



# Effect of Cement Industry on Ambient Air Quality and Potential Health Risk: A Case Study from Riyadh, Saudi Arabia

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## Abstract

This study aimed to determine the cement industry's impact on ambient air quality inside and around a Saudi Arabian cement plant. Air quality has assessed in terms of several indicators: carbon dioxide, carbon monoxide, nitrogen dioxide, sulfur dioxide, PM<sub>10</sub>, PM<sub>2.5</sub>, ozone, and volatile organic compounds. AERMOD model was used to predict the concentrations of pollutants in the surrounding area. Results obtained revealed that the concentration of all impurities is within the standard limits for ambient air quality. In comparison with OSHA guidelines, only PM<sub>10</sub> concentration exceeded the allowable limit. The higher concentrations of pollutants are recorded at the site closest to the plant site (S1, a housing compound located 0.8km ESE from the plant). Concentrations at the other monitoring sites decreased significantly. Except for PM10, the calculated hazard quotient (HQ) of all pollutants was <1 which indicated no health effects are expected. The HQ of emissions can be ranked as: PM<sub>10</sub>> PM<sub>2.5</sub>>CO<sub>2</sub>>O<sub>3</sub>>CO>VOCs>NO<sub>x</sub>>SO<sub>2</sub>>H<sub>2</sub>S. The hazardous index (HI) was: 3.59, 2.76, 2.18, and 2.67 for S1, S2 (located 17km NNE), S3 (located 10.6km SE), and S4 (located 6.4km SSW), respectively. The affected organs can be ranked based on health risk calculation as respiratory system>cardiovascular system>Eye irritation>Allergy infection>Nervous system>Development>Hematology >Alimentary endocrine. The cancer risk factor was shallow and ranged from 4.04x10<sup>-6</sup> for S4 to 1.88x10<sup>-5</sup> for S1, which indicated a very low-risk potential. In terms of emissions concentrations, AERMOD predicted higher concentrations than the actual monitoring data for all measured parameters.

**Paper type:** Research paper

**Keywords:** cement, air quality, health, dust and gases, AERMOD.

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## Introduction

There is a large amount of evidence in the literature that ambient air pollution can affect human health to various degrees. Children are believed to be more affected by ambient air pollution than adults because they do not have a complete defense mechanism and because they inhale a higher volume of air per body weight. Higher rates of allergen sensation, worsening asthma and decreased lung function have been associated with higher exposure to fine particles in ambient air (Salvi, 2007). There is also sufficient evidence that air pollution can result in higher congenital disability rates (Ritz *et al.*, 2002), lower birth weight, premature birth, and can cause respiratory deaths in the postneonatal period (Sram *et al.*, 2005). Ambient air pollution has been associated with higher cardiovascular (Metzger *et al.*, 2004) and respiratory (Peel *et al.*, 2005) emergency department visits. Long-term exposure to ambient air pollution has been found to increase cardiovascular morbidity and mortality (Kunzli *et al.*, 2005). There appears to be an association between higher concentrations of Ozone (O<sub>3</sub>), Nitrogen Dioxide (NO<sub>2</sub>), Carbon Monoxide (CO), Particulate Matter (PM), and organic carbon with specific respiratory problems (Peel *et al.*, 2005). The World Health Organisation (WHO) has associated ambient air pollution with acute lower respiratory infections, lung cancer, chronic obstructive pulmonary disease, stroke, and ischaemic heart disease (WHO, 2016)

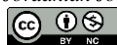
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Global cement production was about 4.2 billion tons in 2014 (Balaji *et al.*, 2017; USGS, 2014). Cement manufacturing contributes considerably to ambient air pollution. About 5% of global carbon emissions are caused by cement manufacturing (Rampuri, 2017). It is estimated that the production of only one tone of cement clinker can produce 46.7g of dust, 1.80kg of NO<sub>x</sub> as NO<sub>2</sub>, 0.504kg of Sulfur Dioxide (SO<sub>2</sub>), 52.4g of VOC as C, 9.8g, and Hydrochloric Acid (HCl), 0.7g of Hydrofluoric Acid (HF) (WBCSD, 2020). Air pollutants emitted from cement manufacturing can be affected by the raw materials' compositions and the production method. The proportions of raw materials used are approximately limestone 65%, silica 21%, alumina 6%, iron oxides 3.5%, in addition to the miner oxides (MgO, K<sub>2</sub>O, Na<sub>2</sub>O, and SO<sub>3</sub>) (Akanni *et al.*, 2014). These materials are first mixed to obtain a homogeneous mixture. Then the mixture is preheated and burned in a rotary kiln at a temperature of about 1400–1500°C. The resulting partially fused material is known as clinker. The resulting clinker is first cooled and then ground in cement mills along with 5% added gypsum to a fine powder. Gypsum is added to control the cement setting (Al Smadi *et al.*, 2009, EPA; 2010). The main two types of emissions from cement plants that significantly impact health are dust and gaseous emissions (IFC, 2007).

