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Structural, Economic and Environmental Study of Concrete and Timber as Structural Members for Residential Buildings in Nigeria

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ABSTRACT
The construction Industry in Nigeria is relatively monotonous in terms of the building material used, as evidenced by the vast number of residential buildings in Nigeria made of heavy weight materials such as concrete blocks. Since concrete is in high demand in the society, the cost of getting concrete constituent materials is becoming high thereby leading to high cost of living. This is largely due to the fact that alternatives to concrete for residential buildings in Nigeria are not readily available or explored. It is therefore of necessity to motivate stakeholders to alternative building materials that will not only rival concrete in cost, but also serve as a viable competitor in terms of sustainability, maintenance, constructability and client satisfaction in all necessary ramifications. With this in mind, timber has been selected in this research as "the" alternative material to rival concrete in the Nigerian building sector. This research studies both concrete and timber materials under structural, economic environmental and energy perspectives as to help designers with a choice of considering one over the other. This will give the Nigerian client, architect, engineer and builder the justification to choose one material over the other in order to meet the needs of the society. Various Autodesk software are adopted for Modelling and Structural Design of a duplex building of concrete and then timber materials. Cost Analysis of the two models are compared. Environmental Impact Assessment is conducted on the two building models with Athena Impact Estimator software. Results obtained are very promising for timber material.

Keywords: *Affordable Homes, Concrete, Design, Energy, Environmental Impact, Sustainability, Timber*

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I. INTRODUCTION

The challenges of choosing one building material over another, has been a subject of much concern and arguments in the construction industry as clients, architects as well as design engineers have their own preferable choice probably based on the availability of materials, ease of erection, cost of material, aesthetics and technical knowledge to name a few. In the more recent times, environmental and sustainability factors are becoming very important for building material selection [1]. In Nigeria, there are two basic construction materials adopted for construction of residential apartments. One of the materials is concrete which is used for concrete block walls and timber used more often for less important structural elements and constructions. The adoption of concrete is more common in Nigeria [2] while timber is rarely utilized except for temporary structures, structures of low value and in the riverine areas. As abundant timber material is readily available, it is important to explore its potential and see if it worth being considered by designers as a cost effective alternative to concrete. More so, concrete structures have experienced frequent collapse in Nigeria in the recent years [3]. From this point of view comes the much needed comparison between concrete and timber under structural, economic, environmental and energy perspectives as to help designers with a choice of considering one over the other. This is needed because adequate knowledge of engineering materials is vital for viable structural design. Timber is a natural and traditional building material and over the years, considerable knowledge and information has been gained on its important material properties and their effects on structural design and service behavior in the advanced nations, yet it is not a valued option for major structural elements in Nigeria. A proper understanding of the physical characteristics of wood aids the building of safe timber structure [4] and for that is the need for this research.

II. LITERATURE REVIEW

Concrete is one of the greatest inventions in the field of construction engineering. Nevertheless, concrete is known for its low tensile strength and as such has been limited in its utilization in its earlier years of invention. Today, the versatility of concrete have greatly increased [5]. The addition of steel reinforcement to concrete mix compensates for the tensile weakness of concrete. The combined mix of both concrete and steel reinforcement is called reinforced concrete and is the second generation of concrete after the unreinforced mass concrete. Today, reinforced concrete is one of the most important materials used in the design of structural members worldwide. It is a composite material per excellence [6] and it is widely used because of its constituents. The two materials, concrete and reinforcing steel have complementary properties. Concrete is very good in compression, and thus possess a high compressive strength, but very weak in tension. This is compensated with the introduction of steel reinforcements in the concrete mix, since steel has a comparatively high tensile strength. Steel notably will give way to buckling when subjected to lower compressive stresses, and as such both concrete and steel provide complementary support to each other, compensating for the weaknesses in the properties of each material [7]. But the reinforcing steel material used in Nigeria is of low quality and is likely one of the factors contributing to frequent building collapses [8]. Also, every components of concrete including the aggregate size has an enormous effect on the quality such that the general compressive strength is very easily compromised [9].

