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The Influence of Different Shoes and Different Flooring Materials on Particle Resuspension

By

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Submitted in partial fulfillment of the requirement for
The degree of Bachelor of Engineering (Honours) in Building Engineering
(Building Services Engineering)

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Abstract

The resuspension of airborne particulate matters (PM) indoors causes the effect harmful to the human's health. Such of the exposure could be induced by human activities such as walking. This work investigated the resuspension and translocation of PM from different flooring materials by human walking. In the experiment, four types of flooring materials (PVC plate, tile, shag rug and short wool rug) and five types of shoes (boots, sneaker, slipper, high heels and leather shoes) were chosen to carry out the study. The flooring materials were seeded in the chamber with solid dust (ISO 12103-1, A2 Fine Test Duct with the size range from 0.714 to 10μm, since 10μm is the upper limit of test range from the optical particle size spectrometer) through the venture vacuum generator and the pump set. After the deposition of dust, the test took place in a sealed test chamber in the laboratory. The airborne particulate matter concentration was measured by the optical particle size spectrometer (OPSS) in different height during the resuspension test.

Scanning electron microscopy (SEM) of carpet fibers was used to determine the fraction of dust available for resuspension. The data of mass concentration recorded from the OPSS and some background information from this study were used to generate the emission factors by particle size for walking with two frequencies, 84 steps per minute and 120 steps per minute on all the flooring samples. It is found that the dust loading did not affect the emission factor, indicating that the amount of resuspension PM was directly proportional to the available PM in the flooring sample. According to the study, the emission factor of shag rug was much larger than the others and the whole result taking by the leather shoes was also larger than the slippers with flatten base. The result was supported by induced velocity test.

Acknowledgements

I would like to express my gratitude to my research supervisor Dr. Lai, Chi Keung Alvin for his guidance and some constructive ideas on the research topic. He provided some invaluable support and advice to inspire me when I encountered the difficulties during the experiment. The advices helped me a lot for the whole research study.

My special thanks to the technical staff in Building Services Laboratory of City University of Hong Kong for helping to make the heavy roller, connection cable and give some advice for the design and function of some equipment. They also lend me some equipment to assist my research study.

Moreover, I appreciate the help of the Department of Physics and Materials Science for scanning the electronic microscopy on some flooring samples. The technical staff gave me some advice to do the SEM, such as the sample size and some concern to take the samples to that laboratory.

Furthermore, I would like to express my thanks to Ms. Poon, Ka Man Carmen for her assistance in the experimental setup and gave me some advices. She shared some experience of doing the experiment with the topic that was similar to the thesis studied.

Last but not least, I especially express my gratitude to my partner Mr. Chan Hiu Fai and helper Ms. Chui Tsz Kwan for participating in the experiment. They helped me to prepare the work and set up the equipment. Also, they gave me some supportive advice and encouragement.

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Thesis Outline

The thesis consists of five chapters in total. Each chapter with briefly description is outlined as follows.

- Chapter 1: Introduction

  It sets the objective of this research study and shows the brief description.

- Chapter 2: Literature Review

  It summarizes the previous literature journals study in the resuspension field.

- Chapter 3: Methodology

  It describes the setup and the procedure of the experiment. For instance, the deposition of dust particle onto the flooring samples for preparation and the resuspension test carried on in the enclose chamber with different shoes etc.

- Chapter 4: Result and Discussion

  It presents the data recorded in the experiment in calculation and graphic form. Comparison is made between each type of shoes and also the flooring materials. It summarizes the experimental data and also the emission factors. The result is listed and discussed with different parameters. Also, some encountered difficulties and recommendation are made in this part.

- Chapter 5: Conclusion

  It briefly discusses the whole process and the result of the experiment and gives some comment about it.

Chapter 1

1. Introduction

Recently, the importance of indoor air quality is advocated since people spend most of their time indoors, such as working with the computer, sleeping and doing exercise. The PM exposure is closely related to the indoor activities and the resuspension likes a source for indoor PM concentration. Some dust particle is adhered on the furniture, floor and wall etc and then trap inside the crack. However, people always walk on the floor no matter of their activities. The dust particle may suspend and mix with the indoor air. It reduces the indoor air quality and harm to our health. Since the indoor PM comes from many sources such as the environment, ventilation, track-in on shoes etc and it is able to pose health threat to people after resuspension of PM back to the main airstream by human activities (Qian and Ferro, 2008).

To investigate the relation and the behavior of resuspension, the study aims to compare the mass concentration of PM resuspended from different flooring materials against human walking with different shoes. Since each type of shoes have different grooves, and then the research will focus on the grooves against the degree of resuspension. The experiment was carried on with the velocity test. It used to find out the position of testing which can produce the highest value and support the theme study.

1.1 Test Dust Particle Size Distribution

The particle size distribution is determined by the Multisizer AccuComp® providing from the manufacturer. The table lists of bellows showing the volume percentage of each size range of test dust.

Table 1.1: Test Dust Volume Distribution in Each Size Range

Size (μm)	Volume Fraction (%)
0.714	0
0.8	0.855
1.005	2.83
1.987	7.73
4.934	23.12
9.759	18.6

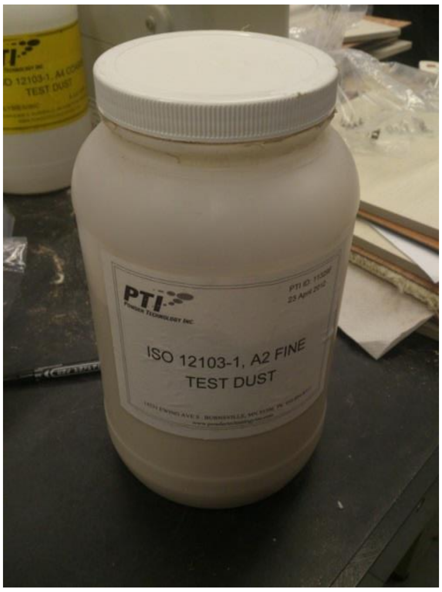


Fig 1.1: ISO 12103-1, A2 Fine Test Dust

Chapter 2

2. Literature Review

There are lots of research papers studying the resuspension of particles according to human activities. Long et al. (2001) reported that indoor activities could result in the increase of PM concentration up to several orders of magnitude higher than the background levels. Ferro et al. (2004) showed the indoor activities including the walking, cleaning and sitting on furniture can also cause the resuspension. The study of Qian and Ferro (2008) showed the resuspension rate on carpet was higher than the hard floor with size range between 1 and 10μm. It carried out the walking experiment repeatedly and found the larger size of particles and fast walking resulted in higher resuspension regardless of the participant's weight. Johnson, Kendall and Roberts developed the JKR adhesion model to indicate the effects of the surface energy and surface deformation on particle adhesion and also the detachment. Andrea R. Ferro (2004) also studied the source strength of resuspend particulate matter. To take the resuspension data, a step model used to simulate the walking motion by down and up, was treated as the motions of two circular disks moving towards and away from the floor continuously with a step down velocity of 0.5m/s and 0.515m/s. Some using a combination foot model machine and required the power supply to drive the foot model. However, Thatcher and Layton (1995) reported that the particle size under 25μm can be resuspended with normal human activity in higher emission rate.

Table 2.1: Summary of Part of the Existing Research Study on Particle Resuspension

Research Paper	Description of Experiment	Result
Estimating the Resuspension Rate and Residence Time of Indoor Particles (2012)	**Location**: Single family with two stories, temporarily unoccupied residence in Potsdam, NY **Activities**: Walking at a normal and vigorous pace, siting on furniture **Procedure**: 1 hour low activity for instrument download and set up, 1 hour non low activity period, two 30 min periods for prescribed activity, empty house with instrument running until the next morning	The mass concentration of an aerodynamic diameter less than 10 μm has an average of 2.5 times as high as the background level and stay in the combined indoor air for a long time
Resuspension of Particulate Matter from Carpet Due to Human Activity (2008)	**Location**: US EPA test house facility in Cary, NC and te RTI chamber facility in Research Triangle Park, NC **Activities:** Walking or cleaning **Procedure:** 5mins experiment sampling 15mins for ensuring the PM concentrations elevated by resuspension during walking and placement of instrument can back to the background level	Less resuspension in high RH. HVAC ON has a better mixing volume and hence get a higher resuspension result. Resuspension occurs on the top 2mm of carpet pile.
Particle Detachment, Resuspension and Transport Due to Human Walking in Indoor Environments (2008)	**Location:** Chamber in the BEESL laboratory at Syracuse University **Activities:** Walking, siting **Procedure:** A foot model stepping down and up. It was treated as the motions of two equivalent circular disks moving toward or away from the floor. Rolling detachment was also tested to see the particle detachment.	Shoes bottom roughness, foot size, walking velocity, background velocity as well as the foot stepping velocities, down and up are all affected.

Chapter 3

3. Methodology

The experiments were carried out in the Building Services Laboratory in City University of Hong Kong. The data of resuspended particles were collected by using the optical particle size spectrometer (OPSS) and exported to Excel file by Aerosol Instrument Manager Software.

3.1 Experimental Setup

3.1.1 Deposition Chamber

To start the experiment, some seeded flooring sample with dust should be prepared. A model used for dust seeding process was made. The experiment setup consisted of two main components: a deposition chamber and also the resuspension chamber. The deposition chamber (fig 3.1) was used for loading of test particles on the flooring samples. The purpose is distributing the dust evenly on the samples. The deposition chamber was made of acrylic with inner dimension of 50cm (W) x 50cm (H) x 50cm (L). Four mixing fans were installed inside the chamber to provide air mixing. There was a circular inlet port of the ceiling where the test particles can inject into the chamber. According to Tian (2012), the test particles injected to the chamber through the venture mini-vacuum generator by connected to the compressed air pump.

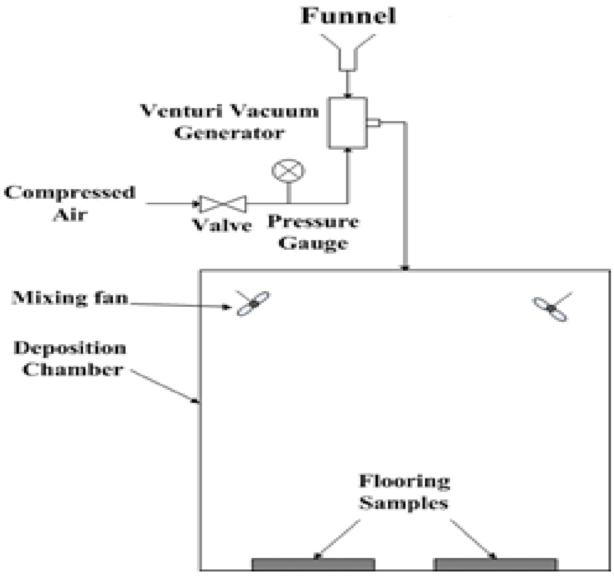
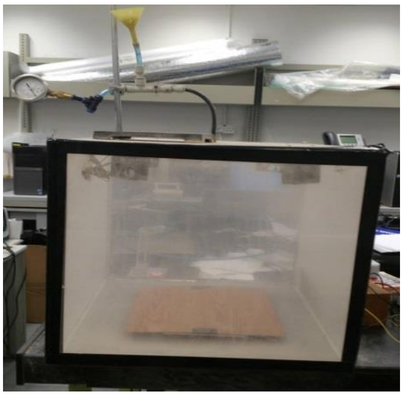


Fig 3.1: Schematic Diagram of Deposition Chamber

The deposition chamber contains different components, the main components are shown as follows, such as

a. Glass funnel (Fig 3.2)	
b. Venturi mini-vacuum generator (Fig 3.3)	

c. Acrylic chamber with inner dimensions of 50cm x 50cm x 50cm (Fig 3.4)	
d. Four mixing fans hanged on the ceiling of the deposition chamber (Fig 3.5)	
e. Pressure gauge (Fig 3.6)	

The glass funnel, venture mini-vacuum generator, pressure gauge and some valves were located at the top of the deposition chamber. There was a door opening on one side for transferring the flooring samples and it should be closed and sealed when not use. Four mixing fans mounted on the top corners on the ceiling of the deposition chamber. It aims to generate a turbulence region to get a better mixing of the dust particle deposited on the flooring sample evenly. In this experiment, the fans were switched on before and after the injection of test dust with 5 minutes respectively.

3.1.2 Resuspension Chamber

The resuspension experiments was carried out in the resuspension chamber making of stainless steel with inner dimension of around 2m (L) x 2m (W) x 2m (H). The flooring sample was pre-loaded with test particles by the deposition procedure and placed at the center of the chamber. In this study, four types of flooring materials including PVC plate, tile, shag rug and short wool rug were tested. The participant performed the walking at two frequencies of 84 steps per minute and 132 steps per minute recommended in the study of Rowe DA (2011). These two frequencies were simulating the different human activities condition. The optical particle sizer spectrometer (OPSS Model 3330) was monitored the mass concentration with size range of 0.3-10μm setting at four intervals (0.8-1μm, 1-2μm, 2-5μm, 5-10μm since the minimum size of test dust is 0.714μm). The inlet of the spectrometer was placed 2.5cm apart from the flooring sample pointing to the center of it. The test was carried out in three levels initially, ground level (static height of 0.043m between inlet and the flooring sample), hip level (static height of 0.7m between inlet and the flooring sample) and nose level (static height of 1.44m between inlet and the flooring sample).

