CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the Study

Foamed concrete is a lightweight material with self-compacting rheological properties. Conventionally, it is produced from a mixture of cement, fine aggregate (dredged sand) and mechanically entrained foam. Kearsley (1996) explained that the entrained foam is an inert material, so it does not react with any component of the concrete, but increases the volume of the mortar while reducing the density.

LightConcrete (2003) and Van (1991) described the process of making foamed concrete to include mixing of the fine aggregate, cement and water to form consistent cementious paste. In addition, foam is mechanically entrained into the cementious paste to create multitude of micro/macroscopic discrete air cells which are uniformly distributed throughout the mix. The foam has an approximate life span of 45minutes, thereafter it starts to degenerate to create air voids in the structure. At this time the cement paste is expected to have developed sufficient strength to maintain its shape around the air void.

According to Brady *et al.* (2001), there was confusion in the early literature between foamed concrete and similar materials such as aerated concrete and air-entrained concrete. They defined the difference between foamed concrete and these similar materials based on the volume of dispersed air pores and the method of entraining air into the mortar matrix. Thus, in aerated concrete the air pores are formed through chemical reaction between aluminium powder and some products (calcium hydroxide and other alkalis) released during cement hydration. Whilst air entrained concrete contains lower volume of entrained air compared with foamed concrete. Also, they reported that for most common usage, the air content of foamed concrete is typically between 40 and 80 per cent of the total volume of the concrete. And the entrained air bubbles vary in size from around 0.1 to 1.5 mm in diameter but coalescence might produce voids considerably larger than this, particularly at the top of pours. They concluded that the high volume of entrained air makes the rheological properties of foamed concrete such as yield stress and flow viscosity (measured with spread diameter and flow rate) important factors for determining its quality and predicting the structural properties at production stage.

Story-Beton Inc. (2008) stated that foamed concrete has diverse characteristics that differentiate it from the conventional normal-weight concrete. These characteristics are associated with its plastic and hardened states. Foamed concrete at plastic state is self-compacting, which means that its workability is generally excellent with flowing consistency: it is pourable, homogeneous and has small possibility of bleeding and segregation. So it requires no compaction, and will flow readily from a pump outlet to fill restricted and irregular cavities and could be pumped successfully over significant heights and distances. At hardened state, some of its unique properties are:

a) wide range of densities (300 – 1,600 kg/m^3)
b) low water absorption capacity
c) high fire resistant capacity
d) acoustic insulation property.

In developed countries such as United Kingdom, and Norway extensive studies which include: Dransfield (2000), Jones *et al*. (2005), Jones and McCarthy (2006) investigated and characterized available local materials for foamed concrete production, structural properties of foamed concrete and performance of structural elements made with it. Data obtained from those studies formed the bases of its industry application in trench reinstatement, stabilization of bridge abutment and tunnels, reduction of dead load in building and civil engineering structures.

Foamed concrete can be produced on site or in a factory (as precast elements). Generally, the process is the same either on site or in a factory, which involves mixing of the fine aggregate, cement and water in a clean concrete mixer till a consistent paste is achieved; and passing diluted foam concentrate through a foam generator to produce foam that is entrained into the mix. The amount of foam added determines the density; thus, foamed concrete with wide range of densities can be produced by adding various quantities of foam into the consistent paste. The quality of foamed concrete produced depends amongst others things on the quality of the foaming agents. Foaming agent is a liquid concentrate that is classified on the basis of the active ingredient which may be protein, surfactant or enzyme based. Nonetheless, the foam produced must be stable during mixing and placing of the foamed concrete regardless of its source.

Conventionally, river dredged sand is the fine aggregate used in foamed concrete production. However, according to Jones *et al*. (2005) and Pan *et al.* (2006) other fine aggregates including incinerator bottom ash, recycle glass, rubber tyres (crumbs), foundry sand China clay, ultra- granulated blast-furnace slag, pulverized fly ash, condensed silica fume could be used as partial replacement of dredged sand.

In developing countries including Nigeria, foamed concrete is a new construction material. The dearth of data on characterization of local materials for its production, structural properties and performance of structural elements made with it, are responsible for its non- application in construction. The construction industry in these countries is denied the technical and cost advantages foamed concrete offers in the construction of houses and civil engineering infrastructures.

The application of foamed concrete in developing countries would be made possible through research findings on its production with locally available materials. Research such as Osunade (2002), Ikponmwosa and Falade (2006), Ikponmwosa and Salau, (2010) on normal weight concrete have shown that laterite is a type of fine aggregate that is usually near to project sites and it is less expensive to procure in most countries including Nigeria. Also, they explained that it is suitable as partial replacement of dredged sand in normal weight concrete production, because it improves the particle size distribution of dredged sand. Nonetheless, they observed that laterite increases the surface area and the inter-particle bond of dredged sand. Consequently, it increases the amount of water required to achieve surface saturation and reduces the workability or flowing property of the concrete. These findings and the advantages foamed concrete offers in the construction industry in countries where it is utilised necessitated this study on the production of lightweight foamed concrete with laterite as partial replacement of dredged sand.

1.2 Statement of the Problem

The conventional method of foamed concrete production which involves addition of foam into a mixture of fine aggregate, cement, and water creates evenly distributed macro and micro air pores in the concrete structure was reported in Kearsley (1996). Macro air pores are defects, and when present in large volume reduce the structural properties (compressive strength, split tensile strength and modulus of rupture) of foamed concrete. Brady *et al*. (2001) found that one of the factors that contribute to the formation of macro pores is inter-particle voids in dredged sand.

In addition to the inherent problem with the conventional method of foamed concrete production, there is limited information on the structural properties of foamed concrete made with local materials and its performance in structural elements in Nigeria. Inevitably, this information is required to promote its application in the construction industry.

Interestingly, Jones *et al.* (2005) explained that foamed concrete could be produced with most fine aggregates in different parts of the world. But industry application is based on research findings on the structural properties of foamed concrete made with available local materials and structural capacities of elements produced with it.

According to Ikponmwosa and Falade, (2006) laterite is available and less expensive to procure in most countries including Nigeria. Also it was explained that it could be used to reduce fine aggregates inter-particle voids in normal weight concrete. Thus, there is a need to investigate the application of laterite as partial replacement of dredged sand foamed concrete to reduce macro pores with acceptable impact on the rheological properties; structural properties of foamed concrete with laterite and structural capacities of beam made with it.

1.3 Research Aim and Objectives

The aim of this study is to assess the impact of laterite as partial replacement of dredged sand on the rheological and structural properties of foamed concrete. The specific objectives are to:

i establish the rheological and compressive strength properties of foamed concrete incorporating laterite as a replacement for dredged sand

ii determine the structural properties (compressive, flexural and split tensile strengths) of foamed laterized concrete

iii determine the structural behaviour (deflection and modes of failure) and capacities (flexural capacity and shear capacities) of reinforced foamed laterized concrete beam under flexural load

iv establish the cost per cubic metre of foamed concrete with laterite content and compare it with foamed concrete without laterite through cost-benefit analysis (CBA) method.

1.4 Scope and Delimitation of Study

The scope of this study covers the investigation of structural lightweight self-compacting foamed laterized concrete with 28th day density of 1600 ± 100 kg/m^3.

The study is limited to the investigation of the rheological properties foamed concrete at plastic state; structural properties: compressive strength, modulus of rupture, and split tensile strength; structural strengths and modes of failure of reinforced foamed laterized concrete beam under flexural load.

The study is divided into the preliminary and main investigations. The different stages of the study are closely linked and complementing to one another.

1.5 Significance of Study

In developing countries, the Government and individuals are faced with the challenges of providing housing and infrastructure to satisfy the demands of citizens and families. For example, Ibiene (2015) reviewed the reports of National Bureau of Statistics and World Bank on housing need in Nigeria and it brought to fore an estimated 17 million housing deficit in Nigeria. Also, it was revealed that the housing deficit is mostly demanded by the middle and low income earners. More so, this class of people contribute to large per cent of the country's population growth.

Consequently, it was estimated that in addition to resolving the existing deficit, an estimated additional 700,000 houses must be built annually to keep up with the rising demand. Startlingly, he reported that the current number of houses built annually by both government and private sectors was still less than 100,000 units.

Different factors were identified as the causes of this problem, and amongst them is high cost of building houses in Nigeria. And it was attributed to non-access of cheap and high quality building materials. In this regard, it was estimated that the cost of building a house in Nigeria is approximately 1.4 and 1.9 times costs of building the same house in South Africa and India respectively.

Obviously, conventional construction materials are grossly inadequate to address this challenge. So, innovative and economic ways of solving this problem cannot be overemphasized. One of the methods that could be adopted to solve this housing problem is the use of innovative construction products made from available local raw materials.

Unequivocally, this study demonstrates that foamed laterized concrete is an innovative construction product that utilises local raw materials: laterite and dredged sand for its production. Also it could be used to reduce the cost of construction because it has the following advantages.

a) It eliminates the use of coarse aggregates in building houses.
b) It is lightweight: it reduces dead load in building and civil engineering infrastructures which consequently reduces the cost of the sub-structure.
c) The fine aggregates (laterite) are cheap to procure because of their proximity to project sites in every part of the country.

Furthermore, industry application of foamed laterized concrete in developing countries would create jobs opportunities in the areas of production and maintenance of foam generators, production of foaming agents and setting up of foamed concrete batching plants. Also, being a premier study on foamed laterized concrete, it would provide a basis for further studies in this area.

1.6 Operational Definition of Terms

The operational definitions of some of the terminologies used in this study include:

Base mix

It is the mixture of cement, fine aggregate(s), and water with fluid consistency in a concrete mixer before the addition of foam.

Compressive strength

It is the maximum compression force in Newton per millilitre square which the foamed concrete can sustain without fracture.

Deflection

It is a measure of the deformation of reinforced foamed concrete beam under flexural load from its original unloaded position.

Dredged sand

It is fine aggregate (sand) obtained from rivers, and it is free from deleterious materials.

Flexural–Shear failure

This mode of failure of reinforced foamed concrete beam is initiated by the yielding of the reinforcement with accompanying flexural warning cracks; and ultimate failure when the applied shear force is greater than the shear capacity of the beam.

Foamed concrete

It is a self-compacting lightweight material produced from a mixture of cement dredged sand and mechanically entrained foam.

Foamed laterized concrete

It is a foamed concrete made with laterite as partial replacement of dredged sand.

Foaming agent

It is a liquid concentrate which when diluted with water and agitated produces stable foam.

Foam

Foam is a liquid substance formed when air mixes with diluted foam concentrate under high pressure to form bubbles of stable air entrained pores.

Hardened state

It describes the properties of foamed concrete in the solid state.

Laterite

It is a type of fine aggregate with particle size distribution that contains sand and clay particles.

Modulus of rupture

It is the maximum indirect tensile force in Newton per millilitre square that causes bending which the foamed concrete can sustain without fracture.

Moment capacity

It is the maximum bending force a reinforced foamed concrete beam can sustain without fracture

Plastic state

It describes the behaviour and properties of foamed concrete in the viscous state.

Rheology

It is the flow behaviour of foamed concrete in plastic state; it is measured as spread diameter in spread test.

Shear capacity

It is the maximum force in Newton per millilitre square that causes bending which a reinforced foamed concrete beam concrete can sustain without fracture.

Shear failure

It is a mode of failure of reinforced foamed concrete beam, it occurs when the applied shear force is greater than the shear capacity of the beam; and most times with no advance warning (brittle).

Split tensile strength

It is the maximum indirect tensile force per millilitre square which the foamed concrete can sustain without fracture.

Spread

This is the ability of foamed concrete to flow under its own weight to a certain radius, when a truncated cone is filled with it and lifted up.

Structural properties

These are the properties of foamed concrete that determine the magnitude of different structural loads the concrete could sustain.

CHAPTER TWO

2.0 LITERATURE REVIEW

Foamed concrete is generally designed to achieve low density with the addition of large volume of voids in its matrix. These voids reduce the structural properties, with compressive strength decreasing with increase in porosity (Neville, 2003). Thus, Jones *et al*. (2005) stated that "it is perhaps important to regard foamed concrete as material in its own right; it cannot be a direct substitute to conventional normal weight concrete nor to crushed rock fill". This is because foamed concrete is typically proportioned to achieve only low compressive strength between 0.5 and 10 N/mm^2 which is less than the minimum (17 N/mm^2) recommended for structural lightweight concrete in ACI 213R (2014).

Consequently, in the last decade researchers: Eric *et al*., (2003); Van (2002), Falade *et al*., (2013), Jones and McCarthy (2005a), and Sin (2007) have carried out various investigations geared toward improving the structural properties of foamed concrete. Towards this end, different models have been adopted which included innovative mix composition with agricultural, and industry wastes and other naturally occurring fine aggregates; use of fibre reinforcement and improved curing methods. The results of these investigations have shown that those models were effective for achieving the objective.

With respect to the aim of this study, the following literature review discusses results and findings on subjects with similar objectives. These include chemical interaction between components of foamed concrete, innovative mix composition with different materials as partial replacement of fine aggregates and the cement, rheological properties at plastic state, structural and mechanical properties at hardened state.

The literature review brings to fore the findings of other researchers and provides the bases for the explanation of the results of this study which either support or disagree with them.

2.1 Foamed Concrete Formation Mechanism

According to Van (1991) the conventional materials used for foamed concrete production are fine aggregate, cement, water and entrained foam. So, the internal structure of foamed concrete depends on the interaction of these constituents. Eric *et al.* (2003), Cox and Van (2002) in different studies investigated the internal structure and load transfer mechanism in hardened foamed concrete. They found that its internal structure consists of solid cement-sand matrix and over 40 per cent pores with diameter between 0.3 and 0.4mm. They explained that load is transferred through the solid component, which is surrounded by the pores.

According to Story-Becton Inc. (2008), density of foamed concrete is one of the criteria that determine the properties and its suitable area of application in building and civil engineering projects. Four major groupings of the areas of applications were identified and are presented in Table 1

Table 1

Major groupings of foamed concrete areas of applications

Densities (kg/m^3)	Areas of applications
300-600	. Thermal insulation for flat roofing with required gradient
	. Block in fills for sub-floor slab
	. Cavity walls filling
	. General thermal and acoustic insulation
600-900	. Internal partition wall blocks and panels
	. Slabs for false ceiling
	. Sub-surface for stables, Poultry farms and large cool room
	. Façade Panels
	. Trench reinstatement
	. Thermal insulation and soundproofing screeds in buildings
900-1200	. External wall blocks and panels, both structural and non-structural
	. General sound proofing in industrial areas
1200-1600	. Medium weight blocks
	. Large reinforced slabs and panels.
	. In-situ casting of walls
	(stabilization of bridge abutment, tunnels,
	embankments, shafts and wells.)

Story-Becton Inc. (2008)

2.1.1 Cement-Sand Matrix Formation Mechanism

Gambhir (2013) explained that during concrete production, cement and water combine in the process of hydration to form the binder material that binds the aggregates particles, whilst the aggregates provide volume stability and durability to concrete. According to Mydin and Wang (2012) the extent of hydration of cement and the resultant microstructure of the hydration products (hydrates) influence the physical properties of concrete. In addition, they observed that the rate of hydration and the hydration products formed are determined by the proportions of the different constituents of ordinary Portland cement (OPC). These constituents majorly consist of four main compounds which are presented in Table 2.

Table 2

Compound composition of ordinary Portland cement

Compound	Symbol	Percentage by mass
Tricalcium silicate	C_3S	25 – 50
Dicalcium silicate	C_2S	20 – 45
Tricalcium aluminate	C_3A	5 – 12
Tetracalcium alumino ferrite	C_4AF	6 – 12

Gambhir (2013)

The different constituents of OPC in Table 2 chemically combine with water during hydration and proceed at different rates to produce different hydrates, and amount of heat. Hydration is an exothermic chemical reaction between cement and water, which commences immediately they come in contact with each other. The products of this reaction include calcium silicate hydrate and calcium hydroxide. Mindess *et al*. (2003) suggested that hydration reaction proceeds in five stages and could be described by reaction stoichiometric, rate of hydration, and the heat of hydration. These stages are shown in Table 3.

Table 3

The different stages of hydration reaction

s/n	Reaction stage	Kinetics of reaction	Chemical process	Relevance to concrete properties
1	Initial hydrolysis	Chemical Control (Rapid)	Initial Hydrolysis (Dissolution of ions)	
2	Induction period	Nucleation control (Slow)	Continue dissolution of ions	Determines initial setting time
3	Acceleration	Chemical control (Rapid)	Initial formation of hydration products	Determines final setting time and rate of initial hardening
4	Deceleration	Chemical and diffusion control (Slow)	Continued formation of hydration products	Determines the rate of early strength gain
5	Steady state	Diffusion control (Slow)	Slow formation of hydration products	Determines the rate of later strength gain

Mindess *et al.*, (2003)

The chemical reactions at the different stages of hydration process are based on reaction stoichiometric according to Gambhir (2013). Against this background, stages 1 and 2 of hydration process involve the dissolution of calcium tetraoxosulphate (VI) ($CaSO_4$) to provide ions which react with C_3A of the cement constituent. This reaction expressed as

$$C_3A + 32H + 3CaSO_4 \rightarrow C_3A \cdot 3C\bar{S}H_{32} \rightarrow C_6AS_3H_{32} \quad (1)$$

yields calcium trisulfate hydrate (ettringite). This hydrate precipitates as a crystalline product, and prevents flash setting of cement (or hardening without strength).

Furthermore, as the $CaSO_4$ in the solution depletes, stage 3 of the hydration process is initiated. The reactions at this stage involve combination of C_3A with depleted amount of $CaSO_4$ expressed as

$$C_3A + 18H + 3CaSO_4 \rightarrow C_3A \cdot C\bar{S}H_{18} \rightarrow C_4A\bar{S}H_{18} \quad (2)$$

and the hydration of the remaining quantity of C_3A which is expressed as

$$2C_3A + 21H \rightarrow C_4AH_{13} + C_2AH_8 \rightarrow 2C_3AH_6 + 9H \quad (3)$$

to produce monosulfate hydrate ($C_4A\bar{S}H_{18}$) and calcium aluminate hydrate (C-A-H) respectively. In addition, large amount of heat is released and the hydration and hardening of C_3S is catalysed.

Finally, the last stages (4 and 5) in the hydration process are responsible for strength development in concrete. These stages involve the hydration of C_3S and C_2S to yield calcium silicate hydrates and calcium hydroxide. The reaction in stage 4 expressed as

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3Ca(OH)_2 \tag{4}$$

overlaps stage 3 and is responsible for early strength development within 28 days, whilst the hydration of C_2S which is expressed as

$$2C_3S + 4H \rightarrow C_3S_2H_2 + Ca(OH)_2 \tag{5}$$

is responsible for later strength development in concrete.

2.1.2 Pores Formation Mechanism

Kearsley (1996) suggested that pores in foamed concrete are formed when the pre-formed foam which is introduced and properly mixed with high workable mortar degenerate after approximately forty five minutes. Also, according to Nambiar and Ramamurthy (2007) pre-formed foam can either be wet or dry, which depends on the process of production; and the processes of producing both wet and dry foam require initial mixing of estimated amount of water and foam concentrate to form diluted solution. The equipment and material required for foam production include:

a) foam generator with air compressor
b) suitable foaming agent.

Luca Industries International (2009) explained that foam generators are ready to use foaming system with integrated air-system, and they are in different sizes depending on the foam production capacity. Also, the two types of foam generators which are commonly used in the industry are continuous and mobile generators. The difference in these generators is on the mode of operation.

2.1.2.1 Continuous foam generator

A typical of this foam generator is shown in Figure 1. It has two different inlet pumps. One of the pumps is used for the addition of water while the other pump for the foaming agent into the mixing chamber. No premixing of foaming agent and water is necessary because it is automatically done. The system is a continuous one and it is suitable for automated foamed concrete plants. It is mostly used on construction sites and in concrete factories.

Figure 1. Continuous foam generator (Luca Industries International, 2009)

2.1.2.2 Mobile foam generator

This type of foam generator is shown in Figure 2. It is compact and a complete ready to use system. It has a single pump through which the water and the foaming agent are fed into the machine. The pre-mixing of water and foaming agent is manually carried out. It is mostly use in the laboratory for first testing of foamed concrete.

Figure 2. Mobile foam generator (Luca Industries International, 2009)

2.1.2.3 Foaming agent

Foam concentrates are surface-active agents. Therefore, they dissolve in water to produce ions with negative charges (anions). Excess of anions in the solution reduces the surface tension of water, which enables it to hold air when agitated to produce foam. Foaming agent is classified on the basis of the active ingredient. The different types of liquid concentrate are:

a) protein-based
b) surfactant-based (synthetic foaming agents)
c) enzyme-based.

Protein-based standard foaming agents are obtained from hydrolysis of animal proteins from horn, blood, bones of cows, pigs and other remainders of animal carcasses. Surfactant-based foaming agents are purely chemical products with constant quality. Enzyme-based foaming agents consist of highly active proteins of mainly vegetable origin and are not based on protein hydrolysis.

However, regardless of the source of the foam concentrate, Aldridge (2005) explained that the quality of the foam concentrate and foam produced is more important as it contributes to the final properties of the foamed concrete. Also, the foam must be stable so as not to collapse during mixing with other components. This quality of foam depends on the dilution factor of the foaming agent, the foam-making process and the adding and blending process with the mortar.

Narayanan and Ramamurthy (2000) stated that two types of foam namely wet and dry could be produced. Also, the type foam produced depends on the method of agitation of the diluted solution of the foam concentrate. The wet foam is produced by spraying a solution of foaming agent over a fine mesh with 2-5 mm bubble size and is relatively less stable. Dry foam is produced by forcing the foaming agent solution through a series of high density restrictions and forcing compressed air simultaneously into the mixing chamber. Dry foam is extremely stable and has a size of smaller diameter than 1 mm.

Figures 3 and 4 respectively show the schematic representation of dry foam production process and sample of dry foam produced. From Figure 3, the air compressor is connected to a power source while its outlet is connected to the foaming lance. The system is activated when the power is switched on. The compressed air mechanically agitates the diluted foaming agent to produce foam through the foaming lance.