Fuel combustion is the primary source of gaseous emissions, which include carbon oxides (CO and CO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), sulfur dioxide (SO<sub>2</sub>), and total volatile organic compounds (TVOCs). If these emissions are not controlled, they may cause a significant deterioration of the surrounding environment (Mishra and Siddiqui, 2014). Dust, which poses the cement industry's significant health impact, is emitted by almost all production processes. These include rock explosion, drilling, crushing of rocks, loading and unloading, materials' storage, clinker milling, clinker storage, and cement packaging. The crusher and cement mill units are the primary sources of particulate matter (PM<sub>10</sub> and PM<sub>2.5</sub>). It was found that about 80% of the samples taken from these units exceeded the environmental quality standards for particulate matter (Waqas *et al.*, 2013). Several pathological conditions have been encountered in cement industry workers. These include respiratory tract diseases, skin diseases, chest pain, irregular heartbeat, rheumatic conditions, hearing and visual disorders, and cancer (Mehraj *et al.*, 2013; Mwaiselage *et al.*, 2005; Rai *et al.*, 2013). A strong association between the lung and respiratory functions and exposure to cement dust has been reported. Workers at the crushing and packaging units are exposed to high dust emissions, which may cause several health problems (Ahmed and Abdullah, 2012). It was also found that high dusty areas have caused eye disorders, mainly during work times when the workers touch their eyes with their hands which are covered with cement dust (Soussia *et al.*, 2014). Several studies have stressed the importance of personnel protective equipment (PPE) in reducing the hazards facing workers in the cement manufacturing industry (Rampuri 2017; Samuel *et al.*, 2016). Using PPE and dust control measures and raising workers' awareness can minimize workers' respiratory health issues (Gizaw *et al.*, 2016). The cement industry substantially impacts the environment, especially the adjacent area, which receives the highest emissions concentration. The concentration of the emissions in a particular site depends on the plant's distance, meteorological conditions, terrain, and barriers such as buildings, fences, and trees.

The purpose of the current study is to assess the cement industry's impact on the ambient air quality in four sites around a cement plant in Saudi Arabia. The emissions concentrations were compared with applicable international standards for ambient air quality. Also, the possible health effect, health risks, and cancer risk assessment are investigated. AERMOD model is applied to predict the concentrations of pollutants in a domain area of 50x50km around the cement plant.

## 1 Materials and Methods

### 1.1 Area of study

The plant is located in Saudi Arabia in Riyadh province. The area is classified as a desert with extremely harsh weather during summer due to high temperatures. While January is the coldest month, July is the warmest. Meteorological conditions have a high impact on the dispersion of pollutants, subsequently the ground level concentration, and the effect of pollution. The average minimum daily temperature ranged from 9 in January to 26.9°C in July, while the average max daily temperature ranged from 20.3 and 42.6°C for both months. The average rainfall is about 67mm that mostly occurs from November to April and is rare in the other months. The average relative humidity in the area varies significantly from 22% in June to more than 56% in December. The daylight ranged from 10.6 in December to 13.7 hours in June, with the sunny days of 18 days in February and 29.3 days in June. The average solar energy ranged from 4.2kWh in December and 8.3kWh in June. Long-term data indicated that 35%, 26%, 10%, 10%, 5%, 3%, 3%, 2%, and 2% of the wind blows from N, SSE, NNE, SE, S, E, ENE, NE, and NNW respectively. **Table 1** shows the monthly temperature, direction, and speed of wind in King Khaled airport in Riyadh (Weather Atlas, 2020, Metoblue, 2020).

**Table 1** Wind direction and velocity.

Month	Direction	Wind speed, (m/s)	Average. temperature, (°C)
January	N	3.60	14.3
February	NE	3.60	16.8
March	ESE	4.12	21.4
April	SSE	4.12	25.7
May	NNE	4.12	31.1
June	N	4.63	33.6
July	N	4.63	34.7
August	N	4.12	32.6
September	NE	3.09	31.8
October	ESE	3.09	26.6
November	ESE	3.09	20.6
December	ENE	3.09	15.7

Source: Weather Atlas, (2020), Metoblue, (2020)

## 1.2 The plant's process

During the study period, there were four production lines in operation while the others were shut down. The plant consists of many units, which include: furnaces, raw material mills, crushers, cement mills, quality control labs, power plants, water desalination, wastewater treatment plant, warehouses and stores, administration, labors' housings, medical center, packaging, and loading and limestone quarries. The plant uses heavy fuel as a primary energy source, while diesel fuel is used for starting operations. The operation process consists of successive stages, which include: extraction of the raw materials, crushing, seizing, mixing of the raw materials (limestone, clay, pozzolana), grinding of raw materials, preheating the mixed materials, burning in the furnace at 850-1350°C, clinker cooling to 80°C, clinker storing in silos, adding gypsum, cement milling, storing of cement, packaging, and loading in trucks. The plant uses bag filters to control dust, while electrostatic precipitators are used to control gases.

## 1.3 Sources of emissions

During the study period, more than 35 dust sources have been identified, including furnace stacks, mixing basins, homogeneity basins, conveyers' belts, clinker cooling, milling of raw materials, cement milling, cleaning of filters, transfer of materials on belts, loading, and unloading of materials and products, clinker storage, leakage from belts and filters and disposal of dust. Additionally, the operations inside the quarry are considered significant sources of dust. Fugitive gases are generated mainly from the combustion process, including furnaces, clinker cooling, energy plant, vehicles, and equipment. The kiln preheater emissions were 10.7, 3.9, 7.1, and 197 mg/m<sup>3</sup> for PM<sub>10</sub>, PM<sub>2.5</sub>, SO<sub>2</sub>, and NO<sub>x</sub>, respectively, while the concentration of the same pollutants from the clinker cooler were: 9.0, 3.17, 3.1, and 4.7mg/m<sup>3</sup> respectively.