Fig 3.7: Optical Particle Size Spectrometer

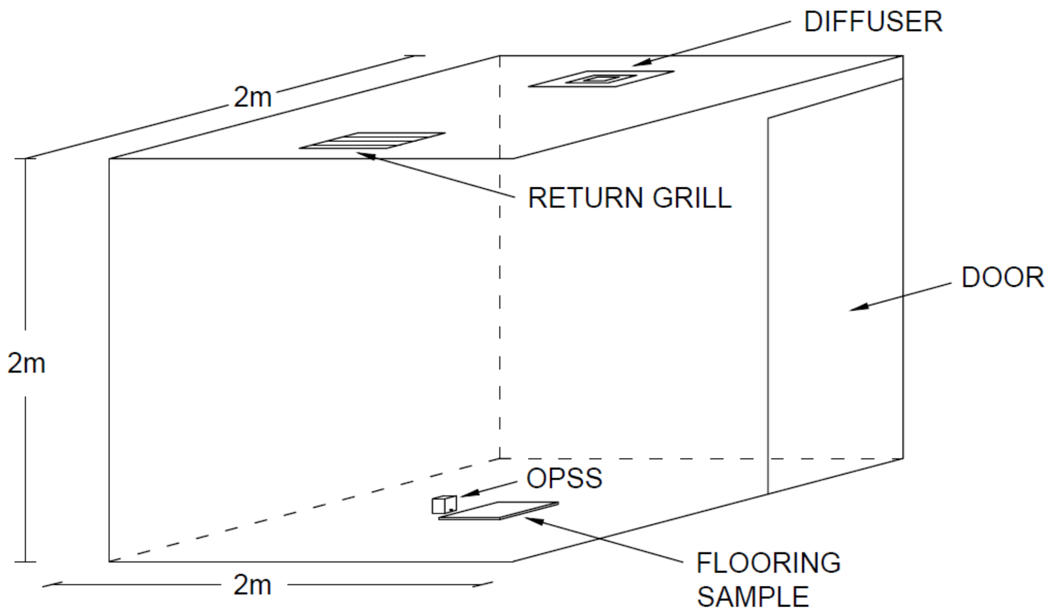


Fig 3.8: Schematic Diagram of Resuspension Chamber

3.2 Experiment Procedure

3.2.1 Flooring Samples Preparation – Deposition

Before the experiment started, it was confirmed that the deposition chamber should be cleaned and no crack for dust leakage. After connecting all the components, a sample size of 30cm x 30cm was measured its weight and the value obtained in this stage was recorded as W(B). After that, the sample was placed into the chamber immediately and then closed and sealed the deposition chamber. Any gaps or openings were sealed with masking tape to ensure no infiltration. Then, the air mixing fans inside the chamber were switched on. After 5 minutes, 3 grams test dust were prepared and injected into the chamber. The test dust was put into the glass funnel and then the valve connected to the air compressor was turned on. When the air pressure reached 40 psi observed by the pressure gauge, the compressor air tripped the venturi mini-vacuum generator and then drew the test dust inside the deposition chamber.

After the particle injection, the connection between the chamber and the air compressor was disconnected and the value was turned off to avoid the back flow of mixing air. Then, the mixing fans remained on for 5 minutes. After that, the mixing fans were turned off and the chamber was untouchable for 4 hours deposition. Wan (2012) reported that 2.5 hours was sufficient for particle falling down to the floor from the ceiling of the chamber. After 4 hours, the chamber was opened and the flooring sample was taken for another weight measurement. The weight obtained in this stage was recorded as W(A).

For shag rug and short wool rug, one more step was made. According to Roger D. Lewis (1999), the dust was embedded by dragging a heavy rod over the rug surface. It used to make sure the test dust can deposit onto the rug but not only the surface part. The rod was dragged into four dimensions with a relative low speed since more dust suspend to the air by a high speed dragging. The dust loading on the sample can be calculated as W(A)- W(B) – Loss on roller.

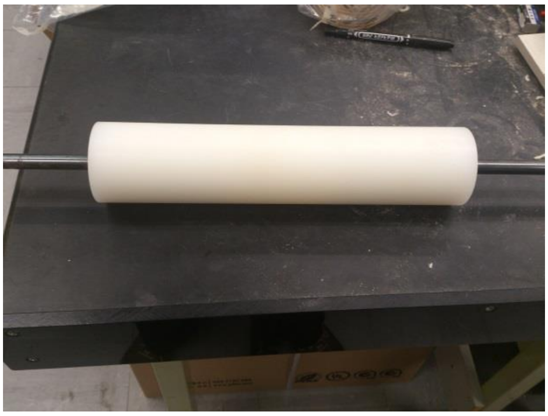


Fig 3.9: Roller

3.2.2 Uniformity Test of Deposition

According to the calculation of loading onto the flooring samples, the loading was not equal to the amount of injection test dust, some may lost during the injection process and some may lost by mounting to the mixing fans and also the inlet side of the chamber. But it is not possible for the remaining dust particle can be evenly distributed. Somewhere may receive more since it can be observed that there was an accumulation of dust particle to form a small area.

For the deposition process, turbulent flow created was not adequate so that the distribution of dust cannot evenly distribute. The method used in the deposition procedure was to inject the dust particle by pumping the compressed air with 40 psi. However, the pressure drop caused by the nozzle was relatively high and sometimes the dust was accumulated in the component like the ventrui-vacuum generator. It blocked the compressed air and made the inverse flow, such that the dust was blew upward and left from the funnel instead of downward movement to the deposition chamber.

Also, it was quite difficult to control the supply flow rate. Since the deposition chamber was sealed, when the compressed air entering into the chamber, the induced pressure inside the chamber was kept increasing. Therefore, the air would passing through the crack if it was not sealed entirely and flew inverse to the supply air direction. It can be observed that the dust was lost to the mask tape that used to seal the crack and even the surrounding. The irregular flow made the dust deposition not uniform onto the flooring sample.

To determine the uniformity of dust particle, another set of flooring sample was tested. Nine samples of plate with a dimension of 5cm x 5cm were placed in different position in the chamber. The arrangement was shown as fig 3.10 with marking. The process was same as the normal deposition test.

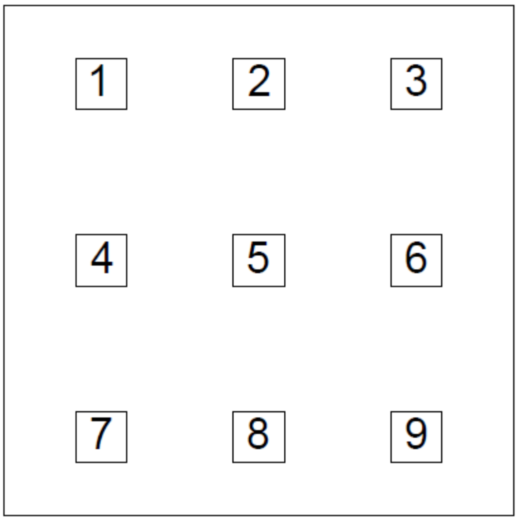


Fig 3.10: Arrangement of Uniformity Test Samples

By repeating the deposition process and recorded the loading, the uniformity of dust particle inside the deposition chamber can be estimated by some calculation based on the research done by Chane-Yu Lai (2006).

Scanning Electron Microscope (SEM) was the other method to see the deposition of dust particle. In this experiment, a fiber of both shag rug, short wool rug and also the plate were scanned by SEM. After the deposition of dust, the samples were cut into a small pieces and then put in a small sealed unit before scanning. It avoids the resuspension of dust and also the infiltration.

3.2.3 Velocity Test

Since different shoes have their different grooves, the resuspension rate may be affected by the induced velocity. The test was carried out by using the anemomaster 1550 software and three velocity testers with 0.1 s intervals in the resuspension chamber. Each tester was placed 5 cm apart from the shoes and 0.7 cm above the floor. The position of footprints was marked to ensure the step could not too close or too far from the testers. Then, the tester position was divided into 12 points that covered different dimensions. It can be referred to fig 3.17. After setting all the components, the experiment was started in three stages. Stage 1 was 5 minutes background measurement stage. After 5 minutes, 1 step was required to see the induced velocity and this stage was lasted for 1 minute only. Then, the tester monitored 10 minutes post-event background (Stage 3) to see the time for the value back to the background velocity so the total was 16 minutes. Since it had 3 velocity testers, the experiment was repeated in 4 times to get all the data in different position.

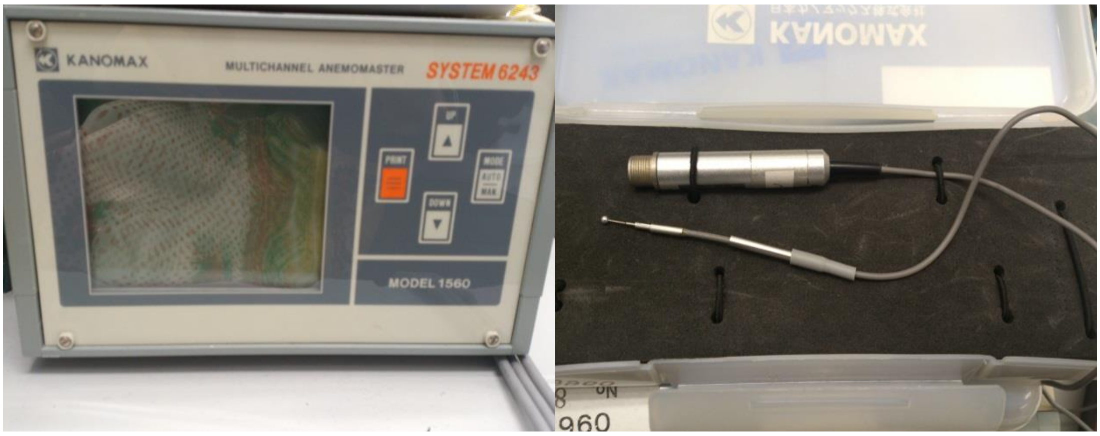


Fig 3.11: Multichannel Anemomaster and Velocity Tester

There were five types of shoes being used in the velocity test. Each of them has different grooves but it can be mainly classified into three groups.

- Shoes with clear grooves

  Example: Leather shoes, sneaker

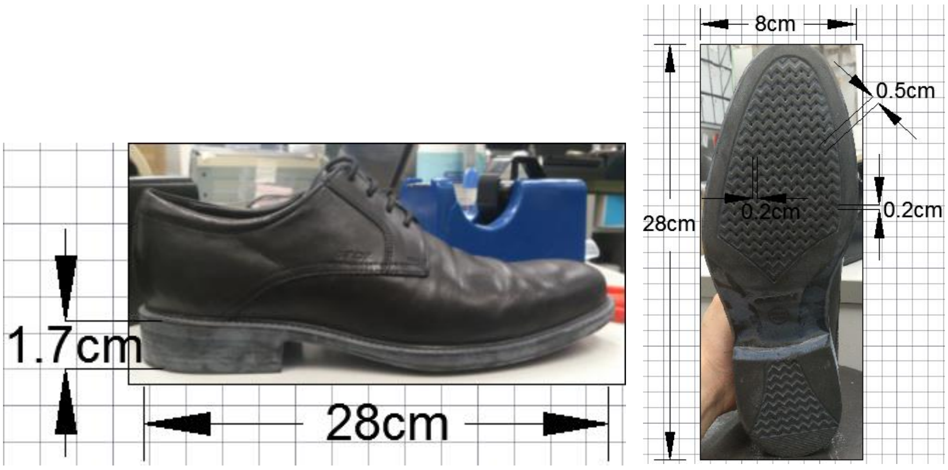


Fig 3.12: Side View and Bot View of Leather Shoes

The length and width of leather shoes used in the experiment is 0.28m and 0.08m respectively. For the front cover of 0.14m x 0.08m, the grooves are comprised of 0.005m (length) x 0.002m (width) x 0.002m (height). For the back cover of 0.06m x 0.065m, the grooves are comprised of 0.005m (length) x0.002 m (width) x0.002 m (height).

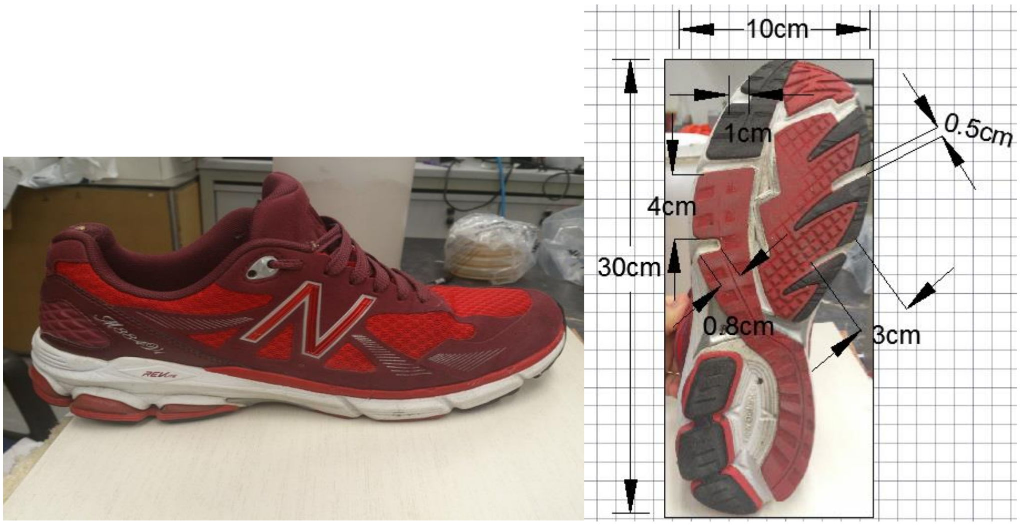


Fig 3.13: Side View and Bot View of Sneakers

The length and width of sneakers used in the experiment is 0.3m and 0.1m respectively. For the front cover, the grooves are comprised of 0.03m (length) x 0.01m (width) x 0.002m (height) in the inner foot side and 0.01m (length) x 0.008m (width) x 0.002m (height) in the out foot side. For the back cover, no grooves can be observed in the boundary of the shoes.

- Shoes with flatten grooves

  Example: Slippers

Fig 3.14: Side View and Bot View of Slippers

The length and width of the slippers used in the experiment is 0.24m and 0.07m respectively. For the whole slippers, no grooves can be observed clearly and the bottom of shoes are assumed as a flatten part.

- Shoes with no grooves

  Example: High heels, Boots

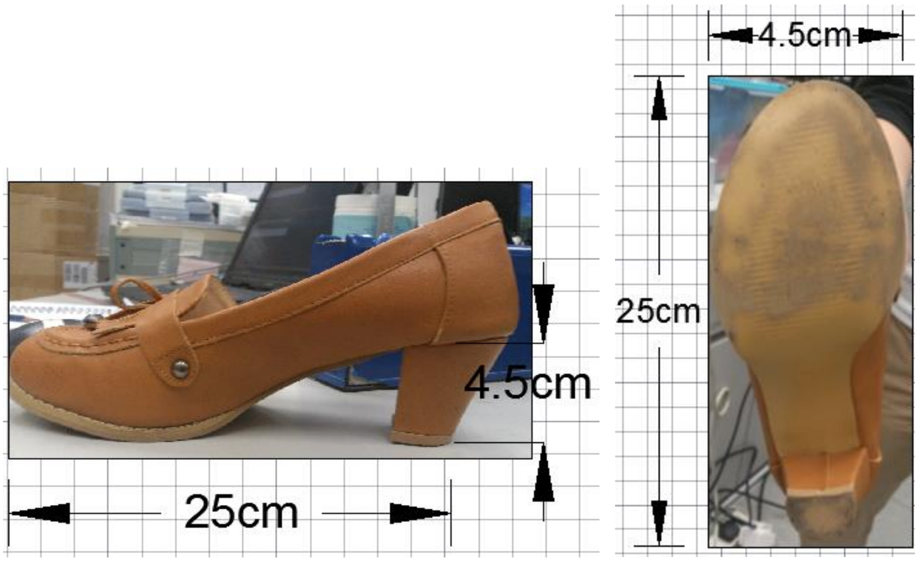


Fig 3.15: Side View and Bot View of High Heels

The length and width of the high heels used in the experiment is 0.25m and 0.045m respectively. For the whole high heels, no grooves can be observed. The heel is 0.045 m high at the back cover of the shoes. Since the heel is high, it forms a large space region between the toe region and the heel.

