

Article

Environmental Particulate Matter (PM) Exposure Assessment of Construction Activities Using Low-Cost PM Sensor and Latin Hypercubic Technique

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Abstract: Dust generation is generally considered a natural process in construction sites; ergo, workers are exposed to health issues due to fine dust exposure during construction work. The primary activities in the execution of construction work, such as indoor concrete and mortar mixing, are investigated to interrogate and understand the critical high particulate matter concentrations and thus health threats. Two low-cost dust sensors (Sharp GP2Y1014AU0F and Alphasense OPC N2) without implementing control measures to explicitly evaluate, compare and gauge them for these construction activities were utilized. The mean exposures to PM₁₀, PM_{2.5} and PM₁ during both activities were 3522.62, 236.46 and 47.62 µg/m³ and 6762.72, 471.30 and 59.09 µg/m³, respectively. The results show that PM₁₀ and PM_{2.5} caused during the concrete mixing activity was approximately double compared to the mortar. The Latin Hypercube Sampling method is used to analyze the measurement results and to predict the exposure concentrations. The high dust emission and exposure from mixing activities fail to meet the World Health Organization and Health and Safety Commission standards for environmental exposure. These findings will leverage the integration of low-cost dust sensors with Building Information Modelling (BIM) to formulate a digital twin for automated dust control techniques in the construction site.

Keywords: particulate matter (PM); health hazards; low-cost PM sensors; environmental exposure monitoring; primary construction activity; PM monitoring; worker safety



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1. Introduction

The construction industry contributes a large amount of particulate matter to the environment, putting public health at risk [1–3]. Particulate Matters (PM) is produced during the construction phase, from the early stages of material transport to the dismantling phase, and the regular construction operations involving the soil and materials are the primary sources of dust. Regular operations such as cement mixing, demolition and grinding of concrete are the main activities involved in the formation of fine (particles smaller than 2.5 µm) and ultrafine PM particles (particles smaller than 1 µm) in the soil, according to the results of a study conducted in Hong Kong by Li et al. [1]. Furthermore, even using prevention mechanisms such as water suppression and local exhaust ventilation (LEV), particles (PM) cannot be entirely removed from the environment. However, particle concentrations in the air can be reduced by 70–80% [4]. Li et al. [5] measured environmental exposure to PM by performing various construction activities, such as sawing, drilling and sanding, using the LEV as a monitoring tool to extract various particles from the

construction site, and found exposure ranging from 0.127 to 2.114 mg/m³. However, by combining different approaches, existing methods to minimize environmental pollution can still be improved and helped in reducing health issues [6].

PM emission is considered inevitable at most construction sites. As a result of their proximity to PM, workers face both short- and long-term health problems [7]. According to the US Occupational Safety and Health Administration [8], environmental exposure pollution causes serious health problems for about 0.05 percent of the 2 million construction workers in the US. Studies have shown that PM exposure causes serious health problems and even causes hereditary genetic damage [9,10]. Furthermore, researchers have highlighted the risks of environmental exposure to PM contamination and its long- and short-term effects on workers' health [11–13], with Peters et al. [13] reporting that cement PM exposure is a significant cause of cancer in construction workers. As a result, companies and government should follow the guidelines for existing and prospective construction projects and collaborate to ensure a healthy work environment [14].

More research is needed to minimize and track environmental exposure from suspended particles from construction sites. As a result, control measures should not be applied in a general manner but should be highly targeted based on operation, materials and tools employed [15]. In practice, the Federal Reference Method (FRM) and the Federal Equivalent Method (FEM) of the US Environmental Protection Agency (EPA) are used to track PM [16]. The PM collectors in the FRM system are placed in different positions to gather PM for periods ranging from days to weeks. The obtained samples are subjected to laboratory experiments using a gravimetric method to assess the PM particle size composition and distribution [17,18]. The FRM solution is time-consuming, expensive and requires a trained practitioner to complete. The FEM technique, on the other hand, is a modern way of measuring PM in real-time using the Internet of Things (IoT) and producing PM concentration graphs over a given period. Therefore, through FRM method, we can monitor the environmental exposure and compare it with exposure standards.

The estimated allowable concentrations (MPCs) for PM₁₀ and PM_{2.5} are 0.3 mg/m³ and 0.16 mg/m³, respectively, according to Sazonova et al. [19], with the mean dose being 6.87 and 5.33 times the MPC value, respectively. The WHO has proposed various environmental exposure limits for different sized PMs as a guide for air quality monitoring requirements: the 24-h exposure limit levels for PM₁₀ and PM_{2.5} are 50 µg/m³ and 25 µg/m³, respectively, while the average annual limit is 20 µg/m³ and 10 µg/m³, respectively [20]. Australian environmental quality levels [21] and European environmental quality levels [22] have the lowest PM₁₀ values of any nation. Despite all of these regulations and rules, environmental PM exposure in most countries exceeds the MPL [23–25]. All those standards can be monitored with the help of low-cost environmental PM sensors.

Recent advances in electronics and computer science have enabled smart sensors and circuits to monitor environmental exposure and worker protection using low-cost PM sensors for monitoring air quality exposure [26]. As low-cost sensors are less expensive and have almost similar sensitivity and accuracy to air quality monitoring systems validated and evaluated, and supported by EPA, they can be used to measure PM's temporal and spatial distribution [27,28]. To measure and monitor environmental exposure from construction materials, the authors mainly used the FEM method. The efficacy of PM sensors for indoor and outdoor conditions has been evaluated by groups such as the EPA [28], the South Coast Air Quality Management District [29] and Carnegie Mellon University's CREATE Lab [30]. They found that the low-cost PM sensor and the reference PM sensor were highly correlated. Low-cost sensors may be advocated as an environmental exposure monitoring option. Other researchers have discovered a strong connection between low-cost PM sensors and PM monitoring in both indoor (laboratory) [31–33] and outdoor (field) environments [34–37]. Scientists have stressed developing an environmental exposure emission database from construction activities using low-cost PM sensors in recent reports [38,39].

Very few studies have used low-cost PM sensors to monitor particulate emissions from construction activities. Naticchia et al. [39] calibrated a Sharp PM sensor together with a Grimm sensor to measure indoor PM pollution from the cement and aggregate mix; the same particle dynamics were recorded at both the reference point and the low-cost PM sensor, and the findings for both followed the same graphic pattern for PM detection. Based on these results, low-cost PM sensors can be used to detect particles on a massive scale [25,40]. Wang et al. [41] used three PM sensors (Sharp, Samyoung and Shinyei) for laboratory assessment and calibration to verify their linearity, accuracy, repeatability, detection range and particle size sensitivity as the impact of temperature and humidity on them. The Sharp sensor had the best measuring accuracy and linearity of the three. Liu et al. [40] used Sharp and Shinyei sensors to monitor concrete PM exposure in an indoor environment; the results revealed that the two sensors have a close relationship with their respective reference instruments, DustTrak and AirBeam. Li et al. [5] used a low-cost PM sensor and a benchmark unit (SidePak TSI) to monitor PM environmental exposure emissions over 4000 s by using an LEV control system during woodworking practices. In addition, when using LEV, the amount of environmental pollution was higher from the recorded data than the WHO exposure value.

During the welding and assembly of steel frames during renovation, Ahmed and Arocho [42] reported that PM environmental exposure is higher than the EPA's prescribed limits. However, no study has been carried out on tracking the environmental exposure caused by the construction of reinforced concrete structures (RCCs). Furthermore, research work should be conducted on job sites to track and record environmental PM emissions from various mixing ratios, tools and equipment. Furthermore, PM dispersion from RCC structures should be tracked when considering various factors such as horizontal and vertical distance. This study will pave away to develop the base for the environmental PM exposure inventory base on type of activity, tool and equipment used.

2. Materials and Methods

2.1. Construction Materials

To investigate and monitor the environmental exposure of various PMs during indoor construction activities. As a pilot test study, we used mortar mixing (cement and sand) to build a solid block wall measuring 0.6×0.5 m (area = 0.3 m^2), and concrete mixing to build a foundation measuring $0.5 \times 0.6 \times 0.1$ m.

2.2. The PM Monitoring System

Majority of low-cost PM sensors work on the principle of light scattering. There is an entrance and an exit for the air passage through the PM sensor. The air (containing dust particles) enters through the opening, where the infrared diode illuminates the particles, and the scattered light becomes the signal through the phototransistor. The signals collected are amplified by an amplifier circuit and then processed for particle concentration. The intensity of scattered light depends on the particle size of PM. The greater the intensity of light will be when many dust particles are present in the air. From the previously published research articles researchers mentioned that the linearity of low-cost PM sensors affected by temperature and humidity [43–46], power supply [47] and wind speed and direction [48]. When low-cost sensor is used to monitor the dust concentration at the atmosphere then aforementioned factors need to be considered while deploying the sensor at the field monitoring as shown in Equation (1).

$$f(x) = ax + b + H + T + W.D + W.S \quad (1)$$

where x is the calculated voltage, a is the slope, b is the intercept, H is the humidity, T is the temperature, $W.D$ is the wind direction and $W.S$ is the wind speed.

