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Air quality assessment and modelling of pollutants emission from a major cement plant complex in Nigeria

Jamiu Adetayo Adeniran[a], Rafiu Olasunkanmi Yusuf[a], Bamidele Sunday Fakinle[b], Jacob Ademola Sonibare[c,*]

[a] Environmental Engineering Research Laboratory, Department of Chemical Engineering, University of Ilorin, Ilorin, Nigeria
[b] Department of Chemical Engineering, Landmark University, Omu-Aran, Kwara State, Nigeria
[c] Group Environment Department, Dangote Oil Refining Company Ltd., Dangote Industries Ltd, Union Marble House, 1 Alfred Rewane Road, P.O. Box 40082, Falomo, Ikoyi, Lagos, Nigeria

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ABSTRACT

Cement manufacturing contributes to the elevation of air pollutants in the atmosphere and thus impact on the nearby communities. This study assessed air quality in a major Cement Plant in Ibese Ogun State, Nigeria, through an ambient air quality monitoring and air emission dispersion modelling. Particulate Matter (PM) and gaseous pollutants were measured using portable samplers and AERMOD View was used for the emission dispersion modelling. Combustion products including SO_2, NO, NO_2, CO and VOCs were the gaseous pollutants detected along the complex fenceline and in the receptor environments. Pollutants measurements were undertaken at 23 locations within the fence line and receptor locations. The daily SO_2 and NO_2 Federal Ministry of Environment - Nigeria (FMEnv) limits were exceeded in ten (10) and five (5) locations along the fenceline, respectively. Particulates were detected in all the locations along the fenceline and in the communities. The cumulative gaseous pollutants resulting from simultaneous operations of all the identified plant air emission point sources are 0.01–276.13% of their respective 24-h limits along the fenceline, with 1-h SO_2 within the threshold limit at all fenceline locations, but 1-h NO_X exceeds the threshold limit at all locations 16–21 times. The 24-h CO and VOCs are within their limits at all fenceline locations; however the 24-h SO_2 and NO_X are breaching the limits at some locations 30–34 times (0.34–0.39% of the investigation period) and 44–87 times, respectively. Daily and Annual averaging concentrations of PM_{10} was 14.32–31.54% and 4.90–52.60% of their respective limits. Process facilities are the major point sources of atmospheric emissions identified in the factory. Several fugitive emission sources were also identified during the field work. Comprehensive evaluation of the fugitive emission sources should be carried out in the cement plant for immediate attention.

1. Introduction

Cement is the most common and widely used binding material for aggregates in construction. The production of cement has increased astronomically due to rapid urbanization. As of 2014, the annual global production of cement reached 4.3 billion tonnes (Karstensen et al., 2016). In Nigeria, annual production of cement increased significantly from less than 2 million tonnes in 1990 to over 28 million tonnes in the year 2013 (Oni et al., 2017). Rapid industrialization, urbanization and the need to increase local contents of manufactured commodities has brought about the increase in the number of cement manufacturing plants *vis-a-vis* quantity of cement produced in Nigeria. Cement manufacturing involves a series of processes and use of high volume materials. The use of a large amount of energy and materials is a major requirement in cement manufacturing (Aprianti, 2017; Ayer and Dias, 2018; Salas et al., 2016). High demand, rising infrastructure and availability of raw materials have encouraged local production.

Production of cement is associated with the release of hazardous air pollutants from the manufacturing activities and power generation utilities (Hua et al., 2016; Zou et al., 2018). Air pollutants released from the production activities include particulates (PM), carbon monoxide (CO), oxides of nitrogen (NO_X), sulphur dioxide (SO_2), and

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* Corresponding author. Permanent address: Environmental Engineering Research Laboratory, Department of Chemical Engineering, Obafemi Awolowo University, Ile – Ife, Nigeria.

E-mail addresses: adeniran.ja@unilorin.edu.ng (J.A. Adeniran), yusuf.ro@unilorin.edu.ng (R.O. Yusuf), fakinle.bamidele@lmu.edu.ng (B.S. Fakinle), asonibar@oauife.edu.ng (J.A. Sonibare).

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hydrocarbons. Pollutants are released from raw material handling, clinker production and storage, cement bulk loading, packaging of final product and power utilities (Fore and Mbohwa, 2015; Gupta et al., 2012; Hasanbeigi et al., 2012). Air pollutants released from stationary and mobile sources in cement manufacturing plants can have a negative impact on environment and health. Previous studies have suggested that communities around cement facilities receive greater doses of pollutants emitted (Abdul-Wahab, 2006; Bertoldi et al., 2012; Eom et al., 2017; Jayadipraja et al., 2017; Rovira et al., 2011). Studies have attributed pollutants dispersed from cement production plants to increased morbidity and premature mortality of people living in the nearby receptor locations (Bertoldi et al., 2012; García-Pérez et al., 2015; Koh et al., 2011). A wide range of health challenges ranging from infertility, cancer, respiratory diseases, pulmonary and cardiovascular diseases have been attributed to exposure to PM and gaseous fuel combustion products (Adeniran et al., 2017b; Akintunde et al., 2017; Olatunji et al., 2015).

Information about air quality status and modelling of air pollutants concentration levels in Nigerian cement plants' receptor environments is limited in the literature. Dispersion modelling tools that have proven useful in estimating air quality impact of industrial activities on receptor environments include CALPUFF, AERMOD and HYSPLIT (Abdul-Wahab et al., 2018; Abdul-Wahab, 2006; Çetin Doğruparmak et al., 2018; Ma et al., 2018). The AERMOD has been described as a more refined dispersion model in complex and simple terrain for determining the impact of air pollutants emanating from industrial sources on receptors (Abril et al., 2016; Adesanmi et al., 2016; Kumar et al., 2018; Otero-Pregigueiro et al., 2018; Tamjidi et al., 2018; Teggi et al., 2018; Tunlathorntham and Thepanondh, 2017; Tuygun et al., 2017). Determination of concentration levels of pollutants within the fenceline of the plant and those transported to the nearby communities is important. This will assist in the evaluation of associated potential risks and in the formulation of relevant policies and control measures. The prime objective of this study is to investigate the variability of concentration levels of pollutants associated with the operations of the plant to ambient air quality in its area of influence.