Fig 3.16: View and Bot View of Boots

The length and width of boots used in the experiment is 0.26m and 0.05m respectively. For the whole boots, no grooves can be observed. The back cover is 0.06m (length) x 0.05m (width) x 0.03m (height). Since the heel is high, it forms a space region between the toe region and the heel.

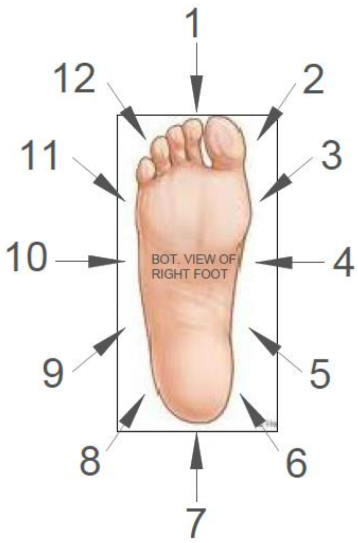


Fig 3.17: View of Tester Position on Right Foot Side

Table 3.1: Summary of Five Types of Shoes					
	Leather Shoes	Sneakers	Slippers	Boots	High Heels
Dimension (m x m)	0.28 x 0.08	0.3 x 0.1	0.24 x 0.07	0.26 x 0.05	0.25 x 0.045
Grooves Area (m x m)	Front: 0.14 x 0.08 Back: 0.06 x 0.065	Front: 0.03 x 0.01 Back: 0.01 x 0.008	/	/	/
Separation between Grooves (m)	0.002	0.04	/	/	/

3.2.4 Resuspension Experiment

The OPSS was set and connected to the computer software Aerosol Instrument Manager Software. This software can display the data in both tabular and graphical forms during the measurement. The detected particle size channel was divided into four main size, 0.8-1µm, 1-2µm, 2-5µm and 5-10µm. The time was set as 720 s in total. The measurement of OPSS was set as 1 s interval so 720 data was collected in each set of experiment. Then, the flooring sample prepared after deposition was taken to the resuspension chamber. The OPSS was placed at the outside of right foot position since it was the most effective part by the result of velocity test. The inlet of spectrometer was 2.5 cm apart from the center line of flooring material in right foot side. The chamber was closed to ensure air tight. Then, the experiment began. It contained three stages and lasted for 12 minutes in total. Stage 1 was a 5 minutes background concentration measurement. Any movement in this stage was not allowed. Then, the participant kept walking on the flooring sample with specific frequency of 84 steps per minute and 120 steps per minute for the next 5 minutes (Stage 2). After that, walking was stopped and the spectrometer measured the post-event concentration for last 5 minutes (Stage 3). After finishing 3 stages, the flooring material was taken out from the chamber and then cleaned and stored for the next experiment.

Chapter 4

4. Result and Discussion

4.1 Uniformity of Deposition Calculation

Uniformity was important for deposition since it was hard to ensure the dust distribution evenly in every experiment. If the test dust was grouped in a certain area on the flooring sample, it was meaningless for doing the resuspension test. According to the study of Lai (2006), there were some mathematic equations to calculate the coefficient of variation (CV) and then estimated the uniformity of deposition (U). The equations were given as follows.

$$\mathrm{CV} = \frac{\sigma}{\mu} \qquad \text{……………………….(1)}$$

$$\mathrm{U} = e^{-\mathrm{CV}} \qquad \text{……………….............(2)}$$

$$\mathrm{SE}(\widehat{\mathrm{CV}}) = \sqrt{\frac{1}{B-1}\sum_{b=1}^{B}(CV^{b} - \overline{CV})^2} \qquad \text{…………………….(3)}$$

$$\mathrm{SE}(\widehat{U}) = \sqrt{\frac{1}{B-1}\sum_{b=1}^{B}(U^{b} - \overline{U})^2} \qquad \text{………………………..(4)}$$

CV: coefficient of variation

σ: standard deviation of coverage of the particle area

μ: mean coverage of particle area

U: uniformity of deposition

$\mathrm{SE}(\widehat{\mathrm{CV}})$: standard error of CV

$\mathrm{SE}(\widehat{U})$: standard error of U

$\overline{CV}$: mean of CV

$\overline{U}$: mean of U

Equation (1) is the calculation of coefficient of variation. When the value of CV decreased, the variation among the dust distribution is less evenly. The exponential of the negative CV value was a transformation to easily understand the uniformity of the particular matter. So the equation (2) can be generated. However, the deposition of dust was fluctuated in each experiment. Therefore, the standard error was evaluated as equation (3) and (4).

After five samples were taken, the CV of the deposition was 0.46858 ± 0.04722 and the uniformity was 0.62645 ± 0.02979. According to the result, the uniformity was around 63%. That means some of the position received more and some may receive fewer particles. Actually, it can be observed that some large test particles were deposited and accumulated on the flooring sample without well distribution. The possible reason was the dust particles stored in the crack of fans or even the corner of the chamber so they fell directly to the flooring samples.

4.2 Determination of Dust Loading

The flooring materials loading per unit area was calculated using the equation

Deposited Mass of specific size range = [W(A) – W(B) – Loss on roller] x Volume %

Since the mass deposited on the flooring sample contained different dust size, it is necessary to find out the mass of specific size of dust on the flooring sample. The dust particle used in the each experiment was the same, so it was assumed that the density of each size of particular matter were also the same. Based on the simple calculation of density by mass divided by the volume, the deposited mass on the flooring sample can be estimated. After taking those deposited mass of each size range of dust particle, the result would be used for the calculation of emission factors later.

Besides, SEM method can also indicate the loading pattern of the flooring sample. In this experiment, a carpet fiber of both shag rug and short wool rug was used to do the scanning electron microcopy.

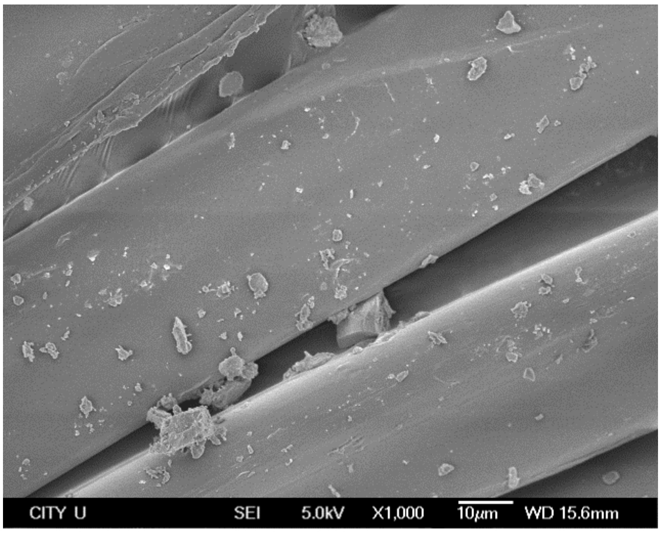


Fig 4.1: SEM of Carpet Fiber

According to the study of Jack A. Rosati (2008), all the particles from the carpet were assumed to resuspend in the upper 2mm of fiber. Based on the SEM result, the dust loading between the shag rug and shot wool rug was similar. Since the fiber size of short wool rug is 1 cm and the fiber size of shag rug is 2 cm, the dust was assumed to be deposited on the top surface only. Only few of them were dragged in the upper part of fiber. The reason may come from the insufficient weight of the roller.

4.3 Determination of Velocity against Time

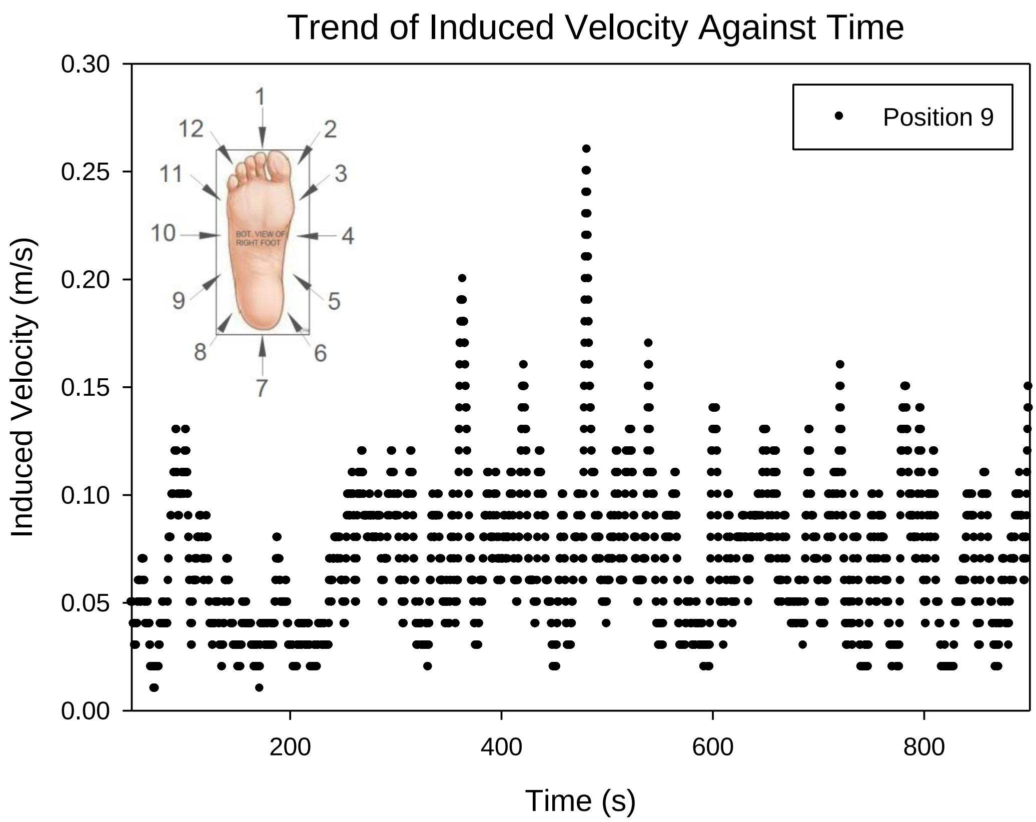


Fig 4.2: Graph of Induced Velocity against Time

According to fig 4.2, the stepping was made between 300 and 400 s. It can be observed that the induced velocity was suddenly increased in around 380s. Although the background data was fluctuating, the induced velocity was dropped to the low level around 600s. For the other position, the induced velocity also dropped down to the background level between 600 and 800s.

4.4 Comparison of Induced Velocity of Different Position

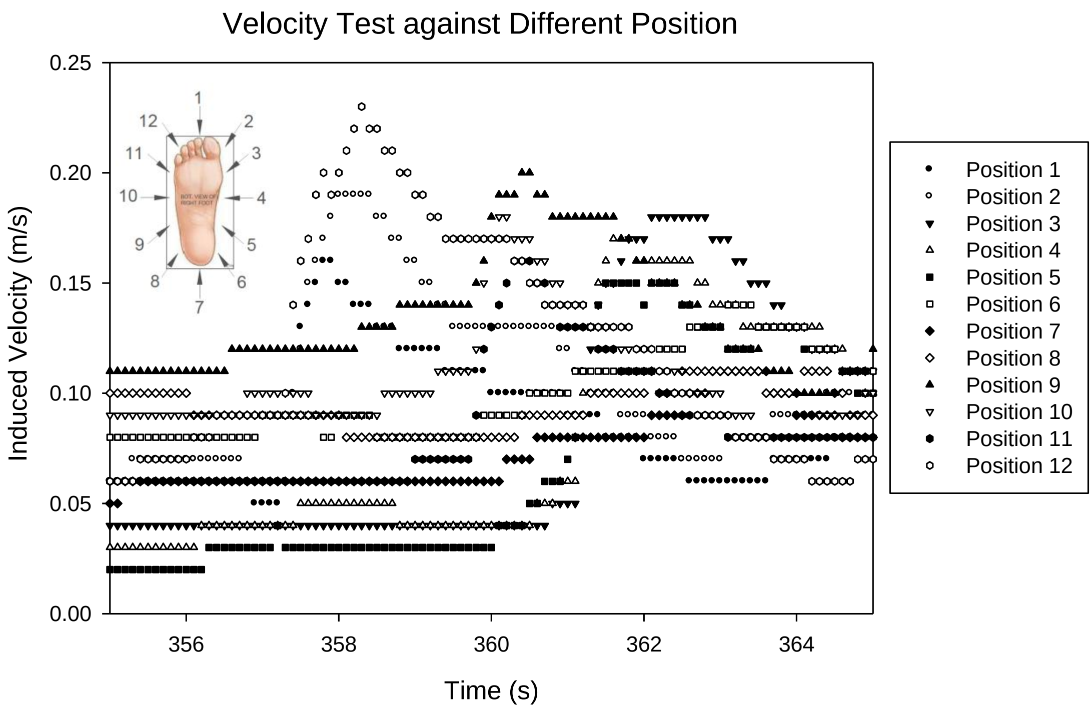


Fig 4.3: Graph of Induced Velocity against Different Position

Fig 4.3 showed the different position of velocity test. Position between 9 and 12 are the outside of the feet. From the result, position 9, 10 and 12 induced the velocity higher than the other positions. Therefore, the out feet side was the dominant of induced velocity in the velocity test.

4.5 Comparison of Induced Velocity against Different Shoes

The velocity test was carried out by the participant who stepped on the floor with different shoes in the experiment. It aims to find out the relationship of grooves against the induced velocity. Since the out feet side can induced higher velocity, the result only cover the position 9, 10, 11 and 12 only.

