FEDERAL UNIVERSITY OF TECHNOLOGY MINNA

SUSTAINABILITY IN CONCRETE PRACTICE:
IMPERATIVE PANACEA FOR RESOURCES CONSERVATION

By

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INAUGURAL LECTURE SERIES 105

4th October, 2023

Published by:
University Seminar and Colloquium Committee,
Federal University of Technology, Minna.

PREAMBLE

In the name of Allah, the most beneficent, the most merciful. I feel privileged to be here today to deliver the 000th Inaugural Lecture of Federal University of Technology, Minna.

Mr. Vice-Chancellor, other principal officers, members of the University community, and distinguished guests the theme of today's lecture is "Sustainability in Concrete Practice: Imperative Panacea for Resources Conservation". Concrete is a composite material composed of inclusions mainly from the natural environment. The utilisation of these materials for making concrete depletes the natural raw materials and thereby distorts the ecosystem. This is not sustainable as it militates against the attainment of Goal 12 (Responsible consumption and production) of the Sustainable Development Goals (SDG) – Agenda 2030 and Goal 7 (Environmental sustainability) of the Agenda 2063- the Africa we want. Against this background, the presentation of today dwells on sustainable issues with respect to concrete practice that encourage consumption of material in a way that is not detrimental to the environment so that the earth is not exhausted. Some of these viable ways are the utilisation of waste materials in concrete, optimal use of concrete materials and novel method of mix design and production of concrete.

1.0 INTRODUCTION

Concrete is a man-made building material which looks like stone. The word "concrete" is derived from the latin *concretus*, meaning "to grow together." Concrete is a composite material composed of coarse granular material (the aggregate or filler) embedded in a hard matrix of material (the cement or binder) that fills the space among the aggregate particles and glues them together (Li, 2011; Neville, 1995; Abdullahi, 2006; Somayaji, 1995). In most literature, the term concrete usually refers to Portland cement concrete, if not otherwise specified. For this kind of concrete, the compositions are mainly water, cement, fine and coarse aggregate (Figure 1). Admixtures and supplementary cementitious materials are sometimes added to modify some properties of the concrete. Utilisation of these materials degrade the environment. This raises concern over continuous availability of conventional materials of concrete for future use and also the safety of life.

Figure 1: Basic constituent materials of concrete

Concrete is the most widely used construction material in the world and its popularity can be attributed to two aspects; it is used for many different structures and the amount of concrete used is much more than any other material (Vasoya & Varia, 2015; Mindess *et al.* 2003; Nawy, 2001; Kosmatka & Wilson, 2011, Kett, 2000).

Concrete has been used to build various structures (Figures 2 to 6):

1. World's tallest building: Burj Khalifa, mixed-use skyscraper in Dubai, United Arab Emirates (height: 830m).
2. Tallest building in Africa: Sentech Tower in Johannesburg, South Africa (height:237m).
3. Tallest building in Nigeria: NECOM House, Marina Lagos (height: 160m).
4. Tallest building in Niger State: CBN Office Complex, Minna (height:16.6m)
5. Senate building, FUT Minna (height: 11m).

Figure 2: Burj Khalifa, in Dubai, United Arab Emirates
Source: https://www.burjkhalifa.ae/en/the-tower/facts-figures/

Figure 3: Sentech Tower in Johannesburg, South Africa
Source: https://www.trip.com/review/sentech-tower-28682881-158136863

Figure 4: NECOM House, Marina Lagos
Source: https://www.legit.ng/1089743-tallest-building-nigeria.html

Figure 5: CBN Office Complex, Minna
Source:
https://ng.infoaboutcompanies.com/Catalog/Niger/Minna/Bank/Central-Bank-Of-NIgeria

Figure 6: Senate Building, FUT Minna
Source: https://centers.futminna.edu.ng/?c=LEGAL

2.0 COMPOSITION OF CONCRETE

Concrete is composed mainly of cement, water, fine and coarse aggregates.

(i) Cement

Cement is an instant glue that bonds aggregates together in the presence of water to produce concrete. Different concrete requires cement with different properties. Examples of cements are Ordinary Portland cement, rapid hardening Portland cement, moderate sulfate resistant cement, high early strength cement, low heat cement, and high sulfate resistant cement (Neville, 1995; Mamlouk & Zaniewski, 2011).

(ii) Water

Any potable water is suitable for making concrete (Mindess *et al.* 2003; Abdullahi, 2012). However, some non-potable water may also be suitable. In most cases, unprocessed (questionable) surface or well water is used in the production of concrete. However, impurities in the mixing water can affect concrete set time, strength and long-term durability. The acceptable criteria for unprocessed water are specified in ASTM C 94. After seven days, the average compressive strength of mortar cubes made with the unprocessed water should not be less than 90% of the average compressive strength of cubes made with potable or distilled water (ASTM C109-93).

(iii) Aggregates

Aggregate is a mass of crushed stone, gravel and sand predominantly composed of individual particles, in some cases including clays and silts (Mamlouk & Zaniewski, 2011). Generally, aggregates are classified into two categories.

(a) **Fine aggregates:** Aggregate particles that pass through a 4.75 mm sieve (No.4). A No. 4 sieve has four openings per linear inch.
(b) **Coarse aggregates:** Aggregate particles that are retained on a 4.75mm sieve (No.4).

Other ingredients are required in concrete to modify some of its properties. These include admixtures and supplementary cementitious materials.

2.1 Properties of Concrete

The quality of concrete is governed by the chemical composition of the Portland cement, hydration and development of the microstructure, admixtures and aggregate characteristics. The quality is strongly affected by placement, compaction and curing (Abdullahi, 2012). The performance of a concrete structure through its service life is largely determined by the methods of mixing, transporting, placing and curing the concrete in the field. The ingredients of a "good" concrete may be the same as those of a "bad" concrete. The difference depends on the expertise of the Engineer and Technicians who are handling the concrete during construction. The properties of concrete are categorise into fresh and hardened properties (Mamlouk & Zaniewski, 2011).

2.1.1 Fresh properties of concrete

A common test for the properties of fresh concrete is the workability. Basically, workability is the amount of useful internal work necessary to produce full compaction. According to ACI 116R-90, workability is the ease and homogeneity with which fresh concrete can be mixed, placed, consolidated and finished.

Another term used to describe the state of fresh concrete is consistency. It is the degree of wetness; within limit, wet concretes are more workable than dry concretes, but concretes of the same consistency may vary in workability. The ACI defines consistency as the relative mobility or ability of freshly mixed concrete or mortar to flow. Tests for properties of fresh concrete include slump test, compacting factor test, vebe test and flow test.

2.1.2 Hardened properties of concrete

The major properties of hardened concrete are the compressive strength, splitting tensile strength, flexural strength and modulus of elasticity (Mohammed *et al.* 2014, Mohammed *et al.* 2013).

Compressive strength test is most commonly performed to ascertain the quality of hardened concrete. This is because it is very easy to conduct and also is one of the main structural design requirements to ensure that the structure will be able to carry the intended load. Compressive strength increases with decrease in water-cement ratio. Since water-cement ratio is directly related to the quality of concrete, compressive strength is also used as a measure of quality, such as durability and resistance to weathering (Neville, 1995). The compressive strength of normal-weight concrete is between 20 N/mm^2 to 40 N/mm^2. Compressive strength above 40 N/mm^2 is for High Strength Concrete

(HSC) requiring addition of admixtures and supplementary cementitious materials.

2.2 Sustainability from Allah's Commandments

The Holy Quran, Chapter 55, verses 8-10 says "That you not transgress within the balance. And establish weight in justice and do not make deficient the balance. And the earth He laid [out] for the creatures". [**Surat Ar-Rahman 55: 8-10**].

Also, there are 7 verses from the Holy Quran on the Environment, but the one of interest here is on "Preserving the Ozone layer:"

"And we made the sky a protected ceiling, but they, from its signs, are turning away." (Quran, 21:32) – [Surat AL-Anbya].

This means that the production of concrete should be done in such a way that the natural environment is protected to ensure sustainable living for all creatures.

2.3 Sustainable Issues in Concrete Practice

The world is characterised by finite natural resources and sources of energy. Unfortunately, these natural resources are being used at a rate that cannot be sustained indefinitely. Moreover, the energy that is expended in exploiting these resources, and the ways in which they are used and consumed, produces pollution and degradation of the environment. In particular, the *greenhouse gas emissions* resulting from the use of resources (mainly carbon dioxide, methane, and nitrous oxide), contribute significantly to global climate change (Kosmatka & Wilson, 2011; Penttala, 1997). To achieve a sustainable living there is the need to pay much attention to the way in which human deal with the natural environment. This leads inevitably to the concept of sustainable development, which is most commonly defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland, 1987; Li, 2011). Embodied in this definition is the necessity of taking a holistic approach to sustainability, by considering not only the environmental, but also the social and economic consequences of human behaviour, as indicated schematically in Figure 7 (Brundtland, 1987).

