DUST EMISSIONS FROM 3D PRINTING OF CONCRETE

An Undergraduate Research Scholars Thesis

by

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RESEARCH COMPLIANCE CERTIFICATION

Research activities involving the use of human subjects, vertebrate animals, and/or biohazards must be reviewed and approved by the appropriate Texas A&M University regulatory research committee (i.e., IRB, IACUC, IBC) before the activity can commence. This requirement applies to activities conducted at Texas A&M and to activities conducted at non-Texas A&M facilities or institutions. In both cases, students are responsible for working with the relevant Texas A&M research compliance program to ensure and document that all Texas A&M compliance obligations are met before the study begins.

We, Mehtab Ellahi, Ahmad Hammoud, Nathan Braganza, and Mohammad Shaaban, certify that all research compliance requirements related to this Undergraduate Research Scholars thesis have been addressed with our Faculty Research Advisors prior to the collection of any data used in this final thesis submission.

This project did not require approval from the Texas A&M University Research Compliance & Biosafety office.

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ABSTRACT

Dust Emission From 3D Printing Of Concrete

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The process of 3D printing concrete is a relatively new concept compared to traditional manufacturing and even novel techniques such as 3D printing using plastics and metal. A general concern in the construction industry is that of dust emissions during the process of mixing and applying concrete to workers in the vicinity. The study aimed to evaluate the critical stages of the 3D-printing of concrete process that led to dust emissions. PM2.5 concentrations were measured during the mixing, pumping, and printing stages of the process for both small-scale and large-scale printing. The study found that the mixing stage was the most critical stage and the maximum concentration of PM2.5 reached during this stage was 1600 µg/m^3 and 33000 µg/m^3 for the small-scale printer and the large-scale printer respectively. The pumping and the printing stage showed the lowest concentrations of 92 µg/$m^3$and 143 µg/m^3 for small-scale and large-scale printers respectively. The study suggests that adequate safety measures need to be

implemented to protect workers and reduce the environmental impact during all stages of both small and large-scale printers as the measurements recorded in the laboratories were above 28 μg/m^3, the allowable standard value of PM2.5 concentrations over a 24-hour period set by CAAQS. The findings of this study offer crucial insights into the health risks associated with the 3D-printing of concrete, highlighting the importance of taking appropriate safety measures to safeguard the well-being of workers and the environment.

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The data of the dust emissions was obtained by the 3D printing of geopolymer concrete experiment carried out under Mr. Yousef Mortada and our student team carried out the data collection of the experiment.

All other work conducted for the thesis was completed by our team.

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NOMENCLATURE

ASTM	American Society for Testing and Materials
TAMUQ	Texas A&M University at Qatar
3D	3 Dimensional
PM	Particulate Matter
PPE	Personal Protective Equipment
LEV	Local Exhaust Ventilation
CAAQS	Canadian Ambient Air Quality Standards

1. INTRODUCTION

Air pollution has evolved into a severe global environmental problem [1]. Air pollution has been linked to being the source of numerous respiratory diseases. When inhaled, particulate matter can lead to several respiratory diseases and be the direct cause of premature deaths [2]. The construction sector is one of most countries' most prominent contributors to air pollution [3]. Moreover, the construction sector is labor based, requiring workers to work alongside many dust sources. In addition, several construction activities, like cement-mixing, could generate ample amounts of dust during the construction stage [3] [4]. These produced dust particles contaminate the environment that surrounds the construction site [5], which endangers the health of construction workers [6][7]. Various researchers have concluded that the type of work in construction sites could lead to an increased risk of cardiovascular, respiratory, and skin diseases [8] [9]. Thus, the adverse effects of construction sites on workers' health have grabbed the attention of the entirety of the construction sector and the academic sector.

Various researchers researched the impact of particulate matter on the health of workers [3] [11] [12] [13]. The three related research interests are health impact assessment, dust monitoring, and dust control and prevention. Some researchers did the first area regarding the health impact analysis by collecting medical data for several years to confirm the negative impact of construction dust on construction workers. Bergdahl et al. [11] followed the lives of 317,629 construction workers for 28 years to find the relation between mortality due to chronic obstructive pulmonary disease (COPD) and exposure to construction dust. Bergdahl et al. [11] showed an increased risk of mortality due to COPD among workers exposed to construction dust. In general, the conclusions from many researchers related to the health impact were that construction dust severely endangers the health of construction workers. [11][12][14].

One method used to provide accurate monitoring results was the up-down wind direction method which eliminates the background interference and reveals the absolute values of incremental dust concentrations in construction sites [5] [15] [17]. In addition, during the process of dust monitoring, researchers found that some environmental factors like wind speed [18], humidity [19], and temperature [20] affect the accuracy of the dust measuring sensors. Furthermore, researchers found that the type of construction activity affects the dust concentrations [3] [4] [5] [15]. Li et al. [3] found that cement mixing, concrete breaking, and manual demolition are the top three inhalable exposures. Researchers also investigated the chemical composition of dust in construction sites [16] [21] and the diffusion law for dust in construction sites [15] [17].

Regarding dust monitoring equipment, numerous modern-day devices like sensors, especially wireless sensor networks (WSN), have been applied to monitor dust particles. Air quality stations have also been applied to collect dust concentration data; however, such stations have limitations regarding size, cost, and power requirements [22]. To overcome such limitations, researchers applied different low-cost sensors and WSNs to measure and monitor dust concentrations on construction sites. One research suggested that air quality monitors could also be replaced with low-cost sensors because of their ease of use [23]. Another research utilized low-cost, Sharp, and Alphasense sensors to measure and monitor particulate matter, and the results showcased the excellent performance of these sensors during the monitoring process [24].

While recent technology of the 3D printing of buildings using various build materials like geopolymers have been researched to reduce setting time and improving strength, the dust emissions and health risk associated from the entire process have been merely addressed in the available research. The conventional concrete production has dust as one of the primary airborne pollutants formed but recently 3D printing of buildings have been introduced using various build materials. 3D printing in construction using various build materials is actively being researched to achieve higher strength, faster setting time and better layer cohesion of the material. This particular research focuses on geopolymer mix composed by TAMUQ and CyBe team used for 3D printing. Even though using these materials can potentially improve the concrete properties, it is unknown about the concentrations of dust produced during the different activities of making the structure. Therefore, our research targeted to measure PM 2.5 concentrations produced during the mixing, pumping and printing stage of the 3D printing process. PM2.5 refers to particular matter less than or equal to 2.5 micrometers in diameter and can pose health risks when inhaled. Once PM2.5 data is collected our goal would be to compare the measurements with the air safety standards set by Canadian Ambient Air Quality Standards (CAAQS).