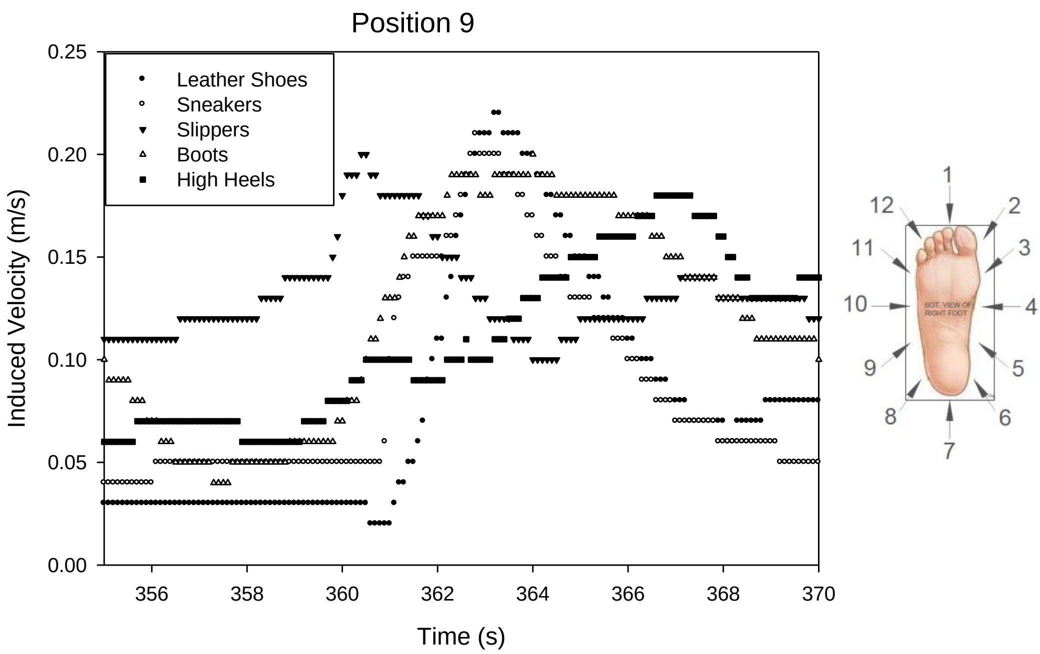


Fig 4.4: Comparison of Different Shoes in Position 9

For the position 9, it can be observed that leather shoes can induce the highest velocity while high heels induced the lowest one. From the result, the highest values of induced velocity in different shoes were similar except the high heels.

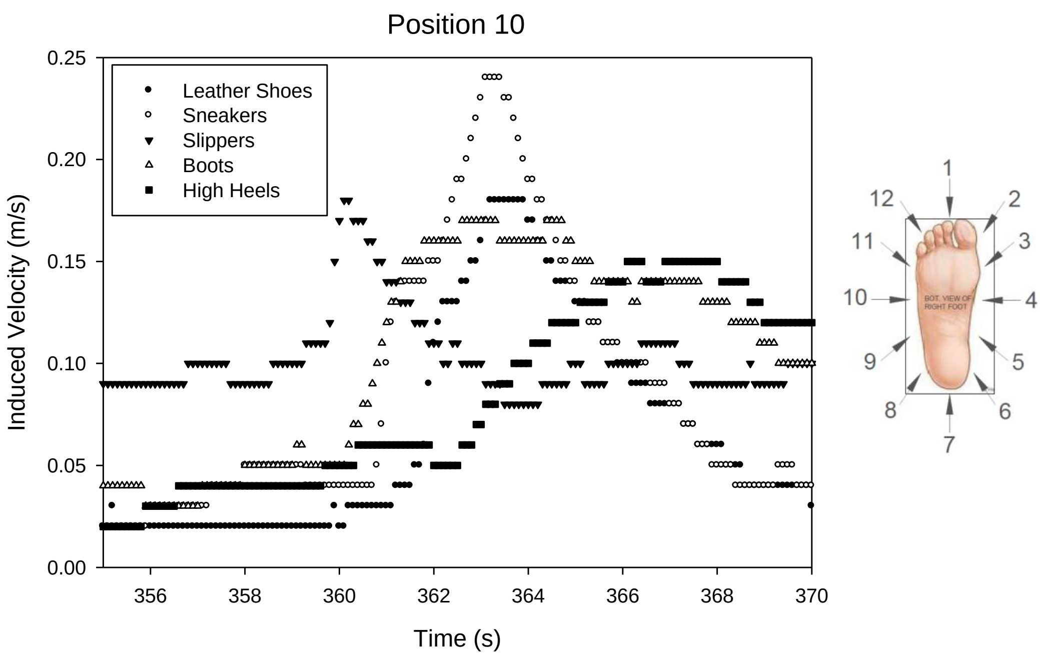


Fig 4.5: Comparison of Different Shoes in Position 10

For the position 10, it can be observed that sneakers can induce the highest velocity and high heels induced the lowest one. In this time, the value of induced velocity of sneakers was much larger than the others. From the result, the highest value of induced velocity of leather shoes and slippers were similar and the value of boots was closed to them.

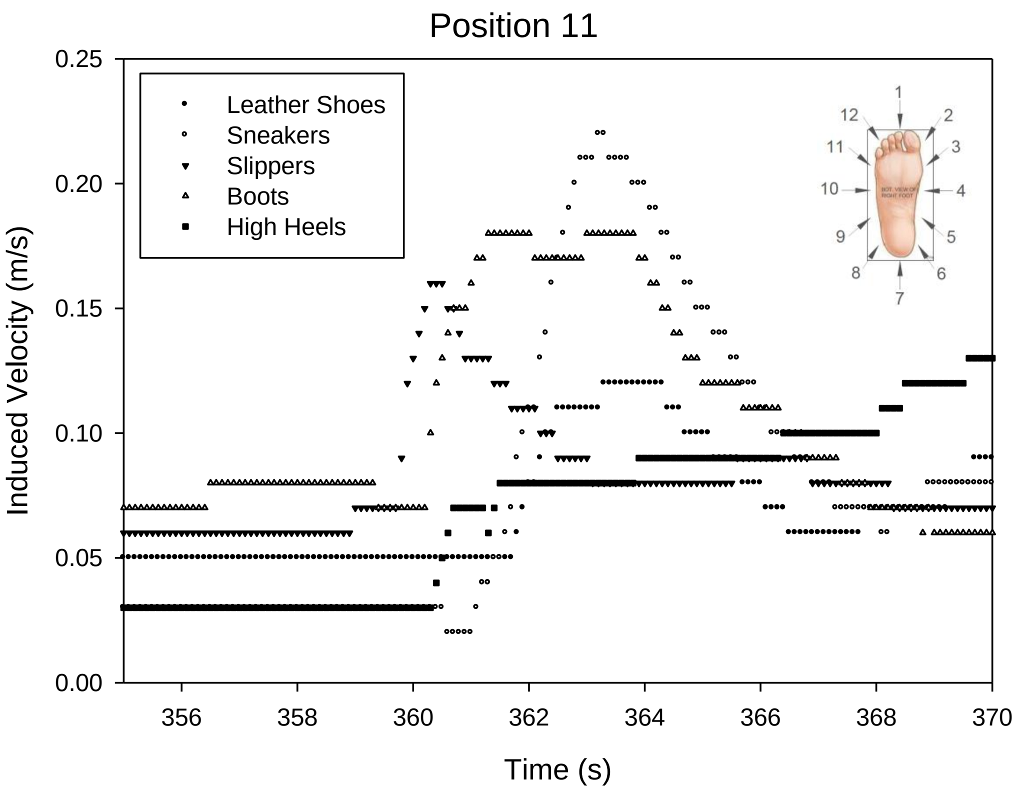


Fig 4.6: Comparison of Different Shoes in Position 11

For the position 11, it can be observed that sneakers can induce the highest velocity and high heels induced the lowest one. In this time, the value of induced velocity of leather shoes was a little bit low but the background velocity was also low. To compare the net velocity, the induced velocity of leather shoes and sneakers were similar.

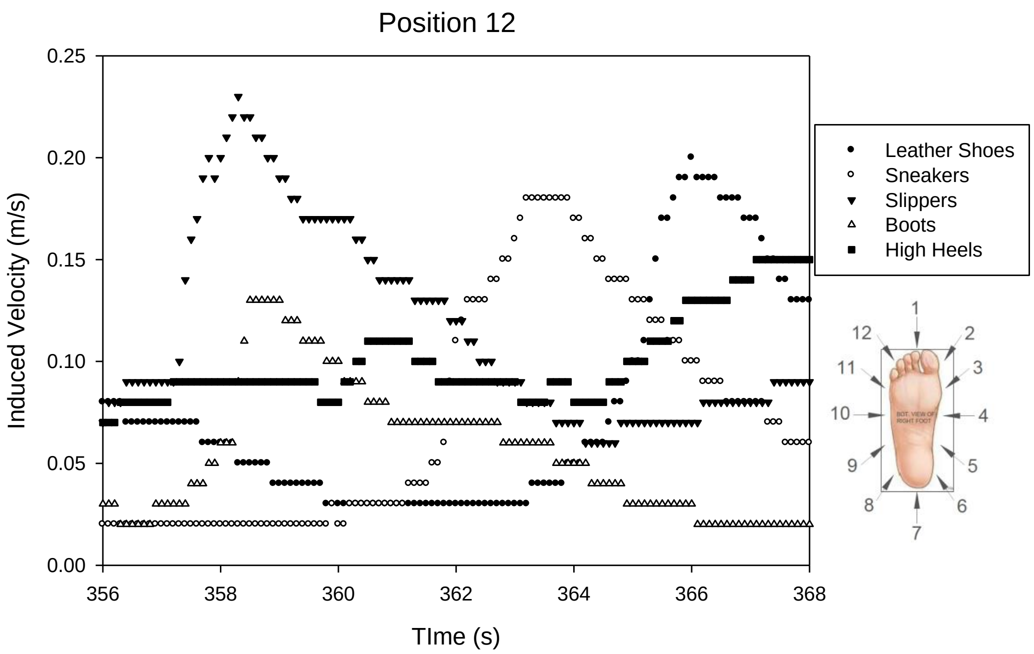


Fig 4.7: Comparison of Different Shoes in Position 12

For the position 12, it can be observed that the induced velocity of leather shoes, sneakers and slippers were similar. However, to compare the net velocity, the induced velocity of leather shoes and sneakers were larger than the others. The summary of net velocity was grouped into a table showing bellows.

Table 4.1: Net Velocity of Different Shoes Against Different Positions

Type/ Position	1	2	3	4	5	6	7	8	9	10	11	12
Sneaker	0.17	0.17	0.22	0.23	0.21	0.21	0.24	0.24	0.24	0.23	0.27	0.2
Leather Shoes	0.21	0.25	0.28	0.28	0.32	0.19	0.2	0.23	0.31	0.3	0.27	0.23
Boots	0.16	0.15	0.17	0.18	0.18	0.18	0.18	0.16	0.25	0.19	0.17	0.15
Slipper	0.21	0.19	0.17	0.22	0.21	0.13	0.14	0.16	0.2	0.2	0.19	0.23
High Heels	0.16	0.15	0.15	0.17	0.1	0.13	0.13	0.13	0.17	0.16	0.13	0.15

According to the result, the larger value of induced velocity was generally the outside foot position (9,10,11). By comparing all the net velocity of different shoes, it was found that the induced velocity increase when the grooves of the shoes were more. The largest value was obtained by the tested leather shoes while the smallest was the high heels. These data would compare with the concentration test for more detail investment.

4.6 Determination of Concentration against Time

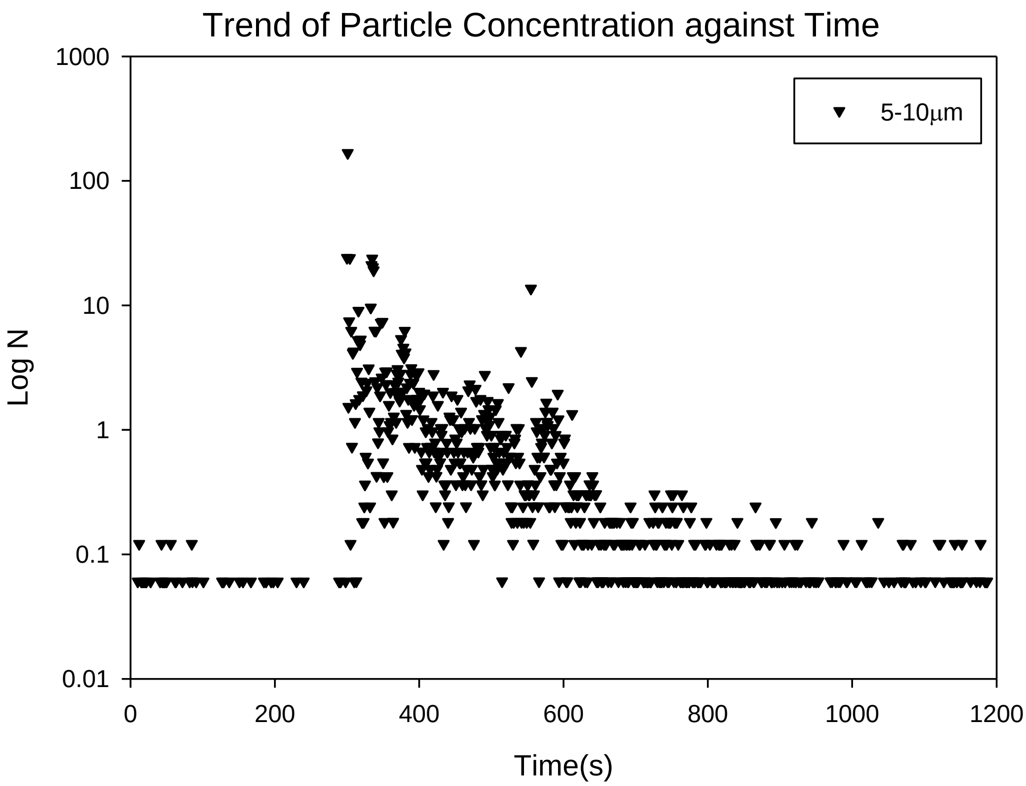


Fig 4.8: Graph of Particle Concentration against Time

According to Fig 4.8, the particle concentration is affected by the human activities. Since the experiment was carried out into three stages, the background, walking and the post-event stage, it can be observed that the dust concentration increased suddenly from 300s because the stepping was started until 600s. In that period, the particle concentration (log N) rose from 0 to around 100. After the first step, the concentration decayed by time being.