2. Methodology

2.1. Description of the sampling location

The studied plant is a world-class cement producing facility located in Ibese, Ogun State, about 120 km north-west of Lagos, Nigeria. The plant is equipped with four production lines, namely Lines 1 & 2 and Lines 3 & 4, having a capacity of 6 million metric tonnes per annum each and a plant total of 12 million tonnes per annum. They commenced operation in February 2012 and late 2014, respectively. The plant runs on natural gas with a recent conversion to coal due to the shortfall of gas supply in the country and having capacity to use diesel as back-up fuel. Plant operations include product packing (12 cement packing machines with a capacity of 2400 bags/hr), truck loading facility and product delivery by means of approximately 1500 trucks. Limestone is supplied by a quarry operated by the Plant with an expected life time of up to 78 years. Power is supplied by 5 × 37 MW captive power plants. The Plant was designed to guarantee 30 mg/Nm^3 particulate emissions at the kiln stacks, a threshold which is below the Nigerian, IFC, and European emission standards. The Plant is surrounded by fallow lands, farm lands and some communities (Fig. 1). To its southwest are located Ilaro and Ibese, while Balogun, Wasinmi Imasaye and Cement Plant Staff Quarters are located to its northwest. To the north of the Plant are located Abule Oke and Abule Maria with Aga Olowo and Afami located in the east of the plant. The respective coordinates of the sampling locations are presented in Table 1.

2.2. Air Quality Assessment

2.2.1. Particulate matter (PM) monitoring

Particulate matter (PM) was measured during this survey with an AEROCET 531S Particle Mass/Particle Count Monitor, supplied by Met One Instruments. $PM_{2.5}$, PM_{10}, and TSP fractions of the total particulates were the focus of these measurements. Measured PM values were adjusted using the calibration equations previously reported (Adeniran et al., 2017a, 2018).

2.2.2. Gaseous pollutants monitoring

All the gaseous pollutants were monitored with the WolfPack™ Modular Area Monitor. All the gaseous pollutants were monitored with the WolfPack™ Modular Area Monitor, an environmental air monitoring equipment. It is embedded with WinCE® computer that runs GrayWolf's WolfSense® 2009 application software for displaying, documenting, and logging key parameters. The equipment monitors up to 20 sensors and simultaneously generates 30 readings and runs on rechargeable battery that can lasts 15 h of continuous measurements. It has facility for Short Term Exposure Limit (STEL) from which the carbon monoxide concentration for the last 15 min can be determined; the Time Weighted Average (TWA) from which the accumulated reading of the gas concentration since the monitor was turned on is divided by 8 h; and the Peak Reading, which is the highest reading since the monitor was turned on. Its resolution for NO, NO_2, and O_3 is 0.01 ppm and 0.1 ppm for SO_2, NH_3, VOCs, and CO. Concentration of SO_2 less than 0.1 ppm may not be detectable because of the detection limit of the SO_2 sensor.

2.2.3. Air Quality Assessment

Several approaches were employed to assess the present air quality status in Cement Plant located in Ibese, Nigeria. These include comparison with the Ambient Air Quality Standards (AAQS), computation of Air Quality Index (AQI) and execution of air emission dispersion modelling.

2.2.4. Comparison with Ambient Air Quality Standards (AAQS)

The present air quality status of the Cement Plant Complex Fenceline (extent of plant), Host Communities and Production were investigated by determining their level of compliance with the National and World Bank Ambient Air Quality Standards (Table S1).

2.2.5. Air quality index

The air quality index (AQI), a tool used to better inform the public about air quality, was employed in this study to determine the status of ambient air quality associated with operation of Cement Plant Complex in Ibese, Ogun state, Nigeria. It is an index for reporting daily air quality and it indicates how clean or polluted an air shed is with the possible associated health effects that might be of concern. It is established for six common air pollutants (particulate matter, carbon monoxide, sulphur dioxide, ozone, volatile organic compounds and nitrogen dioxide) for which there is evidence of adverse effects on health and the environment. The AQI has been found to be a useful communication tool in translating technical air pollution information that the public can understand and use (WHO, 2006). Summarized in Table S2 are the classes of AQI and their possible health implications are reported in Table S3.

Calculation of AQI is carried out using the USEPA (2006) method with the guiding equation (1)

$$I_P = \frac{I_{Hi} - I_{Lo}}{BP_{HI} - BP_{Lo}}(C_P - BP_{Lo}) + I_{Lo} \tag{1}$$

where:

I_P = the index value of pollutant p
C_p = the truncated concentration of pollutant p
BP_{HI} = the breakpoint that is greater than or equal to C_P as given in

Fig. 1. Location of the cement plant in Ibese, Ogun state, Nigeria.

Table S4
BP_{Lo} = the breakpoint that is less than or equal to C_p as given in Table S4
IH_i = The AQI value corresponding to BPH_i
IL_o = The AQI value corresponding to BPL_o

2.3. Air pollutants contribution determination

The air pollutants' contribution from the facilities to ambient levels at the Plant Fenceline and the communities was determined using the ISC-AERMOD View version 16216. The major sources of air emissions from the plant production processes include the kilns, and the cement mill stacks.

2.3.1. Raw mill

An important point of call for raw materials meant for cement production in any cement plant production line is the raw mill. In this mill, raw materials are reduced to desirable sizes that can be managed in the kiln. During this size reduction process, there are dust emissions which are being controlled by the air pollution control equipment which may be baghouse filters or an Electrostatic Precipitator (ESP). Depending on the efficiency of the air pollution control equipment, dust emissions from this source can be of concern in the cement plant. The Plant Line 1&2 raw mill emissions are conveyed to the two Line's ESP stacks for dust abatement while Lines 3&4 emissions are conveyed to the two Lines' Baghouse filter stacks.

Table 1
The cement plant complex fenceline and host communities sampling location.