## 1.4 Sampling

Continuous monitoring for 24 hours was performed in four monitoring sites using a mobile station. The selected areas are located in different directions related to the cement plant, as described in **Table 2**. The monitoring process includes the measurement of the concentration of various pollutants (CO, NO<sub>x</sub>, SO<sub>2</sub>, H<sub>2</sub>S, O<sub>3</sub>, VOCs, PM<sub>10</sub>, and PM<sub>2.5</sub>) in addition to metrological parameters (wind direction, wind velocity, relative humidity, and temperature). All instruments used for gas monitoring are approved by the Environmental Protection Agency (EPA) and Australian standards, while a high-volume sampler was used for dust monitoring.

**Table 2** Location of the receptors.

Receptor	Description	Description of the site	Direction related to the plant	Distance to the plant (km)
S1	Housing	The housing of the laborers, arid area, with limited vegetation cover	ESE	0.8
S2	Small community	a small community with a population of about 5000 inhabitants, arid area, medium traffic load, with rare vegetation cover	NNE	17
S3	Scattered houses	Scattered houses with a population of about 500 inhabitants, arid area, with rare plant cover	SE	10.6
S4	Scattered houses	Scattered houses with a population of about 100 inhabitants, arid area, with rare plant cover	SSW	6.4

## 1.5 Air dispersion model

AERMOD model was used to predict the concentration of pollutants in the surrounding areas of the cement plant. AERMOD model is a near-field steady-state Gaussian model designed for short-range (<50km) dispersion of air pollutant emissions from stationary industrial sources. The model is utilized to determine various pollutants in urban and rural areas and flat and rough. This USEPA approved model was developed in 1995. AERMOD predicts the maximum ground-level concentrations to varying distances for discrete and network receptors. The model's input data include the type of fuel, stack height, stack diameter, gas velocity, gas temperature, the emission rate of pollutants (g/s), metrological data (wind direction, wind speed, temperature, atmospheric pressure,...), and the area terrain. The output file includes tables summarizing each averaging period's highest values and source groups (EPA, 2018b; Matalqah *et al.*, 2017). The elevations of the receptors in the area were determined using AERMOD Terrain Pre-processor (AERMAP). In contrast, Shuttle Radar Topography Mission (SRTM) digital terrain file in AERMAP is used to extract the study domain's elevation data (50x50km). AERMET pre-processor is used to calculate the meteorological parameters, including wind speed and direction, temperature, and cloud cover (EPA, 2004). It is assumed a steady-state plume, the concentration dispersion similar to Gaussian in both the vertical and horizontal direction; the terrain is flat, constant flow rate emissions from the sources, and no obstructions that alter pollutants, rare vegetation cover will not affect the pollutants' dispersion.

## 1.6 Health risk calculation

One of the well-known health risk indicators is the hazard quotient ( $HQ$ ) index which aims to predict the type and potentiality of the adverse impact of non-carcinogenic pollutants on the receptor (Alzboon and Forton, 2019b). The  $HQ$  has been successfully used to estimate the health risk of different pollutants (Liu, *et al.*, 2015; Alzboon and Forton, 2019a).  $HQ$  is calculated for each pollutant as the ratio of the pollutant's concentration to the reference concentration as shown in equation (1):

$$HQ = \text{Exposure concentration/reference concentration} \quad (1)$$

The reference concentrations were determined based on Occupational Safety and Health Administration (OSHA) guidelines for CO, CO<sub>2</sub>, SO<sub>2</sub>, H<sub>2</sub>S, NO<sub>x</sub>, O<sub>3</sub>, and VOCs. A Hazard Index ( $HI$ ) is the sum of  $HQ$ 's for all pollutants in the same receptor (Alzboon and Forton, 2019b).

Cancer risk due to exposure to the pollutant can be calculated as the following (Liu *et al.*, 2015):

$$\text{Cancer Risk} = C \times UF \quad (2)$$

$C$  is the concentration of pollutant (ppm), and  $UF$  is the risk unit factor, represents the number of cancer cases per one unit of concentration.

## 1.7 Regulations

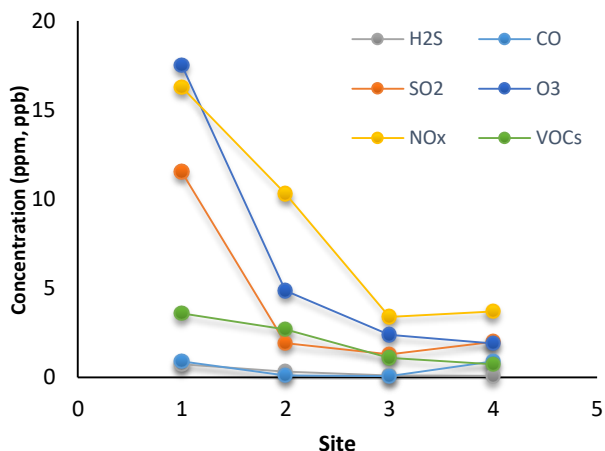
Many national and international regulations control the emissions from cement plants. In Saudi Arabia, there are standards for emissions from sources and ambient air quality standards. According to the meteorology and environment (PME) presidency standards, dust from cement furnaces should be <0.15kg/MT, and 0.05kg/MT from the clinker's cooler. For ambient air quality, there are limits for SO<sub>2</sub>, NO<sub>2</sub>, CO, H<sub>2</sub>S, O<sub>3</sub>, Benzene, PM<sub>10</sub>, and PM<sub>2.5</sub>. There are no local standards for emissions inside the workplace (indoor air quality). Most of the conducted studies used international guidelines such as OSHA, WHO, and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) for assessing the environmental quality in the workplace.