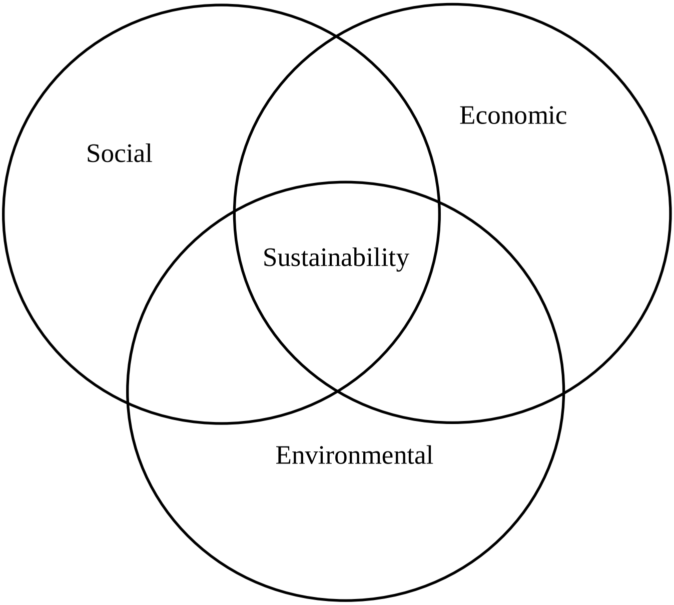

Figure 7: Holistic view of sustainability
Source: (Brundtland, 1987)

Concrete is, next to water, by far the most widely used construction material around the world, because of the economic and widespread availability of its constituents, its versatility, its durability, and its adaptability (Ngab, 2004). Table 1 shows the world utilisation of materials.

Table 1: 2021 Annual world utilisation of materials, in tonnes (metric tons)

Material	Production	Source
Concrete	30 Billion	https://www.nature.com/articles/d41586-021-02612-5
Portland cement	4 Billion	www.greenbiz.con
Steel	2 Billion	Worldsteel.org/steel-topic/statistics/world-steel-in-figures-2022
Coal	8 Billion	http://www.org/news/the-world-s-coal-consumption
Crude oil	4.9 Million	worldometers.info/oil/
Wheat	787 Million	http://www.statista.com/statistics/1094056/total-global-rice-consumption/
Salt	290 Million	http://www.statista.com/statistics/237162/wordwide-salt-production/
Sugar	168 Million	https://www.isosugar.org/sugarsector/sugar#:~:text=Consumption,2016%20high%20of%2023.0%20kg.

The production of Portland cement requires the utilisation of huge amount of energy. An energy input of about 4900 MJ is per tonne of cement. This translates to about 900 MJ per tonne of concrete. Also a considerable amount of carbon dioxide (CO_2) is liberated; on average, about 1 tonne of CO_2 is liberated per tonne of cement produced. This amounts to about 7% of the world's CO_2 emissions.

In addition to Portland cement, the concrete industry uses vast quantities of other materials. About 50 billion tonnes of sand, gravel, and crushed rock, and over 4 trillion cubic metres of fresh water per year go into the production of concrete (popularmechanics.com; http://www.parksandrecbusiness.com). This too may have considerable ecological effects. To reduce the ugly trend, it is imperative to make the concrete industry much more sustainable. Fortunately, with the current worldwide reserviour of knowledge, this is an achievable goal.

2.3.1 Steps to sustainability

There are a number of approaches to making concrete more sustainable, including:

a. The use of higher strength concretes.
b. Making concrete much more durable.
c. Replacing up to half of the Portland cement with supplementary cementing materials (SCMs).
d. Using fillers.
e. Manufacturing Portland cement more efficiently
f. Using waste materials as fuels
g. Using recycled concrete, and other industrial wastes, as aggregate sources.
h. Finding ways to capture and store or sequester CO_2 emissions.
i. Using cement kiln dust in some applications.
j. Using less water.
k. Improving structural design and building codes.

A sustainable concrete structure is one that is constructed such that the total societal impact during its entire life cycle is minimal. Designing with sustainability in mind includes accounting for the short-time and long-time consequences of the structure. An integrated sustainable design process can reduce the projects costs and operating costs of the development. Achieving sustainable development requires methods and tools to help quantity and compare the environmental impacts of creating and providing the goods and services used by our society (Figure 8) (Kusuma *et al.*, 2015).

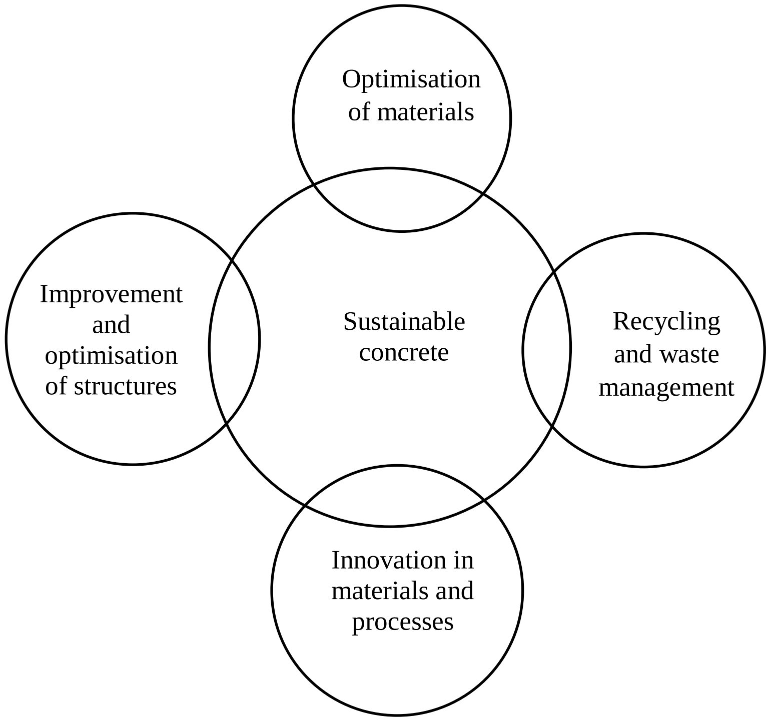

Figure 8: How to make sustainable concrete
Source: (Kusuma *et al.*, 2015).

3.0 MY CONTRIBUTIONS

I have been involved in researches in sustainability in concrete practice spanning over twenty years. Some of my research outputs are in the areas of alternative construction materials, development of mix design methods, testing and characterisation of concrete products and numerical modelling of concrete properties. Some of these research works are as follows:

3.1 MODELLING THE SLUMP, COMPRESSIVE STRENGTH AND DENSITY OF CONCRETE CONTAINING COCONUT SHELL AS PARTIAL REPLACEMENT FOR CRUSHED GRANITE

Crushed coconut shell was used to partially replace crushed granite as coarse aggregate in the production of concrete (Abdullahi *et al.*, 2017a). A total of 108 cubes were cast, cured and crushed at 28 days to determine their compressive strength. The concrete developed in this work has maximum slump of 135 mm. Compressive strength ranges from 8.94 N/mm^2 – 27.11 N/mm^2 and density ranging from 1757.04 kg/m^3 to 2198.52 kg/m^3 respectively. This indicates that the concrete can be used for structural applications.

Polynomial models were developed with the capability of explaining the under-lying relationship of 93.5 %, 75.0 % and 77.6 % for slump, compressive strength and density respectively.

The derived models are:

$$\text{Slump, } Y_1 = 79.46 - 71.87X_1 - 29.55X_3 + 1236.85X_1^2 + 14.14X_3^2 - 225.86X_1X_3 \quad (1)$$

$$\text{Compressive strength, } Y_2 = -17.75 + 201.8X_1 - 5.58X_2 - 0.21X_3 - 47.59X_4 - 248.56X_1^2 + 124.82X_2^2 - 1.71X_3^2 + 69.79X_4^2 - 151.63X_1X_2 + 30.95X_1X_3 - 50.7X_1X_4 - 10.17X_2X_3 - 82.81X_2X_4 + 2.71X_3X_4 \quad (2)$$

$$\text{Density model, } Y_3 = 4615.71 + 235.91X_1 - 6682.83X_2 - 283.89X_3 + 1857.5X_4 - 1683.64X_1^2 + 6136.89X_2^2 - 14.76X_3^2 + 293.84X_4^2 - 537.89X_1X_2 + 519.29X_1X_3 + 1336.17X_1X_4 + 196.83X_2X_3 - 5536.19X_2X_4 - 46.72X_3X_4 \quad (3)$$

Where,
X_1 = Water-cement ratio
X_2 = Total aggregate-cement ratio
X_3 = Coarse-total aggregate-cement ratio

3.2 CHARACTERISTIC OF PALM OIL CLINKER AGGREGATE

An experimental study was conducted to investigate the possibility of utilising palm oil clinker (POC) as aggregate for concrete making (Abdullahi *et al.*, 2010). Substantial amount of solid waste (palm oil shell) is being generated in the milling process of palm oil. POC is obtained by incinerating this waste at high temperature. The clinkers were crushed and sieved to the desired aggregate sizes. The properties of the aggregate were investigated to ascertain their suitability for concrete work. Tests conducted included bulk density, specific gravity, water absorption, and sieve analysis.

The results obtained were in agreement with the specification in ASTM C330-05 (standard specification for lightweight aggregates for structural concrete). This shows that POC is a lightweight aggregate and can be used for concrete production. Successful utilisation of POC as aggregate in concrete work would serve as a means of disposal of solid waste and consequently sanitise the environment. Palm oil clinker aggregate is shown in Figure 9 and a few test results are shown in Tables 2, 3 and 4.

