalite and Quartz is 0.05 mg/m^3.

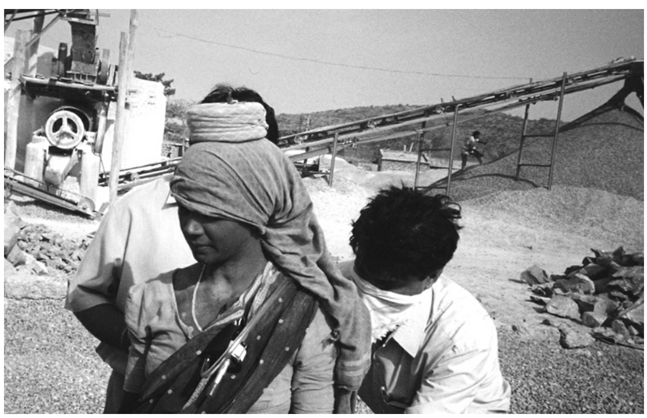
[c]95%UCL are maximum likelihood estimates assuming lognormal distribution. Calculations performed with U.S. EPA ProUCL v. 4.0.

trict in Orissa, India, before and after the introduction of atomizing water spray dust suppression systems. The pre-implementation results for respirable crystalline silica were in a range for which significant chronic lung disease is expected. The dust generated during the stone crushing process likely contributes to increased morbidity and mortality rates in India from lung cancer, silicosis and other lung disease (including TB). Even with the reductions observed following the implementation of water-spray dust controls, exposures in this industry would likely still pose a significant health risk. These risks are particularly important given the large number of child laborers observed and the presence of residential dwellings occupied by workers and their families in the immediate vicinity of the stone crushing operations.

Air monitoring was conducted in a total of seven mills while water spray systems were in operation (post-implementation). However, in some cases, one or more of the spray nozzles were not functioning and other neighboring mills in close proximity did not have any pollution control equipment. This situation may have increased the dust levels observed during the post-implementation phases.

In some cases, sprinklers were also installed along roads leading to and from the stone crushing units and at waste storage locations. These sprinklers are intended to reduce the amount of fugitive airborne dust generated by wind or vehicles traveling on these roadways. As these sprinklers were not consistently in operation, and no samples were collected from these geographical areas away from the mill operations, it is unlikely that they have much impact on the reported results.

Comparisons were made to pre-implementation respirable particulate mass and silica levels from similar mills in the immediate area. It was not possible to



Worker being fitted with air sampling pump for sampling respirable silica concentrations.

TABLE 4 Exposure Levels of Respirable Dust at Stone Crushing Units Post-Implementation—Dry Season, Khurda, India

Sample ID	Operation Unit	Sample Time (min)	Respirable Particulate Mass (mg/m³)	Respirable Cristobalite (mg/m³)	Respirable Quartz (mg/m³)	PEL[a] (mg/m³)	Respirable Particulate Mass/PEL	Cristobalite/ REL[b]	Quartz/ REL
16	G	183	7.98	0.14	0.63	0.739	10.8	2.80	12.6
17	G	138	0.42	**0.03***	**0.01***	0.510	0.83	0.59	0.30
18	G	247	0.27	**0.02***	0.04	0.366	0.74	0.33	0.72
19	G	178	0.31	**0.02***	**0.01***	0.614	0.51	0.44	0.22
1	G	139	3.00	0.07	0.19	0.795	3.78	1.32	3.71
2	G	158	0.68	**0.03***	0.06	0.534	1.27	0.57	1.13
20	D	296	2.84	0.03	0.18	0.942	3.02	0.68	3.54
21	D	284	0.38	**0.01***	**0.01***	1.010	0.38	0.3	0.15
22	D	282	0.22	**0.01***	**0.01***	0.651	0.33	0.29	0.14
5	D	224	0.27	**0.02***	**0.01***	0.579	0.47	0.41	0.20
23	D	229	0.27	**0.02***	**0.01***	0.659	0.40	0.34	0.17
3	D	277	0.44	**0.02***	0.02	0.746	0.59	0.33	0.33
4	D	102	1.55	**0.04***	0.06	0.854	1.82	0.89	1.24
24	E	309	0.50	**0.01***	0.03	0.802	0.62	0.26	0.52
25	E	300	0.64	**0.01***	0.03	0.903	0.71	0.28	0.61
7	E	300	0.44	**0.02***	0.04	0.567	0.78	0.30	0.79
26	H	240	0.43	**0.02***	0.02	0.711	0.61	0.34	0.37
27	H	242	0.25	**0.02***	**0.01***	0.655	0.38	0.33	0.16
6	H	252	1.23	**0.02***	0.09	0.839	1.46	0.36	1.71
8	H	319	0.27	**0.01***	**0.01***	0.781	0.35	0.29	0.14
28	I	249	1.01	**0.02***	0.07	0.841	1.19	0.33	1.34
30	I	250	0.23	**0.02***	**0.01***	0.629	0.37	0.32	0.16
10	I	213	0.34	**0.02***	**0.01***	0.675	0.50	0.42	0.21
29	J	242	0.23	**0.02***	**0.01***	0.584	0.39	0.34	0.17
11	J	241	0.21	**0.02***	**0.01***	0.490	0.42	0.38	0.19
9	J	242	1.20	**0.02***	0.11	0.709	1.69	0.38	2.15
12	J	160	0.24	**0.02***	**0.01***	0.438	0.55	0.50	0.25
Mean:			0.96	0.03	0.06	0.690	1.29	0.52	1.23
Standard Deviation:			1.58	0.03	0.12				
95% UCL[c]: 2.50			0.05	0.19					

