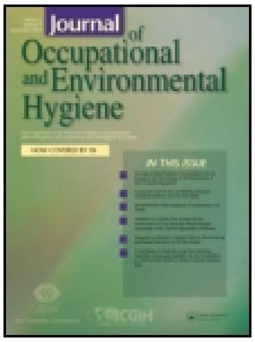

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The Effect of Debris Accumulation On and Filter Resistance to Airflow for Four Commercially Available Vacuum Cleaners

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Mortar removal with right-angle grinders can cause excessive exposure to respirable crystalline silica. To control this dust exposure, vacuum cleaners need to exhaust 2.3 m^3/min (80 cubic feet per minute) from the grinder's exhaust hood. Maintaining this airflow while collecting as much as 15.9 kg (35 lb) of debris in the vacuum cleaner has been problematic. A laboratory study was conducted to evaluate how mortar debris affects vacuum cleaner airflow and filter pressure loss. Four vacuum cleaners were tested. Two of the vacuum cleaners used vacuum cleaner bags as a prefilter; the other two vacuum cleaners used cyclones to reduce the amount of debris that reaches the filter. Test debris was collected by a masonry restoration contractor during actual mortar removal using a grinder fitted with a hood. The hood is attached to a vacuum cleaner with cyclonic pre-separation. The vacuum cleaner fan curves were obtained experimentally to learn how pressure loss affects vacuum cleaner airflows. Then, 15.9 kg (35 lb) of mortar removal debris was sucked into the vacuum cleaner in 2.27-kg (5-lb) increments. Before and after adding each 2.27-kg (5-lb) increment of debris, vacuum cleaner airflows were measured with a venturi meter, and vacuum cleaner static pressures were measured at the inlet to the vacuum cleaner motor, and before and after each filter. The vacuum cleaners equipped with cyclonic pre-separation were unaffected by the mass of debris collected in the vacuum cleaner and were able to maintain airflows in excess of 1.98 m^3/min (70 cfm) throughout the testing program. As debris accumulated in the vacuum cleaners that used bags, airflow decreased from 2.3 m^3/min (80 cfm) to as little as 0.85 m^3/min (30 cfm). This airflow loss is caused by the increased airflow resistance of the bags that increased from less 0.03 kPa/m^3/min (0.1 inches of water per cfm) to 16.7 kPa/m^3/min (1.9 inches of water/cfm). Apparently, vacuum cleaners using bags should be used in applications where adequate dust control can be achieved at airflows less than 0.85 m^3/min (30 cfm). Vacuum cleaners with cyclonic pre-separators provided superior and cost-effective dust control compared with vacuums with bags when dust loading was high and when more than 30 cfm of airflow is needed for dust control.

Keywords airflow, construction, dust control, pressure loss, silica, vacuum cleaner, ventilation

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INTRODUCTION

During construction and renovation tasks, the cutting and grinding of concrete and masonry material can cause excessive and obvious (Figure 1A) exposure to respirable crystalline silica.[1] More than 35,000 nonresidential construction workers in the United States are exposed to more than twice the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit (REL) for respirable crystalline silica (0.05 mg/m^3).[2–4]

The ACGIH® threshold limit value (TLV®) for respirable crystalline silica is an 8-hr time-weighted average (TWA) of 0.025 mg/m^3 of respirable crystalline silica, and this TLV intended to prevent pulmonary fibrosis (silicosis) and lung cancer.[5,6] The use of right-angle grinders to remove deteriorated mortar from buildings causes excessive exposure to respirable crystalline silica that, reportedly, can be as high as 5 mg/m^3.[7] Other construction and renovation tasks such as concrete grinding, concrete drilling, brick cutting, and cutting roofing tile are also reported to cause excessive exposure to crystalline silica.[1] Thus, effective control measures are needed to reduce worker exposure to crystalline silica.

To remove deteriorated mortar, workers use hand-held, right-angle grinders equipped with an 11-cm (4.5-inch) grinding wheel rotating at 10,000–12,000 rpm to pulverize the deteriorated mortar that contains crystalline silica (Figure 1A).[8] While operating the right-angle grinder, the worker applies pressure to the grinding wheel to maintain a cut depth of 1–2 cm (0.39–0.79). To capture the dust, a vacuum cleaner can be used to exhaust a minimum of 2.3 m^3/min (80 cfm) from a hood that is mounted on the grinder as shown in Figure 1B.[7,9]

During field trials, respirable crystalline silica exposures for 22 samples had a geometric mean of 0.06 mg/m^3 and a range of less than 0.01 to 0.86 mg/m^3.[8] In other studies, geometric mean respirable crystalline silica exposures during mortar removal were between 0.35 and 1.1 mg/m^3.[1,7,10] The use of local exhaust ventilation (LEV) during tuck point grinding dramatically decreases personal dust exposure levels about

(A) Mortar removal without dust control

(B) Mortar removal with dust control

FIGURE 1. Mortar removal with and without dust control. Without dust control, mortar removal creates an obvious dust exposure. As shown in B, dust is controlled by using a vacuum cleaner to exhaust air from the grinder hood at a flow rate of 2.3 m^3/min.

5–20 times less than tuck point grinding conducted without any engineering control.[8]

During field trials, the vacuum cleaners lost airflow as debris accumulated, and these airflows showed a periodic fluctuation as vacuum cleaner filters were treated to dislodge debris that had caked onto filters.[8] The average flow rate decrease was between 0.08 to 0.01 m^3/min^2 (3 to 0.4 cfm) over a range of vacuum cleaners and hose diameters.[8] Vacuum cleaners that used vacuum cleaner bags in combination with more efficient final filters lost an average of 0.08 to 0.02 m^3/min^2 (1–3 cfm) of grinding. At a flow rate loss of 0.08 m^3/min^2 (3 cfm), vacuum cleaner airflows can be negligible after a period of only 30 min.

