Evaluation of Lateritic Coarse Aggregates as a Partial Replacement for Granite Coarse Aggregates in Structural Concrete

By:

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A dissertation submitted to the University of Zambia in partial fulfilment of the requirements of the degree of Masters of Engineering in Structural Engineering

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DECLARATION

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CERTIFICATE OF APPROVAL

This dissertation of **Musunga Musonda** is approved as fulfilling the requirements for the award of the Degree of Master of Engineering in Structural Engineering by the University of Zambia (UNZA).

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Abstract

In Zambia, coarse aggregates for concreting are normally produced by crushing granite, limestone and basalt among other rock types. However, these rocks are scarce diminishing natural resources and henceforth; the need to study other naturally available materials for full or partial replacement; with the intention of reducing the cost of concrete. The main aim of this research was to evaluate concrete produced by partially replacing Granite Coarse Aggregate (GCA) with Lateritic Coarse Aggregates (LCA). The properties of LCA concrete evaluated included; but were not limited to the fresh and hardened state properties of LCA concrete, some durability properties of the concrete such as Sorptivity, water accessible porosity and residual strength after exposure to high temperature. Mineral composition of Lateritic Coarse Aggregates was analyzed using X-Ray Diffraction (XRD). The results showed that crushed lateritic aggregates were composed of 43.7% Crystalline iron oxide (FeO (OH)) (Goethite), 38% Kaolinite i.e. Clay mineral (Al_2O_3 $2SiO_2 \cdot 2H_2O$), 18.3% Quartz (SiO_2) and abundant amorphous (non-crystalline) iron oxide minerals such as Ferrihydrite ($Fe_2O_3 \bullet H_2O$). A trial mix for 30MPa concrete was done in the laboratory, using granite coarse aggregates, river sand, 42.5R Portland Cement and portable water. Thereafter, alternative mixes were done by replacing GCA with LCA in the proportions, 90:10, 80:10, 70:30, 60:40, 50:50, and 0:100, by mass. The study results showed a trend of reducing crushing and split tensile strengths with increase in the LCA amount in the concrete mix. Mathematical relationships obtained from this study showed that replacing 19.2% of LCA for GCA in a 30 MPa concrete mix can achieve a concrete with a characteristic strength of 25 MPa at 28 days, while a 27% replacement of LCA for GCA would achieve a compressive strength of 25 MPa at 50 days. This range of replacement was found to produce normal weight concrete. The study also showed that concrete with less than 30% of GCA replaced with LCA had higher, but acceptable sorptivity and water absorption rate than plain concrete. Further, LCA concrete replaced with up to 30% of GCA at 28 days showed identical mass and crushing strength loss to that of plain concrete; upon the specimens being exposed to elevated temperature.

Keywords: Workability, Water absorption, Granite coarse aggregate, Lateritic coarse aggregate, Structural concrete

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Dedication

I would like to dedicate this work to my beloved Sons;

Christian Bryans Musonda

and

Kevyn Bryans Musonda

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Acronyms and Abbreviations

CA	Coarse Aggregates
GCA	Granite Coarse Aggregates
FA	Fine Aggregates
LCA	Lateritic Coarse Aggregates
OPC	Ordinary Portland Cement
UNZA	University of Zambia
LA	Laterite Aggregates
HSC	High Strength Concrete
MK	Meta-Kaolin
LC3	Limestone Calcined Clay Cements
LRC	Laterite Rock Concrete
SEM	Scanning Electronic Microscopy
GGBS	Ground Granulated Blast Furnace
LITS	Load Induced Thermal Strain
CNBM	Chinese National Building Materials
RMC	Ready Mix Concrete
SCM	Supplementary Cementitious Materials

Institutions and Societies

Reference to a technical society, institution, association or governmental authority are made in accordance with the following abbreviations.

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
BS	British Standard
BSCP	British Standard Code of Practice
BSI	British Standards Institution
C & CA	Cement and Concrete Association
CRSI	Concrete Reinforcing Steel Institute
CS	Concrete Society
DoE	Department of Environment
EN	Euro Norm
ISO	International Organization for Standardization
LITS	Load Induced Thermal Strain
QCS	Qatar Construction Specifications

CHAPTER ONE: INTRODUCTION

1.1 Background

Zambia, as a developing nation with a rising population which currently stands at more than 19.6 million (Zambia Statistics Agency, 2023). The country still has a great deal of infrastructure deficit, that has to be constructed. This infrastructure, by structural classification predominantly includes; concrete framed structures, steel framed structures and masonry structures, all of which requires the use of structural concrete at one construction stage or the other. Therefore, the influence of the cost of concrete on the overall cost of local infrastructure is obvious. The cost of concrete is dependent on the cost of cement, coarse aggregates, fine aggregates and in some cases; admixtures and additives. The aggregates constitute about 60-80 per cent of concrete. Hence, any attempt to replace the constituents with alternative cheaper materials is expected to significantly reduce the overall cost of concrete. The continuous desire to reduce building cost worldwide has called for appraisal of conventional constituents (Asiedu, 2017).

Nonetheless, in Zambia, the price of cement is not the major factor that causes the spatial variations in the price of concrete, as the local supply of cement is fairy adequate on the market, and the price range is usually within reasonable variance from one location to the other. On the other hand, the case with the price of coarse aggregates is different, as this resource is commonly produced by crushing rocks which include; granite, basalt and limestone among other types, which are scarce in some parts of the country. This leads to increased construction costs of concrete structures in these regions, as huge volumes of coarse aggregates are ferried over very long distances to construction sites.

The diminishing natural aggregate resources, automatically stimulates the need to look out for alternative naturally existing locally available alternative materials that can replace coarse materials, either entirely or partially; in structural concrete, consequently bringing down the cost of constructing local amenities and infrastructure.

One of the most common locally available materials in a hot and wet climate tropical country like Zambia are laterite aggregates. Laterite stone as a local material is prospective enough to be used as a coarse aggregate in the manufacture of concrete (Marewangeng et al, 2020).

1.2 Statement of the Problem

Granite is the rock material commonly crushed for use as coarse aggregates in concrete production in Zambia. This rock material is scarce in some parts of the country and is a non-renewable natural resource. Coarse aggregates are a key ingredient in terms of strength and volume in concrete. With the continuous need for construction of new amenities and infrastructure in Zambia, the demand for granite stones in concrete production is increasing but the resources are being overexploited and the natural stock is decreasing at an alarming rate. In order to slow down the rate of depletion, and/or reduce the cost of concrete in some parts of the country, it is inevitable to conduct studies on all possible substitute materials for coarse aggregate. In this regard, for a Savanna tropical country like Zambia, laterite aggregates are a reasonable option to be considered.

Despite naturally occurring in a number of forms, with trivial differences in both chemical and physical properties, the most common forms are the Iron oxide rich lateritic aggregates and the less common aluminous lateritic bauxite rock. In Zambia, laterite based concrete can be investigated for both wet and hardened states important properties. So far, studies conducted on this material were more focused on compressive strength of lateritic aggregates/stones and laterite soil material as a replacement for both coarse and fine aggregate as compared to granite/sand aggregate concrete. Further, for structural concrete, it is imperative to investigate the optimal partial replacement percentage of Lateritic Coarse Aggregates (LCA) for Granite Coarse Aggregates (GCA), while using standard fine aggregates, Portland Cement and portable water. Durability and elevated temperature performance are also important factors that need to be investigated by evaluating various concrete mixes for structural use. This study therefore focused on the properties of Lateritic Coarse Aggregates (LCA) as a partial replacement material for Granite Coarse Aggregates (GCA) in structural concrete.

1.3 Main Objective

The main objective of this research was to evaluate lateritic coarse aggregates as partial replacement for granite coarse aggregates in structural concrete.

1.4 Study Objectives

1. To determine the fresh and hardened state physical properties of concrete with Granite Coarse Aggregates (GCA) partially replaced with Lateritic Coarse Aggregates (LCA)
2. To evaluate the residual strength and weight loss of LCA Concrete after exposure to high temperature
3. To establish absorption rate (sorptivity) of concrete with GCA partially replaced with LCA as regards durability of concrete
4. To determine optimal percentage replacements of LCA for GCA that may be applicable for structural concrete

1.5 Research Questions

1. How would LCA replacement for granite coarse aggregates in structural concrete affect the fresh and hardened state physical?

2. Would LCA concrete possess fire resistance attributes required for structural concrete?

3. Would LCA concrete possess durability attributes similar to GCA?

4. What is the optimum percentage by mass replacement of LCA for GCA that can be allowable if the concrete is to remain of structural use as regards compressive strength and durability?

1.6 Hypothesis

'If the vast deposits of lateritic coarse aggregates found in Zambia can be used to partially replace the scarcer granite coarse aggregate, and the achieved concrete strength upon testing; found to possess properties comparable to conventional structural concrete, then LCA can be used as partial replacement material for GCA in order to reduce the cost of construction of concrete structures'

1.7 Rationale

- To add to the body of knowledge; on the suitability of lateritic coarse aggregates found in Zambia; for use as a partial replacement material for granite coarse aggregates in structural concrete.
- To help alleviate the rising depletion rate of granite rocks used as concrete coarse aggregates in Zambia
- To render more affordable alternative methods of producing concrete in Zambia

1.8 Significance of the study

The Study is chiefly aimed at reducing the cost of concrete especially in rural areas of Zambia with little or no deposits of granite that are normally used for coarse aggregates, by first studying the chemical and physical properties of the more available lateritic aggregates, and thereafter studying how they can perform as partial replacement for granite aggregates in structural concrete. By establishing whether the locally available lateritic aggregates can be used to partially replace the less available and more expensive granite aggregates normally transported over long distances sometimes even from other provinces, the cost of concrete can be reduced tremendously. A case study of the cost of concrete was done for Samfya and Manyinga Districts of Luapula and North-western Provinces, respectively, which among other rural districts of Zambia, are facing this problem.

This study focused on evaluating the possibility of using locally available lateritic aggregates to partially substitute granite coarse aggregates in structural concrete, in a quest to reduce the cost of concrete in future construction projects and also alleviate the alarming rate of depletion of granite deposits. Whereas other scholars considered using laterite soil as a partial replacement for fine aggregates, in addition to the coarse aggregates replacement with crushed lateritic stones, this study used the locally available river sand as the sole fine aggregates. Further, because of the dissimilarities in the different forms of lateritic aggregates and stones in different parts of the world, owing to diverse chemical composition and mineralogy, results from different continents or continental regions cannot be directly applied to the Zambian local scenario.

1.9 Scope of the study

The scope of the study included collecting quantitative data on the following parameters under consideration, by laboratory / experimental methods;

- Mineral properties of lateritic aggregates
- Properties of coarse aggregates
- Properties of fine aggregates
- Workability of fresh concrete
- Compressive strength at 7, 14, 28, 50 and 100 days
- Split tensile strength at 28 days
- Physical appearance of LCA concrete
- Specific gravity of concrete at 100 days
- Specific gravity of concrete at 28 days after exposure to elevated temperature
- Crushing strength of concrete exposed to elevated temperature
- Water absorption rate and sorptivity of LCA Concrete of concrete at 100 days

In this study, several laboratory tests were conducted. Lateritic coarse aggregates were tested for properties including:

- Mineral composition
- Specific gravity

Fine aggregates were tested for the following:

- Sieve analysis for grading purposes
- Water absorption rate, and
- Specific gravity.

10-15mm size GCA and LCA were tested for:

- Water absorption
- Specific gravity.

Concrete cube specimens were tested for compressive strength using the compressive testing machine. Concrete cylinder specimens were tested for tensile strength of concrete using the Split Cylinder Concrete Test. Concrete cube specimens were also tested for durability.

CHAPTER TWO: LITERATURE REVIEW

2.1 Structural Concrete

The ACI 318-05: Building Code Requirements for Structural Concrete; defines structural concrete as all plain or reinforced concrete used for structural purposes. This covers the spectrum of structural applications of concrete from non-reinforced concrete to concrete containing non-prestressed reinforcement, prestressing steel, or composite steel shapes, pipe, or tubing. Further, the code stipulates the minimum requirements for design and construction of structural concrete elements. For structural concrete, the code specifies that the characteristic strength of structural concrete shall not be less than 17.23 MPa (2500 psi). Various structural design standards use concrete with a characteristic strength of 25 MPa as the threshold or minimum strength applicable in the design and construction of load bearing members of a structure. In general, concrete is a mixture of Portland cement, water, aggregates, and in some cases, admixtures. The cement and water form a paste that hardens (hydrates) and bonds the aggregates together. Concrete quality is directly related to the amount and properties of the materials used, and the way that it is placed, finished, and cured. Concrete is a versatile construction material, adaptable to a wide variety of agricultural and residential uses. With proper materials and techniques, it can withstand many acids, silage, milk, manure, fertilizers, water, fire, and abrasion. Concrete can be finished to produce surfaces ranging from glass-smooth to coarsely textured, and it can be colored with pigments or painted. Concrete has substantial strength in compression, but is weak in tension. Most structural uses, such as beams, columns, slabs, and walls, involve reinforced concrete, which depends on concrete's strength in compression and steel's strength in tension (Shelton, 1982).

2.1.1 Grades of Structural Concrete

- Where strength is classified with respect to compressive strength, Table 2.1 gives the concrete grade with the requirements for water-cement ratio and cementitious content.

- The characteristic compressive strength at 28 days of 150mm cubes (f_{ck}, cube) or 150mm diameter by 300mm cylinders (f_{ck}, cyl) may be used for the classification.
- Exception will be made for concrete mixtures containing fly ash, silica fume or Ground Granulated Blast Furnace (GGBS), where testing shall be requested at 56 days, or 90 days.

Table 2.1:Cementitious and water content for structural concrete

	Minimum characteristic cube strength (f_{ck}, cube) (N/mm^2)	Minimum characteristic cylinder strength (f_{ck}, cyl) (N/mm^2)	Minimum cementitious content (kg/m^3)	Maximum Water: Cementitious Ratio (w/c)
C 25	25	20	260	0.60
C 30	30	25	300	0.58
C 35	35	28	320	0.55
C 40	40	32	335	0.50
C45	45	35	355	0.47
C 50	50	40	370	0.45
C 60	60	50	380	0.40
C 75	75	60	390	0.35

Source (QCS, 2014)

2.2 Lateritic Coarse Aggregates

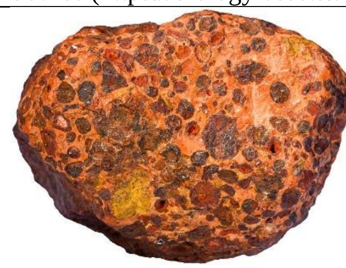
2.2.1 Overview of Lateritic materials

Laterite is a reddish weathering product of basalt. However, not all laterites are enriched in iron and sometimes they are not even reddish. Some lateritic rocks (bauxite) are mined because of their high aluminum content. Iron-rich (Iron Oxide) variety is mostly used as a construction stone. It is mostly composed of iron, aluminum, titanium, and manganese oxides because these are the least soluble components of the rocks undergoing a type of chemical weathering known as laterization or lateritization. Certain conditions are needed for the laterite deposits to form. Modern examples are found in climatic regions which are characterized by warm air temperature, abundant rainfall, and dry periods. Lateritic soils/rocks are common in savannas, but not in the rainforests and jungles (Carroll, (2012)). Figure 2.1 to Figure 2.4 compiled in Table 2.2 show common examples of lateritic materials.

Table 2.2:Common Lateritic Materials

1	Lateritic Soils (Latosols, Ultisols and Oxisols) (Baligar et al, 2004)	 *Figure 2.1:Lateritic Soil:* (https://www.123rf.com/photo_45007551_laterite-soil-or-red-earth-background.html)
2	Laterite: (Classified as both soil rock and soil type) (Mohd et al, 2015)	 *Figure 2.2:Laterite* (Source https://www.indiamart.com/proddetail/laterite-soil)

Table 2.2 (Cont'd)

3	Lateritic Gravel/Stones (Kasthurba et al, 2007)	 *Figure 2.3:Lateritic Gravel/Stones:* Source (https://biology-assets.anu.edu.au)
4	Lateritic Rock:	 *Figure 2.4: Lateritic rock* (https://www.sandatlas.org/laterite)

2.2.2 Varieties of Lateritic Aggregates

Iron-rich variety: consists of hematite and goethite. These minerals give reddish color to the soil/rock whereas Aluminium-rich variety or Aluminous laterite variety is called Lateritic bauxite which are very often indurated, consist of Al oxi-hydroxides (gibbsite AI(OH), boehmite AIOOH) and Fe oxi-hydroxides (goethite FeOOH, haematite $Fe_2\ 0_3$) resulting from weathering of the parent rocks. Degree of weathering varies according to their chemical and mineralogical compositions, and to the climatic and drainage conditions. The alkalis and alkali-earths are completely removed, while Si is either completely or partly leached (Boulange et al, 1997).

Most bauxite is formed via silica rocks to form lateritic bauxite where long term leaching of silica and other soluble materials due to a wet tropical or subtropical climate results in the precipitation of aluminium hydroxides, namely gibbsite according to the findings from an investigation on Lateritic Bauxite mineralogy, carried out by Gu et al, 2013; The main components of the ores (Lateritic Bauxite) are Al2O3, Fe2O3, SiO2 and TiO2. Immobile elements like Zr, Cr, Hf, Nb, Ta, Th, U and REEs were distinctly enriched during the bauxitization. Factors such as carrier minerals contained in the bauxite, pH variations in weathering solutions, adsorption process, groundwater chemical characteristics, Fe concentration variations in weathering profiles, leaching degree of minerals and geochemical characteristics of elements were shown to play vital role in distribution of trace and rare earth elements during weathering of the lateritic bauxite (Yang et al, 2018).

2.2.3 Availability of Lateritic Aggregates on Earth

Lateritic Bauxites are formed under humid tropical climates. They are associated with latosols (soft lateritic soils) and ferricretes (indurated iron accumulations) which are formed under contrasted tropical climates. Bauxites, latosols and ferricretes are widely distributed in North and South America, in West, Central or East Africa, as well as in Australia, India or in South-East Asia. Their geographic distribution is larger than the latitudinal zones of climates (humid tropical), under which they are normally formed or developed. Obviously, a part of bauxites and, particularly, the young profiles are, presently, developing under humid tropical climate (Tardy et al, 2007).

Lateritic soils are found mostly in tropical and humid climates, the iron oxide content is high, has a red color like rust, generally contains large amounts of quartz and titanium, zircon, iron, tin, aluminum and manganese oxides, which are left behind in the wear process, depending on location, climate, and depth. The tropical climate and the influence of chemical elements determine the thickness, quality, and mineral content. Old-age Laterite soil, containing low organic matter with a relatively dense and sturdy texture, brownish red in color because it predominantly contains iron and aluminum (Ishola et al, 2019).

Andrews et al, (2006) conducted a research using remote sensing spectral properties of clays and iron minerals in a quest to mapping of three laterite facies. He found that Lateritic palaeosols cover roughly 33% of Earth's land surface. Figure 2.5 shows the global distribution of latosol (collective laterite) deposits on the earths tropical regions.

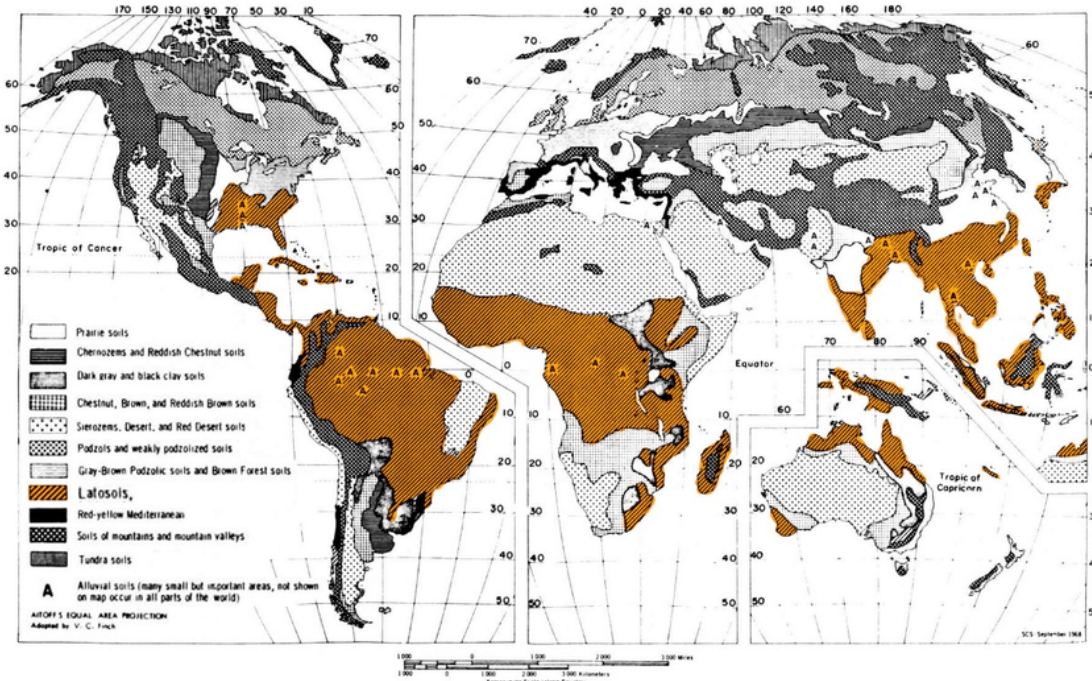


Figure 2.5: Global distribution of Latosols (Sujeeth, 2015)

2.2.4 Mineralogy of Lateritic Deposits in Zambia

Lweya et al. (2015) conducted a study "Groundwater transport of Cu in laterites in Zambia- Applied Geochemistry". The mineralogy of the laterite was studied using X-ray analysis, infrared and Mössbauer spectroscopy, and results revealed a homogeneous composition of strongly weathered primary silica minerals, mainly quartz, muscovite, biotite and feldspars, and secondary minerals dominated by disordered kaolinite, iron oxide (goethite/hematite mixtures or solely goethite) and minute amounts of vermiculite.