Abbreviations: PEL = Permissible Exposure Limit; min = Minutes ; REL = Recommended Exposure Limit; 95%UCL = 95th percentile Upper Confidence Limit.

*Concentration calculated using 1/2 the reported Limit of Detection.

[a]PEL = 10/(2+% Quartz + (2 × % Cristobalite)).

[b]REL for Cristobalite and Quartz is 0.05 mg/m³.

[c]95%UCL are maximum likelihood estimates assuming lognormal distribution. Calculations performed with U.S. EPA ProUCL v. 4.0.

sample at the same mills during the pre- and post-implementation phases, but all the mills in the cluster were similar in size and utilized the same technologies to crush stone. Results indicate that respirable particulate mass levels were lower by 75.2% and by comparable amounts for respirable cristobalite and respirable quartz in the post-implementation period. Given that pre-implementation samples were collected only during the dry season, a more appropriate comparison may be restricted to results with water spray under the same conditions. The dry season comparison indicates a reduction of 63.7% for respirable particulate mass and 69.4% and 74.9% for respirable cristobalite and respirable quartz, respectively. These reductions are similar to those noted in other work environments using water spray for dust suppression.

Recently, reported levels of respirable particulate mass from a similar cluster of stone crushing mills in the State of Tamil Nadu in South India indicated substantially higher concentrations averaging 35.7 mg/m^3. The rock in this area is reported to have a free silica content of 18.8%, which is in the mid-range of the concentrations that we observed. Green et al. reported a mean concentration of respirable crystalline silica of 1.09 mg/m^3 for personal air monitoring conducted in a group of stone crushing units in the Indian State of Madhya Pradesh.[19] The average results reported here for respirable particulate mass at 2.6 mg/m^3 from the dry season before water spray systems were installed are consistent with these other observations.

In contrast, a survey of 19 stone crushing operations (i.e., limestone, granite and traprock) in the U.S. conducted by NIOSH had a geometric mean of 0.28 mg/m^3 for respirable dust in personal air samples with concentrations up to 8.3 mg/m^3. It was reported that approximately 14% of all personal samples exceeded

TABLE 5 Summary of Percent Reduction in Respirable Dust & Silica Exposures, Khurda, India

Sampling Period	Mean[a] (mg/m^3)	Standard Deviation	95% UCL[b] (mg/m^3)	% Reduction[c]
Pre-Implementation				
Respirable Particulate Mass	2.63	2.612	7.905	**N/A**
Cristobalite	0.09	0.0785	0.249	**N/A**
Quartz	0.25	0.117	0.694	**N/A**
Post-Implementation Monsoon Season				
Respirable Particulate Mass	0.19	0.19	0.58	92.6
Cristobalite	0.02	0.01	0.04	75.9
Quartz	0.01	0.01	0.03	94.3
Post-Implementation Dry Season				
Respirable Particulate Mass	0.96	1.58	2.50	63.7
Cristobalite	0.03	0.01	0.05	69.4
Quartz	0.06	0.12	0.19	74.9
Post-Implementation Combined				
Respirable Particulate Mass	0.65	1.28	2.00	75.2
Cristobalite	0.02	0.03	0.05	72.0
Quartz	0.04	0.13	0.11	82.7

Abbreviations: 95%UCL = 95th Percentile Upper Confidence Limit: N/A = Not Applicable.

[a]Samples detected at below the laboratory limit of detection (LOD) were calculated by taking 1/2 of the LOD.
[b]95%UCL are maximum likelihood estimates assuming lognormal distribution. Calculations performed with U.S. EPA ProUCL Version 4.0 software
[c]Percent reduction based upon the mean respirable dust concentration in pre-implementation samples compared to the mean respirable dust concentration in post-implementation samples using the formula ("Pre"-"Post")/"Pre" × 100.

the Mine Safety and Health Administration (MSHA) PEL for crystalline silica.[20]

We reported average exposures for respirable particulate mass, respirable quartz and respirable cristobalite that combined personal and area air samples that were collected near the stone crushing equipment. The average respirable quartz and cristobalite levels in samples taken during post-implementation monitoring (monsoon and dry seasons) with results less than the LOD were calculated by using one-half the LOD.