Cyclonic pre-separators can be used to keep collect debris upstream of the filters (Figures 2A and 2B). Used with a cyclonic pre-separator, the Dustcontrol 2700 vacuum cleaner (Dustcontrol, Norsborg, Sweden) lost an average of only 0.02 m^3/min^2 (0.4 cfm). The cyclonic pre-separator for the Dustcontrol vacuum cleaner has a pressure loss of 1.5 kPa (6 inches of water) at 2.4 m^3/min^2 (85 cfm), which reduces the initial airflow by about 0.25 m^3/min (9 cfm).[11] However, the cyclones may reduce the amount of debris that accumulates on the vacuum cleaner's filter, which helps the vacuum cleaner maintain the needed airflow. Thus, this research was conducted to evaluate how the accumulation of mortar debris affects vacuum cleaner airflow and the pressure loss across vacuum cleaner filters.

Vacuum cleaner airflows decrease with increasing static pressure measured at inlet to the vacuum cleaner motor. The relationship between static pressure at the inlet to the motor is termed the vacuum cleaner fan curve. In past studies, vacuum cleaner fan curves have been empirically found to follow this approximate relationship:[8,11]

$$Q = m(\Delta P_{v-sp}) + b \qquad \textbf{(1)}$$

where

$Q =$ the airflow (cfm),
$\Delta P_{v-sp} =$ the static pressure at the vacuum cleaner motor inlet (the pressure difference between atmospheric pressure and the absolute pressure at the inlet to the vacuum cleaner motor), and
$m, b =$ regression coefficients for, respectively, the slope and intercept.

The R^2 values, the fraction of the variability explained by the vacuum cleaners' fan curve, was better than 0.98.[8] The intercept (b) is the airflow with no pressure loss, and this airflow is sometimes called "the free airflow." The slope (m) is always less than zero as flow rate decreases with increasing static pressure. Slopes of –0.57 to –0.14 m^3/min/kPa (–5.1 to –1.3 cfm/inch of water) were reported.[8] The airflow rate loss attributed to a filter is the product of the slope multiplied by the pressure loss.

Generally, airflow through a filter is proportional to the pressure loss across a filter. This proportionality constant should be independent of air velocity or airflow.[11–13] For each filtration element, this proportionality constant (K_{filter}) is termed "filter resistance" and is stated as:

$$K_{filter} = \Delta P_{filter}/Q \qquad \textbf{(2)}$$

where

$\Delta P_{filter} =$ pressure loss across a filter, and
$Q =$ vacuum cleaner airflow.

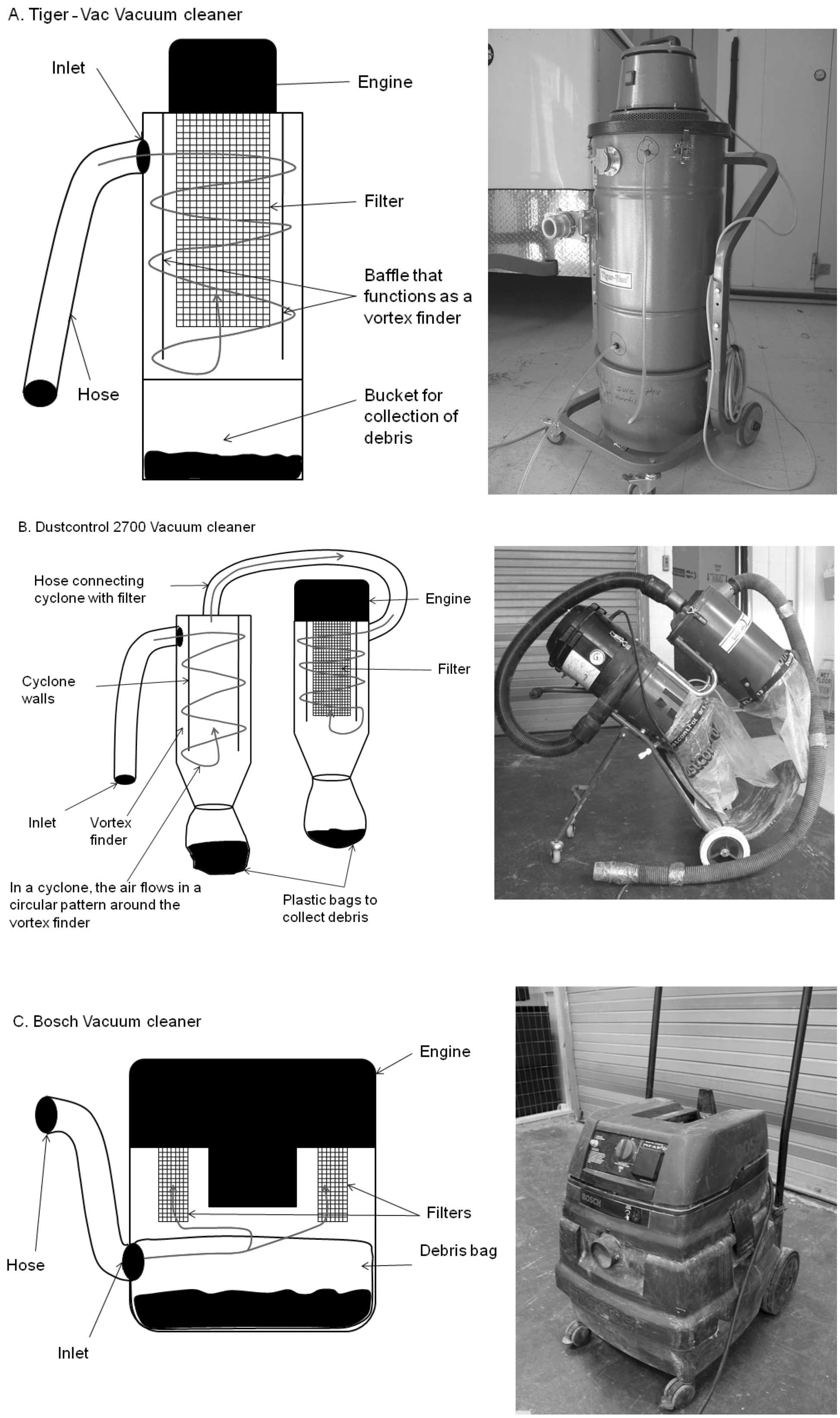

FIGURE 2. Schematic description and photographs of vacuum cleaners that were tested. The Tiger-Vac and the Dustcontrol vacuum cleaners incorporate cyclonic pre-separation upstream of the final filter. The Bosch and Dust Director vacuum cleaners rely upon vacuum cleaner bags to keep debris off the final filters.