4.7 Comparison of Concentration against Height

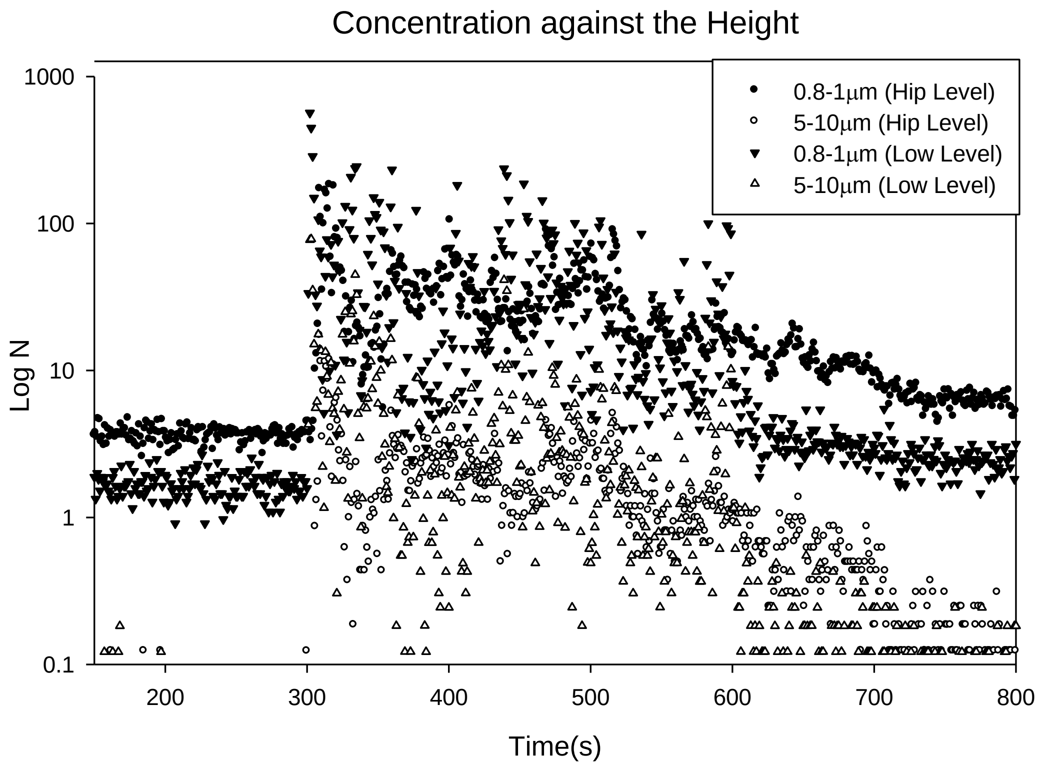


Fig 4.9: Graph of Concentration against Height

In Fig 4.9, the smallest size range (0.8-1 μ m) and largest size range (5-10 μ m) were shown for both of the low level measurement and hip level measurement since the other tested size range had the resuspended behavior between them. Low level means the OPSS inspector was located about 0.04m above the flooring material. Hip level means the OPSS inspector was located about 0.7m above the flooring material. According to the result, the concentration of dust particle was larger in the floor side no matter of the dust size. The dust particle will mix with the indoor air so that the concentration was decreased along with the height. By calculating the peak value of concentration, the dust particle number resuspend to the air in low level was around 3 to 7 times than the hip level one.

4.8 Comparison of Concentration in both Ventilation On and Off

Some paper had studied that the dust particle can resuspend more with the ventilation is provided. Jacky A. Rosati (2008) claimed that the concentration at 1.2m was 20-40% of the same condition with the ventilation in his experiment. In fact, ventilation can provide the air movement inside the chamber. The turbulence flow can create a better mixing condition and hence the degree of resuspension can be higher.

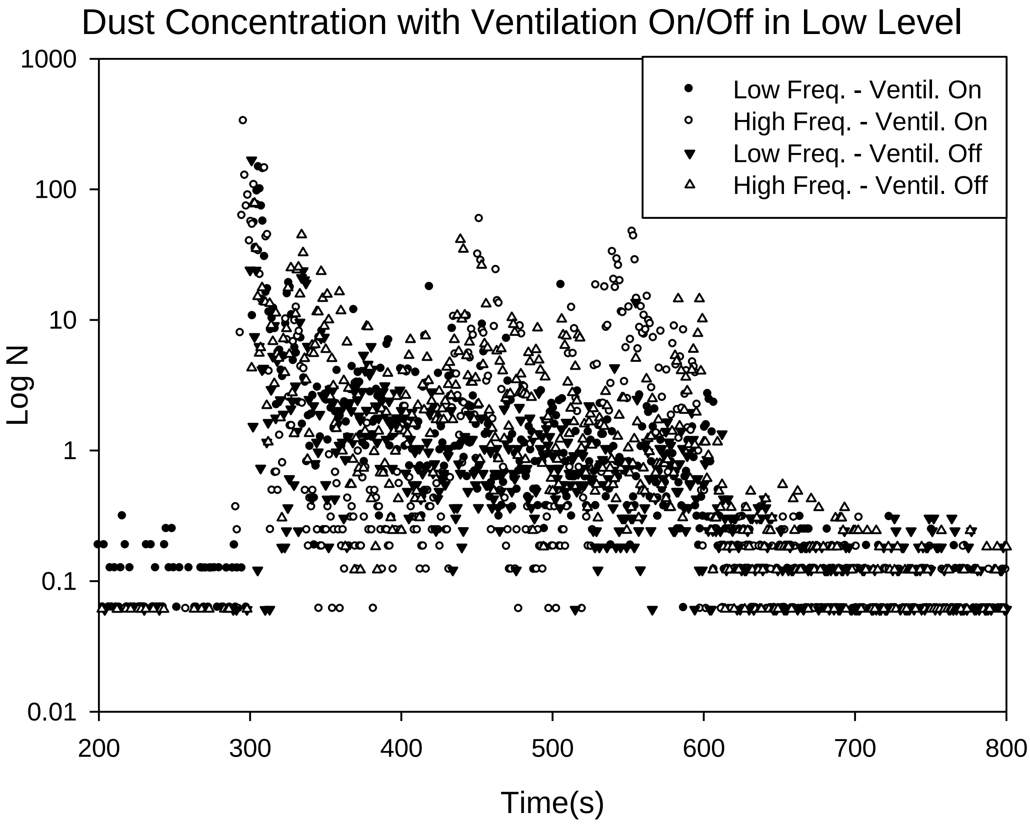


Fig 4.10: Graph of Concentration with Ventilation in Low Level

According to Fig 4.10, there was a difference in both of the ventilation on and off condition. For low frequency of 84 steps per minute, the concentration of dust particle was similar in the first step at the low level side in both conditions. However, the concentration was larger with the time being since more and more air was mixed together and hence the dust particle can resuspend faster. High frequency of 120 steps per minute can clearly showed the difference. At 300s, the dust concentration of no ventilation had a log value of around 8 but some hundreds in ventilated condition. It indicated that the ventilation was a dominant factor to control the resuspension. Since the data was measured at the low level side, the travelling height of the resuspended particle was concerned because it may be inhaled in the body.

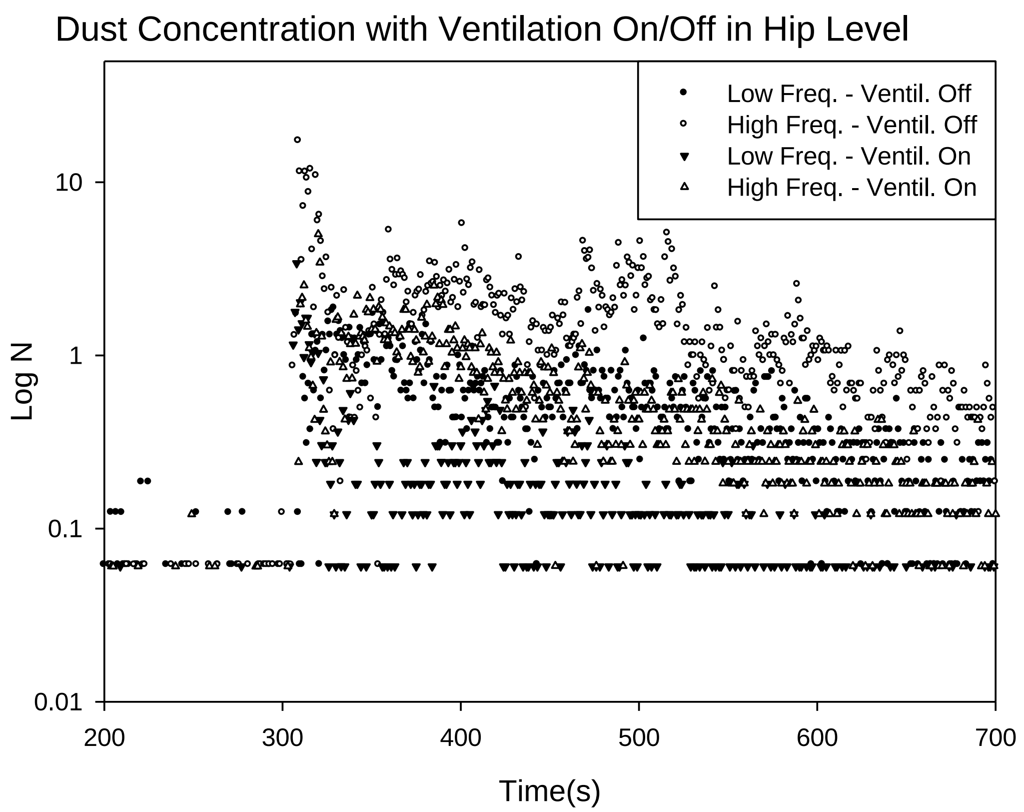


Fig 4.11: Graph of Concentration with Ventilation in Hip Level

Different with the low level one, the dust particle concentration in hip level had the similar situation no matter of the function of ventilation. The data point did not form a sequence and all the data was randomly distributed. That means the dust concentration in the hip level (around 0.7m above the flooring material) was independent to the ventilation. The possible reason was the air mixing inside the testing chamber was focused on the low level side. Since the pre-load material size was small and the resuspension chamber size was big, it was not possible to have a fully mixing in it. Therefore, a reduction of mixing height can be observed.

4.9 Comparison of Concentration against Different Flooring Materials and Shoes

In fact, the resuspension was affected by the flooring material. Since different material can produce different electrostatic force due to different surface and the adhesive force. Some of the research indicated that the resuspension rate of rug was much larger than the others. Wan (2012) found it was double of that from wood PVC and 3 times of that from vinyl tile.

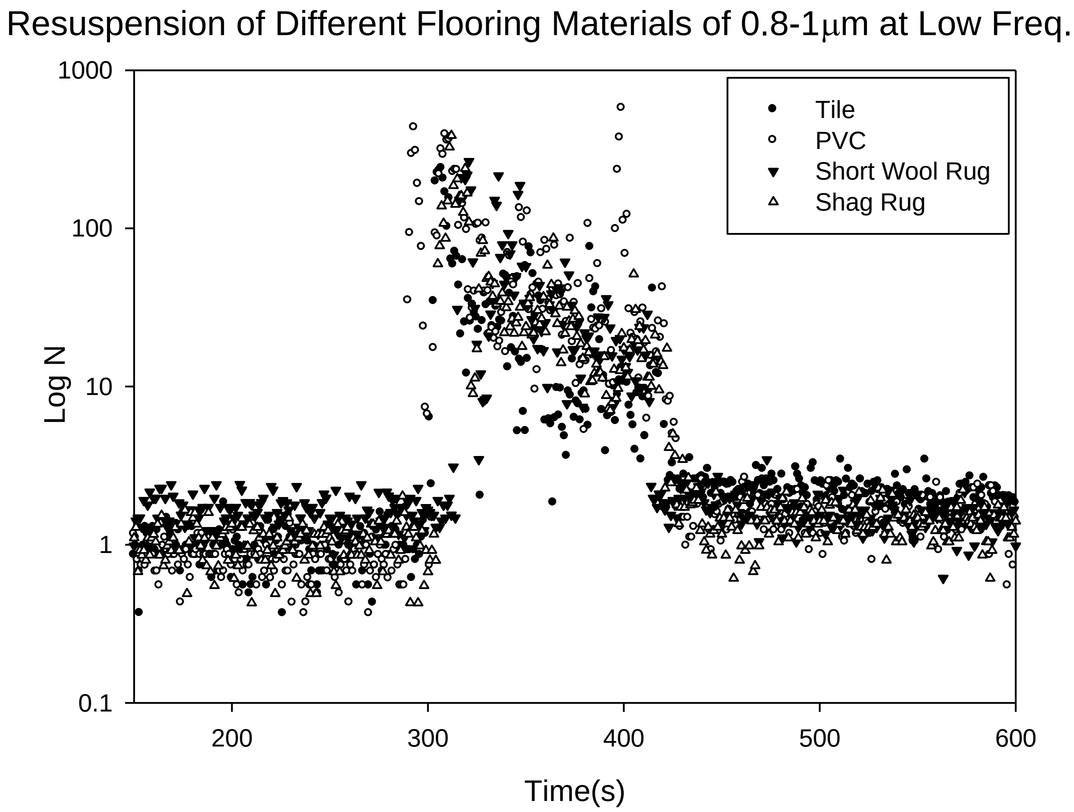


Fig 4.12: Graph of Resuspension at Low Freq. of 0.8-1 μ m in Different Floorings

According to Fig 4.12, the resuspension of dust particle was similar among all the tested flooring material with the particle size range of 0.8-1 μ m. In the experiment, stepping was kept between 300s and 420s. Since the number of dust particle in this range was the largest one, the concentration in the measured point also got the highest number of it. The result of stepping with low frequency was not clear enough and hence another set of data with high frequency was prepared.

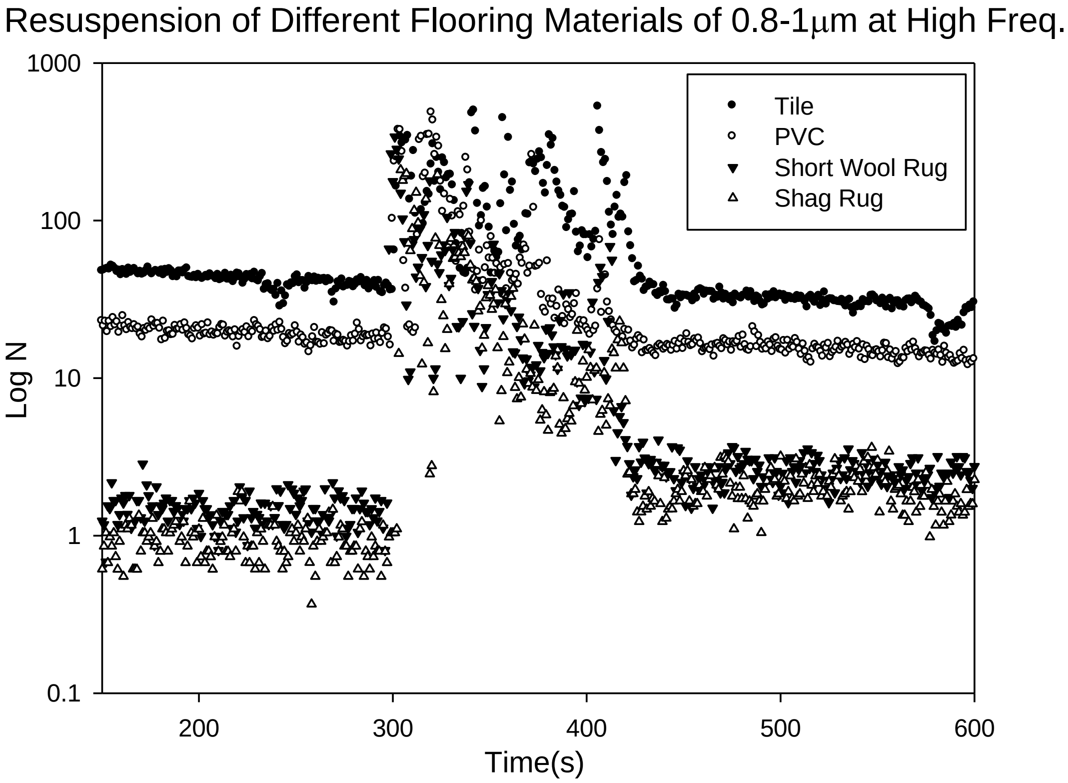


Fig 4.13: Graph of Resuspension at High Freq. of 0.8-1 μ m in Different Floorings

According to Fig 4.13, the dust particle resuspension can be classified as two groups. Since the tile and PVC had a higher background value and their performance were similar, so they were treated as one group. For the rug section, they had the lower background value but the dust particle can resuspend to a high level comparing to the first group. It showed that the dust particle was able to resuspend more in the rug material. The result was matched with the other studies since all the paper got the same result of higher resuspension from rug.