## 2 Results and Discussion

### 2.1 Effect on ambient air quality

**Figure 1** illustrates the concentration of pollutants at different monitoring sites. The monitoring results revealed that the highest concentrations of pollutants were recorded at site S1, located at a distance of 0.8km from the plant. In comparison, the lowest concentrations were found at S3 and S4 located at a far distance from the plant (10.6 and 6.4km, respectively). This result indicated that the cement plant's impact depends strongly on the receptor's location and how far it is from the source. Site S2 is located on the main highway, which explained the high concentrations of pollutants in the site due to vehicle emissions. Compared with PME ambient air quality standards, all pollutants' concentrations are far below the designated limits of 32, 0.35, and 0.28, 0.12ppm for an averaging time of 1hr for CO, NO<sub>2</sub>, SO<sub>2</sub>, and O<sub>3</sub>, respectively. The concentrations of PM<sub>10</sub> were 131, 107, 84, and 81μg/m<sup>3</sup> for the measured sites, respectively, against 340μg/m<sup>3</sup>, the allowable concentration limit. Similarly, the concentration of PM<sub>2.5</sub> (21, 15, 13, 13μg/m<sup>3</sup>) in the four sites is far below the standard limit of 35μg/m<sup>3</sup>. Deficient concentrations of Benzene have been measured (0.8, 0.6, 0.46, 0.16ppb) in the four areas, respectively, in comparison with the PME limit of 4.4ppb/y. Since site S1 is located close to the plant site, the pollutant concentrations were compared with OSHA standard limit for indoor air quality. It was found that all pollutants have concentrations below the permissible exposure limit of 25, 2, 20, 3ppm, and 100ppb for CO, SO<sub>2</sub>, H<sub>2</sub>S, NO<sub>x</sub>, and O<sub>3</sub>, respectively. WHO recommended desirable limits of 50 and 20 for PM<sub>10</sub> and PM<sub>2.5</sub>, respectively. In this study, it is assumed that the total VOCs represent the summation of Benzene, Toluene, O-Xylene, P-Xylene, and Ethylbenzene, and it is recommended a concentration of 120ppb as a healthy indoor environment (Fernández-Agüera *et al.*, 2019).

**Figure 2** shows the concentration of PM<sub>10</sub> and PM<sub>2.5</sub> in the monitoring sites. Compared with PME ambient air quality standards, the concentration of PM<sub>10</sub> and PM<sub>2.5</sub> is within the acceptable limit, while PM<sub>10</sub> is more than WHO guidelines in all sites. Site S1 has a high concentration of dust due to its direct effect and the short distance between the site and the plant (0.8km). Although there is no



**Fig.1** Concentration of pollutants at different monitoring locations (*in ppb except of CO in ppm*).

exceedance in pollutants' concentration, it is necessary to establish a continuous monitoring program, especially in the residential areas and the plants' surrounding sites. Continuous monitoring of emissions from the stacks is a must to avoid any violent or unexpected events.

## 2.2. Health Effect

### 2.2.1 Carbon monoxide

Carbon monoxide is generated due to incomplete combustion, mainly from fossil fuels. The effect of CO on human health depends on the exposure period, CO concentration, and the receptor's sensitivity. Breathing of air with a high CO concentration causes headache, vomiting, nausea, dizziness, and may cause heart disease, angina, reduces brain function, unconscious, or die at high concentration. CO exposure's profound acute health effect includes weakness, dyspnoea, cardiac dysrhythmias, muscle fatigue, palpitations, confusion, hypotension, cardiac and respiratory arrest, impaired vision, pulmonary edema, myocardial ischemia, and coma. Since the blood hemoglobin binding affinity to CO is more than 200 times greater than its relationship to O<sub>2</sub>, a high concentration of CO causes an increase in the level of carboxyhaemoglobin. Many studies reported no health effect at low CO concentration (200, 1000, 1200ppm) at a short time of exposure (Wilbur *et al.*, 2012). Since CO concentrations are <0.9ppm in all sites and far below the reported limit, no health effect is expected.