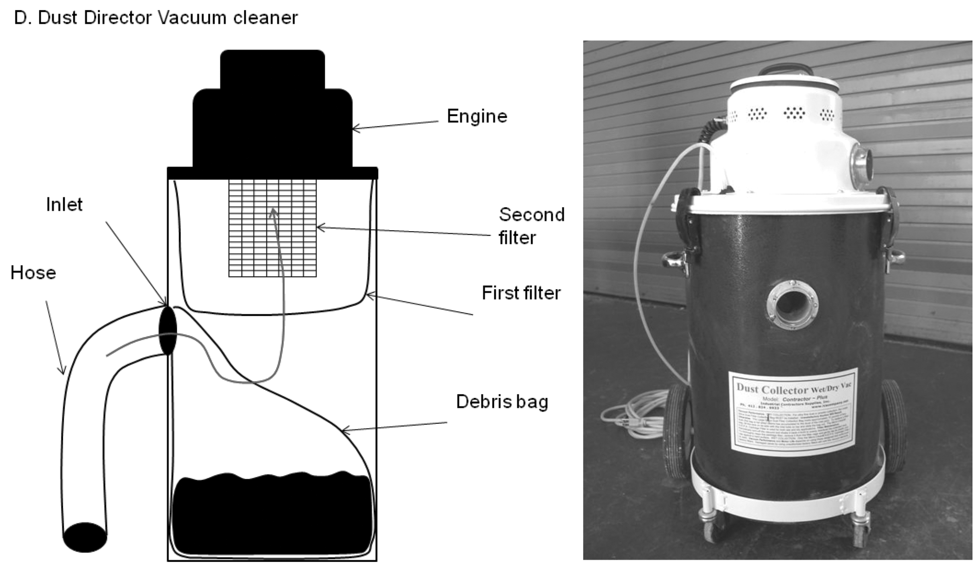

FIGURE 2. *Continued*

This model assumes laminar flow through the filters. As presented in Table I, the filter areas for the final filters in the vacuum cleaner were between 0.4 and 2.1 m^2. At 80 cfm, the filter face velocities are between 5.4 to 0.24 m/min (18 and 0.8 fpm). These velocities are consistent with laminar flow. However, data were not taken to evaluate this assumption. Because filter pressure loss is a function of flow rate and debris accumulation reduces airflow, the filter resistance normalizes pressure loss data for the decrease in airflow with debris accumulation.

MATERIALS AND METHODS

This research was conducted to assess how the mass of material collected in four vacuum cleaners affects vacuum

TABLE I. Vacuum Cleaners Selected for Study

Manufacturer	Model	Filtration	Description of Filter Cleaning for Final Filter
Tiger-Vac (Laval, Quebec, Canada)	2D-20DT	This vacuum cleaner incorporates a cyclone as a prefilter and a 99.97% at 0.3 μm final filter. The final filter has an area of 2.11 m^2.	Manually pulse vacuum clean by blocking the vacuum cleaner inlet and opening the vacuum release flap. Turn motor on and off. The debris falls into a detachable pan.
Dustcontrol (Norsborg, Sweden)	2700	Filter and sometimes used with cyclone. This vacuum cleaner has a tangential inlet. The filter area is 1.5 m^2. The advertised filtration efficiency is "better than 99.9%."	Cover inlet to vacuum cleaner and release vacuum removing plastic cover from a vent hole. This causes the final filter to flex and drop material into a plastic bag.
Industrial Contractor's Supply Dust Director (Pittsburgh, Pa.)	Contractor Plus Vacuum Cleaner	A paper vacuum cleaner bag and a final filter with an area of 0.4 m^2. Final filter efficiency is 99.97% at 0.3 μm. This manufacturer does not use model numbers.	Manually shake vacuum cleaner, turn vacuum cleaner on and off. This vacuum cleaner is not supposed to need cleaning.
Bosch (Mt. Prospect, Ill.)	3931	Bag and Filter with a surface area of 0.86 m^2. The advertised filter efficiency is 99.93% of particles at 0.3 μm and larger.	Electric motor used to vibrate final filter when vacuum cleaner motor is off.

TABLE II. Statistics Describing Vacuum Cleaner Fan Curves

	Vacuum Cleaner			
Regression Statistics	Tiger-Vac	Dustcontrol 2700	Bosch	Dust Director
Intercept (m^3/min)	2.54	3.38	3.38	3.37
Slope (m^3/min/KPa)	−0.13	−0.16	−0.19	−0.15
Std. error of estimate (m^3/min)	0.04	0.04	0.07	0.08
Std. error, intercept (m^3/min)	0.02	0.02	0.04	0.07
Std. error, slope (m^3/min/KPa)	0.002	0.002	0.004	0.005
N	19	16	15	12
R^2	0.997	0.998	0.993	0.989
Flow rate range (m^3/min)	0.42–2.29	0.38–2.34	0.35–2.86	0.33–2.19

cleaner airflow and filter pressure losses. These vacuum cleaners have different characteristics, which are listed in Table I, and those characteristics influence the pressure loss across the various vacuum cleaner filters and the vacuum cleaner airflow.

Vacuum Cleaners

The vacuum cleaners listed in Table I are all commercially available. All of these vacuum cleaners require less than 17 amperes at 120 volts and can be reasonably used on swing stages. These vacuum cleaners were selected because the design features differ. The range of filter area for the final filters is 0.4 to 2.1 m^2. Two of the vacuum cleaners use bags as prefilters. All of these vacuum cleaners are available with optional filters that are 99.97% efficient at 0.3 μm (HEPA filters).

