Estimating on-site emissions during ready mixed concrete (RMC) delivery: A methodology

Abstract

Sustainability represents a critical challenge in the construction industry and many approaches have been developed to reduce the environmental impact of on-site construction processes. However, scant academic attention has been given to the environmental impact of logistical support for ready mixed concrete (RMC) on-site delivery emissions in developing countries. This paper develops a methodology for capturing emissions from RMC equipment and material during on-site delivery operations. A literature review was conducted to define and delineate upon greenhouse gases emitted during RMC operations and the appropriate methods to calculate them. A methodology was then developed and validated by analysing ten delivery cycle times in a case study. Data collected was analysed using simple descriptive summary statistics (viz: mean, bar charts and standard deviation). The study's results illustrate that on-site emissions incurred were: CO_2 account for 99.38% of the total emissions from RMC equipment while HC (0.03%), CO (0.11%), NO_x (0.26%), PM_{10} (0.02%), and SO_2 (0.20%) account for 0.62%. Embodied CO_2 in RMC also contributes majorly to emissions in on-site delivery operations. Alternative materials such as fly ash represent a viable means of reducing embodied emissions in RMC but proper handling is required to avert harmful environmental impacts. The study provides deeper insights into the on-site emissions arising from RMC delivery operations and a bespoke methodology that could be used as an organisational learning tool for RMC companies.

Keywords: Ready mixed concrete, sustainability, on-site delivery operations, transportation, emissions

1. INTRODUCTION

Construction industry activities significantly contribute to environmental pollution and degradation, and circa one-third of carbon dioxide (CO_2) emitted for each constituent of energy consumed [1-4]. Furthermore, construction and mining operation's total greenhouse gas (GHG) emissions were estimated at around 6.8% of all industrial emissions [3]. According to the United States Clean Air Act Advisory Committee, non-road engines used for construction and mining operations account for 32% of nitrogen oxide ($NO + NO_2 = NO_x$) and 37% of particulate matter (PM_{10}) [1], [5-6]. Fan [6] emphasized that construction equipment powered by diesel is the fundamental cause of GHG during the construction phase of a large scale infrastructure project. Concomitant pollutants produced by this industrial activity (such as carbon monoxide (CO), NO_x, and PM_{10}) jeopardize people's respiratory health and wellbeing and degrade the immediate ecosystem [6].

Buildings constitute a leading causes of resource utilization and environmental emissions [7]. Indeed, buildings contribute to: nearly 17% (1/6) of freshwater retractions globally thus, further exacerbating environmental impact [8-9]; and over 25% of global CO_2 emissions, with an average growth rate of around 2.7% per annum [10-11]. Ready mixed concrete (RMC) production and delivery to site significantly contribute to these global emissions and over 60% of all modern buildings utilise concrete [12-13]. Furthermore, RMC is an integral material used in most major building elements starting from foundations to roofs and is therefore, consumed in large quantities [12]. In 2009, global annual concrete production was estimated to be between 13 and 21 billion tonnes – a trend fuelled by population growth and sprawling urbanisation [14]. In 2019, the global demand for RMC stood at $656.1 billion and residential construction application accounted for 34.3% of the revenue share [15]. Increasing volumes of production mean that the supply, delivery and in-house operations of an RMC plant must be optimised to avoid lost-time-to production and inextricably linked profit losses[16]. Nevertheless, the negative environmental impacts of RMC processes should not be neglected. Several countries have sought to reduce the environmental impact that takes place during the construction phase of a building's life cycle [11]. In India, almost 24% of the total CO_2 emissions are due to construction sector's concreting activities [17]. Research also reveals that transportation is a significant polluter and contributor to GHG emissions. Cumulatively, the transportation sector contributes to about 23% of the world's total GHG emissions [18] and transportation of RMC to construction sites represents a major component of energy use and emissions [19]. Palaniappan *et al*. [19] revealed that selecting an RMC plant near to the construction site will intuitively reduce emissions but by how much remains an enigmatic conundrum.

Earlier research on sustainable construction primarily focused on achieving energy efficiency during the building in-use phase, increasing productivity, minimizing waste and recycling/reuse of materials [13], [14], [20]. Considering RMC related research, several studies have focused on the scheduling of RMC production and delivery (cf. [21-24]) and productivity [25]. For instance, Lin *et al*. [21] applied specialized optimization tools to enhance the daily operational efficiency of RMC small-to–medium sized enterprises (SMEs) by maximizing all the available prospects in their environment. Liu *et al* [22] demonstrated the capability of a heuristic algorithm in enabling managers of RMC plants to develop more suitable schedules. Furthermore, Maghrebi *et al.* [24] used machine learning techniques to automatically measure the feasibility of performing RMC dispatching jobs and achieved improved accuracy (i.e. over 80%) in the scenarios examined. This aforementioned body of knowledge reveals that very few RMC related research studies have focused on on-site emissions [7-8], [26-29].

Large infrastructure projects are heavily dependent upon heavy construction plant and equipment for groundworks, materials handling and distribution during the construction process [38]. Pollutants emitted from heavy construction equipment (HCE) raise concerns from the general public because of the serious health hazards posed [6]. Various solutions devised include JCB's electric mini excavator [30] and the introduction of tier V engines conformant to Regulation (EU) 2016/1628 for non-road mobile machinery (NRMM) in the European Union [31-32]. These technological and legislative developments are in response to the introduction of rigorous control and regulation of HCE emissions in many countries [6]. For example, the Greater London Authority (GLA), UK introduced the dedicated lower emissions zone which restricts the usage of tier IV engines and above only on-site. In addition, many studies have focused on RMC raw materials and production without considering emissions generated via on-site delivery [33]. Many developing countries have experienced an increase in demand for RMC and yet, there is scant knowledge of the environmental impact of on-site delivery operations of RMC. Consequently, most research on the environmental impacts of ready-mixed concrete is centred on a cradle to gate processes and onsite activities have been neglected. Against this contextual backdrop, this research develops and validates a methodology that will facilitate the estimation of emissions during RMC on-site delivery in the developing country of Nigeria. The study is significant because it provides a rationale for greening the on-site delivery operations of RMC.

2. GREENHOUSE GASES EMISSIONS IN CONSTRUCTION CONTEXT

In developing countries, diesel or gasoline-powered electricity generators represent the predominant source of power generation [34]. Reliance on fossil fuels, further exacerbates national sources of GHG emissions and airborne pollution that engulfs the atmosphere in Nigeria's major cities [35]. Despite the construction industry's intrinsic role in social and economic development [36], studies underscore the sector's significant contributions to GHG emissions generated and the associated impact upon the natural environment [6], [11]. Large infrastructure projects are heavily dependent on HCE for construction works [37]; where typical heavy items include mass 360-degree excavators, piling rigs and highways cranes (cf. [38]). In addition, the industry is inextricably linked to most sectors of an economy (e.g. energy production and real estate), the totality of which further intensifies global climate change. Without infrastructure and buildings, these linked-sectors could operate inefficiently and economies could be damaged irreparably. Experts maintain that knowledge of meteorological conditions is indispensable to the adequate design and successful administration of construction projects [39]. For example, Ekong [40] states that design and construction decisions implemented have major repercussions that exceed the built asset's life expectancy. The built environment is invariably affected by climate change. For example, warmer temperatures or acid rain can impact the performance of components within the critical infrastructure (i.e. assets that are essential to the functioning of an economy) and also increase flood risk [41]. Construction project stakeholders must therefore consider climate change throughout the whole life cycle of their business operations [42]. Smart planning mitigates the negative impacts of climate to improve the quality of the built environment and preserve utilitarian functionality. This philosophical approach establishes the fundamental tenets of environmental sustainability [40]. Environmental sustainability is grounded upon the premise that construction activities on-site have negligible environmental emission and to achieve this requires low embodied energy building materials, prefabricated or automated construction techniques, and efficient and effective transportation of materials to site [43-44]. The building's maintenance phase is usually exposed to the impact of climate variation - consuming substantial energy usage, predominantly for lightning and heating [45]. This results in expeditious wear of the building's outer shells which may require additional repair and maintenance. Consequently, severe weather conditions invariably add to the destruction of building components and significantly increase the in-use building maintenance costs [46-47]. Climate change is a current prodigy that is driven by GHG emissions [48]. A pending dystopian future has prompted calls for all industry stakeholders to acquire a proper understanding of sustainable construction [49-50]. This study therefore contributes to wider polemic debate within the prevailing academic discourse.

3. MAJOR PHASES OF READY MIXED CONCRETE PRODUCTION

Nellickal *et al*. [51] state that RMC production consists of five major discrete phases viz: manufacturing of raw material; transportation of raw materials; operations at the RMC batching plant; delivery of RMC using transit mixer trucks; and construction operations on-site (refer to Figure 1) [13]. This study specifically focuses on the construction operations associated with the on-site delivery of RMC during the construction phase of a building's whole lifecycle.

<Insert Figure 1 here>

3.1.Manufacturing of raw materials

RMC consists of water, sand, cement, coarse aggregates, fly ash and admixtures [52]. Large amounts of energy are also utilised during this process. According to [53], nearly 3 gigatonnes (GTs) of Portland cement were manufactured worldwide, equating to roughly 2.6 GTs of CO_2 discharges per annum under normal production settings [54]. Portland cement production is energy intensive, necessitating within 4–5 gigajoules per tonne (GJ/T) and nearly half of the GHG generated derived from fossil fuel combustion [55]. Calcination of limestone account for the remaining half of harmful emissions released. Approximately, 0.87 tonne (T) of CO_2 is emancipated into the atmosphere for 1 megatonne (MT) of the Portland cement clinker. Nevertheless, this value varies depending upon the location, know-how, productivity, the combination of power sources used in power production, and the range of kiln fuels [52]. Water is typically sourced from local boreholes or natural sources such as artesian wells, watercourses or reservoirs [56]. Sand is obtained from local riverbeds and is washed and screened to remove detritus particulate matter [57].