However, fig 4.12 and fig 4.13 only showed the result of particle size between 0.8 μ m and 1 μ m. Since the particle number in that size range was the largest one in the test dust, the resuspension was also the largest one comparing to the others. To see the phenomena of dust resuspension on different flooring material, all the particle size range tested was shown to prove the result.

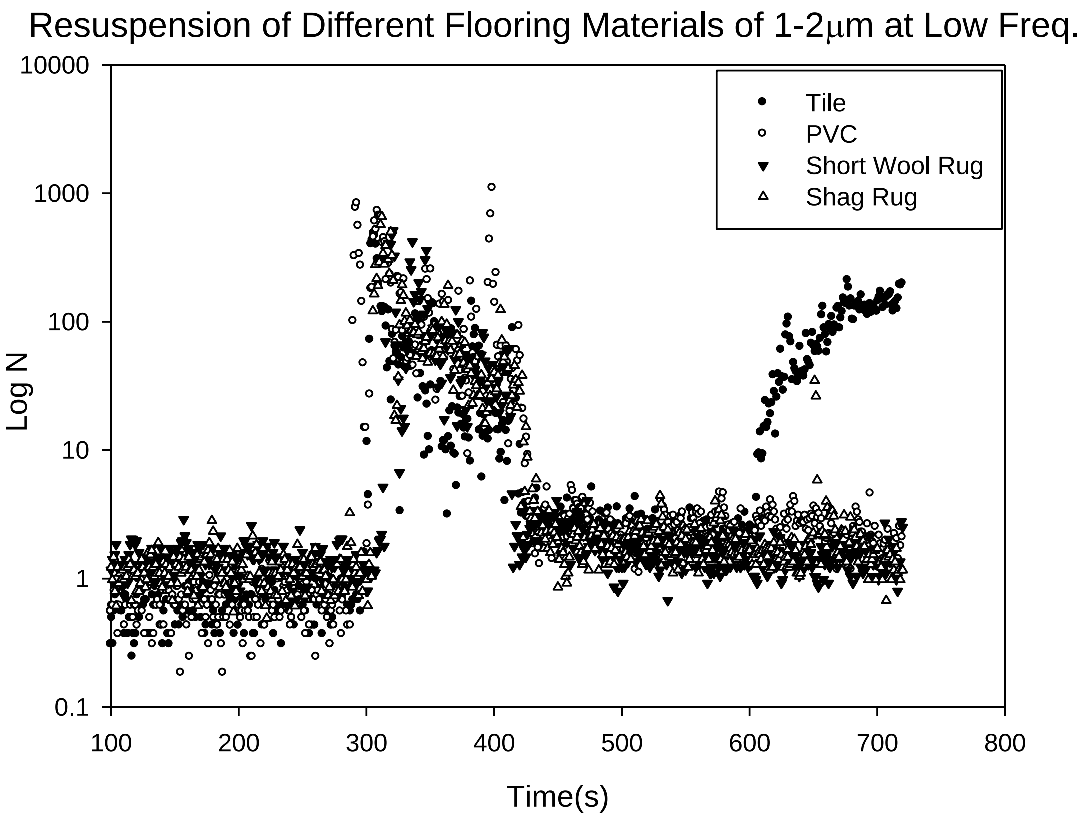


Fig 4.14: Graph of Resuspension at Low Freq. of 1-2 μ m in Different Floorings

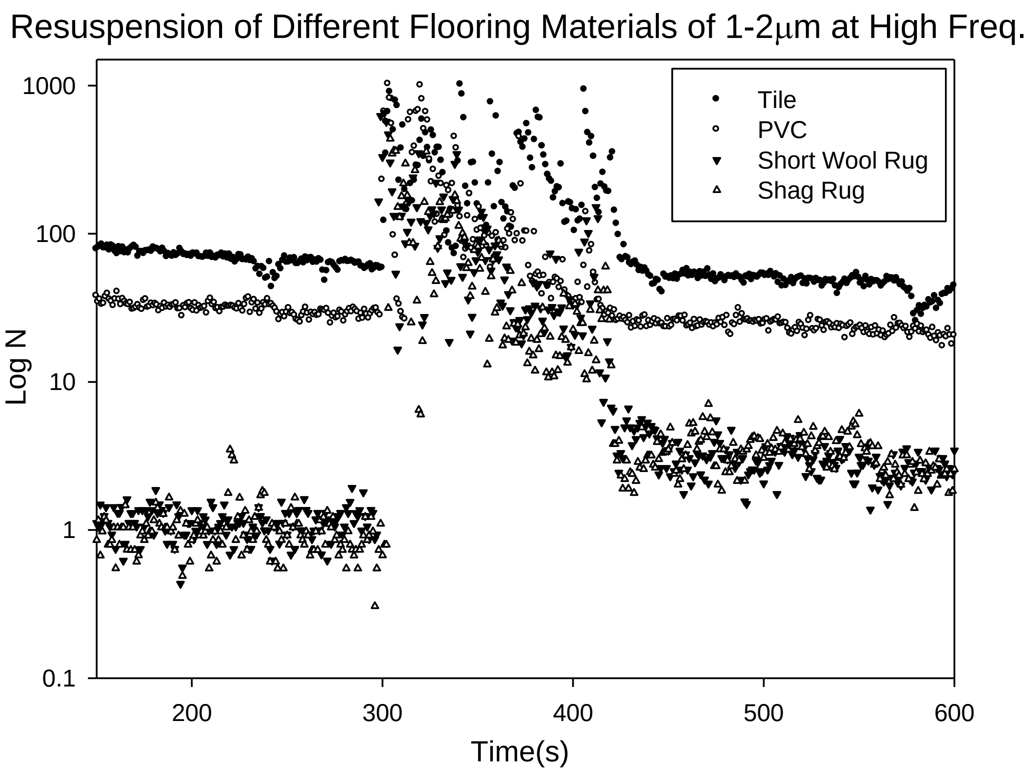


Fig 4.15: Graph of Resuspension at High Freq. of 1-2 μ m in Different Floorings

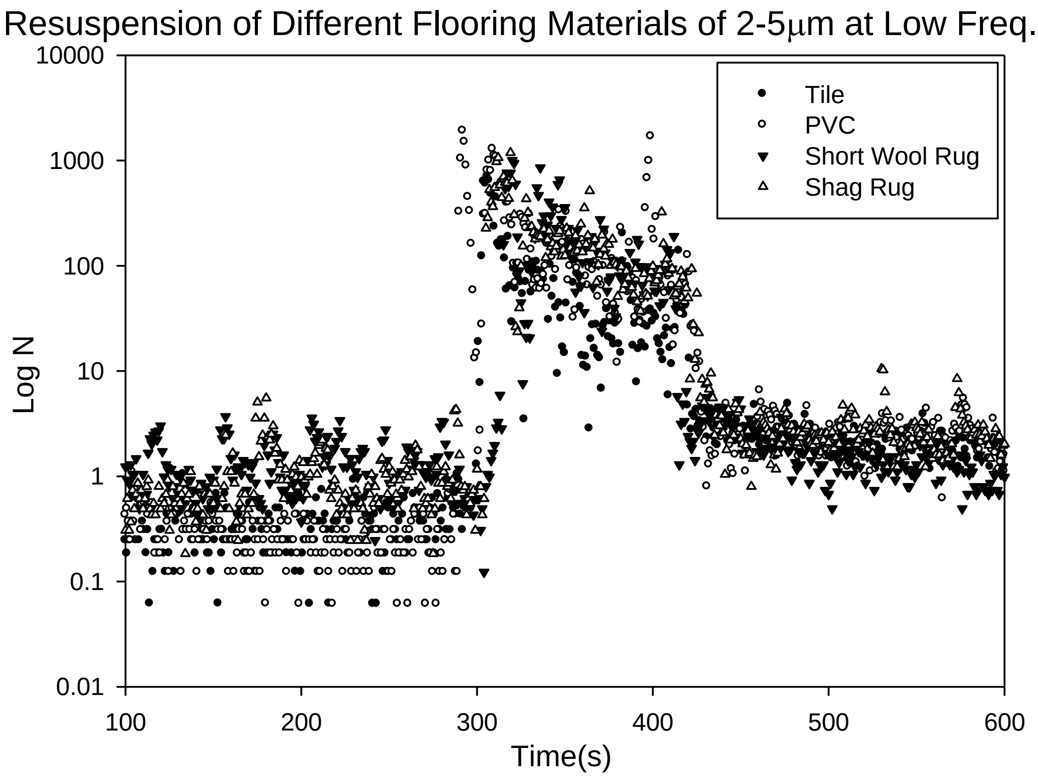


Fig 4.16: Graph of Resuspension at Low Freq. of 2-5 μ m in Different Floorings

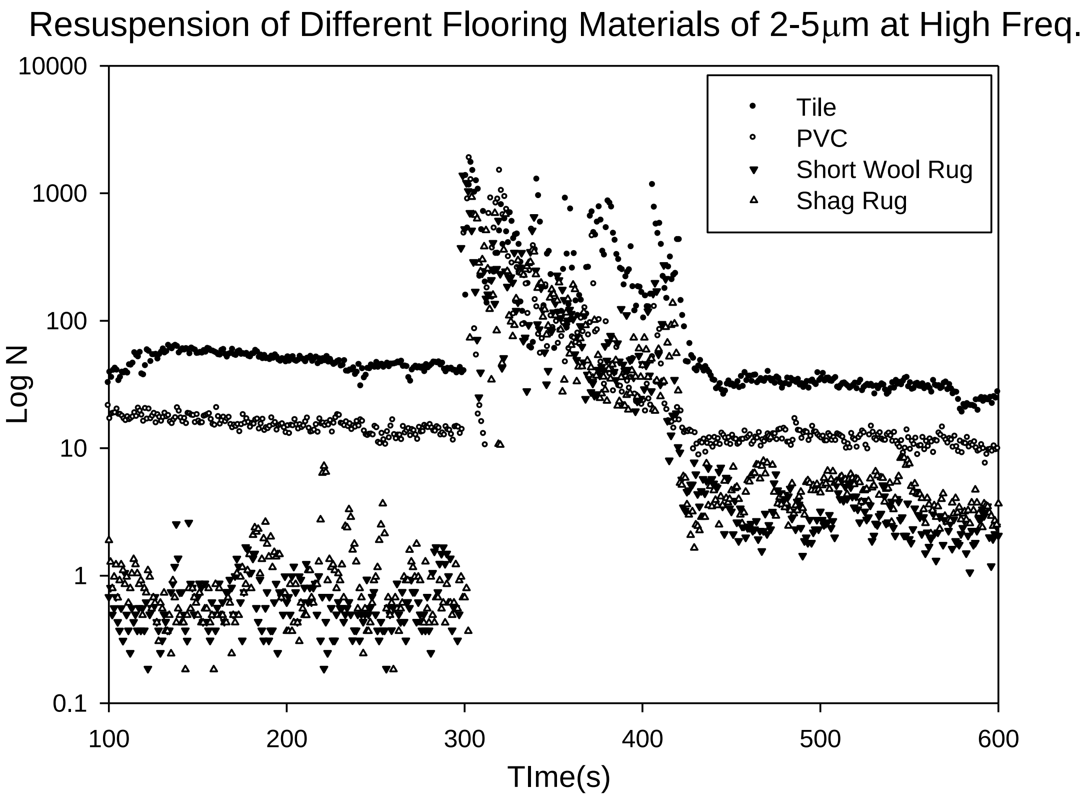


Fig 4.17: Graph of Resuspension at High Freq. of 2-5 μ m in Different Floorings

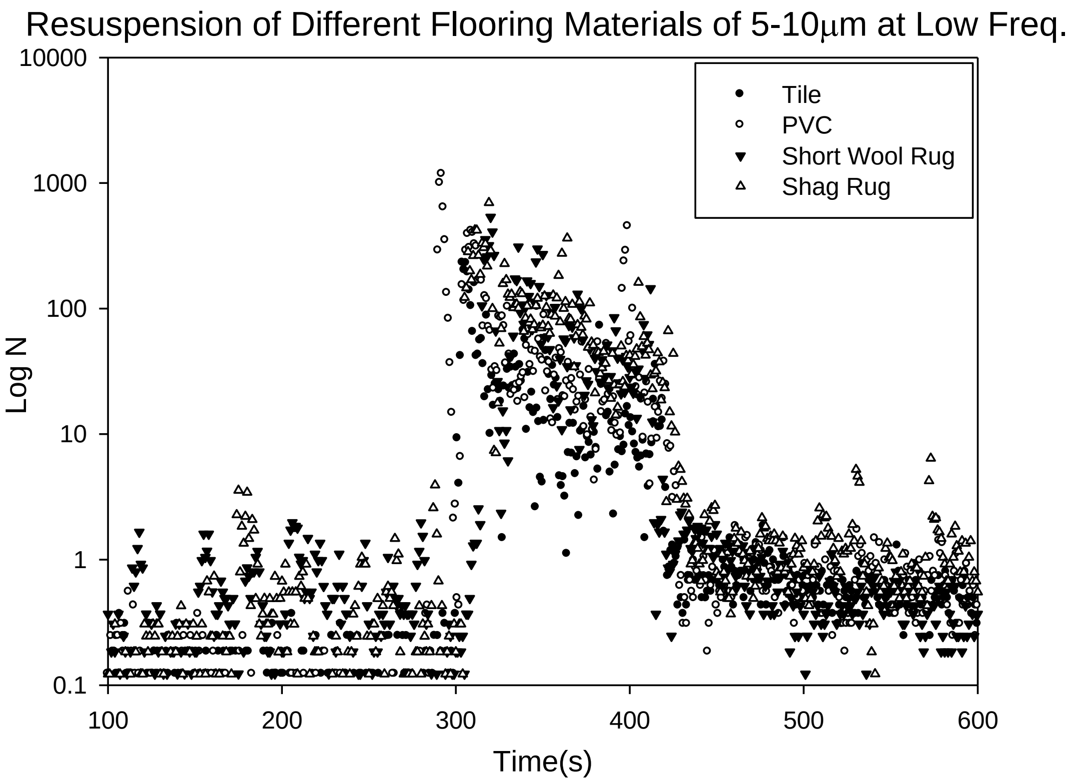


Fig 4.18: Graph of Resuspension at Low Freq. of 5-10 μ m in Different Floorings

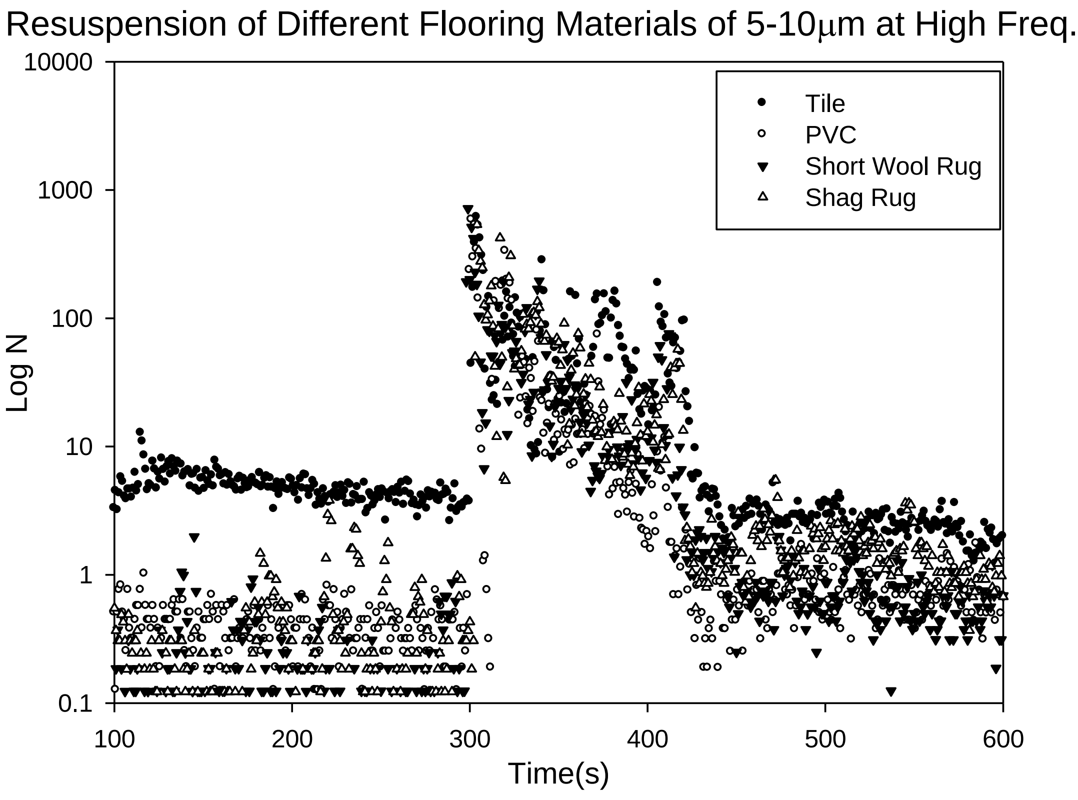


Fig 4.19: Graph of Resuspension at High Freq. of 5-10 μ m in Different Floorings

According to Fig 4.14-4.19, all the tested particular size range against different flooring materials were shown. It is found that the resuspension performance of low frequency in all particle size were all almost the same. No matter of the flooring material and the dust size. However, the dust particle resuspended from the rug was much larger than the tile and PVC plate. That means the dust particular matter may trap inside the rug and then adhered on the fiber. Therefore, more dust particle resuspended to the surrounding, not only from the surface.

For the resuspension performance, the dust concentration between short wool rug and shag rug was similar. From the other studies, the particle resuspension from short wool rug should be larger than the other. However, it did not have the clear result of it in the experiment. Since the short wool rug had a fiber length of 1cm and the shag rug fiber was 2cm, the difference in resuspension may be very small or even the same.