The bodies of the Dustcontrol and Tiger-Vac vacuum cleaners have the shape of a cyclone with the final filter functioning as the vortex finder. This design is intended to separate the debris from the air upstream of the final filter. The settled debris is collected into a plastic bag or a pan. These vacuum cleaners were included in the study because the cyclones may remove airborne debris prior to filtration.

Experimental Equipment

A venturi meter (model 2HVT-FV, S/N7708; Primary Flow Signal Inc., Cranston, R.I.) was used to measure vacuum cleaner airflows.[14] In a venturi meter, the airflow under goes a nearly frictionless contraction to produce a measured pressure differential followed by a gradual expansion to the original diameter. This venturi meter has an inlet diameter of 5.2 cm (2.067 inches) and a throat diameter of 2.76 cm (1.088 inches). Airflow is computed from the pressure difference between the inlet and the throat. The pressure differential was measured with a U-tube manometer and flow rate is computed as described in an ISO standard.[15]

The uncertainty of the flow coefficient is known, and this uncertainty limits the accuracy of the flow rate measurement. For pipe Reynolds numbers larger than 75000, the uncertainty in the flow rate is under 1%. The ISO standard indicates that uncertainty is reduced from 2.5% to 1% as Reynolds number increases from 10,000 to 150,000. For flow rates obtained from this venturi meter, the uncertainty in the flow rates is less than 0.06 m^3/min (2 cfm) over a flow rate range of 0.034 to 6.5 m^3/min (12 to 230 cfm). This venturi meter is reported to cause a pressure loss of 7% of the measured pressure differential.[16] At 2.3 m^3/min (80 cfm), the pressure loss attributed to the venturi meter is 0.2 kPa (0.7 inch of water). As presented in Table II, these vacuum cleaners lose 0.19 to 0.13 m^3/min/kPa (1.6–1.2 cfm/inch of water), and the use of the venturi meter reduces the measured flow by no more than 0.03 m^3/min (1.1 cfm).

U-tube manometer (1211 Slack Tube Manometer; Dwyer Instruments Inc., Michigan City, Ind.) was used to measure vacuum cleaner static pressures before and after vacuum cleaner filters, the static pressure at the inlet to the vacuum cleaner motor, pressure differentials across the venturi meter. The pressure range for this manometer is 0–30 kPa (120 inches of water), and it is readable to the nearest 0.1 kPa (0.5 inches of water).

Pressure transducers (SmartReaderPlus4-30A-part-01-0116; ACR Systems, Surrey, BC, Canada) were used to measure and record vacuum cleaner static pressures during testing. This pressure logger is a digital barometer that measures and records absolute pressure with 12-bit resolution over the range 0–203 kPa (0–30 psia). Thus, this instrument records pressure to the nearest 0.05 kPa (0.2 inches of water). The pressure transducers read pressures that were 1.22 kPa (4.90 inches) of water less than a barometer (Nova Barometer; Princo, Southampton, Pa.). The pressure transducers were used to measure the pressures upstream and downstream of the filter in the Dustcontrol vacuum cleaner.

A shipping and receiving balance (Pelouze model 4010G; Grainger, Lake Forest, Ill.) with 150-lb capacity (68 kg) used to record the mass of material transferred to the vacuum cleaner. This balance weighs material to the nearest 0.1 kg (0.2 lb). A balance (model SP602; OHaus, Grainger) was used to weigh filters before and after completing the tests. This balance has a readability of 0.1 g.

The mortar removal debris was supplied in August of 2007 from a job site in the Midwest. The construction company

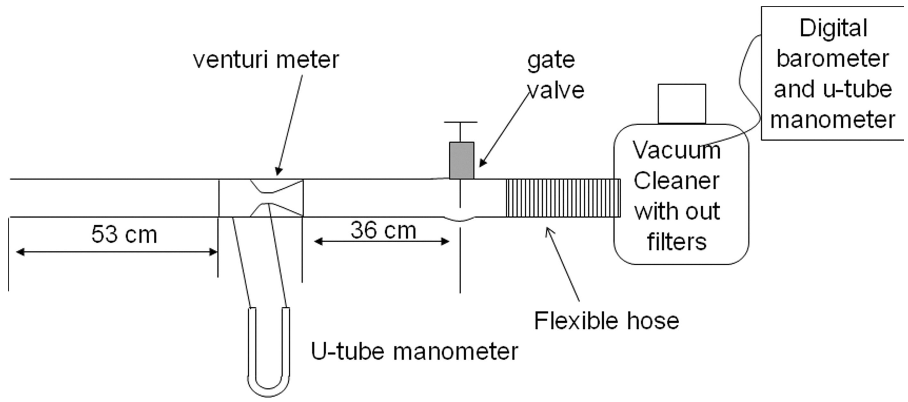

FIGURE 3. Apparatus for obtaining vacuum cleaner fan curve

uses hoods and vacuum cleaners to control the dust generated by mortar removal as described in a prior publication.(8) This debris was collected in the Dustcontrol vacuum cleaners that were used without cyclonic pre-separators shown in Figure 2B.

Experimental Procedures

Prior to studying how debris accumulation affects vacuum cleaner flow rate and the pressure loss across the vacuum cleaners' filters, the relationship between vacuum cleaner airflow and static pressure at the inlet to the vacuum cleaner motor was determined using procedures that were developed earlier.(8) The filters were removed from the vacuum cleaner, and small holes were drilled into their body. Flexible tubing was inserted into these holes, which were sealed with silicone caulk. The flexible tubing was used to measure vacuum cleaner static pressure and the tubing was connected to the pressure loggers or the U-tube manometer.