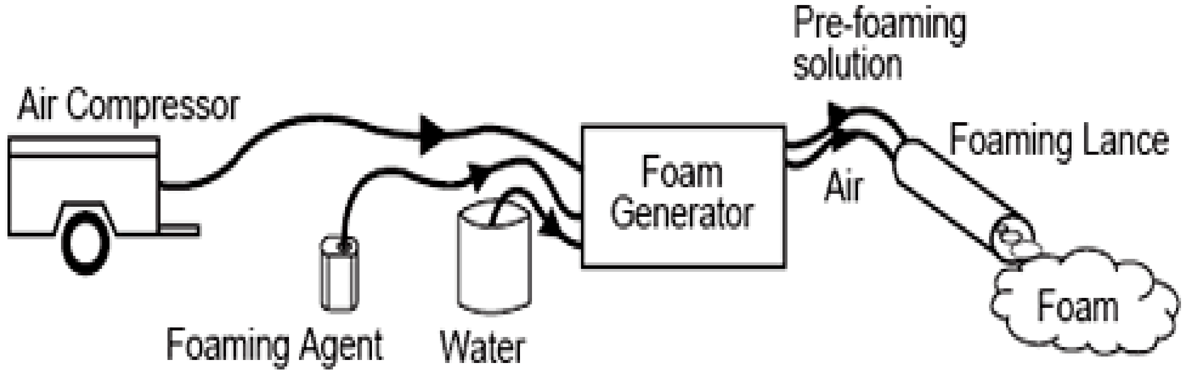


Figure 3. Schematic representation of foam production process (Luca Industries International, 2009)

Figure 4. Sample of foam produced from a foam generator (Luca Industries International, 2009)

Foam production process helps to incorporate controlled amount of air, in the form of millions of minute non-coalescing bubbles distributed throughout the body of concrete. The bubbles which are anions repel one another and are attracted to the positively charge cement particles. Then, resulting to the deflocculation of the cement-sand matrix and improved the mobility of concrete to achieve self-compacting rheological properties.

2.2 Rheological Property of Foamed Concrete

Rheological property of foamed concrete is the flow behaviour in the plastic state. The plastic state properties of cement based materials are very important; although it may be only transient, but it contributes to the ultimate performance at the hardened state (Banfill, 2003; Hanehara & Yamada, 2008). Studies such as Dransfield (2000), Jones *et al*., (2005), Jones and McCarthy, (2005a, 2005b, 2005c, 2006) described foamed concrete as a lightweight material with self-compacting rheological properties. This means that the workability of foamed concrete is generally excellent with nearly fluid consistency: it is pourable, homogeneous and has small possibility of bleeding and segregation.

It is generally accepted among researchers that the rheology of both normal weight and lightweight concrete conforms to the Bingham model (McCarthy, 2004; Banfill, 2006; Brady *et al.,* 2001). This is because in plastic state they can stand unsupported without flowing under their own weight (as in the slump test). According to Banfill (2006), yield stress is directly related to the viscosity of the fluid and the relationship is expressed as

$$\tau = \tau_o + \eta\gamma \qquad (6)$$

where τ = shear stress (N/m^2)

γ = shear rate (s^{-1})

τ_0 = yield stress (N/m^2)

η = plastic viscosity (Ns/mm^2).

Also he stated that Bingham fluid rheological model can be represented with Figure 5. The yield stress and the plastic viscosity are the rheological properties of the concrete. The yield stress is the stress that must be exceeded by the applied shear stress for the fluid to start flowing, and plastic viscosity is the measure of how easily the material flows once the yield stress is overcome. Thus, Banfill proposed the characterization and ranking of concrete (see Table 4) into flowing concrete, self-compacting concrete and normal weight concrete based on the rheological properties.

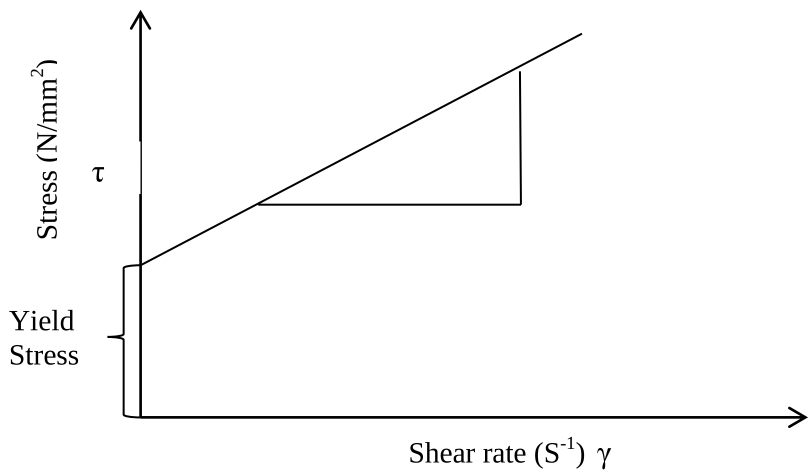


Figure 5. Graphical representation of Bingham equation: relationship of stress to shear rate

Table 4

Rheological characterization and ranking of concrete

Parameter	Cement paste grout	Mortar	Flowing concrete	Self-Compacting concrete	Normal concrete
Yield stress (τ)	10 – 100	80 – 400	400	50 – 200	500 - 2000
Plastic viscosity (η)	0.01 – 1	1 – 3	20	20 - 100	50 – 100

Banfill (2006)

Studies by Banfill (2003) and Tattersall (1991) suggested that rheological properties of concrete are important to the construction industry because it is usually put into place in plastic form. They agreed that rheological properties could be used to identify changes in concrete quality during production without having to wait for the concrete to harden. Also, they reported the test methods for determining rheological properties of concrete, which are divided into two groups.

These groups are single factor test methods and two factors test methods. The difference in the two methods is the experimental output: the results obtained could either be single rheological parameter or the two rheological parameters.

2.2.1 Single factor test methods

These are empirical test methods use for examining fresh concrete property that is related to one rheological parameter. Examples of these methods include; slump test, spread test, flow test, penetrating rod test, vibration test. Domone (2003) expressed the view that the term “workability” as commonly used to describe the results of slum and spread test in normal weight concrete is limited in definition. He suggested that the concept of rheology should be used to describe the behaviour of fresh concrete in order to accommodate self-compacting and flowing concrete.

Research by Kapur *et al*. (1997), Zhou *et al*. (1999), Scales *et al.* (1998) suggested that the rheology of concrete could be predicted from flow rate and spread value. They also suggested that rheological values could be related to the concrete hardened properties for practical applications. Single factor test methods are popular and widely accepted by engineers and concrete technologists for quality control in concrete production (Ferraris, 1996; Banfill, 2006).

Ferraris and Banfill also explained that slump and spread tests with truncated cone which conforms to BS EN 12350-2 (2009) are in such widespread use in the industry that attempts have been made to analyse their performance in rheological terms and relate the results to the rheological properties of materials.

In this respect, Murata (1984) proposed the relationship of yield stress to slump of concrete which can be expressed as

$$\tau_o = \rho g H_o K_1 f_1 \left(1 - \frac{S}{H_o}\right) \tag{7}$$

where S = slump

τ_o = yield stress

ρ = density

g = acceleration due to gravity

H_0 = initial (un-slumped) height

K_1 = constant obtained from curve fitting

R = radius of spread

V_s = volume of sample

r = constant linked to the liquid-vapour interfacial energy and the wetting angle of the material on the plate

f_1 = simple proportionality constant.

Also, Roussel *et al*. (2005) expanded Equation 7 to predict the yield stress of self-compacting concrete from spread diameter in spread test where

$$\tau_o = 1.747 \rho V^2 R^5 - \frac{\Gamma R^2}{V_s} \tag{8}$$

Ferraris (1996), Ferraris and Marty (2003) investigated the relationship of yield stress to spread diameter of self-compacting concrete. They suggested that the pressure exerted by the weight of the sample in the truncated cone on the surface is equivalent to the shear stress whilst the yield stress is equivalent to the inter-particle forces in the mix. Also, self-compacting concrete would continue to flow if the applied shear stress is greater than the yield stress. Figure 6 shows a schematic representation of the truncated cone used for slum test and spread radius of the concrete.

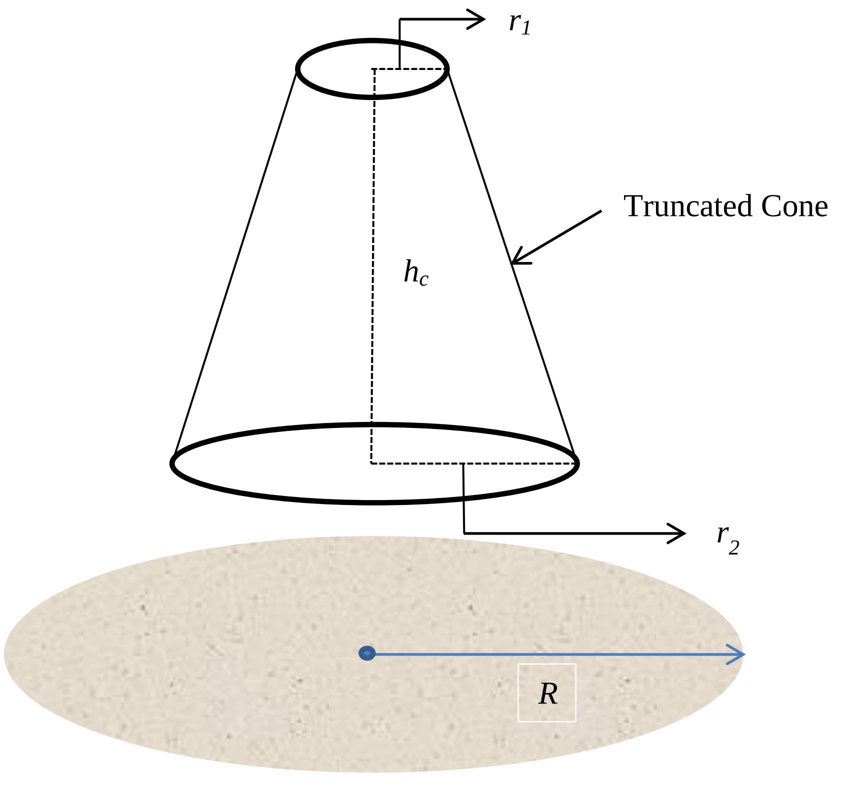


Figure 6. Schematic representation of spread test

In Figure 6

r_1 = smaller radius of the truncated cone

r_2 = greater radius of the truncated cone

h_c = height of truncated cone

R = radius of sample spread after the cone is lifted.

Then, Gambhir (2013) classified different types of concrete based on their flow behaviour (or rheology), which is measured as either slump or spread diameter values as shown in Table 5.

Table 5

Slump and spread test values of different types of concrete

Class of Concrete (Test method)	Slump or Spread diameter (mm)				
	Very low	Low	Medium	High	Recommended Value
Slump concrete (Slump test)	0 - 25	25 - 50	50 - 75	75 – 150	-
Flowing concrete (Spread test)	350 - 410	410 - 480	480 - 550	560 - 620	-
Self-Compacting concrete (Spread test)	-	-	-	-	560 - 760

Gambhir (2013)

Gambhir explained that slump and spread values give an indication of the yield stress of concrete, while the plastic viscosity is measured with flow test. Brady *et al*. (2001) explained the use of modified Marsh cone which is shown in Figure (7) to measure the flow rate of self-compacting concrete. They suggested empirical flow classification for self-compacting concrete (shown in Table 6) and concluded that for foamed concrete to develop self-compacting rheological properties its flow rate value should fall into class A or B. In addition, Roussel and Leroy (2005) proposed a relationship of the flow rate to plastic viscosity of a Bingham fluid through an orifice of radius R of a modified Marsh cone in which case

$$Q = \frac{\pi R^4}{8\eta L_f}\left\{P - \frac{4p}{3} + \frac{p^4}{3p^3}\right\} \tag{9}$$

where Q = rate of flow

P = pressure gradient driving the flow

P = minimum pressure at which flow begins

L_f = flow length

η = fluid viscosity.

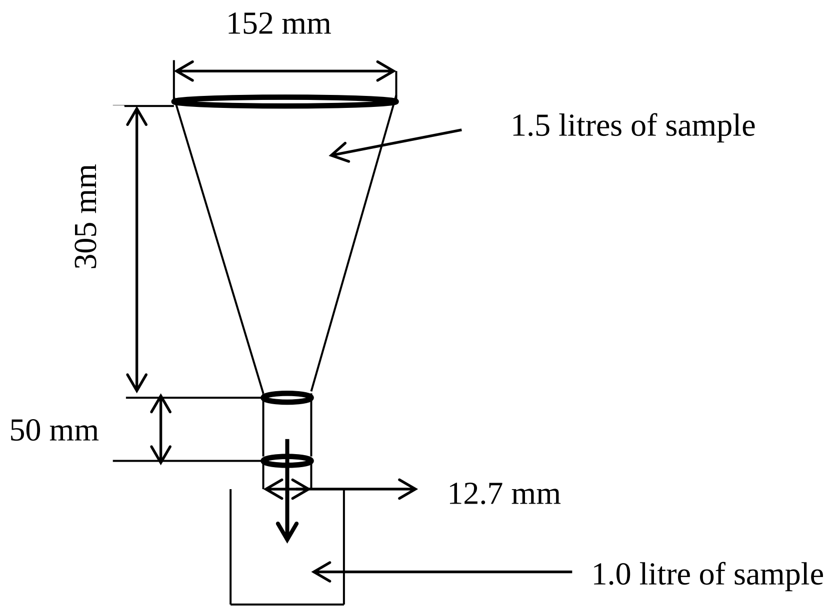


Figure 7. Modified Marsh cone use for flow test

Table 6

Foamed concrete classification based on modified Marsh cone flow

Main Class	Flow rate	Sub class	Description of flow
1	1 litre in < 1 minute	A	Constant flow
2	1 litre in > 1 minute	B	Interrupted flow
3	0.5 litres <efflux< 1 litre > 1 minute	C	Completing of flow after gentle tamping

Brady *et al*. (2001)

2.2.2 Two Factor Test Methods

The output of these test methods give two parameters which are indirectly related to rheological parameters (yield stress and viscosity) of Bingham fluid. Ferraris (1996) noted that Tattersall two-point test (viscometer) is the first and most widely known instrument for measuring the flow properties of concrete. The apparatus: Figure 8 is designed such that an interrupted helical impeller rotates in a cylindrical bowl of fresh concrete, and the resistance (torque) on the impeller due to the concrete is measured. Then the relationship of the speed of rotation of the impeller to the torque is obtained.

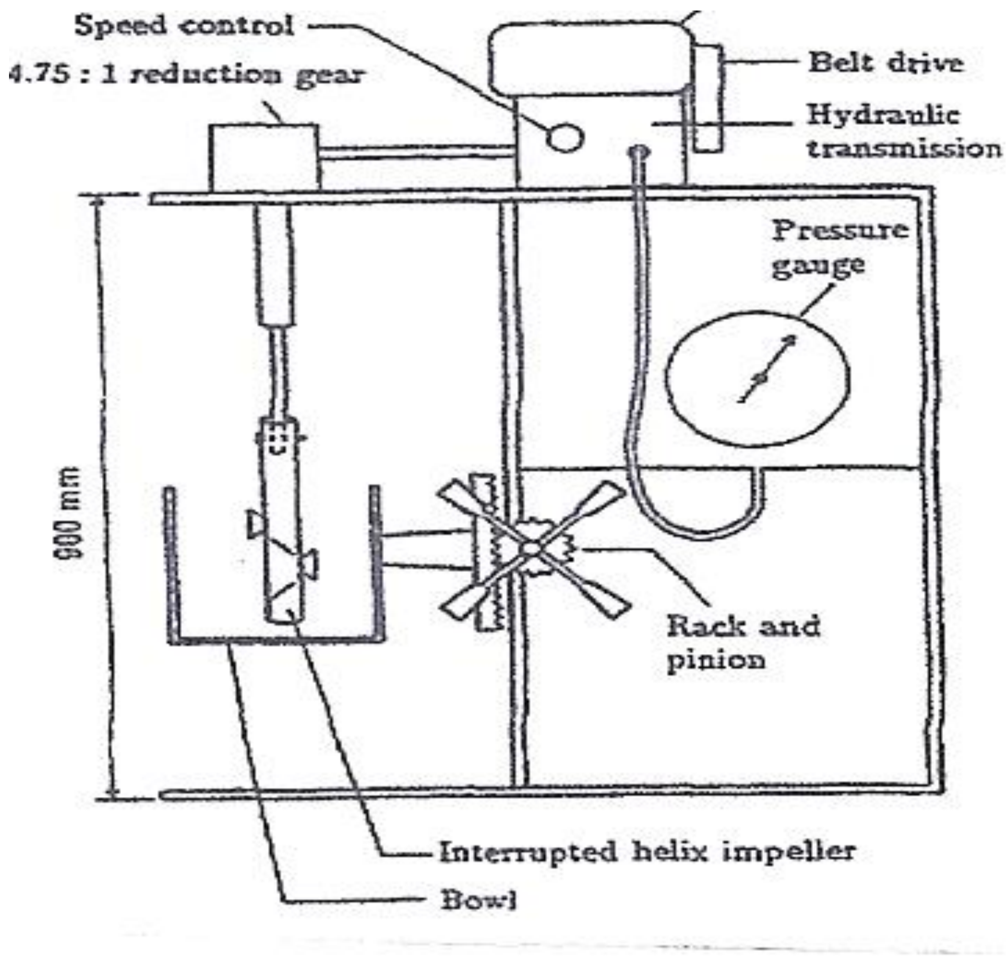


Figure 8. Schematic diagram of Tattersall two-point apparatus (Tattersall and Banfill, 1983)

Tattersall and Banfill (1983) investigated the behaviour of concrete in Tattersall two-point apparatus. The study was based on the assumption that the mean effective shear rate is proportional to the speed of rotation of the impeller as shown in Figure 9, and can be expressed as

$$T = (G/K)\tau_o + (G\eta)N \qquad (10)$$

where T = torque

G = constant obtained by calibration with Newtonian fluids

K = constant obtained by calibration with non- Newtonian fluids

N = speed of the impeller

τ_o = yield stress

η = viscosity.

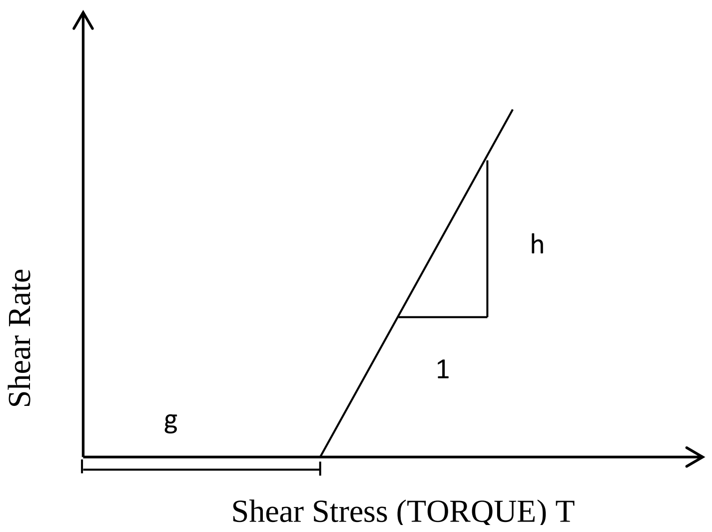


Figure 9. Relationship of shear rate to change in shear stress

Research findings identified the inadequacies of the two-point apparatus for measuring the rheological properties of cement paste, cement slurry, mortar and other concentration suspensions which include; risks of slippage at the walls of the apparatus, sedimentation of the particles and plug flow (Nachbaur *et al.*,2001; Vlachou & Piau, 2000; Wallevik, 2003) .

Notwithstanding the inadequacies in the two-point test methods and estimation errors in single factor test methods, Wallevik (2003) recommended the rheological parameters measured with these methods as the design criteria in the mix design of self-compacting concrete. In addition, he concluded that self-compacting concrete must possess acceptable values of the yield stress and viscosity. And these could be achieved through trial mixes and adjusting the components of the concrete.

2.3 Compressive Strength

Neville (2003) stated that compressive strength usually gives an overall picture of the quality of structural concrete and it is directly related to the internal structure of the cement paste. Also, Penttala (2009) explained that the internal structure of hardened cement paste contains hydrates and pores system that consists of the gel pores, capillary pores and air entrained pores. Then, the compressive strength of cement paste (concrete) is dependent on the hydrate-space ratio (porosity of concrete) expressed as

$$\text{hydrate/space ratio} = \frac{\text{Volume of hydrate}}{\text{Volume of hydrate} + \text{Volume of pores}} \tag{11}$$

This is the fraction of volume occupied by hydrated cement in the total space occupied by hydrated cement, capillary and air entrained pores.

Neville (2003) suggested that the strength of cement or concrete is primarily governed by its porosity expressed as

$$f_{cu} = f_0(1 - p_o)^{\mathrm{n}} \tag{12}$$

where f_{cu} = compressive strength

f_0 = compressive strength at zero porosity

P_0 = porosity

n = empirical constant from curve fitting.

This general relationship for all types of concrete has been modified to account for the unique properties of foamed concrete. In this respect, Kearsley (1996) proposed an empirical relationship of porosity and dry density of foamed concrete in which case

$$P_0 = 18665\gamma_d^{-0.844} \tag{13}$$

where P_0 = porosity (%)

γ_d = dry density (kg/m^3).

Kearsley suggested that the volume of pores in foamed concrete could be estimated from measured density. These findings were supported by research findings in Jones *et al.* (2005), Nambiar and Ramamurthy (2000b) which showed that the density of foamed concrete gives an indication of the compressive strength. Therefore, John and Phil (2003) classified foamed concrete in Table 7 based on its density and compressive strength.