Coarse aggregates well below 10mm are usually used for concrete production dependent upon the strength characteristics of the cured concrete required [13], [58]. Thermal power plants provide another major source material 'fly ash'. Fly ash is a pozzolanic material made of siliceous and/or siliceous and aluminous materials produced as a derivative of sweltering crushed coal in electricity generation plants [59-60]. This waste by-product is ground into a fine ash which when mixed with water forms a cementitious material [60]. Fly ash is often lighter than cement and cheaper [61]. Admixtures are manufactured through a combination of various chemicals [51].

3.2.Transportation of raw materials to batching plant

Raw materials obtained from various sources are then transported to the batching plant for the production process to commence using rail, truck or for larger sites, conveyor belts from source to batching plant [62]. Fly ash and cement are usually deposited in silos while sand and coarse aggregates are kept in separate storage yards [62]. Admixtures are supplied in cylindrical barrels connected to the batching plant mixer [14]. Water is supplied to the plant in tankers [51].

3.3.Operations at the RMC batching plant

RMC is manufactured in a fully computerized environment powered by diesel, electricity and/or both [13] to produce different mix design strengths based on client requirements [63]. At this phase, a wheeled articulated loader face shovel (as material handling equipment), belt conveyor, motor vehicles, etc. are the major source of energy consumption [51].

3.4.Delivery of RMC using transit mixer trucks

The final concrete or other cementitious product (i.e. mortar or screed) is then poured into transit mixer trucks for site delivery. The truck helps preserve the inherent properties of concrete during transit [51] but traffic congestion within major urban conurbations presents a major issue that increases transit times [63].

3.5.Construction operations on site

This current study focuses on emissions generated from construction operations on-site to: 1) generate greater knowledge on one phase of the production process; and 2) control the inherent variability that occurs in other phases and thus, lead to a more accurate result. Hence, the research was limited to the construction operations phase of RMC delivery (refer to Figure 2).

<Insert Figure 2 here>

On-site construction operations subdivide into five stages (refer to Figure 2) viz: waiting; mounting of RMC pumping and transit truck setup; obtaining sample for slump and cube tests; dispatching concrete in prepared formwork/designated location; and cleaning of the transit mixer and any attachments used. On arrival of the RMC pumping and transit trucks to site, they wait for site security operative(s) clearance and for instructions regards on-site risks and rules to mitigate these (such as designated traffic routes). Firstly, the RMC pumping and transit trucks are mounted which generates emissions from the RMC equipment and the RMC embodied emissions.

Secondly, samples for slump and cube tests are obtained to determine the concrete's workability and strength. The cube sample is normally tested after seven and 28 days' intervals to assess the concrete's compressive strength and its suitability for the building element. After that, the RMC is fed into a concrete pump to its final destination. A slump test is the most popular test used to characterize the workability of fresh concrete; namely, the concrete's ability to maintain uniform constituents and become compacted with uniform quality, without phenomena like 'bleeding' and 'segregation in layers' [64]. As a full skill asset, workability includes the contents in three aspects of water retention, flow ability and cohesiveness [64].

The next stage involves dispatching the concrete. Emissions arise from the ready-mix concrete and material embodied emissions. Cleanout of RMC pumping and transit mixer trucks is the last stage and the only source of emission here is the RMC equipment (pumping and transit mixer trucks).

4. PARAMETERS THAT INFLUENCE EQUIPMENT EMISSION

Fan [6] identified nineteen (19) variables affecting emissions from construction equipment that were classified into four thematic groups viz: equipment and conditions; operating conditions; equipment operations; and equipment maintenance. Multilinear regression analysis was used to explore the relationship between NO_x emission rate and some selected variables. The emission modeling was founded on US Environmental Protection Agency's (EPA) nonroad model. Similarly, Jassim *et al*. [29] studied the power utilization and CO_2 discharges of excavators in mass excavation earthwork processes - variables adopted were: excavating depth, cycle time, pail contents, bank density of materials and engine capacity. An artificial neural network and multivariable linear regression were employed to envisage the power utilization and CO_2 releases from excavators based on EPA nonroad model. Giwa [65] conducted research on the inventory of GHG productions from petrol and diesel burning up in Nigeria using uncertainty analysis, Latin Hypercube and Monte Carlo Sampling. Fuel consumption was the main factor influencing emissions that included CO_2, CH_4 and N_2O (estimated using IPCC (Intergovernmental Panel on Climate) GHG Inventories).

Barati and Shen [66] used ordinary least square and multivariable linear regression analyses to study the most favourable driving model of on-road equipment. The study revealed three operational parameters affecting construction equipment emissions viz: speed, road slope and payload. The analysis (*ibid*) revealed that by increasing the equipment payload and highway gradient, the GHG discharges from equipment escalate substantially while the best possible driving velocity is sustained minimally. Similarly, Jassim *et al*. [67] assessed the power utilisation and CO_2 emissions of articulated haulage vehicles using operational data collected from trucks. An optimization technique (namely location-based planning and linear optimization) was adopted and the emission was estimated based on EPA nonroad model. Achour cf. [68] also researched into controlling air pollution in cars using 355,682 vehicles based on a number of variables. The emissions considered were CO, NO_x and hydrocarbon (HC) - descriptive analysis was employed while COPERT emission factors were used for emission estimation. Ahn *et al*. [69] studied emission estimation using discrete-event simulation and variables such as duty cycle, engine power and model year. The duty cycle starts from stripping topsoil to stock pile which includes the use of different equipment such as bull dozers, off road trucks, excavators and graders. The GHGs considered were CO, CO_2, NO_x, PM and HC. The emission rates used were based on a non-road model with reference to the methodology proposed by [70-71]. Dabbas [71] conducted research to test vehicle emission interdependencies using real-world measurement data. The study utilized secondary lab based data comprising of 542 commuter vehicles, to explore the speculation of vehicle GHG discharges interdependencies. HC, CO, and NO_x discharges were gathered under six test drive cycles, for every vehicle when vehicles were tuned. Furthermore, classification and regression trees (CART) were employed to reduce the amount of variables while a 3-stage least squares regression analysis. Results revealed that HC, CO, and NO_x are mutually reliant on a system of synchronous equations [71]. Lastly, Palaniappan *et al*. [19] identified six factors that influence CO_2 emissions from RMC transportation viz: slab size (or building element size), site distance to subdivision of RMC plant (site proximity), truck type, fuel efficiency of truck and fuel type. Simple regression analysis used examined the relationship between the amount of emissions and different variables while CO_2 was estimated based on the EPA widely used nonroad model.

5. EMISSIONS FACTOR

Air pollutant during a typical equipment duty cycle is estimated with the aid of the emissions factor (*EF*). EF connects the process or activity creating emissions with the amount of atmospheric discharge [72]. The general mathematical expression for EF is shown in equation (1):

$$E = A \times EF \times \left[1 - \left(\frac{ER}{100}\right)\right] \qquad (\mathbf{1})$$

Where EPA (cf. 2013) indicated that:

$E\ =\ emissions$; $A\ =\ activity\ rate$;

$EF\ =\ unrestrained\ emissions\ factor$; and

$ER\ =\ general\ emission\ reduction\ efficiency\ measured\ in\ percentage.$

5.1.Non-road equipment emission factors

Fan [6] and Edwards *et al.* [73] indicate(s) that the construction process utilizes different plant and equipment ranging from light to heavy equipment. These vehicle's characteristics are dissimilar to highway vehicles and are usually referred to as 'non-road' or 'off-highway'. Thus, construction plant and equipment are categorized as non-road equipment because they are usually used off the road and mostly with diesel powered engines (machines such as a the 'rubber duck' – a tyre-wheeled 360 degree excavator (cf. [74]) being an exception). To estimate equipment emissions, reference is made to machinery utilisation rates. Furthermore, equipment operation is largely influenced by the machinery age, operation hours, model year and engine characteristics. However, this may differ according to manufacturer's specification and operation characteristics of equipment [1]. The following subsections (5.1.1

to 5.1.4) explain how the emission factors for HC, CO, NO_x, PM_{10}, CO_2 and sulphur dioxide (SO_2) are determined.