The experimental apparatus shown in Figure 3 was used to determine the vacuum cleaner fan curve. The outlet of the venturi meter was connected by 5 cm diameter (2 inch diameter), schedule 40 PVC pipe and flexible hose to the inlet of the vacuum cleaner. The vacuum cleaner airflow was obtained by measuring the pressure differential across a venturi meter with a U-tube water manometer. The static pressure at zero airflow was measured by blocking the inlet with a smooth piece of plywood. Then, measured pressure differential was used to compute an airflow rate as described by an ISO standard.(15) The U-tube manometer and the pressure logger (SmartReaderPlus4 -30A-128kb memory; part-01-0116; ACR Systems) were used to measure vacuum cleaner static pressure.

The formula for computing vacuum cleaner static pressure (ΔP_{v_sp}) from the pressure transducer measurements is: $\Delta P_{v\_sp} = P_{ambient}$ -$P_{measured}$. The terms $P_{ambient}$ and $P_{measured}$ are, respectively, the absolute pressures measured by the pressure transducer when the vacuum cleaner was off and when it was running.

A total of at least 10 equally spaced flow rates and vacuum cleaner static pressures were obtained by adjusting the gate valve shown in Figure 3 for each of the vacuum cleaners. Regression analysis (Regression tool is a component of Microsoft Excel 2007) was used to fit the data to this model described by Eq. 1. Regression analysis was used to compute the slope, intercept, the standard error of estimate, fraction of variability explained by the model, and the standard error for the intercept and slope.

Vacuum Cleaner Flow Loss, Changes in Filter Pressure Losses, and Accumulated Debris

The cumulative effect of material debris accumulation on the pressure loss across vacuum cleaners' filters and airflow was determined. In increments of 2.27 kg (5 lb),15.9 kg (35 lb) of debris were sucked into vacuum cleaners. Before and after each 5-lb increment, vacuum cleaner airflows and pressure losses were measured as shown in Figure 4. The mortar debris used for the test was previously obtained from a contractor in the Midwest. For each vacuum cleaner listed in Table I, this test was repeated three times.

The pressure difference across the final filter and the initial air cleaner were measured with data logging pressure transducers (Smart Reader SRP-004-5G-128K 0-5 PSI-G, ACR Systems for the Dustcontrol vacuum cleaner). For the other vacuum cleaners, static pressure upstream and downstream of each filter was measured with a U-tube manometer and the

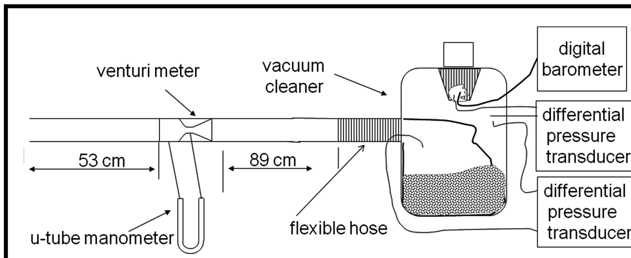

FIGURE 4. Apparatus for measuring pressures and flows before and after loading vacuum cleaner with mortar debris. When filter pressure losses were measured the venturi meter and pipe was disconnected from vacuum cleaner.

pressure transducer. To measure the static pressures, plastic tubing was run from the pressure logger or U-tube manometer to the appropriate spaces in the vacuum cleaners. This involved drilling holes in the vacuum cleaner body and in end caps for cartridge filters. The resulting holes were sealed with a flexible putty or silicone caulk.

Data collection involved the following steps:

1. The atmospheric pressure was recorded and the weight of the vacuum cleaner filters was recorded.
2. The vacuum cleaner was turned on. The initial airflow into the vacuum cleaner was measured using the test apparatus described by Figure 4. The venturi meter pressure differential was used to compute the airflow as described elsewhere.
3. After measuring the airflow, the venturi meter and pipe were disconnected from the apparatus shown in Figure 4. The following pressure measurements were made: in the space between the final filter and the vacuum cleaner motor, and the static pressures upstream and downstream of each filter in the vacuum cleaner. For the Dustcontrol and Tiger Vac vacuum cleaners, the vacuum cleaner hose remained attached to the vacuum cleaner. For the Dust Director and Bosch vacuum cleaners, the vacuum cleaner hose was removed because it was impractical to insert a hose through both the vacuum cleaner hose and the inlet to the vacuum cleaner. Thus, the vacuum cleaner hose was removed and tubing was inserted for the static pressure measurements directly into the vacuum cleaner bag.
4. The mortar removal debris was in a bucket that sat on a scale (Pelouze model 4010G, item 4TH71; Grainger). The vacuum cleaner was turned on and the vacuum cleaner hose was used to suck 2.27 kg (5 lb) of mortar debris into the vacuum cleaner.
5. The procedure described in Steps 2 and 3 was used to measure the final airflow and static pressures.
6. The vacuum cleaner was turned off and the final filter was cleaned, as recommended by the vacuum cleaner manufacturer. In the case of the Dust Director vacuum cleaner, the authors turned on the vacuum cleaner while blocking the inlet with a flat block of wood and simultaneously removing the block and turning off the motor.

Steps 2–6 were repeated until 15.9 kg (35 lb) of debris were sucked into the vacuum cleaner. Then, the weight of the vacuum cleaner filters was recorded. This procedure was conducted three times for each vacuum cleaner.

Data Analysis

To obtain the vacuum cleaner fan curves, airflows were computed from the pressure differential across the venturi meter as described elsewhere.[15] Regression analysis was used to fit the data to model described by Eq. 1. Regression analysis was performed using the data analysis tools in Microsoft Excel 2007. These vacuum cleaner fan curves were used to estimate airflow during filter pressure differential measurements.

The pressure differences across the vacuum cleaner filters were computed for each 5-lb increment of debris. The vacuum cleaner fan curve was used to compute the airflow from the static pressure measured at the inlet to the vacuum cleaner because the venturi meter is known to cause a permanent pressure loss of 7% of the measured pressure differential cross the venturi meter.[16] These static pressures measured with the pressure transducer at the same time that the static pressures between the filters were measured. Filter resistance, K_{filter}, was computed for each filter as described by Eq. 2. For each filter, the individual values of K_{filter} were plotted as function cumulative mass debris transferred to the vacuum cleaner. Using the data analysis tools, regression analysis was performed that modeled K_{filter} as a linear function of cumulative mass of debris transferred to the vacuum cleaner.