2.2.5 Physical Properties of Lateritic Aggregates

The highly indurate gravels which are characterized by high contents of iron oxides and low amounts of quartz and kaolinite, have high specific gravity, bulk density and impact strength but lower values of absorption (total pore space). In general, the values of the physical properties reflect the strong influence of iron oxide content. The physical quality of the aggregate improves as the content of iron oxide increases. This should be expected because of higher iron content.

2.3 Reviewed Papers

2.3.1 Lateritic Coarse Aggregates as partial replacement for granite coarse aggregates

Afolayan et al (2019) carried out a study to investigate the effects of partial replacement of normal aggregates with lateritic stone in concrete. This study presented the engineering properties of concrete containing lateritic aggregate as partial coarse aggregate replacement. The coarse aggregate was replaced by 10, 20, 30, 40 and 50% with lateritic aggregate. All the specimens were cured and compressive strength test were carried out at the age of 7, 14, 21 and 28 days respectively. The study discovered that replacement of 10% lateritic aggregate can produce lateritic concrete exhibiting comparable strength with normal concrete. Additionally, replacement of lateritic aggregate of up to 30% was able to produce lateritic concrete exhibiting the targeted strength of 25 N/mm^2. It was found that the workability and compressive strength decreases as the percentage of lateritic aggregate in the mix increases.

In addition to this research, other findings by Gowda et al (2018), were that the workability of concrete mixes with unprocessed laterite were substantially lower compared to those with processed laterite. Also, the rate of strength loss with increase in replacement levels is higher for those mixes, with unprocessed laterite than those with processed laterite (strength reduction of 34% was observed for 100% unprocessed laterite based concrete whereas only 7% strength reduction for 100% processed laterite based concrete was observed.

Afolayan et al. (2019) postulated that this may be due to the porosity of the lateritic aggregate that led to absorption of the water in the mix. The result of the two-way analysis of variance showed that both lateritic aggregate and curing age (days) has significant effects of the compressive strength of concrete. From the results of this study, it was recommended that 30% lateritic aggregate is adequate for partial replacement of coarse aggregate in concrete production for structural lightweight concrete.

Babitharani et al (2019) conducted a research about partial replacement of laterite as a coarse aggregate in concrete was carried out. Granite aggregate was replaced by 10, 20, and 30% with laterite aggregate. All the specimens were subjected to water curing until they were ready to be tested. Tests on compressive strength, split tensile strength, flexural strength and workability were carried out. From the study it was concluded that the laterite can be used as the replacement for the coarse aggregate up to 10%. The concrete with 10% laterite aggregate replacement showed similar properties in the hardened and fresh state as that of the normal concrete. The compressive strength of the mix reduced as the percentage of the laterite was increased in the mix but it was found that the value of the compressive strength was comparable with that of the normal mix.

This was in agreement with the study of Raju et al, (1972); who presented a paper of a study where the results of tests conducted on fresh and hardened concrete using laterite as aggregate were discussed. Several mixes of laterite aggregate concrete were made with varying water: cement and aggregate: cement ratios to study the properties like workability, compressive, flexural, tensile strength and modulus of elasticity. The tests indicated that the workability decreases with increasing aggregate-water ratio.

Muthusamy et al (2014) carried out a study on strength and durability performance of concrete containing laterite aggregates. The study found that the use of 20 to 30% of laterite aggregates, as partial replacement for coarse aggregates, resulted in concrete with the targeted strength. The specimens were tested for the determination of compressive strength and durability against acid attack and water absorption. It was found that concrete with low water absorption can be produced through the integration of 50% of laterite aggregates. Similarly, the integration of laterite aggregates of up to 20% produced concrete that exhibits good durability against acid attack, chloride ion penetration, and water absorption.

Asiedu et al (2017) investigated the compressive strength and workability of lateritic gravel used as an all-in aggregate in concrete production. Three prescribed mixes from all-in aggregate concrete were compared with concrete from lateritic gravel. The research investigated the variation in strength of four different aggregate replacements; 100: 0, 90: 10, 80: 20 and 70: 30. The density and compressive strength of each mix was measured at ages of 7 and 28 days, respectively. An increase in slump and compressive strength was observed in the lateritic concrete, as portions of the lateritic gravel were replaced with sand. However, the rate of increase in the compressive strength tended to decrease with increase in part replacement of lateritic gravel with sand, indicating that there was a threshold of percentage of sand increase after which the compressive strengths decreased.

In another study aimed at finding the optimum composition of the ingredients for optimum compressive strength, Alwi (2019) made six different mix designs using laterite. Using cylindrical specimens of these mixture designs of a height of 200 mm and a diameter of 100 mm, testing was done at ages of 1, 3, 7, 14, 28 and 56 days, respectively. The results of the analysis of compressive strength obtained maximum compressive strength of 17.87 MPa and optimum compressive strength of 17.2 MPa with a composition of 38.0% sand, moderate laterite 46.0% and coarse laterite 16.0% so that laterite concrete as a coarse aggregate substitute could be used for mix concrete. From the compressive strength vs time graph, the compressive strength of laterite concrete did not reach the 25 MPa target compressive strength. Because the compressive strength did not reach the target compressive strength but reached values for lower quality concrete, the concrete using laterite soil as a coarse aggregate substitute could still be used in concrete mixes.

Asigo et al, (2017) conducted a study on basic parameters to be used in the design of laterite rock concrete for beams and other structural members by use of experimental procedures in the BS and ASTM standards for testing of materials. Parameters investigated in this work included but were not limited to physical properties such as PSD, specific gravity, density; chemical properties; the flow-ability of laterite rock concrete in its wet state, the compressive, splitting tensile strengths and rate of absorption of water. A stress/strain relationship was determined in its hardened state. Results showed that an average compressive strength of 15 MPa is adequate for use in minor structural works. It was also determined that the splitting tensile strength was about 10% of the compressive strength. However, the water absorption rate was least in the highest grade of LRC of 1:1:2 and the designed mix of 1:1.35:3.15 possessed high propensity of water absorption. Maximum values of 10.92%, 12.02%, 11.12% and 10.24%, respectively, were computed for the four mixes investigated. The relationship between splitting tensile and compressive strength of LRC for the mixes at the age of 28 days showed progressive increase with respect to the strength of the LRC. Hence concrete made with 1:1:2 had a higher resilience to abrasive forces/action.

Akpokodje et al (1992) studied the properties of concretionary laterite gravel concrete, the compressive strength of laterite concrete. The study found that the compressive strength (19-42 MPa) of most of the laterite concrete was comparable with the average strength (45 MPa) of concrete made with the usual granite crushed rock aggregates from the region. The strength of the laterite concrete mainly depended on the aggregate-cement bond whereas the physical properties of the aggregates are only of secondary importance. The laterite concrete showed a net contraction when immersed in hot 1N NaOH solution (i.e. rapid alkali reactivity test). This behavior was attributed to the low/very low contents of silica, clay and lime in the aggregates. The results of the study revealed that concretionary laterite gravels are potential alternative cheap sources of aggregates for structural concrete.

Another study by Asigo et al (2017) on the effects of sulphuric acid on different grades of concrete blocks made of laterite rock concrete, superplasticized laterite rock concrete (LRC) and granite or conventional concrete was carried out. The concrete cubes were first cast and cured in water for 28 days before being exposed to 2% concentration of sulphuric acid for a period of 90 days. The tests were carried out to simulate the deterioration processes of concrete exposed to acidic environment as seen in sewers, foundations, industrial structures. The deterioration parameters included physical deterioration, mass loss and compressive strength loss. Results showed that the deterioration process increased as the immersion period in acid increased. However, on introduction of a polycarboxylate ether superplasticizer, the performance of LRC concrete in an acidic medium was increased considerably and comparable to conventional granite concrete. It was therefore recommended that LRC plus superplacticizer concrete can be used as replacement for granite concrete in areas where sulfuric acid attack is prevalent.

Another study by Akpokodje and Hudec (1992) looked at the factors controlling properties and durability of concretionary laterite gravel aggregates. The concretionary laterite gravels from across Nigeria were subjected to several physical, mechanical, and chemical tests in the laboratory. The relationships between these tests and the major factors influencing the test results were determined by factor (R-mode) analysis. The results of the study revealed that four principal component factors control the measured properties of laterite gravels. They are, in decreasing order of importance; (1) iron oxide content (degree of lateritization); (2) porosity and pore-size distribution; (3) micropores; and (4) adsorbed water. These factors explained 79% of the total variance observed in the measured properties. The degree of lateritization accounted for 51% of the variance, and this indicated its dominating influence on the physical and mechanical properties of laterite gravel aggregates. The results of cluster analysis showed that the parent material rock types also have considerable influence on the physico-mechanical properties of laterite gravel aggregates and on the relative contribution of each factor group to the property variance

The potential utilization of laterite stone as a local material for use as a coarse aggregate in the manufacture of concrete was investigated in a study by Marewangeng et al (2020). The slump test results showed that fresh concrete had proper workability while the hardened specimen exhibited that the mixture can maintain its homogeneity during pouring into the mold and the compaction process led to achieving a good compaction result without honeycombs and large void appeared on the surface of specimens. Compressive strength test showed that the specimens that cured in the tap water and laterite stone as aggregate had a higher 28days compressive strength as compared with the specimens cured with tap water and river stone as aggregate.

Muthusamy and Kamaruzaman (2012) conducted an assessment on the characteristic of Malaysian laterite aggregate discussing further on the influences of this local material towards engineering properties of normal concrete was carried out. Concrete mixes containing 0%, 10%, 20%, 30%, 40% and 50% laterite aggregate replacement level were cast before being subjected to water curing for 7, 14, 28 and 60 days. Workability test, compressive strength test, flexural strength and modulus of elasticity were conducted in accordance to the existing standard. Results showed that replacement of appropriate laterite aggregate content was able to produce workable concrete with satisfactory strength. Addition of 10% replacement laterite aggregate produced a mix with comparable strength to plain concrete. The targeted strength still can be achieved with addition of 30% replacement laterite aggregate.

An experimental investigation was carried out by Karthik and Acharya (2019) on the possibility of effective utilization of lateritic aggregate as partial replacement for both coarse aggregate and fine aggregate in concrete. The incorporation was done for 15%, 20% and 25% of lateritic stone as a coarse aggregate and by taking 15% lateritic soil as constant for fine aggregate by conducting compressive strength which gave the optimum value of 15% replacement for natural soil. Their findings were such that; As percentage of lateritic aggregate replacement increased, the compressive strength, split tensile strength and flexural strength of laterized concrete decreased. The result showed the concrete containing 15% lateritic stone and 15% lateritic soil showed higher strength, indicating that it can be utilized for a maximum of 15% substitution compared to 20% and 25% replacement in concrete. Further it was found that as percentage of replacement was increased, the split tensile and flexural strength of laterized concrete decreased. When compared to other replacements, the concrete containing 15% lateritic stone and 15% lateritic soil showed higher strength, indicating that it can be utilized for a maximum of 15% substitution. Further from their findings, they concluded that it was necessary for future scopes to include the following:

- The investigation of durability properties incorporating laterized concrete can be done.
- The Scanning Electronic Microscopy (SEM) analysis of the concrete can be conducted.
- Effect of admixtures on laterized concrete can be carried out.
- Further study can be done by partially replacing PPC with laterized concrete.

Basing on the same, this research, though concentrated on partial replacement of coarse aggregates, also investigated the integrating the use of fly ash as an admixture.

As part of a study investigating the structural characteristics of concrete using various combinations of lateritic sand and quarry dust as complete replacement for conventional river sand fine aggregate, Ukpata et al (2012) carried out a study. Samples of concrete (cubes) were made using varying contents of laterite and quarry dust as fine aggregate. The quantity of laterite was varied from 0% to 100% against quarry dust at intervals of 25%. The samples were cured for specified periods and tested in the laboratory for compressive strength. Workability tests were earlier carried out to determine the optimum water/cement ratios for three different mixes, namely: 1:1:2, 1:1.5:3 and 1:2:4. It was found that 0.5 water/cement ratio produced higher compressive strengths for 1:1:2 mix, while 0.6 water/cement ratio exhibited better workability for 1:1.5:3 mix proportion. Specifically, compressive strength ranged from 17 to 34.2 N/mm^2 for the mixes considered. These results compared favourably with those of conventional concrete. The concrete was found to be suitable for use as structural members for buildings and related structures, where laterite content did not exceed 50%.

2.3.2 Durability of Laterite Aggregate Concretes

A research was carried out by Raja et al (2022) with the aim of producing sustainable concrete by effectively utilizing laterite scraps as fine aggregates in fly ash-based cement concrete and assessing its durability characteristics. It was expected that the utilization of laterite scraps reduced sand extraction, pollution to the environment, and conserved natural reserves by reducing the need for virgin materials. To evaluate the engineering properties, durability properties and sustainable properties of laterized concrete, a control mix was made with 0% laterite scraps and four mixes made with 25% to 100% laterite scraps at 25% intervals with the same high-quality cement, fly ash, and coarse aggregate. Due to the influence of clay minerals such as kaolinite and montmorillonite in laterite scraps, the slump values dropped from 85 to 15 mm, with the control mix being more workable than the laterized samples. The combination of 75% manufactured sand and 25% laterite scraps in concrete were found to remarkably enhance the residual compressive strength. A significant increase of compressive strength of about 11% was achieved at replacing 25% laterite scraps at 28 days. Higher replacements of 50%, 75%, and 100% laterite scraps decreased cube strength by approximately 3%, 15%, and 28%, respectively. From the compressive strength test results, it was quite evident that utilizing laterite wastes reduced the amount of virgin aggregates needed to produce concrete resulting in less natural resource consumption. Moreover, the test results of durability parameters such as water absorption, permeability, sorptivity, drying shrinkage, and rapid chloride penetration of laterized concrete mixes containing 50% replacement recline within the acceptable limits as per standards, confirm their intended performance throughout the specific structural service life.

In another study, Rajapriya and Ponmalar (2021) varied proportions of lateritic fine aggregates in High Strength Concrete (HSC). Concrete mixes of grade M60 were produced by replacing manufactured sand with laterite in the ratio of 25 to 100 percent (by weight), and properties of the mixes were studied. To attain high strength mix, 10% micro silica and 10% of fly ash (FA) were added to all mixes. Mechanical properties were studied after 7, 28, 56, and 90 days of curing, and laterized specimens achieved approximately 12 percent higher compressive strength than control specimens, whereas the split-tensile and flexural strengths increased up to 11.14% and 12.83%, respectively. The results indicated that 25% substitution of laterite was the optimum percentage in HSC concrete. Microstructural studies of optimum mix and reference mix were conducted at 28 days to better morphological and mineralogical understanding of the laterized HSC. Durability parameters such as water penetration depth, chloride ion permeability, and sorptivity exhibited higher values for laterite mixes than the control mixes. The study results indicated that HSC could be achieved with partial substitution with lateritic fine aggregates and proved that laterite can replace conventional aggregates.

2.3.3 Pozzolanic attributes of laterite constituent minerals

Sabir et al (2001) studied the utilization of calcined clay, in the form of metakaolin (MK), as a pozzolanic material for mortar and concrete has received considerable attention in recent years. This interest is part of the widely spread attention directed towards the utilization of wastes and industrial by-products in order to minimize Portland cement (PC) consumption, the manufacture of which being environmentally damaging. Another reason is that mortar and concrete, which contain pozzolanic materials, exhibit considerable enhancement in durability properties. This paper reviewed works carried out on the use of MK as a partial pozzolanic replacement for cement in mortar and concrete and in the containment of hazardous wastes. The literature demonstrated that MK is an effective pozzolan which causes great improvement in the pore structure and hence the resistance of the concrete to the action of harmful solutions. MK can also be obtained by the calcination of indigenous lateritic soils. On calcination of laterites in the range 750–800°C, kaolinite and gibbsite are transformed into transition phases of MK and amorphous alumina both of which possess pozzolanic properties.

Baris and Hulusi (2004) studied the effect of initial water-curing period on the strength properties of concretes was investigated. Three types of cement, one Ordinary Portland cement (OPC) and two natural pozzolanic cements (blended and trass cements), were used in the concrete mixtures. Six different curing regimes were applied to the specimens, the first of which was continuous water storing, and the second continuous air storing. In the remaining four regimes, the specimens were stored under varying initial water-curing periods of 3, 7, 14, and 28 days, respectively. The compressive strength tests were carried out on the cubic specimens at the ages of 7, 14, 28, 90, and 180 days. The variation of compressive strength with time was evaluated by using a semi-logarithmic function and the strength-gaining rates were calculated by using this equation for different curing conditions. It was found that poor curing conditions are more adversely effective on the strength of concretes made by pozzolanic cements than that of OPC, and it is necessary to apply water curing to the former concretes at least for the initial 7 days to expose the pozzolanic activity. However, when the pozzolanic cement concretes have sufficient initial curing, they can reach the strength of OPC concretes in reasonable periods of time.

Kazim et al (2021) conducted a study focusing on experimentally evaluating the comparative performance of concrete made from limestone calcined clay, limestone calcined laterite and calcined laterite as supplementary cementitious materials by simple test methods. The replacement of the Portland cement with these SCMs was up to 45% to achieve low-carbon cementitious materials. The cementitious materials were characterised and four concrete mixes (100% ordinary Portland cement; 15-30-55% of limestone-calcined clay-Portland cement; 30–70% of calcined laterite-Portland cement; and 15-30-55% of limestone-calcined laterite-Portland cement) were formulated to showcase their performance in terms of workability, strength, and durability. The possibility of a differing influence of varied water-to-binder ratio on the clay and laterite SCMs was also examined. The results showed no significant difference between the performance of the laterite-based and clay-based blended cement concrete. It was concluded that laterite could be interchangeably used in place of clay in limestone calcined clay cements (LC3), especially in tropical regions where laterite is in abundance as much as or more than clay. Further, the research recommended long term performance evaluation. Table 2.3 summarizes recommended properties and typical values for durability of concrete.

Table 2.3:Recommended properties and typical values for durability of concrete (QCS, (2014))

Concrete property	**Test method**	**Age range between 28 and 90 days**	
		High durability	**Minimum durability**
Water absorption (%)	BS 1881: Part 122	2	4
Water penetration (mm)	BS EN 12390-8	5	30
Rapid chloride permeability (coulombs)	ASTM C 1202	500	4000
Chloride migration (m^2/s)	NT Build 492	2.0 $x10^{-12}$	9.0 $x10^{-12}$

- Note: Concrete shall be tested for any of the transport properties at 28 days. Exception will be made for concrete mixtures containing fly ash, silica fume or GGBS, where testing shall (QCS, (2014)).

2.3.4 Testing of Concrete After Exposure to Elevated Temperature

According to Suljević et al, (2020), Common building structures are designed to withstand the load that may occur during building service life. There are dead load and traffic loads of different characters, such as imposed load, wind load, snow load, earthquake load etc. However, special attention must be paid to ensure a satisfactory level of resistance in the case of fire action. The particular danger of fire damage exists in urban areas where low-rise and middle-high-rise residential buildings dominate, usually built of reinforced concrete. Because of all these factors, it is very important to analyze structural fire performance. Mechanical and thermal properties of reinforced concrete as well as other building materials, such as steel and wood, decrease at elevated temperatures.

Additionally, according to Di Qin et al (2022), Concrete has been well known as a low cost building material with high strength and versatility. Though high in compressive strength, concrete is quite brittle with a tensile strength of only 10% of its compressive strength. Concrete being a non-homogenous material consisting of hardened cement paste and aggregates, with an increase in temperature, cracking is initiated due to thermal incompatibilities between the aggregates. Generally, at elevated temperatures, the cement paste would shrink due to the dehydration/decomposition of the hydrates while the aggregates usually expand before disintegration. Thermal stresses and cracks develop under conditions of high temperature exposure. When concrete is heated at a rapid rate, a steep thermal gradient may develop between the outer and inner layers of concrete because concrete is a poor conductor and this gradient can also cause cracking. The thermal gradient largely depends on the heating regime and the concrete thermal properties, such as specific heat, thermal conductivity and thermal diffusivity. Exposure to fire or any extreme heat source can have adverse effects on concretes' mechanical properties; for plain concrete, changes can occur in the pore structures, cracking and spalling, the destruction of the bond between cement paste and aggregates and the deterioration of the hardened cement paste.

From their research study, Li and Bu (2011) reported that the mechanical properties of the tested concretes (compressive strength, tensile strength and elastic modulus) generally decreased with the temperature rise. Between 20 and 150°C, a small loss of strength was observed. It was associated to an evaporation of free water as well as to an increase in porosity of the tested concretes. This porosity increase is an expansion of the pores diameters and therefore leads to an increase in permeability. Between 150°C and 300°C, an increase in compressive strength was observed. Nevertheless, the other mechanical properties (tensile strength and elastic modulus) continued to decrease in a similar way to the observed evolutions between 20 and 150°C, due to the departure of bound water, corresponding to a large mass loss. The increase in strength could be attributed to a modification of the bonding properties of the cement paste hydrates. Beyond 300°C, the mechanical and physical properties of the tested concretes decreased quickly. The specimens subjected to a heating up to 600°C showed very weak mechanical properties. The decrease of the mechanical properties was associated to that of physical properties. Further, they grouped the different types of spalling observed during fire endurance testing into four categories based on the location, nature, and severity of the spalling, as follows:

- Explosive spalling is the ejection of large pieces of concrete from the surface of a member due to high pore pressures caused by the production of steam within the concrete.
- Surface spalling includes pitting, blistering and local removal of surface material
- Aggregate splitting is failure of the aggregate near the surface and is often accompanied by surface splitting.
- Sloughing off occurs when the surface layer or corner of a concrete member is gradually eroded due to extended exposure to fire.