Around the world, there are possibly more buildings constructed with wood than any other structural material. Many of these buildings are single-family residences, mostly bungalows or single storied buildings, but many larger apartment dwellings as well as business and industrial buildings also use wood framing. The use of timber in the construction industry has both economic and aesthetic appeal to the designer and the clients. The ability to construct timber structures with a minimal amount of specialized tools and equipment has put the timber structures in great advantage over other building materials [10], [1]. Moreover steel and reinforced-concrete design have received undue attention with respect to timber design as not sufficient attention is given to it in most Colleges and Universities, and as such timber design in Nigeria is unknown and very scarce in relation to steel and reinforced concrete designs. Timber is natural occurring and is largely utilized as non-major load bearing components in the construction and building industry in Nigeria since it can be found in large quantities in the tropical rain forest parts of Nigeria without having adequate knowledge of the properties. Timber is the most abundant natural occurring and renewable construction material available and has been used since pre historic times. Building elements formed from timber can be dated back to as far as 400,000 years ago making timber the oldest, most common and widely known building material globally, as it can be used for any form of structural element such as beams, columns, walls, roof trusses, floors etc. [11]. Timber is characterized with tremendous insulating properties, light weight and aesthetic appeal. The extent of its usage by professionals in the Nigerian building industry is determined by the availability and perception of the material rather than the understanding of the material. With its known structural property, timber is still not used anywhere near its full potential in the building sector. This is due to the fact that many clients, architects, designers and engineers do not see wood as a building material that can rival concrete and steel. Because much technological attention have not been paid to timber in Nigeria, durability, high structural reliability and serviceability are not generally associated with timber and as such adequate expertise, sufficient skill and knowledge are needed to fully value and realize the potential of timber as a building material in Nigeria[12], [13].

Concrete has been a prevalent construction material for most residential buildings in Nigeria and due to its escalating cost, provision of affordable residential apartments for the low income earner has been a difficult challenge in a developing countries like Nigeria [14]. It is therefore of necessity to motivate stakeholders to alternative building materials that will not only rival concrete in cost, but also serve as a viable competitor in terms of sustainability, maintenance, constructability and client satisfaction in all necessary ramifications. With this in mind [15], timber has been selected as “the” alternative material to rival concrete in the Nigerian building sector and this research studies both concrete and timber materials from different points of view to give the Nigerian client, architect, engineer and builder the justification to choose one of these materials over the other in order to meet the needs of the society.

III. METHODOLOGY

The detailed order of carrying out this research includes producing an architectural design to be used for both models with the aid of AutoCAD drafting software, developing of a structural model for the major structural members, which include: slabs, beams and columns of the building using Revit 2014, analyzing the structure with Autodesk Robot software and then a comprehensive BOQ would be generated to evaluate the costs of construction of both models and a Life Cycle Analysis of both models would be done using Athena Impact Estimator for buildings. Fig. 1 below shows the developed architectural plan on the AutoCAD work-plane.

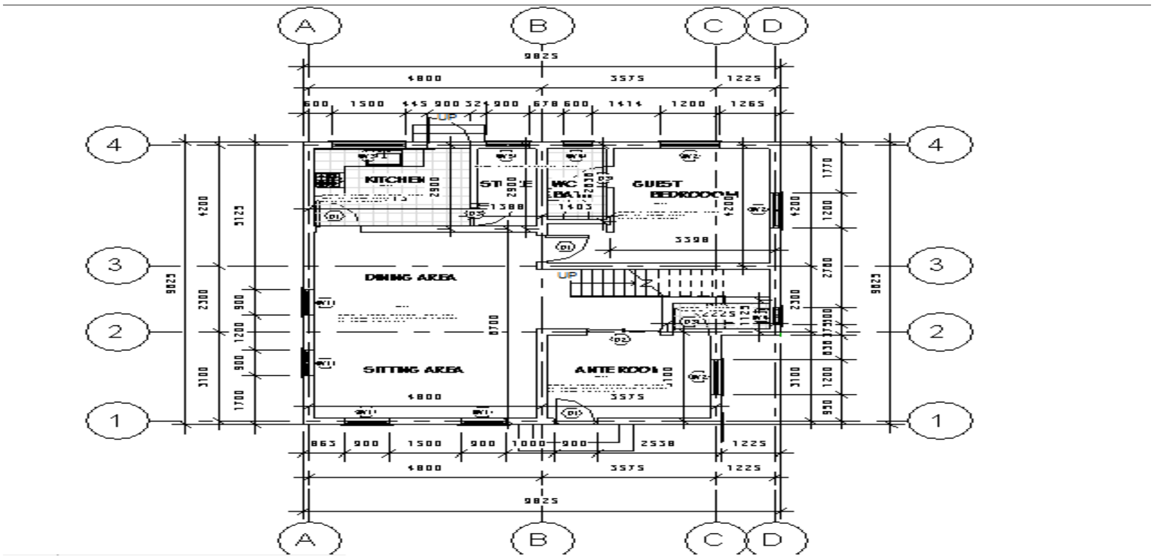

Figure1: Plan of the building model

AutoCAD is an application for 3D computer-aided design (CAD) and drafting, which is widely used by architects and engineers for their designs. The software was used in the development of the floor plan of a building. Autodesk Revit is a Building Information Modeling (BIM) application software made for architectural, structural and systematic modeling of buildings and its components for the 3D structural model was applied to the plan to model the structural elements. Properties of the members such as grade/class, material type, and physical properties were selected. Load types and cases are also selected here, and the appropriate loadings are assigned to their respective locations. The structural analysis and design was then done on Autodesk Robot 2014. The characteristic loads are estimated according to BS 648 (1964) and BS 6399 (1996), and the design load combination for a slab is given as N = 1.4G_k + 1.6Q_k [16].