Table 7

Classification of lightweight concrete

Property	Class and Type 1 Structural	11 Structural/Insulating	111 Insulating
Compressive Strength (N/mm^2)	>15	> 3.5	> 0.5
Coefficient of thermal conductivity (W/mK)	-	< 0.75	< 0.3
Approximate density range (Kg/m^3)	1600- 2000	< 1600	<< 1450

John and Phil (2003)

The pore structure of foamed concrete is an important micro structural characteristic which influences the physical (density) and structural (compressive strength) and durability properties (Kalliopi, 2005; Metha & Monteiro, 2005). In addition, Nambiar and Ramamurthy (2007) stated the parameters of the pores which influence the properties of foamed concrete to include shape, spacing factor and size distribution. Then, Beningfield *et al.* (2005) concluded that those properties of the pore structure are responsible for the change in compressive strength, rather than common w/c ratio and aggregate-cement ratio as in conventional concretes.

Wee *et al*. (2006) investigated "Air-void System of Foamed Concrete and its Effect on Mechanical Properties." They found that the air pores in foamed concrete have greater effect on compressive strength than modulus of elasticity, also that the combined effects of spacing factor and air pores sizes control the mechanical properties of foamed concrete.

Notwithstanding the effects of the pore system of foamed concrete on its properties, the w/c ratio and quantity of cement also contribute to its quality and structural properties (Kearsley, 1999; Brady *et al*. 2001; Nambiar & Ramamurthy 2006; Jones 2000). They explained that too little water potentially leads to disintegration of foam in the mix, while too much water leads to segregation.

According to Jones (2000) the w/c ratio of the base mix required to achieve adequate workability is dependent upon the type of binder(s), the required strength of the concrete and whether or not a water-reducing or plasticizing agent has been used. Also the quantity of cement required for foamed concrete production lies between 300 kg/m^3 and 500 kg/m^3. Furthermore, cement content above 500 kg/m^3 was found to be associated with the risk of thermal cracking, while the resulting gain in strength after hydration of cement was minimal.

Gambhir (2013) explained the effects of hydration products and curing methods on the compressive strength development in concrete. In this respect, the volume and quality of hydration products (hydrate) determines the rate of strength gain in concrete and the strength developed (see Figure 10). From Equations (11) and (12), high value of hydrate-space ratio implies large volume of hydrates, reduction in the porosity and increase in the compressive strength of concrete. But high water/cement ratio and air entrained pores decrease the hydrate/space ratio, thus increasing the porosity and decreasing the strength of concrete.

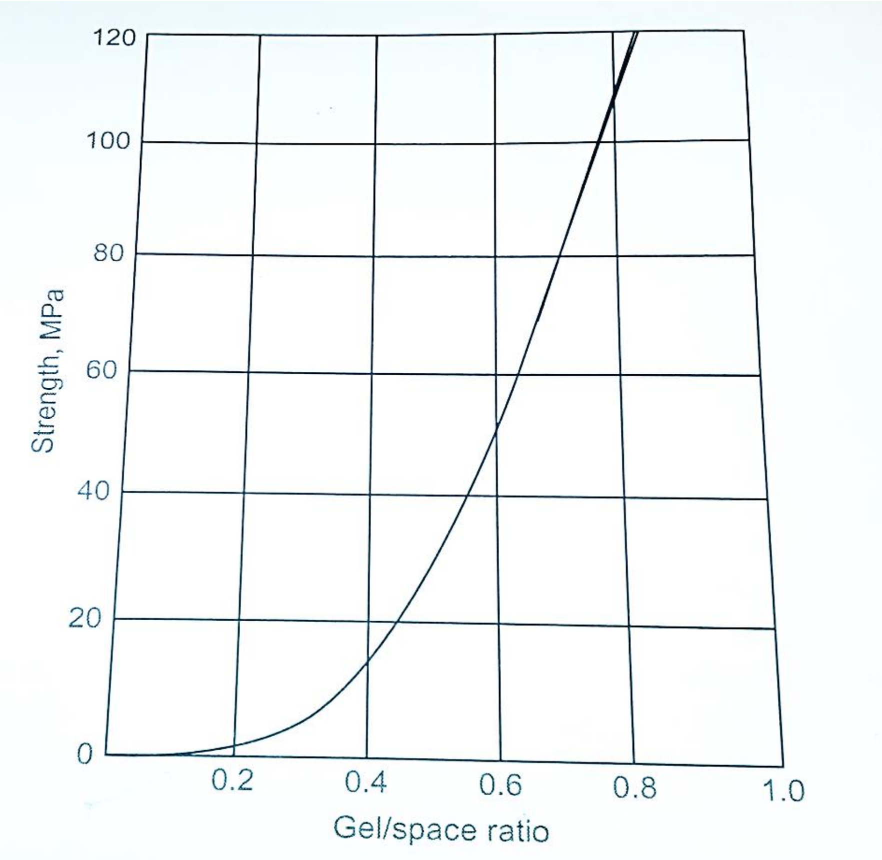


Figure 10. Relationship of compressive strength to gel/space ratio of normal weight concrete (Gambhir, 2013)

Hydrates are the products of hydration of cement. The hydrate which contributes to strength gain in concrete is called calcium silicate hydrate ($C_3S_2H_3$). This hydrate is produced by the chemical reaction of water and the two silicates: C_3S and C_2S expressed as

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3Ca(OH)_2 \quad (13)$$

and

$$2C_2S + 4H \rightarrow C_3S_2H_3 + Ca(OH)_2 \quad (14)$$

respectively.

The hydration of tricalcium silicate (C_3S) is faster and is mostly responsible for the gain of strength up to about 28 days by growth and interlocking of C-S-H gel. The later age increase in strength is due to the hydration of diacalcium silicate (C_2S). Factors which affect the hydration reaction in concrete include: curing regime, cement type and content and water/cement ratio.

Curing of concrete is the process of creating an environment during a relative short period immediately after the placing and compacting of concrete, which is favourable for the setting and hardening of concrete. Different types of curing methods have been adopted in concrete technology and they include: sealed curing at different temperatures, moist curing, steam curing at atmospheric pressure, and high pressure steam curing (also called autoclaving). All the curing methods of concrete conform to BS EN 13670 (2009) in order to provide the desired conditions for concrete at early age. These desired conditions are namely, a suitable temperature which governs the rate at which the chemical reactions involving setting and hardening take place; the provision of moisture or prevention of loss of moisture; avoidance of premature stressing or disturbance of the concrete.

Gambhir (2013) explained that specimens of normal weight concrete which were exposed to air curing after production developed the least compressive strength. Also, specimens with varying degrees of moisture curing developed different compressive strengths at the curing periods (see Figure 11). He concluded that specimens cured in water for 14 days developed maximum compressive strength at 28^{th} day.

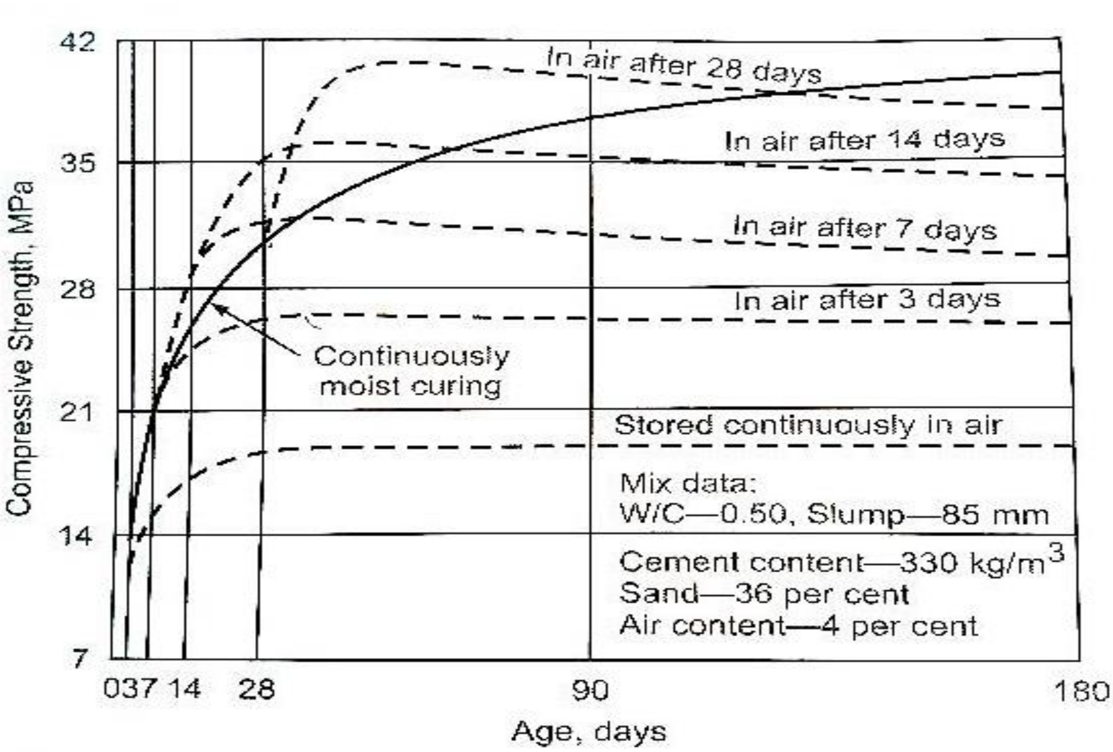


Figure 11. Relationship of compressive strength to duration of curing in water of normal weight concrete at various curing periods (Gambhir. 2013)

Kearley (1996) explained that the importance of curing concrete after production is well known to Civil Engineers and Concrete Technologists and has been implemented since the inception of concrete production. Although methods of curing conventional concrete have been established, but the curing methods of foamed concrete are still a subject of research. So, he reported the findings of the investigation on different curing methods of foamed concrete namely, conventional water curing, sealed curing at different temperatures, moist curing, steam curing at atmospheric pressure and high pressure steam curing (also called autoclaving). It was concluded that water-cured foamed concrete exhibited the lowest compressive strength. Also, Falade *et al*. (2011) compared the 28th day compressive strength developed in foamed concrete specimens cured in air and water. They found that specimens cured continuously in air developed higher compressive strength than specimens cured continuously in water.

According to Penttala (2009) the pore water in hardened cement paste and concrete influences the compressive strength developed at various curing periods. The pore system in concrete includes the gel pores, capillary pores and air entrained pores. These pores have wide range of dimensions from nanometre in gel pores to several millimetres in air entrained pores (see Figure 12). The saturation of the different pores affects the compressive strength of the concrete in different ways. Saturation of gel and capillary pores aids continuous hydration of cement in the concrete with increases in compressive strength. Whilst, the saturation of air entrained pores exert tensile stresses in the concrete structure, which weakens it and causes reduction in the compressive strength.

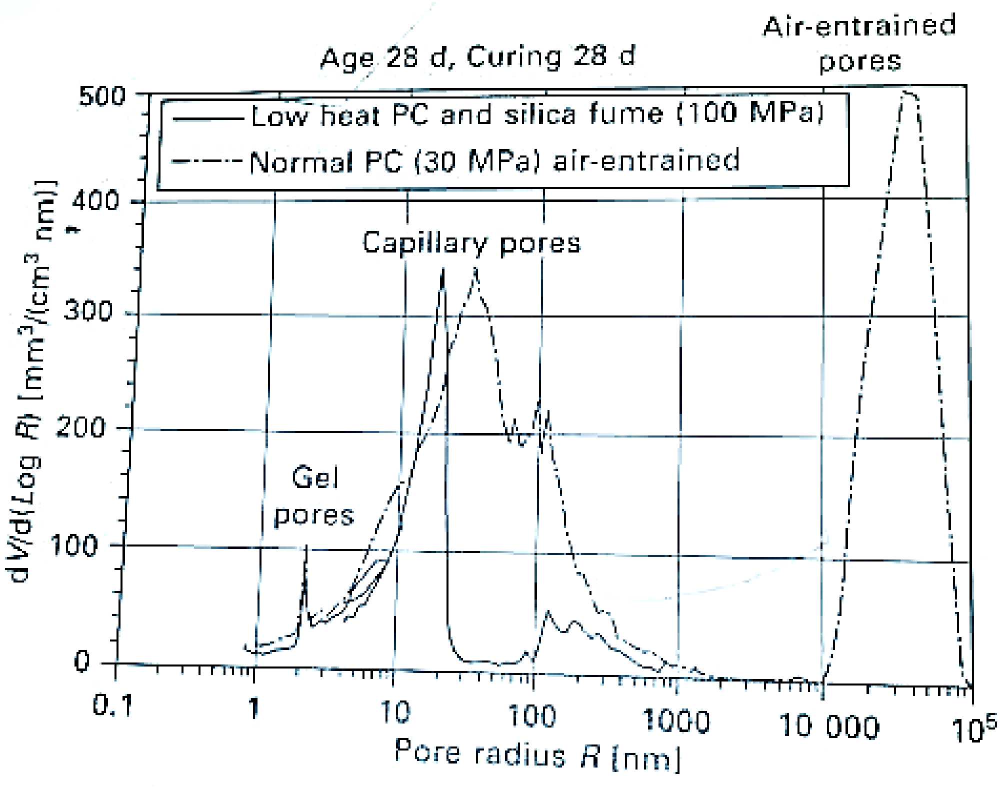


Figure 12. Pore size distribution of binder pastes for cement paste of low heat Portland cement and ordinary Portland cement. (Penttala, 2009)

2.4 Tensile Strength

Research findings by Building-Research Institute (2014) and Civil-Engineering-World (2009) have shown that the tensile property is one of the basic and important properties of concrete. They explained that the tensile strength of concrete influences structural concrete performance and design decisions in its application because of the following properties of concrete structures:

i Concrete structures are highly vulnerable to tensile cracking due to various kinds of effects and applied load.

ii Structural concrete member behaviour changes after tensile cracks have developed.

iii Tensile strength is a criterion in the designing of highway and airfield structural slabs.

They also stated that a direct application of a pure tension force, free from eccentricity, on concrete specimen is very difficult. Then, tensile strength of concrete is measured with indirect methods as the split tensile strength (f_t) and modulus of rupture (f_r) in split cylinder test and flexural test respectively.

According to Civil-Engineering-World (2009) the factors that affect the split tensile strength of concrete (f_t) are age, curing method and air entrainment. Furthermore, it was explained that the tensile strength increases more slowly than the compressive strength (f_{cu}) after 28 days, therefore the ratio f_t/f_{cu} decreases with time. Also, air-cured concrete has a lower f_t/f_{cu} ratio than concrete cured in water and tested in wet condition. In addition, it was noted that air-entrainment affects the f_t/f_{cu} ratio because the pressure of air lowers the compressive strength of concrete more than the tensile strength of the concrete.

Empirical formulae proposed by Gardner and Poon (1976), Raphael (1984) modified in Oluokun *et al*. (1991) and BS 8007 (1987) cited in Civil-Engg-World (2009) as shown in Table 8, show that the relationship between f_t and f_c can be expressed as

$$f_t = k\,(f_{cu})^n \tag{15}$$

where k, and n are coefficients of power equation of trendline.

Table 8

Numerical relationship between tensile strength and compressive strength

Source	Compressive strength test specimen	Relationship between f_t and f_{cu}
Gardner and Poon (1976)	Cylinder specimen	$f_t = 0.3\,(f_{cu})^{2/3}$
Raphael (1984): modified in Oluokun (1991)	Cylinder Specimen	$f_t = 0.2\,(f_{cu})^{0.7}$
BS 8007:1987	150mm cube	$f_t = 0.12\,(f_{cu})^{0.7}$

Civil-Engineering-World (2009)

Likewise, Arthur *et al.* (2010) contrast the relationship of tensile strength to compressive strength of normal weight and light weight concrete in Table 9.

Table 9

Approximate values of tensile strength of concrete expressed as a fraction of the compressive strength

Tensile Strength	Normal Weight Concrete (N/mm^2)	Light Weight Concrete (N/mm^2)
Split Tensile Strength (f_t)	0.5 to $0.66\sqrt{f_{cu}}$	0.33 to $0.5\sqrt{f_{cu}}$
Modulus of rupture (f_r)	0.66 to $1\sqrt{f_{cu}}$	0.5 to $0.66\sqrt{f_{cu}}$

Arthur *et al.* (2010)

2.4.1 Methods for Testing Tensile Strength of Concrete

The test procedures for determining the split tensile strength and modulus of rupture of concrete are reported in different codes of practice. The tests are split cylinder test and third point load test respectively.

2.4.1.1 Split cylinder test.

In this test, the split tensile strength of concrete is measured in accordance with BS EN 12390-6 (2009). The procedures include production of concrete cylindrical specimens (150 x 300 mm); proper curing of specimens in water; testing of specimens at 28th day. The concrete cylindrical specimen is laid in the machine with its vertical axis placed horizontal between the platens of a compression machine as shown in Figure 13.

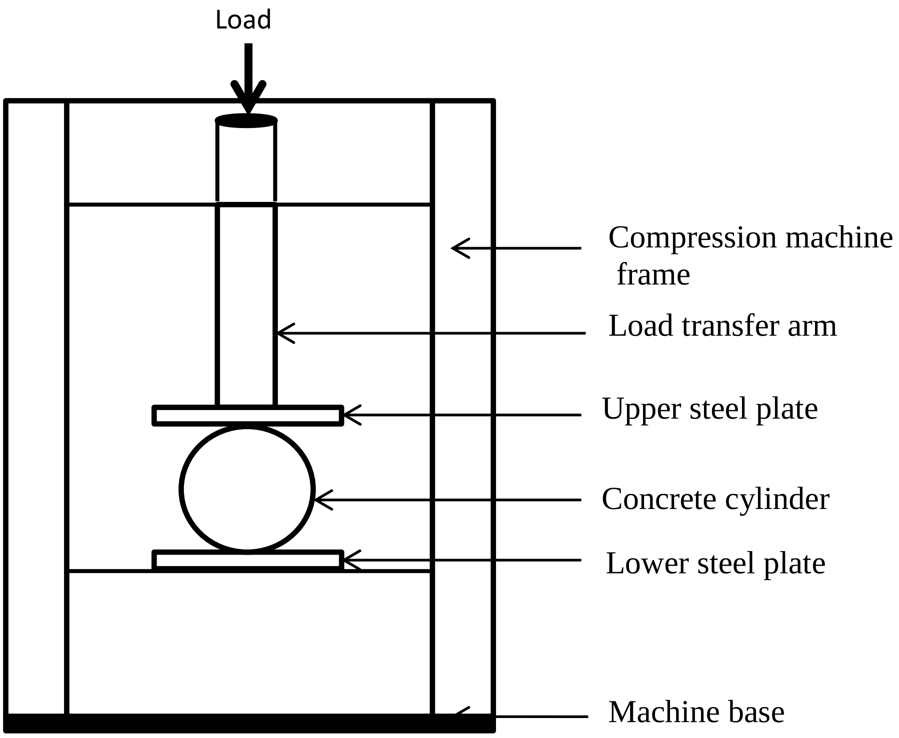


Figure 13. Schematic representation of split tensile test

The load is applied on an incremental basis until failure by indirect tension in the form of splitting along the vertical axis takes place. ACI (2015) states that splitting tensile strength closely relates to direct tensile capacity of the concrete and it is obtained from the relationship expressed as

$$f_t = \frac{2P_i}{\pi l d_c} \tag{16}$$

where f_t = split tensile strength (N/mm^2)

P_i = maximum applied load by the testing machine (N)

l = length of cylinder specimen (mm)

d_c = diameter of cylinder specimen (mm).

2.4.1.2 Third point load test.

In this test, the flexural capacity of concrete is measured in accordance with ASTM C-9 (2016) and BS EN 12390-5 (2009). The procedure includes production of concrete beam specimens (150 x 150 x 750 mm); proper curing of specimens in water; testing of specimens at 28th day. The beam specimens are tested in the third point loading machine as indicated in Figure 14. Then load is applied in an incremental basis until the beam fails in bending.