Engineering controls and administrative controls are two strategies that can be used to reduce exposure to PM2.5 on construction sites. Engineering controls involve modifying the construction site or equipment. Administrative controls involve implementing policies and procedures to modify work practices, schedules, and training to reduce exposure to PM2.5. These controls can complement engineering controls and personal protective equipment to provide a comprehensive approach to reducing exposure to PM2.5. However, challenges associated with implementing these controls include cost, variability of construction activities, and the need for proper maintenance and monitoring.

1.1 Engineering Controls to Reduce PM2.5 Concentrations

Engineering controls can be divided into two main categories: source control and exposure control. Source control measures aim to reduce the amount of PM2.5 generated at the source, while exposure control measures aim to reduce the amount of PM2.5 that workers are exposed to.

1.1.1 Source Control Measures

Source control measures are designed to reduce the amount of PM2.5 generated at the source. One effective strategy is the use of water sprays to control dust during activities such as cutting and grinding. Water sprays can be applied using a variety of methods such as fixed or mobile sprayers, and misting systems. The water droplets collide with the PM2.5 particles and cause them to settle, reducing their concentration in the air. This approach is particularly effective when paired with appropriate ventilation systems to capture the airborne particles [25].

Another effective source control measure is the use of local exhaust ventilation (LEV) systems to capture and remove PM2.5 at the source. LEV systems are particularly effective when cutting, drilling, or grinding materials such as concrete, which are known to produce high levels of PM2.5. The LEV system works by creating negative pressure at the source of the PM2.5 emissions, drawing the particles into the system where they are filtered before being released back into the environment. LEV systems can be integrated into tools and machinery, such as grinders and saws, or can be standalone systems [26].

1.1.2 Exposure Control Measures

Exposure control measures are designed to reduce the amount of PM2.5 that workers are exposed to. One effective exposure control measure is the use of general ventilation systems to dilute the concentration of PM2.5 in the air. General ventilation systems use fans to circulate air throughout the work area, reducing the concentration of PM2.5. These systems are most effective when the air exchange rate is high, and the air is filtered before being recirculated [27].

Another effective exposure control measure is the use of barrier enclosures to prevent PM2.5 from spreading to other areas of the construction site. Barrier enclosures are commonly used in construction activities such as sandblasting, painting, and concrete cutting. The enclosures are designed to contain the PM2.5 generated during these activities, preventing it from spreading to other areas of the construction site. The enclosures are typically made of plastic or other materials and can be custom-fitted to the specific activity [28].

Finally, administrative controls can also be used as exposure control measures. Administrative controls involve changes in work practices and policies to reduce exposure to PM2.5. For example, limiting the duration and frequency of activities that generate PM2.5, such as cutting or grinding, can significantly reduce exposure. Limiting the number of workers performing tasks that generate PM2.5 can also reduce exposure. Additionally, rotating workers between tasks can minimize exposure and reduce worker fatigue, which can improve productivity [29].

1.1.3 Challenges with Engineering Controls

Despite the effectiveness of engineering controls, there are several challenges associated with their implementation. One challenge is the cost of implementing these controls. Some controls, such as LEV systems and general ventilation systems, can be expensive to install and maintain. Additionally, the installation of these controls can disrupt work activities, leading to project delays and increased costs [27,28].

Another challenge is the variability of construction activities. Different activities generate different amounts of PM2.5, and the effectiveness of control measures can vary depending on the activity. For example, water sprays may be effective at controlling dust during cutting and grinding activities but may not be effective during demolition activities. Similarly, LEV systems may be effective at capturing dust during drilling or sawing activities but may not be effective during activities that generate larger particles, such as breaking concrete with a jackhammer [27,28].

Another challenge is the need for proper maintenance and monitoring of these controls. If not properly maintained, these controls can become less effective over time, reducing their ability to control PM2.5 concentrations. Additionally, monitoring is required to ensure that the controls are working properly and that the concentration of PM2.5 is being effectively reduced. Regular monitoring can also help identify areas where control measures may need to be adjusted or improved [27,28,29].

1.2 Administrative Controls

Administrative controls are an important aspect of reducing worker exposure to PM2.5 on construction sites. These controls involve implementing policies and procedures to modify work practices, schedules, and training to reduce exposure to PM2.5. Administrative controls can complement engineering controls and personal protective equipment to provide a comprehensive approach to reducing exposure to PM2.5 [25,26].

1.2.1 Work Practices and Procedures

Work practices and procedures can be implemented to reduce the generation and release of PM2.5. For example, wet methods can be used to control dust generated during cutting, drilling, or grinding operations. These methods involve adding water to the work surface or tool to prevent the dust from becoming airborne. Similarly, work procedures can be modified to minimize the use of tools that generate large amounts of PM2.5 or to use tools that are equipped with dust collection systems [25,26].

1.2.2 Scheduling

Scheduling can also be used as an administrative control to reduce exposure to PM2.5. For example, construction activities that generate high levels of PM2.5 can be scheduled during times when fewer workers are present or when the public is less likely to be exposed. Additionally, workers can be scheduled to work in areas with lower concentrations of PM2.5 when possible [26,28].

1.2.3 Training

Proper training is critical to ensure that workers understand the hazards associated with exposure to PM2.5 and the measures that can be taken to reduce exposure. Workers should be trained on the use of personal protective equipment, such as respirators, as well as the use of engineering controls and work practices to minimize exposure to PM2.5. Training should also include information on the health effects associated with exposure to PM2.5 and the importance of reporting any symptoms or concerns to their employer [26,28].

1.2.4 Communication

Effective communication is another important aspect of administrative controls. Workers should be informed of any changes in work practices or schedules that may affect their exposure to PM2.5. Communication can also be used to identify areas where exposure to PM2.5 may be higher than expected, allowing for the implementation of additional control measures [26,28].

1.2.5 Challenges

The effectiveness of administrative controls can be influenced by a number of factors. One challenge is the need for consistent implementation of these controls. Failure to consistently implement administrative controls can result in increased exposure to PM2.5 and an increased risk of health effects. Additionally, the effectiveness of administrative controls can be influenced by worker behavior. Workers may not follow established work practices or may not use personal protective equipment correctly, reducing the effectiveness of these controls [26,28].