Furthermore, they noted that there are several factors that influence the occurrence and scale of spalling. These include; Moisture content of the concrete, Compressive stress caused by restraint of thermal expansion or external load, Aggregate type, Rapid temperature rise at exposed surface and concrete density and permeability. From these five factors it was generally accepted that the first three are the most influential to spalling.

Khoury (2008) studied the compressive strength property of concrete in fire. The strength varies not only from concrete to concrete depending on its constituents but also due to other factors such as external loading, heating and moisture conditions. During heating, concrete also experiences thermal strain, shrinkage, as well as Load Induced Thermal Strain (LITS). LITS comprises several components such as transient creep. LITS acts to relieve thermal and parasitic stresses. Rapid heating during fire could induce explosive spalling with serious consequences to structure and people. The two mechanisms of explosive spalling are thermal stress spalling and pore pressure spalling. Thermal stress spalling could be reduced by the use of thermal stable aggregates of low expansion, while pore pressure spalling could be reduced by the use of polypropylene fibres in the mix.

2.3.5 Testing of Laterite Based Concrete After Exposure to Elevated Temperature

Muthusamy et al (2014) conducted a study to investigation the effect of laterite aggregates as partial coarse aggregate replacement towards performance of concrete upon exposure to elevated temperature. Two mixes namely plain concrete with 100% granite aggregate and laterite concrete with 10% laterite stone as partial coarse aggregate replacement were prepared in form of cubes. All the specimens were water cured for 28 days before being exposed to various levels of high temperature. After that, the cubes were left to cool down to room temperature by applying air cooling system. Behaviour of concrete upon exposure to high temperature was then evaluated through determination of mass loss and compressive strength reduction. The percentage of mass loss and compressive strength ratio pattern displayed by laterite concrete was similar to plain concrete. However, the variation in the percentage of mass loss and strength ratio of laterite concrete was governed by the different physical properties of laterite aggregate in comparison to granite aggregate. They reported that temperature between 300 ^{o}C and 800 ^{o}C may be regarded as critical to the strength loss of laterite concrete.

Udoeyo et al (2010) carried out an experimental program to investigate the strength performance of laterized concrete when subjected to elevated temperatures of 200, 400 and 600°C. Six concrete mixes incorporating 0, 10, 20, 30, 40 and 50% Laterite as a replacement by weight of sand was prepared. After heat pretreatment, specimens were cooled using either rapid cooling (water-cooling) or natural cooling (air-cooling). An analysis of variance test showed that exposure temperature, cooling regime, and their interaction had a significant influence on the compressive strength of the samples. When subjected to the investigated temperatures specimens experienced strength losses that increased with temperature. Their study further revealed that air-cooled concrete specimens maintained higher residual strength values than water-cooled specimens. A comparison of the residual compressive strength data obtained in this study with code provisions in Eurocode and CEB design curve showed that these codes could be applied to laterized concrete subjected to temperature below 400°C.

Metakaolin (MK) is a pozzolanic materials which is thermally activated alumino-silicate produced from kaolinite clay through a calcining process. Poon et al (2003), conducted an experimental investigation to evaluate the performance of metakaolin (MK) concrete at elevated temperatures up to 800 °C. Eight normal and high strength concrete (HSC) mixes incorporating 0%, 5%, 10% and 20% MK were prepared. The residual compressive strength, chloride-ion penetration, porosity and average pore sizes were measured and compared with silica fume (SF), fly ash (FA) and pure ordinary Portland cement (OPC) concretes. Their study finding was that; after an increase in compressive strength at 200 °C, the MK concrete suffered a more severe loss of compressive strength and permeability-related durability than the corresponding SF, FA and OPC concretes at higher temperatures. Explosive spalling was observed in both normal and high strength MK concretes and the frequency increased with higher MK contents.

Balogun (2003) carried tests on 100 mm laterized concrete cubes, containing ordinary portland cement, crushed granite, sharp sand and fine laterite in varying proportions. The percentage of sand by weight of total fine aggregate was varied in increments of 25% up to a maximum of 100% corresponding to normal concrete. The mix proportion was 1:11/2:3. The test specimens were exposed to varying temperatures ranging from 30°C (i.e. room temperature) to 800°C and allowed to cool for 24 hours before crushing. The results showed that unlike normal concrete, the residual compressive strength of laterized concrete increased, by up to 50% of the nominal strength, with increasing temperature up to 200°C before falling to about 20% of the nominal strength at 800°C. The gain in strength depended on the sand content. The results further showed that within the limits of water/cement ratios normally used in concrete works (i.e. 0.55 to 0.65), the residual strength of laterized concrete was independent of the water/cement ratio. Also, the density of laterized concrete was not significantly affected by changes in temperature.

Another study by Apeh & Ogunbode (2012) investigated the strength performance of Laterized concrete at elevated temperature. Four concrete mixes incorporating 0, 10, 20 and 30% laterite as a replacement by weight of sand was prepared. A concrete mix ratio of 1:2:4 (Cement: laterite/sand: granite) with water/cement ratio of 0.65 was used for their study. The laterite content in the fine aggregate was varied from 0 – 30% at 10% interval. Specimens cured for 7, 14, 21 and 28days were subjected to uniaxial compressive loading tests at room and elevated temperatures of 200, 400 and 600^{o}C. Results showed that for the varying percentage replacement of sand with laterite, compressive strength of laterized concrete decreases; and with increase in temperature, the strength decreases. It was also observed that an air-cooled lateritic concrete specimen has higher residual strength values than water- cooled specimens. A maximum compressive strength value of 24.10N/mm^2 was obtained for the mix with 30% laterite – 70% sand at 400^{o}C which indicates the strength of laterized concrete that is sufficient for use at elevated temperature not exceeding 400^{o}C.

2.4 Summary of Literature Review

Table 2.4 summarizes the research work that has been carried out by other scholars on Laterite based concrete. The table highlights the main results and possible research gaps identified.

Table 2.4: Summary of Literature Review

S/N	Author year	Title	Main results	Research Gap
1	Babitharani et al, 2019	partial replacement of laterite as a coarse aggregate in concrete	The concrete with 10% laterite aggregate replacement showed similar properties in the hardened and fresh state as that of the normal concrete.	The investigation of durability of concrete with Laterite as a coarse aggregate partial replacement in concrete
2	Raju et al, (1972	Properties of laterite aggregate concrete	The tests indicated that the workability decreases with increasing (laterite) aggregate-water ratio	Need for development of guiding relationships to use for correction of water cement ratio
3	Muthusamy et al, 2014	durability performance of concrete containing laterite aggregates	The study found that the use of 20 to 30% of laterite aggregates, as partial replacement for coarse aggregates, resulted in concrete with the targeted strength the integration of laterite aggregates of up to 20% produces concrete that exhibits good durability against acid attack, chloride ion penetration, and water absorption	investigation on the potential of using laterite aggregate as partial aggregate replacement in other modern concretes Investigation of durability performance for other percentages of replacement of LC
4	Asiedu et al, 2017	Using lateritic gravel as all-in aggregate for concrete production	the rate of increase in the compressive strength tended to decrease with increase in part replacement of lateritic gravel The use of lateritic gravel for the concrete required additional water than using the typical all-in aggregate	Need to come up with standard batch mixing water correction methods Need to investigate further on durability of lateritic gravel concrete
5	Alwi, 2019	Compressive Strength of Concrete with Laterite Aggregate as Substitute of Coarse Aggregate	obtained maximum compressive strength of 17.87 MPa for a target strength of 25MPa at 28 days	Need to investigate the strength and properties of other percentages of replacements and durability

Table 2.4 (Cont'd)

6	Akpokodje & Hudec, 1992	Properties of concretionary laterite gravel concrete	The results of the study indicate that concrete made with concretionary laterite gravels possess compressive strengths that are comparable with concrete produced with granitic crushed rock aggregates The strength of the laterite concrete is mainly dependent on the aggregate-cement bond whereas the physical properties of the aggregates are only of secondary importance	Further examination on durability of Laterite Gravel Concrete
7	Asigo et al, 2017	Effects of sulphuric acid on different grades of concrete blocks made of laterite rock concrete	LRC plus superplacticizer concrete can be used as replacement for granite concrete in areas where sulfuric acid attack is prevalent	Investigating on other percentages of replacement of Laterite aggregates in concrete
8	Akpokodje & Hudec, 1992	Factors controlling properties and durability of concretionary laterite gravel aggregates	parent material rock types also have considerable influence on the physicomechanical properties of laterite gravel aggregates principal component factors measured properties of laterite gravels include (1) iron oxide content (degree of lateritization); (2) porosity and pore-size distribution; (3) micropores; and (4) adsorbed water	Need to compare the physical properties of lateritic aggregates across the earth's surface

Table 2.4 (Cont'd)

9	Marewangeng et al, 2020	Compressive strength of laterite stone mixed concrete	The slump test result showed that fresh concrete had proper workability and can maintain its homogeneity during pouring into the mold and the compaction process, achieve a good compaction result without honeycombs and large void on the surface of specimen. Compressive strength test showed that the specimens containing laterite stone as aggregate had a higher 28days compressive strength as compared with the specimens containing river stone as aggregate	The investigation of durability properties , high temperature performance
10	Muthusamy & Kamaruzaman, 2012	An assessment on the characteristic of Malaysian laterite aggregate	Addition of 10% replacement laterite aggregate able to produce mix with comparable strength to plain concrete. The targeted strength still can be achieved with addition of 30% replacement laterite aggregate	Investigation for percentages higher than 50% LA, testing after 90 days of curing
11	Karthik & Acharya, 2019	Lateritic aggregate as partial replacement for aggregate in concrete-an experimental investigation	As percentage of lateritic aggregate replacement increased, the compressive strength, split tensile strength and flexural strength of laterized concrete decreased	The investigation of durability properties incorporating laterized concrete can be done. Effect of admixtures on laterized concrete can be carried out.
12	Muthusamy, 2014	Influence of elevated temperatures on compressive strength of concrete containing 10% laterite aggregate	The percentage of mass loss and compressive strength ratio pattern displayed by laterite concrete is similar to plain concrete	Performance of other percentages of replacement of Laterite concrete when exposed to elevated temperature, optimal percentage of replacement for high temperature best performance

Table 2.4 (Concluded)

13	Raja et al, 2022	Durability studies on fly-ash based laterized concrete: A cleaner production perspective to supplement laterite scraps and manufactured sand as fine aggregates	durability parameters such as water absorption, permeability, sorptivity, dryin g shrinkage, and rapid chloride penetration of laterized concrete mixes containing 50% replacement recline within the acceptable limits as per standards	durability parameters such as water absorption, permeability, sorptivity, dryin g shrinkage, and rapid chloride penetration of laterized of Latertite as partial replacement for Coarse aggregate
14	Rajapriya & Ponmalar, 2021	Investigations on Mechanical Characteristics and Microstructura l Behavior of Laterized High Strength Concrete Mix	25% substitution of laterite was the optimum percentage in HSC concrete. Durability parameters such as water penetration depth, chloride ion permeability, and sorptivity exhibited higher values for laterite mixes than the control mixes	Durability parameters such as water penetration depth, chloride ion permeability, and sorptivity for Latertite as partial replacement for Coarse aggregate
15	Apeh & Ogunbod e (2012)	Strength performance of Laterized concrete at elevated temperature	strength of laterized concrete that is sufficient for use at elevated temperature not exceeding 400ºC	Performance above 400ºC Lateritic coarse aggregates performance at elevated temperatures
16	Balogun (2003)	Effect of temperature on the residual compressive strength of laterized concrete	nominal strength, increased with temperature up to 200°C before falling to about 20% of the nominal strength at 800°C	Lateritic coarse aggregates performance at elevated temperatures
17	Udoeyo et al (2010)	Residual compressive strength of laterized concrete subjected to elevated temperatures	residual compressive strength data of laterized concrete was in line with code provisions in Eurocode and CEB design curve showed that these codes could be applied to laterized concrete subjected to temperature below 400°C	Performance above 400ºC Lateritic coarse aggregates performance at elevated temperatures

2.4.1 Summary of Literature Review

Based on the literature reviewed on the use of lateritic aggregates as partial replacement of coarse aggregates, the most cross cutting knowledge gaps were found to be associated with the apparent variation of the mineralogy and physical properties of lateritic aggregates found in different tropical parts of the world. Most research has so far been carried out in Malaysia, Indonesia, India, Nigeria and Ghana. Besides this gap, durability and high temperature performance of Lateritic Aggregate Concretes are other areas that need more studies in different tropical regions of the world. Further, there is still little literature on the use of admixtures to improve the properties of Lateritic Aggregate Concretes.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This chapter describes the methodology for the evaluation of fresh properties (workability), hardened properties (density, compressive strength and splitting tensile strength), durability properties (sorptivity and water absorption) and mineralogical & microstructural characteristics (X-Ray diffraction, i.e., XRD of LCA samples). In this chapter, procedures adopted for physical testing of constituent materials for making concrete, i.e., cement, coarse aggregate (GCA), river sand and LCA, are described. The chapter also includes procedure adopted for mix design of concrete, details of test specimens for various tests, procedure of casting as well as for testing of specimens at various ages. The study was laboratory based, i.e., experimental. Research design was established to develop reliable relationships amongst the variables and the parameters by manipulating independent variables. The parameters manipulated were the percentage replacement of LCA for GCA. The independent variables were monitored and recorded during the study.

3.2 Research Method

The study was carried out by conducting the following experimental investigations:

1. Concrete mix design for C30 (30MPa) was be prepared using GCA, Dangote Zambia 42.5R Cement, river sand and tap (Portable) water.
2. 19 150mm cubes with C30 mix were produced as control specimens.
3. Five other mixes of concrete were done based on the C30 mix design, but with the GCA being partially replaced with LCA in the ratios 90:10, 80:20, 70:30, 60:40. and 50:50
4. Workability by slump and compaction for all mixes of concrete were tested
5. 19 150mm cubes were prepared for each mix. i.e. a total of 114 No. 150mm cubes specimens were prepared

6. Three 100 mm diameter x 200 mm long cylinders were cast for each mix, i.e. a total of 18 concrete cylinder specimens
7. All specimens were placed in the curing tank, in portable water for required periods
8. Hardened state physical properties for all mixes were tested. Properties including;
    - Compressive strength (without further treatment) and 7, 14, 28, 50 and 100 days,
    - Compressive strength (for residual strength after exposure of specimens to high temperature) at 28 Days
    - Split tensile strength at 28 Days
9. Durability testing of concrete including water absorption and Sorptivity tests

3.3 Testing Standards

Testing and procedures in this study were in accordance with the following standards:

- BS EN12620:2002 – Concrete Aggregate Testing
- BS EN 933-1:2012 – Tests for geometrical properties of aggregates Determination of particle size distribution. Sieving method
- BS 1377 – 2:2021 – Methods of Tests for Civil Engineering Purposes
- BS EN 1097 – 6:2022 – TC – Determination of Absorption Rate of Coarse aggregates
- BS 5328 – Part 2: 1997– Methods for Specifying Concrete Mixes
- BS EN 12390 – 3:2019 – Testing Hardened Concrete
- BS EN 12350 – 1 :2019 – Testing Fresh Concrete
- BS EN 12350 – 4:2009: Testing Fresh Concrete: Part 4 Degree of Compatibility
- BS EN1992 – 1 – 2 – Design of Concrete Structures General Rules – Structural Fire Design
- ASTM C 1585:2020 – Water Absorption (Sorptivity) Testing of Concrete

- ASTM C1585:2020 – Rate of Absorption of Water by Hydraulic – Cement Concretes
- BS 1881-122:2011+A1:2020 – Testing concrete Method for determination of water absorption

3.4 Outputs of the Study

The following outputs were obtained from the study results:

- Mineral Composition of LCA
- Compressive strength of concrete at 7, 14, 28, 50 and 100 days
- Split tensile strength at 28 days
- Compressive strength (for residual strength after exposure of specimens to high temperature) at 28 Days
- Dry and bulk density of concrete
- Accessible Porosity of concrete
- Water Absorption and Sorptivity coefficient of concrete

3.5 Facilities used

The experiments and tests in this study were conducted at the following facilities:

1. UNZA Civil Engineering Laboratories
2. UNZA Geology Laboratories
3. RDA Lusaka Laboratories

3.5.1 Mix Design Approach

The mix design of the 30MPa control concrete that was used in this study was in accordance with British DoE method (BS). The structural concrete grade of C30/35 was used. This concrete grade was chosen technically because it has ample range above the C25/30 which is the lower threshold of the characteristic strength required for the design and construction of structural members as per various structural design standards. The strength range in compressive strength above C25/30 was deemed important as the anticipated trend in the strength of the laterite based concrete reported by other scholars was a decreasing one. Furthermore, C30/35 concrete is one of the commonly specified grade of concrete for construction of structural members in Zambia. From the trial mixes done in the Laboratory, the concrete cubes upon crushing gave a compressive strength with an average of 20.1MPa at 7 days, being approximately 67% of the target strength of (30MPa). The mix was adopted for this study as it had a compressive strength higher than 19.5 MPa at 7 days.

3.5.2 Collection of Constituent Materials for concrete

3.5.2.1 Granite Coarse Aggregate (GCA) from CNBM

Coarse Aggregate are particles greater than 4.75mm BS EN sieve. The coarse aggregate used was obtained from CNBM quarry in Chifwema village of Chongwe District. Aggregates with a nominal size of 5-10mm were used as coarse aggregate in this Study. This size of GCA was preferred as it was comparable to the predominant size of LCA.

3.5.3 Lateritic Coarse Aggregate from Chalala

The lateritic Coarse Aggregates used in this study was collected from a borrow pit located behind Tick College of Education along Kasama Road, in Chalala (Hillview Park) area of Kafue and Lusaka Districts, Lusaka Province. The location coordinates of the borrow pit is around **UTM 35L 642991 8286203**. The borrow pit has deposits of Laterite.

Laterites are considered as both a rock type and soil type that is highly weathered material rich in secondary oxides of Iron, Aluminium or both. It is nearly devoid of base and primary silicates but may contain large amount of quartz, and Kaolinite. The Lateritic aggregate dug from the pit contained lateritic rock fragments, lateritic stones and gravel and also lateritic soils. Therefore, the sample was screened after quarrying using 20mm sized grating and 4.75mm size sieve in order to get rid of boulders and lateritic soil and fines respectively. Figure 3.1 is a google map of the borrow pit were the LCA was sourced.

Figure 3.1: Location of Laterite Borrow Pit in Chalala: 35L 642991 8286203, Source: Google Earth

3.5.3.1 Fine Aggregate (River Sand) from Kasisi

The river sand used as Fine Aggregates in this study was procured within Lusaka and originally sourced from Kasisi quarries in Chongwe District. On visual inspection, the Fine Aggregate was found to be free from organic matter and debris. Physical properties of natural sand, i.e., sieve analysis, specific gravity, water absorption and bulk density, were evaluated in accordance with the outlined methods in BS EN12620:2002.

3.5.4 Testing of Constituent Materials for concrete

3.5.4.1 Grading of Aggregates (Sieve Analysis)

GCA, LCA and FA were tested in accordance with BS EN12620:2002 and BS EN 933-1:2012.

3.5.4.2 Loose Bulk Density

The Loose Bulk Density of Granite Coarse aggregates (GCA), Lateritic Coarse Aggregates(LCA) and Fine Aggregates (FA) was conducted in accordance with the procedure and methods stipulated in BS EN 1097-3:1998. Bulk densities were performed on both oven-dried and saturated surface dry material.

3.5.4.3 Water Absorption

The determination of the water absorption of the aggregates was done in accordance with BS EN 1097-6:2022 - TC.

3.5.4.4 Specific Gravity of Aggregates

In this study, the specific gravity of Granite Coarse aggregates, Lateritic Coarse Aggregates and Fine Aggregates was conducted in accordance with the procedure and methods stipulated in BS 1377-2:2022. The specific gravity was calculated using equation Equation 3.1

$$G_s = \frac{m_2 - m_1}{(m_4 - m_1) - (m_3 - m_2)} \text{ ……………………………….. } \textit{Equation 3.1}$$

where:

G_s is the specific gravity of the Aggregate

m_1 is the mass of the bottle

m_2 is the mass of the bottle + Aggregate

m_3 is the mass of the bottle + Aggregate + water

m_4 is the mass of the bottle full of water

3.5.4.5 Specific Gravity of Fine Aggregates:

River sand was tested for specific gravity, water absorption and bulk density.

Specific gravity of aggregates was calculated by pycnometer/container method, as follows:

Procedure

- The Weight of the Container was determined (W1)
- The Container was filled with Aggregate and weighed (W2)
- Then the Container was filled with water up to the top surface level and weighed (W3)
- The Container was emptied and is filled with water and weighed (W4)

Equation 3.2 gives the specific gravity.

$$\text{Specific Gravity} = \frac{(W2 - W1)}{(W4 - W1) - (W3 - W2)} \text{ ………………………… } \textit{Equation 3.2}$$

3.5.4.6 Mineral Testing of LCA

The sample for mineral testing was prepared by first sieving 25 kg of LCA sample and thereafter pounding 2.5 kg then sieving using 0.425mm sieve. The crushed and sieved sample was then analyzed using X-Ray Diffraction (XRD) Machine with the diffraction angle, 2θ, defined between the incident beam and the detector operating conditions; had the following conditions:

- XRD range: 5 - 55°
- Sample Size (amount): 15 mg
- X-Ray tube voltage: 30kV
- X-ray tube power: 10W
- Diffraction peak angle position: 2θ (Co)
- Sampling: Dry powder placed into a small chamber

3.5.1 Mix Proportioning of different Concrete Mixes and Water Correction

From the absorption rate experiment for LCA, it was established that LCA had higher absorption rate than GCA and therefore its addition to replace GCA in the concrete mix would instantly affect the water cement ratio and consequently the workability of the resulting concrete. As the quantity of aggregate calculated in mix design of concrete was based upon the GCA condition of aggregate, it was therefore necessary to introduce additional water to the mix in order to correct the water cement ratio to the required value of 0.54 and allow for a required range of slump to be achieved for the entire range of concrete LCA concrete mixes.