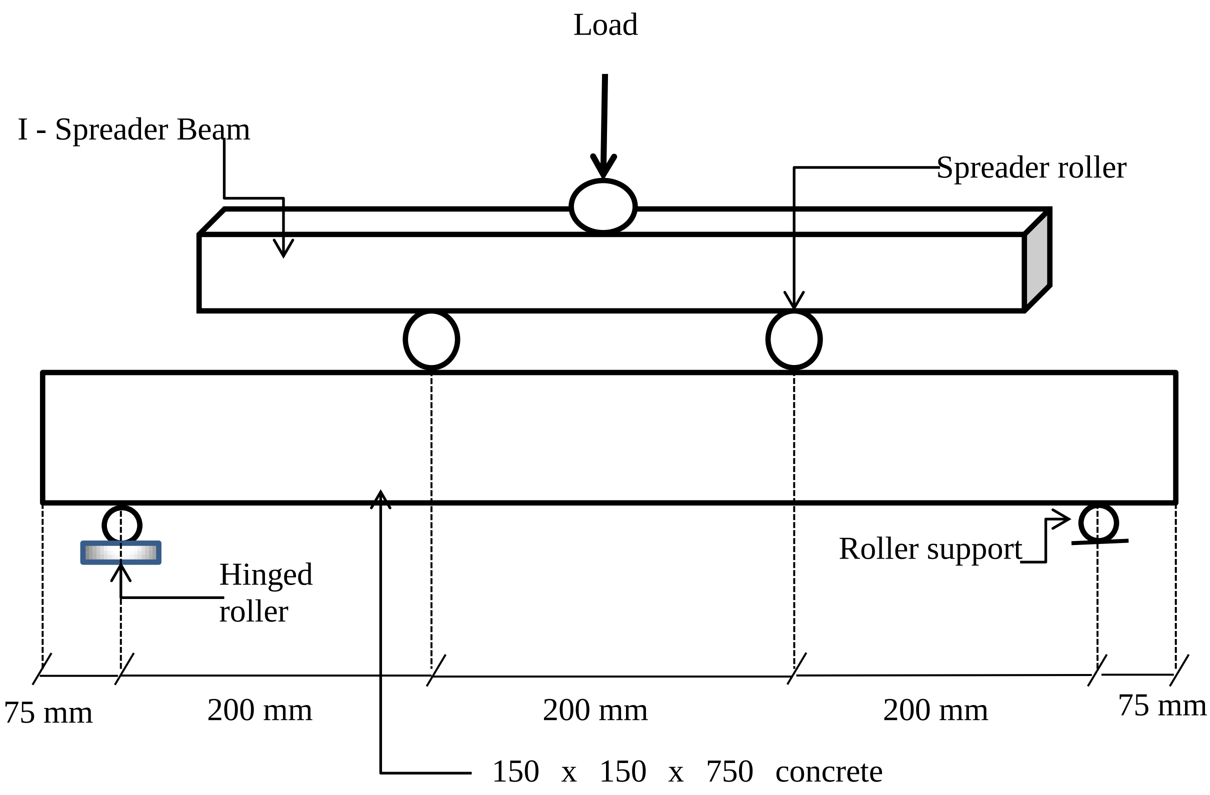


Figure 14. Schematic representation of third point loading system

The maximum tensile stress reached at the outermost fibre of the beam under tension at failure is the flexural strength of the concrete which is expressed as the modulus of rupture (f_r), and its value depends on the mode of failure of the beam. The two different modes of failure are:

a) when the failure crack occurs within the middle third of the span length as represented in Figure 15, then the split tensile strength can be expressed as

$$f_r = \frac{P_i L}{b d^2} \tag{17}$$

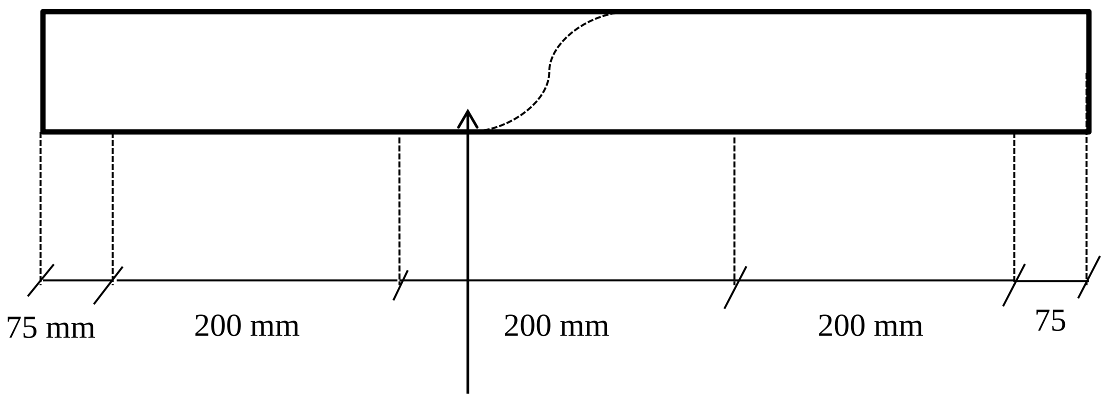


Figure 15. Schematic representation of failed beam within the middle third

b) when the failure crack occurs outside the middle third of the span length, as indicated in Figure 16 but not more than 5 % of the span length. The split tensile strength of the concrete can be expressed as

$$f_r = \frac{3 P_i a}{b d_f^{\,2}} \tag{18}$$

where f_r = modulus of rupture (N/mm^2)

P_i = maximum applied load as indicated on the testing machine (N)

L = span length (mm)

B = average width of the specimen at the fracture (mm)

d_f = average depth of the specimen at fracture (mm)

a = distance between the line of fracture and the nearest support measured on the tension surface of the beam.

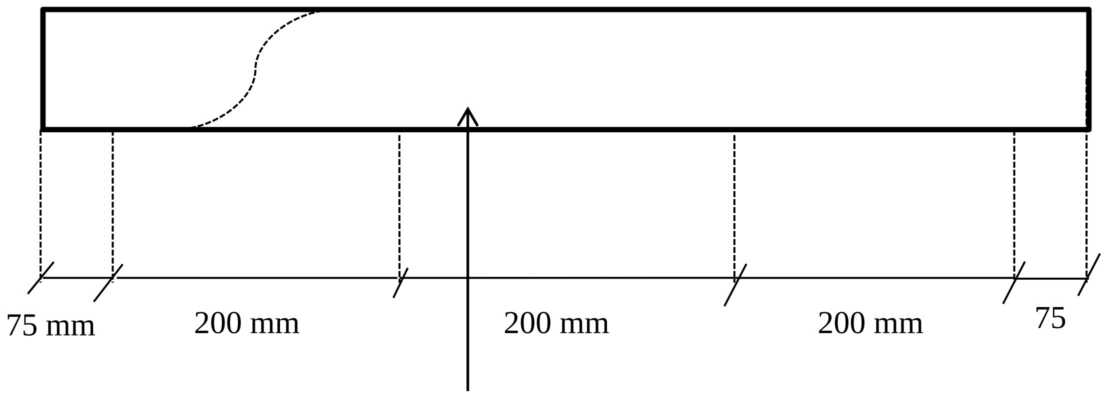


Figure 16. Schematic representation of failed beam outside the middle third

2.5 Flexural Capacity of Reinforced Concrete Beams

Arthur *et al*. (2010), Mosley *et al*. (1999), and ACI (2015) explained the behaviour of beam under flexural load, modes of failure and laboratory methods of determining flexural and shear capacities of reinforced beams. Also, they defined the relationship of moment and shear capacities to structural concrete properties: (split tensile strength and modulus of rupture) and geometric dimensions of concrete beams.

2.5.1 Flexural Behaviour of Reinforced Concrete Beams

According to Arthur *et al.* (2010), an adequately reinforced concrete beam with shear and flexural reinforcement will undergo three distinct stages before failure which are:

i the applied stresses are less than the elastic limit of concrete

ii the applied stresses are beyond the elastic limit of concrete.

iii the applied stresses create nonlinear stress-strain relationship.

2.5.1.1 The elastic limit state of concrete.

The flexural stress developed at this stage is less than the modulus of rupture of the beam. So, the entire concrete is effective in resisting stresses in compression on one side and tension on the other side of the neutral axis of the beam. The stress at any given point in the cross section is proportional to the strain as shown in Figure 17 and can be expressed as

$$f = \frac{My}{I} \tag{19}$$

where y = distance from the neutral axis

f = bending stress at a distance y from neutral axis

M = external bending moment

I = moment of inertial of cross section about neutral axis.

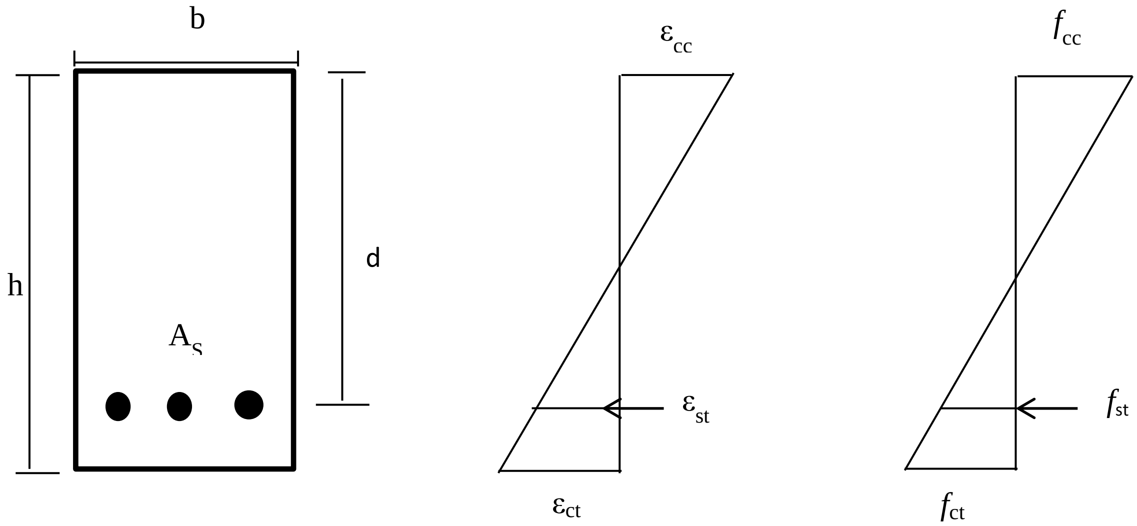


Figure 17. Distribution of strains and stresses within elastic limit of reinforced concrete beam

In Figure 17

A_s = area of tensile steel

b = width of beam

d = depth of tensile steel from top most compression fibre

h = overall depth of beam

ε_{cc} = compressive concrete strain

ε_{ct} = tensile concrete strain

ε_{st} = tensile steel strain

f_{cc} = compressive concrete stress

f_{cc} = tensile concrete stress

f_{cc} = tensile steel stress.

2.5.1.2 Beyond the elastic limit of concrete.

The flexural stress in the beam is greater than the modulus of rupture and the split tensile strength of the concrete but less than approximately half of the compressive strength of concrete ($f_{cu}/2$). Therefore, stress-strain relationship continues to be closely proportional; but tension cracks are developed. The tensile stresses in the crack sections are transmitted by the reinforcement provided in the beam. This is shown in Figure 18.

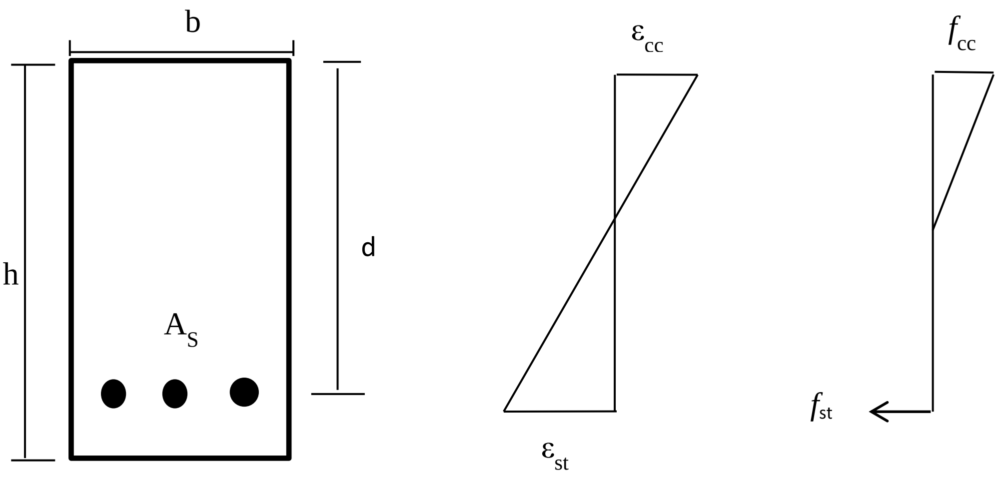


Figure 18. Distribution of strains and stresses in a cracked section of reinforced concrete beam

2.5.1.3 Nonlinear strain and stress state.

The stress-strain relationship illustrated in Figure 19 is no longer proportional. Further addition of load would develop flexural-shear cracks which are preceded by flexural cracks. Thus, the load carrying capacity of the beam is reached and ductile failure occurs. The failure is gradual and is preceded by visible signs of distress, such as the widening and lengthening of the tensile cracks and marked increase in deflection.

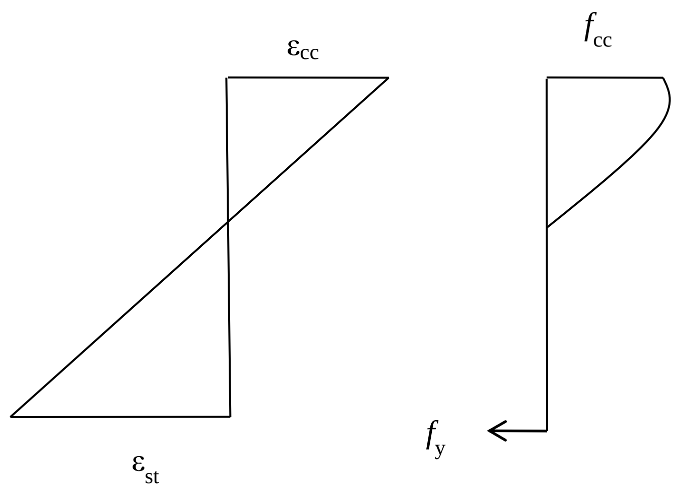


Figure 19. Distribution of stresses and strains in a reinforced concrete beam at ultimate limit

In Figure 19

f_y = characteristic tensile strength of steel.

Tan *et al*. (2015) investigated the flexural behaviour of reinforced foamed concrete beams. Two different mix proportions which contain cement and sand in the ratio of 3:1 and 2:1 were used to produce different samples of foamed concrete. The properties that were examined included ultimate compressive strain, mode of failure, and displacement – ductility ratio. They found that both samples of foamed concrete have ultimate compressive strain value of 0.0036, failed in flexural-shear mode, and the displacement-ductility values were less than three (3). They concluded that the displacement-ductility value of foamed concrete makes it inadequate construction material for earth quake resisting structure.

2.5.2 Moment and Shear Capacities of Reinforced Concrete Beam

The moment and shear capacities of reinforced concrete beams are determined with third point loading system which is represented in Figure 20 (ASTM C-9, 2016; BS EN 12390-5, 2009).

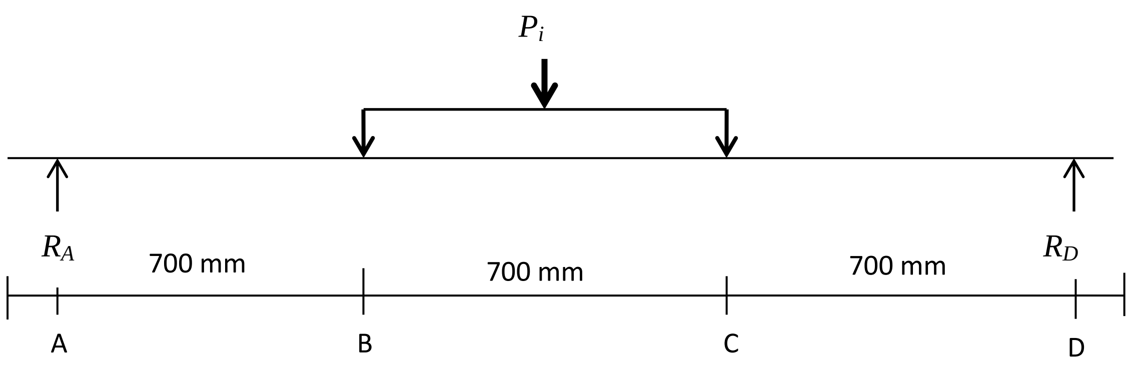


Figure 20. Schematic drawing of third point load test

In Figure 52

support type = simply supported

vertical force (V) = R_i

horizontal Force (H) = 0

rotation (Φ) = 0

end moment (M) = 0.

As the load is increased, at a certain value the beam will fail either in shear or flexural mode. The applied moment and shear force in the beam at failure (ultimate limit) are determined with static equilibrium equations of vertical forces and moment expressed as

$$\sum F_y = 0 \tag{20}$$

$$\sum M_D = 0 \tag{21}$$

respectively. The moment and shear force diagrams are shown in Figures 21 and 22.

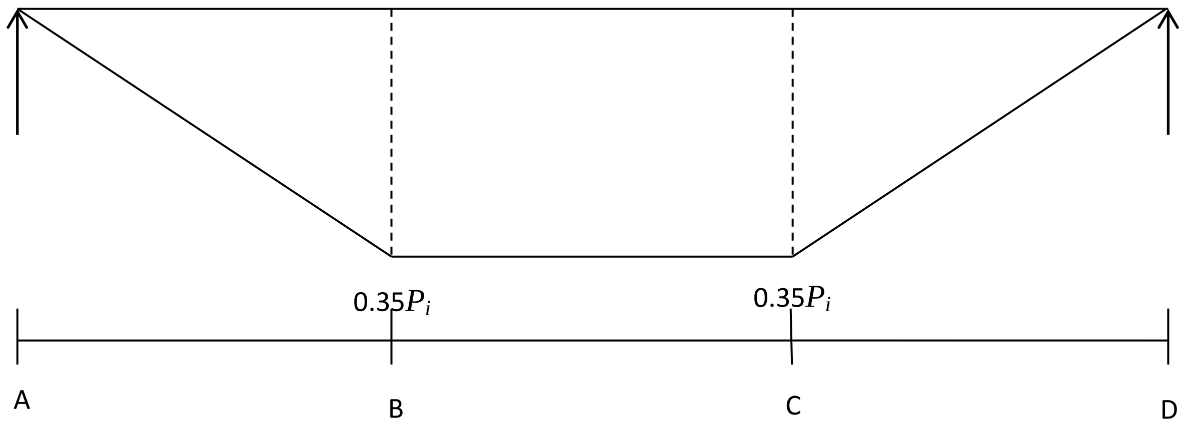


Figure 21. Moment diagram at ultimate load

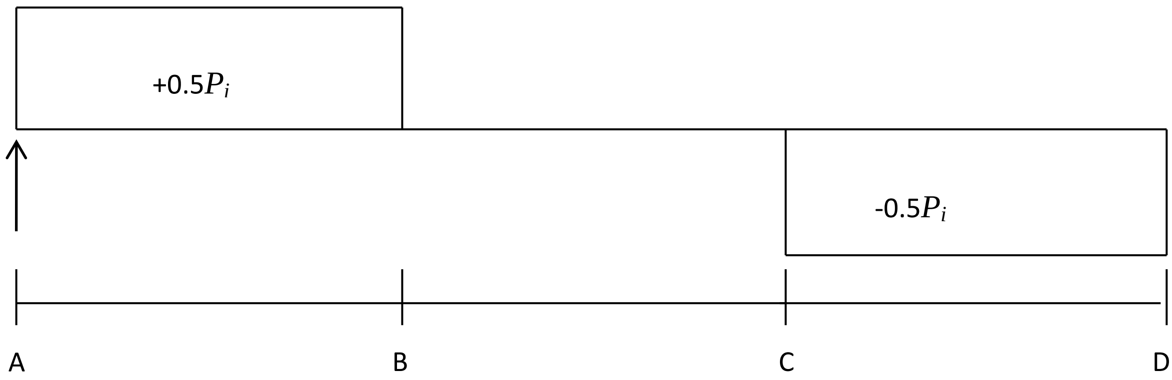


Figure 22. Shear force diagram at ultimate load

According to Arthur *et al*. (2010) and Mosley *et al*. (1999) the moment and shear capacities of reinforced concrete beams are determined from of equilibrium of forces, stress and strain distribution in the member as shown in Figures 23 to 25.

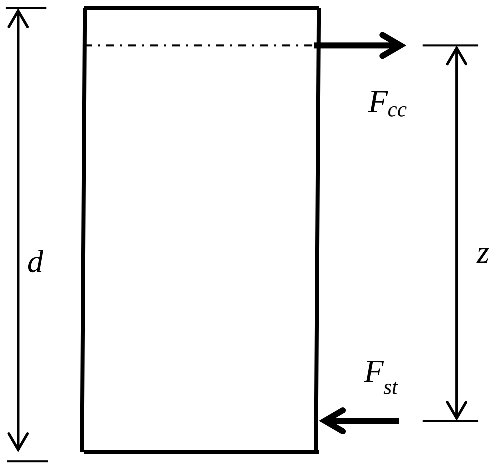


Figure 23. A Section of a beam showing internal equilibrium of forces at ultimate load

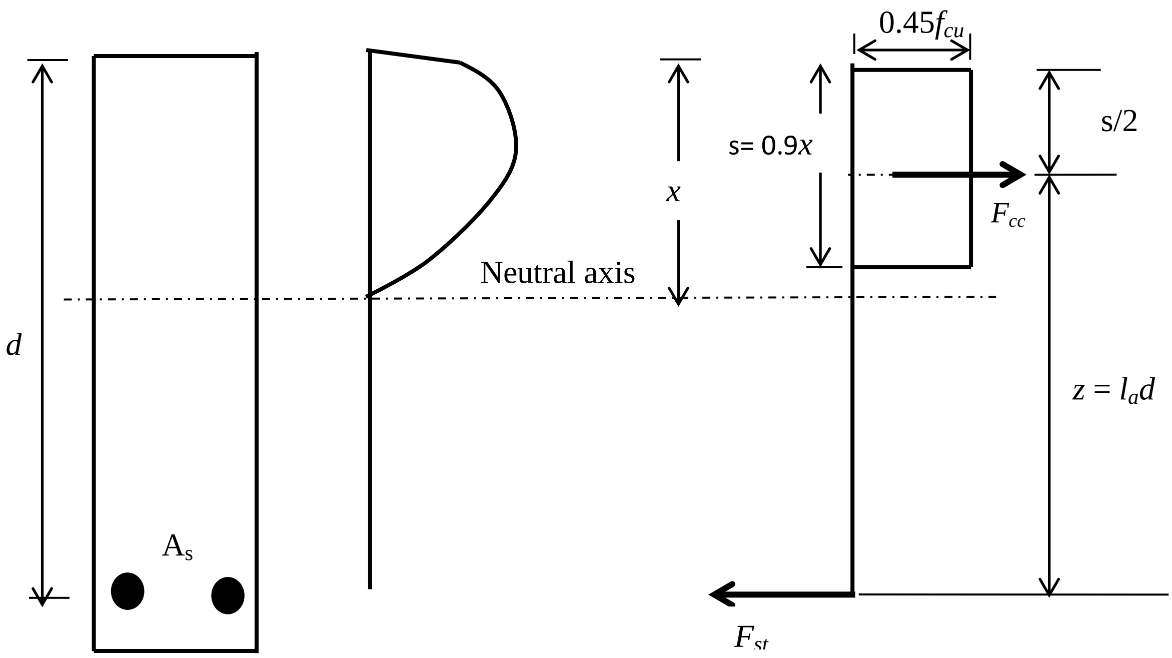


Figure 24. Actual and equivalent rectangular stress distribution at ultimate load

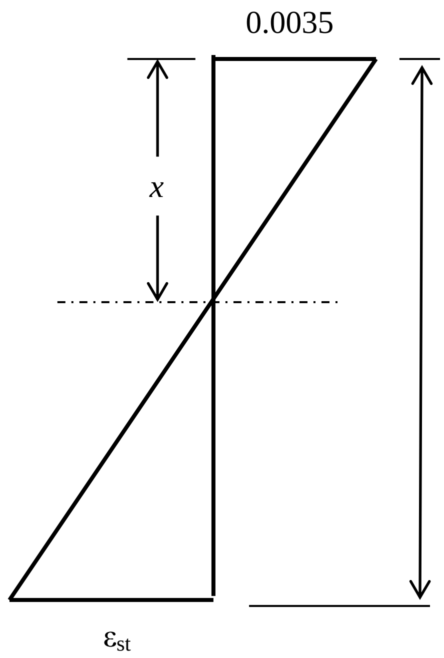


Figure 25. Net tensile strain at ultimate load

In Figures 23 to 25

F_{cc} = compressive force

F_{st} = tensile force

f_{cu} = characteristic compressive strength of concrete

f_{st} = characteristic tensile strength of steel

A_s = area of steel reinforcement

d = depth of tensile steel from top fibre

x = depth of neutral axis from top fibre

s = equivalent depth of neutral axis from top fibre

z = lever arm

ε_{st} = tensile strain.