COSTING

The costing of both concrete and timber models were done with a comprehensive bill of quantities produced for both models. Cost comparison is based on the variables of both models, which include Substructure, Frame, Slabs and staircase, Walls, Finishes, Paintings and Decorations.

ENVIRONMENTAL IMPACT ASSESSMENT PROCESS AND ENERGY EVALUATION

The Environmental Impact assessment was carried out using the Athena Impact Estimator, which is capable of modeling 1,200 structural and envelope assembly combinations and providing a cradle-to-grave life cycle inventory profile for a whole building. The inventory results comprise the flows from and to nature: energy and raw material flows plus emissions to air, water and land.

Building assemblies are designed and described through dialogue boxes that request simple data like bay sizes, loadings, concrete type etc. Bill of materials can also be imported directly from any CAD program. After modeling, the software calculates the associated environmental impacts. TABLE 1 shows the material properties for the two models while Fig.2 show the building assembly of the timber model.

Table 1: Concrete model and timber model design information

CONCRETE

Parameter	Value
Characteristic strength of concrete, f_{cu}	25.00 N/mm^2
Reinforcement cover c	25mm
Characteristic strength of steel f_y	460 N/mm^2
Unit weight of concrete	25 KN/m^3

TIMBER

Parameter	Value
Type	Hardwood
Bending Strength	60 N/mm^2
Compression Parallel to grain	40 N/mm^2
Compression perpendicular to grain	3.6 N/mm^2
Shear Parallel to Grain	6.2 N/mm^2

Unit weight of blocks	4.5 KN/m^3
Behaviour	Isotropic
Young's modulus	23,250 N/mm^2
Poisson's ratio	0.17
Shear Modulus	9,964 N/mm^2
Density	2,407.31 Kg/m^3
Shear Strength Modification	1.00
Yield Strength	2.4 N/mm^2
Tensile Strength	2.4 N/mm^2

Tension Parallel to Grain	80 N/mm^2
Tension Perpendicular to Grain	1.7 N/mm^2
Average Modulus	12,000 N/mm^2
Shear Modulus	1,200 N/mm^2
Construction	Natural
Poisson's ratio	0.38
Density	559.04 kg/m³

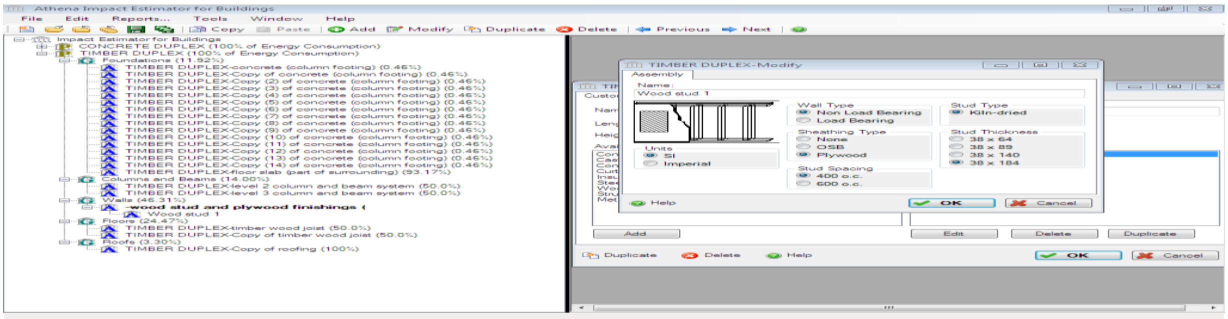

Figure 2: Building assemblies of the timber model

IV. RESULTS AND DISCUSSIONS

Here the results of the structural, economic, environmental and energy analysis carried out on both models are presented.

STRUCTURAL ANALYSIS AND DESIGN RESULTS

Concrete Model: The structural model was analysed using the finite element method, and the results of the forces and deformations were obtained. After running the concrete model analysis, the structural analysis showed that there was no failed members. The required reinforcements for each member in the model were gotten from the designed model.

Timber Model: After running the timber model analysis, there was no failed structural elements.

COST ANALYSIS AND COMPARISON RESULTS

Summaries of the costings of the variable/elements expressed in Nigerian Naira for the concrete model and the timber model are shown in the TABLES 2 and 3 below. The cost margin between the concrete model and the timber model is of N 3,850,425.00. Comparison of the principle elements represented in the tables is shown in Fig.3.

For the maintenance of the two models over a period of 30 years, the difference in operational costs between the timber and concrete frame was N 1,828,425.00.