In a similar study, Asiedu et al (2017) observed that the higher the surface area, the more water required for moistening. Muthusamy and Kamaruzaman (2012) reported that Pure laterite/cement mixes require relatively high water content for easier mixing, also suggested that the reduction in the laterite concrete mix workability is probably due to the higher rate of water absorption of this aggregate which possess higher porosity as compared to granite aggregate.

Since water absorption of LCA was used as the basis for adjusting the water to be applied to LCA concrete mix, the amount of water increased with the amount of LCA introduced in the mix. Water correction applied at the time of casting is expressed in Equation 3.3.

Water correction for LCA = Weight of LCA (kg) in mix x absorption rate of LCA (kg of Water/kg of LCA) …………………………… *Equation 3.3*

3.5.1.1 Concrete Mixing Approach

All the materials were made free of contaminants and they were weighed before mixing. A small concrete mixer was used to mix all the materials, they were added in the order: sand, stone, cement and they were mixed for one minute. Water was weighed and then added to the mixture and was mixed for 3 minutes, thereafter the concrete was poured on a tray for fresh concrete tests. After the fresh concrete tests were completed, the concrete was placed in the moulds and they were vibrated. All the mixes/moulds were vibrated in the same way for consistency purposes. The moulds were firstly vibrated for 20 seconds and then completely filled then vibrated for another 40 seconds. Thereafter the moulds containing concrete were weighed.

The fresh concrete in the moulds was left to set at room temperature, the concrete was removed from the moulds after 24 hours from the time cast and was put in a water bath for curing. This procedure was also applied to the cylinder moulds for the concrete specimens.

3.5.2 Testing of Fresh Concrete

3.5.2.1 Workability by Slump Test

Workability of concrete is the ease with which concrete can be properly mixed, transported, compacted and finished, with minimum loss in homogeneity. The test was done according to BS EN 12350 which describes the determination of slump of cohesive concrete of medium to high workability.

3.5.2.2 Workability by Compacting Factor Test

The test was done according to BS EN 12350. The upper hopper of the compacting apparatus was filled with fresh concrete and the bottom of the hopper released open to allow the concrete fall down to the lower hopper. The bottom hopper was released opened to allow concrete to fall into the cylinder. The excess concrete was cut across the top of the cylinder and the net mass of the concrete in the cylinder was determined. The cylinder was emptied and then refilled and placed in a vibrating table so as to compact it and then the weight of the compacted concrete measured. Equation 3.4 gives the Compaction factor.

$$\textit{Compacting factor} = \frac{Mass\ of\ partially\ compacted\ concrete}{Mass\ of\ fully\ compacted\ concrete} \ldots\ldots\ldots\ldots\ldots. \textit{Equation 3.4}$$

3.5.3 Testing of Hardened Concrete Compressive Strength:

3.5.3.1 Compressive Strength Testing

Compressive strength is regarded as the most important property of hardened concrete. Compressive strength test was done as per BS EN 12390-3:2019. Compressive strength of concrete was evaluated at age of 7 days, 28 days, 50 and 100 days using standard 150mm cube specimens. Compression Testing Machine (CTM) of 5000 kN capacity was used for the testing of compressive strength of concrete. Equation 3.5 gives the compressive strength.

$$\sigma = P/A \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \textit{Equation 3.5}$$

where,

- σ = Compressive Strength (MPa)

- P = Maximum load sustained by the cube (N)
- A = Area of cross section of cube (mm^2)

Results of the compressive strength testing were reported as average of compressive strength of 3 specimens at 7 days, 14days, 28 days, 50 and 100 days for each concrete.

3.5.3.2 Split Tensile Strength

The tensile strength of the concrete indicates the start of cracking in tension zones. Splitting tensile strength is an indirect method to determine tensile strength of concrete. The Split tensile strength test was conducted as per BS EN 12390-3:2019 – Testing Hardened Concrete, at ages of 7 days, 28 days and 90 days for cylindrical specimens of 100mm diameter and 200mm height. Equation 3.6 gives the splitting tensile strength.

$$\sigma_{st} = \frac{P}{\pi DL} \text{.................................. } \textit{Equation 3.6}$$

Where;

- σ_{St} = Splitting Tensile Strength (MPa)
- P = Maximum load sustained by the cylinder (N)
- D = Diameter of cylinder (mm)
- L = Length of cylinder (mm)

Results of the splitting tensile strength testing were reported as average of splitting tensile of 3 specimens at 28 days for each concrete mix in MPa.

3.5.4 LCA Concrete Durability Testing

3.5.4.1 Dry Bulk Density and Saturated Density of LCA Concrete

Density of concrete is an important aspect, as it plays a major role in the calculation of dead weight of a structure. At the time of demoulding of 150mm cube specimens used for testing of compressive strength, mass of 3 sample cubes was taken using a weighing balance of 10 kg capacity with an accuracy of 1.0g and density of concrete was calculated using Equation 3.7.

$$\rho = \frac{M}{V} \text{... } \textit{Equation 3.7}$$

where,

ρ = Density of concrete in kg/m^3

M = Mass of 150mm cube in kg

V = Volume of cube in m^3

3.5.4.2 Water Absorption and Porosity of Concrete

Pore structure of concrete plays a very important role to have an idea about the durability aspects of concrete. Water absorption of concrete is an indicator of how dense the microstructure of concrete is. Water absorption of concrete was evaluated at various specified ages as per the procedure given in ASTM C.

Water absorption test was performed at 100 days. Oven dry mass and saturated mass of the concrete specimens were determined as per the standard procedures given in ASTM C. Water absorption of concrete was calculated using Equation 3.8.

$$Absorption\ after\ Immersion\ (\%) = \frac{100(A-B)}{A} \text{ …………………. } \textit{Equation 3.8}$$

where,

- B = Oven Dried mass of specimen in air (g)
- A = Mass of surface-dry specimen after immersion in air (g)

Results of oven dry density of concrete and apparent water absorption, tested at 28 days for each concrete mix were also used to compute the accessible pore volume (Porosity) of each mix of concrete.

3.5.4.3 Sorptivity:

Movement of liquids through interconnecting pores plays a very important role to determine the durability of concrete. Sorptivity of concrete is rate of absorption of water by one dimensional capillary action. Sorptivity of concrete was evaluated as per the procedure given in ASTM C 1585:2020. Absorption rate and sorptivity were conducted at 100 days, on standard cylindrical specimens of 100mm diameter and 50mm height. Each specimen was prepared as per the procedure give in ASTM C 1585:2020. Sides of the specimen were sealed with epoxy coating. Mass of each specimen was taken and it was recorded as initial mass. As soon as the specimen was placed in water, a stop watch had been started and mass of the specimen was taken after 10, 15, 20, 25, 30,35,45, 60, 90, 120, and 150 minutes. At each specified time slot, specimen was lifted and its surface in contact with water was surface dried with the help of a towel and its mass was recorded.

For calculation of Sorptivity of concrete specimen, first of all, rate of absorption of water, I, was calculated using change in mass of the specimen divided by the product of the ross-sectional area of the test specimen and density of water. For this purpose, density of water was adopted as 0.001 g/mm^3 and the units of I are mm^3/mm^2 or mm. Equation 3.9 gives the Sorptivity.

$$I = \frac{M_t}{ad} \qquad \text{Equation 3.9}$$

where:

I = Rate of absorption (mm^3/mm^2 or mm)

M_t = the change in specimen mass at time t (g)

a = Exposed area of the specimen (mm^2)

d = Density of water (g/mm^3)

Then, rate of absorption of water, I, was plotted against square root of time in min, $t^{0.5}$ and curve was obtained. By linear regression analysis, slope of the curve was obtained. The slope of the curve is regarded as Sorptivity with units mm^3/mm^2/min$^{0.5}$ or mm/min$^{0.5}$.

3.5.4.4 Residual Strength and Density of High Heat Exposed Concrete

In this study, testing for elevated heat performance was conducted in order to evaluate the performance of LCA concrete with this treatment, the experiments were done based on recommendations given in BS EN1992-1-2. Three 150mm cubes specimens at 28 days; for each mix of LCA concrete were heated to a temperature of 450°C for 1.5 hours in a furnace and afterwards left to cool down naturally at room temperature. 450^{o}C was chosen as it above 400^{o}C, a temperature at which Laterite based concrete start to lose strength (Li and Bu 2011; Muthusamy et al, 2014; Udoeyo et al, 2010, Poon et al 2003; Balogun 2003; Apeh & Ogunbode, 2012).

The cubes were well marked and weighed before and after heating in the furnace. The three specimens were heated in the furnace at the same time. The furnace was first heated to 450°C. The furnace temperature was kept constant for about 1.5 hours. This was followed by natural cooling down to room temperature in the furnace.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Overview

This section presents and discusses the results of this study. With this research being laboratory based, assorted data; both quantitative and qualitative, was collected and analyzed for results presentation and discussion. The tests on LCA Concrete were conducted chiefly to ascertain the optimum percentage by mass replacement of LCA for GCA that can be allowable in conventional C30 concrete, if the concrete is to remain of structural use as regards compressive strength (i.e. above 25MPa) and further, comparison of some properties between LCA concrete and GCA concrete such durability and fire resistance were conducted.

4.2 Testing of Constituent Materials of Concrete

4.2.1 Mineral Testing of LCA

The essence of testing the mineralogy of the LCA was the following:

- To confirm the aggregates were lateritic in nature
- To document the constituents by percentage of the minerals in the sampled laterite, and thereby add to the body of knowledge as regards comparisons of lateritic aggregate mineralogy across the globe, as these properties are reportedly different from one continent and location to another, owing to the different rainfall pertains and temperatures over thousands of years, generally in the tropics, this fact is also reported by Ola, who in 1980, found that Comparison of concretionary laterites from Nigerian specimens were found superior to their Ghanaian counterparts.
- To use the test results to help explain any phenomena that would be linked to the material properties of LCA in the course of the study

From the analysis carried out in this study using **e**xperimental XRD, peak pattern data were analyzed by High Score Pan Analytical software which detects the peak shape, height, and position. Software matches descriptors of the test pattern to known XRD patterns in crystalline databases allowing the identification of the minerals in the sample. Refinement methods such as Rietveld refinement were used to analyze experimental XRD patterns.

4.2.1.1 Results of the XRD analysis

Figure 4.1 to Figure 4.3 show sample preparation and equipment used for testing of the LCA sample.

Figure 4.1 : Crushing of LCA

Figure 4.2: Sieving of crushed LCA using 0.425mm sieve

Figure 4.3:XRD Analyzer Machine Used

The sample was found to be dominated by the following minerals:

i. Crystalline iron oxide mineral known as Goethite (FeO(OH)) and abundant amorphous (non-crystalline) iron oxide minerals such as ferrihydrite (Fe_2O_3•H_2O) which gives the XRD pattern a thick background profile

ii. Clay mineral known as Kaolinite (Al_2O_3 $2SiO_2 \cdot 2H_2O$) was found to be present. This type of clay is generally a low/ (limited) expansive clay

iii. Quartz (SiO_2)

Figure 4.4 shows the XRD analysis results.

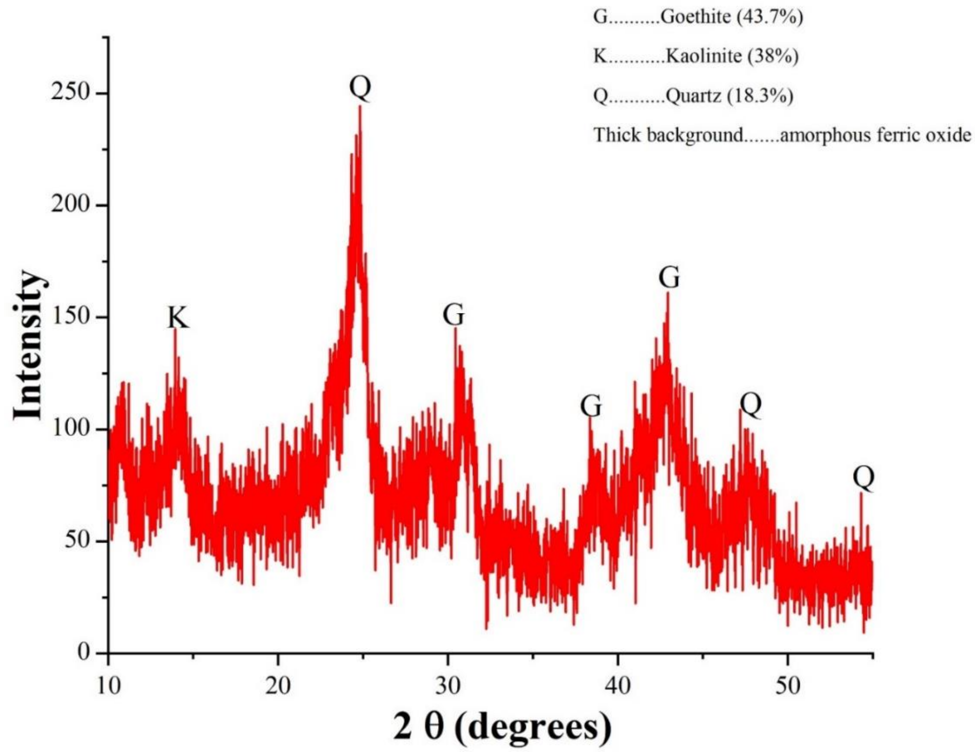


Figure 4.4: Results of the XRD analysis

The results of the experimental XRD showed that the sampled LCA aggregates minerology had ample goethite essential for the mechanical and physical properties generally required for laterite based coarse aggregates and consequently suitability for use as partial replacement of GCA in Concrete. The constituent minerals and their compositions were found to be comparable to those found by other scholars, such as Kasthurba et al (2008) who carried out XRD tests on lateritic aggregate samples in India for building purposes. From the four sampled borrow pits, their study reported that the minerals in lateritic aggregates ranged from 57.8 to 71.7% for SiO_2, 11.7 to 23.4% for Fe_2O_3 and 7.96 to 11.9% Al_2O_3. These results show similar composition to the results in this study, but with Zambian laterite having superior content of Goethite, which intels better concretionary properties than the Indian sampless. Goethite and hematite are accessory minerals in hardened laterite and determine to a large extent the dominant physical and mechanical properties of laterite (Kasthurba et al, 2008).

4.2.2 Grading of Aggregates

4.2.2.1 Grading of Granite Coarse Aggregates

Figure 4.5 shows the granite aggregates (GCA) sourced from CNBM quarry.

Figure 4.5: Granite aggregate sourced from CNBM used in the study (Source: Image Author)

Table 4.1 shows Sieve analysis data for coarse aggregates while Figure 4.6 shows particle size distribution curve as per Sieve Analysis of GCA.

Table 4.1:Sieve analysis data for coarse aggregates

Weight of dry sample (g) =1500.9 g							
Sieve No.	**Sieve Opening (mm)**	**Mass of Sieve (g)**	**Mass of Sieve & soils (g)**	**Mass of soils Retained (g)**	**% Retained**	**Cum. % Retained**	**Cum.% Passing**
1	16.00	572.40	572.40	0.00	0.00	0.00	100.00
2	9.52	1058.20	1412.10	353.90	23.57	23.57	76.43
3	8.00	525.10	1094.50	569.40	37.92	61.49	38.51
4	6.00	526.00	1041.40	515.40	34.33	95.82	4.18
5	4.00	522.00	581.00	59.00	3.93	99.75	0.25
6	2.00	309.50	312.80	3.30	0.22	99.97	0.03
7	1.18	275.10	275.30	0.20	0.01	99.98	0.02
8	0.60	253.00	253.30	0.30	0.02	100.00	0.00
9	0.43	461.20	461.20	0.00	0.00	100.00	0.00
10	0.30	323.10	323.10	0.00	0.00	100.00	0.00
11	0.15	220.30	220.30	0.00	0.00	100.00	0.00
12	0.06	291.40	291.40	0.00	0.00	100.00	0.00
13	Pan	182.00	182.00	0.00	0.00	100.00	0.00
Total Mass				1501.50			
% Fines	0.00	**%C.A**	99.75	**%F.A**	0.25		
D60		8.86144					
D30		7.504269					
D10		6.33896					

Cu	D60/D10	1.40
Cc	D30^2/D10*D60	1.00

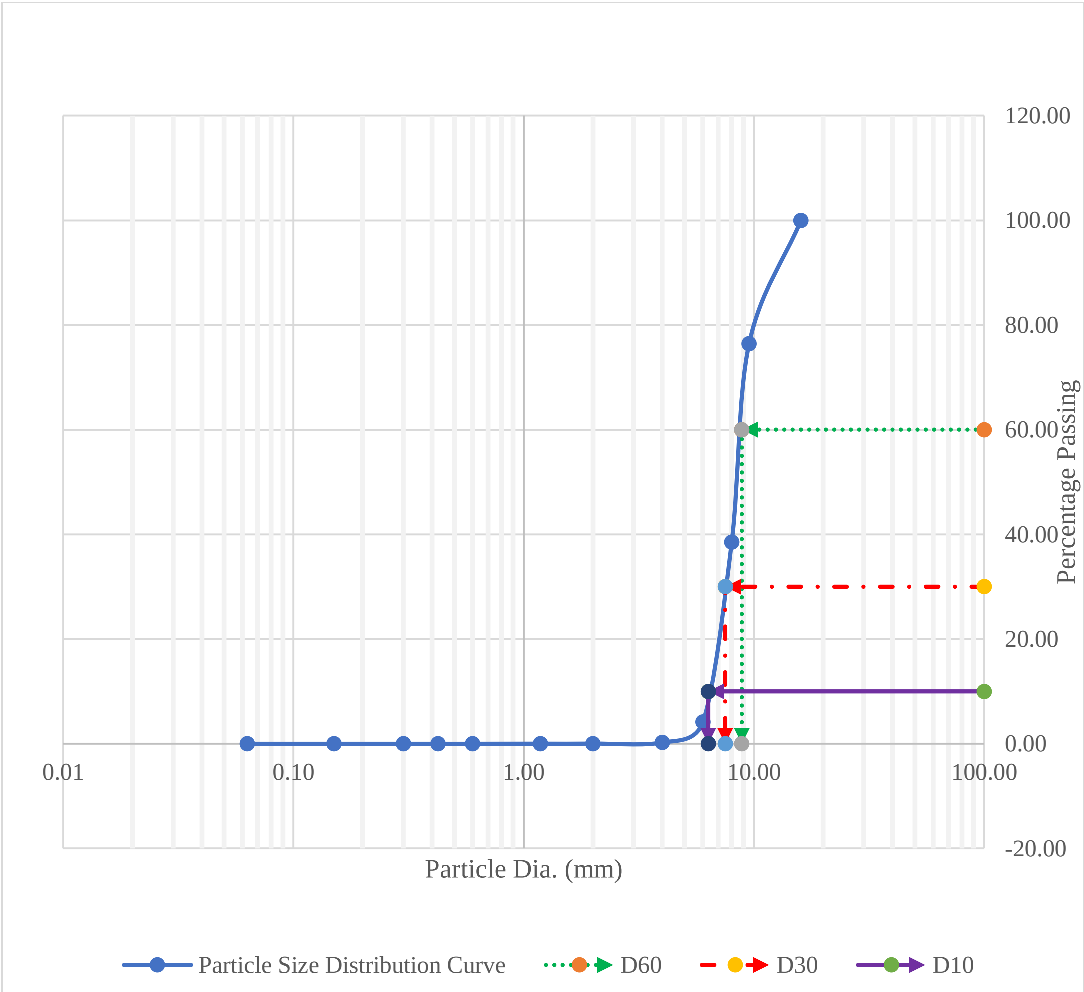


Figure 4.6: Coarse Aggregate Sieve Analysis Grading Curve

Figure 4.6 shows the particle size distribution of GCA curve shows that the D_{60} is 8.86, D_{30} is 7.50 and D_{10} is 6.34 mm, respectively. The coarse aggregate uniformity coefficient (Cu) was computed to be 1.40 while the coefficient of curvature (Cc) was computed to be 1.0. The Cc and Cu show that the coarse aggregate is poorly graded. Table 4.2 summarizes Mechanical and Physical Properties of Coarse Aggregates.

4.2.2.2 Grading of Lateritic Coarse Aggregate

Figure 4.7 shows the natural lateritic deposits at the borrow pit. Figure 4.8 shows Screening of Laterite using Sieve No. 4 while Figure 4.9 shows Washed LCA sample for sieve analysis.

Figure 4.7:Natural appearance of lateritic materials at borrow pit (Source: Author)

Figure 4.8: Screening of Laterite using Sieve No. 4

Figure 4.9: Washed LCA sample for sieve analysis

Table 4.2 shows the data collected on the LCA sieve analysis; while Figure 4.10 shows LCA Sieve Analysis curve.