Some research had studied the surface and the stiffness of the flooring materials against the resuspension. However, this experiment showed that those factors were independent of particle resuspension. Perhaps it can be developed more in electrostatic part but it didn’t include in this paper.

After getting the result of the particle resuspension on different flooring material, the shoes may also be the factor to affect the emission. Based on the velocity test result, the tested shoes can be classified as three groups. The shoes with clear grooves, the shoes with flatten grooves and the one with no grooves. Leather shoes, slippers and high heels were tested in the resuspension experiment representing the groups mentioned in above.

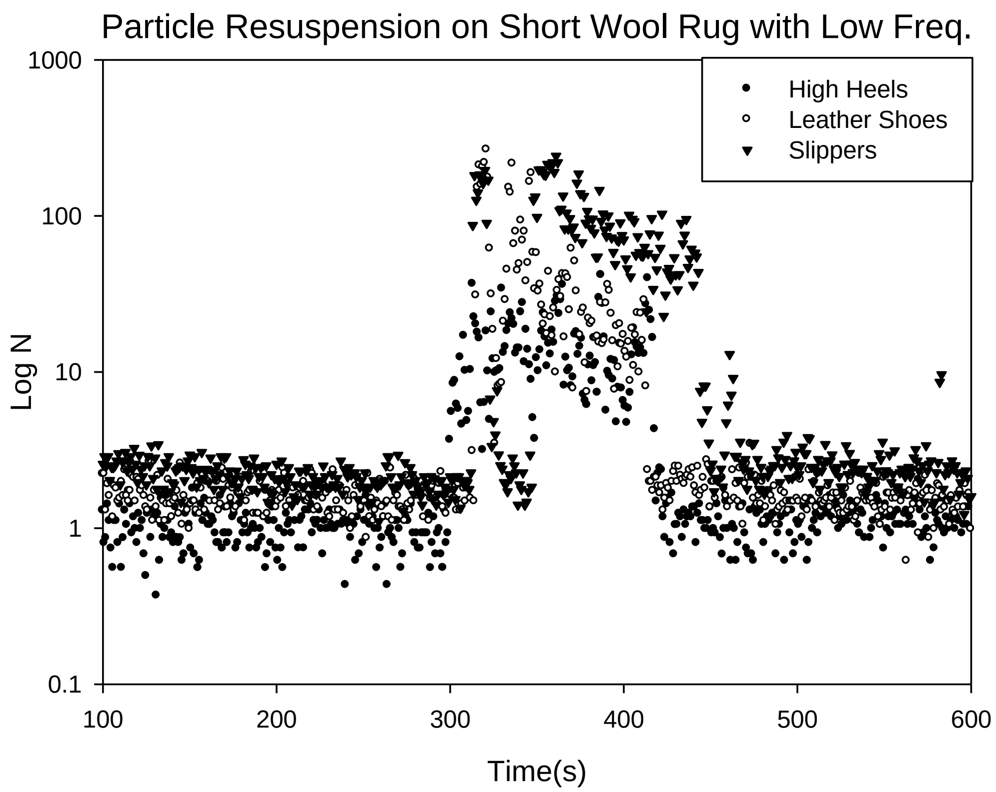


Fig 4.20: Graph of Resuspension on Short Wool Rug with Low Freq.

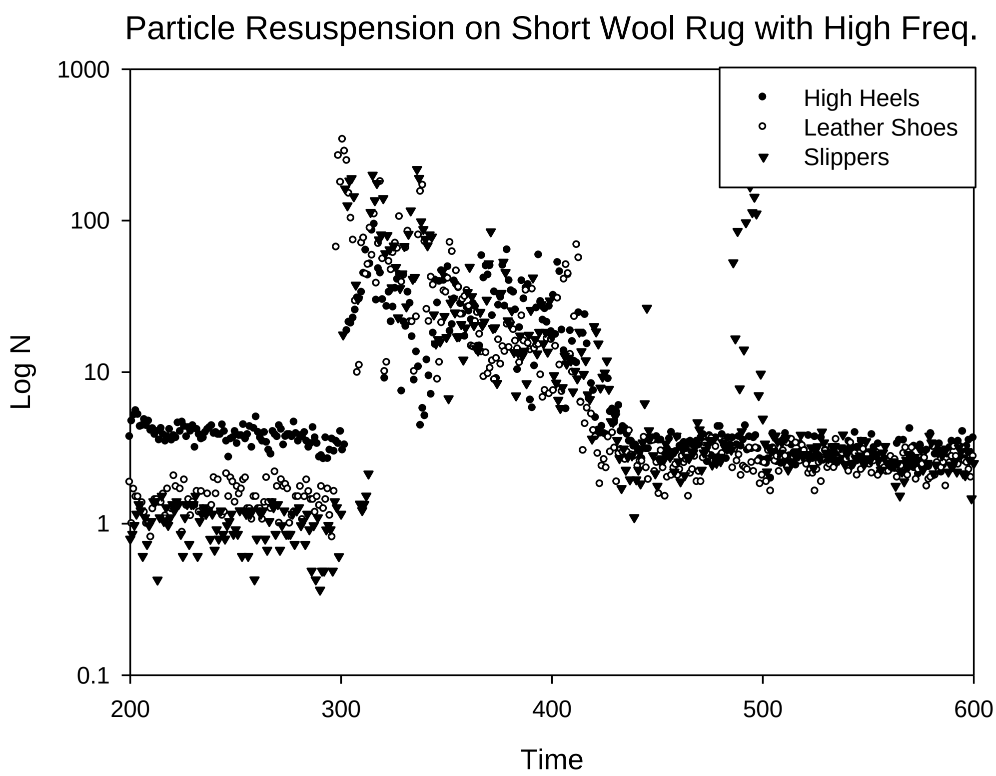


Fig 4.21: Graph of Resuspension on Short Wool Rug with High Freq.

According to Fig 4.20 and Fig 4.21, the leather shoes can produce a highest resuspension of dust particle while the high heels produced the lowest. It was found that the concentration between leather shoes and slippers was similar. But it cannot make a conclusion yet because the dust loading were difference in every flooring sample.

Based on the result of chapter 4.9, rug was considered to suspend more dust particle. However, high heels only generated not a big difference of dust concentration during walking event. In theory, the performance of high heels was even lower to other flooring materials.

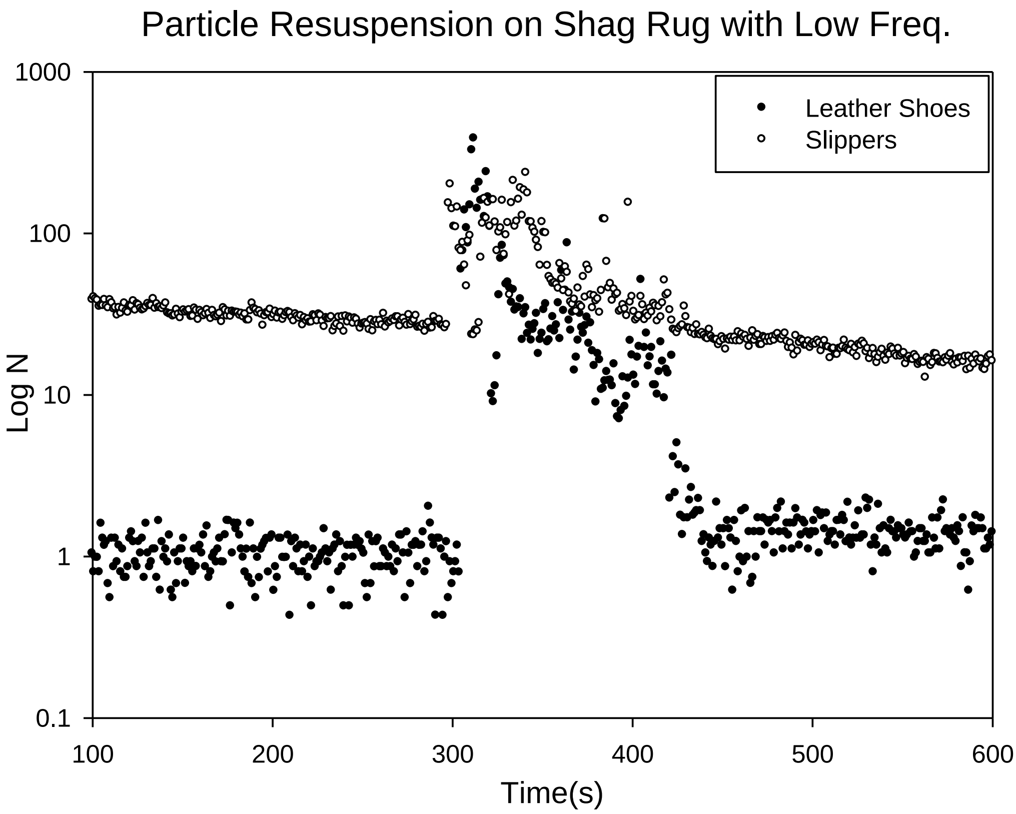


Fig 4.22: Graph of Resuspension on Shag Rug with Low Freq.

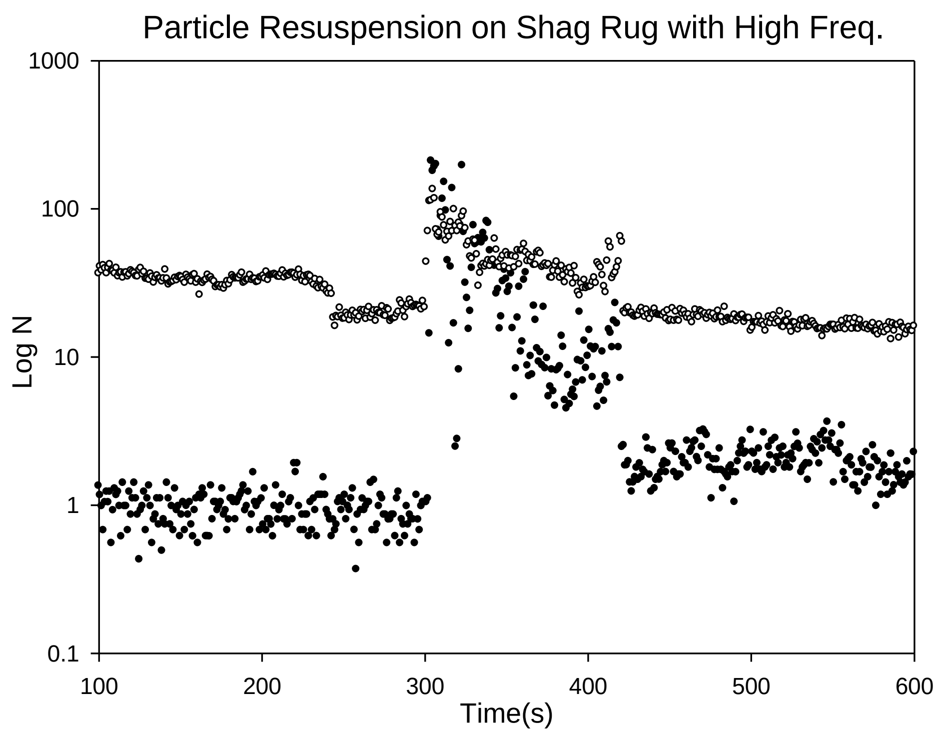


Fig 4.23: Graph of Resuspension on Shag Rug with High Freq.