Table 1: Summary of costs for the concrete model

	SUMMARY	**AMOUNT**
1	SUBSTRUCTURE	3,169,460
2	FRAME AND SUSPENDED SLAB	2,012,900
3	EXTERNAL AND INTERNAL WALLS	1,612,410
4	FLOOR WALL AND CEILING FINISHES	2,334,200
5	PAINTING AND DECORATION	357,375
6	ROOF	2,304,240

7	WINDOWS	954,000
8	DOORS AND IRONMONGERY	1,040,000
9	PLUMBING INSTALLATIONS	669,600
10	ELECTRICAL INSTALLATIONS	800,000
11	EXTERNAL WORKS	600,000
	ESTIMATED TOTAL COSTS	15,655,735

Table 2: Summary of costs for the timber model

	SUMMARY	**AMOUNT**
1	SUBSTRUCTURE	1,470,300
2	FRAME AND SUSPENDED SLAB	1,369,710
3	EXTERNAL AND INTERNAL WALLS	901,800
4	FLOOR WALL AND CEILING FINISHES	1,825,100
5	PAINTING AND DECORATION	69,000
6	ROOF	2,304,240
7	WINDOWS	954,000
8	DOORS AND IRONMONGERY	1,040,000
9	PLUMBING INSTALLATIONS	669,600
10	ELECTRICAL INSTALLATIONS	800,000
11	EXTERNAL WORKS	600,000
	ESTIMATED TOTAL COSTS	12,003,750

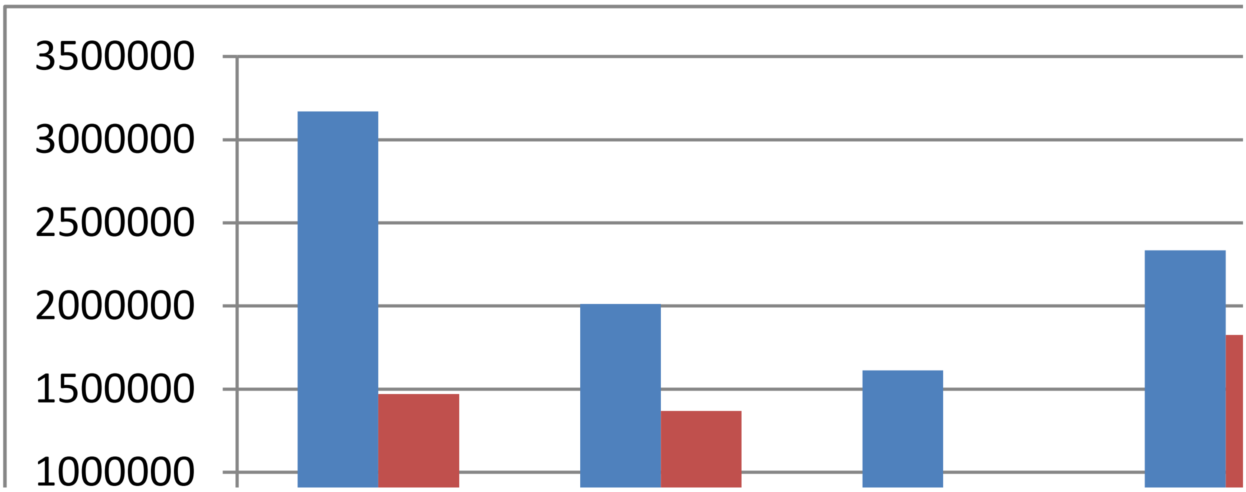

Figure 3: Cost Comparison of the principle elements used for the two models.

ENVIRONMENTAL IMPACT AND ENERGY ANALYSIS RESULTS

Smog Potential: the concrete duplex has approximately 235% more smog potential than that of the timber duplex throughout their respective life cycles.

Fossil Fuel Consumption: The results obtained indicated a 315% increase in fossil fuel consumption in the concrete model with respect to the timber's. This indicates that more energy and fuel is consumed as regards concrete buildings in relation to timber buildings.

Ozone Depletion Potential: the Ozone depletion potential in both models is highest during the materials production stage. The concrete model has approximately 290% more ozone depletion potential than that of the timber.

HH Particulate: the HH Particulate of the concrete model is 228% more than that of timber model. The results obtained are shown in Figs.4 and 5.

Global Warming Potential: this results indicated a higher global warming potential in the concrete models of up to 6,970% that of the timber model.

