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MORPHOLOGICAL AND CHEMICAL COMPOSITION OF $PM_{2.5}$ EMISIONS FROM A CONCRETE FACTORY IN TOLUCA, MEXICO

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Abstract: The concrete industry is known to produce $PM_{2.5}$ emissions in various production stages. This study analyzes $PM_{2.5}$ emissions originating from a ready-mix concrete factory situated in the Toluca Valley Metropolitan Zone (MZTV) in central Mexico. Samples were collected over different seasons – warm dry, rainy, and cold dry – using a low-volume particle analyzer. The samples were subsequently analyzed to determine, the morphology by Scanning Electron Microscopy (SEM), elemental chemical composition by Energy Dispersion (EDS). The analysis revealed that the concentration of $PM_{2.5}$ emissions exceeded permissible limits, posing significant health risks. The chemical composition of the $PM_{2.5}$ emissions were analyzed, revealing that they mainly comprised O, C, Si, Fe, Ca, Al, K, and Na, which are consistent with Portland cement. The study emphasizes the need for strict environmental controls and tailored management strategies to mitigate the impact of emissions on human health. It also highlights the significant influence of meteorological conditions, which affect particulate dispersion. Finally, in this contribution, the authors aim to better understand the effects of $PM_{2.5}$ emissions originating from the concrete industry providing insight into the need for stringent environmental regulations.
Keywords: $PM_{2.5}$, Concrete industry, Air quality, SEM/EDS, Environmental monitoring.

INTRODUCTION

The growing concern over air quality in urban environments is due to the increase in polluting emissions from various anthropogenic sources.

Stationary source monitoring plays a critical role in understanding these emissions and their impact on public health and the environment. In addition, it provides essential data for the evaluation, control, and mitigation of emissions, as well as for the development of effective environmental policies (EPA, 2006). Occupational exposure to mineral dusts, gases, and fumes has been associated with an increased risk of chronic respiratory diseases, such as chronic obstructive pulmonary disease (COPD), especially in low-income countries (Alif et al., 2016; Cullinan, 2012). Fine particles, known as $PM_{2.5}$ (size less than or equal to 2.5μm), suspended in the air, represent an additional danger to public health, as they can penetrate in depth zones of the lungs and affect immune function (Deng et al., 2019).

The importance of addressing these concerns is reflected in the Sustainable Development Goals (SDGs) adopted by the United Nations (UN) in 2015 as a global guide to address the most urgent socioeconomic and environmental challenges of our time (United Nations, 2018). It is estimated that by 2050, 66% of the population will live in urban areas, which highlights the need to implement effective measures to mitigate air pollution in these environments (United Nations, 2018). Within the global air quality report about cities most contaminated by $PM_{2.5}$, it has been observed that the cities within the Metropolitan Zone of the Toluca Valley (MZTV) have consistently occupied outstanding places in recent years (IQAir, 2022).

One of the significant sources of polluting emissions in urban environments is the concrete industry, which generates a large amount of PM due to its loading, unloading and movement processes of stone materials. This industry tends to be in urban areas and in the process of urbanization and industrialization (EPA, 2006). Global concrete production has seen a considerable increase in recent decades and is expected to continue growing due to increasing population and urbanization in regions such as Africa, India, and Latin America (Global Cement and Concrete Association, 2021). However, the installation of concrete factories can have significant environmental impacts, including the generation of polluting particles, such as cement dust, and the transfer of materials, as well as CO_2 emissions associated with cement production (Flower & Sanjayan, 2007).

In this context, it is essential for environmental management and public health to understand and characterize $PM_{2.5}$ emissions generated by the concrete industry in the MZTV. This study analyzes and quantifies emissions to strengthen air quality management in the region and support the implementation of appropriate regulations for this industry.

In the current context, the study of concrete becomes crucial due to the continuous growth of the world's population, particularly in urban areas, where the demand for infrastructure intensifies. According to United Nations estimates, the world population already exceeds 8 billion people, and it is projected that by 2050 it will reach 9.7 billion. (UN, 2024), with 55% living in urban areas. This trend underscores the urgency of building homes, roads, bridges, buildings, and other essential structures.