As the experiment in this manuscript was conducted indoor where the wind direction and speed is constant, therefore the effect of wind direction and speed are ignored while doing analysis. As the experiment duration was too short therefore the factors have negligible effect on the measured data. Therefore, to calculate the dust concentration following Equation (2) is used.

$$f(x) = ax + b \quad (2)$$

In our communication network system with three low-cost PM sensors (at locations a, b, c and d) as the end-user interface. Figure 1 illustrates the experimental setup to monitor the PM exposure at locations a, b, c and d at 1 m from the pivot point. From the pivot point, the set of low-cost sensors were installed at the angle of 120° . A set of three low-cost PM sensors (Sharp GP2Y1010AU0F and Alphasense OPC-N2 PM) and Kanomax are installed in the big room, having dimensions $6 \text{ m} \times 3 \text{ m}$ in length and width. Kanomax 3443 calculates the number of particles with the timestamp and gives PM_{10} particles concentration as an output. In the case of Alphasense OPC-N2 gives the number of particles, different sizes of PM particles. Kanomax 3443 and Alphasense OPC-N2 are build-in devices, while for Sharp GP2Y1010AU0F different components are integrated to make it functional. Figure 2 describes the communication network between the slave node and master node. The slave node sensors collect the PM exposure data from the primary construction activities and transmit it through cable and Bluetooth. In addition, DHT 22 (temperature and humidity sensor) sensor is attached to Sharp PM sensors to record the temperature and humidity readings while experimenting. In Figure 3, different components of Sharp sensors along with DHT22 are shown, which includes Sharp GP2Y1010AU0F, Alphasense OPC N2, temperature, humidity and Bluetooth sensors.

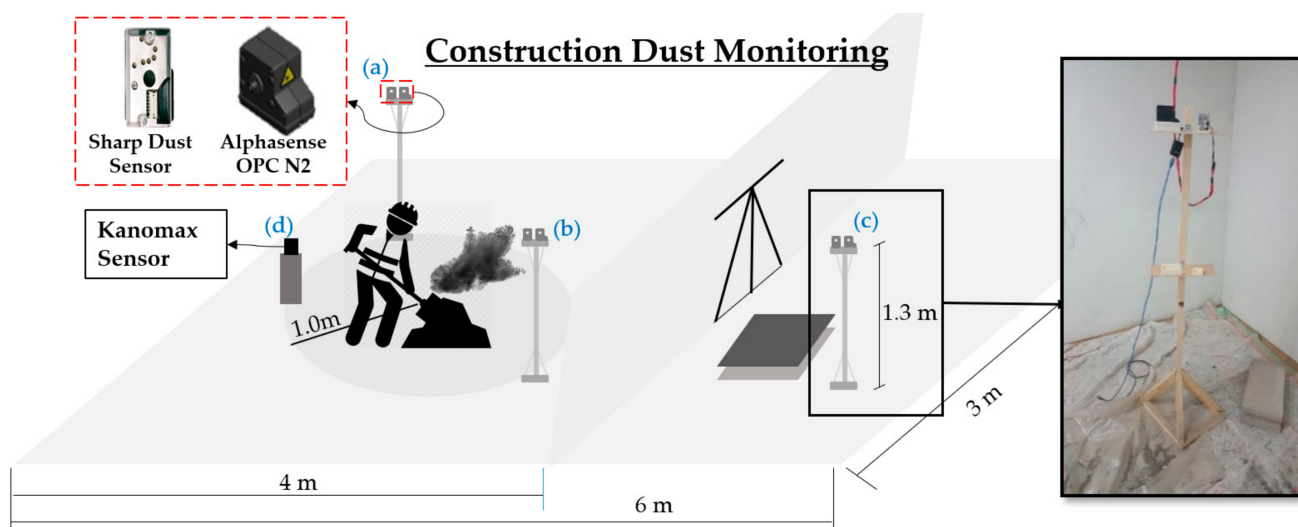


Figure 1. Experimental setup and PM sensor locations: slots (a–d) show the positions of pairs of Sharp GP2Y1010AU0F and Alphasense OPC-N2 sensors.

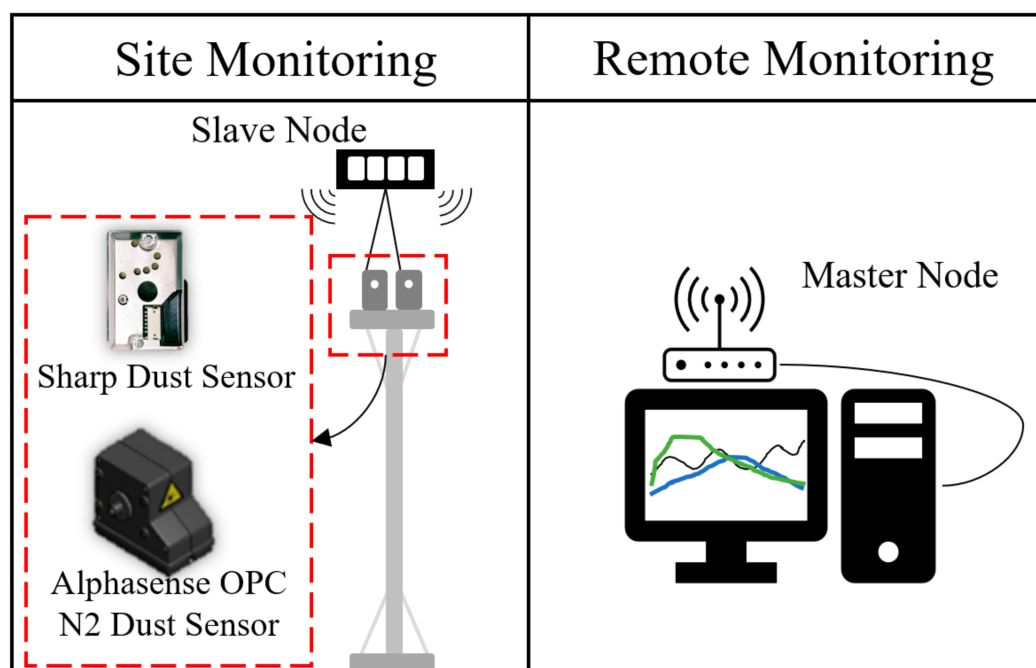


Figure 2. WSN for the PM monitoring system.

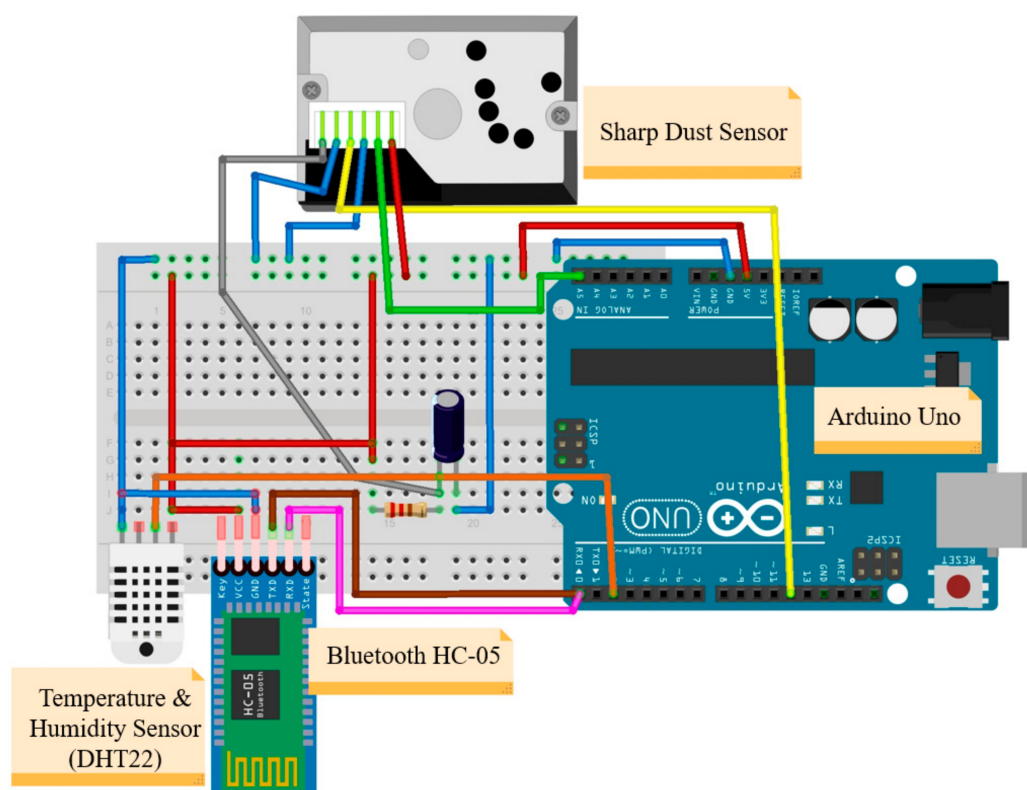


Figure 3. The Sharp GP2Y1010AU0F PM sensor circuit.