Another challenge is the need for ongoing evaluation and modification of administrative controls. As construction activities change or new tools and equipment are introduced, administrative controls may need to be modified to remain effective. Additionally, ongoing monitoring is needed to ensure that administrative controls are being implemented consistently and effectively [26,28].

1.3 Personal Protective Equipment (PPE)

Personal protective equipment (PPE) is a critical aspect of protecting workers from exposure to PM2.5 on construction sites. PPE includes equipment worn to protect the eyes, face, lungs, and skin from exposure to PM2.5. The use of PPE can be an effective means of reducing exposure to PM2.5 when engineering controls and administrative controls are not feasible or effective [29-33].

1.3.1 Respirators

Respirators are the most common type of PPE used to protect workers from exposure to PM2.5. Respirators work by filtering out PM2.5 particles from the air before they are breathed in. There are two main types of respirators: air-purifying respirators (APRs) and supplied-air respirators (SARs). APRs use filters to remove PM2.5 particles from the air, while SARs supply clean air to the user from an external source [29-33].

1.3.2 Selection and Fit

Selection of appropriate respirators is critical to ensure that workers are adequately protected from exposure to PM2.5. The selection of respirators should be based on the concentration of PM2.5 in the air and the duration of exposure. Respirators should be tested to ensure that they provide adequate protection against the specific type and concentration of PM2.5 in the workplace. Additionally, respirators should be properly fitted to ensure that they provide a tight seal around the user's face [29-33].

1.3.3 Maintenance

Proper maintenance of respirators is critical to ensure that they continue to provide adequate protection against exposure to PM2.5. Respirators should be cleaned and inspected regularly to ensure that they are functioning properly. Filters should be replaced regularly, and respirators should be stored in a clean, dry location when not in use [29-33].

1.3.4 Eye and Face Protection

Eye and face protection can be used to protect workers from exposure to PM2.5 particles that may irritate or damage the eyes. Eye and face protection can include safety glasses, goggles, and face shields. Selection of appropriate eye and face protection should be based on the specific hazards present in the workplace [29-33].

1.3.5 Skin Protection

Workers can be exposed to PM2.5 particles through contact with the skin. Protective clothing, such as coveralls and gloves, can be used to protect workers from exposure to PM2.5

particles. Selection of appropriate protective clothing should be based on the specific hazards present in the workplace [29-33].

1.3.6 Challenges

The effectiveness of PPE can be influenced by a number of factors. One challenge is the need for proper selection and fit of respirators. Improperly fitted respirators may not provide adequate protection against exposure to PM2.5, resulting in increased risk of health effects. Additionally, the use of PPE can be uncomfortable and may restrict movement, reducing worker productivity [29-33].

Another challenge is the need for proper maintenance of PPE. Failure to properly maintain PPE can result in reduced effectiveness and increased risk of exposure to PM2.5. Additionally, workers may not use PPE correctly or may not use it consistently, reducing the effectiveness of these controls [29-33].

2. METHODS

The methods section describes the equipment and procedures used to conduct the experiment on monitoring dust emissions during the 3D printing of concrete. The section starts by explaining the apparatus which was used to collect data on weather conditions and PM2.5 concentration in the air during the printing process. The procedure section then describes the steps taken to prepare the site, set up the equipment, collect the data, and then analyze the data. This involved selecting a location for the aerosol monitor, positioning the weather monitoring instrument, and zeroing the aerosol monitor before conducting the measurements. Next, the methods used to collect data during the mixing, pumping, and printing process were reported. Lastly, the analyses section explains the methods used to analyze the PM2.5 concentrations recorded during the small-scale and large-scale 3D printing of concrete. Overall, the following methods section provides a detailed account of the equipment and procedures used to conduct the experiment, allowing for the replication of the study.

2.1 Apparatus

2.1.1 Weather Monitoring Station

The weather monitoring station is a device used to collect data on various weather conditions such as wind speed and direction, temperature, humidity, and barometric pressure. These data are essential in understanding how weather conditions may be impacting the dust emissions during the mixing and printing process.

The specific type of weather station used may vary depending on the experiment requirements, but it typically includes sensors for measuring temperature, humidity, wind speed and direction, and barometric pressure. The sensors are connected to a data logger that records and stores the data at regular intervals. The data can then be downloaded and analyzed using specialized software.

In this study, the weather station was used to monitor relative humidity and the temperature during the mixing, pumping and printing of the concrete. This information can help to understand how weather conditions affect the dust emissions during the printing process.

2.1.2 DustTrak II

The DustTrak II is an aerosol monitor that measures the concentration of particulate matter in the air. It uses a light scattering method to measure the amount of light that is scattered by particles in the air. The instrument works by drawing air into a sample chamber, where the particles in the air pass through a laser beam. The light from the laser beam is scattered by the particles, and the amount of light that is scattered is measured by a photodetector. The amount of light that is scattered is proportional to the concentration of particles in the air.

The DustTrak II can measure particles in the size range of 0.001 to 100 micrometers, and it can measure particulate matter with an aerodynamic diameter of 10 micrometers or less (PM10) and 2.5 micrometers or less (PM2.5).

The DustTrak II has a range of features that make it useful for monitoring dust emissions during 3D printing of concrete, such as its ability to provide real-time data, its portability, and its durability. The instrument can be used in a variety of environments, including construction sites, manufacturing plants, and laboratories. In this study, DustTrack II is used to measure the PM 2.5 dust concentrations during the 3D printing of concrete for both the large- and small-scale printers.

2.2 Procedure

2.2.1 Site Preparation

Before conducting the measurement, it is important to properly prepare the site where the concrete mixing and printing will take place. The DustTrak II instrument was placed at a location that will provide a representative sample of the air within the area of interest. The DustTrak II was secured to ensure the instrument was protected from any potential damage during the experiment. The selected location was stable, free of wind, and was not exposed to any other dust or particulate matter sources.

2.2.2 Positioning of Weather Monitoring Station

The weather monitoring station placed in the area collected the temperature and relative humidity data of the interested environment. This data can be used to understand how weather conditions may be impacting the dust emissions during the mixing and printing process.

2.2.3 Zeroing of Aerosol Monitor

The DustTrak II instrument was zeroed according to the manufacturer's instructions prior to conducting the measurement. This involved attaching a zeroing filter to the instrument and selecting the zeroing option in the run mode feature of the instrument. The instrument then draws air for 60 seconds through the attached filter which read 0 for the concentrations. The instrument had to be zeroed before each measurement session. Once the instrument is zeroed it was positioned close to the weather station and the experimental site.