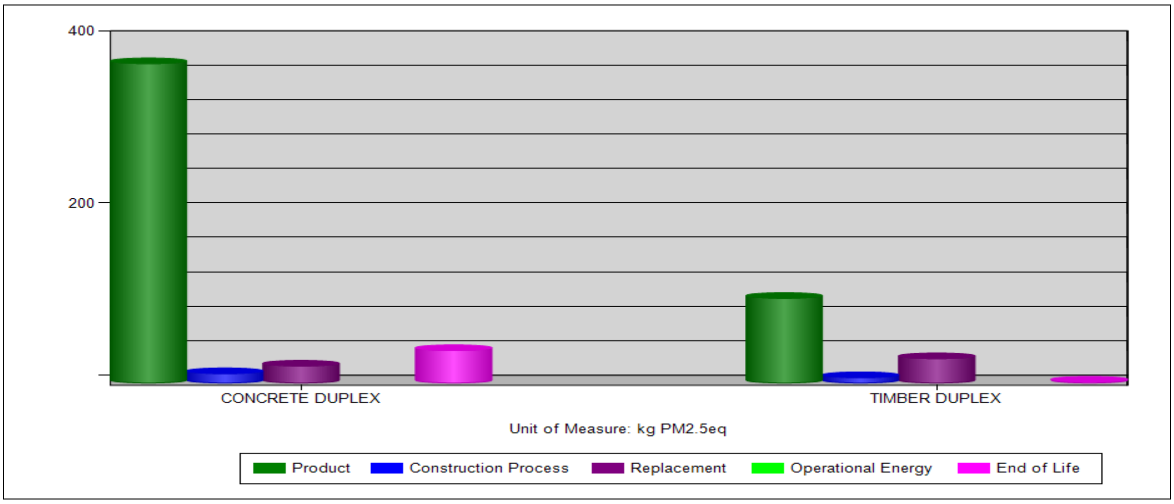

Figure 4: Life cycle stages of HH particulate potential of the concrete and timber model.

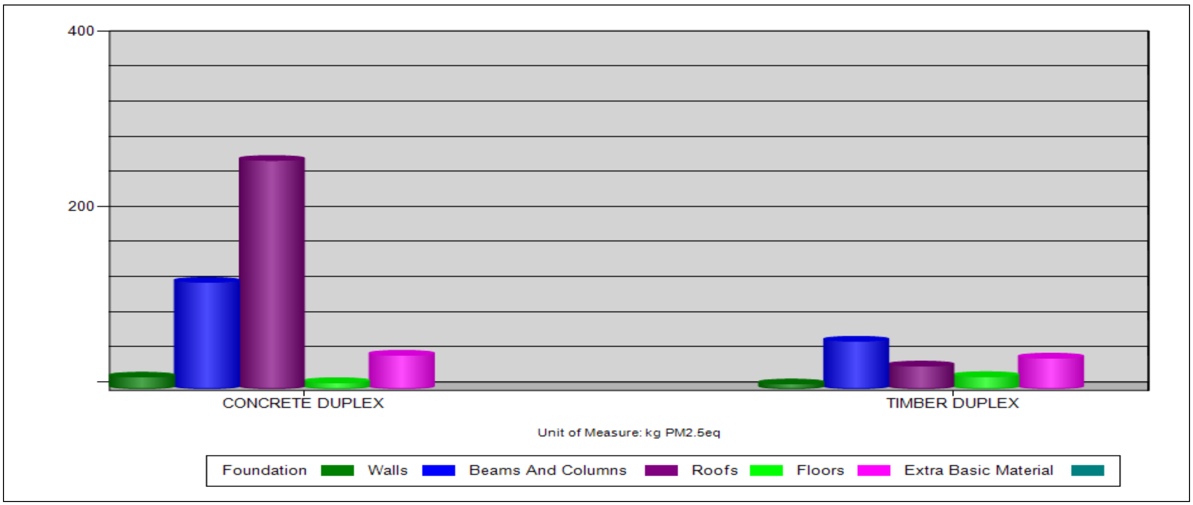

Figure 5: HH particulate potential of the concrete and timber model during construction process.

Eutrophication Potential: the eutrophication potential of the concrete model is 509% more than the timber model.
Acidification Potential: this result indicates a 324% increase in the concrete model with respect to the timber model.
Absolute Value of Resource Use: the various resources used and their quantities are shown in Figs. 6 to 12.