Sampling Location			Designation	Immediate Community
Code	Coordinate			
	Latitude	Longitude		
S1	07° 00.041′ N	003° 02.944′ E	Mine Office Area	Ibese
S2	07° 00.082′ N	003° 03.237′ E	Clay Storage Area	–
S3	07° 00.239′ N	003° 03.406′ E	E Corner	–
S4	07° 00.114′ N	003° 03.415′ E	NE Corner	Ibese
S5	07° 00.155′ N	003° 03.413′ E	NE Fence	–
S6	07° 00.380′ N	003° 03.275′ E	E Fence	–
S7	07° 00.661′ N	003° 03.109′ E	NE Fence	Afami
S8	07° 00.652′ N	003° 02.986′ E	Colony	–
S9	07° 00.645′ N	003° 02.874′ E	Residence	–
S10	07° 00.621′ N	003° 02.615′ E	Lines 1 & 2 Gate	–
S11	07° 00.623′ N	003° 02.500′ E	NW Corner	Wasinmi Imasaye
S12	07° 00.346′ N	003° 02.562′ E	W Fence	–
S13	07° 00.052′ N	003° 02.733′ E	SW Fence	Ibese
S14	06° 59.954′ N	003° 02.801′ E	Lines 3 & 4 Gate	–
S15	06° 54.904′ N	003° 01.596′ E	Ilaro	10 km SW of Plant
S16	06° 57.753′ N	003° 02.156′ E	Ibese Community	5 km SW of Plant
S17	07° 01.174′ N	003° 01.501′ E	Balogun	2 km NW of Plant
S18	07° 00.897′ N	003° 01.864′ E	Wasinmi Imasaye	2.1 km NW of Plant
S19	07° 01.285′ N	003° 02.532′ E	Abule Oke	1.7 km North of Plant
S20	07° 01.961′ N	003° 02.971′ E	Abule Maria	3 km North of Plant
S21	07° 00.691′ N	003° 06.072′ E	Aga Olowo	5.7 km East of Plant
S22	07° 00.782′ N	003° 03.810′ E	Afami	1.9 km East of Plant
S23	07° 01.015′ N	003° 02.375′ E	Cement Estate	0.6 km NW of Plant
	06°56.489′ N	003°13.743′ E	Ewekoro	20.17 km SE of Plant
	07° 09.442′ N	003°20.589′E	Abeokuta	37.24 km NE of Plant

2.3.2. Kiln

Burning processes inside the kiln, its rotation, and the rapid flow of gases cause raw meal particles to become airborne. These are normally vented out through stacks via air emission control equipment and after heat recovery to the extent possible. In addition to the particulate matter are the gaseous emissions. The production of cement involves chemical reactions in which the feed mix in the kiln is heated to high temperatures and oxidation of the feed mix occurs. This oxidation of carbon compounds results in the formation of CO and CO_2. Similarly, NO_X emissions are generated during fuel combustion by oxidation of chemically-bound nitrogen in the fuel and thermal fixation of nitrogen in combustion air. From sulphur compounds in the raw materials and fuel, SO_2 will be generated while incomplete combustion of fuel may result in hydrocarbon (including methane) emissions. The Plant operates four (4) kiln stacks, two (2) for Lines 1&2 and two (2) for Lines 3&4. All lines are provided with Electrostatic Precipitators.

2.3.3. Cement mill

Cement grinding in the cement mill generates considerable amount of dust. It has been established that about 7–10% of cement may be lost due to uncontrolled emissions from the cement mill. Lines 1&2 and Line 3&4 operate three (3) and four (4) stacks, respectively, all provided with bag house filters.

2.4. Emission sources from the cement plant utilities

The major sources of point air emissions associated with the plant utilities are the coal mill and the power plants.

2.4.1. Coal mill

Size reduction of coal to size that can meet the kiln requirements necessitated the installation and operation of a coal mill in the plant. Four (4) stacks are identified as point sources of air emissions in Lines 1 &2, and Line 3&4 coal mills. All these stacks are provided with bag house filters.

2.4.2. Power generators

Fuel combustion activities during operation of power generators usually result in generation of air pollutants as combustion products. The oxidation of carbon compounds available in fuel may result in the formation of carbon monoxide (CO) when there is incomplete combustion, but carbon dioxide (CO_2) when complete combustion is achieved. Similarly, oxides of nitrogen (NO_X) are emitted during fuel combustion by oxidation of chemically-bound nitrogen in the fuel and by thermal fixation of nitrogen in the combustion air. Combustion of sulphur compounds from sulphur in the fuel may also result in the generation of sulphur dioxide (SO_2). While particulates may be generated as a result of some operating conditions in the combustion chambers of the power plants, there may also be emission of unburnt hydrocarbons. The Plant operates on privately generated electricity via five electric power generators. Three of these power generators are 37 MW Siemen SGT-800 and two units are 45 MW GE Turbine gas turbines.

Summarized in Table 2 are the emission sources from Lines 1&2; and 3&4 used in the modelling exercise with their emission rates and stack parameters. The point sources identified from electric power plants are in Table 3. Their air pollutants emission rates obtained from the Plant are summarized in Table 4 for the lines and the Power Plants.

2.5. Emission modelling protocol

This air emission modelling exercise used the AERMOD View emission dispersion modelling software version 16216. The software is a user-friendly interface for three U.S. EPA air dispersion models: ISCST3, ISC-PRIME and AERMOD. It uses pathways that compose the runstream file as the basis for its functional organization. These pathways include: Control Pathway (CO) where the modelling scenario, and the overall control of the modelling run is specified; Source Pathway (SO), where the sources of pollutant emissions are defined; Receptor Pathway (RE), where the receptors to determine the air quality impact at specific locations are defined; Meteorology Pathway (ME), where the atmospheric conditions of the area being modelled are defined, so it can be taken into account when determining the distribution of air pollution impacts for the area; Terrain Grid Pathway (TG), where the option of a gridded terrain data to be used in calculating dry depletion in elevated or complex terrain are taken; Output Pathway (OU), where the output results necessary to meet the needs of the air quality modelling analyses are determined.

2.5.1. Emission sources input scenarios

Four operational scenarios of air emission from the identified sources at the Plant were considered in this study. The scenarios estimated the ground level concentrations of air pollutants associated with the operation scenarios within the Plant, along its fence line, and at it host communities for the prevailing meteorological conditions. The four operational scenarios investigated are as summarized below.