The need for materials such as cement, steel and wood become essential in this scenario. In the last 65 years, cement production has increased tenfold, while steel has only tripled and wood production has remained constant (Habert et al., 2020). By 2022, global cement production reached 4,158 million tons, with China and India as the main producers.

Cement was responsible for 36% of the 7.7 GT of CO2 released globally by construction activities in 2010, making concrete production represent a substantial proportion of global emissions associated with construction (Tkachenko et al., 2023).

Concrete is one of the most consumed materials globally; it has a significant environmental impact, particularly in emissions of fine particles ($PM_{2.5}$), which highlights the importance of responsible management in its production, use, and final disposal to ensure sustainable practices.

Concrete is a material composed primarily of hydraulic cement, water, fine and coarse aggregates and often includes chemical additives and other supplemental cementitious materials to improve its sustainability properties (American Concrete Institute, 2013). The production process begins with the receipt of raw materials, which are stored and dosed to guarantee the quality of the product. Cement, a key component of concrete, is transferred to elevated storage silos pneumatically or by bucket elevator and overseen in a manner that minimizes particulate emissions. Sand and gravel are transferred to elevated hoppers by front loader, lever crane, conveyor, or bucket elevator. From these elevated hoppers, the components are fed by gravity or by screw conveyor, into weighing hoppers, which combine the appropriate quantities of each material to manufacture the product as can be seen in Figure 1.

The concrete industry faces significant environmental challenges, primarily from dust emissions generated during the transfer of cement, or pozzolana, sand, and gravel, as well as from heavy truck and mixer loading, vehicle traffic, and storage mound erosion of sand and gravel, are some particle emissions as the main contaminant and depend on the surface humidity of these materials (EPA, 2006), and on the other hand the management of natural resources used as raw materials. Concrete factories must implement strategies to mitigate impacts such as the use of dust collectors, filters, and water management systems to control the dispersion of particles and pollution (Flower & Sanjayan, 2007).

Studies have found that Portland cement production is the largest source of CO2 emissions in concrete manufacturing, contributing 74-81% of total emissions. Fine and coarse aggregates also play a significant rol in the carbon footprint of concrete, this highlights the importance of exploring sustainable alternatives with lower environmental impact for concrete production (Flower & Sanjayan, 2017).

Evolution towards more sustainable practices in the concrete industry is crucial to reduce its environmental impact, which includes the optimization of the selection and use of raw materials, as well as the implementation of technologies that improve energy efficiency and reduce gas emissions greenhouse effect.

MATERIALS AND METHODS

The MZTV, located in the central part of the State of Mexico, is a geographic area that includes mountains, hills and valleys that affect wind dynamics, with a predominantly temperate subhumid and semi-cold climate in the high parts. It includes 16 municipalities, with Toluca and Metepec being the most populated. The regional economy is focused on the commercial sector and is home to around 22 concrete plants, selecting one in the north for this study. A MiniVol™ Tactical Air Sampler was used to collect airborne particle samples, using a quartz fiber filter media and separating particles down to 10 and 2.5 microns. The sampling campaign lasted three days, collecting 18 samples under climatic conditions that varied by season, and the concentration of $PM_{2.5}$ was determined according to the Official Mexican Standard NOM-035-SEMARNAT-1993.

The collected mass was measured using a meter Toledo micro balance, model MT5, with a maximum capacity of 5.1 g and stability of 1 µm in the laboratory weighing room under average conditions of relative humidity 22.38 % and temperature 28.1°C. The concentration of $PM_{2.5}$ particles was obtained based on the Mexican Official Standard NOM-035-SEMARNAT-1993, which establishes the measurement methods to determine particle concentration (Nom-035-Ecol-1993, 2003), where the collected mass is divided by the sampling airflow.

The samples were analyzed to determine the morphology through Scanning Electron Microscopy (SEM) with accelerating voltage of 1 to 30 kV and tungsten filament coupled to an X-ray detector. SEM micrographs of the samples were obtained at magnifications of 350 X to 5000 X (maximum resolution fifty µm). In the automatic particle analysis, images were obtained at a resolution of 1280 x 960 pixels. A total of thirty-three images were obtained during the three times of the year, which were analyzed in morphology and organized in a database for the analysis.