Table 4.2:Lateritic Coarse Aggregate sieve analysis data

LATERITIC COARSE AGGREGATES							
Weight of dry soils (g)		**Mass Before Washing:**					
912.7		1000					
Sieve No.	**Sieve Opening (mm)**	**Mass of Sieve (g)**	**Mass of Sieve & soils (g)**	**Mass of soils Retained (g)**	**% Retained**	**Cumulative % Retained**	**% Passing**
1	16.00	572.40	572.40	0.00	0.00	0.00	100.00
2	11.20	1058.20	1058.20	0.00	0.00	0.00	100.00
3	8.00	525.10	585.50	60.40	6.82	6.82	93.18
4	6.00	526.60	825.40	298.80	33.74	40.56	59.44
5	4.00	522.00	1048.30	526.30	59.44	100.00	0.00
6	2.00	309.50	309.50	0.00	0.00	100.00	0.00
7	1.18	275.10	275.10	0.00	0.00	100.00	0.00
8	0.60	253.00	253.00	0.00	0.00	100.00	0.00
9	0.43	461.20	461.20	0.00	0.00	100.00	0.00
10	0.30	323.10	323.10	0.00	0.00	100.00	0.00
11	0.15	220.30	220.30	0.00	0.00	100.00	0.00
12	0.06	291.40	291.40	0.00	0.00	100.00	0.00
13	Pan	182.00	182.00	0.00	0.00	100.00	0.00
Total Mass				885.50			
% fines	0.00	**%coarse**	100.00	**%sand**	0.00		
loss %	0						
D60		6.03					
D30		5.01					
D10		4.34					

Cu	D60/D10	1.39
Cc	D30^2/D10*D60	0.96

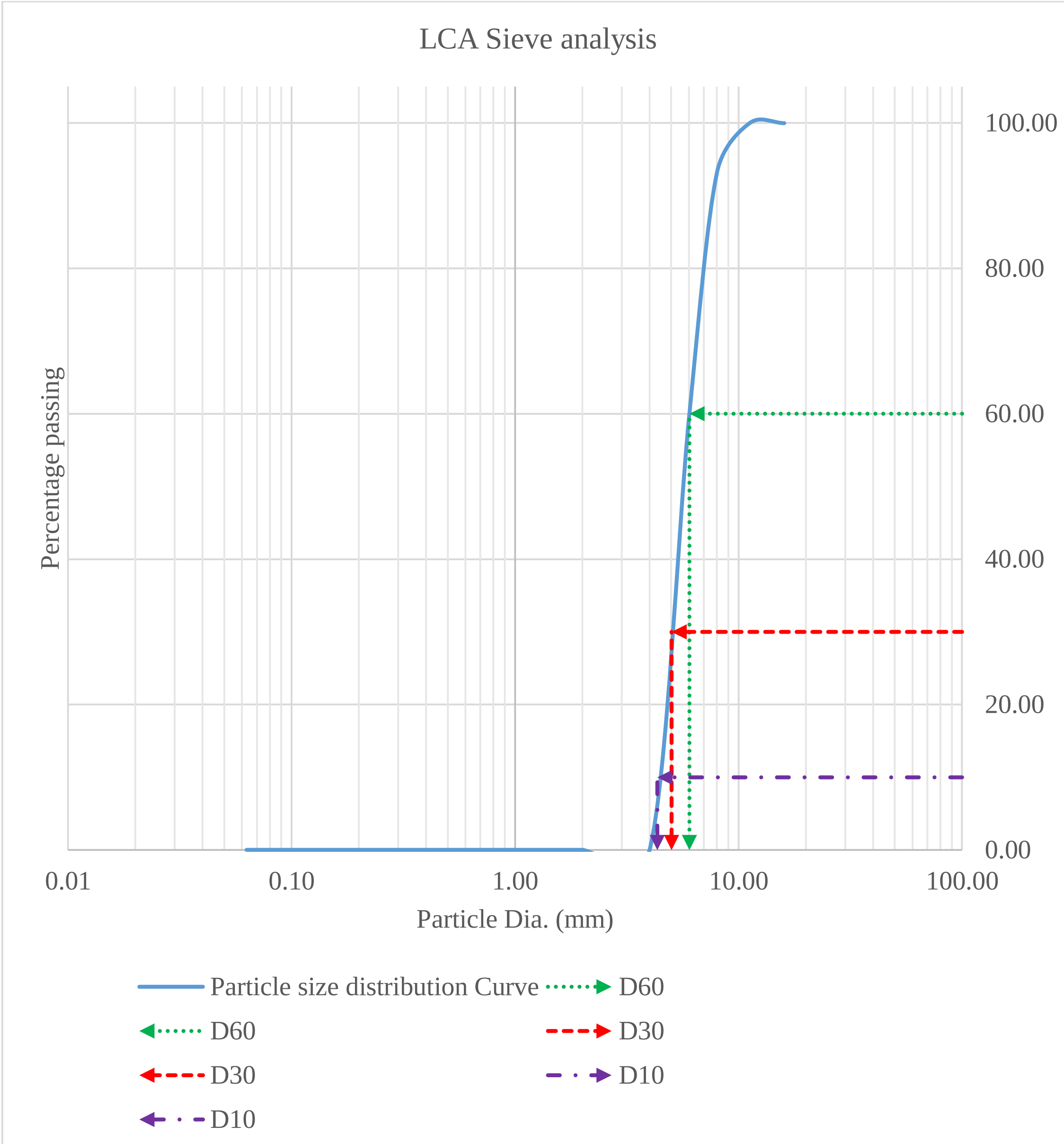


Figure 4.10: LCA Sieve Analysis Grading Curve

Figure 4.10 shows the LCA particle size distribution curve where D_{60} is 6.03mm, D_{30} is 5.01mm and D_{10} is 4.34mm. The coarse aggregate uniformity coefficient (Cu) was computed to be 1.39 while the coefficient of curvature (Cc) was computed to be 0.9. The Cc and Cu show that the LCA is poorly graded.

4.2.2.3 Grading of Fine Aggregate (River Sand)

Table 4.3 shows Sieve analysis data for Fine Aggregates (River Sand)

Table 4.3: Sieve analysis data for Fine Aggregates (River Sand)

Sand Fine Aggregate							
Weight of dry soils (g)							
896.1							
Sieve No.	**Sieve Opening (mm)**	**Mass of Sieve (g)**	**Mass of Sieve & soils (g)**	**Mass of soils Retained (g)**	**% Retained**	**Cum. % Retained**	**Cum. % Passing**
1	16.00	572.40	572.40	0.00	0.00	0.00	100.00
2	11.20	1058.20	1058.20	0.00	0.00	0.00	100.00
3	8.00	525.10	525.10	0.00	0.00	0.00	100.00
4	6.00	526.00	530.80	4.80	0.54	0.54	99.46
5	4.00	522.00	529.60	7.60	0.85	1.38	98.62
6	2.00	309.50	373.60	64.10	7.15	8.54	91.46
7	1.18	275.10	453.80	178.70	19.94	28.48	71.52
8	0.60	253.00	654.70	401.70	44.83	73.31	26.69
9	0.43	461.20	535.40	74.20	8.28	81.59	18.41
10	0.30	323.10	370.80	47.70	5.32	86.91	13.09
11	0.15	220.30	299.40	79.10	8.83	95.74	4.26
12	0.06	291.40	323.00	31.60	3.53	99.26	0.74
13	Pan	182.00	188.60	6.60	0.74	100.00	0.00
Total Mass				896.10			
% Fines	0.74	**%C.A**	1.38	**%F.A**	97.88		
Loss %	-1.3E-14						
D60		1.03					
D30		0.64					
D10		0.25					
Cu	D60/D10	4.17					
Cc	D30^2/D10*D60	1.62					

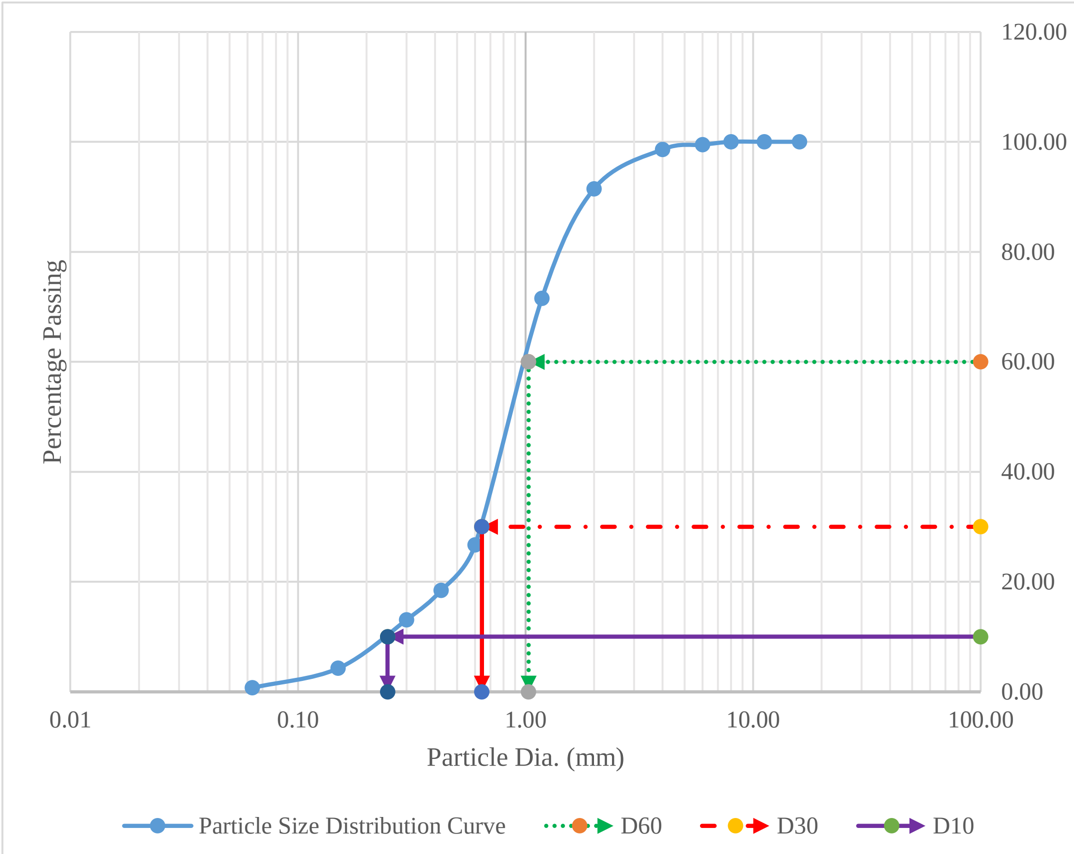


Figure 4.11: River Sand (F.A) Sieve Analysis

Figure 4.11 shows the particle size distribution curve for River Sand (FA). The particle size distribution curve shows that the D_{60} is 1.03, D_{30} is 0.64 and D_{10} is 0.25. The uniformity coefficient (C_u) of River Sand / Fine aggregates was computed to be 4.17 while the coefficient of curvature (Cc) was computed to be 1.62. The Cc and Cu show that the river sand (FA) was well-graded. This sand grading is in Zone II, with 71.52% (i.e. between 55-90%) passing the 1.18mm sieve. Grades I, II and III sands are recommended for concrete works while grade IV is not due

4.2.2.4 Specific Gravity of Fine Aggregate (River Sand)

Table 4.4 shows the computed specific gravity for Fine Aggregate (river sand)

Table 4.4: Computation of Specific gravity of FA from collected data

Specific Gravity of Fine Aggregate (River Sand)				
Trial Number	1	2	3	Average
Weight of Container (W1), (g)	446	446	446	
Weight of Container e + Sand (W2), (g)	922	959	944	
Weight of Container + Sand + Water (W3), (g)	1533	1556	1546	
Weight of the Container full of water (W4), (g)	1250	1250	1250	
Weight of Sand = (W2 - W1)	476	513	498	
Weight of water = (W3 - W2), (g)	611	597	602	
Volume of Sand = (W4 - W1) - (W3 - W2)	193	207	202	
specific gravity of the soil particles (S.G)	2.466	2.478	2.465	2.47

4.2.2.5 Specific Gravity of Granite Coarse Aggregates

Table 4.5 shows the computed specific gravity for Granite Coarse Aggregate (GCA).

Table 4.5: Computation of Specific gravity of GCA from collected data

Specific Gravity of Granite Coarse Aggregate (GCA)				
Trial Number	1	2	3	Average
Weight of Container (W1), (kg)	4.24	4.24	4.24	
Weight of Container + GCA (W2), (kg)	23.25	23.15	23.32	
Weight of Container + GCA + Water (W3), (kg)	27.26	27.18	27.22	
Weight of the Container full of water (W4), (kg)	15.3	15.3	15.3	
Weight of GCA = (W2 - W1), (kg)	19.01	18.91	19.08	
Weight of water = (W3 - W2), (kg)	4.01	4.03	3.9	
Volume of GCA = (W4 - W1) - (W3 - W2)	7.05	7.03	7.16	
Specific gravity of the GCA particles (S.G)= (W2 – W1) / (W4 – W1) – (W3 – W2)	2.70	2.69	2.66	2.68

4.2.2.6 Specific Gravity of Lateritic Coarse Aggregates

Table 4.6 shows the computed specific gravity for Lateritic Coarse Aggregate (GCA).

Table 4.6: shows the computed specific gravity for Lateritic Coarse Aggregate (GCA)

Specific Gravity of Lateritic Coarse Aggregate (LCA)				
Trial Number	1	2	3	Average
Weight of Container (W1), (kg)	4.24	4.24	4.24	
Weight of Container + LCA (W2), (kg)	21.08	21.15	21.33	
Weight of Container + LCA + Water (W3), (kg)	25.22	25.32	25.42	
Weight of the Container full of water (W4), (kg)	15.3	15.3	15.3	
Weight of LCA = (W2 - W1)	16.84	16.91	17.09	
Weight of water = (W3 - W2), (kg)	4.14	4.17	4.09	
Volume of LCA = (W4 - W1) - (W3 - W2)	6.92	6.89	6.97	
specific gravity of the LCA particles (S.G)= (W2 – W1) / (W4 – W1) – (W3 – W2)	2.43	2.45	2.45	2.45

4.2.3 Summary of Tests on Constituent Materials of Concrete

Three forms of aggregates used in this study were tested for physical and mechanical properties including grading, specific gravity, water absorption rate and Aggregate Crushing Value (ACV). Specific gravity test of aggregates was done to measure the strength or quality of the material while water absorption test was done in order to predetermine the water holding capacity of the coarse and aggregates. The results of these test were within acceptable limits stipulated by various standards. LCA was found to have the least specific gravity and weaker crushing values than GCA. Correspondingly, the water absorption rate of LCA was found to be higher than GCA. These results proposed an expected increase in the amount of water to be used in the mix of LCA concrete for the water cement ratio to be constant, and further prevent the reduction in the slump. The value of the absorption rate of LCA was therefore used to predict amount of additional water to be introduced for every increment percentage of replacement of LCA for GCA. Table 4.7 Summarizes the test results on the properties of aggregate used in this study.

Figures 4.12 and 4.13 show soaked GCA and LCA samples during absorption testing.

Figure 4.12:GCA Absorption rate test

Figure 4.13: LCA absorption rate test

Table 4.7: Summary of test results of properties of GCA, LCA and FA

	GCA	**LCA**	**FA**
Aggregate crushing value %	23.6 %	40 %	-
Water absorption %	1.6 %	3.7%	2.3%
Specific Gravity	2.68	2.45	2.47
Flakiness Index	6.4	8.2	-
Bulk density	1525 kg/m^3	1476 kg/m^3	1612 kg/m^3

4.2.4 Concrete Mix Design

Table 4.8 summarizes the mix design of the control concrete.

Table 4.8:Concrete mix design output for control mix

Required Characteristic Compressive Strength	$30N/mm^2$
Required Slump	30 – 60 mm
Water Cement Ratio	0.54
Binder	Dangote Zambia Cement 42.5R
Water source	Tap Water (Portable Tap water)
Amount of cement	490 kg/m^3
Water	262.9 kg/m^3
Fine aggregate	744.4 kg/m^3
Coarse aggregate	1688.5 kg/m^3
Mix ratio (By volume)	1:0.89:1.86

Water quantity to compensate for the absorption rate of LCA was calculated and added to the corresponding LCA Mix water amount. The accuracy of this correction was proven by monitoring the workability (Slump) of the mixes. The typical amounts of ingredients for LCA concrete for the required number of concrete cube specimens during this study were as tabulated in Table 4.9 The amount of absorption correction water introduced is also clearly indicated in the appropriate column.

Table 4.9:Concrete Mix Constituents for LCA Concrete specimen preparation with water absorption correction

BATCH MIX FOR SPECIMEN PREPARATION

Mix Name:	Control	Target Strength:	30MPa	LCA Abs. Rate	0.037	No. of Cubes:	19	No. of Cylinders:	3
Constituent Material	Cement	Granite Coarse Aggregate	River Sand	Water	LCA absorption	Corrected Water	Lateritic Coarse Aggregates	Water Cement Ratio	Percent Replacement
Quantity (kg)	31.2	95.37	47.4	16.74	0	16.74	0	0.54	0

Mix Name:	10% LCA	Target Strength:	30MPa			No. of Cubes:	19	No. of Cylinders:	3
Constituent Material	Cement	Granite Coarse Aggregate	River Sand	Water	LCA absorption	Corrected Water	Lateritic Coarse Aggregates	Water Cement Ratio	Percent Replacement
Quantity (kg)	31.2	85.83	47.4	16.74	0.352869	17.09	9.54	0.54	10

Mix Name:	20% LCA	Target Strength:	30MPa			No. of Cubes:	19	No. of Cylinders:	3
Constituent Material	Cement	Granite Coarse Aggregate	River Sand	Water	LCA absorption	Corrected Water	Lateritic Coarse Aggregates	Water Cement Ratio	Percent Replacement
Quantity (Kg)	31.2	76.30	47.4	16.74	0.71	17.45	19.074	0.54	20

Mix Name:	30% LCA	Target Strength:	30MPa				19	No. of Cylinders:	3
Constituent Material	Cement	Granite Coarse Aggregate	River Sand	Water	LCA absorption	Corrected Water	Lateritic Coarse Aggregates	Water Cement Ratio	Percent Replacement
Quantity (Kg)	31.2	66.76	47.4	16.74	1.06	17.80	28.61	0.54	30

Mix Name:	40% LCA	Target Strength:	30MPa			No. of Cubes:	19	No. of Cylinders:	3
Constituent Material	Cement	Granite Coarse Aggregate	River Sand	Water	LCA absorption	Corrected Water	Lateritic Coarse Aggregates	Water Cement Ratio	Percent Replacement
Quantity (Kg)	31.2	57.22	47.4	16.74	1.41	18.15	38.15	0.54	40

Table 4.9 (Continued)

Mix Name:	50% LCA	Target Strength:	30MPa	No. of Cubes:	19	No. of Cylinders:	3

Constituent Material	Cement	Granite Coarse Aggregate	River Sand	Water	LCA Absorption	Corrected Water	Lateritic Coarse Aggregates	Water Cement Ratio	Percent Replacement
Quantity (Kg)	31.2	47.69	47.4	16.74	1.76	18.50	47.69	0.54	50

Mix Name:	100% LCA	Target Strength:	30MPa	No. of Cubes:	19	No. of Cylinders:	3

Constituent Material	Cement	Granite Coarse Aggregate	River Sand	Water	LCA Absorption	Corrected Water	Lateritic Coarse Aggregates	Water Cement Ratio	Percent Replacement
Quantity (Kg)	31.2	0	47.4	16.74	3.53	20.27	95.37	0.54	100

4.3 Testing of Fresh State Concrete

4.3.1 Workability

4.3.1.1 Workability of Concrete by Slump Test

Workability of the different mixes of the fresh state LCA concrete was measured by slump testing. The slump test is sensitive to the consistency of fresh concrete. All slump tests conducted yielded true slump, i.e. the concrete remained substantially intact and symmetrical. Figure 4.14 shows Slump test for LCA fresh concrete while Figure 4.15 shows fresh concrete in moulds being vibrated.

Figure 4.14:Slump test for 100% LCA fresh concrete

Figure 4.15: Vibrating of fresh Concrete in moulds

Since each LCA concrete mix had their batch mixing corrected for water cement ratio due to the increase in the porosity with increase in the amount of LCA introduced into the mix. This was done in order to prevent the slump from decreasing with the increase in the amount of LCA introduced into the mix, as recommended by Gowda et al (2018), Asiedu et al (2017) and Muthusamy and Kamaruzaman (2012) for the control of workability of concrete mixes with lateritic aggregates. In this study, the target values for slump were between 30mm and 60 mm. The results on workability by slump and compaction values in interactively presented in on a combined bar-chart and line graph shown in Figure 4.16 . All slump values recorded in this study, were well within range.

4.3.1.2 Workability by Compaction factor

The workability by compaction of LCA concrete was computed for each mix from the data collected in the laboratory. The compaction factors of the concrete ranged from, 0.83 to 0.85. According to Pranay et al (2020), this level of compaction entails that the workability of the concrete can be classified as ‘stiff to plastic’ or otherwise concrete of ‘low to medium’ workability. The results on workability by compaction factor are presented in the bar-chart shown in Figure 4.17.