(a) Lumped POC (b) Fine POC (c) Coarse POC

Figure 9: Palm oil clinker aggregate (POC)

Source: Abdullahi *et al.*, 2010

Table 2: Properties of Fine and Coarse Palm Oil Clinker

Aggregate Properties		**Fine Palm Oil Clinker**	**Coarse Palm Oil Clinker**
Absorption -SSD (%)		14.29	5.39
Bulk density (kg/m^3)		1122.10	793.14
Voids in aggregate (%)		36	54
Specific gravity	Oven dry	1.75	1.73
	SSD	2.00	1.82
	Apparent	2.35	1.92

Source: Abdullahi *et al.*, 2010

Table 3: Sieve Analysis of Fine Palm Oil Clinker

Sieve Size (mm)	**Mass Retained (g)**	**Mass Passed (g)**	**Percentage Retained (%)**	**Cumulative Percentage Retained (%)**	**Percentage Passing (%)**	**ASTM C 330-04 Limitation (%)**
5.00	0	350	0.00	0.00	100	
2.34	90	260	25.71	25.71	74.29	
2.00	20	240	5.71	31.42	68.58	
1.18	60	180	17.14	48.56	51.44	40 – 80
0.85	30	150	8.57	57.13	42.87	
0.6	30	120	8.57	65.70	34.30	
0.30	60	60	17.14	82.84	17.16	10 – 35
0.15	20	40	5.71	88.55	11.45	5 – 25
0.075	20	20	5.71	94.26	5.71	
0.063	5	15	1.43	95.69	4.31	
Pan	15	0	4.31	100	0	
Total	350	350				

Source: Abdullahi *et al.*, 2010

Table 4: Sieve Analysis of Coarse Palm Oil Clinker

Sieve Size (mm)	Mass Retained (g)	Mass Passed (g)	Percentage Retained (%)	Cumulative Percentage Retained (%)	Percentage Passing (%)	ASTM C 330-04 Limitation (%)
14	0	3000	0.00	0.00	100.00	100
10	1130	1870	37.67	37.67	62.33	40 – 80
6.3	1180	690	39.33	77.00	23.00	
5	650	40	21.67	98.67	1.33	
4.75	40	0	1.33	100	0.00	0 – 20
2.36	0	0	0.00	100	0.00	0 – 10
Pan	0	0	0.00	100	0.00	
Total	3000					

Source: Abdullahi *et al.*, 2010

3.3 TRIAL MIX DESIGN OF POC CONCRETE

Accurate determination of the properties of POC aggregate such as sieve analysis, specific gravity, water absorption and unit weight are very difficult. The absence of these data makes the mix design of POC concrete an impossible venture. This is because the aggregate is new and there in no standard procedure for its mix design. The result of the POC aggregate characterisation was used to produce first trial mixes (Abdullahi *et al.*, 2008). The constituent materials of the concrete were water, cement, fine aggregate and coarse aggregate. Both fine and coarse aggregates are POC; producing all-lightweight concrete. The consistency, slump, and fresh unit weight and yield of the paste were noted. The mixes were adjusted to improve on the rheology. Three cubes were cast where the mixes were considered homogeneous otherwise, the mixes were discarded. Test results showed defined region of feasible mixes (Figure 10). This indicates that the utilisation of POC aggregate in concrete is possible without any admixture.

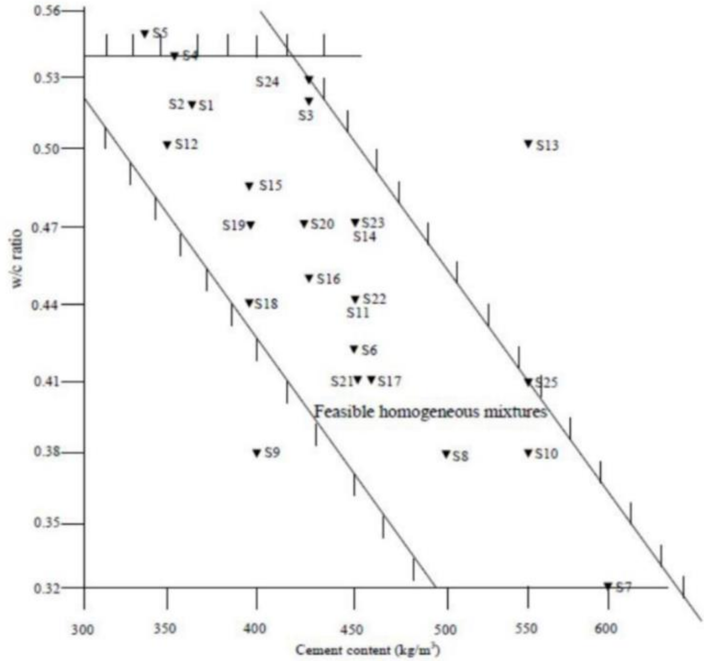

Figure 10: A chart of w/c ratio verses cement content
Source: Abdullahi *et al.*, 2008

3.4 COMPRESSIVE STRENGTH AND ABSORPTION OF CONCRETE COMPOSED OF NATURAL AND PALM OIL CLINKER (POC) AGGREGATES

An experimental programme on concrete containing natural and palm oil clinker (POC) aggregate was conducted (Hassan *et al.*, 2008). Concrete cube specimens were cast, cured and tested for compressive strength and water absorption. Compressive strength and density in the ranges of 26.2 N/mm^2 to 41.6 N/mm^2 and 1821 kg/m^3 to 2214 kg/m^3 at 28 days were obtained indicating that POC concrete can be used as structural lightweight concrete with full replacement. Partial replacement of POC not exceeding 25% can be used to increase strength and improve durability. The result of compressive strength is shown in Table 5.

Table 5: Compressive strength and absorption of concrete containing POC aggregates

	Compressive strength (N/mm²)				
Age (Days)	**POCC_0**	**POCC_25**	**POCC_50**	**POCC_75**	**POCC_100**
1	12.6	13.6	12.7	11.2	10.8
3	21.6	25.3	19.3	16.5	14.6
7	30.9	32.9	27.3	24.6	22.8
14	39.5	40.5	33.7	27.1	25.3
28	40.3	41.6	35.1	29.7	26.2
Water absorption (%)	1.2	1.1	1.4	1.7	2.3

Source: Hassan *et al.*, 2008

3.5 NUMERICAL MODELLING OF LIGHTWEIGHT CONCRETE MIXTURES USING PALM OIL CLINKER (POC) AS AGGREGATE

A statistical technique was developed for the modelling of lightweight concrete mixtures using Palm Oil Clinker (POC) as aggregate (Abdullahi *et al.*, 2009e). POC is obtained from the by-product of palm oil milling. The material is still new and accurate determination of its properties are very difficult. Aggregate characterization was conducted and a central composite design (CCD) was used for the factor settings to develop mix constituents using absolute volume method. Statistical modelling was done at 95% confidence interval. Test result showed that a polynomial model is adequate to predict the slump, air-dry density and compressive strength of POC concrete. The model statistics showed reasonable response prediction capabilities.

The four polynomial models developed are:

Slump model:
Models Statistics (R^2 = 96.9%, R^2 adjusted = 95.4%, p-value for lack of fit test = 0.108)

$$Y_1 = 17890.77 - 15294.66X_1 - 32.61X_2 - 18028.75X_3 + 8181.82X_1X_2 + 17.19X_2X_3 + 35.94X_1^2 \quad (4)$$

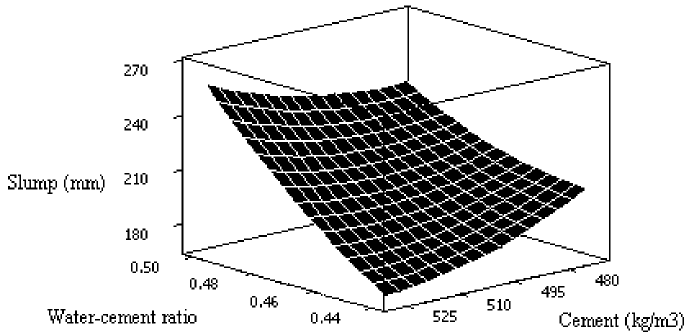

Figure 11: Response Surface Plot for Slump Versus Water-Cement Ratio and Cement Content
Source: Abdullahi *et al.*, 2009e

Air-dry density model:
Models Statistics (R^2 = 99.5%, R^2 adjusted = 99.3%, p-value for lack of fit test = 0.763)

$$Y_2 = -287.985 - 15120.1X_1 + 28.5377X_2 - 4192.25X_3 - 19375X_1X_3 + 28.125X_2X_3 + 29739.4X_1^2 - 0.0485234X_2^2 \quad (5)$$

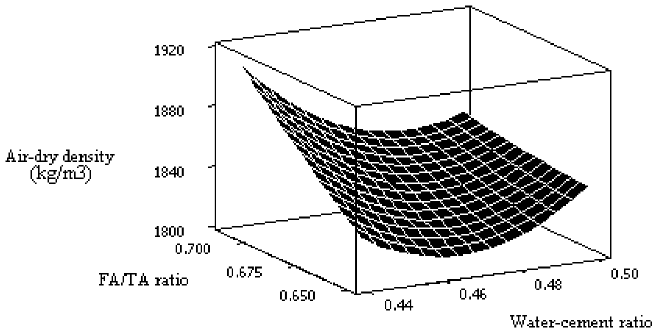

Figure 12: Response Surface Plot for Air-Dry Density Versus Water-Cement Ratio and FA/TA Ratio
Source: Abdullahi *et al.*, 2009e

Compressive strength model:
Models Statistics (R^2 = 94.9%, R^2 adjusted = 93.0%, p-value for lack of fit test = 0.364)

$$Y_3 = 742.79 - 1778.38X_1 - 1.32X_2 - 42.56X_3 + 1817.61X_1^2 + 0.00137X_2^2 \quad (6)$$

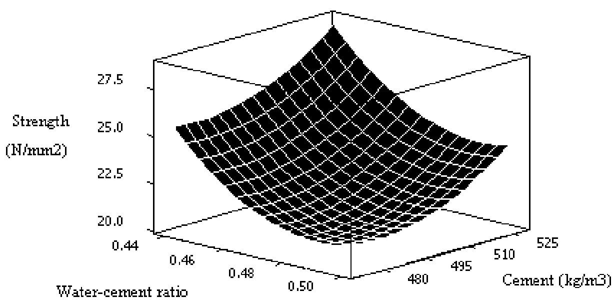

Figure 13: Response Surface Plot for Strength Versus Water-Cement Ratio and Cement Content
Source: Abdullahi *et al.*, 2009e