To examine the effect of debris accumulation on vacuum cleaner airflows, vacuum cleaner airflows were computed directly from the venturi meter pressure differentials.[15] For each vacuum cleaner, airflows were plotted as a function of the cumulative mass of debris transferred to the vacuum cleaner. Regression analysis was performed that modeled vacuum cleaner airflow as a simple linear function of cumulative mass of debris transferred to the vacuum cleaner.

RESULTS AND FINDINGS

The vacuum cleaner fan curves are described by Eq. 1 as flow rate decreases linearly with increased vacuum cleaner static pressure over the range of the data list in Table II. The R^2 statistic for this model was better than 0.989, and the standard error of estimates for the four vacuum cleaners were between 0.04 and 0.08 m^3/min (1.3 and 2.7 cfm). The slope of the fan curve shows how flow decreases with increased vacuum cleaner static pressure. The impact of pressure loss on airflow is simply the product of the slope and the pressure loss. The standard error of estimate for the slope is less than 4% of the slope.

The flow rates provided by the Tiger-Vac and the Dustcontrol vacuum cleaners were largely unaffected by debris accumulation (Figures 5A and 5B). Debris accumulation had very little affect on the flow rate measured before and after cleaning the filters, as values of R^2 were under 0.06 and this was not statistically significant (Table III). The Tiger-Vac and the Dustcontrol vacuum cleaners used cyclones to collect most debris before the air flows through the filters.

In contrast, debris accumulation reduces the airflow provided by the Bosch and Dust Director vacuum cleaners (Figures 5C and 5D), and this result was statistically significant as $P < 0.0003$ (Table III). Furthermore, the slopes of the trend lines in these plots showed that these vacuum cleaners lost between 0.09 and 0.045 m^3/min/kg (1.4 and 0.73 cfm per lb) of debris accumulation (Figures 5C and 5D). As a result, airflows decreased from 2.3 to 0.8 m^3/min (80 to 30 cfm) for the Bosch vacuum cleaner (Figure 5C) and from 2 to 0.8

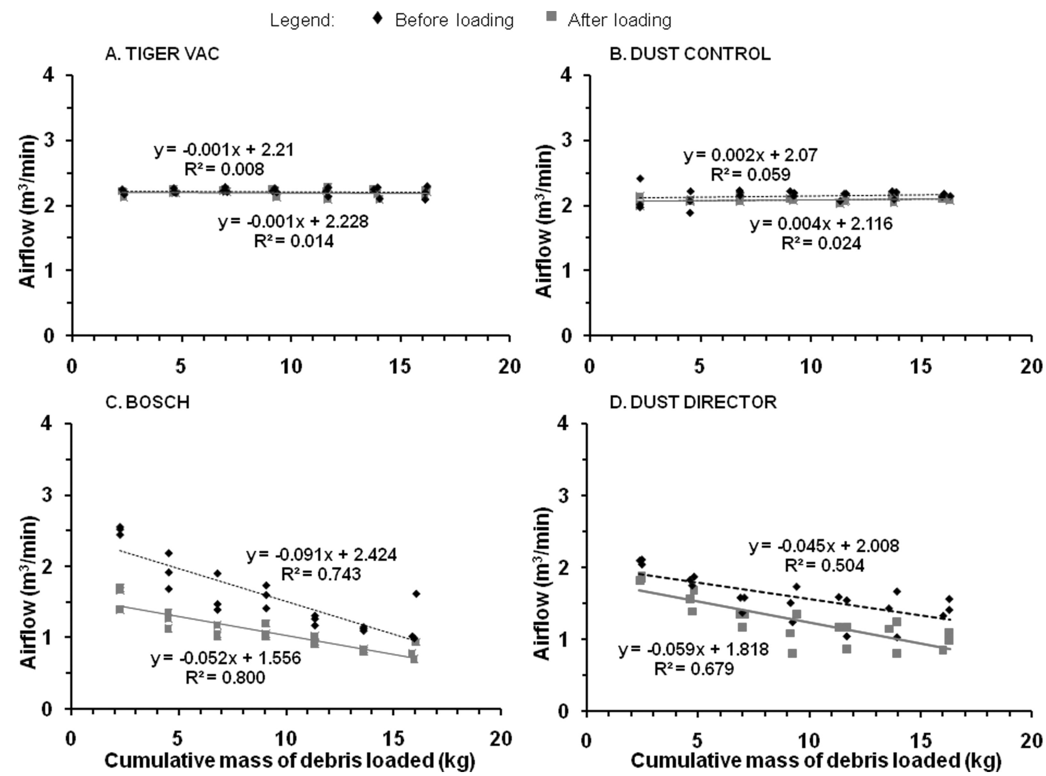

FIGURE 5. Airflows for vacuum cleaners that involved cyclonic pre-separation were unaffected by debris accumulation within the vacuum cleaner.

m^3/min (70 to 30 cfm) for the Dust Director vacuum cleaner (Figure 5D).

The flow rate decreases for the vacuum cleaners that used vacuum cleaner bags (the Bosch and Dust Director vacuum cleaners) are quite noticeable (Figure 5C and 5D) and are statistically significant ($P < 0.0007$ in Table III). The resistance to airflow by the vacuum cleaner bags and prefilters increases with debris accumulation (Figure 6). Before sucking

TABLE III. Probability That Chance Explained the Fit of the Regression Line to the Data

		Vacuum Cleaner			
Figure No.	Dependent Variable in Figure	Tiger-Vac	Dustcontrol 2700	Bosch	Dust Director
3	Vacuum cleaner airflow before adding 5-lb increments	0.6037	0.4999	P < 0.0001	0.0003
	Vacuum cleaner airflow after adding 5-lb increment	0.6987	0.2904	P < 0.0001	P < 0.0001
4	K, flow resistance for vacuum cleaner bag, after cleaning			P < 0.0001	0.0007
	K, flow resistance for vacuum cleaner bag, before cleaning			P < 0.0001	P < 0.0001
	K, flow resistance for filter between vacuum cleaner bag and final filter, before cleaning				0.0021
	K, flow resistance for filter between vacuum cleaner bag and final filter, after cleaning				0.0296
5	K, flow resistance for final filter after cleaning	0.0123	0.1945	P < 0.0001	P < 0.0001
	K, flow resistance for final filter before cleaning	0.0140	0.0723	P < 0.0001	0.0032

Note: Blank cell indicates that vacuum cleaner does not have this filter.