From the analysis of equilibrium of forces, stress and strain distribution, Mosley *et al.* (1999) states that the moment and shear capacities of singly reinforced concrete beams is determined with relationships expressed as

$$M_u = 0.156 bd^2 f_{cu} \tag{22}$$

and

$$V = vbd = 0.95 f_{yv} A_{sv} \tag{23}$$

respectively.

They explained that moment capacity of a concrete beam depends on the geometrical dimensions, compressive strength of concrete and provision of adequate shear reinforcement that is estimated using the expression

$$\frac{A_{sv}}{s_v} = \frac{vb}{0.95 f_{yv}} \tag{24}$$

where M_u = moment capacity of concrete beams

V = shear force at ultimate load

v = shear stress

f_{yv} = characteristic tensile strength of link reinforcement

s_v = spacing of links along the member

A_{sv} = cross-sectional area of shear reinforcement in the form of links.

Arthur *et al.* (2010), states that moment capacity of a singly reinforced concrete beam is developed if the flexural compression force in the concrete is greater than the tensile force in the steel reinforcement. Also, they explained that this condition is achieved by providing the right quantity of steel in the beam that is between the minimum and maximum limits expressed as

$$A_{s,min} \geq \frac{0.21 bd f_r}{f_y} \tag{25}$$

and

$$A_{s,max} \leq \rho_m bd \tag{26}$$

where $A_{s,\,min}$ = minimum steel

b = width of beam

d = effect depth of tension reinforcement

f_r = modulus of rupture of concrete

f_y = characteristic strength of steel

$A_{s,max}$ = maximum steel required

ρ_m = maximum reinforcement ratio ($0.000590 f_{cu}$).

Arthur *et al.*, also illustrated the two different modes of failure of reinforced concrete beams which are flexural-shear and shear modes of failure and are represented in Figures 26 and 27 respectively.

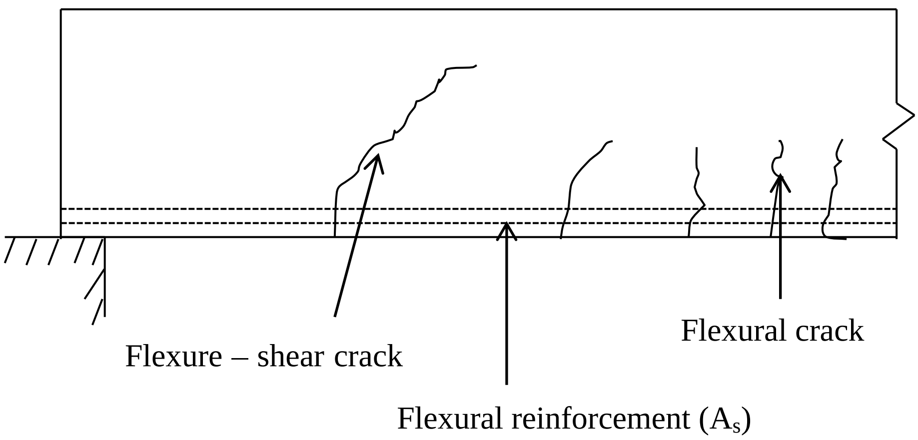


Figure 26. Schematic representation of failed reinforced concrete beam on flexural shear mode

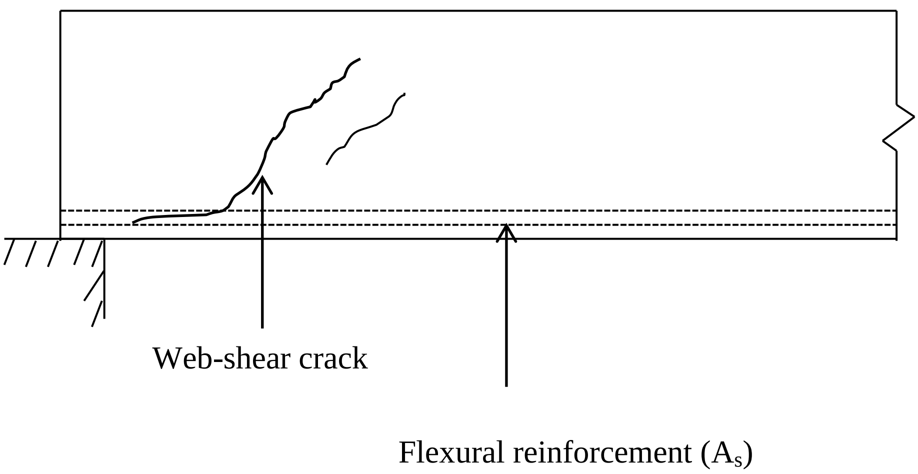


Figure 27. Schematic representation of failed reinforced concrete beam on web-shear mode

They explained that flexural- shear failure usually occurs in reinforced concrete beams with adequate shear and flexural reinforcement. This mode of failure occurs with the development of a flexural crack close to the middle third of the beam and it is preceded with flexural cracks within the middle third. The failure is gradual (or ductile) with visible distress signs such as the widening and lengthening of the tensile cracks and marked increase in deflection. In the same vain, they explained that shear failure occurs in reinforced concrete beams without shear reinforcement or inadequate shear and flexural reinforcement were provided. They noted that this mode of failure is sudden (or brittle) and occurs with web-shear cracks, and without any visible distress signs.

2.6 Foamed Concrete: Conventional and Innovative Mix Composition

Conventional foamed concrete is composed of cement as binding material, sand as filler, water and foam obtained from diluted foaming agent. The different degrees of interaction of these materials in a fresh foamed concrete determine the physical and structural properties of the product. According to Kearsley (1996), cement paste sets around the air bubbles and these air bubbles degenerates after approximately three quarters of an hour. Within this period, the paste was found to have acquired sufficient strength to maintain its shape around the air void.

In this regard, the microstructure of foamed concrete consists of the solid hydrate structure and the cellular structure (non-connected system of cells voids). The hydrate structure contributes to the structural properties, whilst the voids determine the non-structural properties: density, water absorption capacity, thermal and sound insulation capacities. Thus, the qualities of the hydrate structure and void have been subject of research interest.

Nambiar and Ramamurthy (2008), and Wee *et al*. (2006) explained the different methods of foam production and their effects on the quality of the foam. These methods are pre-formed foam process and agitation of the mixture of mortar and foaming agent such as detergents, resin soap, glue resins, saponin, and hydrolysed proteins. The pre-formed foam process was found to produce foamed concrete with superior qualities because it has controllable pore forming process and there are no chemical reactions involved. Also this method is divided into two categories namely, wet foam and dry foam production process.

Wet foam is produced by spraying a solution of foaming agent and water over a fine mesh. The wet foam produced has size range of 2 mm to 5 mm in diameter. The dry foam is produced by forcing a similar solution of foaming agent and water through a series of high-density restrictions, combined with forced compressed air into a mixing chamber. Aldridge (2005) found that dry foam is stable, small and less than 1mm in diameter, thick, tight and produce foamed concrete with superior properties.

British Cement Association (1994) investigated the effect of fine aggregates sizes on the compressive strength of foamed concrete. The findings revealed that finer aggregates sizes were suitable for foamed concrete production; because the weight of coarse aggregates might be more than the foam could suspend, which would lead to collapse of the foam during mixing. Thus, they recommended that the maximum fine aggregate size for foamed concrete production should be 2.0 mm with 60-90 % of it passing through 600micron sieve. Also, Maziah (2011) suggested that finer aggregates sizes help to improve the foamed concrete flow characteristics and stability.

In addition to the effect of aggregate sizes on the quality of the hydrate structure of foamed concrete, Westend Indutries Pty Ltd (2010) and Litebuilt (2008) stated that water/cement ratio is also an important factor. They suggested that an average w/c ratio between 0.4 and 0.8 is adequate for foamed concrete production. Also it was concluded that if the water/cement ratio of the mortar is lower than 0.4, the necessary amount of water required for workability to be achieved would be extracted from the foam. Then, some of the foam would collapse, which is naturally an expensive way of adding water to the mix. More so, if higher water/cement ratio is used, it could cause segregation of the concrete components.

Brady *et al.* (2001) suggested quality control measures in Table 10 for the mix design and production of foamed concrete; which would help to ensure that the required qualities are achieved.

Table 10

Quality control measures for the design and production of foamed concrete

Property	Control Limits
28th day dry density	400 – 1600 kg/m^3
Plastic density	150 –200 kg/m^3 greater than the corresponding dry density
Standard volume for measuring plastic density	5Litres container in accordance with BS EN 12350- 6 (2009
Measurement tolerance of plastic density	±50 to ±100 kg/m^3

Brady *et al.* (2001)

In recent times, research findings in Jones and McCarthy (2005a), Kunhanadan and Ramamurty (2006), Pan *et al.,* (2006), and Falade *et al*., (2013) have suggested different innovative foamed concrete mix composition. The innovative mixes were achieved through the replacement of any conventional component of foamed concrete with other materials or addition of new component. This idea is geared toward achieving a product with superior quality, lower cost of production or both advantages.

In this respect, Jones and McCarthy (2005a) examined the potential of foamed concrete as a structural material; using fine fly ash, coarse fly ash as fine aggregates. They observed reduction in shrinkage strain; improved compressive strength and improved modulus of elasticity.

Kunhanadan and Ramamurty (2006) investigated the effect of using fly ash as fine aggregate on the properties of foamed concrete. They observed that the plastic density of foamed concrete depends on the type of the fine aggregate; particle size distribution (of the fine aggregates). They also observed that foamed concrete with varying proportions of fly ash developed higher compressive strength when compared with sample without fly ash.

Pan *et al.* (2006) investigated preparation of high performance foamed concrete; using ultra- granulated blast-furnace slag, pulverized fly ash, condensed silica fume as replacement of fine aggregates. They concluded that the foamed concrete made with these materials developed an improved compressive strength up to 44.1N/mm^2 for oven dried specimens at 28-day; improved workability (excellent flow-ability) and low thermal insulation capacity.

Falade *et al*. (2013) investigated the effect of partial replacement of cement with pulverized cow bone on the structural properties of foamed concrete. They concluded that up to 20 % of the cement component of foamed concrete could be replaced with pulverized cow bone without significant effect on the structural properties.

Jones *et al*. (2005) examined the potential use of Recycled and Secondary Aggregates (RSA) as partial replacement of sand in foamed concrete. The RSA used were namely, incinerator bottom ash, crumbs of rubber tyres, foundry sand and China clay. The effect of those RSA on the compressive strength of foamed concrete was examined. They concluded that RSA are good replacement of fine aggregate in foamed concrete production.

Grigorij *et al.* (2006) investigated "Foamed Concrete Reinforced by Carbon Nanotubes". In the investigation, carbon nanotubes synthesized from aromatic hydrocarbon were added into the foamed concrete and the effects on the compressive strength, heat conductivity and rate of carbonation of foamed concrete were examined. The results showed 70 per cent increase in compressive strength, 20 per cent reduction in heat conductivity, and high rate of carbonation. It was concluded that carbon nanotubes synthesized from aromatic hydrocarbon could be used to improve the internal structure of foamed concrete.

Admittedly, much work has been done on innovative foamed concrete mixes but no study on the use of laterite to improve particle size distribution of the fine aggregate in foamed concrete has been reported. However, research findings (Ikponmwosa and Falade, (2006), and Ikponmwosa and Salau 2010) revealed that laterite could be used as partial replacement of dredged sand in normal weight concrete production. They observed that laterite increases the surface area and the inter-particle bond of dredged sand. Consequently, they noted that it increased the amount of water required to achieve surface saturation and reduced the workability or flowing property of the concrete.

Buchanan (1807) cited in Jayarajan (2004) described laterite as highly ferruginous deposit which is diffused in immense masses, without any appearance of stratification. He also explained that it contains pores, and large quantity of iron in the form of yellow and red ores; and that it is capable of hardening on exposure to moisture and drying. Also, Tardy (1997) defined laterite as a reddish soil type rich in Iron and Aluminium, formed in hot and wet tropical areas at or near the earth's surface through the process of tropical weathering (laterization). Dalvi *et al.* (2004) described laterization process as a prolonged chemical weathering which produces a wide variety in thickness, grade, chemistry and ore mineralogy of the resulting soil. This is because the product of laterization is formed from the leaching of parent sedimentary rocks (sand stones, clays, limestones) metamorphic rocks (schists, gneisses, migmatites) and igneous rocks (granites, basalts, gabbros, peridotites) under the high temperature of a humid sub-tropical climate.

Hill *et al*. (2000) observed that an essential feature for the formation of laterite is the repetition of wet and dry season. Yamaguchi and Kosei (2003) explained that rocks are leached by percolating rain water during the wet season; the resulting solution containing the leached ion is brought to the surface by capillary action during the dry season. These ions from soluble salt compound dry on the surface and are washed off during the preceding wet season. Dalvi *et al.* explained that laterite varies significantly according to their location, climate and depth. So, Laterite deposits have been described on the basis of the dominant extractable minerals in it.

The two commonly found laterite deposits are:

a) ferruginous laterite (iron ore): The chemical composition of this laterite is such that $Fe_2O_3:Al_2O_3 > 1$ and $SiO_2:Fe_2O_3 < 1.33$

b) aluminous laterite (bauxite): The chemical composition of this type of laterite is such that $Fe_2O_3:Al_2O_3 < 1$ and $SiO_2: Al_2O_3 < 1.33$.

Other laterite deposits are:

c) manganiferous laterite (manganese ore)

d) nickeliferous laterite (nickel ore)

e) chromiferous laterite (chrome ore).

According to Osunade (2002), Olawuyi and Olusola (2010) laterite is useful in Civil Engineering and Building construction works. In this respect, Osunade (2002) explained that laterite in a moist state could be easily cut into regular sized blocks, and on exposure to the atmosphere it loses its water and becomes hardened. Also, he suggested that laterite is one of the major geotechnical and building materials in Nigeria, because of its extensive presence. Olawuyi and Olusola (2010) stated that laterite either in raw or improved form is used both in rural and urban areas for housing construction in form of masory blocks. They reported that Federal Low-Cost Housing Estate in Lagos, Kebbi and Ekiti states were constructed with interlocking stabilized laterite blocks.

Falade and Ikponmwosa (2006) stated that the strength properties of fibre-reinforced laterized concrete under normal laboratory temperature showed consistent trend of increase in strength with age. They also observed that 25 per cent laterite as partial replacement of dredged sand was the maximum that satisfied the workability requirement with increase in the compressive strength.

2.7 Cost Benefit Analysis

Thayer (2012) stated that Cost Benefit Analysis (CBA) is a tool that estimates and totals up the equivalent money values of the benefits and costs of the community of projects to establish whether they are worthwhile. He noted that CBA could be applied in different types of projects such as dams, highways, training programmes, and health care systems. Also, MindTools (2015) suggested that CBA involves adding up the benefits of cause of action and then compare it with sum of the costs associated with the project. Also, it was explained that the steps required to evaluate a project are brainstorm costs and benefits, assign monetary values to costs and benefits, and compare costs and benefits.

2.7.1 Brainstorm Costs and Benefits

This process involves identifying and documenting all costs associated with the project and the benefits of the project. The costs include the costs of physical resources, human efforts in all phases of the project, and overheads. Also, the benefits include financial value of the project, and the intangible or soft impacts of the project.

2.7.2 Assign Monetary Values to Costs and Benefits

The authors (Thayer (2012) and MindTools (2016) agreed that in CBA, the costs and benefits must be expressed in terms of a common unit; and that the most common unit is money. So, all benefits and costs of a project are measured in terms of their equivalent money values at a particular time. Therefore, costs are the market prices of the physical resources, human efforts and overheads required in the project. In the same vein, the benefits are conservatively, the market price that the product is sold.

2.7.3 Compare Costs and Benefits

This is the final step in the cost-benefit analysis process. It involves comparing the value of the costs with the value of the benefits of the project; in order to determine whether benefits outweigh the costs. But for some projects, the conclusion is based on payback period concept. This concept reveals that high cost compared with profit of a project in the early stage does not make it worthless, provided that within the payback period the benefits repay the costs.

The flexibility of CBA tool in decision making process to determine the worth of a project was reported in Ronald (1998) on the fundamental principles of CBA. He concluded that CBA could be reduced to several major principles that collectively described the assumption base, objectives, analytical tasks, and the merits of project assessment methodology.

In this respect, CBA tool is used to justify the replacement of sand with laterite in foamed concrete.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Theoretical Frame Work

The theoretical frame work for this study is based on research findings that established relationship of applied shear stress to yield stress of self-compacting concrete. In self-compacting concrete the applied shear stress is usually greater than the yield stress; and the shear and yield stresses are equivalent to the weight of the sample volume in the truncated cone as shown in Figure 6 and the inter-particle forces in the mix respectively (Banfill (2006); Ferraris & Martys, 2003). Ferraris (1996) states that foamed concrete would continue to flow when the cone is lifted; under this condition, the shear stress is greater than the yield stress and the shear stress can be determined by using the expression

$$\tau = \frac{\rho g V s}{\pi r_1^{\,2}} \tag{27}$$

where τ = shear stress due to the weight of sample volume

ρ = density of foamed concrete

g = acceleration due to gravity

V_s = volume of cone = $\frac{1}{3\pi}(r_1^2 + r_1 r_2 + r_2^2)h_c$

r_1 = the smaller radius of the truncated cone

r_2 = the greater radius of the truncated cone

h_c = height of truncated cone.

The concrete will spread to radius R where $\tau = \tau_o$ and the shear stress is expressed as

$$\tau = \tau_o = \frac{\rho g V s}{\pi R^2} \tag{28}$$

where τ_o = yield stress

R = radius of sample spread after the cone is lifted.

The spread test is used to measure the effect of replacing river dredged sand with laterite on rheological properties measured as plastic density and spread value of foamed concrete. Two models are developed from the experimental results obtained by replacing river dredged sand with laterite from 0 to 100 % at interval of 10 units. These models are plastic density and spread value prediction models and are expressed as

$$D = f(\phi) \tag{29}$$

and

$$S_D = f(\phi) \tag{30}$$

where D = plastic density of foamed concrete

S_D = spread diameter

Φ = proportion of laterite.

3.2 Materials Preparation and Methods

The laboratory activities that were carried out in this study included Preliminary investigation and main investigation. The main investigation is of two parts namely phase I and phase II.

3.2.1 Preliminary Investigation

The preliminary investigation activities involved the following: sourcing and characterization of materials; mix design and trial mix; determination of the effect of replacing sand with laterite on plastic density, spread diameter and the compressive strength; effect of curing duration in water and variation of w/c ratio on compressive strength of foamed concrete.

3.2.1.1 Materials

The materials that were used in this study are OPC, fine aggregates (river dredged sand and laterite), water and foam concentrate.

3.2.1.1.1 Ordinary Portland Cement (OPC)

Two different types of OPC cement commonly used in Lagos for construction were sourced from local retailers and their properties were compared. The cement samples have descriptions as 42.5R and 32.5N. The properties of the cement examined were consistency, initial and final setting times in accordance with BS EN197-1 (2011).

3.2.1.1.2 Fine aggregates

The fine aggregates used in this study were river-dredged sand and laterite. The river-dredged sand was obtained from Ogun River in Abeokuta, Ogun State. The sample of laterite was obtained in a laterite borrow pit (see Appendix A1) at Mowe, in Ogun State. The particles size distribution of the fine aggregates was determined with sieve analysis (see Appendix A2) in accordance with BS EN 12620 (2013). The sample of the laterite was washed in 150 μm sieve. Particles retained in the sieve were oven dried to constant weight. The dried sample was used to determine the particle size distribution of the sand component of the laterite. Additional properties of laterite examined included optimum moisture content and cohesion coefficient. The fine aggregates were prepared by air drying in the laboratory, and then sieved with 2.36 mm sieve aperture to remove gravel particle sizes.

3.2.1.1.3 Water

Clean and portable water supplied to the laboratory from the University was used for this experiment. It was clean and free of deleterious materials. This property is important because it prevents any undesirable chemical reaction that could affect the properties of the foam concentrate and the concrete both in plastic and hardened states.

3.2.1.1.4 Foam Concentrate

The foam concentrate used is enzyme-based LithoFoam SL 200-L. Luca Industries International (2009) explained that LithoFoam SL 200-L is stable, and has neutral odour. Also that one kilogram of it produces an average of about 275-350 litres of foam. The foaming agent was stored in a cool dry place in the laboratory.

3.2.1.2 Mix design

The mix design was carried out to establish the appropriate combination of various materials to achieve the desired plastic density and targeted characteristic compressive strength (f_{cu}). Kearsly and Mostert (2005a) stated that the general rules regarding water/cement ratio (w/c), free water content and maintaining a unit volume applies in foamed concrete design as in normal weight concrete design. The design procedure includes: definition of design criteria, determination of the quantities of water and sand to achieve viscous consistency

3.2.1.2.1 Design criteria

The design criteria used in this work are as follows:

D_o = dry density of foamed concrete at 28th day = 1,600 ±100 kg/m^3 (*Brady et al.*, 2001; John and Phil, 2003).