Scenario 1: This scenario assumed that only Lines 1&2 are in operation using both the coal mill and the power generators.
Scenario 2: In this scenario, it was assumed that Lines 1&2 is down for maintenance while Lines 3&4 are in operation using the coal mill and the five power gas turbines.
Scenario 3: Scenario 3 investigated a situation in which the four cement lines are down for maintenance but using all the five units' power plants. It is the Cement Plant Complex power plants "worst case" scenario.
Scenario 4: This scenario investigated the operations and utilities "worst case" scenario, i.e. the four production lines are in operation

Table 2
Point sources of air emissions in the cement plant complex.

S/No	Facility	Coordinates		Height (m)	Diameter (m)	Exit Velocity (m/s)	Exit Temp (K)
		Latitude (North)	Longitude (East)				
Lines 1&2							
1	Raw Mill A ESP Stack	07° 00.467′	003° 02.951′	117.7	4.5	21.39	378
2	Raw Mill B ESP Stack	07° 00.432′	003° 02.952′	117.7	4.5	21.39	378
3	Line A Cooler ESP Stack	07° 00.426′	003° 02.804′	40	4	14.49	523
4	Line B Cooler ESP Stack	07° 00.396′	003° 02.832′	40	4	14.49	523
5	Cement Mill A Bag house Filter Stack	07° 00.446′	003° 02.728′	55	4.25	23.1	363
6	Cement Mill B Bag house Filter Stack	07° 00.445′	003° 02.721′	55	4.25	23.1	363
7	Cement Mill C Bag house Filter Stack	07° 00.431′	003° 02.715′	55	4.25	23.1	363
8	Coal Mill A Bag house Filter Stack	07° 00.453′	003° 02.914′	57	2	20.66	353
9	Coal Mill B Bag house Filter Stack	07° 00.425′	003° 02.914′	57	2	20.66	353
Lines 3&4							
10	Raw Mill C Bag house Filter Stack	07° 00.110′	003° 02.837′	117.7	4.5	21.39	369
11	Raw Mill D Bag house Filter Stack	07° 00.069′	003° 02.891′	117.7	4.5	21.39	369
12	Line C Cooler ESP Stack	07° 00.226′	003° 02.822′	40	4.25	17.62	523
13	Line D Cooler ESP Stack	07° 00.208′	003° 02.867′	40	4.25	17.62	523
14	Cement Mill D Bag house Filter Stack	07° 00.283′	003° 02.739′	55	4.5	20.61	363
15	Cement Mill E Bag house Filter Stack	07° 00.231′	003° 02.774′	55	4.5	20.61	363
16	Cement Mill F Bag house Filter Stack	07° 00.240′	003° 02.785′	55	4.5	20.61	363
17	Cement Mill G Bag house Filter Stack	07° 00.317′	003° 02.813′	39	2.8	45.85	363
18	Coal Mill C Bag house Filter Stack	07° 00.144′	003° 02.894′	57.5	2	20.66	353
19	Coal Mill D Bag house Filter Stack	07° 00.137′	003° 02.898′	57.5	2	20.66	353

using all the five gas turbines.

2.5.2. Receptors locations

The Cement Plant Complex is located close to very important communities and settlements. Both the immediate and distant environments of the project site were considered as receptors to air pollutants from this study. All the significant receptors in a 50 km radius within the Plant location were considered in the study to have a better understanding of the ait pollutants emission impact of the plant complex operations on the wider receptor environments.

2.5.3. Meteorological data

An essential input requirement of ISC-AERMOD View air dispersion modelling is the meteorological information. Surface and upper air observations of Ibese, the Cement Plant host community, were compiled using data from Lakes Environmental observations (Met Data Order # MET 134283) and the project acquired surface meteorological data on site. They have winds with prevalence for south-westerly direction (Fig. 2).

2.5.4. Land surface characteristics data

Several parameters representing certain features that affect complex dispersion processes to accomplish its calculations are used in the ISC-AERMOD View, the adopted modelling software. Information is also sought about the nearby terrain and surface features that induce turbulence in addition to hourly surface and upper air meteorological data. These include the roughness length, which represents the height of trees or other obstructions to wind flow. The parameters must be specified for each upwind sector since they will vary depending on land use in each direction the wind may blow. For the area around the project site, there is only one type of surface: overland winds which come principally with tree heights ranging generally from 10 to 15 m. The value used for the roughness length in this study is 0.16 for the overland fetch as recommended by the U.S. EPA for these types of terrain.

3. Results and discussion

3.1. Ambient air quality status along the Cement Plant Complex Fenceline

The measured air quality parameters along the Cement Plant Complex during the study are presented in Table 5.

3.1.1. Gaseous pollutants

The gaseous pollutants detected along the fenceline were SO_2, NO, NO_2, CO and VOCs, though H_2S, NH_3 and O_3 were also monitored. The 1 – hour concentrations measured are indicated in Table 5. In none of the locations was the 0.1 ppm 1-h SO_2 FMEnv limit exceeded.

The daily average of the pollutants measured are indicated in Table 6. The daily SO_2 0.01 ppm FMEnv limit was exceeded at all the sampling locations along the fenceline except at the Mine Office Area (S1), Clay Storage Area (S2), NE Fence (S7), and along the West fence (S12) of the Plant.

The daily NO 0.04–0.06 ppm limit was not breached in any location along the fenceline. However, the daily NO_2 breached the same limit in five locations including the Residence (S9), NW Corner (S11), W Fence (S12), SW Fence (S13) and Lines 3&4 Gate (S14).

In none of the sampling locations along the fenceline was the daily CO 10 ppm FMEnv limit and the daily VOCs 1.6 ppm FMEnv limit breached during the study. Since all the detected gaseous pollutants along the fenceline are combustion products, their sources could

Table 3
Point sources of air emissions in the cement power plants.

Name	Capacity (MW)	Latitude (North)	Longitude (East)	Height (m)	Diameter (m)	Exit Velocity m/s	Temp (K)
Siemen SGT-800	37.745	07° 00.580′	003° 03.059′	15.00	4.5	14.49	814
Siemen SGT-800	37.745	07° 00.566′	003° 03.031′	15.00	4.5	14.49	814
Siemen SGT-800	37.745	07° 00.553′	003° 03.064′	15.00	4.5	14.49	814
GE LM6000	45	07° 00.529′	003° 03.069′	27.5	2.8	17.62	723
GE LM6000	45	07° 00.513′	003° 03.069′	27.5	2.8	17.62	723

Table 4
Air emissions rates from the cement plant lines and power plants.