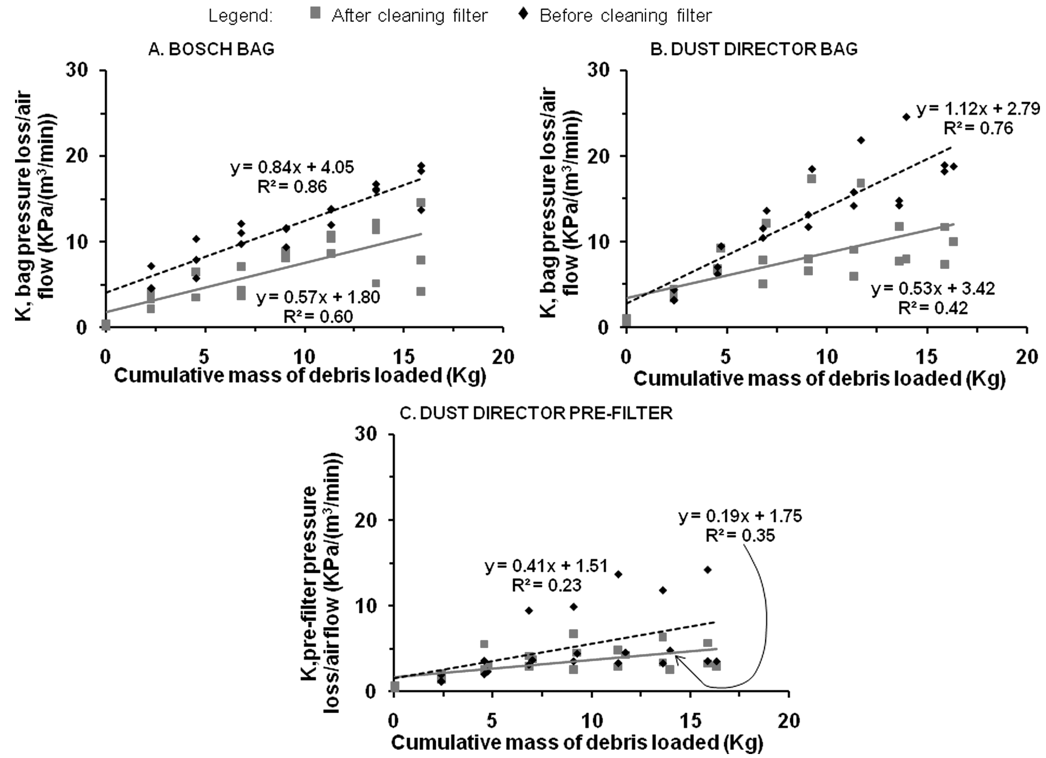

FIGURE 6. Debris accumulation increases airflow resistance of the vacuum cleaner bags and the pre-filters.

debris into the vacuum cleaner bags and pre-filters, the resistance to airflow of the vacuum cleaner bags is under 0.03 kPa/m^3/min (0.1 inches of water per cfm). With increasing debris accumulation, the resistance to airflow by the vacuum cleaner bags can exceed 16.7 kPa/m^3/min (1.9 inches of water/cfm). At airflows of 0.8 m^3/min (30 cfm), this is a filter pressure loss of 14.1 kPa (57 inches of water). Based on the slope of the vacuum cleaner fan curves for the Bosch and Dust Director vacuum cleaners (Table II), a 14.1 kPa (57 inch of water) pressure loss would cause the vacuum cleaner airflows to decrease by 2.6 and 2.1 m^3/min (91 and 74 cfm), respectively. With no pressure loss, these vacuum cleaners provide an airflow of 119 cfm (the intercepts for the fan curves listed in Table II).

Considering only the pressure loss caused by the vacuum cleaner bags, the flow moved by the Bosch and the Dust Director vacuum cleaners is estimated to be under 0.76 and 1.2 m^3/min (27 and 43 cfm), respectively. Clearly, increased pressure loss through the vacuum cleaner bags largely explains the decrease in airflow as debris accumulation increased in the Bosch and Dust Director vacuum cleaners.

The filter resistance for final filters in each vacuum cleaner was not as high as the resistance found for bags and for pre-filters in Bosch and Dust Director vacuum cleaners. Figure 7 shows that the filter resistances do not increase dramatically with cumulative mass of debris loaded into each vacuum cleaner. The slopes for the trend lines in Figure 7 are smaller than 0.02 kPa/(m^3/min)/kg (0.001 inches of water/cfm/lb) of debris accumulation. This indicates that the resistance to airflow for the final filters is gradually increasing, and these filters will eventually need to be changed. The vacuum cleaner filters downstream of the cyclone or the vacuum cleaner bags gained less than 200 g after completing the three tests. These results are tabulated in Table IV.