The chemical analysis was by means of Energy Dispersion (EDS), with a resolution of 137 eV. The distance conditions used were from 2 to 12 mm, and voltage from 2 to 20 kV, without covering the samples with a conductor. In this analysis, it was measured in specific regions of the micrographs with magnification of 1, 3 and 5 KX (Figure 3) and in the entire SEM area of the same figures. 33 particles were analyzed with a total of 21 chemical elements detected.

RESULTS

The $PM_{2.5}$ concentrations found were shown in a range of 26.06 µg/m^3 and 136.41 µg/m^3 during the period 2022. The general average $PM_{2.5}$ concentration was 60.16 ± 44.40 µg/m^3.

These values oscillated significantly, showing a seasonal peak that suggests a marked influence on meteorological and operational conditions in the generation of particular, in accordance with the patterns

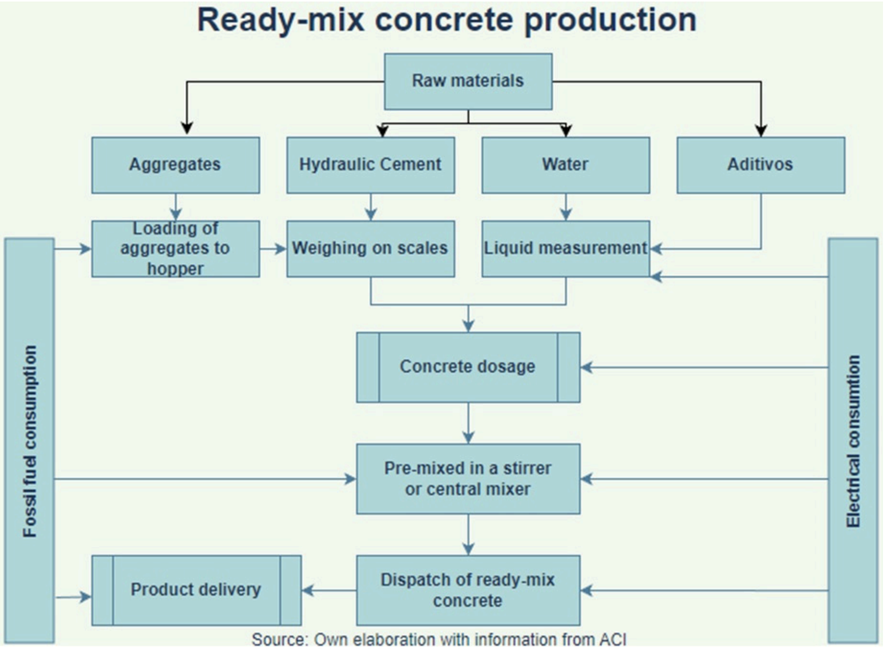

Figure 1.Typical Concrete Batching Process.