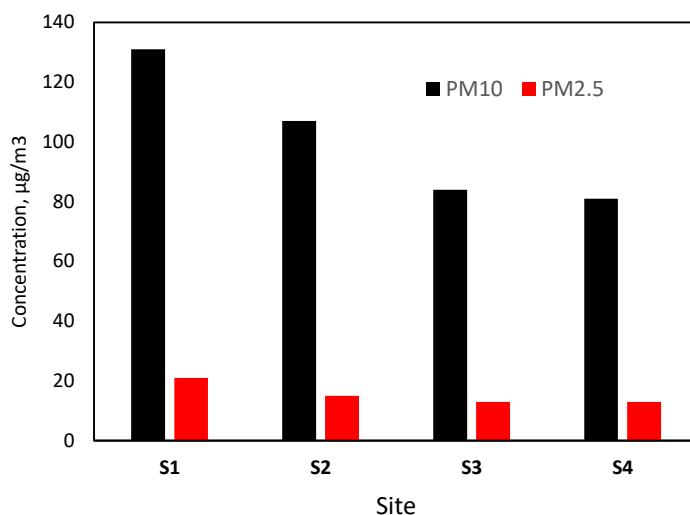


Fig. 2 Concentration of PM<sub>10</sub> and PM<sub>2.5</sub> in the monitoring sites.

### 2.2.2 Sulfur dioxide

The industry is the primary source of sulfur dioxide in the atmosphere, especially the power plants, oil and gas industries, mineral processing, vehicles with diesel engines, and fossil fuel combustion containing sulfur. Sulfur dioxide can cause many health effects, especially for sensitive people with lung diseases, children, and the elderly. Its effects include irritation of the nose, throat, eyes, respiratory system, and lungs. The common symptoms at high concentration are breathing difficulties, reduced lung function, harsh asthma attacks, and aggravation of heart diseases for sensitive groups. The chemical reaction of SO<sub>2</sub> with chemicals in the atmosphere produces acid particles that harm the respiratory system and lungs. It was reported that SO<sub>2</sub> is responsible for an increase in hospital respiratory admissions by 4% in Paris and Milan, 6-9% in chronic obstructive lung disease admission in Barcelona. Epidemiological studies showed that the prolonged exposure to SO<sub>2</sub> concentration of 10ppm caused damage to the airways' epithelium, while at a higher concentration of 300ppm, slowing of ciliary transport of mucus occurred (WHO, 2002a). National Park Services (NPS) of USA classified air quality index in six categories based on SO<sub>2</sub> concentration as: good (0.0-0.1ppm), moderate (0.1-0.2ppm), unhealthy for sensitive groups (0.2-1.0ppm), harmful (1.0-3.0ppm), and very unhealthy (3.0-5.0ppm) and hazardous (>5ppm) (NPS, 2018). The concentrations of SO<sub>2</sub> in all sites ranged from 2.00 to 11.92ppb; subsequently, air quality can be classified as good (0.0-0.1ppm) according to the NPS classification, and therefore no adverse health effects are expected.

### 2.2.3 Nitrogen oxides

Nitrogen oxides are generated from the combustion of fuel, vehicle emissions, power plants, and off-road equipment. Exposure to NO<sub>x</sub> can irritate the respiratory system and throat, asthma, cough, difficulty breathing (EPA, 2020). Previous studies indicated that short-term exposure (1hr) to a concentration of 200µg/m<sup>3</sup> has insufficient evidence of health effects. In comparison, exposure to a concentration of 50µg/m<sup>3</sup> for 24hrs showed an increase in hospital admissions for respiratory diseases and mortality (Latza *et al.*, 2009). It was reported that a concentration of 0.3ppm for 30-minute is the lowest limit that can affect the pulmonary function, and there were no symptomatic complaints at an exposure limit of 1.0ppm by either asthmatics or healthy groups. Higher concentrations (3.0-4.0ppm) caused a significant effect on lung function and lung protein activity (WHO, 2002b). The maximum concentration of NO<sub>x</sub> was measured in S1 with an average value of 16.28ppb, which is far below the lowest limit of the health effect of 200µg/m<sup>3</sup> (97.4ppb), or the limitation of 0.3ppm that affect the pulmonary function.

### 2.2.4 Hydrogen sulfide

Most hydrogen sulfide ( $H_2S$ ) is generated naturally from different sources such as thermal springs, lakes, and saline marsh. In industry, inorganic compounds and sulfate with insufficient oxygen level,  $H_2S$  can be formed. Wastewater treatment plants, oil refining, tanning industry, viscose rayon mill, and kraft pulping industry are possible sources of  $H_2S$ . While the respiratory system is the main route of  $H_2S$  exposure by humans, it concentrates in the liver with a small amount in the lungs and kidneys. A concentration of 750-1400 $mg/m^3$  is considered an acute lethal level with immediate collapse. Sulfide and hydrogen sulfide anions are strong bases with a significant impact on the nervous system, which caused conjunctival irritation at 10ppm (15 $mg/m^3$ ). Also, it can cause respiratory irritation and eye damage at a concentration above 150ppm, pulmonary edema at a concentration of 267ppm, loss of olfactory sense at a concentration level of 150-250, CNC stimulation at a concentration of 530-1000ppm, and paralysis of respiration at a concentration of 1000-2000ppm. Epidemiological studies reported that daily exposure of workers to  $H_2S$  with a concentration of >20ppm (>30  $mg/m^3$ ) resulted in the complaint of 70% of the workers from many symptoms such as headache, fatigue, drowsiness, vertigo, poor memory, disquiet, and eye irritation (WHO, 2002c). The concentration of  $H_2S$  in the measured sites were: 16.28, 10.3, 3.4, and 3.3ppb for sites S1, S2, S3, and S4, respectively. These are far below the limit that causes an effect on the nervous system (10ppm), or the limit that irritates (20ppm), nor the limit that causes an impact on the respiratory system (1000ppm). Therefore, no adverse health effects are expected due to the exposure of  $H_2S$  at the current concentration level.