5.1.1. Emission factors for HC, CO, and NO_x

The *EF* for HC, CO, and NO_x are calculated by multiplying the steady state emission factor (EF_{ss}), transient adjustment factor (*TAF*), deterioration factor (*DF*) and age factor [1]. The technology type is identified by EF_{ss} which is a component of equipment power rating (horsepower) and model year. EPA developed *EF* by experimenting with the emissions of several equipment with different power ratings and model years under normal test environments. Because of disparity between real life and standard test conditions, adjustment factors were introduced to balance the emissions. *TAF* adapts with equipment operational characteristics while *DF* is a factor engine age and type [1]. The age factor is the product of cumulative hours of usage and load factor, divided by the useful hours of the equipment's life. Sandanayake *et al*. [7] also adopted this approach to estimate emissions arising from piling operations. Overall, the general formula for estimating pollutants (HC, CO, and NO_x) *EF* is shown in equation (2):

$$EF_{(HC,CO,NO_x)} = EF_{ss} \times TAF \times \left\{1 + DF_{rel} \times \left(\frac{Cumulative\ hours\ \times\ Load\ Factor}{Useful\ hours}.\right)^b\right\} \qquad \mathbf{(2)}$$

$b\ =\ constant\ for\ a\ given\ pollutant/technology\ type;\ b\ \leq\ 1. For\ diesel\ fuel, b\ =\ 1.$

5.1.2. Emission factor for PM_{10}

The estimation of *EF* for PM_{10} is almost the same as that of HC, CO, and NO_x but sulphur content allowance is made. This is because PM_{10} depends heavily on fuel sulphur content. Shao [75] emphasized that sulphate can be a major component of PM_{10} emissions from diesel engines, and emissions of sulphates are positively correlated with the sulphur content of diesel fuel. Because sulphur content in diesel fuel differs significantly from that in the testing fuel, it is important to adjust the PM_{10} emissions appropriately in the model [7], [75-76]. EPA [76] factored the mean change in PM emissions using different sulphur levels as 0.1573. PM emissions are influenced by PM sulphate (H_2SO_4 + $7H_2O$). This implies there is 7.0g of sulphate in 1.0g of sulphur in PM sulphate. Consequently, the portion of fuel sulphur converted to PM sulphur is $\frac{0.1573}{7} = 0.02247$g [76]. Sulphur adjustment is expressed mathematically in equation (3):

$$S_{PM\,adj} = BSFC \times 453.6 \times 7.0 \times SO_x\mathrm{conv} \times 0.01 \times (SO_x bas - SO_x dsl) \qquad (\mathbf{3})$$

Where EPA (cf. 2010a) indicated that:

$SPM\ adj\ =\ PM\ sulphur\ adjustment\ (g/hp - hr)$;

$BSFC\ =\ in - use\ adjusted\ brake - specific\ fuel\ consumption\ (lb\ fuel/hp - hr)$;

$453.6\ =\ conversion\ from\ lb\ to\ grams$;

$7.0\ =\ grams\ PM\ sulphate/grams\ PM\ sulphur$;

$SO_x conv\ =\ grams\ PM\ sulphur/grams\ fuel\ sulphur\ consumed$;

$0.01\ =\ conversion\ from\ percent\ to\ fraction$;

$SO_x bas\ =\ default\ certification\ fuel\ sulphur\ weight\ percent\ =\ 0.3300$; and

$SO_x dsl\ =\ episodic\ fuel\ sulphur\ weight\ percent\ (specified\ by\ user)$.

After making the necessary adjustment for sulphur present in fuel, the *EF* can then be computed. The formula for estimating the emission factor for PM_{10} is shown in equation (4).

$$EF_{PM10} =\ EF_{ss} \times TAF \times \left\{1 + DF_{rel} \times \left(\frac{Cum.hrs. \times Load}{Useful.hrs}\right)^b\right\} - S_{PM\,adj} \qquad (\mathbf{4})$$

5.1.3. Emission factor for CO_2

As noted in EPA [76], the *EF* for CO_2 is estimated by the product of atomic weight ratio of CO_2 (44g) and CO (12g), carbon fraction (87%), brake-specific fuel consumption (*BSFC*), *TAF* and lb to grams conversion factor (453.6), subtracting HC since a little volume of carbon is lost as HC components into the air. BSFC is a function of engine productivity. It is calculated by dividing fuel consumption with rate of power production and used to estimate the quantity of CO_2 emissions [1], [76]. The general formula for estimating *EF* for CO_2 is shown in equation (5):

$$EF_{CO_2} = \frac{44\ gCO_2}{12\ gC} \times 0.87 \times (BSFC \times TAF \times 453.6 - HC) \qquad (\mathbf{5})$$

5.1.4. Emission factor for SO_2

The process of estimating the *EF* of SO_2 is almost the same as that of CO_2. It is estimated by the product of atomic weight ratio of SO_2 (64g) and S (32g), fraction (0.01), SO_xdsl, brake-specific fuel consumption (*BSFC*), *TAF*, lb to grams conversion factor (453.6) and 1 - SO_xconv, subtracting HC. The default weight of sulphur in industrialized diesel is 0.33% [1], [76]. It can be expressed mathematically as shown in equation (6):

$$EF_{SO_2} = \frac{64\ gSO_2}{32\ gS} \times 0.01 \times SO_x dsl \times (BSFC \times TAF \times 453.6 \times (1 - SO_x conv) - HC) \qquad (\mathbf{6})$$

5.2.Emission factors for RMC embodied carbon emissions

Owning to various building characteristics such as type of materials utilized and futuristic suppositions as regards power source and service lifespan, embodied carbon can represent somewhere in the range of 2% and 80% of life cycle carbon emissions [44], [77]. The pre-use phases of construction have received remarkable attention due to its strong link with building materials and embodied emissions and energy [78]. Several studies have determined the emission factor for embodied carbon emissions in RMC. For instance, Hammond and Jones (2008) revealed the embodied carbon emission factor of 1:2:4 for general concrete used in under three storeys building construction to be 0.035kgC/kg. Kumanayake *et al*. [44] used 0.123kgCO_2/kg as the emission factor for embodied carbon in RMC with a density of 2400kg/m^3 to convert the concrete volume to mass (kg) before applying the factor.

Chaudhary [79] used 133kgCO_2/tonne for concrete with 35MPa and 107kgCO_2/tonne for concrete with 35MPa and 30% fly ash.

Furthermore, the National Lifecycle Inventory database by the Korea Environmental Industry and Technology Institute [80] and Korea Institute of Civil Engineering and Building Technology [81] indicated 400.4kgCO_2/m^3 for RMC (25-210-12) and 419.6kgCO_2/m^3 for RMC (25-240-15). Kang *et al.* [82] recently adopted these emission factors to study embodied emissions in building construction projects. Similarly, Jun *et al.* [83] used 419kgCO_2/m^3 for RMC (25-210-15), 409kgCO_2/m^3 for RMC (25-210-12), 414kgCO_2/m^3 for RMC (25-240-12), and 429kgCO_2/m^3 for RMC (25-240-15). Boarder *et al.* [43] provided embodied CO_2 (ECO_2) for concrete. C30 concrete includes Portland cement, water, aggregates (silica sand and granite); RMC including fly ash and coarse aggregate mixtures; and RMC encompassing fly ash and normal coarse aggregate [43]. The inclusion of fly ash and light weight aggregates (LWA) in concrete reduces embodied emissions considering the drop in ECO_2 from 388kgCO_2/m^3 to 298kgCO_2/m^3. Table 1 shows the breakdown of ECO_2 concrete while Table 2 presents the emission factors for ECO_2.

<Insert Table 1 here>

<Insert Table 2 here>

6. NONROAD RMC EQUIPMENT EMISSIONS

Construction plant and equipment (CPE) emissions derive from fuel burning, fuel and lubricant leakages, and replacement of fluids under maintenance in the equipment [84-85]. Assessing the emissions of CPE will enable effective usage of the equipment and improve construction site air quality. The emissions from CPE in many models are the product of fuel consumption and emission coefficients [86]. In addition, non-road [87] and off-road [88] models, the emission rates of individual equipment with reference to power rating group and model year were classified. After the estimation of *EF* for each pollutant (i = CO_2, SO_2, NO_x, CO, PM_{10}, HC), the emissions from the CPE are estimated using the general equation revealed by the EPA [76] for each of the pollutants in equation (7):

$$Emissions_i = EF_i \times T \times PW \times LF \qquad \textbf{(7)}$$

Where:

$Emissions_i = emissions\ from\ pollutant\ i$;

$EFi, = emission\ factor\ for\ impact\ i\ (g/hp-hr)$;

$i = type\ of\ pollutant\ (CO_2, SO_2, NO_x, CO, PM_{10}, HC)$;

$T = hours\ of\ use$;

$PW = average\ power\ of\ the\ equipment\ measured\ in\ horsepower$;

$LF = load\ factor\ \left(\frac{power\ during\ operation\ (hp)}{maximum\ power\ (hp)}\right)$.

7. EMBODIED EMISSIONS FROM RMC

Previous emission studies on CPE utilised during the construction phase of a project focused upon embodied emissions and energy from construction materials [89-91]. Although several reasons are apparent for this trend, the main reason is that emissions from materials and embodied energy accounted for nearly 80% of the overall emissions arising from the building construction phase. Some researchers used input/output (I/O) based models to estimate emissions from materials owing to inadequate data availability [92-96], [20]. Other studies used a similar type of procedural-based mathematical equation to compute embodied energy and emissions from materials [20], [26], [44], [88]. A universal depiction of models for estimating embodied emission in materials is presented in equation (8):

$$E = \sum Q_i \times f_i \quad \textbf{(8)}$$

Where:

E is the total of emissions (kg) from material type i;

Q_i *is the* quantity of material i (kg); and

f_i *is the emission factor for the material i in* $\left(kg\ of\ \frac{emssions}{kg}\right)$.

For this study that is focused on ECO_2 from RMC, the volume of concrete and other delivery details are extracted from the delivery ticket issued to the driver before leaving the RMC plant.

8. US ENVIRONMENTAL PROTECTION AGENCY TRIAL DATA FOR DIFFERENT EQUIPMENT CLASSIFICATIONS

8.1. Steady-state emission factors (EF_{ss}) and BSFC

The EF_{ss} for CPE are based on equipment characteristics (engine power rating and model year) and emission control standards [1]. EPA endorsed ISO-C1 procedure was used to test the steady-state condition of equipment in different equipment categories i.e Tier 1 – 4 [1], [76]. The EF_{ss} and the BSFC were established for each equipment category specified by EPA. Table 3 provides a summary of EF_{ss} and BSFC for different equipment category.