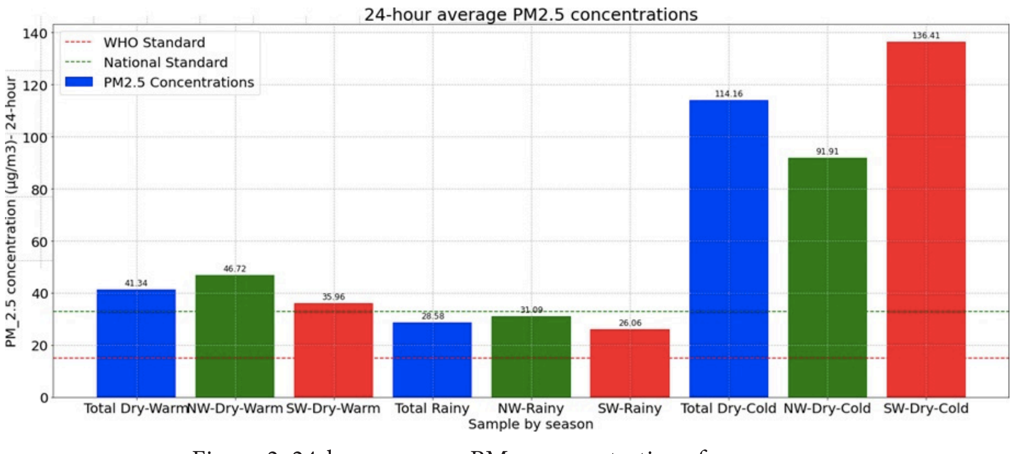

Figure 2. 24-hour average $PM_{2.5}$ concentrations for season.

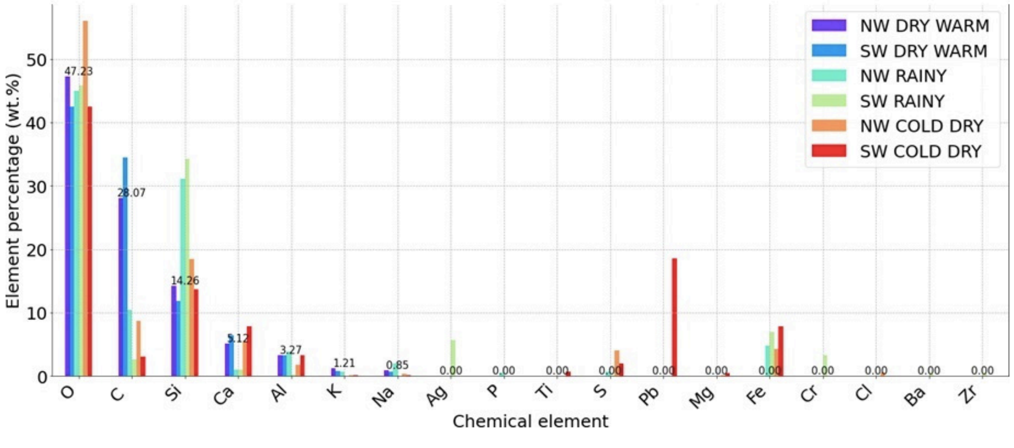

Figure 4 Average elemental chemical composition $PM_{2.5}$ µm

observed in other studies, such as the one conducted in a concrete factory in Toronto, which also reflected fluctuations. significant depending on industrial activity and climatic conditions (Lachapelle & Ramdayal, 2015).

As seen in Figure 2, in two of the measured seasons, warm dry and cold dry, the average concentrations remained above the maximum permissible limits established by national standard 025 of the Ministry of Environmental Health (41 μg/m3) for 24 hours (NOM-025-SSA1-2014, 2014). The last cold dry season presented values higher than the national norm. However, in all periods the value of the 24-hour guideline (15 μg/m3) established by the World Health Organization was exceeded (World Health Organization, 2021). This highlights a significant discrepancy between national health standards and international recommendations, emphasizing the need to review and possibly strengthen environmental mitigation strategies, especially given that even at the lowest levels they exceed WHO guidance, which represents a risk to the health of the population exposed to fine particles (Peng et al., 2009), underscoring the urgency of adopting more effective strategies to reduce emissions and improve air quality.

MORPHOLOGICAL CHARACTERIZATION

The morphology of the particles varies from particles with irregular shapes and globular agglomerates with a variable chemical composition associated with an anthropogenic origin and related to diesel engine emissions Figure 3 (Liati et al., 2013); solid spherical particles that have commonly been associated with industrial processes that are carried out at high temperatures (Breeda C.A. et al., 2002); particles with regular shapes with symmetries similar to peaks that have been related to natural sources of mineral and rocky substrates but that due to the relative abundance of the elements that compose it are indicators of anthropogenic activities

Figure 3. Considering the content of the most abundant elements in the particles and the possible impact on health in this type of industry (Moghadam et al., 2020).