### 2.3 VOCs

In terms of VOCs, it was reported that several compounds of VOCs have a carcinogenic impact. EPA said that VOCs are responsible for 35-55% of the ambient air cancer in the USA, and out of 27 carcinogenic pollutants, 17 are VOCs. Health Canada found that VOCs also have noncarcinogenic effects ranging from drowsiness, weakness, fatigue, joint pain, tightness in chest at low concentration (<0.3 $\mu g/m^3$ ) to irritation, discomfort at a concentration of 0.3-25. In contrast, higher concentration caused a significant effect on the respiratory system and pain (Ayers, 2002). The development of VOCs depends strongly on the type of VOC compounds, as will be discussed later. It was reported that the reference concentration of VOCs is 0.56ppm, 0.018ppm for Benzene, 0.46ppm for Ethyl Benzene, 0.079ppm for toluene, and 0.0537ppm for Xylenes (Liu, *et al.*, 2015), benzene, ethylbenzene, toluene, and xylenes' concentration ranged from 0.16-0.8, 0.07-0.3, 0.16-0.81, and 0.34-1.67ppb, respectively are far below the reported limits of effect.

### 2.4 $PM_{10}$ and $PM_{2.5}$

Dust is the primary environmental challenge to the cement industry due to the high fugitive emissions from most operation processes. While the PME ambient air quality standard limited  $PM_{10}$  and  $PM_{2.5}$  at 340 and 35 $\mu g/m^3$ , there are no local indoor air quality standards for them. For indoor air quality, OSHA recommended a limit of 5  $mg/m^3$  for respirable dust and 15 $mg/m^3$  for total dust in the cement industry compared with 4 and 10 $mg/m^3$  according to UK standards (Alzboon *et al.*, 2019c). WHO reported a significant effect of  $PM_{10}$  on the respiratory system while  $PM_{2.5}$  has a high-risk factor due to its impact on the cardiopulmonary system, and can cause an increase in the mortality cases (6-13% per 10 $\mu g/m^3$ ) in case of long-term exposure time. In this study, the concentrations of  $PM_{10}$  in all sites ranged from 81-131 $\mu g/m^3$ , and all measurements were below the OSHA standard limit for the workplace and PME standard limit for ambient air quality. Although there is no exceedance in the concentration during the study period, it is expected that high exceedances could occur during extreme weather conditions due to the storm dusts that overrun the KSA most of the year. For this reason, the employees should be provided with PPE, and the plant should maintain continuous awareness training programs, implementing periodic medical checks and a regular sprinkling of water to control the fugitive dust.

### 2.5 $CO_2$

$CO_2$  is not regulated as an ambient air pollutant according to most international standards. It is generated as a result of the complete combustion of fuel in all combustion chambers. Additionally, it is emitted from the calcination process of materials in cement plants (EPA, 2018a). Alzboon *et al.* (2019c) found a high concentration of  $CO_2$  at the kiln area, crushing area, and clinker cooling area. According to the health and safety environment, the max allowable limit of  $CO_2$  in the workplace is 1500 and 5000ppm for short- and long-term exposure time, respectively (Alzboon *et al.*, 2019c). It was reported that the minimum concentration that can cause a health effect is 1000ppm for an exposure time of 2.5hr. At higher concentrations (5000ppm), employees showed many symptoms: lethargy, headache, irritation, mental slowness, sleep disruption, while death may occur at a concentration of 7% with a 5-minute exposure time (RFA, 2020). OSHA's standard limit of  $CO_2$  is 5000ppm. The average concentrations of  $CO_2$  in the measured sites ranged from 443 and 597ppm below the reported health effect limit, and therefore, no adverse health effects are expected.

### 2.6 Risk index

Figure 3 shows the hazard quotient (HQ) for each parameter in each site. The HQ values ranged from 0.0032-0.036, 0.00065-0.0057,  $5 \times 10^{-6}$ -0.00003, 0.0011-0.0054, 0.019-0.175, 0.006-0.03, 0.089-0.12, 1.62-2.62, and 0.37-0.6 for CO, SO<sub>2</sub>, H<sub>2</sub>S, NO<sub>x</sub>, O<sub>3</sub>, VOCs, CO<sub>2</sub>, PM<sub>10</sub> and PM<sub>2.5</sub> respectively. The average HQ of different pollutants can be ranked as PM<sub>10</sub>> PM<sub>2.5</sub>> CO<sub>2</sub>> O<sub>3</sub>> CO> VOCs> NO<sub>x</sub>> SO<sub>2</sub>> H<sub>2</sub>S. Except for PM<sub>10</sub>, all of the HQ values are <1 in all sites, which indicates that no significant potential health effect is expected from any pollutant individually (Liu *et al.*, 2015). The high HQ of PM<sub>10</sub> is attributed to the dusty weather in Saudi Arabia for most of the year. It worth mentioning that the monitoring process was conducted in October 2017, which is considered as a month with low dust in Saudi Arabia. The calculated hazardous indexes (HI) were: 3.59, 2.76, 2.18, and 2.67 for S1, S2, S3, and S4, respectively. Excluding the dust indicators (PM<sub>10</sub> and PM<sub>2.5</sub>), HI values are 0.37, 0.19, 0.13, and 0.15 for the four sites, respectively. This result indicated that dust emissions represent the major contributor of the HI, and this may be attributed to the dusty weather in KSA.