2.2.4 Data Collection

After the setup was completed the mixing of the concrete began and the DustTrak II continuously measured the concentration of PM2.5 until the printing process was completed. The data collected by the DustTrak II was recorded in a manner that allows for easy analysis, such as a spreadsheet or database. The data was recorded at regular intervals of 10 seconds to capture the variations in the dust emissions during the mixing and printing process. Both the small-scale and large-scale printing were conducted for 20 minutes, where the small-scale experiment involved measuring concentrations only at one location between the mixer and the printer, while the large-scale involved measuring concentrations at three different locations during the entire printing process.

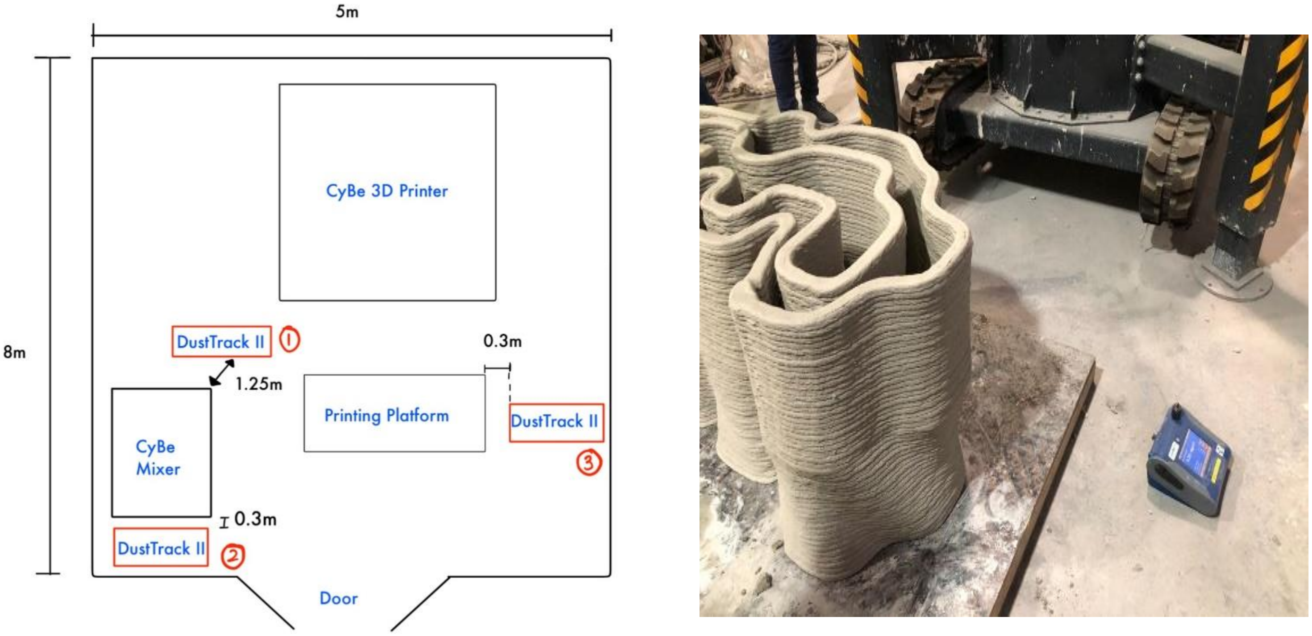

Figure 1: Schematic of large-scale test (DustTrak II at 1.2m elevation at 1 &2, DustTrak II at ground at 3)

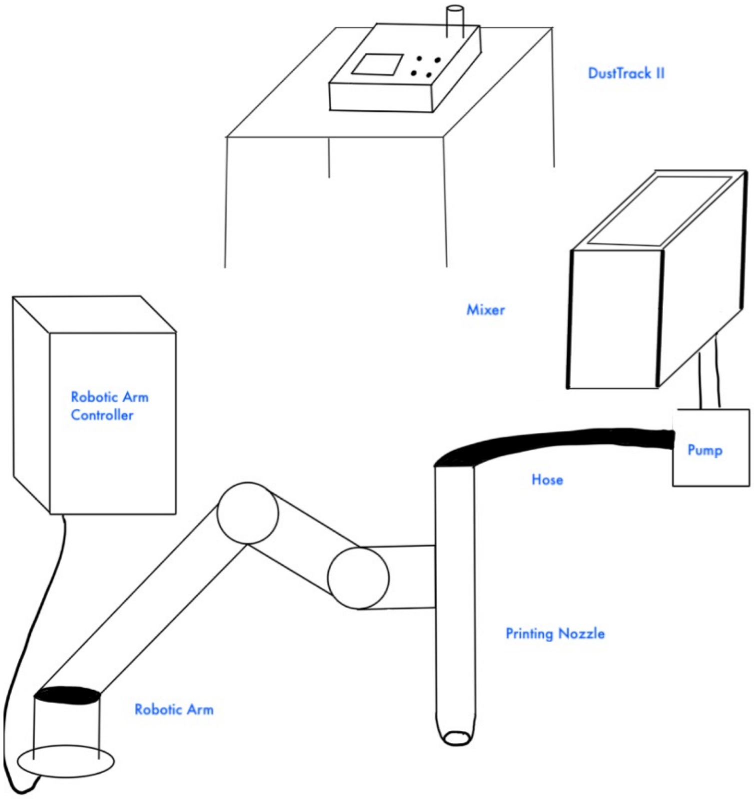

Figure 2: Schematic of the small-scale test (DustTrak II at 1.2m at elevation)

2.2.5 Analysis

The data collected by the DustTrak II and weather monitoring station was analyzed to determine the PM2.5 concentrations, during the mixing, pumping and printing of the concrete. This data was used to assess the potential health risks associated with exposure to dust emissions during the 3D printing of concrete. Average concentration values for both the small and large-scale runs were reported. Then the data was compared with the allowable standard value of PM2.5 concentrations set by CAAQS to identify if it’s safe for workers to be in the concrete 3D printing environment. Next relevant solutions were reported according to the PM2.5 concentrations determined in the experiments.

3. RESULTS

3.1 PM2.5 Concentrations at Critical Stages of 3D-Printing of Concrete

The small-scale measurements were conducted with the objective of evaluating the critical stages of the 3D-printing of concrete process. However before conducting the experiment background dust concentrations had to be carried out that determined the amount of dust concentrations present in air before the 3D printing took place. Figure 3 below showcases the PM2.5 concentrations in the environment before 3D printing of concrete took place.