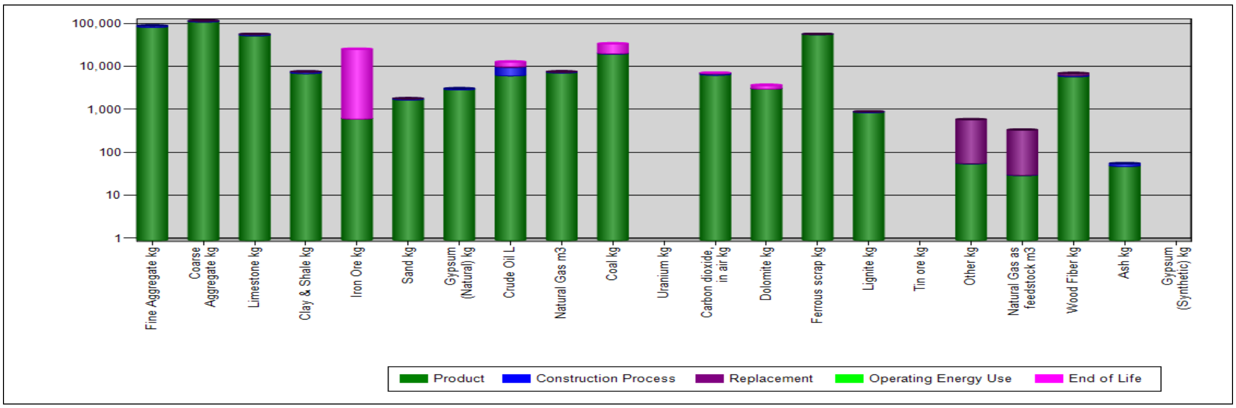

Figure 6:life cycle absolute value of resource use for the concrete model

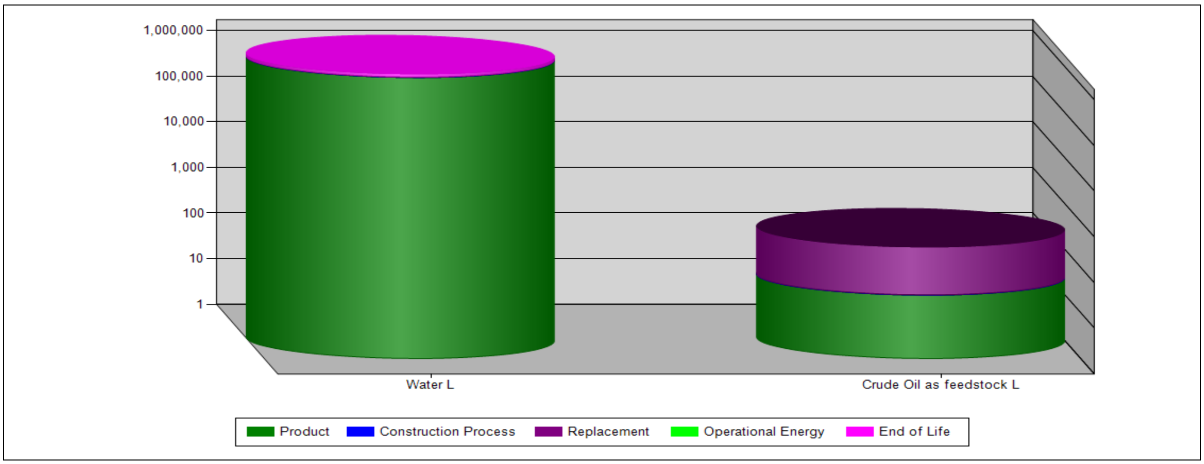

Figure 7: Life Cycle Water and energy consumption for the concrete model

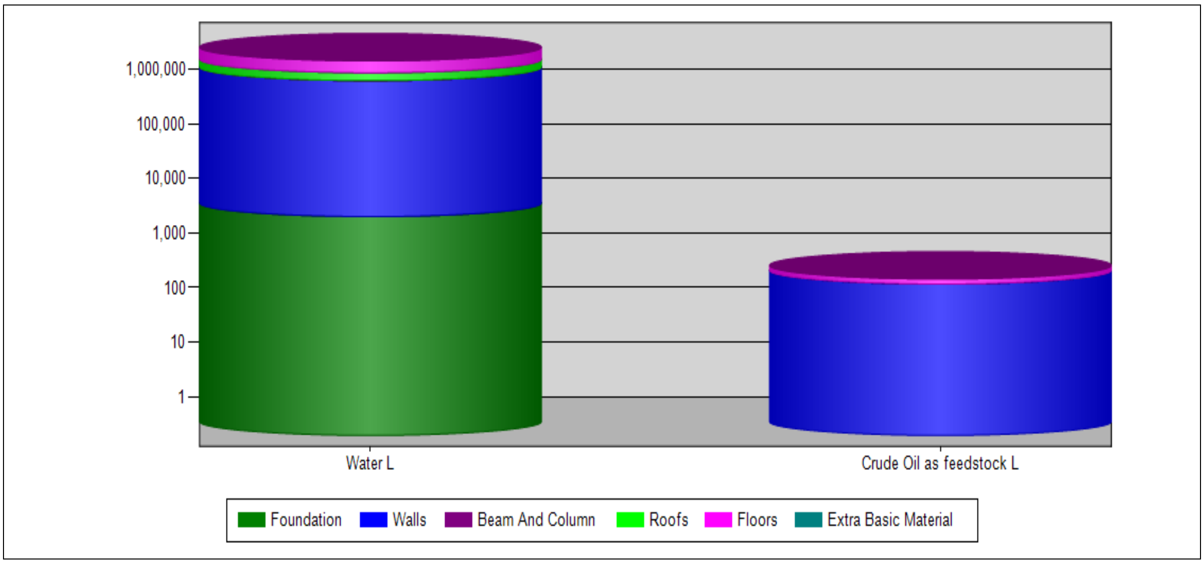

Figure 8: Water and Energy consumption for the concrete model during construction process.