<Insert Table 3 here>

8.2. Transient adjustment factor (TAF)

Emission experimenting of non-road engines is usually based on steady state operations which may not accurately reflect the engine operation in real life applications. The variation can be attributed to engine velocity, transient pressures and load. It is applied to adjust the EF_{ss} of test cycle in order to reflect actual engine behaviour during real operation on field. It is depicted as the ratio of transient emission factor (EF_{trans}) to equivalent EF_{ss}. The EF_{trans} is derived from the data obtained from the usage of different equipment as per the equipment category [1]. With reference to the cycle load factors; the equipment were classified as high load factor (Hi LF) and low load factor (Lo LF). The classifications aided accurate determination of the mean value for Hi LF and Lo LF [76]. This offered a more precise value for the *TAF* for different CPE (refer to Table 4).

<Insert Table 4 here>

8.3.Deterioration factors (DFs)

DFs capture increments in emissions as the age (and condition) of the engine increases over time. In most cases, the emission level of engines increases owning to poor maintenance practice, natural engine wear and coincidental altering of emission control systems. Engine median life marks the end of the deterioration and age factor and is usually 1 at that point. This viewpoint is premised on a supposition that an engine weakens to a level where any further wear and tear is accompanied by maintenance [1], [76]. Table 5 shows the relative deterioration factors (DF_{rel}) for each pollutant according to engine classification. *DF* can be estimated from DF_{rel} of the pollutants using equation (9):

$$DF = 1 + DF_{rel} \times (AgeFactor)^b \qquad (9)$$

Where:

$DF = deterioration\ factor;$

$DFrel = relative\ deterioration\ factor\ \left(\frac{percentage\ of\ increase}{percentage\ of\ useful\ life}\right);$

$AgeFactor = \frac{(cumulative\ hours \times load\ factor\ in\ fraction)}{median\ life\ at\ full\ load}\ in\ hours$; and

$b = \frac{constant\ for\ a\ given\ pollutant}{technology\ type};\ b \le 1. For\ diesel\ fuel, b = 1.$

<Insert Table 5 here>

9. RESEARCH METHODOLOGY

Figure 3 illustrates that a four stage waterfall processes (cf. [97]) was adopted viz: 1) literature review; 2) case study selection; 3) development of proposed methodology; and 4) validation of proposed methodology. To achieve this study's objectives, a critical literature review was conducted [98] on GHG emissions during major phases of ready mixed concrete production, parameters that influence equipment emissions, emission factors, nonroad RMC equipment emissions, embodied emissions from RMC and EPA test data for various equipment categories. This study adopted a case study strategy through which quantitative data [99-100] on RMC on-site delivery operations was sought.

<Insert Figure 3 here>

9.1. Site Characteristics

Case study research can generate a deeper and richer understanding on a complex issue(s), object(s) or circumstance(s) [97]. It surpasses the notions and occurrences regarding an object which is already known through prior studies [101]. A construction project in Lagos, Nigeria provided the contextual case study setting for this research. The project consists of a multi-billion naira faculty and hostel building. The faculty building has eight floors while the hostel building has seven floors. Previous emission studies that have adopted the case study approach include [3], [9], [20] and [44] thus, substantiating the use of this research strategy. The RMC on-site delivery processes were observed to gather data to validate the proposed methodology.

9.2. Data collection

RMC on-site delivery operations were observed to gather real-time data on the main equipment used (e.g. transit mixer and pumping trucks) during the delivery process. Data included: brand, model year, model number, pumping head, number of pumping sections, number of axles, engine power, fuel efficiency and capacity. Additional data gathered during the delivery processes included: the volume of concrete delivered, slump, route and duration of each process recorded using a digital stopwatch. Data obtained on-site was recorded on a checklist specifically designed to record the on-site delivery of RMC. Obtaining data on equipment's' useful life, cumulative hours of usage and the load factor proved difficult so the study adopted the useful life and load factor as indicated by the EPA [102] to be 6,000 hours and 0.59 or 59% (Hi LF) respectively. Furthermore, the EPA [102] expressed that the average activity hours per year for other construction equipment is 606 hours/year. Thus, this study assumes that the RMC equipment used has been purchased in the last four years. Consequently, the assumed cumulative hours of usage of RMC equipment is 2424 hours (four years × 606 hours/year).

9.3. Emissions from RMC equipment

Ten delivery cycles of RMC (C1-C10) were recorded; where cycle starts when the driver waits to enter the site to the time the truck leaves the site. Table 6 shows details of the RMC transit mixer trucks, while Table 7 illustrates the same for RMC pumping trucks.

<Insert Table 6 here>

<Insert Table 7 here>

9.3.1. Emission factors for HC, CO, NOx.

According to the data obtained on-site and via extant literature (presented in Tables 3 to 5), *EF* for HC, CO, NO_x and PM_{10} were computed. The EF_{ss} is a function of type of technology, *TAF* varies across different equipment and *DF* is a component of engine age and type of technology [102]. Equation (10) shows the formula used for emission factor computation.

$$EF_{(HC,CO,NO_x)} = EF_{ss} \times TAF \times \left\{1 + DF_{rel} \times \left(\frac{Cum.hrs.\times Load}{Useful.hrs}\right)^b\right\} \quad \mathbf{(10)}$$

For the transit mixer truck in the first cycle (C1);

$$EF_{(HC)} = 0.167 \times 1.05 \times \left\{1 + 0.027 \times \left(\frac{2424 \times 0.59}{6000}\right)^1\right\} = 0.176\text{g/hp} - \text{hr} \quad \mathbf{(11)}$$

$$EF_{(CO)} = 0.843 \times 1.53 \times \left\{1 + 0.151 \times \left(\frac{2424 \times 0.59}{6000}\right)^1\right\} = 1.336\text{g/hp} - \text{hr} \quad \mathbf{(12)}$$

$$EF_{(NO_x)} = 2.500 \times 1.04 \times \left\{1 + 0.008 \times \left(\frac{2424 \times 0.59}{6000}\right)^1\right\} = 2.605\text{g/hp} - \text{hr} \quad \mathbf{(13)}$$

For the pumping truck in the first cycle (C1);

$$EF_{(HC)} = 0.131 \times 1.00 \times \left\{1 + 0.027 \times \left(\frac{2424 \times 0.59}{6000}\right)^1\right\} = 0.132\text{g/hp} - \text{hr} \quad \mathbf{(14)}$$

$$EF_{(CO)} = 0.084 \times 1.00 \times \left\{1 + 0.151 \times \left(\frac{2424 \times 0.59}{6000}\right)^1\right\} = 0.087\text{g/hp} - \text{hr} \quad \mathbf{(15)}$$

$$EF_{(NO_x)} = 0.276 \times 1.00 \times \left\{1 + 0.008 \times \left(\frac{2424 \times 0.59}{6000}\right)^1\right\} = 0.277\text{g/hp} - \text{hr} \quad \mathbf{(16)}$$

9.3.2. Emission factors for PM_{10}

Regards the data obtained on-site and appropriate values in Tables 3 to 5, the *EF* for PM_{10} are computed by means of equation (17) while the formula for sulphur adjustment is shown in equation (18).

$$EF_{(PM10)} = EF_{ss} \times TAF \times \left\{1 + DF_{rel} \times \left(\frac{Cum.hrs.\times Load}{Useful.hrs}\right)^b\right\} - S_{PM\,adj} \quad \mathbf{(17)}$$

$$S_{PM\,adj} = BSFC \times 453.6 \times 7.0 \times SO_x\text{conv} \times 0.01 \times (SO_x bas - SO_x dsl) \quad \mathbf{(18)}$$

For the transit mixer truck in the first cycle (C1);

SO_xconv = 0.02247

SO_xbas = 0.3300

SO_xdsl = 0.3300

$$S_{PM\,adj} = 0.367 \times 453.6 \times 7.0 \times 0.02247 \times 0.01 \times (0.3300 - 0.3300) = 0\text{g/hp} - \text{hr} \quad \mathbf{(19)}$$

$$EF_{(PM10)} = \ 0.150 \times 1.47 \times \left\{1 + 0.473 \times \left(\frac{2424 \times 0.59}{6000}\right)^1\right\} - 0 = 0.245\text{g/hp} - \text{hr} \quad \mathbf{(20)}$$

For the pumping truck in the first cycle (C1);

SO_xconv = 0.3000

SO_xbas = 0.3300

SO_xdsl = 0.3300

$$S_{PM\,adj} = 0.367 \times 453.6 \times 7.0 \times 0.3000 \times 0.01 \times (0.3300 - 0.3300) = 0\text{g/hp} - \text{hr} \quad \mathbf{(21)}$$

$$EF_{(PM10)} = \ 0.009 \times 1.00 \times \left\{1 + 0.473 \times \left(\frac{2424 \times 0.59}{6000}\right)^1\right\} - 0 = 0.010\text{g/hp} - \text{hr} \quad \mathbf{(22)}$$

9.3.3. Emission factors for CO_2

Using on-site data, appropriate values in Tables 3 and 4 and the results of equations (11) and (14), the *EF* for CO_2 is computed via equation (23).

$$EF_{CO_2} = \frac{44\ gCO_2}{12\ gC} \times 0.87 \times (BSFC \times TAF \times 453.6 - HC) \qquad \mathbf{(23)}$$

For the transit mixer truck in the first cycle (C1);

$$EF_{(CO_2)} = \frac{44}{12} \times 0.87 \times (0.367 \times 1.00 \times 453.6 - 0.176\ ) = 530.482\text{g/hp} - \text{hr} \qquad \mathbf{(24)}$$

For the pumping truck in the first cycle (C1);

$$EF_{(CO_2)} = \frac{44}{12} \times 0.87 \times (0.367 \times 1.00 \times 453.6 - 0.132) = 530.622\text{g/hp} - \text{hr} \qquad \mathbf{(25)}$$