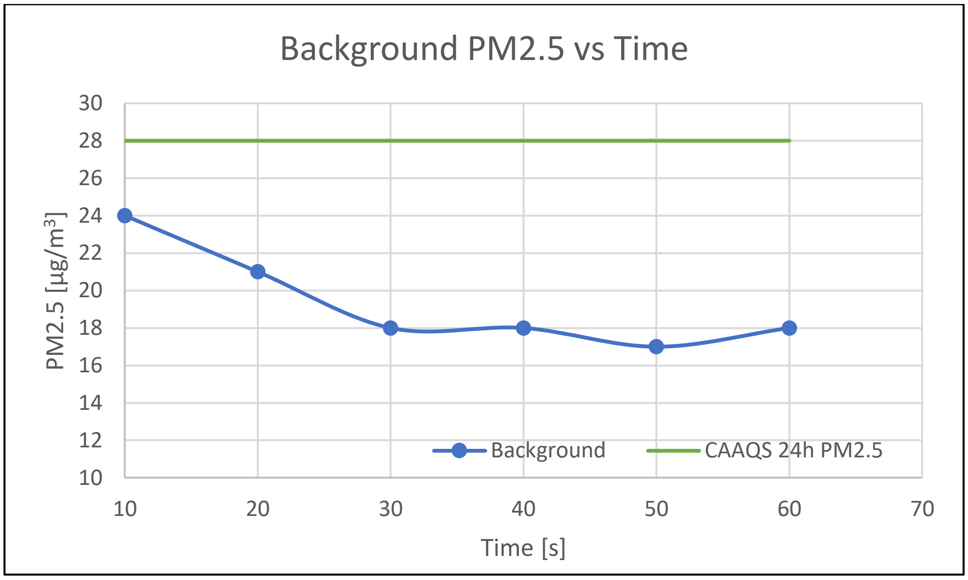

Figure 3: Background PM2.5 concentrations before 3D printing of concrete

The test was conducted for one minute and the results above show that for the same environment as the experimental environment, the PM 2.5 concentration were below the maximum allowable value according to the CAAQS 24 hours standard. This was made possible as the laboratory was connected with the TAMUQ ventilation system ensuring the air quality in the laboratory met the acceptable standard. This confirms that the experiment was conducted in a clean environment and that air quality due to dust concentrations before the experiment had little to no impact on the PM 2.5 concentration measurements during the small-scale experiment.

Figure 4 below showcases the PM2.5 concentrations of the small-scale experiment as a function of time. The process involves several stages, including mixing, pumping, and printing. The mixing, pumping, and printing stages were identified as critical stages due to the potential for significant particle emissions during these stages.

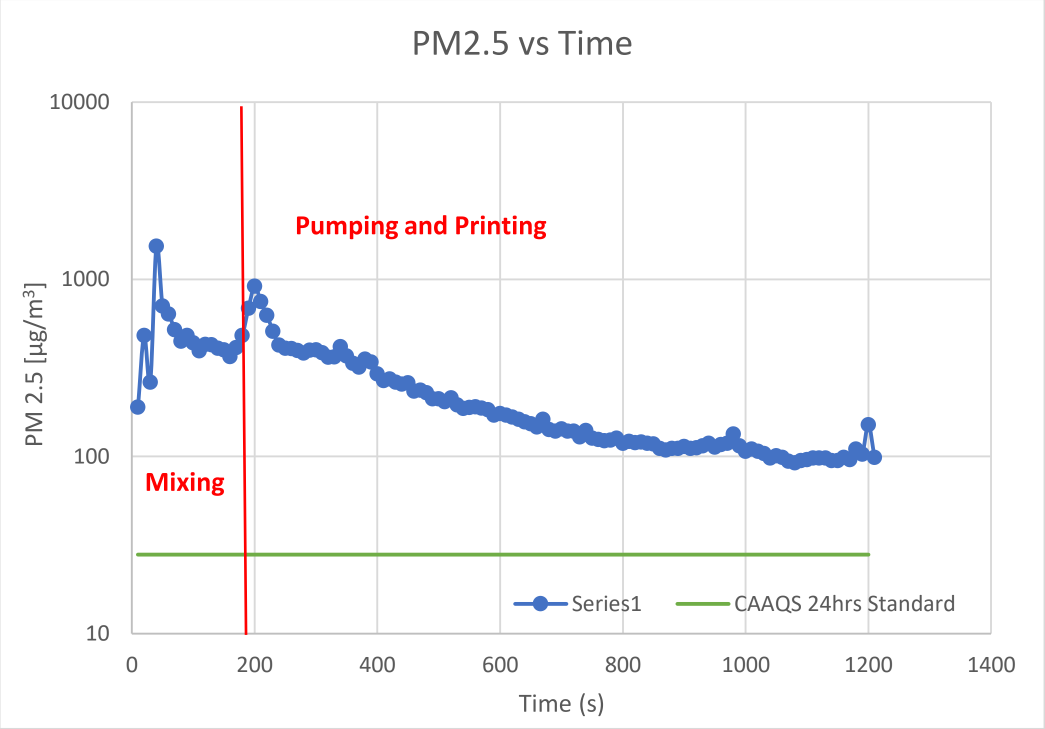

Figure 4: PM 2.5 measured as a function of time for the small-scale printer.

During the mixing stage of the concrete material, the first peak in the concentration of PM2.5 particles was observed, with a measured concentration of 1600 µg/m^3. This peak was relatively high and indicates a potentially significant level of particle emissions during this stage. It is important to note that particle emissions during the mixing stage can occur due to the use of powders, which can become airborne during the mixing process. These emissions can pose a health risk to workers in the vicinity and can also affect the surrounding environment. Therefore, understanding the concentration and distribution of airborne particles during the mixing stage is important for ensuring worker safety and mitigating environmental impact

The second peak in the concentration of PM2.5 particles was observed during the pumping stage of the process, with a concentration of approximately 900 µg/m^3. Although this peak was lower than the first peak during the mixing stage, it still indicates a potentially significant level of particle emissions during this stage. After the pumping had started the concentration of PM2.5 particles started decreasing slightly during the printing stage where the lowest concentrations recorded was 92 µg/m^3. This suggests that the printing stage may produce fewer particle emissions than the mixing and pumping stages.