For Shag rug material, it was clearly observed the leather shoes can produced more particle resuspension than the slippers one.

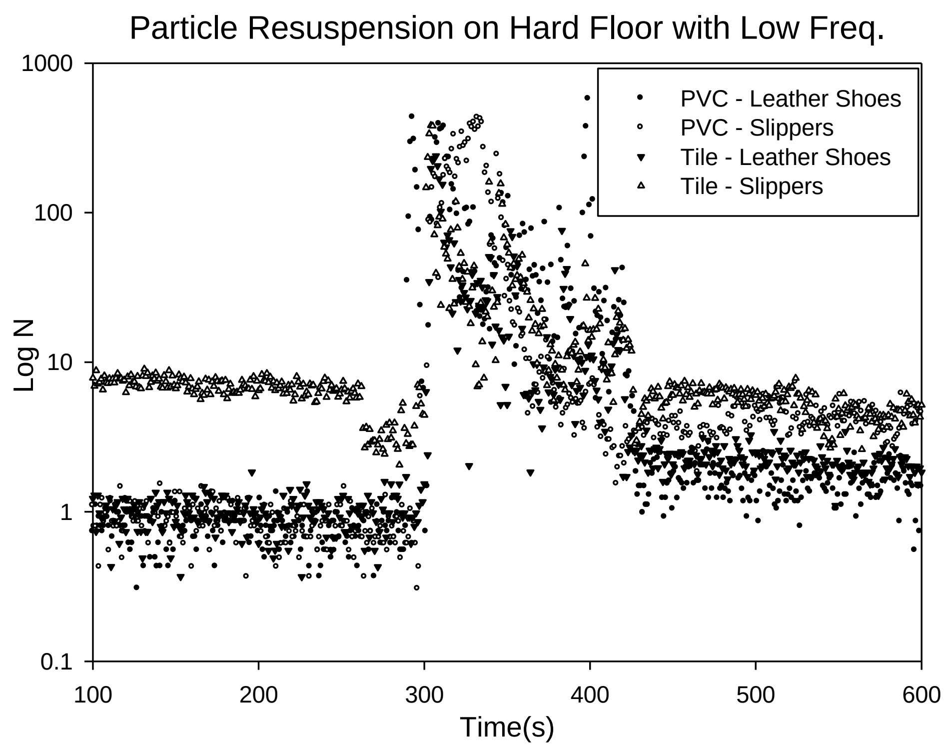


Fig 4.24: Graph of Resuspension on Hard Floor with Low Freq.

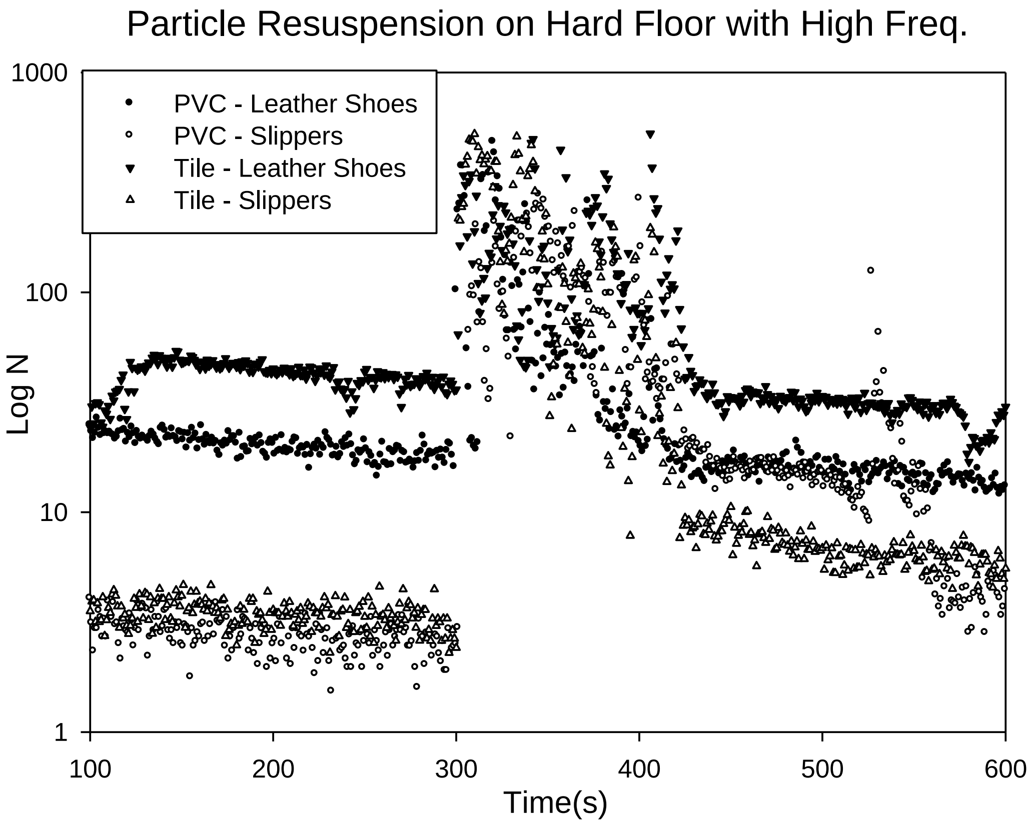


Fig 4.25: Graph of Resuspension on Hard Floor with High Freq.

According to the result, the performance of resuspension on hard floor (tile and PVC plate) was similar. From Fig 4.25, leather shoes produced a larger particle resuspension of tile and PVC plate than the slippers one. It got the same result in high frequency part except the tile. In fact, the performance of particle resuspension is affected by the loading of the flooring sample. If there is more dust deposited on the sample, the source may emit more to resuspend into the surrounding. Since ventilation is also another factor to direct affect the degree of resuspension, it can be ignored because the experiment was carried on with no ventilation in assumption.

4.10 Emission Factor Calculation

Emission factor is represented by the ratio of the mass concentration to the floor loading. This factor contains the mixing volume of dust particle, floor loading and also the measured walk area. It can be more precisely to indicate the behavior of the shoes against the dust particle resuspension. The equation is given as

$$E = \frac{V_{mix} \, x \, C_{in}}{A_{walk} \, x \, C_{load}}$$

Where E = Emission Factor

V_{mix} = Mixing Volume (m^3)

C_{in} = Mass Concentration (μ g/m^3)

A_{walk}= Measured Shoes Area (m^2)

C_{in} was determined from the OPSS located at 0.04m above the flooring sample. Since the mass concentration of hip level (0.7m) with no ventilation was the limited height of particle resuspension, the mixing height was assumed as the half of the hip level. The result was summarized in the following table.

Table 4.2 Emission Factor of Different Shoes on Different Flooring Materials

Emission Factor (g/g)	Size (μ m)	Short Wool Rug		Shag Rug		Tile		PVC Plate	
		Low F.	High F.	Low F.	High F.	Low F.	High F.	Low F.	High F.
Leather Shoes	0.8-1	0.0074	0.0104	0.0077	0.0077	0.0113	0.01313	0.01717	0.1744
	1-2	0.029	0.0412	0.0304	0.0305	0.043	0.04472	0.0621	0.0664
	2-5	0.2619	0.3076	0.29	0.2719	0.3213	0.28449	0.38632	0.411
	5-10	**1.3074**	**1.06141**	**1.7334**	**1.3028**	**1.4155**	**1.1068**	**1.25177**	**1.1026**
Slippers	0.8-1	0.0144	0.0145	0.0051	0.0055	0.0069	0.0172	0.0088	0.0188
	1-2	0.0592	0.0548	0.0234	0.0223	0.0266	0.0641	0.03415	0.0739
	2-5	0.3833	0.3196	0.2207	0.2103	0.1971	0.3648	0.2372	0.3985
	5-10	**1.138**	**0.844**	**1.171**	**1.294**	**1.1033**	**1.0757**	**1.1397**	**1.0555**

Generally, the emission factor was increased with the particle size from 10^{-4} to10^{0}. The result was around 10 to 100 times larger than the other studies. According to the result, shag rug and short wool rug had the largest emission comparing to the other hard floor materials. It proved with the result of concentration part, more dust trapped into the rug fiber, more dust particle will be suspended. Also, the entire emission factor of leather shoes was larger than the slippers. By the resuspension experiment, more mass concentration was detected during the walking event with leather shoes.

4.11. Limitation and the Encountered Difficulties of the Research Study

1. Dust Adhered on the Inner Surface of the Deposition Chamber

Since the deposition chamber was made of acrylic, the electrostatic force can be built easily on the inner surface of the chamber during the deposition process. Also, the dust was accumulated on the blade of mixing fans since they were used to provide a turbulence flow for a better mixing condition. During the mixing process, the dust may be adhered on it. In that case, some tiny dusts were adhered to it causing fewer dust particle settled on the flooring sample. However, the purpose of the seeding experiment was deposited the dust particles evenly distributed on the flooring sample.

2. Leakage through the Crack of the Deposition Chamber

Since there was a door opening on one side of the deposition chamber for transferring the flooring materials, it provided some tiny gaps around it that was large enough for the dust to pass through. The leakage can be observed on the inner surface of the mask tape.

3. Hard to Control the Strength and Frequency of Stepping

Actually, the resuspension test carried on in the experiment was using a real stepping by the helper. Since human is not a machine, it is hard to control the strength and frequency accurately in every step. Due to the tiredness of the participant, the step can be kept the same in first few minutes or even the seconds based on different frequency test. Since the frequency was set as 84 steps per minute and 120 steps per minute, the interval of stepping was determined by the participant based on the simple calculation of 1.4 steps per second and 1 step per second respectively. Fail to keep the strength and frequency may cause little discrepancies in the airborne particles mass concentration during resuspension.

4. Error of Emission Factor with the Size Range of 5 - 10 μm

Emission factors is defined as the relationship between the amount of pollutants produced and the amount of raw material processed. In this experiment, it showed the amount of dust particle resuspend by a certain amount of it deposited on the flooring material. Actually, this factor should be lower than 1. However, the result indicated that the emission factor of a size range of 5-10μm was larger than 1. That was impossible except there were another source to produce that size of dust particle. Since the test dust number of that size range used in the experiment only have a 0.81% in total, 1 number different of received dust particle may result a big difference no matter of the deposition or the resuspension. In fact, the air has not this larger size of dust so it may not come from the atmosphere. The possible reason to get those result are listed as follows.

- Dust trapped in the grooves or adhered to the bottom of shoes
  Since the cleaning was done before the resuspension test, however it is difficult to remove the entire existing dust particle especially the one who adhere into the grooves. Therefore, when it was stepped on the seeded flooring sample, the dust adhering into the grooves may come out.

- Dust accumulated in the OPSS
  The function of OPSS is used to measure the dust concentration by drawing the air to the sensor in the inner part. If it does not clean frequently and replace the filter, the measured value may be overestimated since the particular matte would trap in it and accumulate. Since the experiment took many times to record the different concentration, the accumulation of dust would affect the accuracy of the result. To support the assumption made, a control group of data was made in a condition that had no flooring material provided and no walking.

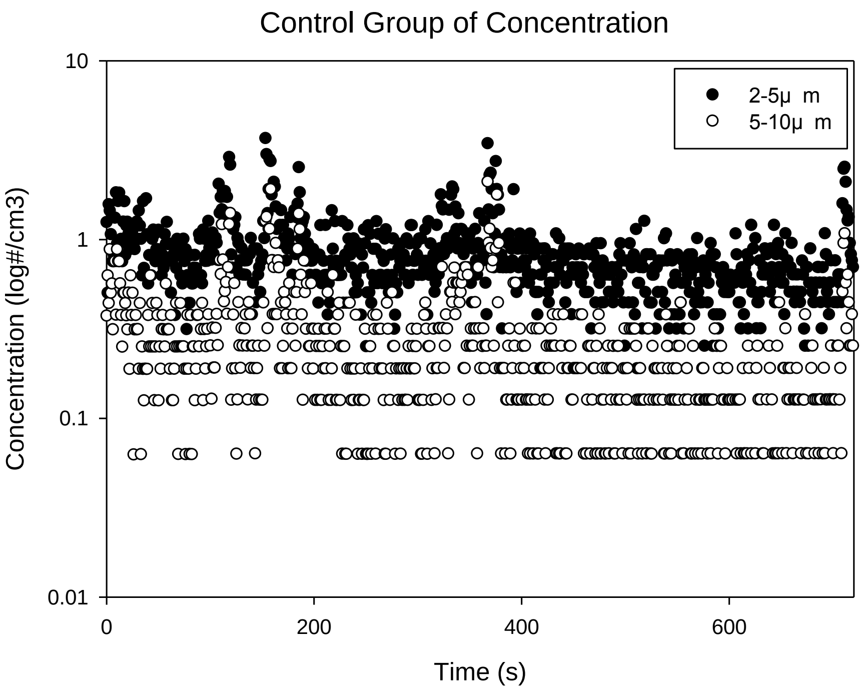


Fig 4.26: Control Group Data

According to fig 4.26, the concentration of the dust particle had a little bit fluctuated with no stepping event. That means the OPSS really collected that size of dust but it had no such size of it in the atmosphere. Therefore the dust of 5-10μm was accumulated inside the OPSS and then overestimated the concentration of it.

5. Background Noise Problem

According to the result of velocity test, the background noise is a problem to affect the accuracy of the result since the recorded data was fluctuated. Based on the experiment, stage one was a 5 minutes background, stage two was a step event with 1 minute and the stage 3 was a 10 minutes post-event background. The purpose of stage 3 was to see how long did the value dropped to the origin. However, the recorded value fluctuated after 5 minutes. Since only one step was made in stage two but the result showed that the induced velocity kept increasing and decreasing after the stepping.

Chapter 5

5. Conclusion

The influence of different shoes and flooring materials on particle resuspension was studied. The experiment contained the deposition of dust, resuspension test with the support data of velocity test and uniformity test. The experiment aims to find out the relationship and the influence of shoes against the degree of resuspension.

According to the result, there were lots of factor to affect the particle resuspension, such as the mixing height and ventilation. Mixing height determined the dust particle mixing volume in the chamber and this height was affected by the ventilation. The ventilation can provide a turbulence flow and made the mixing of dust and air more fluently.

For the flooring materials and type of shoes, soft material such as short wool rug and shag rug can provide a better condition for dust resuspension since the dust particle can trap inside the rug and adhered on the fiber. Similar to that, the shoes with clear grooves can also made the dust particle resuspended more.

6. References

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