9.3.4. Emission factors for SO_2

The *EF* for SO_2 is computed with the aid of equation (26), which utilize the acquired site data, appropriate values in Tables 3 and 4, and the answers of equations (11) and (14).

$$EF_{(SO_2)} = \frac{64\ gSO_2}{32\ gS} \times 0.01 \times SO_x dsl \times (BSFC \times TAF \times 453.6 \times (1 - SO_x conv) - HC) \qquad \mathbf{(26)}$$

For the transit mixer truck in the first cycle (C1);

SO_xdsl = 0.33

SO_xconv = 0.02247

$$EF_{(SO_2)} = \frac{64}{32} \times 0.01 \times 0.33 \times (0.367 \times 1.00 \times 453.6 \times (1 - 0.02247) - 0.176)$$

$$= 1.073 \text{g/hp} - \text{hr} \tag{27}$$

For the pumping truck in the first cycle (C1);

$$EF_{(SO_2)} = \frac{64}{32} \times 0.01 \times 0.33 \times (0.367 \times 1.00 \times 453.6 \times (1 - 0.02247) - 0.132)$$

$$= 1.073 \text{g/hp} - \text{hr} \tag{28}$$

9.3.5. Overall RMC Equipment Emissions

Using the *EF* established from equations (11)-(28) and data obtained on-site (hours of usage, engine power and load factor), the overall emissions are computed using equation (29). The emissions from the RMC equipment (RMC transit mixer and pumping truck) are combined to finalize the overall emissions of each pollutant:

$$Emissions_i = EF_i \times T \times PW \times LF \tag{29}$$

For the transit mixer truck in the first cycle (C1);

$$Emissions_{(HC)} = 0.176 \times \frac{1710}{3600} \times 345 \times 0.59 = 17.0\ g \tag{30}$$

$$Emissions_{(CO)} = 1.336 \times \frac{1710}{3600} \times 345 \times 0.59 = 129.2g \tag{31}$$

$$Emissions_{(NO_x)} = 2.605 \times \frac{1710}{3600} \times 345 \times 0.59 = 251.9g \tag{32}$$

$$Emissions_{(PM_{10})} = 0.245 \times \frac{1710}{3600} \times 345 \times 0.59 = 23.7g \tag{33}$$

$$Emissions_{(CO_2)} = 530.482 \times \frac{1710}{3600} \times 345 \times 0.59 = 51290.3g \quad \textbf{(34)}$$

$$Emissions_{(SO_2)} = 1.073 \times \frac{1710}{3600} \times 345 \times 0.59 = 103.7g \quad \textbf{(35)}$$

For the pumping truck in the first cycle (C1);

$$Emissions_{(HC)} = 0.132 \times \frac{1710}{3600} \times 394 \times 0.59 = 14.6g \quad \textbf{(36)}$$

$$Emissions_{(CO)} = 0.087 \times \frac{1710}{3600} \times 394 \times 0.59 = 9.6g \quad \textbf{(37)}$$

$$Emissions_{(NO_x)} = 0.277 \times \frac{1710}{3600} \times 394 \times 0.59 = 30.6g \quad \textbf{(38)}$$

$$Emissions_{(PM_{10})} = 0.010 \times \frac{1710}{3600} \times 394 \times 0.59 = 5.5g \quad \textbf{(39)}$$

$$Emissions_{(CO_2)} = 530.622 \times \frac{1710}{3600} \times 394 \times 0.59 = 58590.5g \quad \textbf{(40)}$$

$$Emissions_{(SO_2)} = 1.073 \times \frac{1710}{3600} \times 394 \times 0.59 = 118.5g \quad \textbf{(41)}$$

9.4.Embodied emissions from RMC

All the RMC delivered to the site were RMC (25-210-15) and the CO_2 emission factor for such concrete based on Kang *et al*. [82] is 419.6kgCO_2/m^3. From the first to tenth cycle (C1-C10), a total of 91m^3 of RMC was delivered to site. Using the embodied emissions formula in equation (8), the total embodied CO_2 emissions for RMC is 38183.6 kgCO_2 – refer to equation (42):

$$Emissions_{embodied\ CO_2} = 91 \times 419.6 = 38183.6\ kgCO_2 \quad (\mathbf{42})$$

9.5.A proposed methodology for estimating emissions from RMC on-site delivery operations

After a critical literature review and case study observations accrued (refer to sections 6 to 9 of the paper), the methodology depicted in Figure 4 was developed.

<Insert Figure 4 here>

10. VALIDATION AND DISCUSSIONS

To validate the developed methodology, the on-site operations of RMC delivery of ten cycles were observed. Google Earth was used to explore the distance and locations of plants to the site. Alternative routes giving distances and probable travel times based on road traffic were suggested. Two plants (A and B) are near the site, one is on the mainland (Plant A) while the other is on an island (Plant B). Usually, the RMC equipment (transit mixer and pumping trucks) comes from any of the two RMC plants to the site. Plant A is located in Ikeja while Plant B is located in Ikoyi. Figure 5 shows the map from Plant A to the site which can take one of two different routes. The first route (AR1) takes 47 minutes to travel 14.3km while the second route (AR2) takes 58 minutes to travel 15.9km. Conversely, Figure 6 shows the map from Plant B to the site. Three different routes to the site are apparent. The first route (BR1) takes circa 38 minutes to travel 17.1km, the second route (BR2) takes circa 46 minutes to travel 18.7km, while the third route (BR3) takes circa 34 minutes to travel 16.5km to the site. Vehicles represent the main source of air pollution [21]. Likewise, Palaniappan *et al.* [19] emphasized the importance of locating RMC plant close to the construction site to shorten travel time and reduce environmentally harmful emissions generated from RMC transportation. Fan [6] and Lin *et al.* [21] also articulated the benefit of proactive maintenance in reducing emissions from equipment. Similarly, Hong *et al.* [103] revealed the critical factors that influence CO_2 emissions on construction projects viz: equipment maintenance, operator competency, nature of the road and material weight. Weiszer *et al*. [104] also indicated that RMC transportation is profoundly affected by traffic congestion. This connotes that transportation contributes significantly to GHG emissions during RMC production processes.

<Insert Figure 5 here>

<Insert Figure 6 here>

Table 8 shows the on-site data obtained during delivery operations which includes: concrete volume, slump, time is taken for each process and the equipment travel route to the site. The average volume of concrete delivered and slump was 9.1m^3 and 154mm respectively. The average time for waiting, RMC pumping and transit trucks setup, slump and cube test, dispatch, and truck clean-out were 207.00 seconds, 318.60 seconds, 307.20 seconds, 612.00 seconds, and 381.60 seconds respectively. On average, the on-site delivery operations take 1826.40 seconds (approximately 30 minutes). The dispatch time of RMC which accounted for 34% (612 seconds / 10.2 minutes) of the total time for the RMC on-site delivery operations were found to be in line with Hong *et al.* [103] - where it was stipulated that the dispatch time for RMC ranges between 5 and 20 minutes.

<Insert Table 8 here>

10.1. Estimation of Nonroad Emissions for RMC Equipment

10.1.1. Determination of emission factors

Emission factors for the equipment in each cycle were determined based on the type of pollutants (HC, CO, NO_x, PM_{10}, CO_2, and SO_2). Table 9 shows the emission factors for the equipment in each cycle.

<Insert Table 9 here>

10.1.2. Estimation of RMC Equipment emissions (HC, CO, NO_x, PM_{10}, CO_2, and SO_2)

The emissions of RMC equipment were estimated as described in section 9.3.5. Table 10 shows the nonroad emissions from each cycle of delivery operation. It is evident that CO_2 accounts for 99.38% of the total emissions from equipment (1234176.7g / 1234.18kg) while the remaining pollutants HC (0.03%), CO (0.11%), NO_x (0.26%), PM_{10} (0.02%) and SO_2 (0.20%) account for 0.62%. However, it is important to note that these gases are not equally harmful to the environment which may have an impact on its comparison. Chen *et al*. [105] noted that NO_2 is associated with various forms of respiratory diseases and also responsible for acid rain. However, high concentration could result in death. Similarly, Jonson *et al*. [106] acknowledged that diesel engines release more NO_x and less CO_2 accounting for nearly 40% of land-based NO_x emissions from road transport across Europe. CO is extremely dangerous as it cuts oxygen supply to the blood leading to asphyxiation and possibly organ(s) failure [107]. Considering the health impact of HC emissions, it is regarded as a toxic carcinogen, capable of also causing respiratory tract infections [108]. Reşitoğlu *et al*. [109] revealed that several harmful products are generated during engine combustion but the most harmful products include: HC, CO, NO_x, PM_{10}. Hence, appropriate measures are required to reduce these emissions to preserve the environment and humans who are inextricably linked to it. Furthermore, CO and HC, PM, and NO_x can be controlled using emission control systems like diesel oxidation catalyst, diesel particulate filter and selective catalytic reduction respectively [109].

<Insert Table 10 here>

10.1.3. RMC Equipment emissions in each process of on-site delivery

Table 11 and Figure 7 show the emissions in the delivery operations of RMC. This takes into consideration the five different processes during RMC delivery. Dispatching of RMC (33.51%) contributes the most to the total emissions, followed by truck clean-out (20.89%), RMC pumping and transit trucks setup (17.44%), slump and cube test (16.82%) and waiting (11.33%). Overall, the dispatching of RMC and truck clean-out process play contributes significantly to the number of emissions generated. Furthermore, the quantity of emissions per cubic metre of RMC (g/m^3) for each of the pollutants was also calculated viz: HC ($3.8g/m^3$), CO ($15.0g/m^3$), NO_x ($35.2g/m^3$), PM_{10} ($2.6g/m^3$), CO_2 ($13478.5g/m^3$) and SO_2 ($27.3g/m^3$).