2.2.1. Alphasense OPC-N2 PM Sensor

Alphasense OPC-N2 PM sensors work on the principle of light scattering. There is an entrance and an exit for the air passage through the PM sensor. At the exit small fan is attached to prevent the settling of dust particles inside the dust sensor chamber. The air (containing dust particles) enters through the opening, where the infrared diode illuminates the particles, and the scattered light becomes the signal through the phototransistor. An amplifier circuit amplifies the signals collected and then processed for particle concentration

as Alphasense OPC-N2 gives three types of PM size particles such as PM_{10} , $PM_{2.5}$ and PM_1 . PM_{10} means particulate matter size greater than $PM_{2.5}$ and $\leq PM_{10}$ and $PM_{2.5}$ means PM ranges between PM_1 and $\leq PM_{2.5}$ while PM_1 ranges were less than PM_1 particle size. When the size of particulate matter is large, then the light deflects more and compares to small size particulate matter particles. Based on this Alphasense OPC-N2 differentiate and classify the particulate matters into three different PM sizes.

It costs less than \$500 per sensor and simultaneously records PM_1 , $PM_{2.5}$ and PM_{10} data. In addition, the Alphasense OPC-N2 PM sensor has several advantages over the Sharp PM sensor, including a secure digital storage card for data storage and integrated applications with a user-friendly interface. Data collected by the sensor can be transmitted directly to a device through a USB port. The particulate monitoring range ranges from 0.38 to 17 m, with a maximum particle count of 10,000 [49].

2.2.2. Sharp GP2Y1010AU0F PM Sensor

With an initial cost of \$10, this PM sensor is one of the most economical currently available low-cost PM sensors. To make the Sharp GP2Y1010AU0F PM sensor functional requires connecting to an external microcontroller (Arduino UNO board), temperature and humidity sensors and Bluetooth as briefly explained in the below paragraph. Once all these components are paired, as seen in Figure 3, the Sharp GP2Y1010AU0F PM sensor can record the PM concentration in the environment. As seen in Figure 1, four Sharp sensor circuits were developed and mounted in the desired positions. The Sharp GP2Y1010AU0F PM sensor does not have a fixed particle size range for monitoring [50]. From the datasheet of Sharp PM sensor can monitor maximum value of dust concentration is 0.5 mg/m^3 ($500 \text{ }\mu\text{g/m}^3$). Bluetooth is used to record and transmit the data from the sensor node to the computer screen with a sampling time set to 1 s.

- The indoor temperature and relative humidity of the workplace were measured using a DHT22 sensor. It is one-of-a-kind due to its low power consumption and ease of installation in the circuit.
- The HC-05 Bluetooth module must be mounted on both the slave and master node to transmit and receive data up to 100 m, based on weather and geographic conditions.
- The Arduino UNO built on the ATmega328P microcontroller was selected for the Arduino system because of its ease of use and programming libraries.

2.3. Experimental Procedures

The scarcity and advantages of using low-cost PM sensors to detect PM can be determined using a systematic experimental method. Figure 4 depicts the experiment's moves that were carried out in this article. The most popular and primary tasks of any construction project are concrete mixing (cement, sand and coarse aggregates) and mortar mixing (cement and sand). Low-cost PM sensors were used to track the PM exposure from the everyday construction activities.

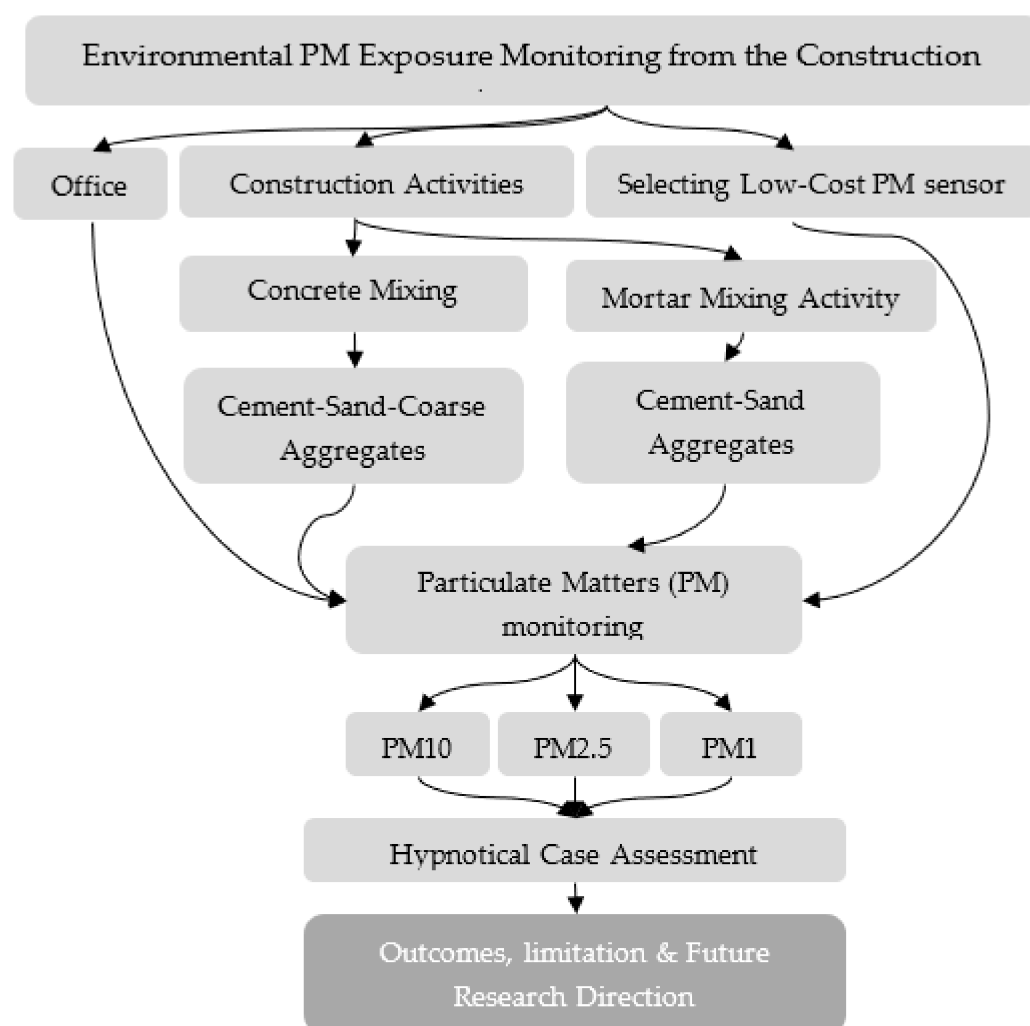


Figure 4. A flow diagram of the proposed research to monitor the environmental PM exposure at construction job sites.

It is essential to collect more comprehensive data on PM emissions from construction activities. FRM instruments are costly, cumbersome and require a trained operator to use. Low-cost PM sensors, on the other hand, are lightweight, simple to use, inexpensive and run at a low voltage (5 V). When using sensors to calculate PM, the distance between the source and the sensors is crucial to getting accurate results. Thus, primary parameters were used to coordinate the horizontal and vertical distances between the PM source and the measuring stations, as well as the sensor angles. PM₁₀, PM_{2.5} and PM₁ were the PM sizes monitored by the sensors over given horizontal (1 m) and vertical (1.3 m) distances. The experimental setup and implementation are further elaborated in Figure 2.