Modulus of Elasticity:

Models Statistics (R^2 = 97.8%, R^2 adjusted = 96.8%, p-value for lack of fit test = 0.449)

$$Y_4 = 299.3572 - 493.6003X_1 - 0.1342X_2 - 422.6524X_3 + 460.4046X_1^2 + 0.000180156X_2^2 + 332.627X_3^2 \quad (7)$$

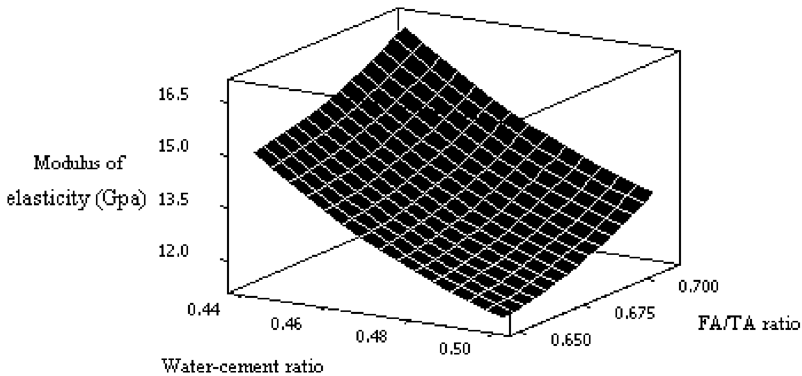

Figure 14: Response Surface Plot for Modulus of Elasticity Versus Water-Cement Ratio and FA/TA Ratio

Source: Abdullahi *et al.*, 2009e

The polynomial models made up of three parameters have been used to describe the effect of mix ingredients on the slump, air-dry density, compressive strength and modulus of elasticity. The effect of the variation of cement content on the compressive strength is minimal within the experimental region considered compared to factors such as water-cement ratio and fine-total aggregate ratio. The fine-total aggregate ratio has significant effect on the strength of lightweight concrete since failure of lightweight concrete is mainly governed by the strength of the aggregate rather than the quality of the hardened cement paste.

3.6 EQUATIONS FOR MIX DESIGN OF STRUCTURAL LIGHTWEIGHT CONCRETE

Equations for mix design of structural lightweight concrete were developed to ease concrete mix design and thereby reducing wastage (Abdullahi *et al.*, 2009a). Conventionally mix design of concrete is conducted using the tabular data and charts in standards (ACI 211.1-91, ACI 211.2-98). This requires extra efforts of understanding the data in the codes and interpolations are often required when intermediate values are needed. Microsoft excel spreadsheet was used to develop equations using the tabular data in ACI 211.2-98 (Standard Practice for Selecting Proportions for Structural Lightweight Concrete). The tabular data and graphs in ACI 211.2.98 were converted to equations. Various models were tried and the best model that adequately represented the data was chosen based on the regression coefficients and its predictive capability.

The mix design equations developed are:

3.6.1 Mixing water and air content:

3.6.1.1 Air-entrained concrete

Mixing water

Slump range, 125 to 150mm

$$y_1 = 0.2267x_1^2 - 8.9879x_1 + 275.92 \quad (8) \quad R^2 = 1$$

Slump range, 75 to 100mm

$$y_1 = 0.1215x_1^2 - 5.6721x_1 + 244.92 \quad (9) \quad R^2 = 1$$

Slump range, 25 to 50mm

$$y_1 = 0.0648x_1^2 - 3.4251x_1 + 207.69 \quad (10) \quad R^2 = 1$$

Entrained air

Slump range, 125 to 150mm

$$y_2 = 0.0013x_1^2 - 0.1964x_1 + 9.2436 \quad (11) \quad R^2 = 1$$

Slump range, 75 to 100mm

$$y_2 = 0.0094x_1^2 - 0.3745x_1 + 8.7051 \quad (12) \quad R^2 = 1$$

Slump range, 25 to 50mm

$$y_2 = 0.0175 x_1^2 - 0.5526 x_1 + 8.1667 \qquad (13) \qquad R^2 = 1$$

3.6.1.2 Non-air-entrained concrete

Mixing water

Slump range, 125 to 150mm

$$y_1 = 0.2996 x_1^2 - 11.591 x_1 + 320.08 \qquad (14) \qquad R^2 = 1$$

Slump range, 75 to 100mm

$$y_1 = 0.143 x_1^2 - 6.8138 x_1 + 279.82 \qquad (15) \qquad R^2 = 1$$

Slump range, 25 to 50mm

$$y_1 = 0.1215 x_1^2 - 5.6721 x_1 + 250.92 \qquad (16) \qquad R^2 = 1$$

Entrapped air

$$y_3 = 0.0094 x_1^2 - 0.3745 x_1 + 5.7051 \qquad (17) \qquad R^2 = 1$$

Water-cement ratio

Non-air-entrained concrete

$$y_4 = -0.3749 \ln(x_2) - 1.8148 \qquad (18) \qquad R^2 = 0.999$$

Air-entrained concrete

$$y_4 = -0.3723 \ln(x_2) - 1.7225 \qquad (19) \qquad R^2 = 0.999$$

3.6.2 Volume of oven-dry loose coarse aggregate per unit volume of concrete

Fineness modulus = 2.4

$$y_5 = -0.002 x_1^2 + 0.0745 x_1 + 0.0546 \qquad (20) \qquad R^2 = 1$$

Fineness modulus = 2.6

$$y_5 = -0.002 x_1^2 + 0.0745 x_1 + 0.0346 \qquad (21) \qquad R^2 = 1$$

Fineness modulus = 2.8

$$y_5 = -0.002 x_1^2 + 0.0745 x_1 + 0.0146 \qquad (22) \qquad R^2 = 1$$

Fineness modulus = 3.0

$$y_5 = -0.002 x_1^2 + 0.0745 x_1 + 0.0054 \qquad (23) \qquad R^2 = 1$$

Or, in terms of the fineness modulus
Nominal maximum coarse aggregate size = 19 mm
$y_5 = -0.1x_3 + 0.98$ (24) $R^2 = 1$

Nominal maximum coarse aggregate size = 19 mm
$y_5 = -0.1x_3 + 0.91$ (25) $R^2 = 1$

Nominal maximum coarse aggregate size = 19 mm
$y_5 = -0.1x_3 + 0.82$ (26) $R^2 = 1$

3.6.3 Weight of fresh light weight concrete

Entrained air = 4%
$y_6 = 426.14x_4 + 1169.3$ (27) $R^2 = 0.9999$

Entrained air = 6%
$y_6 = 423x_4 + 1135.7$ (28) $R^2 = 0.9999$

Entrained air = 8%
$y_6 = 419.29x_4 + 1102.6$ (29) $R^2 = 0.9999$

Or, in terms of entrained air (%)
Specific gravity factor = 2.0
$y_6 = -20.75y_2 + 2106.2$ (30) $R^2 = 1$

Specific gravity factor = 1.8
$y_6 = -19.25y_2 + 2012.2$ (31) $R^2 = 0.9973$

Specific gravity factor = 1.6
$y_6 = -19.25y_2 + 1927.2$ (32) $R^2 = 0.9986$

Specific gravity factor = 1.4
$y_6 = -19.25y_2 + 1844.2$ (33) $R^2 = 0.9986$

Specific gravity factor = 1.2
$y_6 = -17{,}75y_2 + 1749.8$ (34) $R^2 = 0.9999$

Specific gravity factor = 1.0
$y_6 = -19.25y_2 + 1673.8$ (35) $R^2 = 0.9986$

3.6.4 Determination of cement content by volume method:

The equations for cement content as a function of compressive strength were developed using figure 3.3.2 in ACI 211.2-98 and with several mathematical manipulations.

For all-lightweight Concrete, the minimum cement content is

$$x_{5L} = \frac{x_2 + 7.04385}{0.117044} \quad (36)$$

and the maximum cement content is

$$x_{5U} = \frac{x_2 + 16.5291}{0.112159} \quad (37)$$

Similar equations were developed for sand-lightweight concrete. The minimum and maximum cement contents are:

$$x_{5L} = \frac{x_2 + 1.014677}{0.115344} \quad (38)$$

$$x_{5U} = \frac{x_2 + 15.408682}{0.116959} \quad (39)$$

Where,

y_1 = Water requirement (kg/m^3)
y_2 = Entrained air (%)
y_3 = Entrapped air (%)
y_4 = Water-cement ratio
y_5 = Volume of oven-dry loose coarse aggregate per unit volume of concrete (m^3)
y_6 = Weight of fresh lightweight concrete (kg/m^3)
x_1 = Nominal maximum coarse aggregate sizes (mm)
x_2 = Compressive strength (N/mm^2)
x_3 = Fineness modulus
x_4 = Specific gravity factor
x_5 = cement content (kg/m^3)
a_0 = Intercept (regression coefficients)

a_1 = Slope (regression coefficients)
x_{5L} = Minimum cement content (kg/m^3)
x_{5U} = Maximum cement content (kg/m^3)

3.6.5 Application of the derived equations:

The equations derived in this work were used to obtain the mix ingredient of concrete using sample mix design problems from reputable textural sources. The result is shown in Table 6.