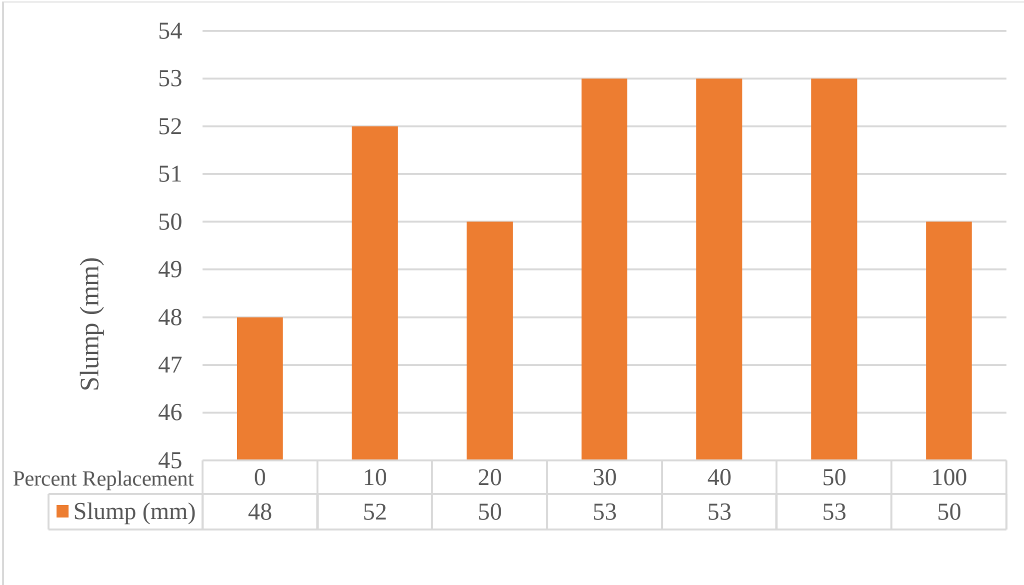


Figure 4.16: Workability by Slump of LCA concrete mixes

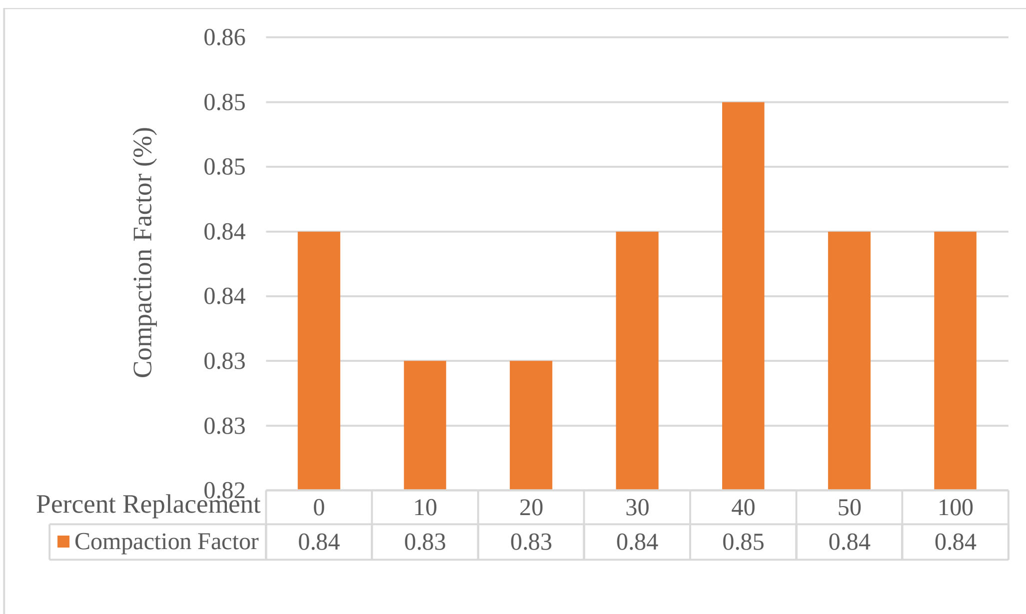


Figure 4.17:Workability by Compaction factor of LCA concrete mixes

4.4 Hardened State Properties of Concrete

4.4.1 Physical Appearance of LCA Concrete

Figure 4.18 to Figure 4.24 compiled in Table 4.10 show the physical appearance of the LCA concrete cores that were cut out from the 150mm cube specimens.

Table 4.10:Physical Appearance of LCA Concrete

 *Figure 4.18: 0% LCA*	 *Figure 4.19:10% LCA*	 *Figure 4.20: 20% LCA*
 *Figure 4.21: 30% LCA*	 *Figure 4.22: 40% LCA*	 *Figure 4.23: 50% LCA*
 *Figure 4.24: 100 % LCA*		

The general observation was a changing matrix of the concrete structure, with increased substitution. As more LCA was introduced in to the mix, the concrete showed more laterite aggregate features and the mix got better aesthetic appearance which could be utilized for architectural purposes. One important observation is that the paste of the concrete remained gray to white in color, with negligible or no lateritic soil colour shades present in its matrix. This shows that the LCA was properly screened and treated prior to introduction into the concrete, and this limited the contamination and alteration of the fine aggregates by the Lateritic Soils normally associated with Lateritic rocks and stones in their natural state.

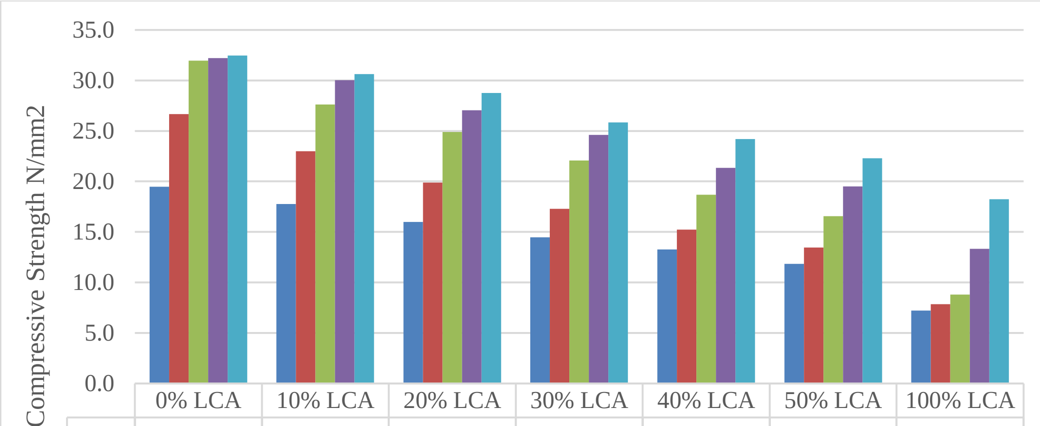
4.4.2 Compressive Strength

Figure 4.25 and Figure 4.26 show compressive testing of cubes in the laboratory.

Figure 4.25: Compressive Strength Testing

Figure 4.26:Failure mode for the 100% LCA Cubes at 7 Days

Figure 4.27 depicts the variation of compressive strength of LCA concrete with age, at various percentage replacements of GCA. As expected, the compressive strength of the concrete increased with increasing age. However, there was a decrease in compressive strength with increasing replacement, at a given age.



	0% LCA	10% LCA	20% LCA	30% LCA	40% LCA	50% LCA	100% LCA
7	19.5	17.8	16.0	14.5	13.3	11.9	7.2
14	26.7	23.0	19.9	17.3	15.2	13.5	7.8
28	31.9	27.6	24.9	22.1	18.7	16.6	8.8
50	32.2	30.0	27.0	24.6	21.3	19.5	13.3
100	32.5	30.6	28.7	25.8	24.2	22.3	18.3

Figure 4.27: Compressive strength of LCA Concrete at ages 7,14,28,50 and 100 days

Another observation from Figure 4.27 is that the control concrete attained the largest compressive strength as compared to the LCA concrete mixtures. This is similar to the findings by Raju & Ramakrishnan (1972) who reported that the compressive strength of laterite aggregate concrete was considerably lower than that of gravel or crushed granite aggregate concrete.

Generally, the rate of gain in the compressive strength is high from day 7 to day 14 and this was more pronounced in the control concrete specimes. The rate of increase in the compressive strength however, showed a reducing trend with an increase in the percentage of replacement of LCA for GCA. This can be seen in Figure 4.28 to Figure 4.34, showing the rate of gain in compressive strength of all mixes. The control gained 21.6% of strength from day 7 to 14 and 16.3% from day 14 to 28. 10% LCA gains 17.1% from day 7 to 14 and 15.1% from day 14 to 28. On the other hand, after gaining 53.2% of the strength in the first 7 days of curing, 50% LCA only gained 7.2% from day 7 to 14 and 13.9% from day 14 to 28. The trend on the 50% LCA is also seen on the 100% LCA, as they both show an increase in the strength gain after 28 days of curing.

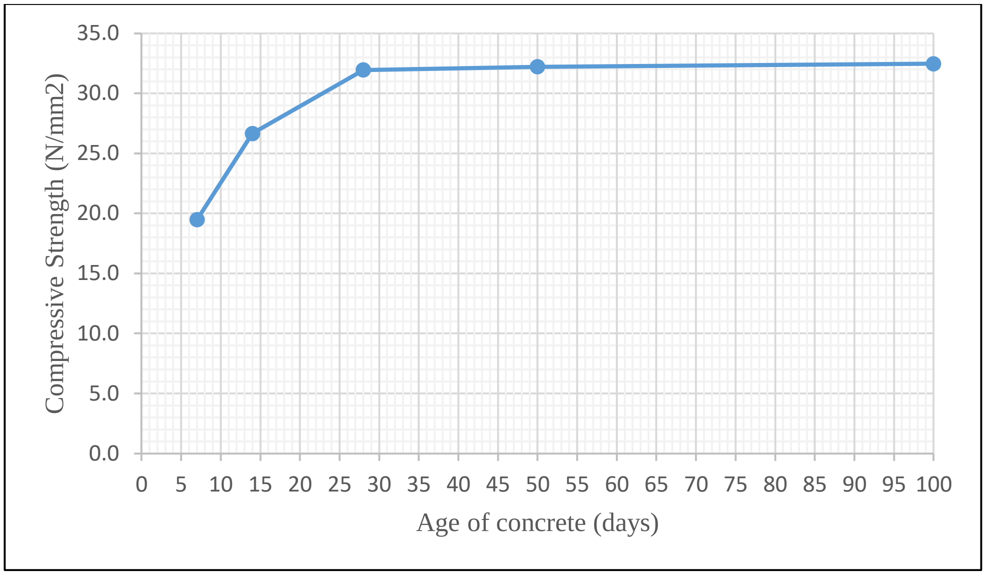


Figure 4.28: Rate of gain in Compressive Strength - control concrete

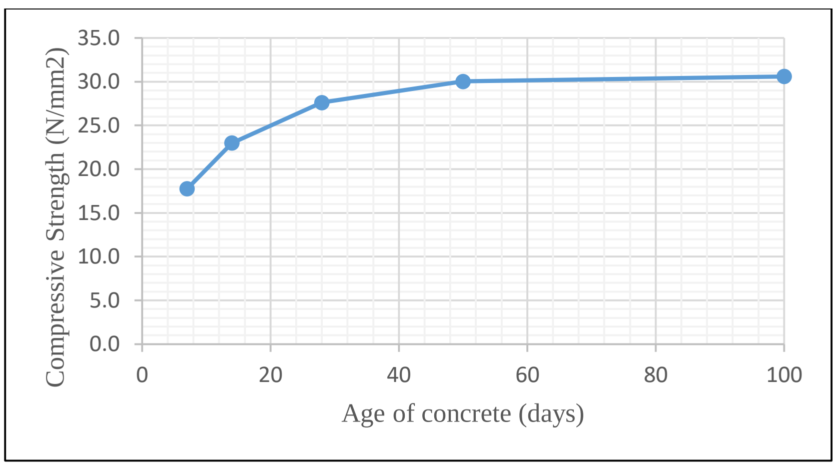


Figure 4.29: Rate of gain in Compressive Strength - 10% LCA concrete

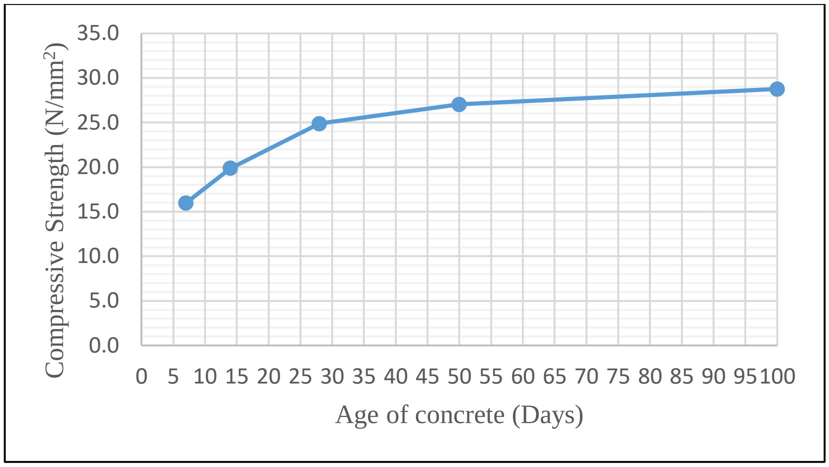


Figure 4.30:Rate of gain in Compressive Strength - 20% LCA concrete

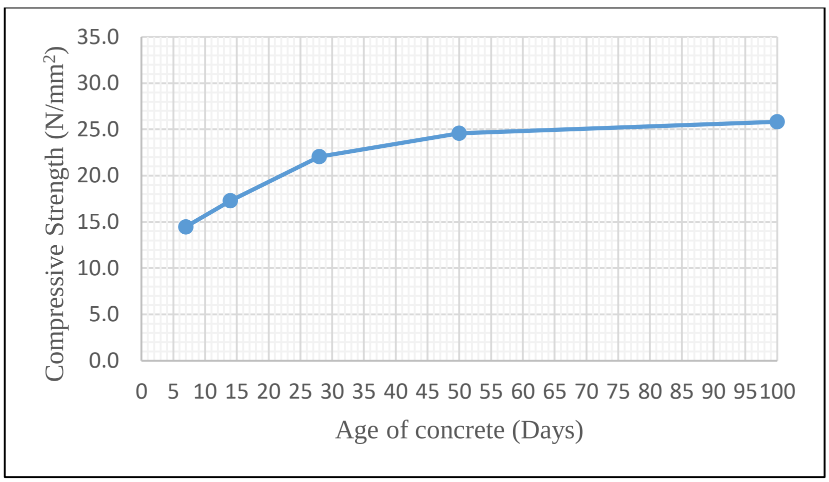


Figure 4.31: Rate of gain in Compressive Strength - 30% LCA concrete

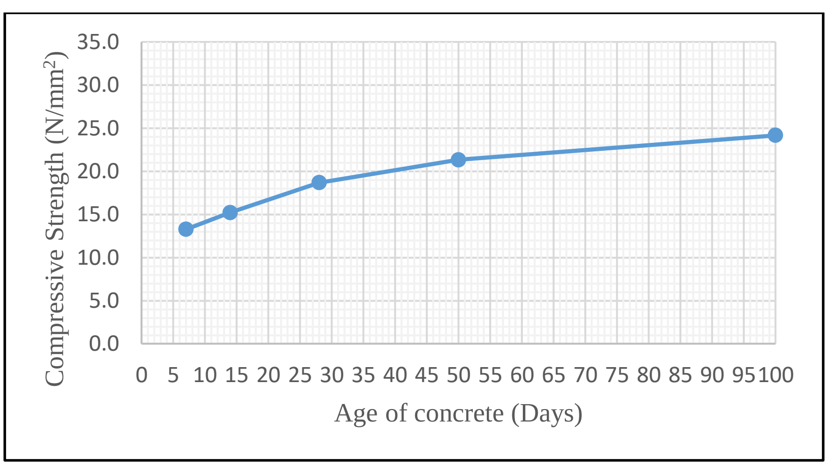


Figure 4.32 : Rate of gain in Compressive Strength - 40% LCA concrete

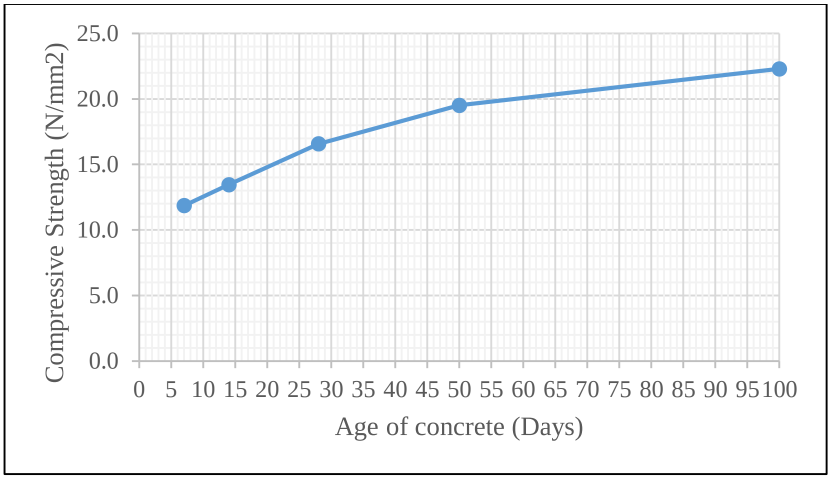


Figure 4.33: Rate of gain in Compressive Strength of 50% LCA concrete

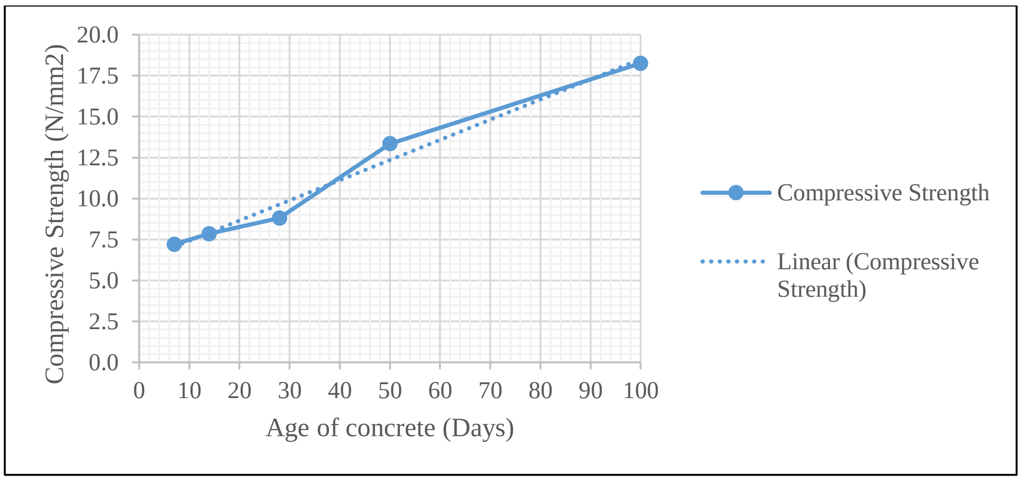


Figure 4.34:Rate of gain in Compressive Strength of 100% LCA concrete

The results of the compressive strength in this study showed that 20% LCA concrete had a compressive strength comparable to those found by Marewangeng et al. (2019), Jaseem et al. and Afolayan et al. (2019) who found 28 day compressive strengths to be 27.78 MPa, 27.02 MPa at 20% Lateritic aggregates and 27.5 MPa at 10% lateritic coarse aggregates. These values resonate with what was found in this study as 10% LCA attained a 27.6 MPa compressive strength after 28 days of curing. Additionally, 20% LCA attained similar if not higher compressive strength of 28.0 MPa but only after 50 days of curing.

Figure 4.35 shows the relationship between the compressive strength and the percent replacement of LCA for GCA. From the graphs it is clear that the compressive strength for each mix increases with curing age. Also it is clear that the compressive strength decreases with the LCA percentage in the mix. The control concrete attained the target compressive strength at 28 days of curing. However, there was only a minimal increase of 0.3MPa and 0.6MPa, that was noticed in compressive strength at 50 and 100 days of curing; respectively. This is however different in the case of the other concrete mixtures. The observation is that concrete with LCA had significant increase in strength from 28days to 50 days to 100 days. This finding agrees with the conclusion drawn by Afolayan et al (2015) stating that; both lateritic aggregate (content) and curing age (days) has significant effects of the compressive strength of concrete. In other words, concrete with LCA attained its strength at a lower rate compared with the granite based control concrete. The observed trend in this study was that; as the percentage of replacement of LCA for GCA was being incremented, LCA exhibited slower gain in compressive strength at 7 days and 14 days of curing than that of the control concrete sample of the same age. This entailed that, there was a drop in the rate of strength gain that was observed as more LCA was introduced into the mix. Further, the observation was that; concretes containing higher percentages of LCA needed more curing days to attain higher strength. For instance, concrete containing 30% of LCA needed 50 days of curing to attain a compressive strength of 24.6 MPa and 100 days to attain 25.8 MPa.

From the XRD test results, the crushed LCA sample contained Crystalline iron oxide mineral known as Goethite (FeO(OH)) and abundant amorphous (non-crystalline) iron oxide minerals such as ferrihydrite ($Fe_2O_3•H_2O$) which gave the XRD pattern a thick background profile. The sample contained a Clay mineral known as Kaolinite (Al_2O_3 $2SiO_2·2H_2O$). This type of clay is generally a low expansive clay. It should be noted that kaolinite can be transformed to a highly amorphous Metakaolin (MK), Al2Si2O7 by calcination or dehydration. Metakaolin is commonly used as a Supplementary Cementitious Material (SCM) due to its pozzolanic properties (Hamdy et al, 2015).

The presence of kaolinite clay minerals influenced the conventional properties of cement; thereby reducing the rate of strength gain of concrete during hydration. The observation as regards the reduction of concrete strength by kaolin clay was also reported by Abdullah et. Al (2018). Further, Baris et al (2004) recorded that when pozzolanic cement concretes have sufficient initial curing, they can reach the strength of OPC concretes in reasonable periods of time. This therefore suggestively explains the delay in the gain of strength. However, in this study, the test on compressive strength were carried out only up to 100 days, and the more advanced percentages of replacement never reached the target strength. Again, from the obtained graphs in Figure 4.28 to Figure 4.34, it is clear that the concrete containing 100% LCA had the slowest rate of hydration in the first 28 days of curing as at 28days; it only gained up to 43% of its strength at 100 days (18.3MPa) as compared to 0% and 50% LCA which gained up to 98.4% and 78.4% respectively. However, for replacement percentages less than or equal to 30% LCA, the concrete showed inferior late strength gain trends nonetheless similar to the control concrete. This is in line with the findings by Akpokodje and Hudec, (1992), who reported that the results of their study indicated that concrete made with concretionary laterite gravels possess compressive strengths that are comparable with concrete produced with granitic crushed rock aggregates.