Alphasense OPC-N2 and Kanomax are factory assembled and have built-in software. From both sensors, we acquire Particle count, PM concentration, along with the timestamp. On the other hand, we do coding in C++ language in Arduino IDE to receive our objective outcomes from the device. We can calculate the concentration of dust particles in the atmosphere using the Sharp GP2Y1010AU0F sensor datasheet, as shown in Figure 5b. One pin of the Sharp dust sensor is linked to the Arduino A5 analog pin to receive data. A multichannel 10-bit converter is included in the Arduino Uno board to convert analog to digital. The highest numeric value for an analog reading when the 5V input is provided to any pin on the board is 1023. To read the dust value initially, we use Equation (3) to determine the voltage.

$$\text{Calculated Voltage} = \text{Voltage measure} \times (5.0/1024.0) \quad (3)$$

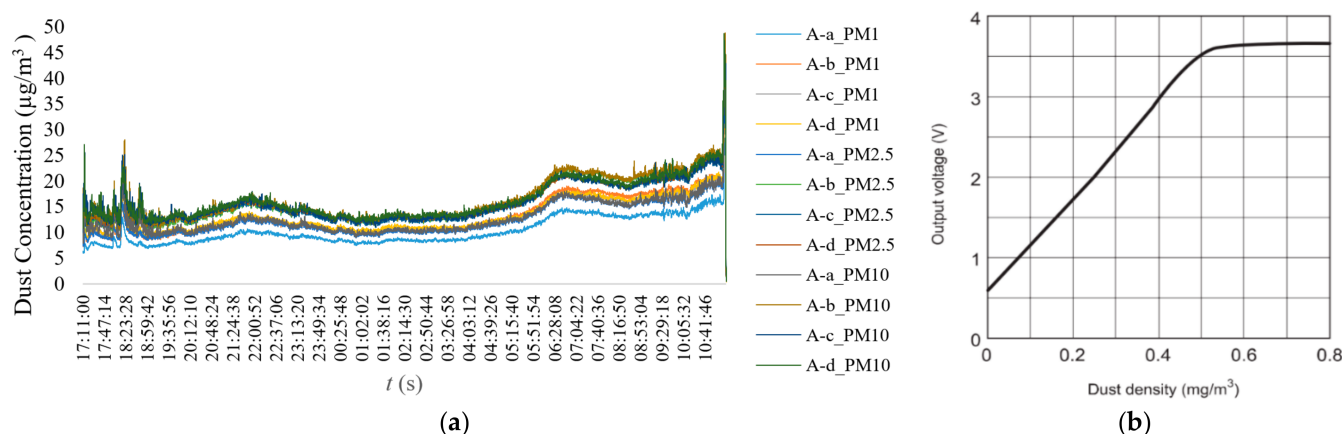


Figure 5. (a) 1-min moving average values for the Alphasense OPC-N2 sensors and (b) the Sharp GP2Y1010AU0F sensor datasheet.

Then calculated voltage is used in Equation (2) to obtain the dust concentration in mg/m^3 . Further equation two is multiplied by 1000 to convert the mg/m^3 into $\mu\text{g}/\text{m}^3$.

The fundamental goal of this study was to use low-cost PM sensors (Sharp GP2Y1010AU0F and Alphasense OPC-N2) to monitor the environmental exposure during the performing the primary construction activities. The authors conducted the whole experiment in a real environment without controlling any perimeter. As the experiment was conducted indoors, most of the factors have a negligible effect on the measured data. A Sharp GP2Y1010AU0F (S-a, S-b, S-c and S-d) and an Alphasense OPC-N2 were put in each slot (a–d) in the experimental setup shown in Figure 1; each slot (a–d) housed a Sharp GP2Y1010AU0F (S-a, S-b, S-c and S-d) and an Alphasense OPC-N2 (A-a, A-b, A-c and A-d). S stands for Sharp sensor, and A stands for Alphasense OPC-N2 sensor at locations a, b, c and d. Kanomax 3443 is considered as a benchmark device to validate the recorded data from the low-cost PM sensors on the base of previous published research articles results. Second, the Kanomax 3443 device cost is 2900\$, which is higher than the 2500\$ limit set by US-EPA to classify the low-cost PM sensor. The Kanomax 3443 dust sensor also works on the light scattering principal method, which measures only the PM_{10} range between 0.001 and 10.0 mg/m^3 . It can be used in several areas: monitoring industrial hygiene, health and safety at work, monitoring exposure to pollution. In the initial phase of the experiment, the low-cost PM sensors were calibrated and evaluated at the office without creating any dust indoors. Further, low-cost PM sensors were installed to collect the environmental exposure from while doing primary construction activity.

Analyze and monitor various PMs' exposure in the environment during indoor construction activities. As a pilot test study, we used mortar mixing (cement and sand) to build a solid block wall measuring 0.6×0.5 m (area = 0.3 m^2) and concrete mixing to build a base measuring $0.5 \times 0.6 \times 0.1$ m.

For monitoring environmental exposure, four sets of low-cost PM (one Sharp GP2Y1010AU0F and one Alphasense OPC N2) sensors are installed at locations a–d (Figure 1). To monitor the environmental exposure of PM from mixing concrete (cement, sand and coarse aggregates) to construct a $(0.5 \times 0.6 \times 0.1)$ m raft. At 3:15 p.m., sensors began collecting data. Before experimenting, sensor data was evaluated and checked at being. Other required works, such as checking installation and material transportation, were conducted in 6 min (3:15:00–3:21:00 PM). Before adding water to the concrete, the cement and aggregates were mixed for 8 min (3:21:00–3:30:00 pm). Once the concrete is adequately mixed, water is added and mixed for 7 min (3:30:00–3:37:00 PM). Then the concrete is moved from the mixing area to the casting area to build the raft foundation.

In the second phase of the mortar mixing experiment, the sensors were set up to monitor the data for 5 min without any physical movement. After this, the required volume and weight of materials were transferred from the stock to the mixing area, and other

appropriate checks were carried out prior to the start of the activity (3:19:00–3:23:00 PM). For 14 min (3:24:00–3:38:00 PM), cement and fine aggregates have been mixed. Using a shovel, we carried out six mixing exercises (three times the dry mixture and the wet mixture). After the mortar was properly mixed, then moved to the casting area to construct a solid block wall. The complete construction of the required wall lasted 21 min (15:38:00–15:59:00).

3. Results

3.1. Calibration, and Correlation of the Low-Cost PM Sensors

At the initial stage of the experiment, the light scattering low-cost PM sensors are tested for static and dynamic properties in both the office space (case 1 = without producing dust) and the mixing field (case 2 = dust generation during construction activities). Three Alphasense OPC-N2 sensors were mounted next to Sharp GP2Y1010AU0F sensors for 18 h with 1-s sampling times at the office installation. Recorded data can be smoothed through the moving average with different time intervals of 1, 5 and 30 min to test the correlation between the sensors as follows:

$$\text{Moving Average} = \sum_{i=1}^n \left(\frac{D_i}{2n} \right) \quad (4)$$

where D_i is the PM reading and n is the total number of PM readings. The sampling time was 2 s.

At one second sample time, the correlation among Alphasense OPC-N2 sensors shown 0.80 correlation for PM1 and PM 2.5 while 0.37 for PM10. After smoothing the curves by taking the five-second average value, a 0.96 correlation is recorded for PM1 and PM2.5, whereas for PM10 it was 0.76 as seen in Figure 5a. At a moving average of 30 s and 60 s, a similar enhancement was recorded. At 1 min moving average, all Alphasense OPC-N2 sensors record 96% similar exposure (number of dust particles or concentration) in the surrounding. It is mean low-cost dust sensor measure the same dust concentration as other sensor present at the site. As construction site is too complex and dynamic its preferable to consider large moving average smoothen curve to obtain high correlation and similar trend of PM particles in the atmosphere.

On the other hand, Every Alphasense OPC-N2 had a Sharp GP2Y1010AU0F sensor mounted next to it, but it does not record any PM in the environment (office space). It is not susceptible to low PM concentrations, as mentioned in previous articles [40,45]. PM measurements begin above $100 \mu\text{g}/\text{m}^3$ according to the Sharp GP2Y1014AU0F datasheet, as shown in Figure 5b. As a result, no reactions to low concentrations were elicited during the tests. All four Alphasense OPC N2 sensors demonstrated high precision and correlation with each other over a one-minute moving average cycle and were more than 99.00 percent accurate.

To validate the low-cost sensor performance for monitoring the environmental exposure dust generated from the construction activity using PM sensor with a simple period of 2 s. Then the collected data is smoothened by moving an average of 5min to acquire a high correlation among sensors. The Sharp S-a and S-b (location) sensors obtained correlations (r) of 0.73 and 0.82 with Alphasense A-a and A-b sensors. Simultaneously, S-a and S-b obtained r of 0.68 and 0.83 with the Kanomax model 3443 (Digital dust monitor model 3443. 2020), respectively, as reported in Table 1. Based on the measured test results, all the sensors showed high r with each other.

Table 1. Five-minute moving average correlations (r) between the two sets of test sensors and the benchmark PM sensor for the mixing construction activity.

Sensor	Alphasense (A-a)	Alphasense (A-b)	Alphasense (A-c)	Kanomax
Sharp (S-a)	0.73	0.56	0.69	0.68
Sharp (S-b)	0.68	0.82	0.65	0.83
Sharp (S-c)	-	-	-	-

3.2. Indoor Construction Activities PM Monitoring

To identify the critical construction activity among the primary activities, the authors monitor the environmental exposure from the concrete and mortar mixing. To identify the critical construction activity among the primary activities, the authors monitor the environmental exposure from the concrete and mortar mixing. In the first section, mortar mixing and the second section of concrete mixing are explained in detail.