Table 6: Results of first trial batch

	Weight method	
Mix ingredient	Equation	Case 1
Water (kg/m^3) Cement (kg/m^3) Fine aggregate (kg/m^3) Coarse aggregate (kg/m^3) Water/cement ratio (%)	181 452.5 539.19 597.51 0.4	180.96 452.69 538.12 597.45 0.4
	Volume method	
Mix ingredient	Equation	Case 2
Water (kg/m^3) Cement (kg/m^3) Lightweight Fine aggregate (kg/m^3) Lightweight Fine aggregate (kg/m^3) Coarse aggregate (kg/m^3) Water/cement ratio (%)	181 350 167.2 554.2 472.5 0.52	180.00 350 168 550 473 0.51

Source: Abdullahi *et al.*, 2009a

The equations presented in this work are capable of giving the material constituents of structural lightweight concrete for the first trial batch from given performance criteria. Mix adjustment of the ingredients can be made simply by choosing suitable input variables and re-calculating the batch composition. The equations can be updated when new version of the code is available by developing new equations to replace the ones presented in this work. Interpolations are avoided with the use of these equations. Addition of equations to future versions of mix design codes may add more value to the existing documents.

3.7 GRAPHICAL USER INTERFACE FOR PROPORTIONING LIGHTWEIGHT CONCRETE

The codes of practice such as ACI 211.2-98 have the advantage of readily conveying the underlying relationships between variables and responses but they are not simple to automate using computer programs.

To automate the mix design procedure for lightweight concrete, a Graphical User Interface (GUI) was developed using MATLAB (Abdullahi *et al.*, 2009c). The GUI provides a pictorial interface between the user and the computer program. It provides a friendlier environment with the help of the components, figures and callbacks. The home page of the GUI is shown in Figure 15.

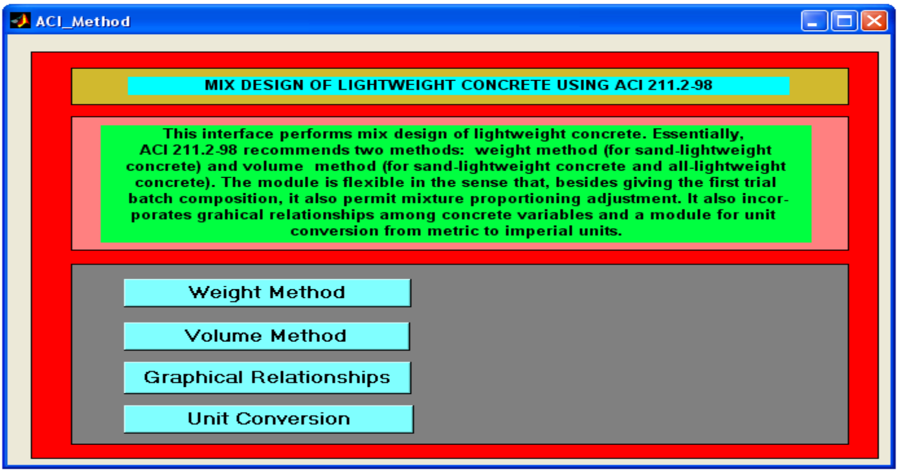

Figure 15: Home page GUI for structural lightweight concrete mix design

Source: Abdullahi *et al.*, 2009c

7.1 Validation of the computer program

To validate the program, sample concrete mix design problems from textural sources were tried. Two such trial problems are presented here (Nawy, 2001; Mindess *et al.* 2003). The results for the program and the textbooks are compared in Table 7.

Table 7: Results of Mix Design of Lightweight Concrete

Weight method			
Mix ingredient	GUI	Trial Problem 1	Error (%)
Water (kg/m^3)	181.01	180.96	0.03
Cement (kg/m^3)	453.85	452.69	0.26
Fine aggregate, SSD (kg/m^3)	537.83	495.41	8.56
Coarse aggregate, SSD (kg/m^3)	597.51	597.45	0.01
Water/cement ratio (%)	0.4	0.4	0
Volume method			
Mix ingredient	GUI	Trial Problem 2	Error (%)
Water (kg/m^3)	180.93	180.00	0.52
Cement (kg/m^3)	350	350	0.00
Lightweight fine aggregate (kg/m^3)	147.78	148.00	0.15
Normal-weight fine aggregate (kg/m^3)	571.9	572.00	0.02
Coarse aggregate, SSD (kg/m^3)	466.86	467.00	0.03
Water/cement ratio (%)	0.52	0.52	0

Source: Abdullahi *et al.*, 2009c

As shown in Table 7, the mix compositions calculated by the GUI agree reasonably well with those from trial problems 1 and 2. The outcome of the work is a MATLAB-based GUI that provides a tool for mix design of structural lightweight concrete in a simple and convenient manner. The program is capable of giving the material constituent of concrete for the first trial batch from given performance criteria. Mixture proportioning adjustments can also be made because the program only calculates the amounts of the constituent materials, but allows the User to select the desired amount.

3.8 EVALUATION OF RUBBERCRETE BASED ON ULTRASONIC PULSE VELOCITY AND REBOUND HAMMER TEST

Several research works have been carried out to study the fresh and hardened properties of concrete containing crumb rubber as partial replacement of fine aggregate (Khaloo *et al.* 2008, Kaloush *et al.* 2005; Eldin & Senouci 1994; Topcu 1995; Papakonstantinou & Tobolsi 2006; Snelson *et al.* 2009). In view of the facts that rubbercrete is being used in the construction industry for a variety of purposes, evaluation of the rubbercrete mixtures using non-destructive tests such as rebound hammer (RH) and Ultrasonic Pulse Velocity (UPV) to establish valid relationship is worthwhile (Mohammed *et al.*, 2011a).

Fifteen mixture with different water-cement ratios and crumb rubber (CR) content percentages were prepared, cast and tested using RH and UPV at different curing ages. Modes were proposed and statistically validated to predict the relationship between compressive strength and UPV and rebound number (RN) for rubbercrete mixtures at 3, 7, and 28 days. The proposed models were statistically validated and have proof to have the capability to explain the underlying relationships. These models are: (Mohammed *et al.* 2011a)

UPV versus crumb rubber content

At 3-days curing period,

w/c 0.41, $UPV = 1.1073(CR)^2 - 71.572(CR) + 3473.5, R^2 = 0.9833$ (40)

w/c 0.57, $UPV = 1.3762(CR)^2 - 79.986(CR) + 3304.5, R^2 = 0.955$ (41)

w/c 0.68, $UPV = 1.0429(CR)^2 - 71.586(CR) + 3076.9, R^2 = 0.9871$ (42)

At 7-days curing period,

w/c 0.41, $UPV = 0.7071(CR)^2 - 52.727(CR) + 3591.4, R^2 = 0.9868$ (43)

w/c 0.57, $UPV = 0.8961(CR)^2 – 60.03(CR) + 3403.8, R^2 = 0.996$ (44)

w/c 0.68, $UPV = 1.2292(CR)^2 – 69.539(CR) + 3228.8, R^2 = 0.9862$ (45)

At 28-days curing period,

w/c 0.41, $UPV=0.1175(CR)^3 - 5.4593(CR)^2 + 26.528(CR) + 3946.3, R^2 = 0.9906$ (46)

w/c 0.57, $UPV = 0.0514(CR)^2 – 31.419(CR) + 3689.7, R^2 = 0.996$ (47)

w/c 0.68, $UPV = 0.1179(CR)^3 - 4.5891(CR)^2 + 1.2758(CR) + 3413.5$, $R^2 = 0.9862$ (48)

RN versus crumb rubber content

At 3-days curing period,

w/c 0.41, $RN = 0.01(CR)^2 - 0.89(CR) + 29.9$, $R^2 = 0.9917$ (49)

w/c 0.57, $RN = 0.02(CR)^2 - 1.08(CR) + 25.7$, $R^2 = 0.987$ (50)

w/c 0.68, $RN = 0.0071(CR)^2 - 0.5843(CR) + 20.043$, $R^2 = 0.99$ (51)

At 7-days curing period,

w/c 0.41, $RN = 0.0081(CR)^2 - 0.8329(CR) + 30.862$, $R^2 = 0.9971$ (52)

w/c 0.57, $RN = 0.019(CR)^2 - 0.79(CR) + 26.8$, $R^2 = 0.9882$ (53)

w/c 0.68, $RN = 0.0071(CR)^2 - 0.6043(CR) + 21.343$, $R^2 = 0.9696$ (54)

At 28-days curing period,

w/c 0.41, $RN = 0.0114(CR)^2 - 1.0429(CR) + 38.529$, $R^2 = 0.9792$ (55)

w/c 0.57, $RN = 0.01(CR)^2 - 0.89(CR) + 32.3$, $R^2 = 0.9809$ (56)

w/c 0.68, $RN = 0.0071(CR)^2 - 0.6443(CR) + 24.943$, $R^2 = 0.9992$ (57)

Also, the models relating UPV, RN and compressive strength (f_{cu}) are as follows:

At 3-days curing period,

$f_{cu} = 2.859e^{0.0007UPV}$, $R^2 = 0.9926$ (58)

$f_{cu} = 6.827e^{0.0593RN}$, $R^2 = 0.9951$ (59)

At 7-days curing period,

$f_{cu} = 1.9817e^{0.0008UPV}$, $R^2 = 0.9928$ (60)

$f_{cu} = 7.5858e^{0.0516RN}$, $R^2 = 0.9951$ (61)

At 28-days curing period,

$f_{cu} = 1.7564e^{0.0008UPV}$, $R^2 = 0.9905$ (62)

$f_{cu} = 9.5879e^{0.0384RN}$, $R^2 = 0.9951$ (63)

The proposed models (40 - 63) were statistically validated and found adequate in predicting the relationship between compressive strength with UPV and RN for rubbercrete at 3, 7, and 28 days of curing at water-cement ratio of 0.41, 0.57, and 0.68 and crumb rubber replacement in the range of 0% - 30%, cement content in the range 357.35 kg/m^3 – 592.68 kg/m^3, fine aggregate content in the range of 543.18 kg/m^3 – 901.96 kg/m^3, and coarse aggregate content in the range of 673.35 kg/m^3 – 792.69 kg/m^3.