Temperature and relative humidity are important parameters to consider when measuring dust concentrations in indoor environments. This is because temperature and relative humidity can influence the behavior of dust particles in the air, as well as affect the health and comfort of building occupants. For example, excessively high temperatures and humidity levels can promote the growth of mold and other allergens, which can release spores that contribute to airborne dust, while excessively low temperatures and humidity levels can cause dryness and respiratory irritation.

The recommended temperature and relative humidity range for the indoor environments is 20°C - 24°C and 30-60% respectively. These ranges are considered to have the least to no impact on the dust concentration measurements. The small-scale temperature and relative humidity were measured during the dust concentrations measurement and are reported below in figure 4.

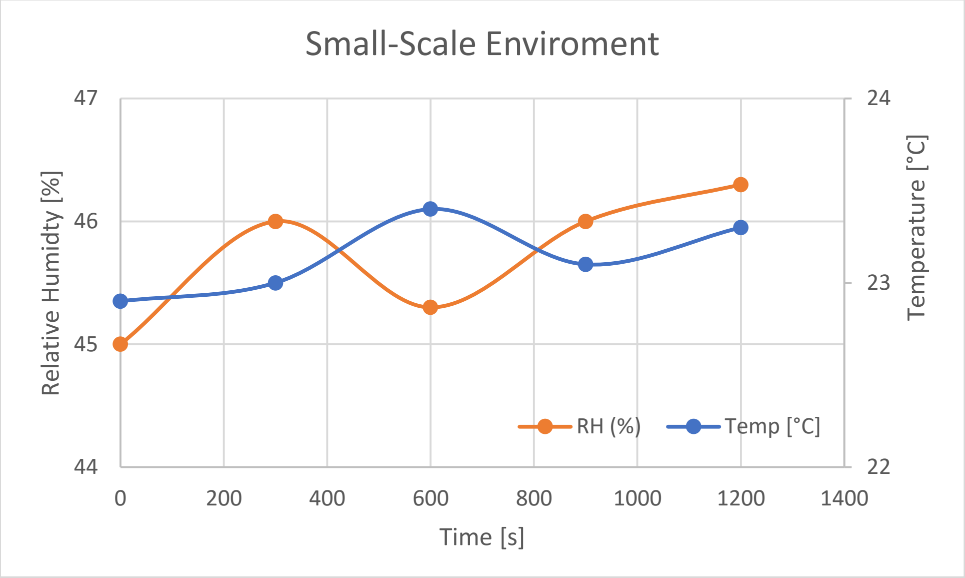

Figure 5: Small-scale experiment temperature and relative humidity

Figure 5 showcases that the temperature fluctuates around 23°C while the relative humidity fluctuates between 45% - 46%. The average of both the temperature and relative humidity was within the recommended range, which confirms that the dust concentration measurements were not impacted by the environment’s temperature and relative humidity.

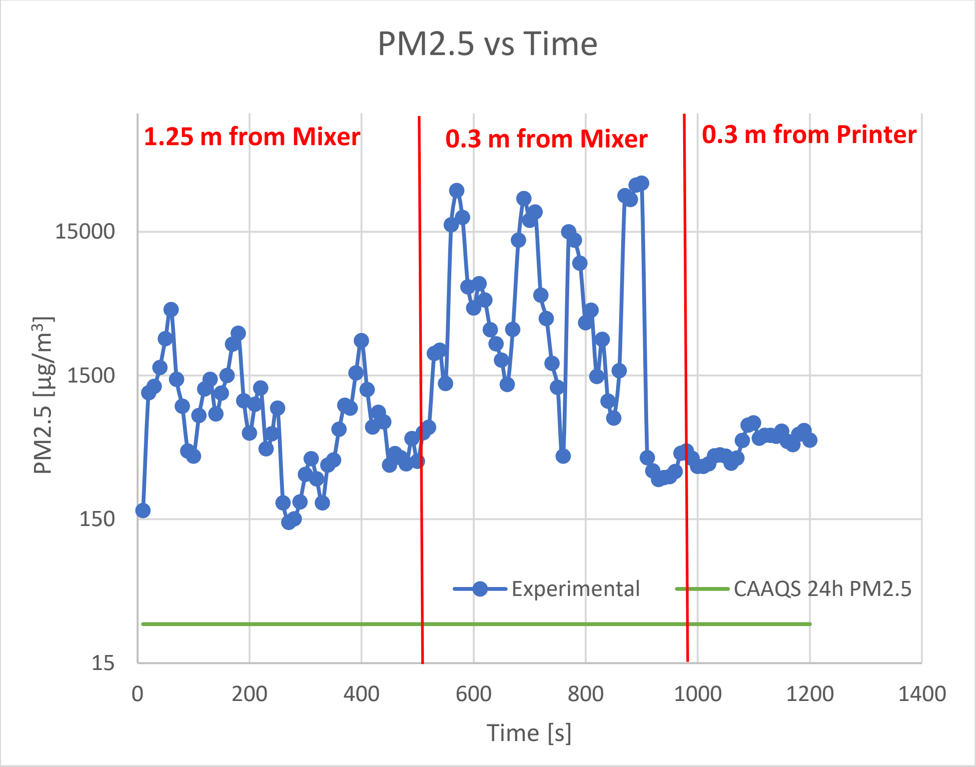

Figure 6: PM 2.5 concentration as a function of time for the large-scale printer

In order to further evaluate the critical stages of printing for small-scale printing, an emissions sensor was employed to capture the amount of emissions at each of the critical locations and stages. The test run was designed to mimic the large-scale printing of concrete process as closely as possible. To achieve this, the test run was divided into three-time stages where the sensor was moved around the laboratory to capture data from different locations. The first 500 seconds of the test run, the sensor was placed between the robotic arm and the mixer. In the subsequent 500 seconds, the sensor was placed next to the mixer, and in the remaining time, the sensor was placed next to the printer's nozzle. The data captured from each location and stage was analyzed to better understand the level and distribution of airborne particle emissions.

Figure 6, showcases the test run conducted, and the variation of the concentration of PM2.5 as a function of time. The data revealed that the concentrations 1.25 meters away from the mixer were relatively low, with the maximum concentration of PM2.5 reaching around 5000 µg/m^3. This is because this location is relatively away from the main source of emissions, which is the mixer. However, once the sensor was placed next to the mixer (0.3 m), multiple large peaks were noticed in the concentration of PM2.5. As the large-scale printer involves a continuous mixing process, where bags of material have to be added continuously into the mixer, each time a new bag of material was added the concentration of PM2.5 spiked. The maximum concentration of PM2.5 reached during this stage was around 33000 µg/m^3.