3.2.1. Mortar Mixing (Cement and Sand Aggregates) PM Monitoring

The Alphasense OPC N2 sensor with a 2-s sampling rate recorded the peak value of PM₁₀ (36,385 µg/m³) at location b. According to Table 2, the total exposure of PM₁₀, PM_{2.5} and PM₁ during case I was 3522.62, 236.46 and 47.62 µg/m³, respectively, using a 5-min moving average (Equation (2)). After monitoring the PM during the entire activity and gauging it, we found that the results were alarming in that the PM exposure was often significantly higher than the levels set by the (WHO 2005) for both PM₁₀ and PM_{2.5}, with annual and daily average exposures of not more than 20 and 50 µg/m³ and 8 and 25 µg/m³, respectively.

Table 2. PM measurements using the Alphasense OPC N2 sensors for the mortar mixing activity.

Sensor	Activity	Number of Readings	PM ₁₀	PM _{2.5}	PM ₁
A-a	Mixing	1302	3700.45	251.49	51.61
A-b		1273	4760.33	264.52	47.09
A-c	Casting	967	2107.09	193.37	44.17
Average		-	3522.62	236.46	47.62

Note: all PM measurements are in µg/m³. The sampling time was 2 s.

During real-time monitoring with 2-s sampling times, the Sharp GP2Y1010AU0F sensors simultaneously reached saturation points. The PM₁₀ peak emission levels measured by the Sharp sensors at locations a and b were 394 µg/m³ and 355 µg/m³, respectively, after applying a moving average of 5 min, as shown in Figure 6a. Furthermore, using the Kanomax 3443 dust sensor as a reference, the mortar mixing operation was monitored for 11 min and a peak value of 490 µg/m³ was observed. During the experiment, the Sharp sensor at C (in the casting area) was damaged. Furthermore, the Sharp dust sensors, the Alphasense OPC N2 sensors were also used to monitor the PM emissions at locations a and b. The Alphasense OPC N2 reported a peak value of 14,098 µg/m³ for the dry mixing phase and remained above 2150 µg/m³ at the end of the finishing activity shown in Figure 6b. During mixing, the emission of PM₁₀ remained suspended in the work environment for around 8.2 min (PM₁₀ settling time) [51]. The PM₁₀ dust concentration levels monitored via the Sharp, Alphasense and Kanomax 3443 sensors were multiple times higher than the recommended levels by the WHO, NIOSH and the Health and Safety Commission (HSC). Most workers are unaware of dust exposure risks during indoor construction activities, and from our exposure data, we conclude that the level of dust concentration for this activity is higher than the recommended level set by the HSC for Portland cement (inhalable at 10 mg/m³ and respirable at 4 mg/m³) and silica (inhalable at 6 mg/m³ and respirable at 2.4 mg/m³) [52]. Exposure to PM is harmful to people conducting construction activities when it exceeds the recommended level.

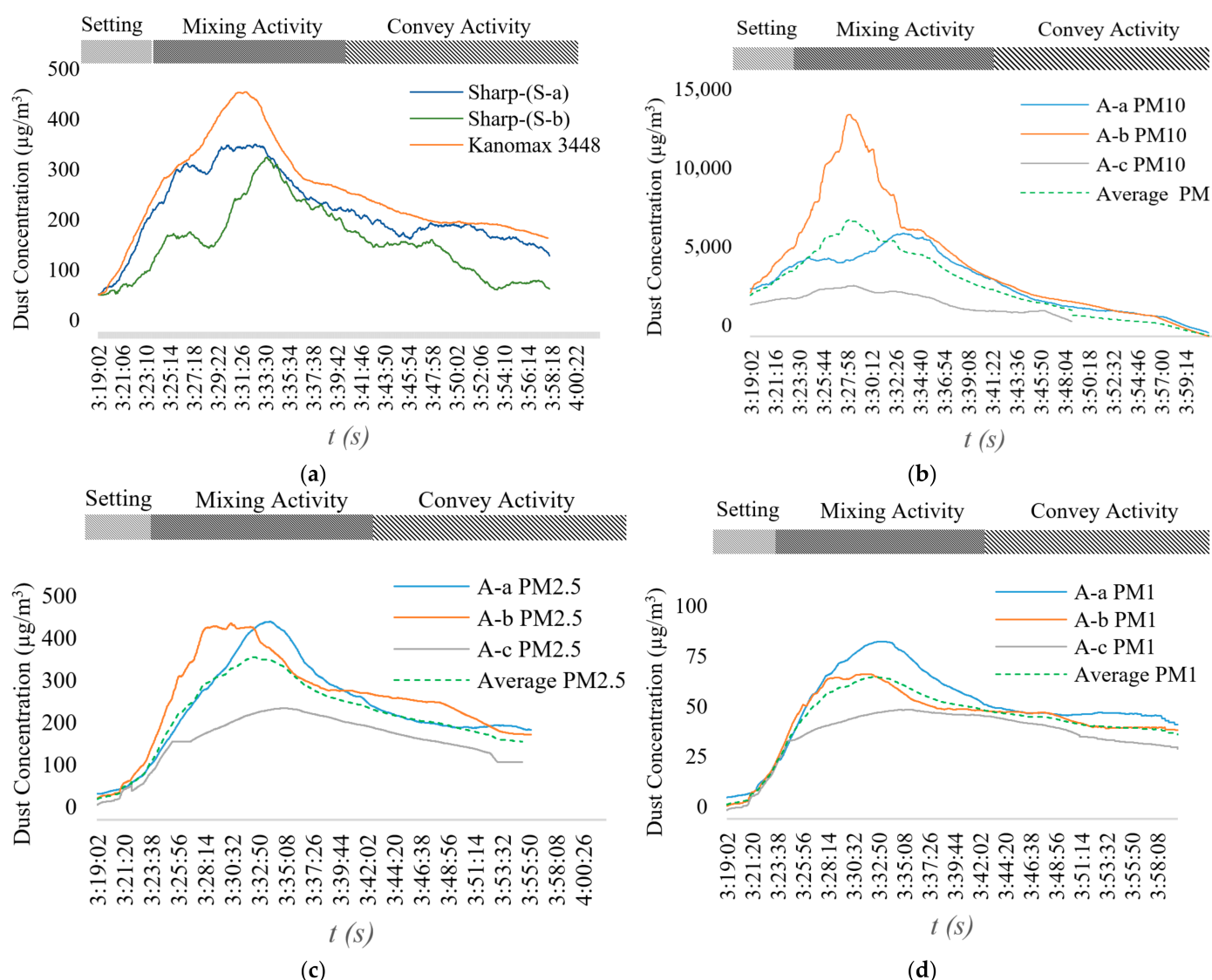


Figure 6. (a) Overall PM emission recorded by the Sharp and Kanomax dust sensors and (b) PM_{10} , (c) $\text{PM}_{2.5}$ and (d) PM_1 levels recorded by the Alphasense OPC N2 sensors for mortar mixing.

The Alphasense sensor showed high sensitivity toward $\text{PM}_{2.5}$ and PM_1 with recorded peak readings of 480 $\mu\text{g}/\text{m}^3$ and 88 $\mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$ and PM_1 , as shown in Figure 6c,d, respectively. Thereby highlighting hazardous exposure results indicate that the particles did not settle and float in the air, even after the activity had been completed. It took 12 h for $\text{PM}_{2.5}$ and PM_1 to settle fully (Baron 2010). At casting location c, the Sharp sensor did not function, whereas the Alphasense OPC N2 (A-c) measured the peak exposure levels of PM_{10} , $\text{PM}_{2.5}$ and PM_1 as 3100 $\mu\text{g}/\text{m}^3$, 280 $\mu\text{g}/\text{m}^3$ and 57 $\mu\text{g}/\text{m}^3$, respectively.

3.2.2. Concrete Mixing (Cement, Sand and Coarse Aggregates) PM Monitoring

As seen in Figure 7a, the Sharp sensors reading got saturated as the environmental exposure level exceeded the low-cost sensor's upper threshold value 500 g/m^3 . The recorded data were smoothed using a 5-min moving average. As seen in Figure 7b–d, the concentrations of PM_{10} , $\text{PM}_{2.5}$ and PM_1 were 19,857, 922 and 98 $\mu\text{g}/\text{m}^3$, respectively, while the estimated dose values for PM_{10} , $\text{PM}_{2.5}$ and PM_1 were 6762, 471.30 and 59.09 $\mu\text{g}/\text{m}^3$, respectively, as stated in Table 3.