3.9 ANALYTICAL AND EXPERIMENTAL STUDIES ON COMPOSITE SLABS UTILISING PALM OIL CLINKER CONCRETE

Palm oil clinker (POC) aggregates was used to fully replace normal aggregates for production of structural lightweight concrete. This concrete was used in the construction of composite slabs with profiled steel sheet. The structural behaviour of the slabs was investigated and compared with conventional concrete slabs. The horizontal shear-bond strength between the concrete and the steel was determined according to two methods; m-k and partial shear connection (psc) methods (Mohammed *et al.*, 2011b). Figure 16 shows the arrangement of the composite floor with steel profile sheet used in the experiment.

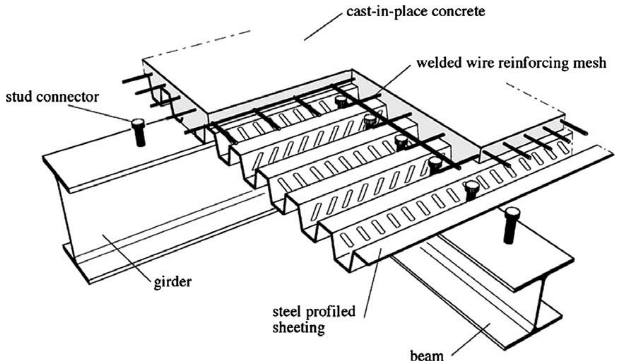

Figure 16: Composite floor with steel profile sheet
Source: Mohammed *et al.*, 2011b

The structural behaviour and the horizontal shear-bond strength of the POCC slabs are nearly similar to the conventional concrete slabs. The mechanical interlock (m) and the friction (k) between the steel and the concrete were 117.67 N/mm^2 and 0.0973 N/mm^2 respectively. The design horizontal shear strength using the m-k and psc methods are 0.248 N/mm^2 and 0.215 N/mm^2 respectively. The difference between the two methods is 13.3%. POCC is therefore suitable to be used for structural applications with a reduction in weight of 18.3% compared to conventional concrete composite slabs. The parameters used for the graph of m-k method are shown in Table 8.

Table 8: Parameters for the graph of m-k method

Slab ID	b (mm)	d_p (mm)	L_s (mm)	A_p (mm^2)	V_t (kN)	Vt/bd_p (N/mm^2)	A_p/bLs
LS1	600	109.5	900	980	21.48	0.326940639	0.001814815
LS2	600	109.5	900	980	21.97	0.334398782	0.001814815
LS3	600	109.5	900	980	19.80	0.301369863	0.001814815
SS1	600	109.5	450	980	34.90	0.531202435	0.00362963
SS2	600	109.5	450	980	36.90	0.561643836	0.00362963
SS3	600	109.5	450	980	35.05	0.53348554	0.00362963

Source: Mohammed *et al.*, 2011b

3.10 SHEAR STRENGTH OF PALM OIL CLINKER CONCRETE (POCC) BEAMS

The shear behavior of reinforced concrete beams made of POCC was investigated (Mohammed *et al.*, 2013). POCC has been classified as a lightweight structural concrete with air-dry density less than 1850 kg/m^3 and 28 days compressive strength more than 20 N/mm^2 (Abdullahi *et al.*, 2009d; Abdullahi *et al.*, 2009e). The parameters considered were the POCC compressive strength, shear span-depth ratio (a/d), and the ratio of tensile reinforcement (ρ). The study revealed that the failure mode of the reinforced concrete beam is similar to that of conventional reinforced concrete beam. In addition, the shear equation of the Canadian Standard Association (CSA) can be used in designing reinforced POCC beam with $\rho \geq 1$ with adequate safety. However, a safety factor of 0.5 should be included in the CSA formula for POCC beams with $\rho < 1$. Table 9 shows the summary of the experimental results.

Table 9: Summary of the experimental results

Beam reference	First shear crack (kN)	Failure load (kN)	Ultimate shear force, V_c (kN)	Failure mode
AD-3	23	55	27.5	Shear/anchorage
AD-1	16	39	19.5	Shear/compression
WC-1	13	43	21.5	Shear/anchorage
WC-3	14	50	25	Shear/anchorage
SR-1	14	61	30.5	Shear/anchorage
SR-3	7	25	12.5	Shear/anchorage
AD/WC/SR-2	10	46	23	Shear/anchorage

Source: Mohammed *et al.*, 2013

3.11 FLEXURAL STRENGTH OF POCC BEAMS

The flexural behaviour of reinforced concrete beams made from palm oil clinker (POC) aggregates was investigated (Mohammed *et al.*, 2014a). An experimental work was conducted involving eight under-reinforced beams with varying reinforcement ratios (0.34 – 2.21%) which were fabricated and tested. Parameters studied included the deflection characteristics, cracking behaviour and ductility indices. It was found that although POCC has a low modulus of elasticity, the test results revealed that the deflection of singly reinforced POCC beams with reinforcement ratio less than 0.524 under the design service load is acceptable as the span-deflection ratios ranged from 250 to 257 and it is within the allowable limit provided by BS 8110. Therefore, BS 8110 based design equations can be used for the prediction of the flexural capacity of POCC beams with reinforcement ratio up to 2.23%. The study showed that the flexural behaviour of reinforced palm oil clinker (POCC) beam is comparable to other types of lightweight concrete and confirms that POC can be used as aggregate in the production of structural lightweight concrete. Tables 10 and 11 show sample experimental data.

Table 10: Comparison between experimental and theoretical ultimate moment

Beam reference	Neutral axis at service moment, M_s (mm) [1]	Experimental design moment, M_{ult} (kNm) [2]	Theoretical design moment, M_{des} (kNm) [3]	Capacity ratio of POCC beams [4]=[2]/[3]
S1	44.04	28.56	26.82	1.07
S2	55.71	35.32	33.35	1.06
S3	66.04	40.39	38.76	1.04
S4	83.63	48.32	47.65	1.20
D1	97.61	70.40	69.58	1.01
D2	123.28	80.10	79.63	1.01
D3	125.63	84.25	83.23	1.01
D4	131.42	93.03	92.21	1.01

Source: Mohammed *et al.*, 2014a

Table 11: Deflection of reinforced POCC beams at service moment

Beam reference	Theoretical service moment (kNm)	Experimental deflection Δexp (mm)	Theoretical deflection Δtheo (mm)	Δexp/ Δtheo	Span/ Δexp
S1	16.81	8.165	9.755	0.84	257.20
S2	20.63	8.394	11.967	0.70	250.18
S3	24.19	8.239	14.034	0.59	254.89
S4	29.38	13.652	15.194	0.90	153.82
D1	43.13	18.104	22.121	0.82	116.00
D2	49.38	17.169	25.385	0.68	122.31
D3	57.50	16.439	29.739	0.55	127.74
D4	61.88	20.419	35.901	0.57	102.85

Source: Mohammed *et al.*, 2014a

3.12 STATISTICAL MODELS FOR CONCRETE CONTAINING WOOD CHIPPING AS PARTIAL REPLACEMENT TO FINE AGGREGATE

The properties of concrete containing wood chippings as partial replacement to fine aggregate was investigated (Mohammed *et al.*, 2014b). Fifteen trial mixes were prepared and cast using three water-cement ratios (0.37, 0.41 and 0.57) at different replacement levels of wood chippings. Fresh concrete properties tested included slump, unit weight and air content. Hardened concrete properties tested at 28 days included compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, rebound hammer (RH) and ultrasonic pulse velocity (UPV). Several statistical models were developed to show the relationships between measured responses and variables, and among measured responses. These models were validated using various model statistics.

Test results show that disposal of wood chipping (WC) in concrete is feasible and appropriate. The models would serve as mix design aids for concrete containing wood chipping as partial replacement to fine aggregate.