Facility	Emission Rate (g/s)				
	PM_{10}	SO_2	NO_X	CO	VOCs
Lines 1&2					
Raw Mill A ESP Stack	26.1949	163.021	100.247	0.0594	0.1435
Raw Mill B ESP Stack	33.6791	163.021	104.803	0.0357	0.1435
Line A Cooler ESP Stack	2.7313	–	–	–	–
Line B Cooler ESP Stack	3.2776	–	–	–	–
Cement Mill A Bag house Filter Stack	9.5525	–	–	–	–
Cement Mill B Bag house Filter Stack	9.4509	–	–	–	–
Cement Mill C Bag house Filter Stack	5.5152	–	–	–	–
Coal Mill A Bag house Filter Stack	2.8364	–	–	–	–
Coal Mill B Bag house Filter Stack	1.363	–	–	–	–
Lines 3&4					
Raw Mill C Bag house Filter Stack	8.7055	167.731	558.973	0.0169	0.883
Raw Mill D Bag house Filter Stack	12.0428	170.448	549.339	0.0184	0.883
Line C Cooler ESP Stack	8.4987	–	–	–	–
Line D Cooler ESP Stack	8.7487	–	–	–	–
Cement Mill D Bag house Filter Stack	2.9501	–	–	–	–
Cement Mill E Bag house Filter Stack	3.6057	–	–	–	–
Cement Mill F Bag house Filter Stack	3.2779	–	–	–	–
Cement Mill G Bag house Filter Stack	–	–	–	–	–
Coal Mill C Bag house Filter Stack	0.0149	–	–	1.8629	–
Coal Mill D Bag house Filter Stack	0.0149	–	–	1.7387	–
Power Plants					
Siemen SGT-800 Turbine	0.0613	0.1096	9.5596	5.7167	0.0664
Siemen SGT-800 Turbine	0.0575	0.1028	8.9673	5.3625	0.0623
Siemen SGT-800 Turbine	0.0525	0.0938	8.1869	4.8958	0.0568
GE LM6000 Turbine	0.0706	0.1262	11.0089	6.5834	0.0764
GE LM6000 Turbine	0.0707	0.1263	11.0217	6.591	0.0765

include the kiln, the electric power plants and mobile plants.

3.2. Atmospheric particulates along the fenceline

Particulates were detected at all the sampling locations along the fenceline during the study as reported in Table 5. The 600 μg/m^3 FMEnv 1-hr limit for TSP was exceeded only at Lines 1&2 Gate (S10). Daily $PM_{2.5}$ and TSP were within their respective limits; however, PM_{10} exceeded the FMEnv limit at Lines 1& 2 Gate (S10) and at SW fence (S13).

3.2.1. Air quality index along the fenceline

The Air Quality Index (AQI), defined using the criteria are summarized in Table S5. In general, the air quality along the Plant fenceline with respect to $PM_{2.5}$, PM_{10} and CO is Good. However, using SO_2 as the air quality indicator along the fenceline, the air quality status during the study was Good in 29% of the sampling locations, and Moderate in 71% of the locations. About 64% of the sampling location has Good air quality with respect to NO_2 while 29% has Moderate air quality. A location (Residential Area of the Plant) which represents 7% of the sampling locations had Unhealthy for Sensitive Groups air quality status. These sensitive people include people with asthma or other respiratory diseases, the elderly, and children are the groups most at risk.

3.3. Ambient air quality in the cement plant complex host communities

The measured ambient air quality parameters in the communities during the study are summarized in Table S6.

3.3.1. Gaseous pollutants

The monitoring results at the communities are summarized in Table S7. Though NO was also monitored, it was not detected in any of the communities. The 1-h SO_2 FMEnv 0.1 ppm limit was not exceeded in any of the communities.

The daily averages of the measured SO_2, NO_2, CO, and VOCs concentrations are reported in Table S7. In none of the sampling locations was the daily FMEnv limits for any of the four gaseous pollutants exceeded.

3.3.2. Atmospheric particulates levels in the host communities

Particulates were also detected in all the sampling locations in the investigated host communities and the related TSP, PM_{10} and $PM_{2.5}$ are reported in Table S6. The 600 μg/m^3 TSP FMEnv 1-h limit was not exceeded in any of the communities. In none of these communities were the particulates daily FMEnv limits exceeded. In particular, the daily $PM_{2.5}$ was 19.02–38.35% of the limit, PM_{10} was 33.27–82.54% of the limit, and TSP was 22.53–84.78% of the limit.

3.3.3. Air quality index of the cement plant complex host communities

Using $PM_{2.5}$ and PM_{10} particulate fractions AQI obtained from their daily concentrations, the air quality at the host communities during the campaign was, in general, Good except at Aga Olowo where it was of Moderate Quality (Table S8). Similarly, the AQI in terms of SO_2, NO_2 and CO could be regarded as Good at all the communities. Results of ground level concentrations of air pollutants associated with all the identified point sources of air emissions during the air quality survey as obtained from the air emission dispersion modelling are presented in this section. Operation scenarios and averaging period standards of air pollutants are the guide in the results summary.

3.4. Cement plant complex air pollutants contributions along its fenceline

The gaseous pollutants from simultaneous operations of all the identified point sources are 0.01–276.13% of respective limits (Table S9). 1-hour SO_2 is within its limits in all the locations, however 1-h NO_X limit is breached in 16–21 times (0.18–0.24% of the investigation period). Similarly, 24-h CO and VOCs are within their limits at all the locations, but SO_2 and NO_X breached the respective threshold limits at some locations 30–34 times (0.34–0.39% of the investigation period) and 44–87 times (0.50–0.99% of the investigation period), while 24-h and annual PM_{10} are 14.32–31.54% and 4.90–52.60% of their respective limits.