4.4.1 Determination of Optimal Percentage of Replacement

Figure 4.35 also shows derived equations that relate the compressive strength to the percentage of replacement of LCA for GCA, at a particular curing ages. By considering the minimum compressive strength of 25 MPa as required for structural concrete in different codes of practice, an optimum percentage of replacement can be derived. Using the 28-day graph and its predicted equation, it was found that a percentage replacement of LCA for GCA of about 19.2% produces a concrete with the 25 MPa. Compareably, in a study by Afolayan et al. (2019) and another by Karthik and Acharya (2021), a replacement of 20% cured at 28 days produced a strength just above the 25 MPa target. Muthusamy and Kamaruzaman (2012) in their study found that addition of 10% replacement laterite aggregate was able to produce a concrete with comparable strength to plain concrete

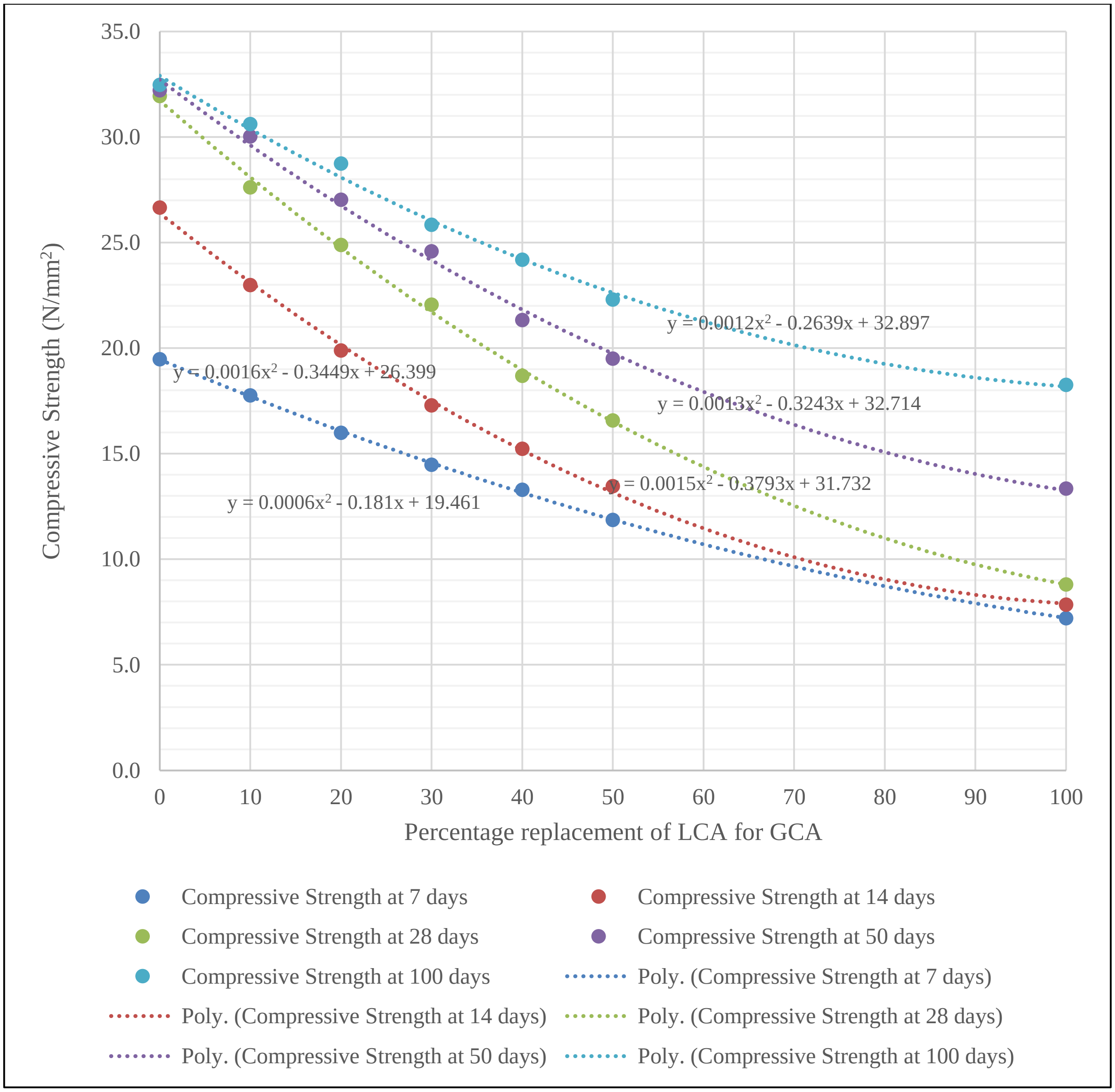


Figure 4.35:Relationship between compressive strength and percent replacement of LCA for GCA and age of concrete

Additionally, their study found that the targeted strength of 30MPa could still be achieved with addition of 30% replacement laterite aggregate. Furthermore, this study showed that replacement of 27% LCA for GCA produces LCA concrete with a compressive of 25 MPa at 50 days (Calculated using the trend line equation for concrete strength at 50 day shown in the graph in Figure 4.35) and also of 30% replacement of LCA for GCA can give a concrete with compressive strength of 25.8MPa at 100 days.

4.4.2 Split Tensile Strength

Figure 4.36 shows split tensile testing of a cylindrical LCA concrete specimen.

Figure 4.36: Split testing of a cylindrical specimen

Table 4.11 shows the average values of split tensile strength of LCA concrete at 28 days while Figure 4.37 shows the relationship Between Percentage Replacement of LCA for GCA against Split Tensile Strength at 28 Days. The control concrete exhibits the greatest split tensile strength and the rest of the LCA concrete have a tensile strength that reduces as the percentage of replacement of LCA for GCA increases. A study by Karthik and Acharya (2021), found a similar pattern in the split tensile strength with values ranging from 3.20 MPa for the control and 2.19 MPa for 25% replacement while Renuka et al. (2018) found values ranging from 3.26 to 3.53 MPa.

The graph in Figure 4.38 shows the relationship between percentage replacement and the tensile-to-compressive strength ratio, it can be seen that this ratio resides around 10 – 12%. According to the studies by Karthik and Acharya cited above, this ratio was mostly between 7 and 8% whereas in the study by Renuka et al., it was around 10% in most concrete mixtures made with different percent replacements of Lateritic aggregates for GCA.

Table 4.11: Average Tensile Strength of LCA concrete at 28 days

Percent replacement	**Average Tensile Strength**
0	2.9
10	2.4
20	1.9
30	1.6
40	1.5
50	1.3
100	0.8

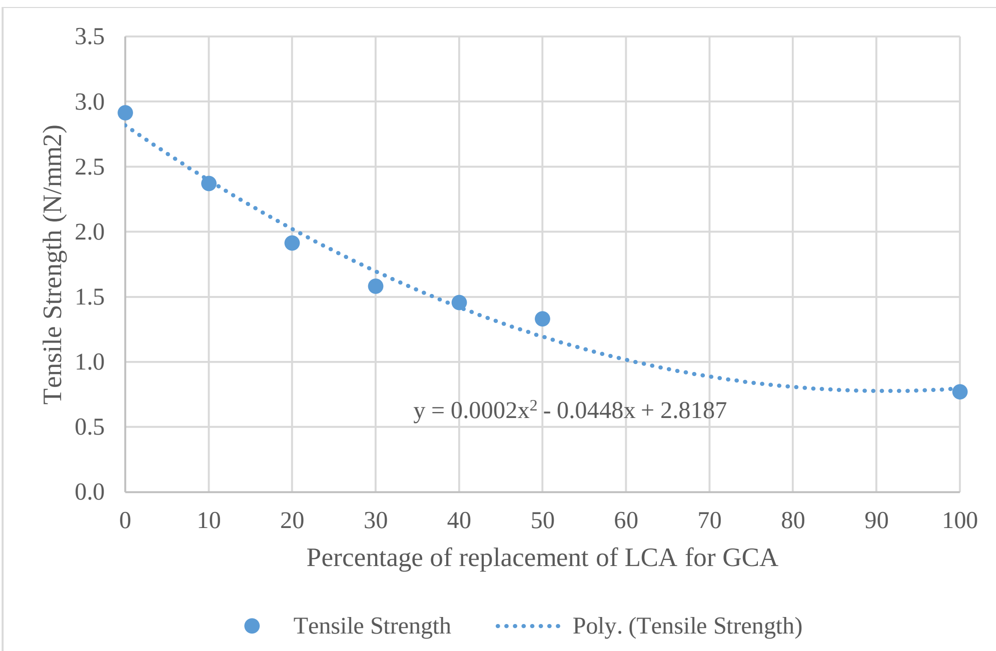


Figure 4.37: Relationship between Percentage Replacement of LCA for GCA against Split Tensile Strength at 28 Days

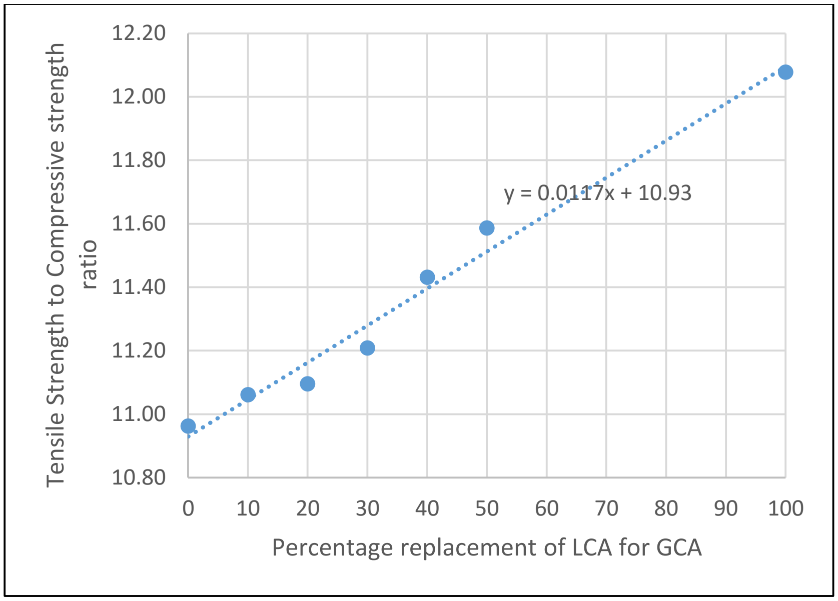


Figure 4.38:Relationship between the percent replacement of LCA for GCA against Tensile Strength to Compressive strength ratio at 28 days

4.4.3 Residual compressive strength after exposure to high temperature

Figure 4.39 shows concrete cubes in an electric furnace after exposure to elevated temperature while Figure 4.40 shows Compressive Strength Testing of cube specimens after exposure to high temperature.

Figure 4.39: Concrete Cubes in electric furnace after exposure to elevated temperature

Figure 4.40 : Compressive Strength Testing of cube specimens after exposure to high temperature

Figure 4.41 shows the results of the residual compressive strength testing after the concrete exposed to high temperatures of 450°C for 1.5 hours. The general finding was that both plain concrete and LCA concrete lost compressive strength upon exposure to elevated temperature stated above. The trend in the compressive strength loss showed an increase in the percentage of strength loss with the increasing amount of LCA composition in the concrete. Control concrete specimen lost 21.3% of the compressive strength. This is in line with the report by Li and Bu (2011) which states that beyond 300°C, the mechanical and physical properties of the tested concretes decreased quickly. On the other hand, 100% LCA concrete specimen showed a loss of 24% of the compressive strength whilst 50% LCA concrete lost 29.9% of its compressive strength. With the losses for the 10%, 20%, 30% and 40% LCA concrete specimens being well in between range of loss between, 22.0 and 29.9% (i.e. a range of 6.8% of lost compressive strength). Conversely, the loss in compressive strength of the specimens with 50% and 100% LCA suggests that more advanced mixes of LCA concrete are likely to have better high temperature, heat and fire resistance. From this result, it can be deduced that, concrete specimens with more than 50% LCA are more likely to undergo less loss in strength than those from the higher spectrum. This can partially be associated with the increasing refractory property of lateritic materials and silicon in the LCA. Further, the results showed that LCA concrete with less than 30% LCA composition has similar strength loss attributes to that of plain concrete as regards fire and high temperature exposure. Concrete with 30% LCA had a residual strength of 14.2 MPa as compared to 25.1 for 0% LCA. 100% LCA mix had a residual compressive strength of only 7.1 MPa.

These findings correspond well with the findings reported by Muthusamy et al. (2016) who studied the influence of elevated temperatures on compressive strength of concrete containing laterite (comparable to 10% LCA in this study).

Further, in relation with Table 3.1 of the EN 1992-1-2:2004; both GCA and LCA coarse aggregates used in this study, are categorized as Siliceous aggregates by nature. The control specimen after exposure to an elevated temperature of 450^{o}C retained 78.7% of its strength, against an interpolated value of 67.5% from Table 3.1 of the EN 1992-1-2:2004. Similarly, 20% LCA concrete retained 74.9% while 30% and 40% LCA concrete retained 72.6 and 71.5% respectively, all against the same interpolated value of 67.5%.

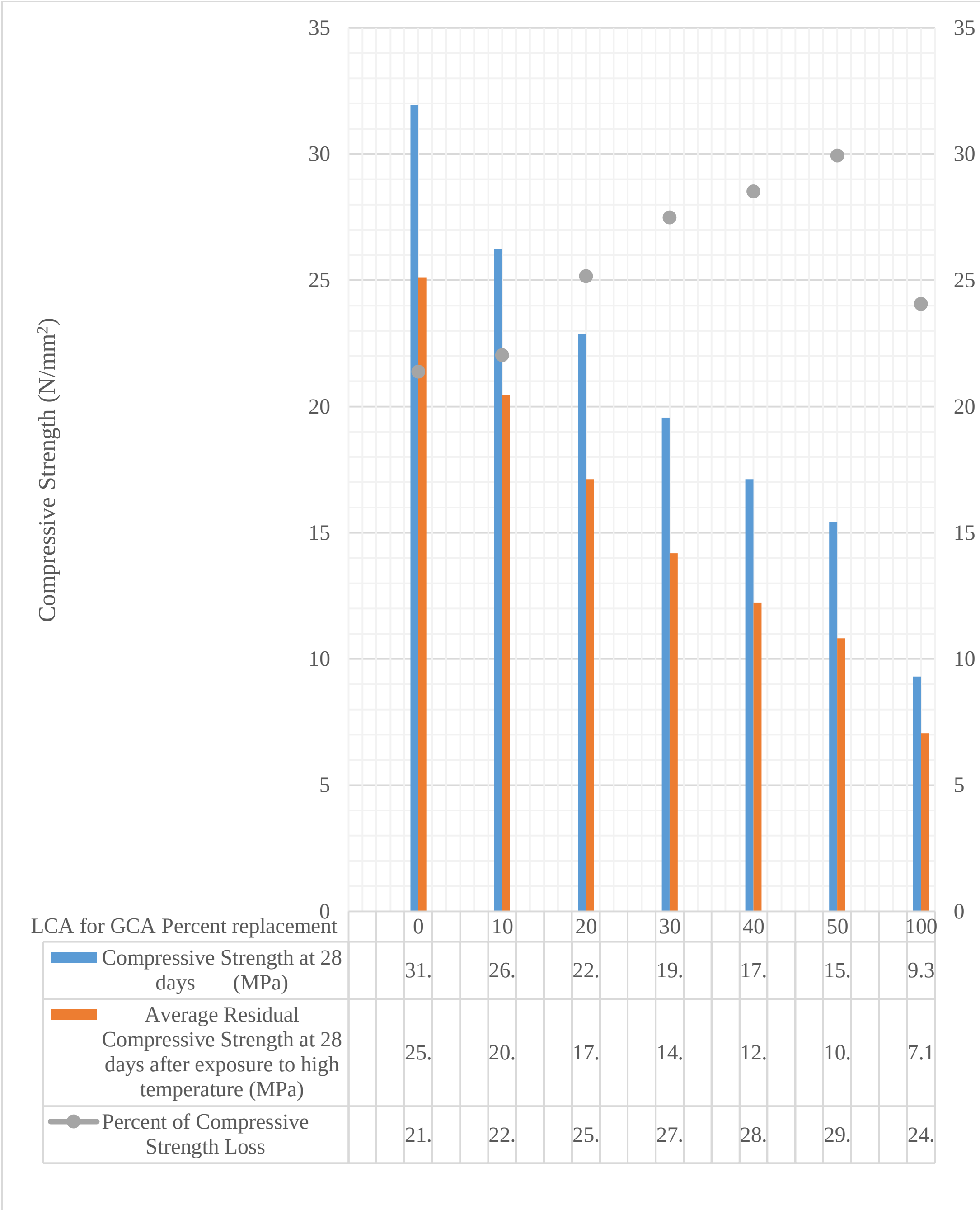


Figure 4.41: Comparison of Compressive strength of LCA Concrete at 28 days and residual strength after exposure to High temperature of 450°C for 1.5 Hours

4.4.4 Mass Loss in LCA after to exposure to high temperature

In this study, there was a noticeable reduction in the mass loss in all the concrete mixes including the control concrete. Figure 4.42 shows that the more the LCA content in the concrete, the higher the mass loss. Arioz (2007) deduced that lower bond strength (cement-aggregate bond) in laterite concrete causes it to face larger strength reduction than plain concrete leading to higher mass loss. In this study, it was observed that mass loss ranges from 5% for control concrete all the way up to 8.7% for 100% LCA Concrete. 10% LCA concrete specimen lost 5.8% of the weight upon being exposed to high temperature. This loss is comparable with the approximately 4.8 % loss recorded by Muthusamy et al. (2016) for 10% replacement of Lateritic coarse aggregate for granite coarse aggregate in a 30MPa concrete. According to Venkatesh (2014) free water disappears when the concrete is heated up and the chemically bound water begins to be released. This happens at temperatures beyond 100°C, as it was the case in this study. Further, it was clear that at least the loss in weight for the mixes with LCA below 50% were well within only 1.5% range, a finding which is similar to one recorded by Muthusamy et al. (2016) that both PC and LC undergoes drops in the mass value almost comparable until 500°C. Beyond 500°C, LC exhibited significant mass loss as compared to PC. From Figure 4.42 which illustrates residual density of LCA Concrete, there was not much of a difference in the percentage of mass loss at the temperature studied.

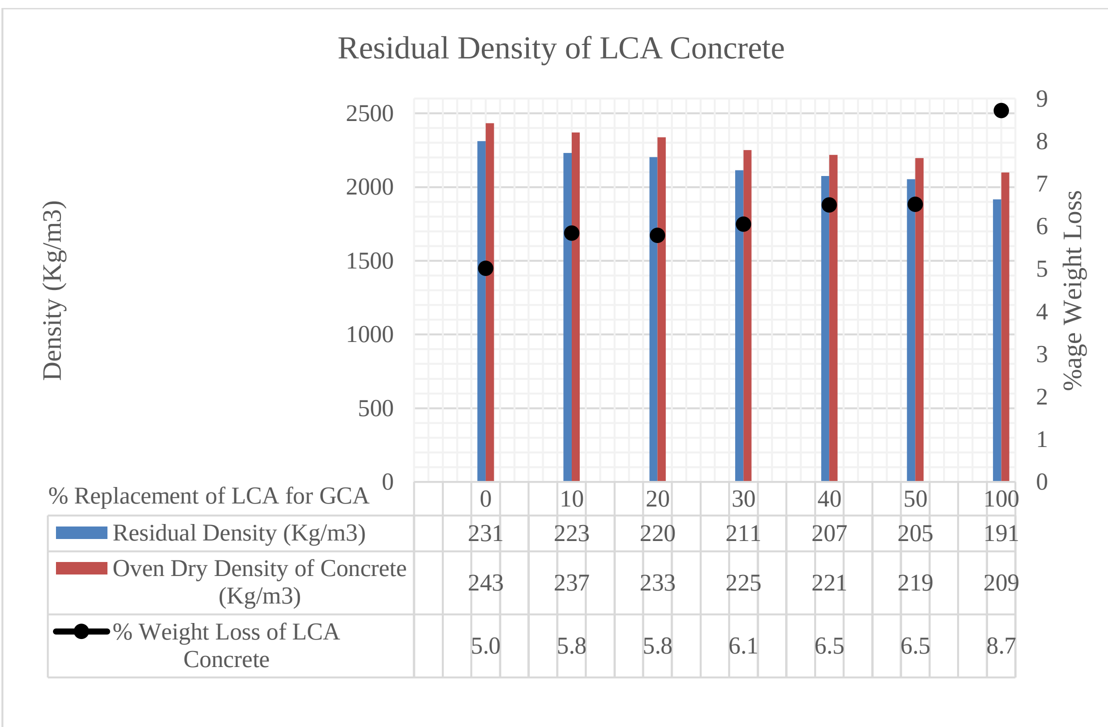


Figure 4.42:Residual Density of LCA Concrete

4.4.5 Surface appearance of specimens exposed to high temperature

From the 40% and 50% LCA concrete specimens, surface spalling, pitting and discoloration, were observed, whereby there was ejection of large pieces of concrete from the surface of a cubes. According to Lateet et al. (2019), this could be due to high pore pressures caused by the production of steam within the concrete. This corresponds with the finding in this study about the increased porosity in 40% and 50% LCA, which pores are likely to bear more moisture. Samples for 10% LCA 20% showed some minor cracking whilst 20% and 30% LCA only showed signs of minor pitting on the surface. The cracking could have been due to the GCA expanding more after being exposed to high temperature. Minor pitting, discoloration, were observed on the surface of the 100% specimen. Figure 4.43 to Figure 4.45 illustrate the surface appearance of different mixes of LCA concrete after exposure to high temperature of 450^{o}C .

Figure 4.43: Appearance of 0%LCA specimen after exposure to high temperature

Figure 4.44: Cracks and minor pitting on 10% LCA concrete specimen after exposure to 450^{o}C for 1.5 Hours

Figure 4.45: Example of Spalling and pitting on the 40% Specimen

4.4.6 Durability Testing of LCA Concrete

In this study, durability properties of LCA concrete were investigated by indirect methods. These included; dry bulk density, saturated density, porosity, and absorption rate (sorptivity).