<Insert Table 11 here>

<Insert Figure 7 here>

10.2. Embodied Emissions for RMC

The total embodied emissions for $91m^3$ of RMC (25-210-15) are $38183.6kgCO_2$ using a corresponding emission factor of $419.6kgCO_2/m^3$. Comparing the emissions from equipment (HC, CO, NO_x, PM_{10}, CO_2 and SO_2) and ECO_2, it is observed that ECO_2 account for 96.77% while emissions from RMC equipment account for 3.23%. This concurs with the findings of Kumanayake *et al.* [44] and Ibn-Mohammed *et al.* [77] who indicated that embodied carbon emissions can account for over 80% of building carbon lifecycle. The study's results revealed that ECO_2 is the largest source of emissions in the on-site delivery process of RMC.

11. CONCLUSIONS, RECOMMENDATIONS AND FUTURE RESEARCH

RMC is a promising source of revenue for the construction industry in the developing country of Nigeria. A novel methodology was developed to estimate emissions from on-site delivery operations of RMC; an area that has hitherto attracted scant academic attention. The methodology was validated through a case study to measure its performance. The study revealed that CO_2 accounts for 99.38% of the total emissions from RMC equipment. The ECO_2 also contributed significantly and the most with 38,183.6kg of CO_2. This means that carbon is largely emitted during the delivery operations of RMC. The emissions per RMC volume for each pollutant was given as; HC (3.8g/m^3), CO (15.0g/m^3), NO_x (35.2g/m^3), PM_{10} (2.6g/m^3), CO_2 (13478.5g/m^3) and SO_2 (27.3g/m^3). The constant provides an expedient estimate of nonroad emissions from RMC equipment based on concrete volume.

11.1. Significant contributions and Implications

This study significantly contributes to the overall body of knowledge on emissions from RMC – predominantly via the development of the novel methodology. Previous research works have mainly focused on RMC production and transportation emissions. Thus, this current study has filled this knowledge gap by exploring the emissions associated with on-site delivery operations of RMC.

11.2. Practical implications

The study generated several practical implications. Firstly, the developed methodology will enable RMC companies to comprehend the environmental impact of their site delivery operations and enable them to develop suitable means to reduce these emissions. Consequently, the methodology could also modernise the decision making process regards sustainability issues concomitant with RMC production operations. It is observed that most

RMC equipment operators do not have thorough knowledge of the emissions generated during the on-site delivery of RMC and how these emissions can be managed to achieve optimum productivity. Secondly, government and other industry stakeholders must develop policies and standard procedures that will facilitate the effective production and delivery of RMC with less environmental impacts.

11.3. Research limitations and future directions

Despite the original contribution made, the research has several shortcomings. Firstly, the study used an assumed cumulative hour (2,424 hours) of equipment usage whereas in real life this figure could vary. Future work may consider securing real cumulative hours of usage from RMC companies to assess how it influences the quantity of emissions. Furthermore, this research centered on on-site delivery emissions, neglecting other emissions arising from transportation of RMC equipment to site – future studies should examine transportation emissions (with focus upon the impact of RMC weight on RMC transit mixer truck emissions). Additionally, research should be conducted to assess the level of knowledge of RMC equipment operators on supply chain emissions, then examine the relationship supply chain emission knowledge on the amount of emissions generated. Lastly, a more holistic view of emissions from RMC production down to on-site delivery is required using digital technologies. For example, this could include using a portable emission measurement system (PEMS), GPS/INS and data logger and/or developing a software for estimating emissions in RMC production processes. In addition, future studies should conduct comparative analysis of the strengths of concrete mix/composition identified in this study with the view to determine the most appropriate mix/composition.

11.4. Recommendation

Based on the study's findings, the following recommendations were made:

- *Staff education and enlightenment*: RMC companies should educate their workers, most especially, machine operators on emission modeling and how to reduce the impact of their driver behavioral activities on the environment. In the long run, this would reduce the amount of emissions generated in a building's construction phase.
- *Proximity of batching plants*: The research revealed that it is more advisable to setup batching plants on site as this reduces emissions arising from transportation and delay in concrete arrival to site owning to traffic.
- *Use of fly ash*: A thorough literature review revealed that fly ash (which is the major source of emission during on-site delivery of RMC) has great potential to reduce embodied emissions by over 20%. Hence, it is recommended that RMC companies look into proper strategies to adopt fly ash usage and also conduct extensive research on fly ash usage in concrete production.
- *Adoption of emission control systems*: RMC companies should be encouraged to use emission control systems such as diesel oxidation catalyst, diesel particulate filter, and selective catalytic reduction as it has been proven to reduce harmful emissions. This will go some way in reducing the amount of emissions generated during on-site delivery of RMC.
- *Development of RMC delivery standards and policies*: Relevant stakeholders should come together to develop appropriate standards and policies that will aid effective delivery of RMC on construction sites with low emissions. This can include enforcing the use of telematics to collect engine data when the engine is working or idling.
- *Creation of RMC regulatory bodies*: The creation RMC regulatory bodies in developing countries will aid effective management and control of RMC emissions, production and delivery processes.

REFERENCES

[1] Sihabuddin, S.S., Ariaratnam, S.T. 2009. Methodology for estimating emissions in underground utility construction operations. Journal of Engineering, Design and Technology, 7(1), 37-64.

[2] UNEP 2009. Buildings and Climate Change – Summary for Decision Makers. United Nations Environment Programme (UNEP), Nairobi, Kenya.

[3] Avetisyan, H.G., Miller-Hooks, E., Melanta, S. 2012. Decision models to support greenhouse gas emissions reduction from transportation construction projects. Journal of Construction Engineering and Management, 138((5), 631-641.

[4] Gan, V J.L., Chan, C.M., Tse, K. T., Lo, I.M.C., Cheng, J. C. P. 2017. A comparative analysis of embodied carbon in high-rise buildings regarding different design parameters. Journal of Cleaner Production, 161: 663-675.

[5] Ahn, C.R., Lee, S.H. 2013. Importance of operational efficiency to achieve energy efficiency and exhaust emission reduction of construction operations. Journal of Construction Engineering and Management, 139((4), 404-413.

[6] Fan, H. 2017. A critical review and analysis of construction equipment emission factors. Procedia Engineering, 196, 351– 358.

[7] Sandanayake, M., Zhang, G., Setunge, S., Thomas, C.M. 2015. Environmental emissions of construction equipment usage in pile foundation construction process – a case study. In Proceedings of the 19th International Symposium on Advancement of Construction Management and Real Estate pp. 327-339. Springer, Berlin, Heidelberg.

[8] Guggemos, A.A. Horvath, A. 2005. Comparison of environmental effects of steel-and concrete-framed buildings. Journal of Infrastructure Systems, 11(2), 93-101.

[9] Chau, C. K., Hui, W. K., Ng, W.Y., Powell, G. 2012. Assessment of CO2 Emissions reduction in high-rise concrete office buildings using different material use options. Resources, Conservation and Recycling, 61: 22-34.

[10] Mao, C., Shen, Q., Shen, L., Tang, L. 2013. Comparative Study of Greenhouse Gas Emissions Between Off-Site Prefabrication and Conventional Construction Methods: Two Case Studies of Residential Projects. Energy and Buildings, 66:165-176.

[11] Hong, J.K., Shen, G.Q., Feng, Y., Lau, W.S.T., Mao, C. 2015. Greenhouse gas emissions during the construction phase of a building: A case study in China. Journal of Cleaner Production, 103: 249-259.

[12] Biruk, S. 2015. Dispatching concrete trucks using simulation method. Budownictwo i Architektura 14(2), 5-10.

[13] Olanrewaju, O. I., Okorie, V. N., Imafidon, M.O. 2019. Estimating Ready Mixed Concrete On-site Dispatch Time Using Concrete Slump and Volume: Case Study of a Construction Site in Nigeria. PM World Journal, Vol. VIII, Issue III (April). Accessed on 24/4/2020 via: https://pmworldjournal.com/article/estimating-ready-mixed-concrete-on-site-dispatch-time.

[14] Visintin, P., Xie, T., Bennett, B. 2020. A large-scale life-cycle assessment of recycled aggregate concrete: the influence of 1 functional unit, emissions allocation and Carbon Dioxide uptake. Journal of Cleaner Production, 248:119243.

[15] Grand View Research 2020. Ready-mix concrete market size, share & trends analysis report by application (commercial building, residential building, infrastructure), by region, and segment forecasts, 2020-2027. ID: GVR-2-68038-011-8. Access from: https://www.grandviewresearch.com/industry-analysis/ready-mix-concrete-market.

[16] Park, M., Kim, W.Y., Lee, H.S., Han, S. (2011). Supply Chain Model for Ready Mixed Concrete. Automation in Construction, 20(1), 44–55.

[17] Parikh, J., Panda, M., Kumar, M.G., Singh, V. 2009. CO2 Emissions Structure of IndianEconomy. Energy, 34(8), 1024 – 1031.

[18] Aukkaravittayapun, S., Surapipith, V., Poshyachinda, S. 2020. Quantifying the contributions of local emissions and regional transport to elemental carbon in Thailand, Environmental Pollution, 262, art. no. 114272.

[19] Palaniappan, S., Bashford, H., Fafitis, A., Li, K., Stecker, L. 2009. Carbon Emissions Based on Transportation for Post-Tensioned Slab Foundation Construction: A Production Home Building Case Study in The Greater Phoenix Arizona Area. International Journal of Construction Education and Research, 5(4), 236 – 260.