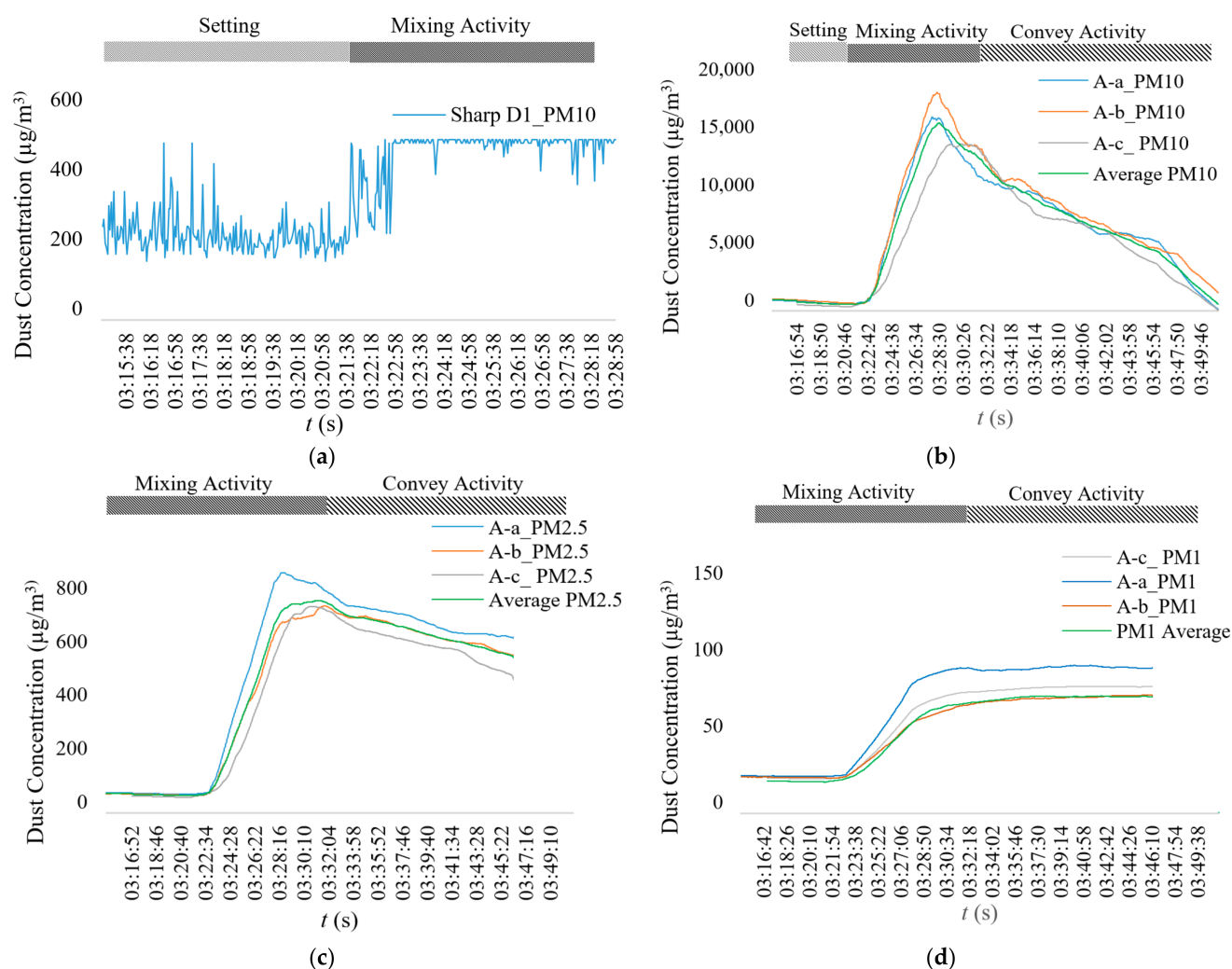


Figure 7. (a) PM emission levels recorded with the Sharp S-a sensor and (b) PM_{10} , (c) $PM_{2.5}$ and (d) PM_1 emission levels recorded with the Alphasense A-a, A-b and A-d sensors for concrete mixing.

Table 3. PM measurements using the Alphasense OPC N2 sensors for the concrete mixing activity.

Sensor	Number of Readings	PM_{10}	$PM_{2.5}$	PM_1
A-a	1094	6753.66	506.97	67.10
A-b	1141	7356.63	470.94	55.90
A-c	1091	6177.89	436.00	54.27
Average		6762.72	471.30	59.09

Note: all PM measurements are in $\mu\text{g}/\text{m}^3$. The sampling time was 2 s.

The authors mounted dust sensors at the mixing area to detect the dust at locations a, b and d because dust emission from the mixing activity was far higher than from the casting activity. During dust monitoring for the solid block wall operation, the Kanomax dust sensor with a $10,000 \mu\text{g}/\text{m}^3$ upper limit became saturated. As a result, we replaced it with an Alphasense OPC N2 (A-c) dust sensor to track the PM levels during construction.

Figure 7b illustrates PM_{10} emission measurements from three separate sensors (A-a, A-b and A-d); the results indicate that A-b measured the maximum peak value of $19,857 \mu\text{g}/\text{m}^3$ dust concentration level remained higher than $5000 \mu\text{g}/\text{m}^3$ after that. Figure 7c indicates that the peak $PM_{2.5}$ concentration for A-a was $922 \mu\text{g}/\text{m}^3$, which is 36.88 times higher than the WHO-recommended daily average $PM_{2.5}$ exposure standard. The maximum mild $PM_{2.5}$ exposure was $470 \mu\text{g}/\text{m}^3$, which is 18.8 times the WHO daily average exposure limit. The maximum mild $PM_{2.5}$ exposure was $470 \mu\text{g}/\text{m}^3$, 18.8 times the

WHO daily average exposure limit. Figure 7 shows that PM₁ particles remained suspended during the exercise (d). The peak value of 98 µg/m³ was observed during the activity, and the PM₁ level remained higher than 65 µg/m³ until the task was completed.

The reported PM levels from the concrete mixing operation were several times higher than WHO (WHO 2005), and HSC (HSC 2005) suggested air quality levels. The estimated PM₁₀ emission values for the concrete and mortar mixing activities were 6762.72 µg/m³ and 3522.62 µg/m³, respectively, and 471.30 µg/m³ and 236.46 µg/m³ for PM_{2.5}, respectively.

3.3. Hypothetical Case Assessment

The recorded dust readings were extended to actual construction activities using the Latin Hypercube Sampling method, for which the 1-day indoor building activity was accounted. To evaluate PM's environmental exposure to three hypothetical construction locations (assuming 100%, 85% and 55% environmental exposure for location 1, location 2 and location, respectively) assigned to the mortar and concrete aggregate mixing activities.

Usually, most construction workers work an 8-h day with 1.5 h break. The pilot test results were divided into dry and wet mixing, conveying and carrying out random activities (other than mixing and conveying). We used a ratio of 3:4:6 for periods of 84, 144 and 165 min, respectively, to apply the pilot test results to mimic the actual exposure at a real construction site. The upper and lower limits of the different PM environmental exposure limits were taken from the average exposure data reported in Table 4. These were used in Latin Hypercube Sampling to generate random values with different limits. MATLAB R2020b was used to run the Latin Hypercube Sampling script to create different PM random values in the defined threshold limit. During the analysis, it was assumed that location 1, location 2 and location 3 were exposed to 100%, 85% and 55% of the total exposure. As the pilot test was conducted without using control measures, a 70% reduction was applied to the calculated measurements [4] to visualize the dust level after applying control measures. Tables 5 and 6 report the different PM exposure levels for the mortar and concrete mixing activities, respectively. The results show that performing construction activities indoors without using control measures is extremely hazardous. In addition, the result collected from the Latin Hypercubic method emphasizes the same results as reported during the experiment construction mixing activities. The environmental exposure monitored from the concrete mixing is double in the volume of the mortar mixing for PM₁₀ and PM_{2.5}. Environmental PM exposure levels exceeded the defined safe limits by the WHO, IOSH and HSE with and without using control measures. Different control measures should be integrated together to control environmental dust emission and exposure from the construction activity while performing.

Table 4. Upper and lower PM exposure threshold values from the average PM exposure data.

Activity		Limit	PM ₁₀	PM _{2.5}	PM ₁
Concrete Mixing	Mixing	Upper	14,376.32	764.90	72.54
		Lower	343.93	64.25	20.22
	Conveyance	Upper	14,301.46	789.57	68.47
		Lower	4014.22	610.53	67.24
	Random Activities	Upper	2000.00	50.00	50.21
		Lower	0.00	0.00	0
Mortar Mixing	Mixing	Upper	9470.79	353.59	50.87
		Lower	3014.25	42.27	18.84
	Conveyance	Upper	6732.00	337.28	47.44
		Lower	2041.18	225.30	42.65
	Random Activities	Upper	2000.00	50.00	50
		Lower	0.00	0.00	0

Note: All measurements are in µg/m³.