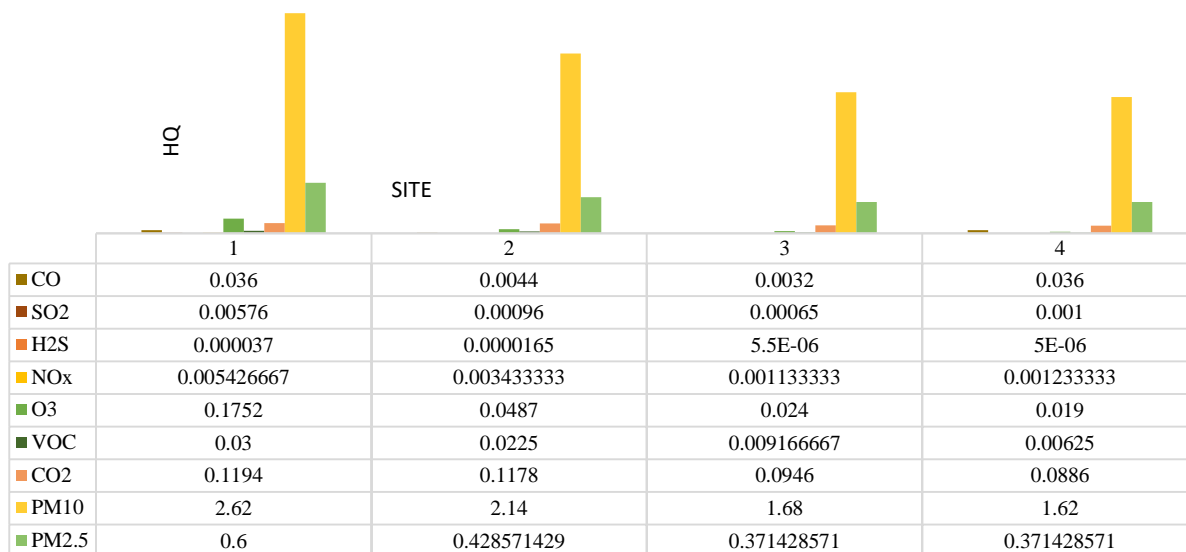


Fig. 3 HQ for all sites.

### 2.7 Target Organs risk factor

In order to determine each pollutant's effect on different organs, it was suggested that the respiratory system is affected by SO<sub>2</sub>, NO<sub>x</sub>, CO<sub>2</sub>, H<sub>2</sub>S, O<sub>3</sub>, and VOCs. The nervous system is affected by VOCs and H<sub>2</sub>S, while eyes' irritation is caused by CO<sub>2</sub>, SO<sub>2</sub>, NO<sub>x</sub>, H<sub>2</sub>S, O<sub>3</sub>, and VOCs. Allergic symptoms and hematology are related to the VOC emissions, while the development system is affected by VOCs. PM<sub>2.5</sub> affects the cardiovascular system (OEHHA, 2015). In order to determine the effect of each compound of VOCs individually, it was reported that Benzene has an impact on hematology, nervous and development systems, Ethyl-benzene affects alimentary, endocrine and growth strategy, toluene effects on nervous, respiratory and development. In contrast, xylenes impact the nervous, respiratory system, and eyes (Liu *et al.*, 2015).

Table 3 HI for the target organs.

Affected organ	S1	S2	S3	S4
Respiratory system	2.97	2.34	1.83	1.74
Nervous system	0.084	0.062	0.048	0.017
Cardiovascular system	0.60	0.43	0.37	0.37
Eye irritation	0.34	0.20	0.14	0.12
Allergy infection	0.084	0.062	0.048	0.017
Hematology	0.040	0.029	0.023	0.008
Alimentary endocrine	0.0007	0.0006	0.0005	0.0002
Development	0.051	0.038	0.029	0.011

Table 3 shows the results of the health risk for each of the target organs/system. The respiratory system is the most affected organ, while development is the lowest affected one. The affected organs/systems can be ranked based on the calculated risk factor as: respiratory system>cardiovascular system>Eye irritation>Allergy infection>Nervous system>Development>Hematology>Alimentary endocrine. For safe environments, it was reported that the HI index for the organ/system should be <1. Except for the respiratory system, all organs and systems have HI<1, which indicates that no health effect on

Table 4 Cancer risk factor.

Receptor	Ethylbenzene	Benzene	Sum
S1	3.28E-06	1.55E-05	1.88E-05
S2	3.13E-06	1.14E-05	1.45E-05
S3	2.43E-06	8.87E-06	1.13E-05
S4	8.70E-07	3.17E-06	4.04E-06

these organs is expected. High *HI* for the respiratory system is attributed to the high concentration of  $PM_{10}$  that causes high health risk.

## 2.8 Cancer risk factor

Regarding cancer risk factors due to VOCs' exposure, the risk unit factor of Ethyl-Benzene is  $1.09 \times 10^{-2}$  1/ppm and is  $1.92 \times 10^{-2}$  1/ppm for Benzes. The EPA reported that no significant evidence to assess the carcinogenic potential of Xylenes and toluene. The calculated cancer risk is shown in **Table 4**. The cancer risk values are below the lifetime cancer risk range of  $1 \times 10^{-4}$ – $1 \times 10^{-6}$  (Liu *et al.*, 2015). A narrow cancer risk factor is due to the low connotation of VOCs from the plant.