The large-scale data further revealed that the most critical location during the 3D printing of concrete was next to the mixer as the mixing process involves the addition of a variety of powders that can easily become airborne and pose a health risk to workers and the environment. Finally, the data showed that the concentrations of PM2.5 reached 1000 µg/m^3 next to the printing nozzle and remained lower than this concentration for the entire printing period. This indicates that the printing process itself does not generate significant dust concentrations and is relatively safer from the mixing stage.

In order to determine the impact from the environment, temperature and relative humidity readings were recorded and compared to the recommended values. Figure 7 below showcases the temperature and relative humidity during the entire large-scale 3D printing process.

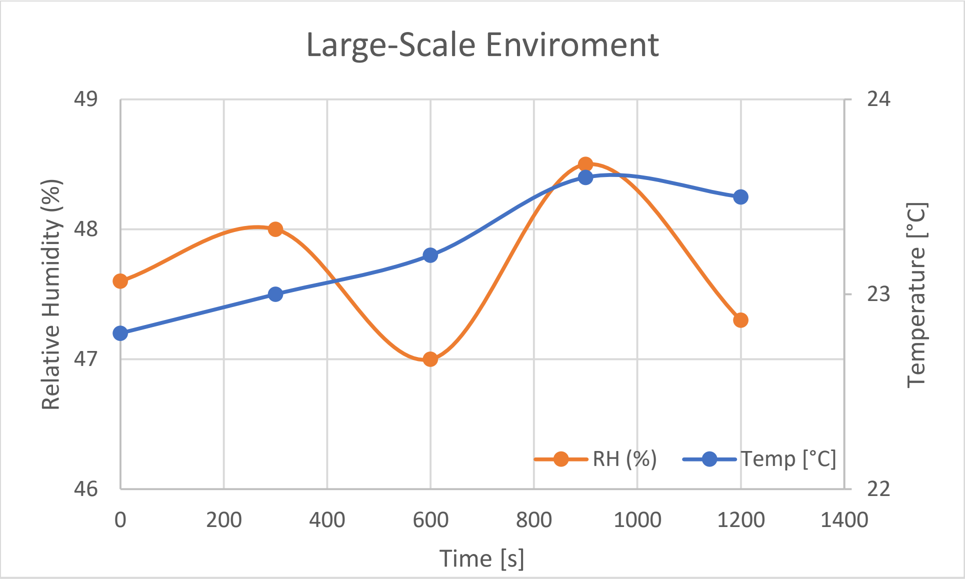

Figure 7: Large-scale experiment temperature and relative humidity.

Similar to figure 5, the temperature for this test also fluctuated around 23°C, while the relative humidity fluctuated about 47.5%. These results were crucial to emphasize that impact from environmental factors, temperature and relative humidity, was little to none as the conditions were optimum according to the recommended values.

There are different standards that can be used to assess the quality of air in the environment. However, the most convenient standard for such engineering applications is the Canadian Ambient Air Quality Standards (CAAQS). The CAAQS is suitable for evaluating the quality of air in both a small-scale workshop and a large-scale workshop. The standard illustrates that the maximum acceptable amount of the particulate matter (PM2.5) in the working environment in 24-hour period shall not exceed 28 μg/m^3 [34]. As such, considering even the lowest recorded measurement in the small-scale laboratory of PM 2.5 concentrations was 92 μg/m^3 during the printing stage, which is still 3 times more than the allowable value of 28 μg/m^3, implying that the small-scale concrete 3D printer has a significant impact on the air quality in the laboratory during the entire process. Students, researchers, and instructors are advised to strictly follow the laboratory safety procedure set by Texas A&M University at Qatar such as wearing the proper personal protective equipment (PPE) especially face masks.

Similarly, for the large-scale workshop the highest recorded PM2.5 was 33000 µg/m^3 and the lowest recorded concentration was 143 µg/m^3. Hence, the air quality of the working environment is highly polluted, and it will cause critical health issues to the researchers and anyone working in the workshop continuously. Assuming workers have to work in factory with similar environment for 8 hours a day, the workers would be exposed to severe dust emissions for 2 hours on average per shift, while the dust concentrations still above the CAAQS standard for the remaining time. Therefore, special safety precautions and controls must be considered and taken into account to ensure a safe and healthy work environment.

In addition, in order to calculate the emission rate of both the small- and large-scale experiments, the data of the concentration versus time of PM2.5 presented in Figures 4 and 6 was utilized. The methodology followed was to divide the plot into set of linear intervals based on the peaks existing in the plots. In Figure 4, the peak of concentration of PM2.5 was 3.18 $\frac{\mu g}{m^3}$ time 40 seconds. Hence, we care about the region between 10 and 40 seconds, where two linear regions were established. Thus, the rate of emissions can be calculated by summing up the derivatives or the slopes of the set of linear functions established. It was found that the rate of emissions for the small-scale experiment is 259 $\frac{\mu g}{m^3}$/s. On the other hand, the case is a little bit more complex for the case of large-scale experiment. The peak of PM2.5 concentration was recorded to be 32.7 $\frac{\mu g}{m^3}$ According to Figure 6, multiple peaks of concentrations could be observed. The same methodology conducted for the small-scale experiment was carried out for the large-scale one. However, this time the region of interest is larger which is between 10 and 900 seconds. As such, is necessary to take into consideration all the peaks up to 900 seconds. A total of 6 significant peaks were recorded. This indicates that the plot should be divided into 12 linear regions as per the established methodology. The slope of each linear region was calculated, and the sum was computed to obtain the rate of emissions of PM2.5 for the large-scale experiment. The recorded rate was 4419.65 $\frac{\mu g}{m^3}$/s which is almost 17 times greater than that of the small-scale experiment 259 $\frac{\mu g}{m^3}$/s. This implies that the rate of emissions of PM2.5 in the large-scale experiment is significantly higher than the small-scale experiment which confirms with our expectations and conclusions.

The finding that the rate of PM2.5 emissions in the large-scale experiment was almost 17 times higher than in the small-scale experiment is a cause for concern, as it indicates that larger scale dust emissions have the potential to be much more harmful than smaller scale emissions. This suggests that managing dust emissions is crucial, particularly in large-scale industrial activities, construction sites, and mining operations, where dust emissions can be significant. Moreover, the methodology used in the study, which involves dividing the concentration versus time plot into linear intervals based on concentration peaks and calculating the emissions rate by summing the slopes of the linear functions, can be applied to other studies on dust emissions. This methodology can help researchers to more accurately determine the emissions rate of dust, which can aid in the development of effective strategies to mitigate dust emissions and their associated health and environmental impacts.