Table 5. PM exposure levels generated by Latin Hypercube Sampling during the mortar construction activity for 1 day.

PM	Without Control Measures			With Control Measures (70% Reduction)		
	Location 1	Location 2	Location 3	Location 1	Location 2	Location 3
PM ₁₀	3250.65	2778.07	1787.86	975.20	833.42	536.36
PM _{2.5}	143.77	122.87	79.07	43.13	36.86	23.72
PM ₁	32.50	27.78	17.88	9.75	8.33	5.36

Note: All measurements are in $\mu\text{g}/\text{m}^3$.

Table 6. PM exposure levels generated by Latin Hypercube Sampling during the concrete construction activity for 1 day.

PM	Without Control Measures			With Control Measures (70% Reduction)		
	Worker 1	Worker 2	Masan	Worker 1	Worker 2	Location 3
PM ₁₀	4931.46	4214.52	2712.30	1479.44	1264.36	813.69
PM _{2.5}	322.42	275.55	177.33	96.73	82.67	53.20
PM ₁	32.50	27.78	17.88	9.75	8.33	5.36

Note: All measurements are in $\mu\text{g}/\text{m}^3$.

4. Discussion and Limitation

The outcomes of this comprehensive study show high levels of PM emission during the primary construction activities of concrete and mortar mixing. The concrete mixing is more critical from the reported data than the mortar mixing activity at the construction site. The sensor data and the Latin Hypercubic method emphasize that the concrete mixing activity contributes twice to the volume of the mortar mixing in the environmental exposure. The WHO's recommended allowable 24-h daily exposure to PM₁₀ and PM_{2.5} is 50 and 20 $\mu\text{g}/\text{m}^3$, respectively. The observed readings of these from the concrete and mortar mixing activities were higher than these within the short duration of the experiments. Each PM has a different settling time: PM₁₀ = 8 min, PM_{2.5} = 12 h and PM₁ = 48 h [51]. Therefore, relative to PM₁₀, the slopes of PM_{2.5} and PM₁ concentrations on graphs (environments) are not substantially reduced. The average PM_{2.5} and PM₁ concentrations were 471.30 and 59.09 $\mu\text{g}/\text{m}^3$ for concrete mixing and 236.46 and 47.62 $\mu\text{g}/\text{m}^3$ for mortar mixing. The execution of both mixing activities created considerable amounts of PM (PM_{2.5} and PM₁), which could affect construction workers' health. Even though the construction sector is a significant contributor to environmental exposure pollution, research on PM production and environmental exposure from construction activities is still infancy. From the results of this study, we conclude that low-cost dust sensors could play a vital role in PM environmental exposure monitoring depending on the activity, equipment and nature of the construction project, thereby making the construction workers aware of the health risks and their consequences due to the environmental exposure at the construction site. With the help of low-cost dust sensors, we can document and record environmental PM exposure from construction activities in real-time.

Based on the measured results, both PM₁₀ and PM_{2.5} environmental exposure dust levels from the concrete mixing activity were approximately twice as high as those from mortar mixing activity. For the concrete and mortar mixing activities, the PM₁₀ levels were 70 and 135 times higher, and the PM_{2.5} levels were 9.87 and 18.84 times higher, respectively, than the WHO 24-h average values, as shown in Table 7. According to Nij et al. [4], the volume of dust can be reduced by up to 70–80% of the total exposure using control measures (water suppression and LEV). However, after lowering the PM₁₀ exposure levels by 70% for concrete and mortar mixing using control measures, they were still 2061.81 $\mu\text{g}/\text{m}^3$ and 1600.43 $\mu\text{g}/\text{m}^3$, which are 41 and 32 times higher, respectively, than the average WHO 24-h exposure limit to PM₁₀ (50 $\mu\text{g}/\text{m}^3$), as shown in Figure 8a. Figure 8b shows the average exposure levels of PM_{2.5} for both construction mixing activities. The PM_{2.5} levels for concrete (485.87 $\mu\text{g}/\text{m}^3$) and mortar mixing (238.27 $\mu\text{g}/\text{m}^3$) were 19.43 and 9.53 times higher, respectively, WHO 24-h PM_{2.5} average exposure limits. When control measures

(70% reduction) were applied, the exposure levels were reduced by 5.67 and 2.99 times, respectively. According to Sazonova et al. [19], the MPCs for PM₁₀ and PM_{2.5} are 0.3 and 0.16 mg/m³, respectively, and using this metric, the average exposures in our study were 6.87 and 5.33 times higher, respectively.

Table 7. RCS and PM dust readings and exposure limits.

Reference	Construction Task	Level (µg/m³)	Exposure Limit	Comment
RCS				
[53]	Concrete Mixing	687.27	RCS = 0.10 PM ₁₀ level	RCS exposure is 10% of the PM ₁₀ level
	Mortar Mixing	533.47		
[2]	Concrete Mixing	343.24	RCS = 0.05 PM ₁₀ level	RCS exposure is 2.5–5% of the PM ₁₀ level
	Mortar Mixing	266.43		
	Concrete Mixing	171.62	RCS = 0.025 PM ₁₀ level	
	Mortar Mixing	133.21		
PM ₁₀ and PM _{2.5}				
[19]	Mortar Mixing	PM ₁₀ = 3522.62	PM ₁₀ = 0.3 mg/m³	PM ₁₀ dust exposure is 6.87 times
	Concrete Mixing	PM ₁₀ = 6762.72	PM _{2.5} = 0.16 mg/m³	PM _{2.5} dust exposure is 5.33 times
[20]	Mortar Mixing	PM _{2.5} = 236.46	PM ₁₀ = 50 µg/m³ PM _{2.5} = 25 µg/m³	PM ₁₀ dust exposure for the mortar and concrete mixing is 70 and 135 times higher, respectively.
	Concrete Mixing	PM _{2.5} = 471.30		PM _{2.5} dust exposure for the mortar and concrete mixing is 9.87 and 18.84 times higher, respectively.

According to Stacey et al. [53] and the Midwest Research Group [2], Respirable Crystalline Silica (RCS) exposure can be calculated as 10%, 5% or 2.5% of the overall mean PM₁₀ concentration. Table 7 displays the RCS exposure determined from the activity of the experimental construction. 10% of the total average exposure was 533.47 and 687.27 µg/m³ when mixing mortar and concrete, respectively, while for 2.5%, they were 171.62 and 133.21 µg/m³, and for 5%, they were 343.24 and 266.43 µg/m³, respectively. The region under the curve is higher than that of several countries' RCS exposure levels [54]. The results show that PM exposure is several times higher than the WHO, IOSH and HSC standards. Companies should pay attention to current and future building project requirements and work together to create a healthy working environment.

The scatter plot of measurements derived from Sharp and Kanomax sensors with PM₁₀ is shown in Figure 9. Linear regression model is fit on the two sensors. It has a slope of 0.76 and an intercept of 33.1. The R-squared co-efficient of determination value is also evaluated, which is the goodness-of-fit measure for linear regression model. The statistic score of 98% R-squared is obtained. It means low-cost sensor can do the same function as expensive PM monitoring sensors.

Despite the successful demonstration, a significant limitation related to the deployment of low-cost dust sensors was noticed during the indoor experiment (close area). At the end of the first experiment, the Kanomax and two Alphasense OPC N2 PM sensors malfunctioned, and while examining them, dust was found inside as well as on the sensor fan. Further, the experiment was conducted indoor (closed) environment without using control measures. As a result, a huge volume of dust was recorded by low-cost sensors. The PM sensor showed high correlation and precision; it can be deployed at the construction site to monitor the PM environmental exposure from the activities.