C = quantity of cement for structural concrete = 350kg/m^3

D = Plastic density = 1,600 kg/m^3 + 150 (margin) (Brady *et al*., 2001)

2R = 560 mm $\leq$ Spread diameter $\leq$ 760 mm (Gambhir, 2013)

The characteristic strength of foamed concrete is dependent on several variables which include w/c, quantity of cement and volume of foam. The mathematical relationship between the compressive strength and these variables are expressed as

$$f_{cu} = f\left({}^{W}\!/_{C}, D_o, C\right) \tag{31}$$

while the plastic density is expressed as

$$D = f\left(V_f\right) \tag{32}$$

where V_f = volume of foam

w/c = water/cement ratio.

Also, the composition of foamed concrete is determined with the expressions

$$D = C + W_w + F + W_f \tag{33}$$

$$W_w = \left({}^{w}\!/_{c} \right)*C \tag{34}$$

$$D = D_0 + 150 \tag{35}$$

where W_w = weight of water/m^3

F = weight of fine aggregate/m^3

W_f = weight of foam/ m^3 (= 0 kg).

3.2.1.2.2 Determination of the quantities of water and sand to achieve mix with viscous consistency

Different combination of cement, sand and water compositions were estimated with the design criteria values. The results of trial mixes of the different compositions showed that w/c of 0.7 was the minimum that prevented balling of the base mix. Trial mixes with lower w/c ratio of 0.5 and 0.6 produced base mixes with inadequate consistency. Consequently, all the foam injected into the mix collapsed without any significant effect on the rheology of the mix. The target plastic density is obtained by substituting the target dry density (1,600 kg/m^3) into Equation (35).

D = 1,600 + 150 = 1750 kg/m^3

In the same vein, weight of water required for base mix is obtained from Equation (34):

$W_w = 0.7 * 350 = 245$ kg/m^3 (base mix)

Here,

D =1750kg/m^3 (target density kg/m^3)

C = 350kg/m^3 (weight of cement in kg/m^3)

W_w = 245kg/m^3 (weight of water in kg/m^3)

The weight of fine aggregate is obtained by substituting these values into Equation 33 which gives

1750 = 350 + 245 +F

which implies

1750 = 595 + F

and

F = 1750 – 595 = 1155kg/m^3

The estimated quantities of the different components for the base mix are presented in Table 11. In the same vein, when the quantity of cement is taken as 500kg/m^3, the minimum w/c ratio that produced viscous consistency mix is 0.5 and the mix composition is shown in Table 12.

Table 11

Base mix composition of foamed concrete in kg/m^{3}with w/c ratio of 0.7

Cement	Sand	Water
350 kg	1155 kg	245 kg

Table 12

Base mix composition of foamed concrete in kg/m3 with w/c ratio of 0.5

Cement	Sand	Water
500 kg	1000 kg	250 kg

3.2.1.2.3 Determination of the volume of foam.

The minimum volume of foam (V_f m^3) required to produce the targeted foamed concrete plastic density is estimated from the relationship of the plastic density of foamed concrete to the density of the mortar (base mix), in which case

$$D = \frac{D_B}{(1+V_f)} \tag{36}$$

where D = 1750 kg/m^3 (targeted foamed concrete plastic density kg/m^3)

D_B = density of base mix (mortar)

V_f = Volume of foam (m^3).

The density of the mortar was measured as described in Table 13. The weight of the sample obtained from the base mix was measured on a digital scale in a pre-weighed container of a known volume of 5-litres.

Table 13

Procedures for the determination of density of the base mix

Parameter		Values
Volume of container	(m^3)	0.0055
Weight of container	(kg)	0.38
Weight of container + slurry	(kg)	11.59
Weight of base mix	(kg)	11.9 - 0.38 = 11.29
Base mix density	(kg/m^3)	11.29/0.0055= 2040

The estimated density of the base mix is substituted into Equation (36) to obtain the required quantity of foam as expressed below.

D_B = 2040 kg/m^3 and D = 1750 kg/m^3

$$1750 = \frac{2040}{(1+V_f)}$$

$$1750\ (1 + V_f) = 2040$$

$$1750\ V_f = 2040 - 1750$$

$$V_f = \frac{290}{1750} = 0.166\ m^3 = 166 \text{ litres}$$

Luca Industries International (2009) states that one kilogram of SL200-L produces average of 275-350 litres of foam. Therefore quantity of SL200-L required = $\frac{166 \text{ x } 1\text{kg}}{275}$ = 0.6 kg.

This value is the net volume of foam required. The gross value of foam volume takes into account loses due to:

a) machine efficiency

b) foam collapse during mixing.

3.2.1.3 Trial mix

Trial mix was carried out to validate the results of the design mix and to establish the foamed concrete mix composition that satisfies the design criteria. It includes the following procedures namely production of foamed concrete, determination of plastic density of concrete and determination of spread diameter of concrete. Several trial mixes were made using various quantities of foam concentrate with dilution ratio of 1:33 (1 part of foam concentrate to 33 parts of water).

3.2.1.3.1 Production of foamed concrete

Trial mix procedures are laboratory activities that were carried out in proper sequence. Firstly, the equipment was cleaned and set-up (see Appendices A3 and A4). These included cleaning of the concrete mixer, cleaning and setting up of the spread test table and the truncated cone, and setting-up of the foam generator. Then, the quantities of materials such as cement, sand, foam concentrate and water were measured and different batches of 0.1 m^3 were prepared with foam concentrate from 0.6 kg to 1.4 kg at interval of 0.1 unit.

The sand, cement and water required to produce the base mix (or mortar) for each batch was fed into the concrete mixer which is powered with in-built engine. The mixer rotates and properly mixed the materials till viscous consistency was achieved. Also, the foam concentrate was diluted with the estimated quantity of water and fed into the foam generator; the foam produced was injected into the concrete mixer (see Appendix A5) and it was properly mixed with the mortar to produce foamed concrete.

3.2.1.3.2 Determination of plastic density

The plastic densities of the different batches were measured with 5 litres container. For each batch of the fresh foamed concrete three samples of 5 litres were taken and weighed on a digital scale (see Appendix A6). The average of the weights was taken as the plastic density.

3.2.1.3.3 Determination of the spread diameter

The truncated cone was placed on a flat non-absorbent surface. The surface was cleaned to ensure it was free of friction. The cone was held firm and filled with fresh foamed concrete, and lifted up to allow the concrete to flow out and spread to a radius (R) (see Appendix A7). The diameters of spread of the foamed concrete over a flat horizontal surface on two perpendicular directions were measured. The average of the two measurements is the spread diameter of the foamed concrete.

3.2.1.4 Effect of replacing sand with laterite on plastic density, spread diameter

The effects of replacing sand with laterite on the plastic density and spread diameter were examined. Eleven different batches with laterite from 0% to 100% at interval of 10 units as replacement of sand were prepared as shown in Table 14. The production of foamed concrete with laterite, measurements of plastic density and spread diameters were carried as described in trial mix procedure.

Table 14

Proportions of materials in different batches

Laterite (%)	Cement (kg)	Sand (kg)	Laterite (kg)	Water^b (kg)	Water^f (kg)	Foam conc (g)
0	35	115.5	-	24.5	4.5	135
10	35	103.95	11.55	24.5	4.5	135
20	35	92.4	23.1	24.5	4.5	135
30	35	80.85	34.65	24	4.5	135
40	35	69.3	46.2	24.5	4.5	135
50	35	57.75	57.75	24.5	4.5	135
60	35	46.2	69.3	24.5	4.5	135
70	35	34.65	80.85	24.5	4.5	135
80	35	23.10	92.4	24.5	4.5	135
90	35	11.55	103.95	24.5	4.5	135
100	35		115.5	24.5	4.5	135

Water^b: water required to produce the base mix

Water^f: water required to make foam

3.2.1.5 Effect of replacing sand with laterite on compressive Strength of foamed concrete

The compressive strengths of the different batches of the foamed laterized concrete were determined in accordance with BS EN 12390-3 (2009). Foamed laterized concrete in plastic state from different batches was placed in 150 x 150 x 150 steel mould (see Appendix 8). Before the steel moulds were used, they were cleaned with oil; this was done to ensure that the de-moulding of the concrete cubes. The steel moulds with fresh foamed laterized concrete were covered with non-porous material (see Appendix A9) to prevent loss of water from the concrete. After twenty four hours the concrete cubes were removed from the moulds and were cured in the appropriate medium for 28 days. Finally, at 28th day the cube specimens were brought out from the curing media and were tested in 600 kN Avery Denison Universal Testing Machine at loading rate of 120 kN/min (see Appendix A10).

Sixty six (66) cubes were made from eleven different batches with various proportions of laterite from 0% to 100 % at interval of 10 units as replacement of sand. Two different curing methods were used namely air and water. Thirty three (33) cubes were cured in air while the same quantity of cubes was cured in water. The specimens cured in water were tested immediately they were brought out of water (wet state). The 28th day compressive strengths of the different batches are the average values of three cubes made from the same batch and cured in the same medium.

3.2.1.6 Effect of curing duration in water on compressive strength.

The effect of varying the initial curing duration of foamed concrete specimen in water on the compressive strength was examined. Forty five cube specimens were made from foamed concrete mix composition in Table 22. The initial curing durations of the specimens in water before the testing days were 0, 3, 7, 14, 21 and 28 days. The cubes were tested in a compression machine at 3rd, 7th, 14th and 28th days.

3.2.2 Main Investigation Phase I

The main investigation phase I involved the examination of the structural properties of foamed laterized concrete which include compressive strength; flexural strength; split tensile strength of specimens with 0, 5, 10, 15, 20 and 25 % of laterite as partial replacement of dredged sand. The choice of these specimens for further investigation at this stage is based on the results obtained in the preliminary investigation. At this stage of the experiment, the total specimens used to measure the structural properties at different testing days were: one hundred and ninety eight (198) 150 mm cube specimens; one hundred and ninety eight (198) 150 x 150 x 750 mm unreinforced beam specimens; one hundred and ninety eight (198) 150 x 300 mm cylindrical specimens.

3.2.2.1 Determination of compressive strength of foamed laterized concrete

The compressive strength of the foamed concrete was determined in accordance with BS EN 12390-3 (2009). One hundred and ninety eight (198) 150 mm cube specimens were made. The specimens were cured in two different curing media: air and water, and three different methods were used to cure the specimens which are:

a) specimens were cured in air for the specified curing period
b) specimens were cured in water for the specified curing period
c) specimens were cured in water for initial seven days and exposed to air curing for the remaining curing period.

Three sets of sixty-six cubes were cured using the three different methods. The cubes were tested in 600 kN Avery Denison Universal Testing Machine at a loading rate of 120 KN/min at 7th, 28th, 56th and 90th days. The compressive strengths of the specimens were calculated using the expression

$$f_{cu} = \frac{P_l}{bd} \tag{37}$$

where f_{cu} = compressive strength

P_l = applied load at failure.

3.2.2.2 Determination of flexural strength of foamed laterized concrete.

The flexural strength of foamed concrete was determined in accordance with ASTM C-9 (2016) and BS EN 12390-5 (2009). One hundred and ninety eight (198) 150 x 150 x 750 mm unreinforced beam specimens were made. The specimens were cured in two different curing media: air and water, and with three different methods which are:

a) specimens were cured in air for the specified curing period (see Appendix A11)
b) specimens were cured in water for the specified curing period (see Appendix A12)
c) specimens were cured in water for initial seven days and exposed to air curing for the remaining curing period.

The beam specimens were tested at 7th, 28th, 56th and 90th days with 150 kN hydraulic third point loading machine (see Appendix A13). All the specimens tested failed within the middle third length of the beams (see Appendix A14). The maximum tensile stress which is the modulus of rupture attained at the outer most fibre of the beam under tension was estimated using Equation (17).

3.2.2.2 Determination of split cylinder tensile strength of foamed laterized concrete.

Split cylinder tensile strength of foamed laterized concrete was measured in accordance with BS EN 12390-6 (2009). One hundred and ninety eight (198) 150 x 300 mm unreinforced cylindrical specimens were used. The specimens were cured in two different curing media: air and water and with three different methods which are:

a) specimens were cured in air for the specified curing period

b) specimens were cured in water for the specified curing period

c) specimens were cured in water for initial seven days and exposed to air curing for the remaining curing period.

The specimens were tested in 600kN Avery Denison Universal Testing Machine (see Appendix A15) at a loading rate of 120 kN/min at 7th, 28th, 56th, and 90th days. The specimens failed by splitting along the vertical axis (see Appendix A16). The values of the split tensile strength of the specimens were estimated using Equation (16) as earlier stated.

3.2.3 Main Investigation Phase II

In the main investigation phase II, the moment capacity, shear capacity and modes of failure of reinforced concrete beams were determined. The moment and shear capacities of reinforced foamed laterized concrete beams were these properties are determined in accordance with ASTM C-9 (2016) and BS EN 12390-5 (2009). Two sets of thirty-six (36) 150 x 300 x 2200 mm beams each were designed and produced. One set was designed to measure moment capacity and flexural mode of failure. The other set was designed to determine shear capacity and shear mode of failure. The beam specimens were prepared and tested at 28th day in a third point loading hydraulic machine.

3.2.3.1 Determination of moment and shear capacities.

The moment capacities of reinforced foamed laterized beams with various proportions of laterite from 0% to 25% at interval of 5 units were determined using beams that were provided with appropriate flexural and shear steel reinforcement. The flexural and shear reinforcement were provided after the estimation of the maximum and minimum reinforcement as shown in Tables 15 and 16, which are required to prevent shear failure in the beam from Equations (25) and (26). Table 17 shows the limits (maximum and minimum) of reinforcement and the actual reinforcement provided in the beams with various proportions of laterite.

The moment capacities of the beams, shear forces at ultimate loads and the required shear links as shown in Table 18 were estimated from Equations (20) to (24) as earlier stated (see Appendix B). While shear capacities were determined with beams that were provided with only flexural reinforcement.

Table 15

Maximum reinforcement required to achieve ductile failure mode in various beam specimens

Laterite cont. (%)	Compressive Strength (N/mm^2)	ρ_{max}	Reinforcement (mm^2)
0	11.1	0.006549	275
5	12.0	0.00708	297
10	13.0	0.00767	322
15	14.1	0.008319	349
20	16.0	0.00944	396
25	20.9	0.012331	518

Table 16

Minimum reinforcement required achieve ductile failure in various beam specimens

Laterite cont. (%)	f_r (N/mm^2)	A_s(mm)
0	3.26	62
5	3.33	64
10	3.42	66
15	3.52	67
20	3.56	68
25	3.72	71

Table 17

Comparison between the limits and reinforcement provided in various beam specimens

	Reinforcement Limits		Reinforcement Provided	
Laterite cont. (%)	Maximum (mm^2)	Minimum (mm^2)	Bar Diameter & Quantity	Area (mm^2)
0	275	62	2-y12	226
5	297	64	2-y12	226
10	322	66	2-y12	226
15	349	67	3-y12	339
20	396	68	3-y12	339
25	518	71	2-y16	402

Table 18

Shear stress and shear reinforcement provided in various beam specimens at ultimate load

Laterite cont. (%)	Moment Capacities (kN-m)	Shear Force (kN)	Shear Stress (N/mm^2)	A_{sv}/s_v Required	A_{sv}/s_v Provided	Bar size:10mm Stirrup Spacing Provided ($^c/_c$) (mm)
0	20.4	29.2	0.695	0.238	0.628	250
5	22.1	31.6	0.752	0.258	0.628	250
10	23.9	34.2	0.814	0.279	0.628	250
15	25.9	37.1	0.883	0.303	0.628	250
20	29.4	42.1	1.002	0.344	0.628	250
25	38.5	55.1	1.312	0.450	0.628	250

3.2.3.2 Laboratory procedure

The laboratory activities carried out to produce the designed beam specimens included; preparation of sawn form work, cutting and fixing of steel reinforcement, production and placing of foamed laterized concrete in the form work, de-moulding and curing of the beams. The sawn form work was made with 18 mm thick marine plywood. The reinforcement were cut and fixed (see Appendix A17). The fresh foamed laterized concrete was carefully placed in the sawn form work. After twenty four hours, the beams were de-moulded, arranged, covered with jute bags and wetted twice daily for the curing period (see Appendix A18). The beam specimens were tested at 28th day using 50 kN hydraulic third point loading machine.

The 50 kN hydraulic third point loading machine was set-up. The specimens were placed on the supports and the dial gauges at the right at the middle third points under the beams. The set-up is completed by placing the hydraulic machine at the centre of the specimen (see Appendix A19)

Load was applied on the beam on incremental value of 0.5 kN. Two modes of failure were observed when the two sets of beam specimens were tested. Specimens without shear reinforcement failed without any visible sign (brittle failure, which is sudden with a bang). The crack that was developed when the specimens failed occurred close to one of the supports (or Web-shear crack) (see Appendix A20) Specimens that were reinforced to resist shear showed visible signs: flexural cracks and deflection (ductility) before failure occurred. It was observed that the flexural-shear cracks that caused failure occurred close to the middle third and were preceded by flexural cracks (see Appendix A21).

3.3 Determination of CBA of Foamed Laterized Concrete

CBA is a systematic process of contrasting cost and benefit of a project. It provides basis for the justification of such project. In this study, CBA is used to justify the application of laterite as a replacement of sand in foamed concrete production.

The costs and benefits of foamed laterized concrete were expressed in monetary terms. The costs of production of the different samples of foamed laterized concrete were obtained from the summation of the costs of the different component materials and cost of production. The costs of the different materials and the prices of the different grades of concrete were obtained through survey carried out in March, 2016 among concrete vendors and producers in Lagos, Nigeria.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

The results of this investigation are presented under the following headings: preliminary investigation and main investigation (phases I and II)

4.1 Preliminary Investigation

The results of preliminary investigation are presented under the following headings: properties of fine aggregates and cement, trial mix, rheological properties and hardened state properties.

4.1.1 Fine Aggregate Characteristics

The results of the sieve analysis and characteristics of the fine aggregates are shown in Figure 28 and Table 19 respectively.

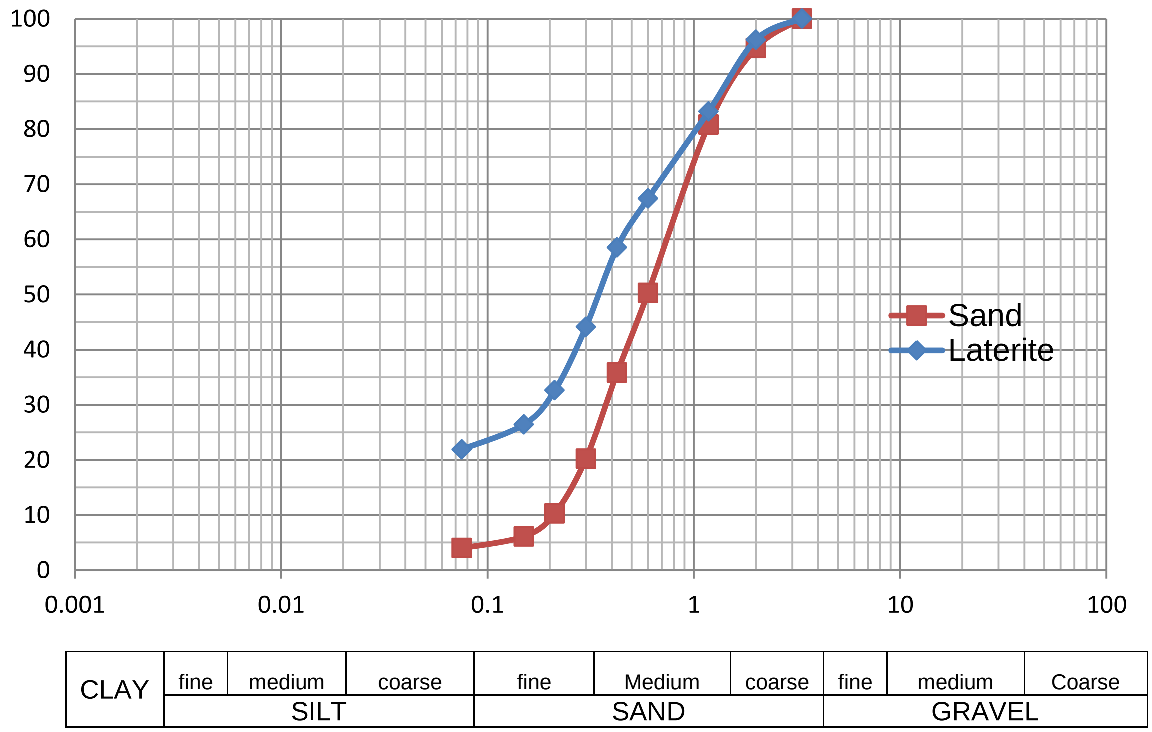


Figure 28. Fine aggregates (sand and laterite) particle size distribution

Figure 28 indicates that the particle size distribution of the Laterite contains 3, 75 and 21 % of gravel, sand and fines particles respectively; whereas, the dredged sand contains 3 and 97 % gravel and sand particles. Table 22 shows the properties and classification of the fine aggregates.

Table 19

Comparison between the physical properties of sand and laterite

Physical Properties	Sand	Laterite
Bulk density (kg/m^3)	1529	1479
Specific density	2.66	2.64
Moisture content (%)	1.3	5.2
Fineness modulus	2.8	1.8
Optimum moisture content (%)	0	7.8
Liquid limit (%)	-	44
Plastic limit (%)	-	15.3
Plasticity Index (%)	-	28.7
Cohesion Coefficient (N/mm^2)	-	35

The results of the sieve analysis of the sand and laterite as presented in Figure 28 and summarized in Table 22 show that laterite contains approximately 21 % by weight of fine grain particles. Other properties of the laterite measured were namely optimum moisture content (OMC), liquid limit (LL), plastic limit (PL), plasticity index (PI), linear shrinkage (LS) and cohesion coefficient (CC). From Table 19, the values of OMC, LL, PL, PI, LS and CC are 7.8 %, 45.5 %, 16.0 %, 29.5, 7.8 % and 35N/mm^2 respectively. These properties show that the laterite contains clay particles which give it cohesive property. The Fineness Modulus of the sand and the laterite are 1.8 and 2.8 respectively.