3.2 Relevant Solutions

3.2.1 Local Exhaust Ventilation System (LEV)

One efficient method to solve the issue of dust emission produced by a concrete 3D printer in a workshop is through using a Local Exhaust Ventilation system (LEV). LEV can reduce dust emissions through incorporating both exhaust and supply ventilation. It is essential to place the exhaust ventilation system at the location where dust is being produced. Meanwhile, the supply ventilation is positioned in such a way that it can produce clean-fresh air. As such, a negative pressure is being developed inside the workshop which in return will lead to the removal of the dust particles, generated by the concrete printer, through the exhaust vents. Moreover, the LEV should possess a filtration system that is capable of capturing dust particles. There are two types of filters that are utilized to capture dust particles, mechanical solid matter and electrostatic precipitators (ESP) filters. Each one of these filters has its own mechanism for capturing dust particles. Mechanical solid matter filters are beneficial in capturing and separating various kinds of dust and fumes. These types of filters are applicable for simple research applications as well as complicated industrial purposes. The electrostatic precipitators rely on electrical energy to isolate and remove dust particles from a gas stream through charging the dust particles. These charged particles will then get attracted to collector plates that possess an opposite charge. In addition to LEV systems, there are other strategies that can be used to reduce indoor air pollution, including the use of air purifiers, source control measures, and the implementation of good indoor air quality practices. The selection of the most appropriate filter for a particular application depends on various factors, including the type of particles to be filtered, their concentration, the air flow rate, the desired level of filtration efficiency, and the cost of the filter.

In the case of large-scale and lab-scale 3D printing of concrete, where the concentration of airborne particles is 33000 µg/m^3 and 1600 µg/m^3, high-efficiency particulate air (HEPA) filters may be a suitable choice. HEPA filters are capable of removing at least 99.97% of particles as small as 0.3 microns in diameter from the air. This type of filter is often used in applications where the air must be extremely clean, such as in cleanrooms, hospitals, and laboratories.

Another option could be electrostatic precipitators, which use an electric field to remove particles from the air. These filters are effective at removing both larger and smaller particles, but they may not be as efficient as HEPA filters at removing particles smaller than 0.3 microns in diameter. It is important to note that in addition to selecting the appropriate filter, other control measures such as proper ventilation, enclosure of the process, and use of personal protective equipment may also be necessary to ensure worker safety and to minimize environmental impact.

To estimate the required flow rate of air, equations based on the air exchange rate and the volume of the area to be ventilated are commonly used. These equations take into account the initial concentration of PM2.5, the desired safe concentration, and the volume of the area to be ventilated, and can be found in literature [35]. By estimating the required flow rate, building managers and HVAC professionals can design and install ventilation systems that effectively improve indoor air quality and protect public health.

3.2.2 Personal Protective Equipment

In terms of individual safety precautions, engineers and employees in the workshop containing a concrete 3D printer are responsible for using their personal protective equipment (PPE). Using the proper PPE is indispensable to minimize the potential hazard associated with dust particles released by the concrete printer. First, employees should use respirators to protect themselves from inhaling toxic or harmful particles such as dust or foam. There are different types of respirators available in the market such as half-mask, full-mask, or disposable respirators. Each type of respirator has a limitation on how much dust it can take. In this case both the small-scale and large-scale required to use the half-mask when next to the mixer but only disposable masks were required for workers during the printing stage.

In addition, workers are advised to wear eye protection equipment such as goggles or a face shield that can protect the eyes from any dust or debris produced during the stages of printing. Also, coveralls that serve as protective clothing are recommended because dust particles have the tendency to contact and stick on the skin. Finally, universities, companies, or any engineering organization should train and educate their employees regarding the potential hazards of exposure to dust emissions. Employees should be educated on how to use their personal protective equipment and how to react if something went wrong. As such, engineers, workers, or anyone working in the workshop, in which a concrete 3D printer is active, are aware of the hazards and risks associated with such working environment.

4. CONCLUSION

The 3D-printing of concrete process is an innovative technology that offers a range of advantages over traditional concrete construction methods. It allows for the creation of complex and customized shapes, reduces the need for formwork and scaffolding, and offers the potential for faster and more efficient construction. However, as with any new technology, there are concerns about its potential environmental impact and the health and safety risks it poses to workers. Due to the quick growth of technological development in this field, certain aspects of the process such as the dust concentrations during the process have not been recorded and compared to industrial dust concentration standards.

The results of this study help to shed light on some of these concerns by identifying the most critical locations and stages during the 3D-printing of concrete process, where particle emissions are likely to be highest. The findings reveal that the mixing process generates the highest levels of airborne particle emissions in both small-scale and large-scale of concrete 3D printing with the maximum concentration of PM2.5 was 1600 µg/m^3 and 33000 µg/m^3 for small-scale and large-scale, respectively; which can be harmful to workers if appropriate safety measures are not in place ranging from small scale to industrial scale printers.

The data also indicates that the printing process itself is relatively safe, with low levels of PM2.5 concentrations measured next to the printing nozzle. It is important to note that even though the printing stage for both small-scale and large-scale had the least concentrations, they were still significantly higher than the CAAQS 24 hours standard value of 28 µg/m^3.

The study underscores the importance of taking adequate safety measures to protect workers and the environment during the 3D-printing of concrete process, especially in critical locations like the mixer. This can be achieved through the use of personal protective equipment, such as masks and gloves, and the implementation of emissions control measures, such as filters, exhausts, and ventilation systems.

In addition to addressing the health and safety concerns associated with the 3D-printing of concrete process, this study also has important implications for the technology's long-term sustainability. By identifying areas where emissions control measures may be necessary, the study provides a roadmap for improving the environmental performance of 3D-printing equipment and processes. The study paves a way for future work to be done in this area, as the 3D printing of concrete is a relatively new and growing field.

Overall, this study provides valuable insights into the critical stages of the 3D-printing of concrete process, which can help to inform future research and development efforts in this area. By continuing to monitor and mitigate the environmental and health risks associated with the technology, we can ensure that 3D-printing of concrete remains a safe and sustainable construction method well into the future.

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