For concrete containing wood chipping concrete the following equations were obtained and statistically validated:

Slump:

$w/c = 0.37, \quad Slump = -0.1286(WC)^2 + 8.8171(WC) + 64.129, R^2 = 0.9759$ (64)

$w/c = 0.41, \quad Slump = -0.2(WC)^2 + 11.3(WC) + 77.5, R^2 = 0.9887$ (65)

$w/c = 0.57, \quad Slump = -0.219(WC)^2 + 11.931(WC) + 95.819, R^2 = 0.9838$ (66)

Air content:

$w/c = 0.37, \quad Air\ content = 0.0052(WC)^2 + 0.2433(WC) + 7.0238, R^2 = 0.9995$ (67)

$w/c = 0.41, \quad Air\ content = 0.0037(WC)^2 + 0.2986(WC) + 9.0543, R^2 = 0.9887$ (68)

$w/c = 0.57, \quad Air\ content = 0.0007(WC)^2 + 0.398(WC) + 11.173, R^2 = 0.9838$ (69)

Compressive strength (f_c):

$w/c = 0.37, f_c = 0.0027(WC)^3 - 0.1184(WC)^2 + 0.4763(WC) + 50.481, R^2 = 0.9984$ (70)

$w/c = 0.41, f_c = 0.0013(WC)^3 - 0.0533(WC)^2 - 0.2903(WC) + 47.297, R^2 = 0.9995$ (71)

$w/c = 0.57, f_c = 0.0029(WC)^3 - 0.1198(WC)^2 + 0.3188(WC) + 42.968, R^2 = 0.9965$ (72)

Splitting tensile strength (f_t):

w/c = 0.37, $f_t = -0.0007(WC)^2 - 0.0152(WC) + 3.5552$, $R^2 = 0.9821$ (73)

w/c = 0.41, $f_t = -0.0002(WC)^2 - 0.0318(WC) + 3.289$, $R^2 = 0.9963$ (74)

w/c = 0.57, $f_t = -0.0007(WC)^2 - 0.0328(WC) + 2.8866$, $R^2 = 0.976$ (75)

Flexural strength (f_b):

w/c = 0.37, $f_b = 0.0003(WC)^3 - 0.013(WC)^2 + 0.044(WC) + 7.0217$, $R^2 = 0.9916$ (76)

w/c = 0.41, $f_b = 0.0002(WC)^3 - 0.009(WC)^2 - 0.011(WC) + 6.4711$, $R^2 = 0.9998$ (77)

w/c = 0.57, $f_b = 0.00001(WC)^3 - 0.0009(WC)^2 - 0.1135(WC) + 6.0915$, $R^2 = 0.9965$ (78)

Modulus of elasticity (E):

w/c = 0.37, $E = -0.2761(WC) + 22.66$, $R^2 = 0.9974$ (79)

w/c = 0.41, $E = -0.2763(WC) + 18.63$, $R^2 = 0.9959$ (80)

w/c = 0.57, $E = -0.2736(WC) + 15.188$, $R^2 = 0.993$ (81)

Flexural strength versus compressive strength:

$f_b = 1.0992$, $R^2 = 0.9902$ (82)

Splitting tensile strength versus compressive strength:

$f_t = 0.9191(f_c)^{0.3524}$, $R^2 = 0.9553$ (83)

Rebound number (RN) versus % of wood chipping replacement:

w/c = 0.37, $RN = -0.424(WC) + 42.76$, $R^2 = 0.9743$ (84)

w/c = 0.41, $RN = -0.473(WC) + 34.575$, $R^2 = 0.9771$ (85)

w/c = 0.57, $RN = -0.38(WC) + 28.36$, $R^2 = 0.9946$ (86)

Ultrasonic pulse velocity (UPV) versus % of wood chipping replacement:

w/c = 0.37, $UPV = 0.4241(WC)^2 - 28.84(WC) + 4448.5$, $R^2 = 0.9953$ (87)

w/c = 0.41, $UPV = 0.3421(WC)^2 - 30.017(WC) + 4225.2$, $R^2 = 0.998$ (88)

w/c = 0.57, $UPV = -0.4185(WC)^2 - 32.786(WC) + 3906.7$, $R^2 = 0.997$ (89)

Compressive strength versus UPV:

$f_c = 0.0872e^{0.0014upv}$, $R^2 = 0.8023$ (90)

Compressive strength versus rebound number:

$f_c = 36.096Ln(RN) - 96.748$, $R^2 = 0.9031$ (91)

3.13 MODIFIED WATER-CEMENT RATIO LAW FOR COMPRESSIVE STRENGTH OF RICE HUSK ASH CONCRETE

This work examined the modification of water-cement ratio law of ordinary Portland cement (OPC) concrete to cater for concrete with rice husk ash (RHA) (Abdullahi *et al.*, 2017b). Chemical analysis of RHA produced under controlled temperature of 600°C was carried out. A total of one hundred and fifty (150) RHA concrete cubes at five different water/binder ratios and at six replacement levels of RHA (5%, 10%, 15%, 20%, 25%, 30%) were produced. Mix design was conducted using absolute method with cement/ water (c/w) content and RHA/water (r/w) content as variables. The compressive strength obtained at 56 days ranges from 3.77 N/mm^2 to 34.04 N/mm^2. The modified w/c ratio law for compressive strength of rice husk ash concrete was obtained as a polynomial model in equation (92)

$$f_{cu} = -7.026\frac{c}{w} - 42.467\frac{r}{w} + 45.305 \qquad (92)$$

3.14 GRAPHICAL USER INTERFACE FOR MIX PROPORTIONING ADJUSTMENT OF LIGHTWEIGHT CONCRETE

A diagnostic tool for mixture proportioning adjustment of structural lightweight concrete was developed (Abdullahi *et al.*, 2009b). The existing mix design codes of structural lightweight concrete are not capable of giving the mix compositions that meet the target requirements. The experience gained by the authour in concrete practice over the years were gathered together to serve as a guide on adjustment of mix ingredients.

A flow chart was developed and used to develop an interactive graphical user interface in MATLAB environment as shown in Figure 17. The program can diagnose the causes of failure of mix performance and give recommendation on necessary adjustment. A typical session is shown in Figure 18.

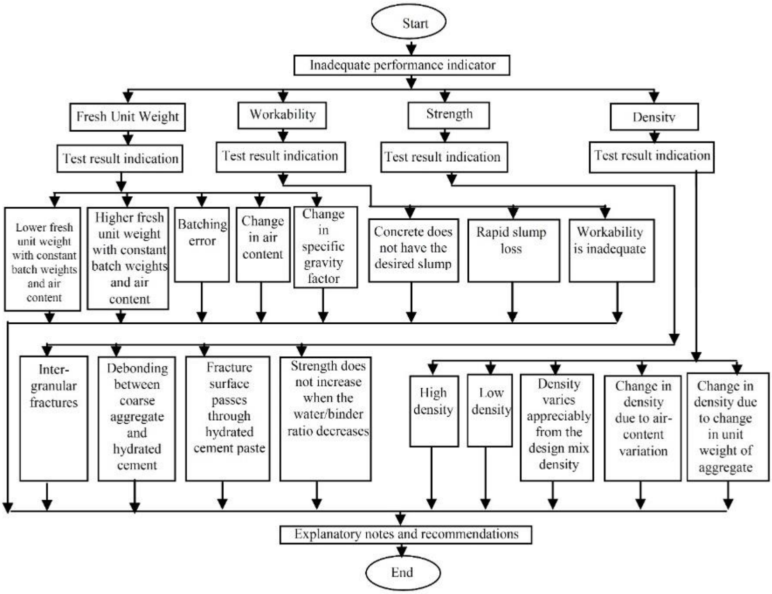

Figure 17: Flow chart of diagnosis of mix performance adjustment
Source: Abdullahi *et al.*, 2009b

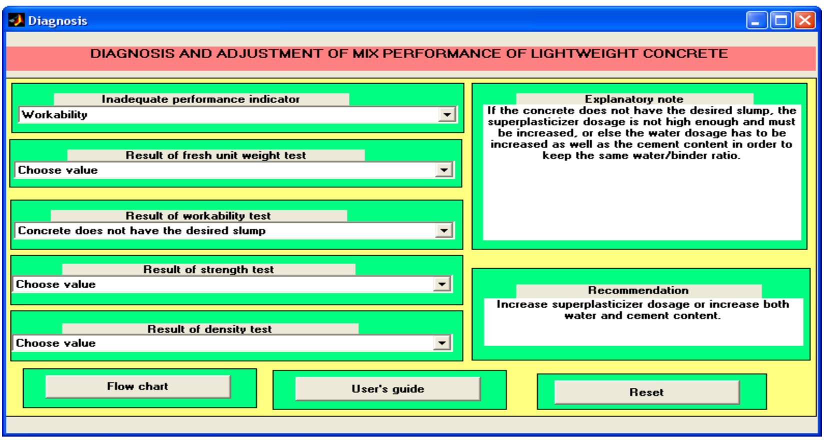

Figure 18: Typical diagnosis session of concrete mixture adjustment
Source: Abdullahi *et al.*, 2009b

Conclusion

Sustainable construction methods and sourcing of materials is apt as it goes along way to ensure resources for the future generation and reduce the degradation of the environment. Disposal of solid waste in concrete is a sustainable way of sanitising the environment which will reduce the use of conventional concrete materials thereby maintaining the ecological balance. Concrete produced from waste materials have shown superior structural characteristics and can be used for structural applications. Polynomial models and response surface plots have the capacity of predict properties of concrete for given mix compositions and give pictorial view of the underlying relationships. Equations have shown to be effective for conducting mix design of concrete which can be used by concrete practitioners. Graphical User Interface Software is an effective tool for mix design of concrete in a simple and convenient manner. All these tools aid mix design process and have the advantage of minimising waste.

Recommendations

Concrete production will continue to increase world-wide especially in developing countries and particularly in Nigeria. Measures need to be taken to reduce the adverse effect associated with the production of concrete. From the issues earlier discussed, the followings are hereby recommended:

1. Engineers and other professionals in the construction industry should put learning into better use so that humanity can benefit.
2. Contractors should be held responsible on sustainable ways of construction, mainly on optimisation of the use of materials and creation of sustainable ways of disposal of unused materials including waste water.
3. The use of sustainable alternative materials for concrete work maintains the ecological balance and should be encouraged both in the public and private sector.
4. Minimisation of waste from construction work reduce material depletion and make preservation for the future use.

ACKNOWLEDGEMENTS

I am very grateful to Almighty ALLAH for all His guidance and support which has made it possible for me to present this Inaugural Lecture. Alhamdulillah.

I wish to greatly appreciate my parents, Late Alhaji Alfa Mohammed and Late Hajiya Kulu Sagi, for their immense efforts in the course of my upbringing and training. May Allah's Rahma be with them and may He accept them in Aljannah firdaus, Ameen. My sincere appreciation also goes to my uncles and aunties who were so kind and supportive throughout my career path. Notable to be mentioned are Late Alhaji Hussaini Mohammed and Late Hajiya Aishetu (Sajo) Mohammed both of blessed memories. They made my stay at ABU, Zaria a home away from home during my undergraduate studies.