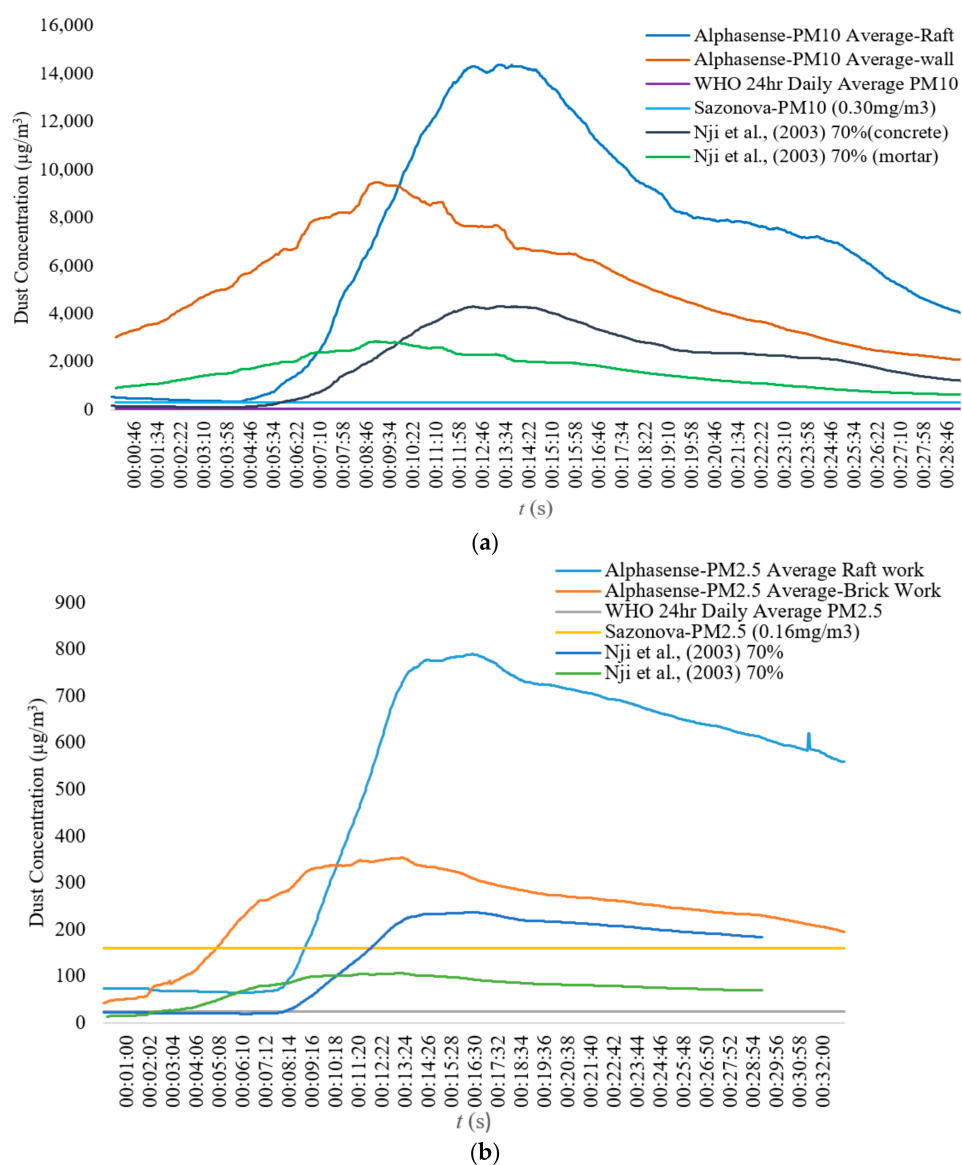


Figure 8. Plots of the average exposure levels of (a) PM₁₀ and (b) PM_{2.5}.

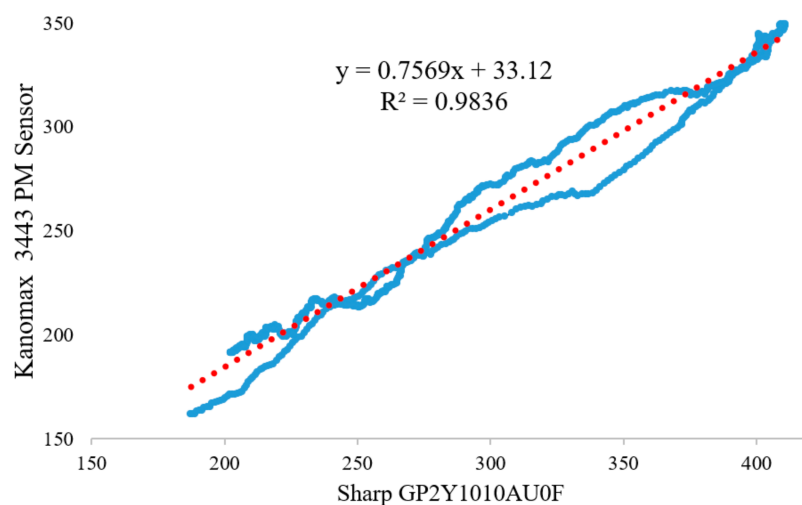


Figure 9. Describes the linear regression between Sharp and Kanomax sensor.

5. Conclusions and Future Outlook

Environmental PM exposure at construction is directly proportional to the doing of the activity. Dust generation is considered a by-product of the action; however, its monitoring is carried out manually. Its monitoring is not considered as high a priority as necessary. Thus far, few research studies have considered low-cost PM sensors to monitor the environmental PM exposure from construction activities. The results of this study will help the site manager plan activities so that workers are not exposed to the dangerous level of PM exposure. Workers will suffer from both short-term and long-term health problems due to exposure. Long-term health problems often take years to manifest symptoms. As a result, the company is facing an insurance burden. Diseases play a more important role in the entire cost of medical treatment and the poor health of what is commonly believed [55]. Therefore, the exposure of employees to particulate matter can be minimized by rescheduling activities and establishing appropriate site controls. In addition, this study helps to broaden the scope of environmental monitoring of PM exposure from primary construction activity to put some effort into it. The results revealed that low-cost PM sensors could be used to accurately monitor the PM level on the site; however, there are still several limitations that need to be addressed in the future in this study.

5.1. Conclusions

This research presented a categoric comparison of the pivotal activities such as concrete mixing and mortar mixing during physical construction to identify the critical activity that contributes to environmental pollution. The statistical data is collected using the low-cost PM sensor for the detection of critical activity, and the Latin Hypercube Sampling method is employed to predicate the results at the real construction site. The significant findings of the study are as follow:

- During the experiment, light scattering PM sensors showed a high correlation between the same sensors and benchmark.
- The PM concentration generated from the dry mortar mixing exceeded the optimal level of exposure: the average exposure levels of PM₁₀, PM_{2.5} and PM₁ were 3522.62, 236.46 and 47.62 µg/m³, respectively, while those for aggregate mixing of concrete were 6762.72 µg/m³, 471.30 and 59.09 µg/m³, respectively. The PM₁₀ and PM_{2.5} concentrations generated by the concrete mixing were twice those from mortar mixing by volume.
- A hypothetical case study was conducted to monitor the actual environmental PM exposure levels in a construction site. The environmental PM exposure levels calculates from the Latin Hypercubic method exceeded the WHO's defined threshold values for the 24-h average environmental exposure levels of PM₁₀ and PM_{2.5} by 70 and 9.87 times for mortar aggregate mixing and 135 and 18.84 times for concrete mixing, respectively. Likewise, the RCS exposure results for mortar and concrete mixing were twice and three times higher than the RCS permissible exposure threshold advised by the EPA.
- Deploying low-cost PM sensors without control measures utilization for indoor construction activity monitoring is not recommended.

Contemplating the outturn of this study, the authors are persuaded to recommend the low-cost dust sensors as a promising approach to detect the advised thresholds by health authorities. Motivated by the figures derived through the Latin Hypercube Sampling method, the authors are convinced that the proposed system could facilitate dust monitoring process using digital twin as an automated controlling technique.

5.2. Future Outlook

So far, no systematic approach has been adopted to monitor environmental dust exposure on construction sites. We will try and provide the criteria for a safe environment for construction site workers in future research. Therefore, we propose a platform on which IoT, real-time location solutions (RTLS) and building information modeling (BIM) technolo-

gies are integrated to provide a safe working environment for construction workers. To do this, we will develop a WSN consisting of low-cost dust sensors (Plantower PMS5003) and real-time position tracking sensors that can be embedded into a safety helmet. In such a way, exposure to various dangerous substances can be measured accurately in real-time by using communication sensors to transmit the data from the slave node to the master node. Furthermore, the system would be connected to control measures equipment. As Environmental exposure PM's level exceeds the allowable exposure limit, the specific control measures will automatically turn on and lower the PM level in the working ambience. It is necessary to monitor the exact amount of dust emitted during a specific activity using low-cost dust sensors to develop dust inventory. The system can also inform the site manager and government officials about the dust level exposure at the PM concentration job site. This research work will be incorporated into BIM 4D for real-time visualization of dust levels on construction sites to pave the way toward digital monitoring. Such a system can help modify construction processes to minimize the environmental PM exposure levels of the workers. The proposed research outcomes would help to decrease the environmental exposure impact on health issues and reduce the insurance burden on an organization. Our fully featured system will help to predict dust levels early in the design phase.

Author Contributions: M.K. conducted the experiments, collected, analyzed the data, wrote the original draft and devised the methodology. N.K. conceptualized the study, devised the methodology and conducted the experiments. M.J.S. reviewed and edited the manuscript. C.P. reviewed and edited the manuscript, supervised the study and acquired the funding. All authors have read and agreed to the published version of the manuscript.

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