[20] Sandanayake, M.S. 2016. Models and toolkit to estimate and analyse the emissions and environmental impacts of building construction. A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy to School of Engineering, RMIT University, Australia.

[21] Lin, P., Wang, J., Huang, S., Wang, Y. 2010. Dispatching ready mixed concrete trucks under demand postponement and weight limit regulation. Automation in Construction, 19:798–807.

[22] Liu, Z., Zhang, Y., Li, M. 2014. Integrated scheduling of ready-mixed concrete production and delivery. Automation in Construction, 48: 31-43.

[23] Liu, Z., Zhang, Y., Yua, M., and Zhou X. 2017. Heuristic algorithm for ready-mixed concrete plant scheduling with multiple mixers. Automation in Construction, 84: 1–13.

[24] Maghrebi, M., Sammut, C., Waller, S.T. 2015. Feasibility study of automatically performing the concrete delivery dispatching through machine learning techniques. Engineering, Construction and Architectural Management, 22(5), 573-590.

[25] Maghrebi, M., Shamsoddini, A., Waller, S.T. 2016. Fusion based learning approach for predicting concrete pouring productivity based on construction and supply parameters. Construction Innovation, 16(2), 185-202.

[26] Cole, R.J. 2000. Building environmental assessment methods: Assessing construction practices, Construction Management and Economics, 18(8), 949-957.

[27] Bilec, M., Ries, R., Matthews, H.S., Sharrard, A.L. 2006. Example of a hybrid life-cycle assessment of construction processes, ASCE Journal of Infrastructure Systems, 12(4), 207-215.

[28] Trani, M.L., Bossi, B., Gangolells, M., Casals, M. 2016. Predicting fuel energy consumption during earthworks. Journal of Cleaner Production, 112(5), 3798–3809.

[29] Jassim H. S. H., Lu, W. and Olofsson, T. 2017. Predicting energy consumption and CO2 emissions of excavators in earthwork operations: An artificial neural network model. Sustainability, 9. (7), 1257.

[30] JCB. 2020. 19C-IE electric mini excavator. Accessed on 24/4/2020 via: https://www.jcb.com/en-us/products/compact-excavators/19c-1e.

[31] EUR-LEX. 2016. Regulation (EU) 2016/1628 for non-road mobile machinery. Accessed on 24/4/2020 via: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02016R1628-20160916&qid=1587741548863&from=EN.

[32] International Council on Clean Transportation 2016. Policy update: European Stage V Non-road emission standards.

[33] Zhao, C., Liu, Y., Ren, S., Quan, J. 2018a. Study on carbon emission calculation method of concrete. Key Engineering Materials. 768:293-305 10.4028/www.scientific.net/KEM.768.293.

[34] Vincent-Akpu, I. 2012. Renewable Energy Potentials in Nigeria, Presented at the Energy Future the Role of Impact Assessment. In 32nd Annual Meeting of the International Association for Impact Assessment. Porto-Portugal: Centro de Congresso da Alfândega.

[35] Ndoke, P. N., Jimoh, O.D. 2005. Impact of Traffic Emission on Air Quality in a Developing City of Nigeria. AU Journal of Technology, 8(4), 222-227.

[36] Olanrewaju, O.I., Idiake, J.E., Oyewobi, L.O., and Akanmu, W.P. 2018. Global Economic Recession: Causes and Effects on Nigeria Building Construction Industry. Journal of Surveying, Construction and Property, 9(1), 9-18.

[37] Edwards, D. J., Pärn, E.A., Love, P.E.D., El-Gohary, H. 2017. Machinery, manumission and economic machinations. Journal of Business Research, 70:391-394.

[38] Edwards, D.J., Harris, F.C., McCaffer, R. 2003. Management of off-highway plant and equipment. London: Spon. ISBN 0-415-25127-3.

[39] Gana A.J., Aliyu S.J. 2015. Climate change and engineering construction practices in Nigeria. World Journal of Engineering and Physical Sciences 3(3),040-042, Available online at https://wsrjournals.org/journal/wjeps.

[40] Ekong (2015). How global Warming affects built Environment. The Nation Newspaper Tuesday, September 2, 2018.

[41] Amasuomo, T.T., Atanda, J., Baird, G. 2016. Development of a building performance assessment and design tool for residential buildings in Nigeria. International High- Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16), iHBE 2016. Procedia Engineering, 180: 221 – 230.

[42] Pärn, E. A. and Edwards, D.J. 2019. Cyber threats confronting the digital built environment: Common data environment vulnerabilities and block chain deterrence. Engineering, Construction and Architectural Management, 26(2), pp. 245-266.

[43] Boarder, R.F.W., Owens, P. L., Khatib, J.M. 2016. The sustainability of lightweight aggregates manufactured from clay wastes for reducing the carbon footprint of structural and foundation concrete. In Sustainability of Construction Materials, 209-244). Woodhead Publishing.

[44] Kumanayake, R., Luo, H., Paulusz, N. 2018. Assessment of material related embodied carbon of an office building in Sri Lanka. Energy and Buildings, 166:250-257.

[45] Dixon, C., Edwards, D.J., Mateo-Garcia, M., Lai, J., Thwala, W.D.D. and Shelbourn, M. 2020, "An investigation into the erroneous access and egress behaviours of building users and their impact upon building performance", Facilities, Vol. ahead-of-print No. ahead-of-print.

[46] Agyekum, K., Ayarkwa, J., and Koranteng, C. 2014. A Holistic Survey of Dampness in A Six Bedroom Residential Apartment. Journal of Science and Technology, 34((1), 30-45.

[47] Kim, T. H., Chae, C.U., Kim, G.H.., Jang, H.J. 2016. Analysis of CO2 emission characteristics of concrete used at construction sites, Sustainability, 8(348).

[48] Asikainen, A., Pärjälä, E., Jantunen, M., Tuomisto, J.T., Sabel, C.E. 2017. Effects of local greenhouse gas abatement strategies on air pollutant emissions and on health in Kuopio, Finland. Climate, 5(43).

[49] GhaffarianHoseini, A., Dahlan, N., Berardi, U., GhaffarianHoseini, A., Makaremi, N., GhaffarianHoseini, M. 2013. Sustainable energy performances of green buildings: A review of current theories, implementations and challenges. Renewable and Sustainable Energy Reviews, 25: 1–17.

[50] Wuni, I.Y., Shen, G.Q.P., Osei-Kyei, R. 2019. Scientometric review of global research trends on green buildings in construction journals from 1992 to 2018. Energy & Buildings, 190: 69–85.

[51] Nellickal, A.G., Rajendra, A.V., Palaniappan, S. 2015. A Simulation-Based Model for Evaluating the Performance of Ready-Mixed Concrete (RMC) Production Processes. R.H. Crawford and A. Stephan (eds.), Living and Learning: Research for a Better Built Environment: 49th International Conference of the Architectural Science Association 2015, pp.658–667. ©2015, The Architectural Science Association and The University of Melbourne.

[52] Gursel, A.P., Masanet, E., Horvath, A., Stadel, A. 2014. Life-cycle inventory analysis of concrete production: A critical review. Cement and Concrete Composites, 51:38-48.

[53] USGS. 2011. Cement – mineral commodity summaries. Cement statistics and information – annual publications, U.S. Department of the Interior, U.S. Geological Survey.

[54] Mehta, P. K., Walters, M. 2008. The roadmap to a sustainable concrete construction industry. Construct Specifier, 61: 48–57.

[55] Mehta, P. K., Monteiro, P. J.M. 2006. Concrete: microstructure, properties, and materials. 3rd. ed. New York, NY: McGraw-Hill.

[56] Hölting, B., Coldewey, W.G. 2019. Groundwater Exploitation. In Hydrogeology. 203-230. Springer, Berlin, Heidelberg.

[57] Guo, M., Hu, B., Xing, F., Zhou, X., Sun, M., Sui, L., Zhou, Y. 2020. Characterization of the mechanical properties of eco-friendly concrete made with untreated sea sand and seawater based on statistical analysis. Construction and Building Materials, 234, 117339.

[58] Nahhab, A. H., Ketab, A.K. 2020. Influence of content and maximum size of light expanded clay aggregate on the fresh, strength, and durability properties of self-compacting lightweight concrete reinforced with micro steel fibres. Construction and Building Materials, 233:117922.

[59] Kamal, J., Mishra, U.K. 2019. Fly ash utilization in lightweight aggregates for sustainable construction. In Sustainable Construction and Building Materials (pp. 23-32). Springer, Singapore.

[60] Khalaf, M.A., Ban, C.C., Ramli, M. 2019. The constituents, properties and application of heavyweight concrete: A review. Construction and Building Materials, 215, 73-89.

[61] Liu, X., Ni, C., Ji, H., Tan, S., and Hong, B. 2019. Construction techniques and quality test and evaluation of lightweight cellular concrete mixed with fly ash as subgrade material. Advances in Materials Science and Engineering.

[62] Alaa, A.S., Pasławski, J., Nowotarski, P. 2019. Quality Management to continuous improvements in process of Ready Mix Concrete production. In IOP Conference Series: Materials Science and Engineering, 518(2), p. 022019). IOP Publishing.

[63] Kazaz, A., Ulubeyli, S., Arslan, A. 2020. Quantification of fresh ready-mix concrete waste: order and truck-mixer based planning coefficients. International Journal of Construction Management, 20(1), 53-64.

[64] Zhao, C., Liu, Y., Ren, S., Quan, J. 2018. Testing and green assessment technology for ready-mixed concrete. Key Engineering Materials, 768: 306-313 10.4028/www.scientific.net/KEM.768.306.