The maximum ground level gaseous pollutants along the fence line associated with Lines 1&2 point emission sources are 0.01–97.69% of limits with the minimum and maximum from 24-h CO and SO_2 respectively. Its 24-h PM_{10} concentrations are 9.82–21.04% of the limit with annual PM_{10} levels of 3.35–34.35% of the limit (Table S9). Operation of Lines 3&4 generates gaseous pollutants which are 0.02–244.15% of their respective limits along the fenceline with the 1-h NO_X limit breached on 21–145 times (0.24–1.66% of the investigation period) (Table S10). While their minimum is from 24-h CO, the maximum are from 1-h NO_X. Its 24-h PM_{10} are 4.46–15.24% of limit with the annual PM_{10} being 1.55–19.60% of the limit.

Simultaneous operation of the five gas turbines generates gaseous pollutants within their respective limits (Table S11). Its minimum is from 24-h CO and the maximum from 1-h NO_X. Its daily PM_{10} concentration is 0.04–0.08% of its limit with annual PM_{10} levels of 0.15% of the limit.

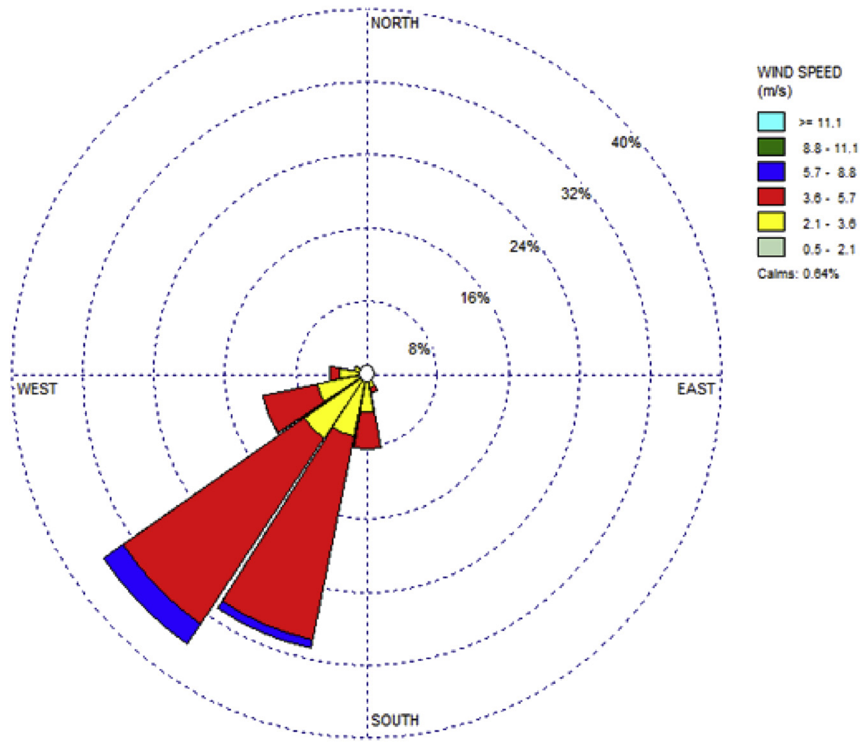

Fig. 2. Annual upper wind condition of the cement plant complex.

Table 5
The cement plant complex fenceline measured air quality concentration.

Sampling Location		Concentration (μg/m^3)			Concentration (ppm)			
Code	Designation	$PM_{2.5}$	PM_{10}	TSP	SO_2	NO_2	CO	VOCs
S1	Mine Office Area	15.5	43.4	140.7	0.02	0.0	1.4	0.15
S2	Clay Storage Area	11.4	57.7	162.0	0.02	0.0	0.5	0.16
S3	E Corner	12.6	51.6	122.3	0.04	0.15	0.1	0.01
S4	NE Corner	11.8	43.0	95.0	0.04	0.0	0.0	0.06
S5	NE Fence	13.0	56.7	131.6	0.04	0.0	0.0	0.06
S6	E Fence	12.4	63.2	164.6	0.04	0.0	0.5	0.05
S7	NE Fence	12.7	98.5	292.9	0.03	0.15	0.0	0.04
S8	Colony	13.6	85.6	176.2	0.04	0.07	0.0	0.04
S9	Residence	12.7	67.8	127.4	0.04	0.29	0.0	0.0
S10	Lines 1 & 2 Gate	17.9	242.0	640.6	0.04	0.0	0.0	0.03
S11	NW Corner	1.7	3.2	7.3	0.04	0.24	0.9	0.03
S12	W Fence	16.0	73.2	136.2	0.03	0.25	0.0	0.03
S13	SW Fence	15.5	171.0	337.6	0.04	0.67	0.0	0.04
S14	Lines 3 & 4 Gate	13.7	93.9	241.7	0.04	0.71	0.0	0.0
FMEnv Limit		-	-	**600**	**0.1**	-	-	-

3.5. The cement plant complex air pollutants contributions to the host communities

Reported in Fig. 3 are the detailed contours of ground level concentrations of both the gases and particulates associated with operations of the Cement plant impact on the receptor environment. The maximum ground level concentrations obtained from the modelling results were compared with the regulatory limits of FMEnV and the World Bank for the worst-case scenario (Table 7). Operation of the five units power plant simultaneously results in gaseous pollutants in the communities that are 0.0–14.86% of their respective limits. Their daily and annual PM_{10} are 0.02% and 0.05% of their respective limits (Table S12). Gaseous pollutants from Lines 1&2 in the host and neighbouring communities are 0.01–81.58% of their limits with the minimum and maximum from 24-h CO and SO_2, respectively (Table S13). The daily PM_{10} concentrations are 2.68–13.84% of the limit with the annual PM_{10} levels at 0.40–3.85% of the limit. Gaseous pollutants from Lines 3&4, they are 0.00–240.02% of limits in the communities, and the daily PM_{10} are 1.36–4.10% of the limit with annual PM_{10} level of 0.20–3.15% of limit. Only 1-h NO_X exceeds its limit 48–101 times (0.55–1.15% of the period under investigation).

The gaseous pollutants from simultaneous operations of all the identified sources of air emissions are 0.00–294.66% of their respective limits in the investigated communities (Table 7, Table S14). Only 1-h NO_X limit is exceeded at all the investigated communities and in 48–101 times (0.55–1.15% of the period under investigation). The daily PM_{10} is 3.96–24.42% of its limit with annual level of 0.60–5.95% of the limit.