A comparison of the average exposures during these periods indicates that respirable particulate mass levels were well below the PEL during the monsoon season, but exposures may have exceeded the PEL for the dry season even with water spray technology. However, we did observe a significant reduction in average exposures from 4.73 to 1.29 times the PEL for respirable particulate mass. Comparing the UCLs reported for the post-implementation phase in the dry season (2.5 mg/m^3) to the average during the pre-implementation phase (2.63 mg/m^3) strongly suggests that the true mean exposure level with the water spray equipment in operation is less than that reported for the operations with no control measures in place.

No attempt was made to convert the sample results (collected over periods less than 8 hours in duration) to equivalent 8-hour TWA values to determine regulatory compliance. The PEL is an 8-hr TWA value based on a 40-hour workweek. The crusher units in the study operate on irregular hours based on product demand, season, weather, and availability of electricity. In some cases, work is repeatedly started and stopped several times a day due to power shortages, equipment breakdowns and other factors, but is estimated to exceed 40 hours per week. Due to these factors, we did not adjust respirable dust concentrations based on the length of the workday, and we did not adjust PELs/RELs based on the total hours worked per week. However, because the typical workweek is longer than 40 hours among these workers, and our average exposure levels pertain to all work time, our reported exposures likely underestimate the cumulative exposures relative to those permitted by the PEL and REL.

Although this study makes no attempts to link these exposures to symptoms of disease among workers, other reports have described the health effects from similar exposures. A recent unpublished report conducted for the New Delhi Government by the Centre for Occupational and Environmental Health at the Maulana Azad Medical College reported the prevalence of disease among a group of 111 former stone crusher mill workers in the Lal Kuan area outside the capital. They found that 68% had silicosis, silicotuberculosis, or tuberculosis.[21] Given the well-established link between silica exposure and susceptibility for TB, these results show the consequences of the absence of dust controls in this industry.

The reductions in respirable crystalline silica and respirable particulate mass concentrations following the introduction of the water spray controls demonstrate the efficacy of this intervention in the absence of other means to control exposures in stone crushing operations. In some cases, the mills may need to take additional measures including the use of boundary walls around equipment, wind suppression, and other steps necessary to further limit exposures and comply with local air pollution regulations. The testing conducted also suggests seasonal variability in reducing dust exposures and the need to be extra vigilant in dry climates. Although data from both seasons showed considerable improvement, there is a clear advantage to wet season conditions.

In the Khurda stone crusher cluster, ongoing outreach and education has resulted in over 40 mills installing water spray equipment with fine mist spray nozzles that were available on the local market. Although several mills also installed new bore wells, the absence of a reliable water supply is a limiting factor in many of the crusher sites. Nevertheless, this study demonstrated the efficacy of these spray systems approximately three years from the date of their initial installation. It suggests that these relatively inexpensive systems can be maintained and operated over an extended time frame.

RECOMMENDATIONS

The stone crushing industry is growing rapidly and is very decentralized. Greater effort is needed to encourage the adoption of technologies to minimize silica exposures. This project demonstrates that, in one locality, an ongoing effort to educate stone crusher mill owners about silica hazards and available controls could greatly reduce exposures.

The application of a fine mist of water has been shown to be an effective means to reduce respirable dust from stone crusher mills in the U.S. and other developed countries. However, these systems are not in widespread use in India due a lack of technical expertise, experience, and incentives to use dust control technologies.

Through the partnership with JRP and OK International, mill owners volunteered to install water spray systems to improve dust control. The project generated a “demand” for control technologies by educating owners and their association about the problem and potential solutions. This type of situation is relatively rare for occupational health/engineering control interventions in developing countries. The motivators for this positive behavior should be further studied and applied to broader situations.

Water-spray engineering controls can be installed and operated with minimum labor. The average cost for this equipment in India is less than US$1,000, which includes the equipment purchase and installation for a small-scale stone crusher mill. Additional costs ranging from US$1,000 to US$5,000 may be necessary to upgrade or develop water supplies from groundwater or water catchment systems.

Further research and action are needed to promote widespread occupational health improvements in the stone crushing industry in India. Below is a list of suggestions to promote efforts to reduce silica hazards in this industry on a broader scale:

- Assess water usage for these systems to evaluate and field test various options for mill owners to gain access to water year round.
- Prepare and disseminate a practical how-to “tool kit” guide to controlling dust hazards during stone crushing operations.
- Build capacity among Indian NGOs, health professionals, government, trade associations, multilateral banks, and others to address these issues with regional training seminars based on the “tool kit.”
- Encourage bulk purchasers of crushed stone in India, as well as those that have influence over such purchases through financing large infrastructure projects (e.g., the World Bank and Asian Development Bank), to require by contract specification and verification that stone is only purchased from stone crushing mills that consistently use and maintain adequate control technologies.

Water spray control methods are among the best available for stone crushing operations. However, they are unlikely to be used unless they are simple to install and maintain, low-cost, and available locally. The systems tested here meet these criteria. The study also suggests that they greatly reduce silica exposures in real world situations.

As more than 500,000 workers in India, including children, are exposed daily to excessive levels of respirable silica while working in stone crushing mills, national and multi-national institutions operating in India should appropriately use their influence to promote the widespread adoption of water-spray and other control technologies among stone crushers.

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