4.4.6.1 Dry Bulk Density and Saturated Density of LCA Concrete

The dry densities of the all concrete LCA mixes used in this study were investigated in the laboratory and calculated. The dry density values were plotted against the percentage replacement of LCA for GCA. Figure 4.46 shows a parabolic reduction of dry Density of LCA Concrete Specimens with increasing percentage replacement of GCA by LCA .

From the data collected, the LCA mixes with 50% LCA or less had a dry density of more than 21.60 kN/m^3 and can thereby be categorized as normal weight concrete as per EN 206:2013. The Control specimen recorded the highest dry density of 23.87 kN/m^3. By considering the equation of the trend line, all mixes with more than 50% are thereby deemed to have a density lower than 21.60 kN/m^3 and can be classified as lightweight concrete. 100% LCA specimen gave the minimum density of 20.59 kN/m^3. This is comparable to the finding by Ephraim et al (2019) who reported that laterite rock concrete (i.e. 100% Laterite rock aggregate) gave average density ranging between 2200 kg/m^3 (21.58 kN/m^3) and 2300 kg/m^3 (22.56 kN/m^3) and therefore fall within the classification of a dense concrete.

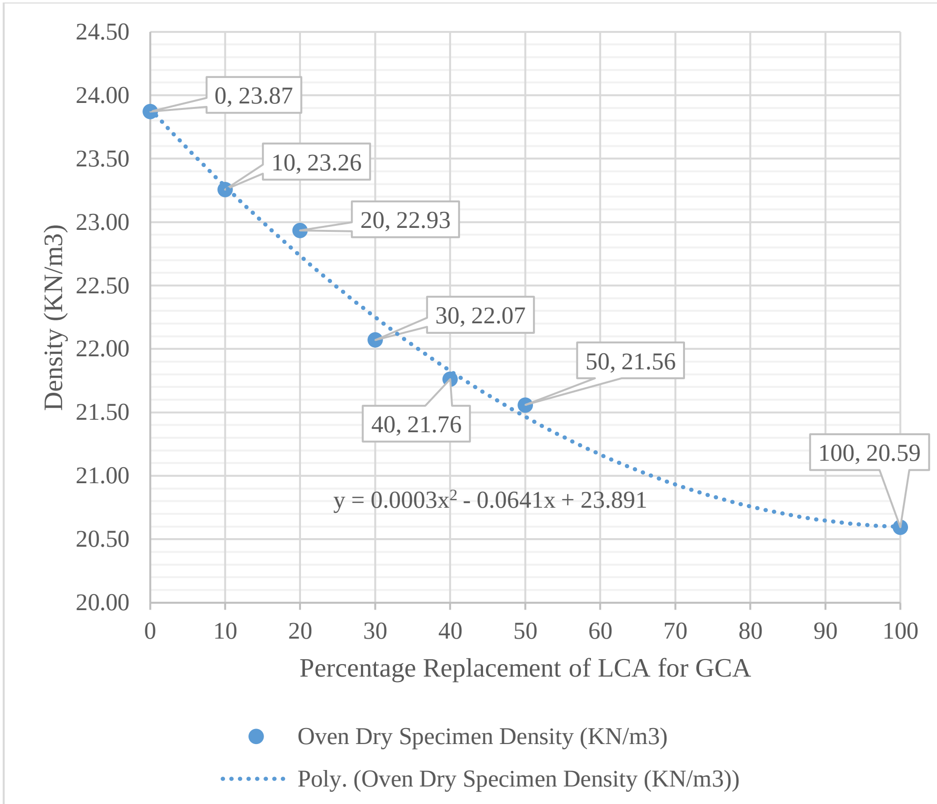


Figure 4.46:Dry Density of LCA Concrete

Figure 4.47 shows a linear variation of water saturated LCA Concrete specimen density with percentage replacement of GCA by LCA.

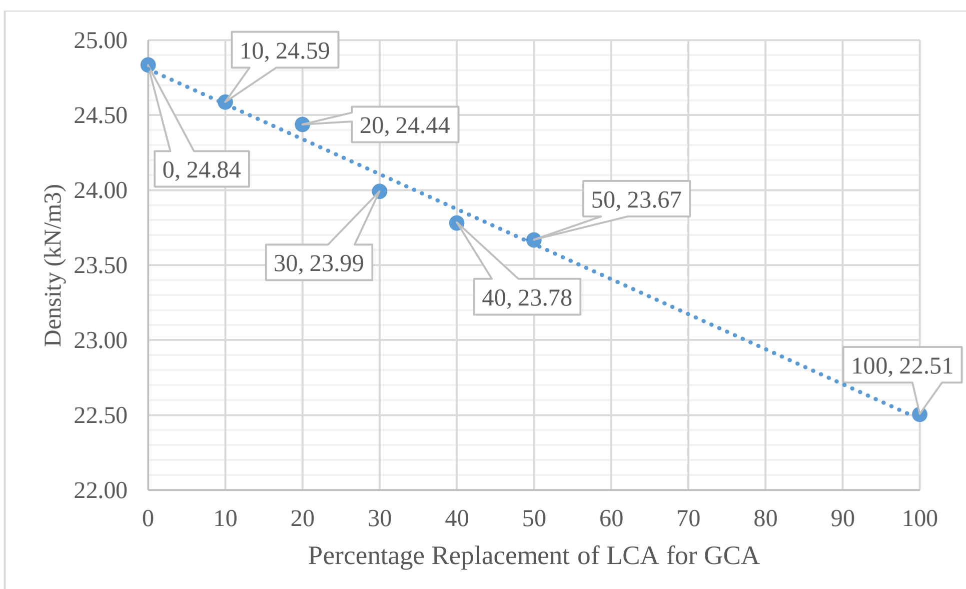


Figure 4.47: Water Saturated LCA Concrete Specimen Density

4.4.6.2 Porosity of LCA Concrete

Figure 4.48 shows a parabolic variation of water accessible Porosity with increasing replacement of GCA with LCA in concrete.

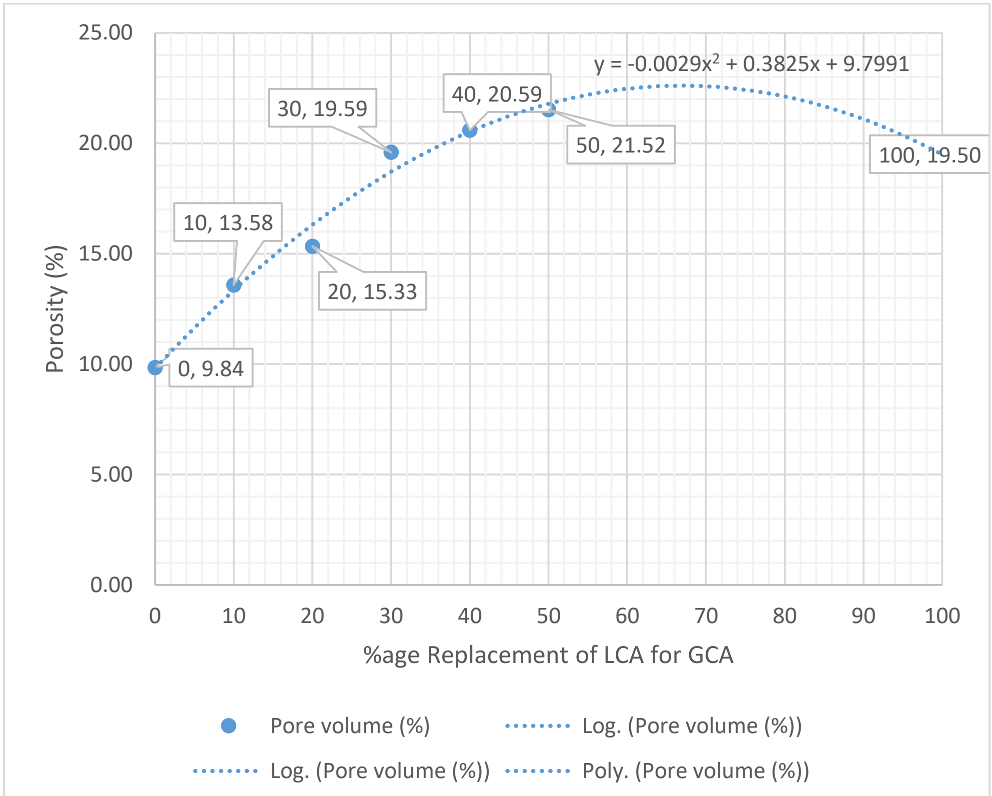


Figure 4.48: LCA Concrete accessible Porosity

The results show that the porosity generally increases from 9.84% with 0% LCA replacement to a projected maximum porosity value of 22.41% with a percentage LCA replacement of 65.95%, after which the porosity starts to decreases to a value of 19.5% at 100% LCA replacement of GCA. Kumar et al. (2003 reported an apparent porosity value 9.67% for 39.3MPa concrete at 84 days of curing of plain concrete, and this value resonates with the porosity for control concrete from this study. The increase in porosity can be attributed to the higher absorption rate of the LCA used in this study, and similar the reduced densities of the achieved concrete.

4.4.6.3 Sorptivity of LCA Concrete at 100 Days

Figure 4.49 shows the Coring through concrete cubes to obtain specimens for absorption and sorptivity of concrete.

Figure 4.49: Coring through concrete cubes to obtain specimens for absorption and sorptivity tests of concrete

Figure 4.50 shows cores from the cube specimens, whilst Figure 4.51 shows oven dry LCA concrete and apparatus for sorptivity test.

Figure 4.50:Achieved cores from the cube specimens

Figure 4.51: Oven Dry LCA Concrete and apparatus for Sorptivity Test

4.4.6.3.1 Sorptivity Plot of LCA concrete

Figure 4.52 shows the sorptivity uptake plot for LCA and control concrete specimens. Sorptivity uptake was plotted as a precondition for calculation of sorptivity coefficients of concrete specimens; as required by the ASTM C 1585:2020. This process helps to capture only secondary absorption rate; which is the part of the sorptivity plot which does not show any systematic curvature. The systemic curvature is associated with the initial absorption rate, and cannot otherwise be used to calculate sorptivity coefficient. This study found secondary absorption sorptivity plots for LCA and control concrete specimens with a linear regression coefficient of above 0.98 as required by the ASTM C 1585:2020, and therefore the data was further used to compute the mean sorptivity coefficients of LCA concrete.

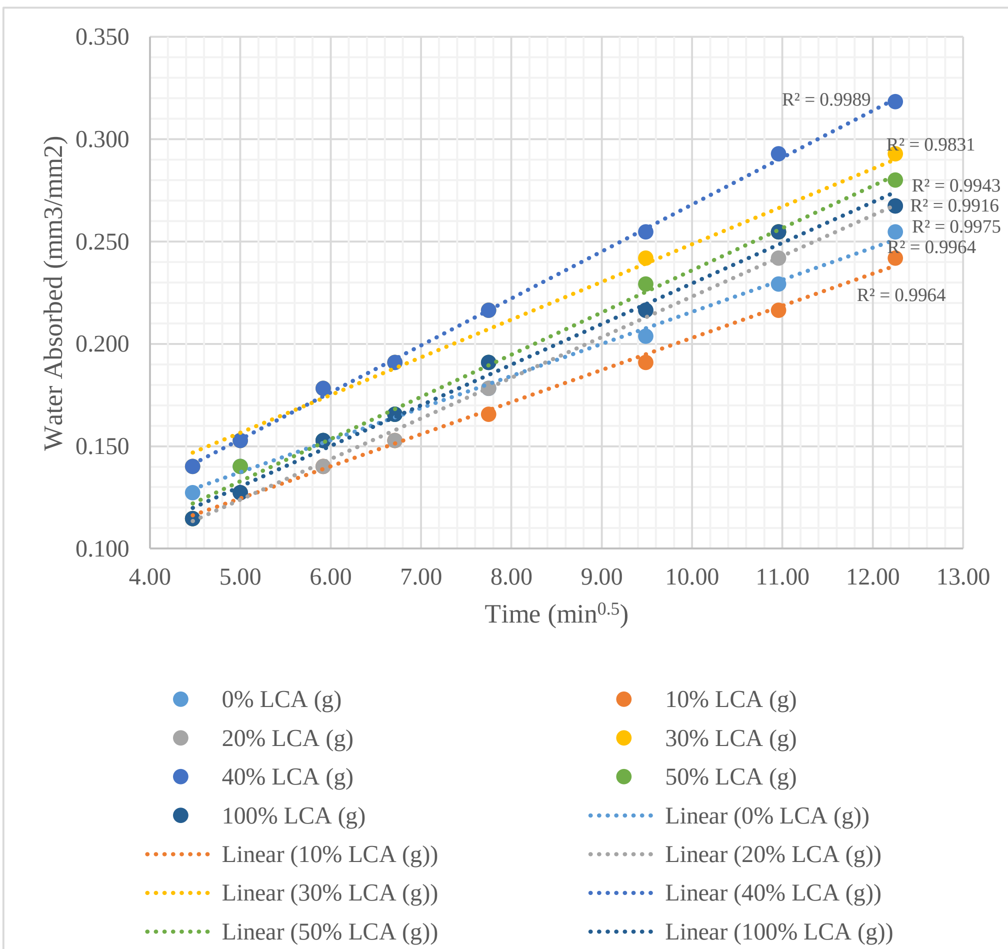


Figure 4.52 :Sorptivity uptake plot for LCA and control concrete specimens

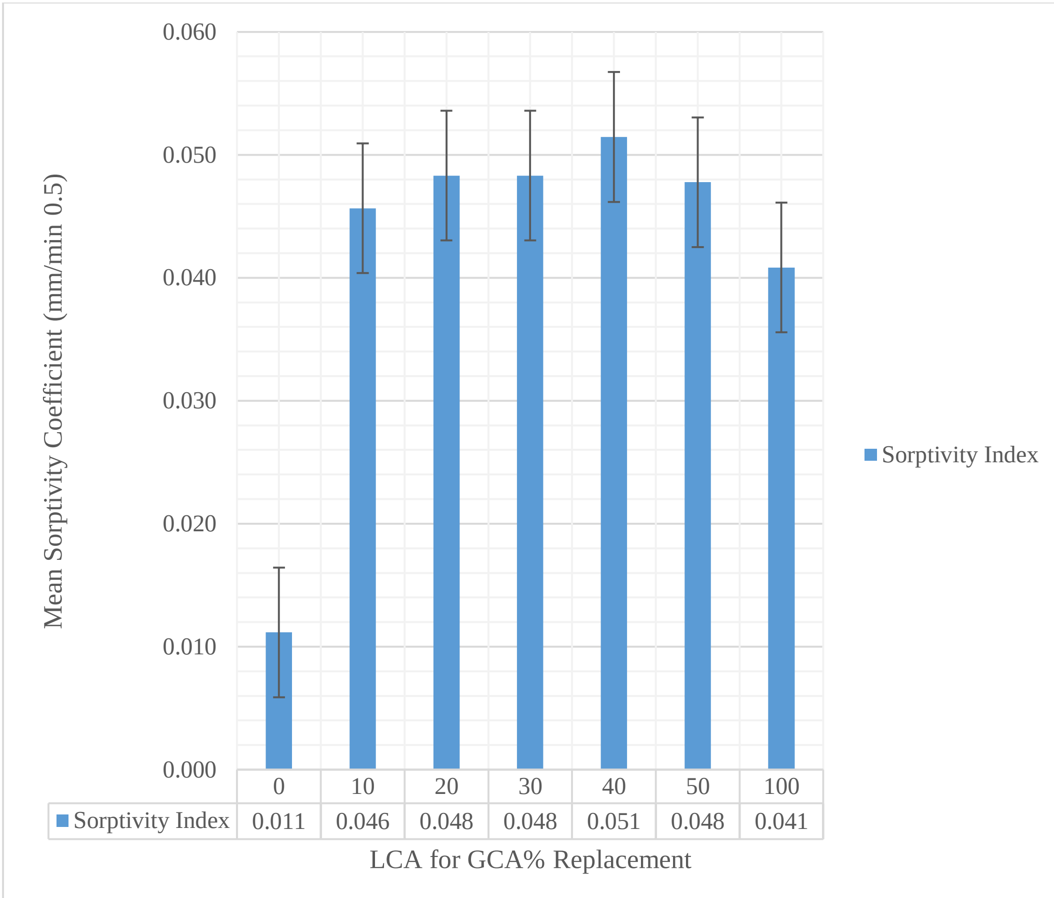


Figure 4.53: Sorptivity Coefficient of LCA after 100 days

Figure 4.53 shows the Sorptivity Coefficient of LCA concrete specimens after 100 days. The illustrated trend shows that LCA concrete exhibited more than 270% higher mean Sorptivity Coefficient than for the control 30MPa concrete, but nonetheless, showed to have acceptable mean sorptivity coefficient. All Sorptivity Coefficient values were well within the allowable limit of 0.21 $mm/min^{0.5}$ for concrete production, as the maximum value recorded was 0.051 $mm/min^{0.5}$ for the 40% LCA specimen.

This observation is consistent with the finding from a study carried out by Rajapriya et al (2021) on the Durability studies of fly-ash based laterized concrete. The study showed that, the test results of durability parameters such as water absorption, permeability, sorptivity, drying shrinkage, and rapid chloride penetration of laterized concrete mixes containing 50% replacement recline within the acceptable limits as per standards, confirm their intended performance throughout the specific structural service life.

The Sorptivity coefficient value of 0.011 mm/min$^{0.5}$ for the 30MPa control concrete was comparable to that found by Neil (2014), which had a value of 0.0154 mm/min$^{0.5}$ for concrete at 56 days, using similar treatment and preparation including oven drying at 50^{o}C for 7 days, and the same methods used in this study. Muthusamy et al (2015) found that concrete with low water absorption can be produced through the integration of 50% of laterite aggregates. This result corresponds and resonates to the findings in this study, moreover 50% LCA concrete showed the highest sorptivity coefficient. However, from this study, all the specimens containing varying amounts of LCA showed acceptable properties towards the ingress of harmful chemicals via water uptake. Nonetheless, Muthusamy et al (2015) did not study 100% replacement of Lateritic aggregates for granite aggregates, and thus their partial conclusion was only up to 50%.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Overview

This study focused on evaluating LCA as a partial replacement for GCA in structural concrete. It assessed if LCA concrete properties could be acceptable for the design of concrete structural members. These properties included but were not limited to: Compressive strength, tensile strength, density and porosity, durability, Modulus of Elasticity, shrinkage of concrete, creep and coefficient of thermal expansion. Thus, the study concentrated on evaluating the first five of the listed properties as they are the most demanded as design inputs by various concrete design codes and these are often used to empirically deduce values for the remaining four properties on the list above. According to Bamforth et al (2008), it is important that the design strength of a structure, which is determined from either durability, fire design or structural design requirements, is established at the preliminary design stage.

5.2 Conclusions

From the results obtained under this study, the following conclusions have been made:

- The first specific objective was to determine the fresh and hardened state physical properties of LCA concrete. All mixes produced slump values between 30cm and 60cm with compaction factors between 0.78 and 0.88. Further, regarding the compressive and tensile strength of concrete; on average, for every 10% increment in LCA, the drops in compressive strength were 8.6%, 8.2% and 6.4%, respectively, at ages 28, 50 and 100 days, for mixes up to 50% replacement. Lastly, LCA Concrete mixes with 50% LCA or less exhibited densities of more than 21.60 kN/m^3 and can therefore be categorized as normal weight concretes.
- The second specific objective was to evaluate the residual strength and weight loss of LCA Concrete after exposure to high temperature. The loss in compressive strength of LCA concrete with LCA replacement ranged from 10% to 40% LCA concrete specimens ranged between 22.0% and 29.9%, compared

to 21.3% for the control mix. The loss in weight for the mixes with LCA replacement below 50% were well within 1.5% range.

- The third specific object was to establish absorption rate (sorptivity) of LCA concrete. The study showed that LCA Concrete had higher but acceptable Sorptivity Coefficient values than plain concrete. With 10% to 40% range of replacement of LCA by GCA, the range of Sorptivity Coefficient was 0.046 to 0.051 mm/min $^{0.5}$ as opposed to the 0.011 mm/min $^{0.5}$ exhibited by the control concrete specimen. The Sorptivity Coefficient of LCA concrete increased with increased with GCA content in the mix; due to the higher absorption rate of the LCA
- The fourth specific objective was to determine optimal percentage replacements of LCA for GCA that may be applicable for structural concrete. The study showed that; for a 28day characteristic strength and 30MPa mix; the optimal replacement percentage was 19.2%. This replacement percentage can give LCA concrete with a compressive strength of 25MPa.

5.3 Limitations of the Study

The following investigations on LCA concrete were not conducted during this study due to non-availability and or limited capacity of specific laboratory equipment, tools and facilities:

- Flexural strength of beams
- Tests on Cement

5.4 Recommendations

According to this study, for 28 days curing period in portable water, 19.2% of LCA can be used as partial replacement by weight of GCA, in 30MPa concrete mix, to achieve a compressive strength of 25 MPa. The following are recommended:

- With the vast deposits of lateritic soils around the country, in regions devoid of either granite, limestone and basalt rocks for the manufacturing of conventional coarse aggregates, LCA can be used as partial replacement for GCA in structural concrete.

- Due to the anticipated variations in the mineralogical composition of Lateritic deposits from one region to another, due to environmental conditions, Geologists should conduct mineralogy testing of the available LCA on a larger scale, to establish suitability.
- Materials Engineers and Technicians should carry out further laboratory based trial mix designs, using the optimum percentages recommended in this research.
- Additional research should be conducted in the following areas:
    - Methods to reduce the water accessible porosity of LCA concrete
    - Methods to reduce the sorptivity of LCA concrete
    - Methods to reduce the curing period of LCA
    - Durability tests on the optimum percentage of replacement to investigate the performance of LCA concrete in acidic and Sulphate environments
    - Electrical resistivity of LCA Concrete

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