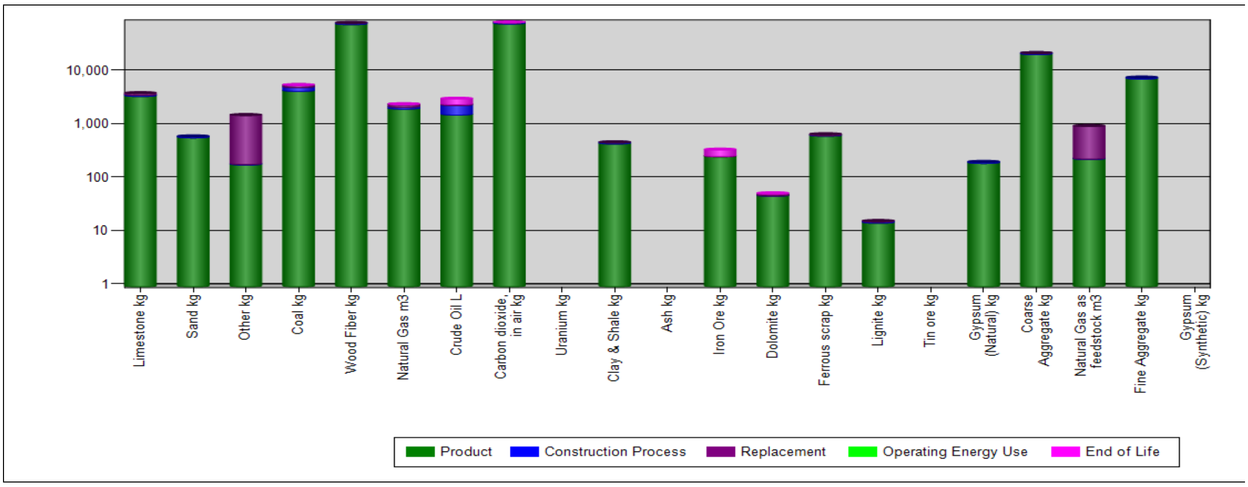

Figure 9: life cycle absolute value of Resource Use for the timber model

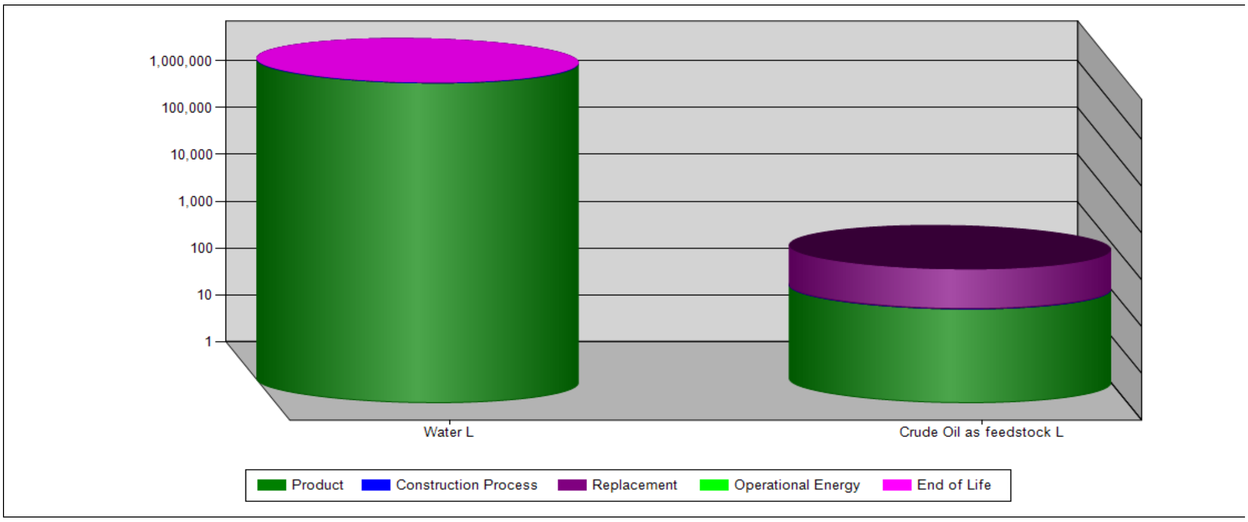

Figure10: Life Cycle Water and energy consumption for the timber model

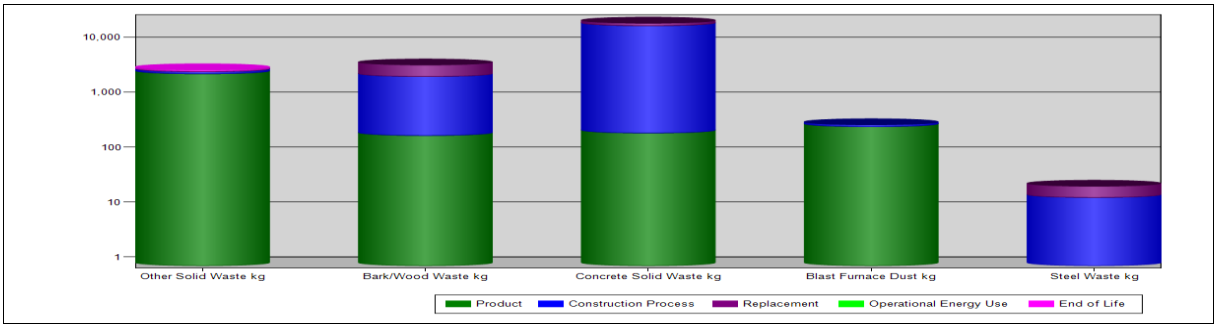

Figure11: Life cycle waste emissions for the concrete model

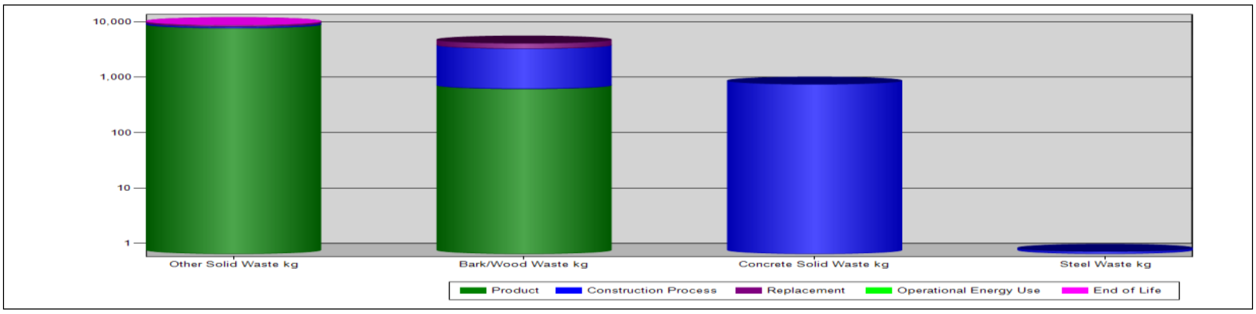

Figure12: Life cycle waste emissions for the wood model

V. DISCUSSION

For the concrete and timber models, structural, economic and environmental and energy analyses have been carried out and results obtained. Discussions on these analyses now follow.

Structural Analysis and Design: from the analysis carried out on both models, the response of the residential building models to the loadings are observed, and it can be seen that concrete structures is stronger and heavier than timber model. Also, due to the low density, this timber building do not require as much solid foundation as the concrete model. This is of a particular advantage where sub-soil conditions are poor. It was also confirmed that timber components withstand movement compared to its concrete counterpart as seen by the deformations obtained. Uneven settlement may easily cause serious cracking in concrete buildings. On the other hand a timber house can accept differential settlement of several centimeters without visible damage. Therefore foundations of timber buildings can be of a light design not only because the timber is light, but because of its ability to accommodate movement.

Cost Analysis: from the result gotten from the cost analysis of both models, the timber model has a better advantage to the concrete's largely because of the way these types of buildings are constructed, the ease with which its constituent materials can be gotten and the mode and ease of construction. Fast erection represents a significant monetary gain.

Constructability and Aesthetics: during the modeling of the timber frame building, there were various methods of designing the frame giving the designer a wide variety of options, and as such modifications can easily be made as regards designs and during the construction process. This is a contrast with respect to concrete structures, as designs and detailing must rigorously follow a lay down rule since adjustments to works on site can be very costly.

Environmental Impact assessment and energy efficiency: also, from the various studies and the results gotten from the analysis, timber made buildings are environmentally friendly compared to concrete structures this is largely due to the fact that wood has a negative impact on carbon emissions, and actively helps in storing atmospheric CO_2 thereby reducing global warming. Also, the energy saving is very visible.

V. CONCLUSION

The results obtained show that concrete is stronger and heavier than timber. The lighter weight of timber structure entails a smaller foundation and therefore economic advantage. The lighter weight of timber is of a particular advantage where sub-soil conditions are poor and prone to differential movements. From the cost point of view, the timber model has a better advantage to the concrete as it appears more economical. From design and constructability point of view, the modeling of the timber frame building has a wide variety of options which makes it easier than concrete design and construction. On environmental impact and energy efficiency analysis, timber made buildings are more environmentally friendly compared to concrete structures. The results of this research prove beyond reasonable doubt that timber is an excellent material for residential buildings and moderate size buildings.

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