I am greatly indebted to the following great scholars for their contribution towards my academic pursuits. Prof. S. P. Ejeh, Prof. O. S. Abejide, Prof. K. J. Osinubi, Prof. J. O. Afolayan, Prof. Y. D. Amartey, Prof. Idris Abubakar all of Ahmadu Bello University, Zaria, Prof. T. Adegboye (now FUT Minna); Prof Hasheem Mohammed Ali Al-Mattarneh (now of Yarmouk University, Irbid Jordan) and Prof Bashar Sami Mohammed (now of Universiti Technologi Petronas).

My special appreciation goes to the present Administration of Federal University of Technology (FUT), Minna under the excellent leadership of the Vice-Chancellor, Prof. Faruk Adamu Kuta and his Management team for the support towards making this occasion a reality. I wish to acknowledge former Vice-Chancellors, Late Prof. Muhammadu Daniya who gave me appointment as an Academic Staff in FUT Minna, Prof. Tukur Sa'ad who gave me study fellowship for my PhD Degree, Prof. M. S. Audu and Prof. M. A. Akanji who considered me worthy to Head the Prestigious Civil Engineering Department, FUT Minna. Prof. Abdullahi Bala, the immediate paste Vice-Chancellor is specially appreciated. He has been a great pillar in my life, being very supportive

and provided opportunities to serve the system in various areas of endeavour. Thank you, Sir. I wish to specially thank other past principal officers, notably Mrs. V. N. Kolo, Prof. A. O. Osunde, Prof. S. O. E. Sadiku, Prof. M. A. T. Suleiman, Prof. Y. A. Iyaka, Late Alhaji U. A. Sadiq, Prof. T. Z. Adama, Dr. M. D. Usman and Hajiya Hajara Abdullahi Kuso for making FUT Minna a comfortable place for my career progression.

My appreciation also goes to all members of staff of SIPET/SEET for their kind support always. Let me specially mention the support and encouragement I have enjoyed from the current Dean of SIPET, Prof. (Mrs.) Z. D. Osunde and all former Deans of the School. I am grateful.

To my darling Department of Civil Engineering, I have received the most encouragement and support from the time I was appointed as an Assistant Lecture to date. I love and appreciate all of you. I must sincerely mention Late Dr. E. B. Oyetola, my first Head of Department; Prof. O. D. Jimoh, my lecturer at Masters Programme; Prof. S. Sadiku, a rare mentor and core administrator; Dr. Musa Alhassan, my current Head of Department; Dr. M. M. Alhaji, my source of motivation; Dr. M. Saidu, my brother who has taken my problems to be his own from the first day we met; my Elder brothers in the Department (Prof J. I. Aguwa, Prof. T. Y. Tsado, Prof. A. A. Amadi, Dr. S. F. Oritola and Engr. J. Olayemi). Others are Dr. T. W. E. Adejumo, Dr. S.S. Kolo, Dr. A. O. Busari, Dr. A. R. Adesiji, Dr. A.B. Abbas, Dr. A. Yusuf, Dr. M. Abubakar, Dr. D.N. Kolo, Mrs. A. O. Gbadebo, Dr. H. S. Abdulrahman, Engr. I. O. Jimoh, Engr. A. O. Ibrahim, Dr. A, Aliyu, Engr. H. O. Aminullai, E. O. Asongwa, S. Mohammed, H. Adamu, S. Adeniyi, A. A. Mohammed, S. Iliyasu, D. Zango, E. Agbese, E. Bechila, U. Mohammed, M. D. Saidu and Alhaji Yanda.

I am grateful to my friends and classmates for their love and support throughout my life. They include: Prof Ahmed Doko Ibrahim, Prof. Jibrin Mohammed Kaura, Engr. Muazu Atiku, Engr Haruna Bala, Engr Bello Mai, Engr. Mohammed Ibrahim, Dr Salisu Dahiru, Engr Rufai

AbdulAziz, Engr Uba Sale, Engr. Moshod Ilyasu, Engr. Habila Bonet, Engr. Abdulhamid Wali, Engr Oguche, Engr. Hassan Yusuf, Engr Ibrahim Buga, Engr. Adamu Bashir, Mal. Ayuba Yahaya, Mal. Kasimu Kuso, Alhassan Abubakar, Dr. Abdulkadir Usman, Abubakar Hassan, Umar Usman Alkali, Abubakar Usman Degri, Abubakar Garba Magaji, Sani Boku, Jibrin Wali, Yunusa Abdulsalam, Adamu Abubakar, Salihu Adamu, Abdulkadir Kuso, Bello Kuso, Mustapha Yahaya, Sulaiman Yahaya, Dr. Usman Abdullahi, Prof Mohammed Yelwa, Dr Adamu Umar, Dr Abdullahi Mohammed, Dr. Umar Apataku, Arc. Bala Usman, Mal Musa Mahmud, and Mohammed Jantabo. Others are my elder and family-friends: Dr. Halilu Shaba Ahmad, Mal. Hamidu Abdullahi, Mal Abdul Garba, and Suleiman Ibrahim (QS).

I am indebted to all staff of Academic Planning Unit for their unflinching support and team-sprit demonstrated in the discharge of the duties of the unit since I assumed the mantle of leadership.

I am grateful to the immediate past and current Chairmen, Prof. Bisi Ayanwale and Prof J. J. Musa, and members of the Seminar and Colloquium Committee for all the support and effort made to make this occasion a reality.

Engr. Isah Kure of Urban Shelter Ltd was responsible for obtaining financial support for my PhD Programme to Malaysia through Niger State Government. I am greatly indebted to you Sir.

I wish to express my special appreciation to past and present students I have had contact with in my lecturing career for their commitment towards academic excellence.

His Royal Highness, Alhaji Umaru Bago III FNSE, FNICE, CON, Etsu Lapai and the entire Emirate Council are specially appreciated for giving me a sense of belonging and for creating time to grace the occasion.

I am a product of polygamous home with so many siblings and cousins. I am proud to be in the midst of a Mega family, togetherness has been a source of inspiration for hard work and dedication. Mentioning all of them will be another Inaugural Lecture of its own. I love you all.

My in-laws have been so wonderful and supportive. Thank you very much for being there for me always. I appreciate all of you.

My special appreciation and gratitude goes to my Wife (Mrs. Rahmatu Mahmud) who has made my life complete and comfortable for over 15 years. You are such a special gift from God. May Allah reward and bless you in abundance. My Children are so wonderful and each of them possesses special attributes I adore. They are Muhammed, Umar, Zainab, Ahmad, and Al-Hussain. Thank you for the happiness we enjoy together as there is never a dull moment at home.

Finally, Mr. Vice-Chancellor, distinguish ladies and gentlemen, thank you very much for being here today to witness my Inaugural Lecture. May Almighty Allah reward you all.

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PROFILE OF THE INAUGURAL LECTURER

Abdullahi Mohammed was born on 28th of February 1972 at Lapai in Lapai Local Government Area of Niger State, Nigeria to the family of Late Alhaji Alfa Mohammed and Late Hajiya Kulu Sagi. He attended Kobo Primary School, Lapai from 1977 to 1983 and later proceeded to Muhammadu Kobo Secondary School, Lapai. He was an Assistant Class Monitor at the Senior Secondary School and represented the School at several oral and written quiz competitions in Niger State. He was in the First set of students that wrote the Senior School Certificate Examination (SSCE) in Niger State in 1989. He was at the School of General and Remedial Studies (SGRS), Ahmadu Bello University, Zaria from 1990 to 1991. He latter gained admission into the Department of Civil Engineering, Ahmadu Bello University, Zaria. He graduated in October 1998 with Second Class Honours (Upper Division). He was with Zenith Engineers, a consulting structural engineering firm based in Kaduna, for the one-year mandatory National Youth Service Corps (NYSC) Scheme from March 1999 to February 2000.

His working career started in year 2000 at Federal University of Technology, Minna where he was offered appointment as an Assistant Lecturer. He obtained his M.Eng in Civil Engineering at Federal University of Technology, Minna and PhD in Concrete Technology at Universiti Tenaga Nasional, Malaysia in 2003 and 2010 respectively. He was promoted to the rank of Professor in 2017.

At Federal University of Technology, Minna he has been involved in teaching, research, community service and administrative duties. He has held several administrative positions such as Level Advicer, Welfare Officer, Project Coordinator, Departmental Examination Officer, Postgraduate Coordinator, Head of Department and currently the Director of Academic Planning. He is also currently a member of the University Governing Council. He has served in several committees at the Departmental, School and University level. Notable among them are Chairman, Task Force on Commercial Activities in the University Campus; Chairman, Minor Works Committee; and Chairman University Loans Committee. He has over 50 publications in national and international journals and conferences. He has supervised several Undergraduate, PGD, M.Eng, and PhD Students.

He has also served as external examiner to several polytechnics and universities in the country at all educational levels. He has served as external assessor for promotion of staff to professorial rank from several universities in the country. He served as a resource person to the Council for the Regulation of Engineering in Nigeria (COREN) and National Universities Commission (NUC) in the resource verification and accreditation of programmes in several universities in the country. He served in the 2022/2023 and 2023/2024 PTDF Selection Committee for Oversea Scholarship Scheme (OSS).

Prof. Abdullahi Mohammed is a corporate member of Nigerian Society of Engineers (NSE) and registered with the Council for the Regulation of Engineering in Nigeria (COREN).

He is happily married with Children.