DISCUSSION

Vacuum cleaners with cyclones provided a more stable airflow and were not affected by debris accumulation. These vacuum cleaners provided airflow between 2.2 and 2.1 m^3/min (78 and 73 cfm (Figures 5A and 5B). Debris accumulation can dramatically increase the resistance to

TABLE IV. Filter Weight Gains After Conducting Three Tests

Filter	Weight Gain (grams)
Tiger-Vac final filter	186
Dustcontrol 2700 final filter	20
Dust Director (liner upstream of final filter)	17
Dust Director final filter	10
Bosch (two filters)	28

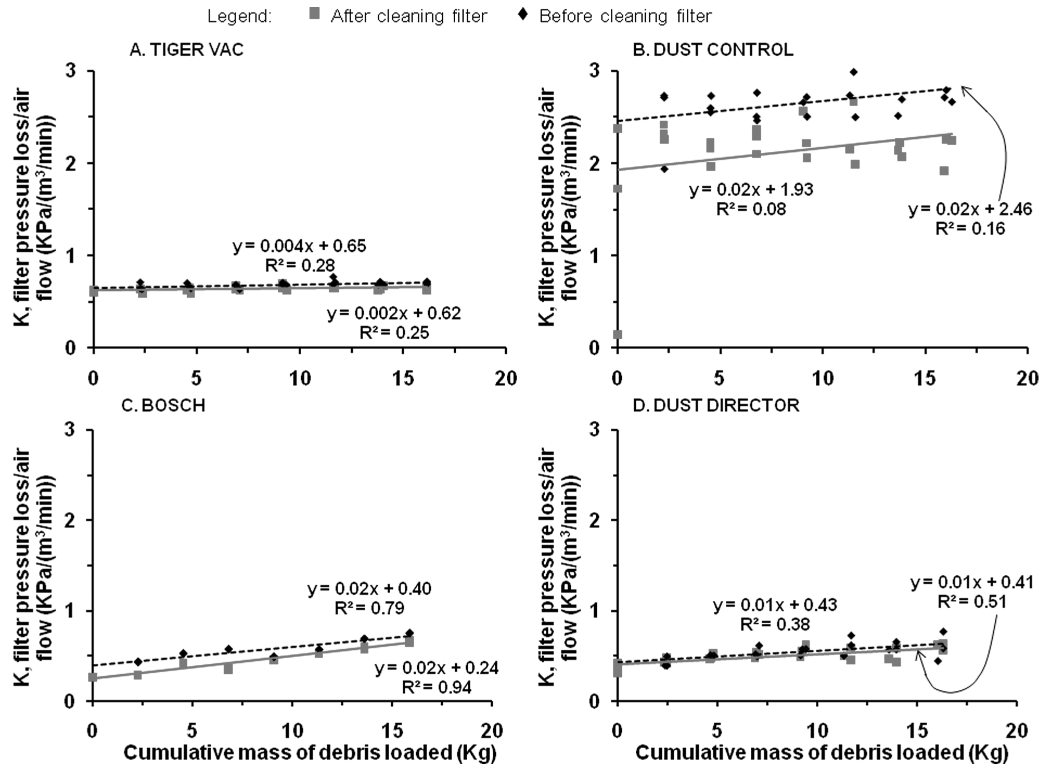

FIGURE 7. The resistance to airflow for the final filters gradually increased with loading indicating that the filters will eventually need to be replaced.

airflow through vacuum cleaner bags (Figure 6) and cause airflows to decrease from 2.4 to 0.8 m^3/min (85 to 30 cfm) (Figures 5C and 5D). Vacuum cleaners with bags should be used only for applications where 0.8 m^3/min (30 cfm) provides adequate dust control. These data were generated with debris collected at a construction site. This may have allowed the powder to agglomerate, and the results obtained during laboratory testing may differ from results obtained at construction sites. However, the increased resistance through the vacuum cleaner bags shown in Figure 6 explains the airflow losses that were reported during field trials.[8]

Vacuum cleaners with cyclones cost substantially more than vacuum cleaners with bags. However, vacuum cleaner bags can be an important operating cost because to maintain airflow they need to be changed 2–3 times per day after collecting 5 to 7 kg of debris. The payback time of the capital cost difference between using a vacuum cleaner with a cyclone and the Bosch vacuum cleaner is about 110 days of grinding. This does not consider the labor costs and lost production associated with changing bags, which may be significant. The actual payback time will depend on the operation. The cyclonic vacuum cleaners will be more cost-effective if the service life is longer than 110 days of grinding. Health and safety professionals should consider this payback time as an advantage of cyclonic vacuum cleaners.

Because vacuum cleaner bags caused decreased flow rates and increased work place dust exposure, researchers and practitioners should measure and log or record flow rates during actual debris accumulation, as results may vary with site-specific conditions. Such results are needed to develop an overall plan to control the worker's dust exposure and to develop minimum airflow rate specifications for various dusty, construction-related tasks. These recommendations include the frequency in which the worker needs to stop and address flow rate decreases by pulsing filters or changing vacuum cleaner bags.

Vacuum cleaners are used to control silica exposures for dust-generating tasks such as mortar removal, hole or core drilling, concrete grinding, and cutting concrete blocks or roofing tiles.[1] Clearly, minimum flow rate specifications need to be developed for these dust-generating tasks, and vacuum cleaners should be selected on the basis of these minimum airflow specifications.

However, the flow rate decreases observed in this study and in an earlier study need to be addressed as part of an overall strategy or occupational safety and health management program.[8,17] Procurement specifications should address the minimum flow required for dust capture, the airflow losses caused by debris accumulation and filter cleaning. Procurement specifications should also include a means of assessing the airflow provided by the vacuum cleaner. The vacuum cleaners should include vacuum cleaner static pressure gauges so that workers can track the vacuum cleaner airflow.

The additional cost of a pressure gauge would be less than 5–10% of the total cost of the vacuum cleaner. The vacuum cleaner fan curve should be known so that pressure measurements can be related to airflow. The workers should be trained to interpret this vacuum cleaner static pressure as a measure of airflow. When static pressure is too high and the airflow is too low, workers need to take action to recover the lost airflow. For vacuum cleaners with bags, the workers need to know when to change these bags to maintain airflow and minimize dust exposure.

CONCLUSION

When much debris is being generated during tasks such as mortar grinding, cyclones should be used as the first stage of filtration. Cyclones can keep the debris accumulation from clogging filters and help the vacuum cleaner maintain airflow. Debris accumulation in vacuum cleaner bags caused pressure losses that were nearly 14.1 kPa (57 inches of water), and this pressure loss reduced the airflow provided by the vacuum cleaners.

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