## 2.9 Model results

Ground-level CO, NO<sub>x</sub>, SO<sub>2</sub>, PM<sub>10</sub>, and PM<sub>2.5</sub> were predicted using the AERMOD model covering a domain area of 50x50km. The maximum concentrations of the predicted pollutants are listed in **Table 5**. The ultimate ground-level concentrations are far below the ambient air quality standards. The max concentration location is in the plant's SW due to the worst-case scenario of the calm wind in that direction.

**Table 5** Model results.

Pollutants	Averaging Period	Maximum model result ( $\mu\text{g}/\text{m}^3$ )	Standard ( $\mu\text{g}/\text{m}^3$ )	Direction related to the plant
CO	1-hour	157	40,000	SW
	8-hour	23	10,000	SW
	monthly	2174	660	SW
NO <sub>x</sub>	annual	Not calculated	100	SW
	1-hour	4318	730	SW
SO <sub>2</sub>	24-hour	246	365	SW
	24-hour	23.7	340	SW
PM <sub>10</sub>	24-hour	0.56	35	SW

### 2.9.1 Comparison of the monitoring data with the model results

**Figure 4** shows a comparison between the model and monitoring results for a one-hour averaging period. The model predicted higher values than the monitoring data for all of the measured parameters. While the monitoring data represents actual results in a specific time and specific environmental conditions, the model predicts the concentrations based on the worst-case scenario during the worst meteorological conditions and the lower atmospheric dispersion. This difference in the environmental conditions explains the difference between the model and the monitoring results. High wind speed causes high dispersion of pollutants, explaining the low concentration of pollutants during the monitoring period. The impact of other activities (vehicle emissions) is pronounced, where a high concentration of pollutants has been measured in S2 site, despite the long-distance between S2 and the plant.

## Conclusions

This study investigated the concentration of pollutants in a cement plant's surrounding area in Saudi Arabia and potential health risks due to the emitted pollutants. The following conclusions are illustrated:

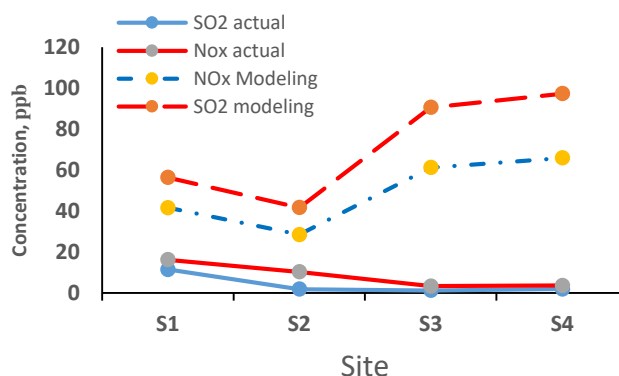
- The concentrations of carbon dioxide, carbon monoxide, nitrogen dioxide, sulfur dioxide, PM<sub>10</sub>, PM<sub>2.5</sub>, ozone, and volatile organic compounds at four locations ranging from 0.8 to 17km from the cement plant are within the allowable ambient air quality limits.
- In comparison to OSHA, only PM<sub>10</sub> concentration exceeded the indoor air quality standards.
- The site closest to the plant (0.8km ESE) recorded the highest concentrations of pollutants, while the other sites (17km NNE, 10.6km SE, 6.4km SSW) recorded significantly lower concentrations of pollutants.
- The calculated hazard quotient (*HQ*) of all pollutants studied (except for PM<sub>10</sub>) was lower than one, which indicated that no health effects were expected from these pollutants at the reviewed sites.
- Health risk assessment indicated that the dust from the cement plant is the major contributor to the *HQ*. The respiratory system is the most affected organ due to the emissions from the cement plant.

## Nomenclature

ASHRE

=American Society of Heating, Refrigerating and Air-Conditioning Engineers

[-]



**Fig. 4** Comparison of the model and the monitoring data



CO <sub>2</sub>	=Carbon Dioxide	[ppm]
CO	=Carbon Monoxide	[ppm]
EPA	=Environmental Protection Agency	[-]
HCl	=Hydrochloric Acid	[ppm]
HF	=Hydrofluoric Acid	[ppm]
H <sub>2</sub> S	=Hydrogen Sulfide	[ppm]
HI	=Hazard Index	[-]
HQ	=Hazard Quotient	[-]
NO <sub>2</sub>	=Nitrogen Dioxide	[ppm]
NO <sub>x</sub>	=Nitrogen Oxides	[ppm]
NPS	=National Park Service	[-]
OSHA	=Occupational Safety and Health Administration	[-]
O <sub>3</sub>	=Ozone	[ppm]
PM	=Particulate Matter	[ppm]
PME	=Presidency of Meteorology and Environment	[-]
PPE	=Personnel Protective Equipment	[-]
SO <sub>2</sub>	=Sulfur Dioxide	[ppm]
SRTM	=Shuttle Radar Topography Mission	[-]
TVOCs	=Total Volatile Organic Compounds	[-]
UF	=Unit Factor	[-]
WHO	=World Health Organization	[-]

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