Then, in accordance with AASHTO (1945) soil classification cited in Braja (1999), the sand and laterite are granular materials in group A-1-b and A-2-7 respectively. Also, according to the criteria defined in BS EN 12620(2013) the sand and laterite are classified as grade zones II and III respectively. These properties show that the sand component of the laterite can fill the inter particle space of the dredged sand.

4.1.2 Analysis of Setting Times and Consistency of Cement

The properties of cement examined were, initial setting time, final setting time and consistency. The results obtained for the two brands of cement are presented in Table 20.

Table 20

The initial and final setting times, consistency of two brands of OPC

Specimen	Setting time (mins)		Consistency	
	Initial	Final	% of water	Penetration (mm)
A: 42.5R	120	190	25.5	7
B: 32.5N	41	151	30	7

Table 20 shows that the initial and final setting times of the two brands of OPC: 42.5R and 32.5N are 120 minutes and 190 minutes; and 41 minutes and 151 minutes. These results conformed to the values stated in Gambhir (2013) that good OPC initial setting time should not be less than 30 minutes and the final setting time should not be more than 600 minutes. Furthermore, he recommended that the initial setting time should be sufficiently long for proper placing and finishing in concreting operation. In this respect, 32.5N brand of cement was adopted in this study because it has an initial setting time of 41 minutes which is less than 45 minutes, the life span of the foam reported in Kearsley (1996). Consequently, before the foam degenerate the cement had set and was able to sustain its shape.

4.1.3 Mix Composition of Foamed Concrete

The composition of foamed concrete used in the investigation as the control specimen was determined with trial mix. The results of trial mixes are shown in Table 21 and it indicates that 1.35 kg/m^3 foam concentrate (SL200-L) is adequate for the production of self-compacting foamed concrete. This is because the foamed concrete produced with it had plastic density and spread diameter of 1720kg/m^3 and 580mm respectively, and they are within the limits of self-compacting concrete as earlier stated in Gambhir (2013).

Comparing this value (1.35 kg/m^3) of the foam concentrate obtained in the trial mix with the value (0.6 kg/m^3) obtained from design mix, it represents a factor 2.25 increase of the calculated foam quantity (2.25x0.6 = 1.35). Two different mix compositions with different quantity of cement and w/c ratios in Tables 22 and 23 have equivalent rheological properties: plastic density and spread values were established and used at different stages of this study.

Table 21

Effect of foam concentrate quantity on the density of foamed concrete

Foam Concentrate (kg)	Base Mix Density (kg/m^3)	Foamed Concrete Density (kg/m^3)	Spread Diameter (mm)
0.6	2040	2040	Nil
0.7	2040	2040	Nil
0.8	2040	2004	Nil
0.9	2040	1980	355
1	2040	1920	390
1.2	2040	1880	430
1.3	2040	1850	460
1.35	2040	1720	580
1.4	2040	1605	705

Table 22

Mix composition of foamed concrete with w/c ratios of 0.7

w/c	Cement kg/m^3	Sand kg/m^3	Water kg/m^3 (Base mix)	Water kg/m^3 (foam)	Foam concentrate kg/m^3
0.7	350	1155	245	44.6	1.35

Table 23

Mix composition of foamed concrete with w/c ratios of 0.5

w/c	Cement kg/m^3	Sand kg/m^3	Water kg/m^3 (Base mix)	Water kg/m^3 (foam)	Foam concentrate kg/m^3
0.5	500	1000	250	44.6	1.35

4.1.4 Effect of replacing Sand with Laterite on the Rheological Properties of Foamed Concrete

The results of the effect of replacing dredged sand with laterite on rheological characteristics of foamed concrete are presented as variation in plastic density and spread diameter with increases in percentage of laterite used.

4.1.4.1 Effect of replacing sand with laterite on plastic density

Figure 29 is the relationship of the plastic density of foamed concrete to the proportion of laterite used as replacement of sand.

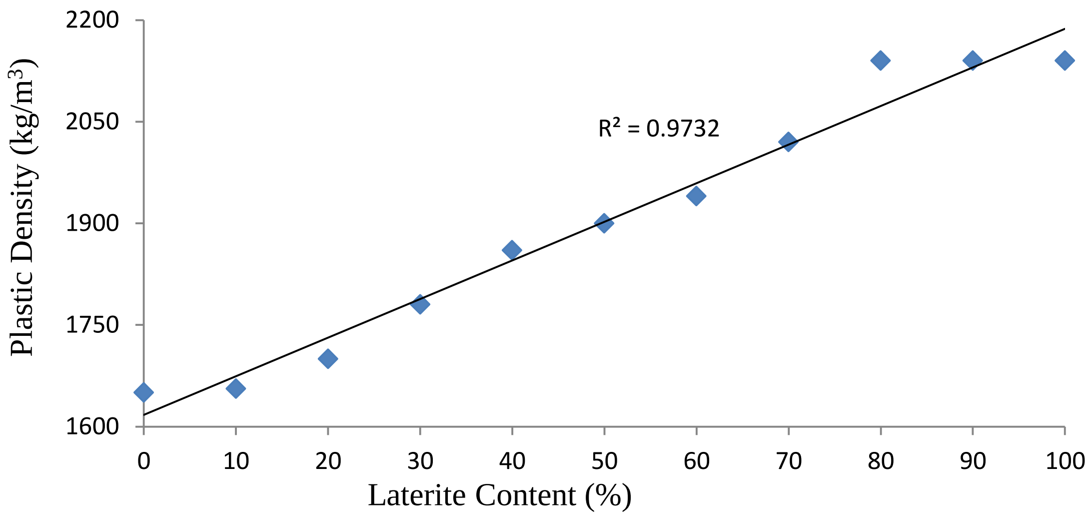


Figure 29. Relationship of plastic density to the proportion of laterite

From Figure 29, the densities of the foamed laterized concrete vary between 1650 kg/m^3 and 2140 kg/m^3 for specimens with 0 and 100 % laterite. The plastic density increased with the proportion of laterite. For example, the plastic densities of foamed laterized concrete with 0, 10, 20, 30, 40 and 50 % of laterite are 1650, 1656, 1700, 1780, 1860 and 1900 kg/m^3.

This observation can be attributed to two factors: difference in particle size distribution of sand and the cohesive property of laterite. From Table 19, the fine aggregates have different properties and they are classified into grade zones II and III. In addition, the laterite has cohesive property. Therefore, partial replacement of sand with laterite reduced the inter-particle voids in the sand to produce fine aggregates with increased surface area. Consequently, the quantity of water required to ensure the consistence of the base mix increased. But the percentage of laterite content was increased, whilst the quantity of mixing water was not increased. So, the additional amount of water required to maintain consistence mix was extracted from the foam. This action caused some of the foam to collapse leading to reduction in volume of entrained air pores, and reduction in the volume of the mix.

Statistical regression equation of the trendline in Figure 29 is linear relationship of plastic density to percentage of laterite which can be expressed as

$$D = 6.09\phi + 1606 \tag{38}$$

From Figure 29, specimens with 0 to 25 % laterite and with plastic densities 1650, 1667, 1727 and 1750 kg/m^3 satisfied the design plastic density criterion (1600 + 150 kg/m^3).

4.1.4.2 Effect of replacing sand with laterite on spread values

Figure 30 is the relationship of spread diameter to the proportion of laterite as replacement of dredged sand in foamed concrete.

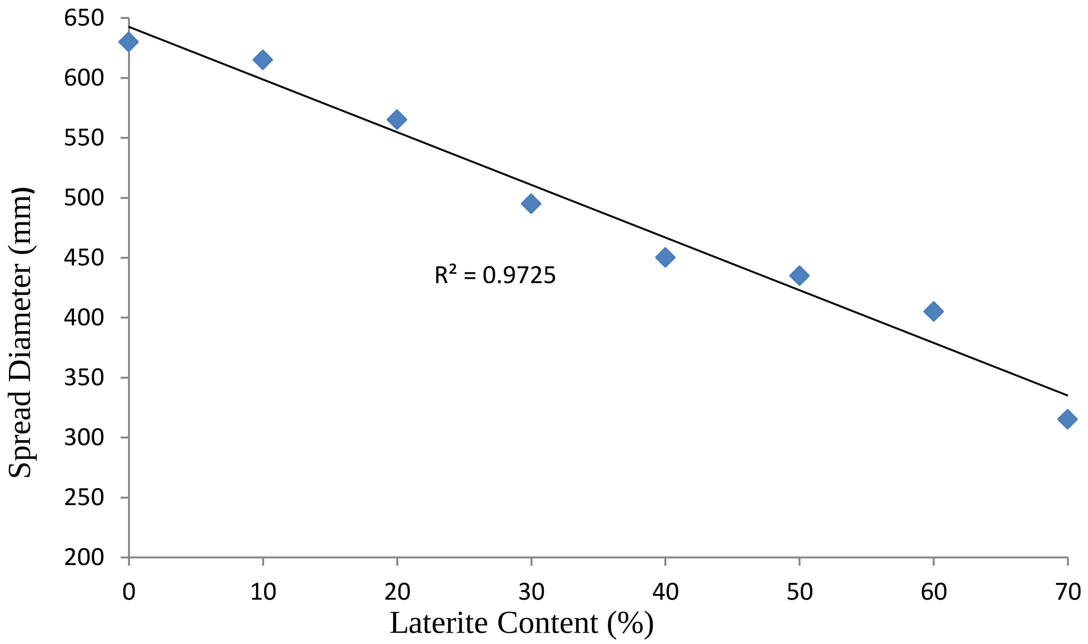


Figure 30. Relationship of spread diameter to the proportion of laterite

Figure 30 indicates that the spread diameter of foamed laterized concrete decreases with increases in laterite content till no spread was observed from 70 % replacement. For example, the spread diameter of the control (0% laterite replacement), 10, 20, 30, 40, 50, 60, and 70 % laterite are 630, 615, 565, 495, 450, 435, 405 and 315 mm respectively. This observation can be attributed to difference in particle size distribution and specific gravity of sand and laterite, and cohesive nature of laterite. From the sieve analysis results in Table 19 the laterite contains clay particles and has specific gravity of 2.64, whilst dredged sand contains 0% clay particles and with specific gravity of 2.66. The effects of these differences in the properties of sand and laterite on the foamed concrete mix are increased surface area of fine aggregates and cohesive property of the aggregates. Consequently, the inter-particle voids decreased and the cohesive property of the laterite increased the inter-particle forces in the mixes as the proportions of laterite were increased. The increased inter-particle forces reduced the flowing capacity of the foamed laterized concrete.

Regression equation of the trendline in Figure 30 is a linear relationship of spread diameter to percentage of laterite which can be expressed as

$$S_D = -4.39\phi + 642 \tag{39}$$

From Equation (39), the estimated spread diameters for specimens with 0, 10, 20 and 25% laterite are 642, 598, 554 and 532 mm and these values correspond to the design spread diameter criterion (560 to 760 ± 5% mm) as earlier suggested by Gambhir (2013).

4.1.5 Hardened State Properties

The hardened state 28th day properties of foamed concrete which were determined included densities and compressive strengths of cube specimens cured in air and water. The results obtained are presented in effect of replacing sand with laterite on the density of foamed concrete and effect of replacing sand with laterite on the compressive strength of foamed concrete.

4.1.5.1 Effect of replacing sand with laterite on the density of foamed concrete.

Figure 31 shows the relationship of density to the proportion of laterite in foamed laterized concrete specimens cured in water and air.

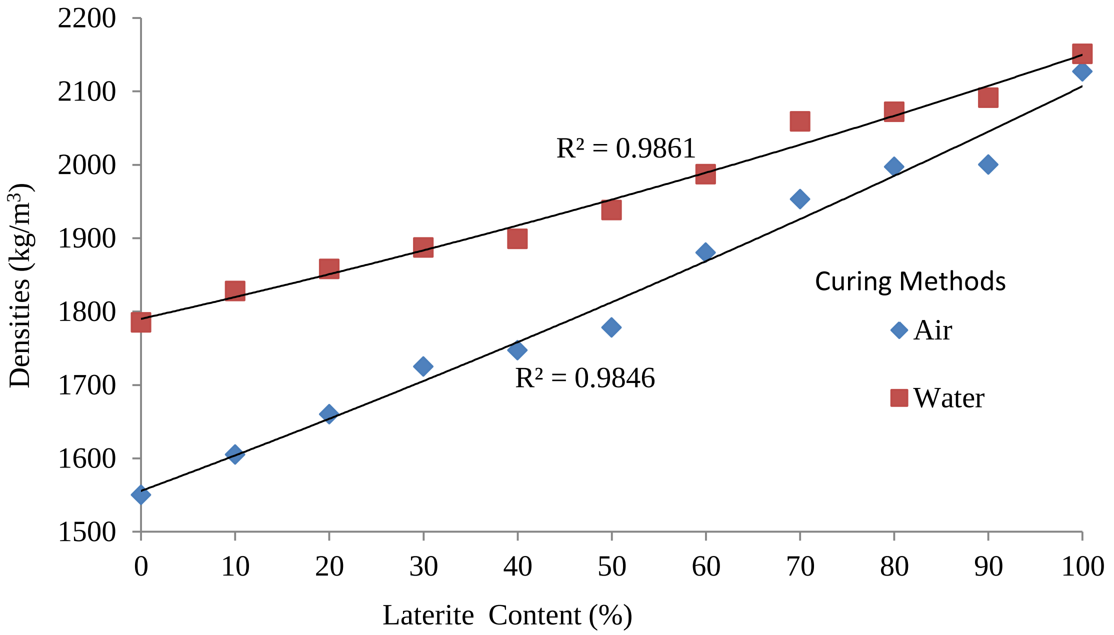


Figure 31. Relationship of density to the proportion of laterite at 28th day

Figure 31 indicates that the densities of the cube specimens cured in both water and air increases with the proportion of laterite. For example, in specimens with 0, 10, 20 and 30 % laterite the dry densities are 1550, 1605, 1660, 1705 kg/m^3 respectively. Also, specimens which were cured with water showed the same trend. For example, in specimens with 0, 10, 20 and 30 % laterite the wet densities are 1785, 1828, 1858 and 1887 kg/m^3 respectively (see Appendix C1).

From Figure 31, the regression equations of the trendlines of the relationship of density to the proportion of laterite for specimens cured in air and water are polynomials of second degree which are expressed as

$$D_{air} = 0.0074\phi^2 + 4.7712\phi + 1555.6 \tag{40}$$

and

$$D_{wet} = 0.0069\phi^2 + 2.9041\phi + 1790.1 \tag{41}$$

where D_{air} = density of specimen cured in air

D_{wet} = density of specimen cured in water.

The densities of cube specimens cured in water are greater than the densities of cube specimens with equivalent percentage of laterite cured in air. This is because water curing prevents loss of evaporable water from concrete and the retained water fills the air entrained pores. For example, specimens with 0, 10, 20 and 30 % laterite the dry densities at the 28th day are 1550, 1605, 1660 and 1705 kg/m^3 and the wet densities are 1785, 1828, 1858 and 1887 kg/m^3 respectively.

Also, the differences between the densities of specimens cured in water and air at various proportions of laterite decreases with increases in the proportions of laterite. For example, at 0, 10, 20 and 30 % laterite content, the differences between the densities of specimens cured in water and air at 28th day are 235, 223, 198 and 182 kg/m^3 respectively. These observations can be attributed to the continuous reduction in the volume of air entrained pores and consequently the weight of evaporable water in the foamed laterized concrete as the percentage of laterite increases.

4.1.5.2 Effect of replacing sand with laterite on compressive strength of foamed concrete

Figure 32 shows the relationship of compressive strength of cube specimens cured in air and water to the proportion of laterite.

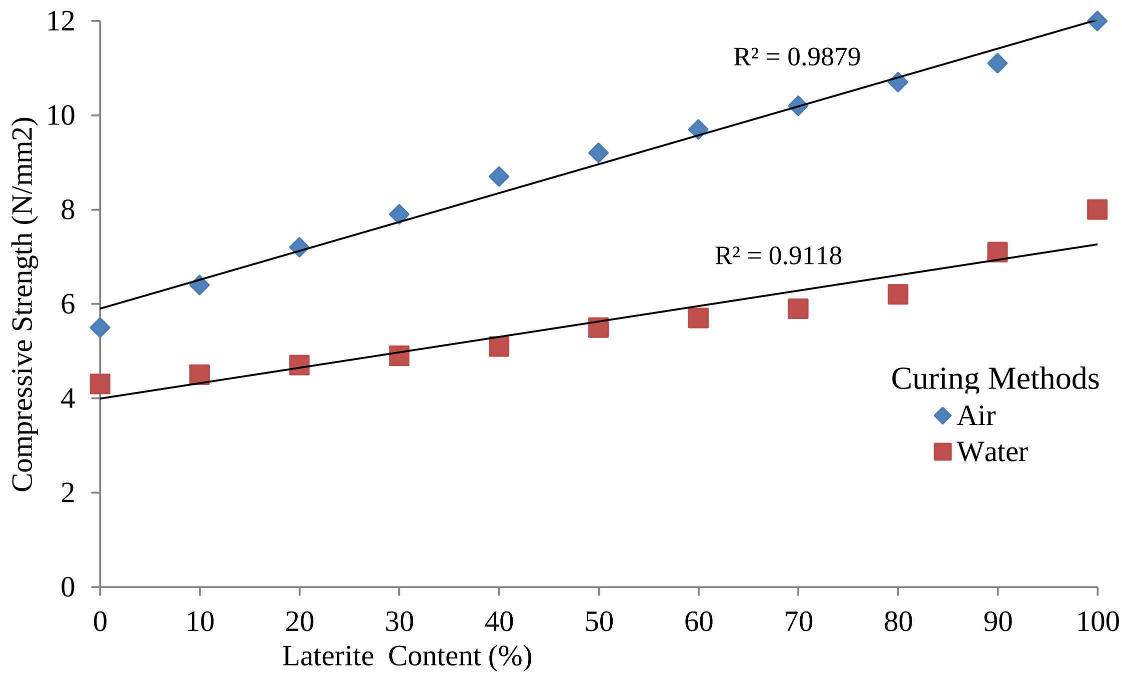


Figure 32. Relationship of compressive strength to the proportions of laterite

From Figure 32, the compressive strengths of specimens which were cured in air and water increases with the proportion of laterite. For example, for specimens with 0, 10, 20, 30 and 40 % laterite, the compressive strength of cubes cured in air are 5.5, 6.4, 7.2, 7.9 and 8.7 N/mm^2; and those cured in water are 4.3, 4.5, 4.7, 4.9 and 5.1 N/mm^2 respectively (see Appendix C2). In addition, the compressive strengths of specimens cured in air are greater than those specimens cured in water.

The regression equations of the trendlines are linear relationships of compressive strength to proportion of laterite for specimens cured in both air and water and can be expressed as

$$f_{cu_{air}} = 0.0613\phi + 5.9 \tag{42}$$

and

$$f_{cu_{water}} = 0.0327\phi + 4 \tag{43}$$

where $f_{cu_{air}}$ = compressive strength of specimens cured in air

$f_{cu_{air}}$ = compressive strength of specimens cured in water.

The regression lines also show that the difference in the compressive strength between the cubes cured in air and water increases with proportion of laterite.

The observed trends in Figure 32 can be attributed to the effect of tensional stress state of pore water which was explained in Penttala (2009). Penttala (2009) states that the saturation of concrete pores: air entrained, gel and capillary pores affect the compressive strength of concrete in different ways. Saturation of gel and capillary pores helps in the continuous hydration of cement in the concrete, which results into increase in compressive strength. Whereas, the saturation of air entrained pores reduces the compressive strength. This is because air entrained pore water exists in tensional stress state which causes tensile cracks in the concrete structure. The induced tensile cracks weaken the concrete structure and reduce the compressive strength.

4.1.5.3 Effect of w/c ratio on compressive strength of foamed concrete

Table 24 shows the effect of water/cement ratio on the compressive strength of foamed concrete.

Table 24

The results of compressive strengths of specimens with 0% laterite content made with different mix proportions

Curing Period (days)	Compressive Strength (N/mm^2) at w/c of 0.7		Compressive Strength (N/mm^2) at w/c of 0.5	
	Curing Media		Curing Media	
	Air	Water	Air	Water
7	3.6	3.1	10.2	9.8
21	5.0	4.4	11.5	10.7
28	5.5	4.8	12	11.3

Table 24 shows the results of the compressive strengths of foamed concrete cube specimens made from different mix compositions as earlier indicated in Tables 22 and 23 at different curing periods. The compressive strengths of the cube specimens made from both mixes increases with curing duration. Nonetheless, the cube specimens made from mix proportion with w/c of 0.5 and cement content of 500 kg/m^3 developed higher compressive strengths at all curing periods. This observation can be attributed to increases in the quantity of hydration products C-S-H in the mortar matrix which is responsible for strength development.

4.1.5.4 Effect curing duration of foamed concrete on the compressive strength.

Figure 33 shows the effect of varying the initial curing duration: (0, 3, 7, 14 and 28 days) of foamed concrete in water before exposure to air curing on compressive strength at testing day.