4. Conclusions

Utilization of air quality modelling tools to investigate the impact of industrial activities on the dispersion of pollutants released into the atmosphere and its attendant impact on the receptor environments is imperative. Air Quality Assessment study and dispersion modelling was carried out on a major Cement Plant Complex in Ibese, Ogun State, Nigeria. Process facilities and utilities air emission control equipment were found to be the major point sources of atmospheric emissions in the factory. Gaseous pollutants from simultaneous operations of all the identified point emission sources in the plant were 0.01–276.13% of statutory limits along its fenceline; 24-h and annual PM_{10} were 14.32–31.54% and 4.90–52.60% of their respective limits. 1-hour SO_2 from simultaneous operations of all the points sources is within the limit at all the fenceline locations. However, 1-h NO_X exceeds its limit at all the locations while 24-h CO and VOCs were within their limits in all the locations. The 24-h concentration values of SO_2 and NO_X breached their limits in some locations. Gaseous pollutants and particulates from simultaneous operations of all point sources of air emissions are within their limits in the surrounding communities except for the 1-h NO_X concentration levels. Further comprehensive studies should be carried out to investigate the emission and dynamics of NO_2 from the

Table 6
The cement plant complex fenceline extrapolated daily air quality concentrations.

Sampling Location		Concentration (μg/m^3)			Concentration (ppm)				
Code	Designation	$PM_{2.5}$	PM10	TSP	SO_2	NO	NO_2	CO	VOCs
S1	Mine Office Area	5.9	16.6	54.0	0.01	0.00	0.00	0.54	0.06
S2	Clay Storage Area	4.4	22.1	62.1	0.01	0.00	0.00	0.19	0.06
S3	E Corner	4.8	19.8	46.9	0.02	0.00	0.06	0.04	0.00
S4	NE Corner	4.5	16.5	36.4	0.02	0.00	0.00	0.00	0.02
S5	NE Fence	5.0	21.7	50.5	0.02	0.00	0.00	0.00	0.02
S6	E Fence	4.8	24.2	63.1	0.02	0.00	0.00	0.19	0.02
S7	NE Fence	4.9	37.8	112.3	0.01	0.00	0.06	0.00	0.02
S8	Colony	5.2	32.8	67.6	0.02	0.00	0.03	0.00	0.02
S9	Residence	4.9	26.0	48.9	0.02	0.00	0.11	0.00	0.00
S10	Lines 1 & 2 Gate	6.9	92.8	245.6	0.02	0.00	0.00	0.00	0.01
S11	NW Corner	0.7	1.2	2.8	0.02	0.01	0.09	0.35	0.01
S12	W Fence	6.1	28.1	52.2	0.01	0.00	0.10	0.00	0.01
S13	SW Fence	5.9	65.6	129.5	0.02	0.00	0.26	0.00	0.02
S14	Lines 3 & 4 Gate	5.3	36.0	92.7	0.02	0.00	0.27	0.00	0.00
FMEnv Limit		**-**	**-**	**250**	**0.01**	**0.04–0.06**		**10**	**1.6**