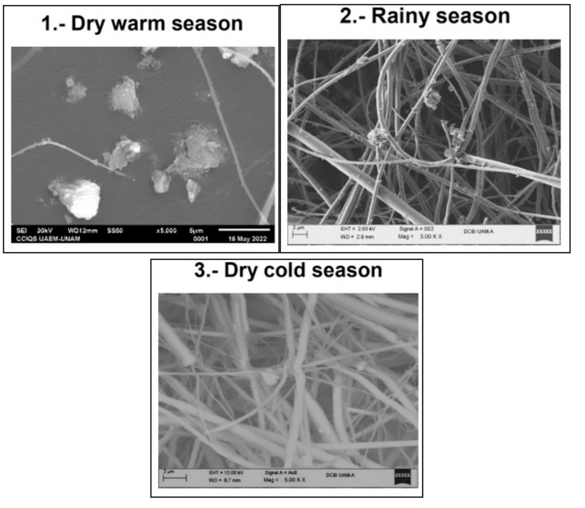

Figure 3 Micrographs by time of year 1.- warm dry,2.- rainy and 3.- cold dry.

CHEMICAL CHARACTERIZATION

As a result of energy dispersive X-ray detection (EDS) adapted to the SEM, the most abundant elements detected were oxygen (O), carbon (C), silicon (Si), aluminum (Al), calcium (Ca), potassium (K) and sodium (Na), present in 75% of the total particles, with O, C and Si being the most abundant. Around 15% of the total particles recorded contents of other elements such as sulfur (S), chromium (Cr), chlorine (Cl), Iron (Fe); A difference was found between the components detected by time of year, and with reference to the measurement point, only in the rainy season samples at the southwest point (SW) was barium (Ba), silver (Ag), zirconium identified. (Zr) and chromium (Cr) while in the cold dry season at the same point (SW) elements such as Lead (Pb), Titanium (Ti) Figure 4. The results are agreed with what were obtained in other studies on chemical characterization in similar industries (Ibrahim et al., 2012).

RECOMMENDATIONS

Good manufacturing practices in the concrete production sector are essential to mitigate particulate emissions and improve surrounding air quality. These practices not only cover the implementation of advanced pollution control technologies, but also comprehensive environmental management strategies, including emission control technologies such as: The use of advanced collectors, such as electrostatic collectors, pulse jet filters in cement silos (Hak-Joon Kim, n.d.) (Çankaya & Özcan, 2019), encapsulation of emission sources, that surrounds the emission source with a structure that contains and controls the release of particles, water spray systems, this is a simple but highly effective technique to suppress dust in material storage areas and transfer points and vegetation barriers that also improves aesthetics and contributes to local biodiversity (EPA, 1978, 1998; Yuefan Zhang, 2023), use of additives to reduce dust generation, localized ventilation and extraction system, and advanced filtration technologies: Bag filters, cartridge filters and high-efficiency filtration systems that can be adapted to the specific needs of plants. In addition to the use of control technologies, environmental management measures can be implemented such as proper maintenance of equipment, training of personnel and optimization of processes to reduce waste of materials and energy. Which will ensure the control and minimization of emissions in concrete plants.

CONCLUSIONS

The present study highlights the importance of rigorous and adaptive environmental management in the context of concrete industry, particularly in the Metropolitan Zone of the Toluca Valley (MZTV). The results obtained reveal fluctuating concentrations of $PM_{2.5}$, which frequently exceed both the maximum permissible limits established by national regulations and the standards of the World Health Organization. This poses a significant risk to public health, especially during dry and cold seasons when concentrations are higher due to the combination of intense industrial activities and adverse weather conditions that prevent proper dispersion of these particles.

The diversity in the chemical composition and morphologies of $PM_{2.5}$ particles detected reflects a complex mix of anthropogenic and natural sources. This underscores the need for detailed studies to better understand the specific contributions of various activities, including concrete production, which release a variety of pollutants into the air.

Given this reality, it is imperative to implement and monitor effective control strategies that address both emission sources and secondary aerosol formation processes. These strategies should include the adoption of more sustainable production practices and the integration of advanced mitigation technologies to minimize the environmental impact of the concrete industry. These measures will not only improve air quality but also ensure public health and the sustainability of industrial practices in densely populated and developing regions.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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