[65] Giwa, S.O., Sulaiman, M.A., and Nwaokocha, C.N. 2017. Inventory of greenhouse gases emissions from gasoline and diesel consumption in Nigeria. Nigerian Journal of Technological Development, 14(1), 1 – 12.

[66] Barati, K., Shen, X. 2017. Optimal driving pattern of on-road construction equipment for emissions reduction. Procedia Engineering, 180: 1221-1228.

[67] Jassim H.S.H., Lu, W. Olofsson, T. 2016. A practical method for assessing the energy consumption and CO2 emissions of mass haulers. Energies, 9(10), 802.

[68] Achour, H. 2012. Estimation of motor vehicle emissions with respect to controlling airpollution. Thesis presented to Dublin City University in fulfilment of the requirement for the degree of Doctor of Philosophy, School of Mechanical and Manufacturing Engineering, Dublin City University, Ireland.

[69] Ahn, C., Pan, W., Lee, S., Pena-Mora, F. 2010. Enhanced Estimation of Air Emission from Construction Operations Based on Discrete-Event Simulation. Proceedings of the international conference on computing in civil and building engineering, Nottingham University press, Paper 119, p. 237.

[70] Lewis, M. P. 2009. Models for estimating non-road emissions. Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles. North Carolina State University, NC, 13-17.

[71] Dabbas, W. M. 2010. Modelling vehicle emissions from an urban air-quality perspective: Testing vehicle emissions interdependencies. A Thesis Submitted in Fulfilment of the Requirements for the Degree of Doctor of Philosophy to Institute of Transport and Logistics Studies Faculty of Economics and Business, The University of Sydney.

[72] EPA 2013. Recommended procedures for development of emissions factors and use of the WebFIRE Database. EPA-453/D-13-001. Accessed on 9 April, 2020: https://www3.epa.gov/ttn/chief/efpac/procedures/procedures81213.pdf.

[73] Edwards, D. J., Pärn, E. A., Sing, C. P. and Thwala, W.D. 2019. Risk of excavators overturning: determining horizontal centrifugal force when slewing freely suspended loads. Engineering, Construction and Architectural Management. 26(3), 479-498.

[74] Edwards, D.J., Love, P. E.D. 2016. A case study of machinery maintenance protocols and procedures within the UK utilities sector. Accident Analysis and Prevention, 93:319-329.

[75] Shao, Z. 2016. Non-road emission inventory model methodology. The International Council on Clean Transportation (Working Paper), 4.

[76] EPA 2010a. Crankcase emission factors for non-road engine modeling compression-ignition. Environmental Protection Agency. Air and Radiation Office. USA. Office of Transportation and Air Quality. Report No. NR-009d.

[77] Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., Acquaye, A. 2013. Operational vs. embodied emissions in buildings - A review of current trends. Energy and Buildings, 66: 232–245.

[78] Franzoni, E. 2011. Materials selection for green buildings: Which tools for engineers and architects?, Procedia Engineering, 883–890.

[79] Chaudhary, M.T. 2016. Structural design of sustainable concrete buildings - LEED v4 and beyond. ACI-KC 4th International Conference, Kuwait. 8-10 November 2016. Paper # 11.

[80] Korea Environmental Industry and Technology Institute [KEITI] 2004. Korea Inventory Database. Available online: http://www.epd.or.kr/lci/lciDb.do (accessed 20 April, 2020).

[81] Korea Institute of Civil Engineering and Building Technology [KICT]. 2008. The final report of National DB on environmental information of building material. KICT: Goyang, Korea.

[82] Kang, G., Cho, H., Lee, D. 2019. Dynamic lifecycle assessment of in building construction projects: Focusing on embodied emissions. Sustainability, 11:3724.

[83] Jun, H., Lim, N., Kim, M. 2015. BIM-based carbon dioxide emission quantity assessment method in Korea. Journal of Asian Architecture and Building Engineering, 14(3), 569-576.

[84] Frey, H. C., Kim, K., Pang, S.-H., Rasdorf, W. J., Lewis, P. 2008. Characterization of real-world activity, fuel use, and emissions for selected motor graders fuelled with petroleum diesel and B20 biodiesel. Journal of the Air & Waste Management Association, 58(10), 1274-1287,

[85] Edwards, D.J., Holt, G.D., Harris, F. C. (1998) Predictive maintenance techniques and their relevance to construction plant. Journal of Quality in Maintenance Engineering, 4(1), pp. 25-37.

[86] Ahn, C., Rekapalli, P.V., Martinez J. C., Pena-Mora, F.A. 2009. Sustainability Analysis of Earthmoving Operations, Proceedings of the 2009, Winter Simulation Conference, IEEE, 2605-2611.

[87] EPA. (2008). NONROAD Model (Nonroad Engines, Equipment, and Vehicles), U.S. Environmental Protection Agency, U.S.A, <http://www.epa.gov/otaq/nonrdmdl.htm> [viewed 24 March 2019].

[88] CARB. 2009. Off-road emissions inventory program, Version 2009; California Air Resources Board, Sacramento. <http://www.arb.ca.gov/msei/offroad.htm> [viewed 27 March 2019].

[89] Chau, C.K., Yik, F.W.H., Hui, W.K., Liu, H.C., Yu, H.K. 2007. Environmental Impacts of Building Materials and Building Services Components for Commercial Buildings in Hong Kong. Journal of Cleaner Production, 15(18), 1840-1851.

[90] Hammond, G. P., Jones, C.I. 2008. Embodied energy and carbon in construction materials. Proceedings of the Institution of Civil Engineers Energy, 161(2), 87-98.

[91] Huberman, N. and Pearlmutter, D. (2008). A life-cycle energy analysis of building materials in the Negev desert. Energy and Buildings, 40(1), 837-848.

[92] Treloar, G. J. 1997. Extracting embodied energy paths from Input–Output Tables: Towards an Input–Output-Based hybrid energy analysis method. Economic Systems Research, 9(4), 375-391.

[93] Seo, S., Hwang, Y. 2001. Estimation of CO2 Emissions in Life Cycle of Residential Buildings. Journal of Construction Engineering and Management, 127(5),414-418.

[94] Crawford, R. H. and Treloar, G. J. 2003. Validation of the use of Australian Input Output Data for building embodied energy simulation. In IBPSA 2003: Proceedings of the Eighth International Building Performance Simulation Association Conference on Building Simulation: For better Building Design, IBPSA, Eindhoven, Netherlands, 235-242. ISBN: 9038615663.

[95] Chang, Y., Ries, R.J. Wang, Y. 2010. The embodied energy and environmental emissions of construction projects in China: An economic input–output LCA model. Energy Policy, 38(11), 6597-6603.

[96] Acquaye, A.A., Duffy, A.P. 2010. Input-output analysis of Irish construction sector greenhouse gas emissions. Building and Environment. 45(3), 784-791.

[97] Al-Saeed, Y., Edwards, D.J., Scaysbrook, S. 2020. Automating construction manufacturing procedures using BIM digital objects (BDOs): Case study of knowledge transfer partnership project in UK, Construction Innovation, Vol. ahead-of-print No. ahead-of-print. DOI: https://doi.org/10.1108/CI-12-2019-0141

[98] Roberts, C. J., Edwards, D. J., Hosseini, M. Reza., Matzeo-Garcia, M. and Owusu-Man, D. (2019) Post occupancy evaluation: a critical review of literature. Engineering, Construction and Architectural Management. 26(9), pp. 2084-2106.

[99] Kothari, C. R. 2004. Research Methodology; Methods and Techniques. 2nd Revised Edition. New Delhi: New Age International Limited Publishers. Publishers.

[100] Edwards, D.J., Rillie, I., Chileshe, N. Lai, J., Hossieni , M. Reza, and Thwala, W.D. (2020) A field survey of hand-arm vibration exposure in the UK utilities sector, Engineering, Construction and Architectural Management.

[101] Algozzine, B., Hancock, D. 2016. Doing case study research: A practical guide for beginning researchers, Teachers College Press.

[102] Environmental Protection Agency (EPA). 2010b. Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling; NR-005d National Service Center for Environmental Publications (NSCEP): College Park, MD, USA.

[103] Hong, T., Ji, C., Park, H. 2012. Integrated model for assessing the cost and CO2 emission (IMACC) for sustainable structural design in ready-mix concrete. Journal of Environmental Management, 103, 1–8.

[104] Weiszer, M., Fedorko, G., Molnár, V., Tučková, Z. and Poliak, M., 2020. Dispatching policy evaluation for transport of ready mixed concrete. *Open Engineering*, *10*(1), pp.120-128.

[105] Chen, T.M., Kuschner, W.G., Gokhale, J. and Shofer, S., 2007. Outdoor air pollution: nitrogen dioxide, sulfur dioxide, and carbon monoxide health effects. *The American journal of the medical sciences*, *333*(4), pp.249-256.

[106] Jonson, J.E., Borken-Kleefeld, J., Simpson, D., Nyíri, A., Posch, M. and Heyes, C., 2017. Impact of excess NOx emissions from diesel cars on air quality, public health and eutrophication in Europe. *Environmental Research Letters*, *12*(9), p.094017.

[107] Walsh MP (2011). Mobile source related air pollution: effects on health and the environment. *Encyclopedia of Environmental Health*.

[108] Krzyżanowski, M., Kuna-Dibbert, B. and Schneider, J. eds., 2005. *Health effects of transport-related air pollution*. WHO Regional Office Europe.

[109] Reşitoğlu, İ.A., Altinişik, K. and Keskin, A., 2015. The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems. *Clean Technologies and Environmental Policy*, *17*(1), pp.15-27.