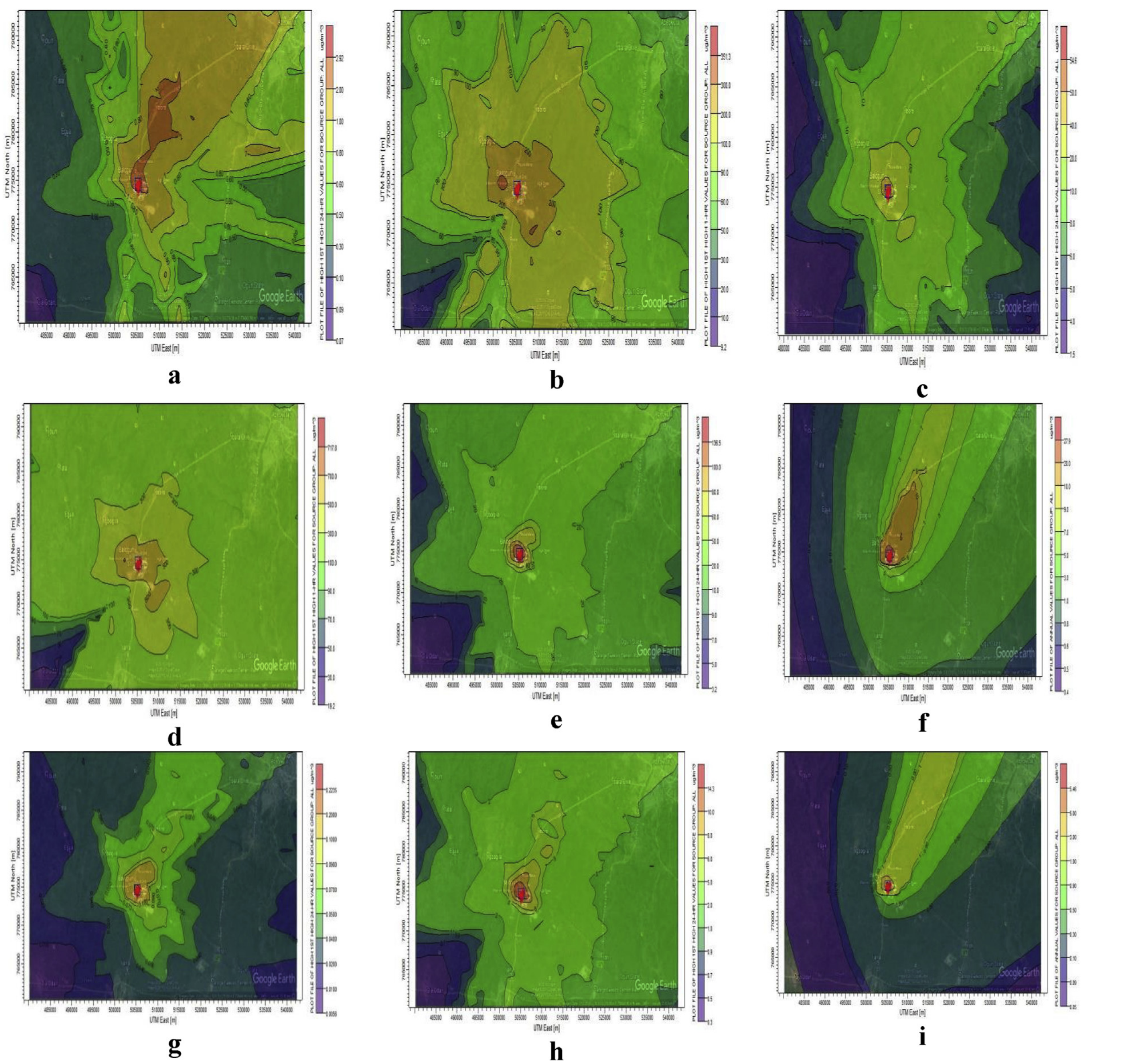

Fig. 3. Isopleths of Ambient Pollutants Levels at the Cement Plant Complex Nearby Communities (All Point Sources). **a** - 24-h CO; **b** - 1-h SO_2; **c** - 24-h SO_2; **d** - 1-h NO_X; **e** - 24-h NO_X; **f** - Annual NO_X; **g** - 24-h VOCs; **h** - 24-h PM_{10}; **i** - Annual PM_{10}.

Table 7
The cement plant complex maximum contribution to fenceline and communities (all point sources).

Sampling Location		Concentration (μg/m^3)								
		1-Hour		24-Hour					Annual	
Code	Designation	SO_2	NO_X	CO	SO_2	NO_X	VOCs	PM_{10}	NO_X	PM_{10}
S1	Mine Office Area	214.9	472.21 21 times (0.24%)	2.46	21.52	76.18	0.11	7.16	14.72	1.03
S2	Clay Area	216.9	552.26 16 times (0.18%)	1.48	32.94 87 times (0.99%)	78.79	0.12	7.36	10.71	1.19
S3	E Corner	98.58	515.19 16 times (0.18%)	1.44	29.9 87 times (0.99%)	64.23	0.11	8.58	14.28	1.22
S4	NE Corner	146.42	550.11 16 times (0.18%)	1.41	29.7 87 times (0.99%)	70.41	0.11	8.73	13.28	1.15
S5	NE Fence	151.16	552.22 16 times (0.18%)	1.68	30.16 87 times (0.99%)	88.77	0.13	8.5	18.5	1.39
S6	E Fence	152.72	508.71 16 times (0.18%)	1.71	27.32 87 times (0.99%)	101.21	0.16	9.63	22.56	1.97
S7	NE Fence	224.28	507.26 16 times (0.18%)	9.73	62.76 44 times (0.50%)	163.11 34 times (0.39%)	0.35	15.77	63.48 39 times (0.45%)	10.52
S8	Colony	222.91	472.21 21 times (0.24%)	6.75	55.41 44 times (0.50%)	99.71	0.22	13.21	62.14 39 times (0.45%)	9.06
S9	Residence	221.19	477.81 21 times (0.24%)	6.91	56.35 44 times (0.50%)	87.51	0.23	14.22	50.76 39 times (0.45%)	7.61
S10	Lines 1&2 Gate	245.48	511.19 16 times (0.18%)	3.74	55.16 44 times (0.50%)	92.71	0.22	15.5	25.93	1.81
S11	NW Corner	243.12	478.91 21 times (0.24%)	2.28	51.47 44 times (0.50%)	116.1 30 times (0.34%)	0.2	14.21	11.67	1.38
S12	W Fence	212.31	472.81 21 times (0.24%)	2.64	35.77 87 times (0.99%)	107.4	0.15	10.38	8.75	1.21
S13	SW Fence	212.31	509.81 16 times (0.18%)	2.67	32.82 87 times (0.99%)	81.2	0.11	11.28	7.93	1.09
S14	Lines 3&4 Gate	231.2	391.28 21 times (0.24%)	2.4	34.07 87 times (0.99%)	77.21	0.11	9.47	5.85	0.98
S15	Ilaro	76.03	159.72	0.52	8.35	11.24	0.03	2.14	1.15	0.12
S16	Ibese	111.77	245.77 48 times (0.55%)	0.44	9.3	19.01	0.03	2.07	2.01	0.21
S17	Balogun	212.72	398.4 61 times (0.70%0)	1.26	13.2	44.3	0.03	8.32	2.8	0.31
S18	Wasinmi Imasaye	203.99	433.24 101 times (1.15%)	0.79	14.37	30.26	0.1	10.23	1.7	0.18
S19	Abule Oke	222.92	589.31 101 times (1.15%)	1.4	23.28	66.84	0.05	10.11	4.45	0.32
S20	Abule Maria	243.34	482.99 101 times (1.15%)	1.4	24.9	48.87	0.09	9.21	8.98	1.1
S21	Aga Olowo	254.1	518.06 71 times (0.81%)	0.85	16.69	37.47	0.06	4.34	6.54	0.66
S22	Afami	246.02	589.31 71 times (0.81%)	1.4	20.28	66.84	0.11	6.33	12.52	1.19
S23	Cement Estate	203.99	575.44 71 times (0.81%)	1.26	18.82	44.48	0.08	12.21	2.99	0.34
	Ewekoro	88.45	196.04	0.48	6.78	19.4	0.03	1.98	1.13	0.12
	Abeokuta	47.31	100.33	1	9.79	20.95	0.04	4.92	3.22	0.45
	Limit	**260**	**200**	**11,400**	**26**	**113**	**160**	**50**	**40**	**20**

cement plant complex. Undertaking a comprehensive investigation on all the air pollution control equipment in the plant to ensure that they are being operated at recommended conditions is important to reduce impact on receptor locations in the air shed. Development and maintenance of engineered mitigation and control measures is necessary to reduce human exposure to emitted pollutants especially in the surrounding communities. Periodic monitoring of ambient concentration levels of pollutants within the plant's fenceline and the receptor environment is highly encouraged. Periodic evaluation of air pollution control facilities installed in the plant complex should be carried out by the relevant stakeholders.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.apr.2018.07.010.

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