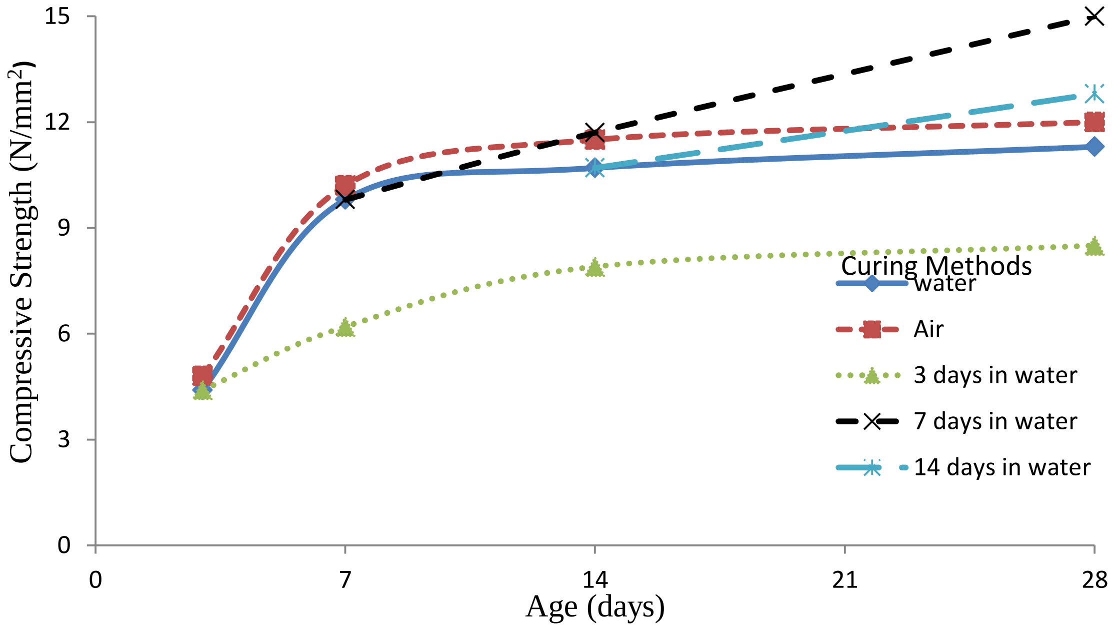


Figure 33. Relationship of compressive strength to curing duration of foamed concrete in water

The results show that at all curing periods, the specimens that had initial curing duration of 3-days in water and later exposed to air curing developed the least compressive strength. For example, the 28th day compressive strength of cube specimens that were cured in water for initial duration of 0, 3, 7, 14 and 28 days are 12.0, 8.5, 15.0, 12.8 and 11.3 N/mm^2 respectively. The 28th day results also show that the specimens which were cured in water for the duration of 7-days and later exposed to air curing developed the maximum compressive strength of 15 N/mm^2. The observed trend agrees with earlier studies by Penttala (2009) and Gambhir (2013) on the effect of the degree of saturation of the concrete pore system on the designed compressive strength. Penttala (2009) noted that variation in the degree of saturation of air entrained pore system in concrete structure can generate large pore water tensions inside the structure and leads to the development of cracks in the concrete; which consequently results to decreases in the compressive strength of the concrete. Gambhir (2013) reported that for concrete to develop the designed strength at 28th day, the curing period should not be the full 28 days because the rate of hydration, and hence the rate of strength development reduces with time.

4.2 Main Investigation (Phase I)

The results of this part of the investigation are presented under the following headings: compressive, flexural and split tensile strengths of foamed laterized concrete.

4.2.1 Compressive Strength of Foamed Concrete Specimens

The results of compressive strength of specimens with 0 to 25 % laterite at intervals of 5 units which were cured in different media are presented in this section.

4.2.1.1 Specimens cured air.

Figure 34 show the relationship of compressive strengths of cubes to the proportion of laterite at various curing periods: 7, 28, 56, and 90 days.

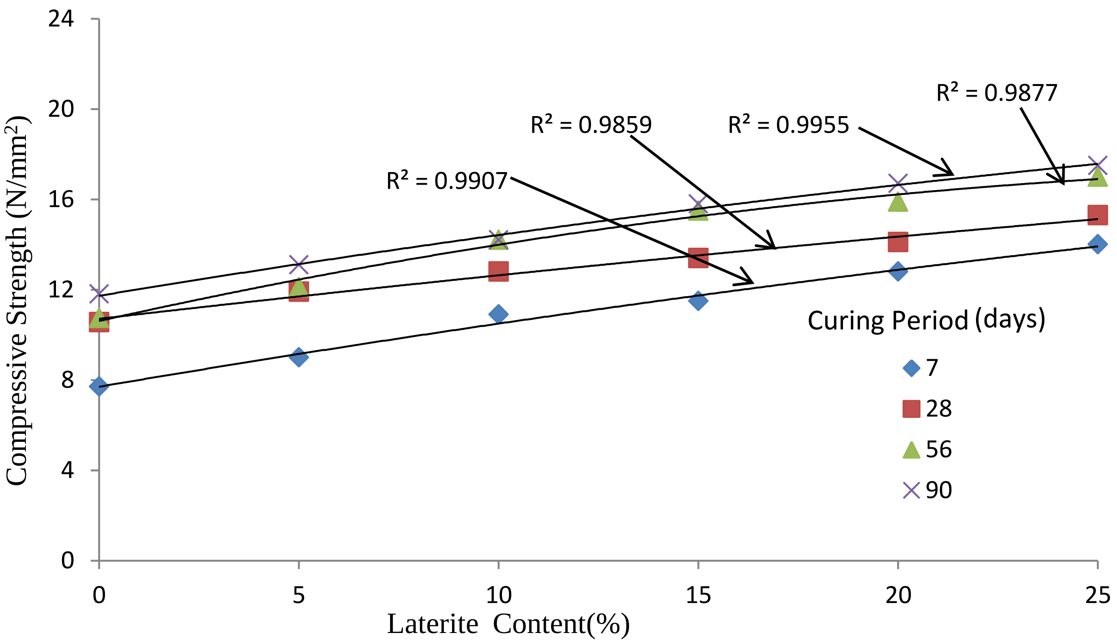


Figure 34. Relationship of compressive strengths to the proportion of laterite at various curing periods for specimens cured in air

Figure 34 indicates that the compressive strength increases with the proportion of laterite at all curing periods. For example, the compressive strength of cubes with 0, 5, 10, 15, 20 and 25 % laterite at 7^{th} day are 7.7, 9.0, 10.9, 11.5, 12.8 and 14 N/mm^2, and at 56^{th} day are 10.75, 12.1, 14.2, 15.5, 15.9 and 17.0 N/mm^2 respectively.

Also, compressive strength increased with curing period for all cube specimens. For example, the strengths of cubes with 0 % laterite content are 7.7, 10.56, 10.76, and 11.8 N/mm^2 at 7^{th}, 28^{th}, 56^{th}, and 90^{th} day curing periods, and for specimens with 15 % laterite the strengths are 11.5, 13.4, 15.5, and 15.8 N/mm^2 at the same corresponding curing periods (see Appendix C3).

The regression lines in Figure 34, conforms to different polynomials of the second degree. Thus, there is no defined pattern in the variation of compressive strength with curing periods for specimens with the same percentage of laterite. Nevertheless, it can be deduced that compressive strengths of all the cubes at 7 days curing are lower than the strengths at other curing periods. Also, the difference in compressive strength at 7 days curing and other curing periods decreases with increases in the proportion of laterite. Beyond 56 days curing, additional gain in compressive strength was minimal. The relationship between the compressive strength developed at 7 and twenty eight days curing are presented in Table 25, which shows that the percentage of 28^{th} day strength developed at 7^{th} day by specimens with 0, 5, 10, 15, 20 and 25 % laterite are 73, 76, 85, 86, 91 and 92 %.

Table 25

Comparison of the compressive strengths developed at 7th and 28th days curing for specimens cured in air

Laterite cont. (%)	f_7 (N/mm^2)	f_{28} (N/mm^2)	f_7/f_{28}
0	7.7	10.6	0.73
5	9.0	11.9	0.76
10	10.9	12.8	0.85
15	11.5	13.4	0.86
20	12.8	14.1	0.91
25	14	15.3	0.92

4.2.1.2 Specimens cured in water.

Figure 35 shows the relationship of compressive strengths of cubes to the proportion of laterite at different curing periods: 7, 28, 56, and 90 days.

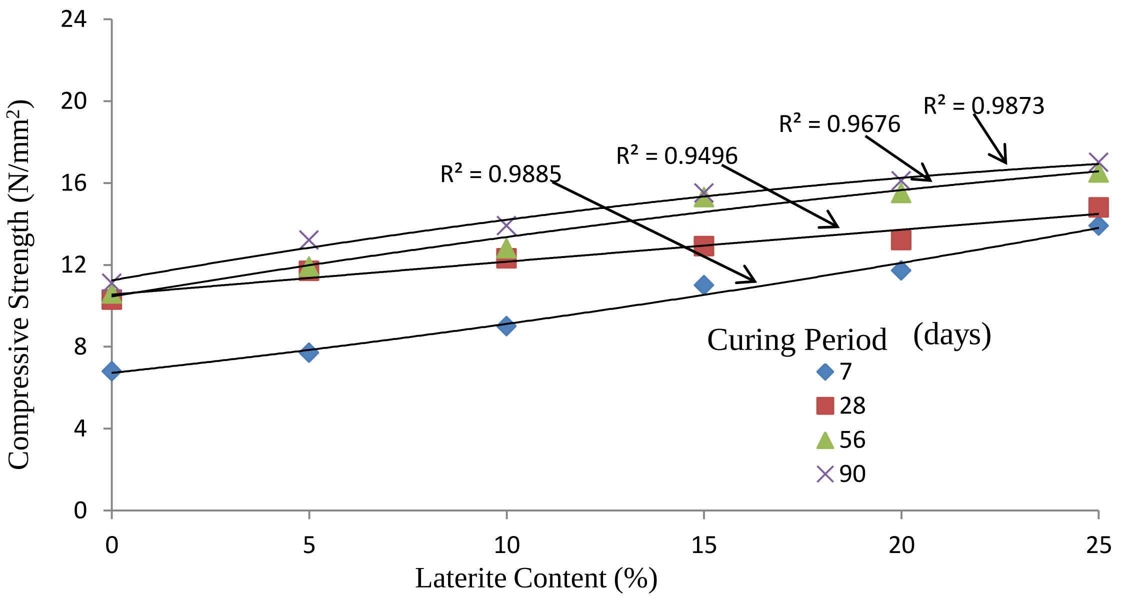


Figure 35. Relationship of compressive strength to the proportions of laterite at various curing periods for specimens cured in water

From Figure 35, the compressive strengths of all specimens with various proportions of laterite increases with the curing period. For example, the compressive strengths of specimens with 5% laterite content at 7th, 28th, 56th and 90th days are 7.7, 12.0, 13.5, and 14.5 N/mm^2 respectively. In addition, the compressive strength developed at different curing periods increases with the proportion of laterite. For example, the compressive strength developed by specimens with 0, 5, 10, 15, 20, and 25 % laterite content after 90 days curing are 13.5, 14.5, 15,2, 17.5, 19.1, and 20.8 N/mm^2 respectively (see Appendix C4).

Also, the difference between the regression lines of the relationship of compressive strength to the proportion of laterite at 7th and other curing days decreases with increases in proportion laterite. This observation implies that increases in compressive strength with age declines as the proportion of laterite is increased. Also, additional increase in compressive strength after 28 days was minimal for specimens with 0, 5, and 10 % laterite content, whilst for specimens with 15, 20, and 25 % continuous gain in strength declines significantly after 56 days of curing.

The relationship between the compressive strength developed at 7 and 28 days curing periods are presented in Table 26. It shows that the percentage of 28th day strength developed at the 7th day by specimens with 0, 5, 10, 15, 20 and 25 % laterite content are 66, 66, 80, 88.5, 94 and 95 % respectively.

Table 26

Comparison of the compressive strengths developed at 7th and 28th days curing for specimens cured in water

Laterite cont. (%)	f_7 (N/mm^2)	f_{28} (N/mm^2)	f_7/f_{28}
0	6.8	10.3	0.66
5	7.7	11.7	0.66
10	9.8	12.32	0.80
15	11	12.9	0.85
20	13	13.8	0.94
25	14	14.8	0.95

4.2.1.3 Specimens initially cured in water for 7 days before exposure to air curing.

Figure 36 show the compressive strength of cubes with the proportion of laterite at different curing periods: 7, 28, 56, and 90 days.

Figure 36 indicates that at all curing periods, the compressive strength increases with the proportion of laterite. For example, at 28 days curing period, the compressive strength of the specimens with 0, 5, 10, 15, 20, and 25 % laterite content are 11.1, 12.0, 13.0, 14.1, 16.0, and 17.2 N/mm^2 (see Appendix C5). Also, the compressive strength developed by all the specimens increase with curing period. In this regard, the compressive strengths of specimens with 25 % laterite content at 7th, 28th, 56th, and 90th, days curing periods are 13.9, 17.2, 19.0, and 20.8 N/mm^2 respectively.

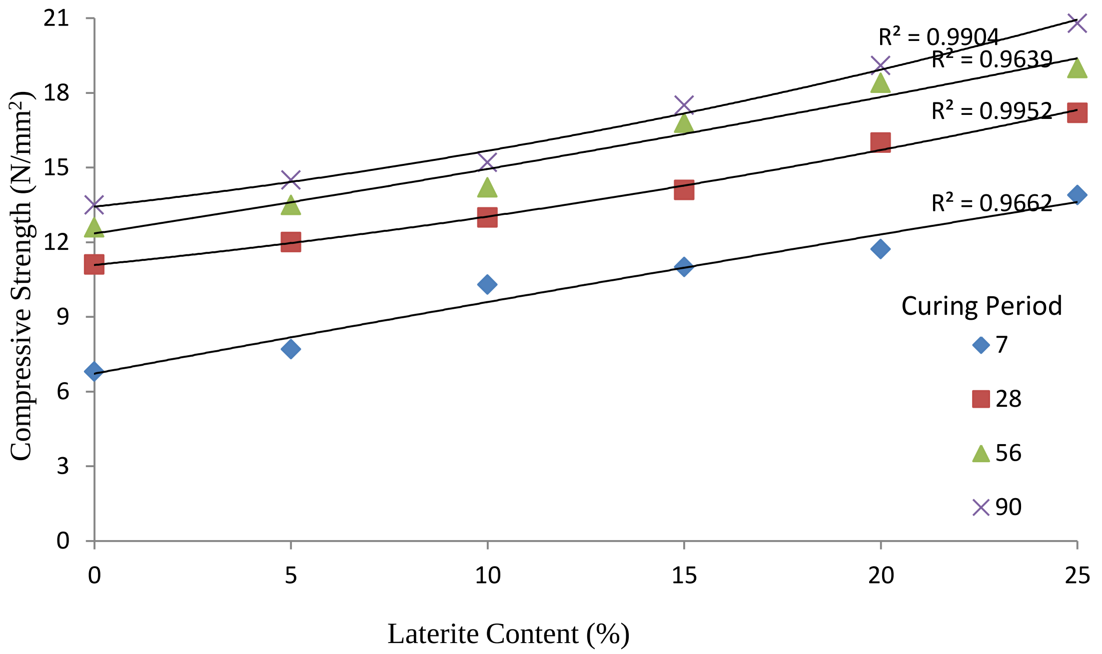


Figure 36. Relationship of compressive strength to the proportion of laterite at various curing ages of specimens cured in water for initial 7days

The relationship of compressive strength to the proportion of laterite at different curing periods has similar regression lines with approximate uniform differences across the different specimens. Thus, all the specimens developed greater percentage increase in strength between 7 and 28 days curing periods. Beyond 28 days curing period, increases in strengths continue to decline. The relationship between the compressive strength developed at7 and 28 days curing periods are presented in Table 27. It shows that the percentage of 28th day strength developed at 7th day by specimens with 0, 5, 10, 15, 20 and 25 % laterite are 61, 64, 75, 78, 81 and 81 %.

Table 27

Comparison of the compressive strengths developed at 7th and 28th days curing periods for specimens cured in water for initial 7 days before exposure to air curing

Laterite cont. (%)	f_7 (N/mm^2)	f_{28} (N/mm^2)	f_7/f_{28}
0	6.8	11.1	0.61
5	7.7	12	0.64
10	9.8	13	0.75
15	11	14.1	0.78
20	13	16	0.81
25	14	17.2	0.81

The results show that the compressive strengths of the foamed concrete specimens cured in different media increases with the proportion of laterite. Also, the cube specimens cured in water for an initial seven days before exposure to air curing developed higher compressive strengths than specimens cured in air and water. For example, the 90th day compressive strengths of the specimens with 0, 5, 10, 15, 20 and 25 % laterite which were cured air are 11.8, 13.1, 14.2, 15.8, 16.7 and 17.5 N/mm^2; for specimens cured water are 11.1, 13.2, 13.9, 15.5, 16.1 and 17.0 N/mm^2; and for specimens that were initially cured in water for seven days before exposure to air curing are 11.1, 11.7, 13, 14.1, 16.0 and 20.9 N/mm^2.

These observations can be attributed to the improved fine aggregates size distribution as the laterite content was increased and effect of degree of saturation of air entrained pores in the concrete structure. The addition of laterite into the mix reduces the inter particle spaces between the fine aggregates particles. The improved fine aggregates size distribution contributes to the reduction of the size and quantity of entrained air pores in the concrete structure. This is in agreement with the conclusion reached in Gambhir (2013) and Kearsley (1996) that the compressive strength of concrete increases with reduction in porosity.

Water in concrete pores system (gel and capillary pores) is important because it supports continuous hydration of cement and also prevents drying of the internal structure. But saturation of air entrained pores in concrete with water results in tensile stress in the concrete internal structure. Then consequently, this leads to a reduction in the compressive strength of the concrete. Therefore a concrete structure requires certain amount of water in its pore system to sustain hydration process and prevent self-desiccation but not cause tensile stresses in the internal structure. Thus this results obtained herein show that curing of foamed concrete for an initial 7 days before exposure to air curing provides it with the adequate amount of water that sustains hydration process without any significant tensile stresses development.

Furthermore, the results in Tables 25 to 27 show the importance of preventing loss of water in the foamed concrete structure to strength development. This conforms to the finding in Gambhir (2013) that concrete gains strength with curing age due to hydration of cement; which takes place only when the capillary pores remain saturated. In this respect, the percentage values of 28th day compressive strength developed at 7th day for specimens cured in the different media: air is between 73 – 92 %; water is between 66 – 95 %; initial seven days of the curing period is between 61- 8 1% respectively.

4.2.2 Split Tensile Strength

The results of split tensile strength in relationship to laterite content at different curing periods of cylindrical specimens cured in air, water and initially cured in water for 7 days before exposure to air curing are presented under the curing methods.

4.2.2.1 Air cured cylindrical specimens.

Figure 37 shows the relationship of split tensile strength of cylindrical specimens to the proportion of laterite (0, 5, 10, 15, 20 and 25 %) at different curing periods: 7, 28, 56, and 90 days.

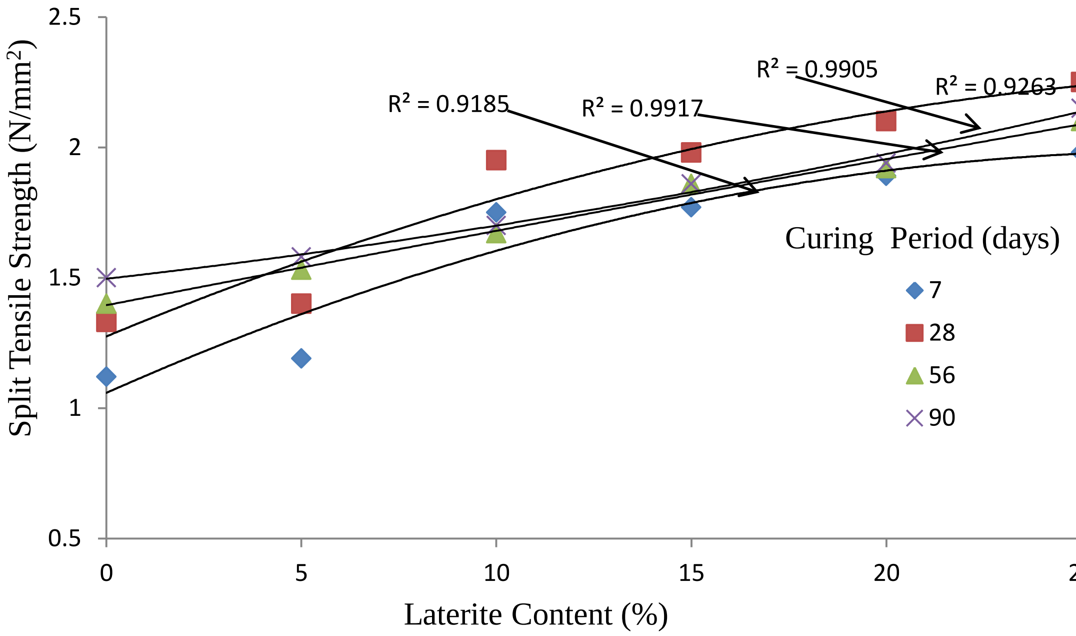


Figure 37. Relation of split tensile strength to the proportion of laterite at curing periods of specimens cured in air

Figure 37 indicates that the split tensile strength at different curing periods increases with the proportion of laterite. For example, for 56 days curing period the split tensile strength of the cylindrical specimens with 0, 5, 10, 15, 20, and 25 % laterite are 1.4, 1.53, 1.67, 1.86, 1.92, and 2.1 N/mm^2 respectively.

In addition, the split tensile strength increases with curing period for specimens with 0 and 5% laterite. Whilst specimens with 10, 15, 20, and 25 % laterite increases with curing period and after 28 days they began to reduce in value. Thus, the strength of specimens with 20 % laterite after 7, 28, 56, and 90 days curing periods are 1.89, 2.1, 1.92, and 1.94 N/mm^2 (see Appendix C6).

The regression lines of the relationship reveal that the strengths of the specimens were developed between 7 and 28 days curing periods. Also curing of specimens in air beyond 28 days leads to reduction in strength.

4.2.2.2 Water-Cured Cylindrical Specimens

Figure 38 shows the results of split tensile strengths of cylindrical specimens cured in water and the relationship of split tensile strength with the proportion of laterite.

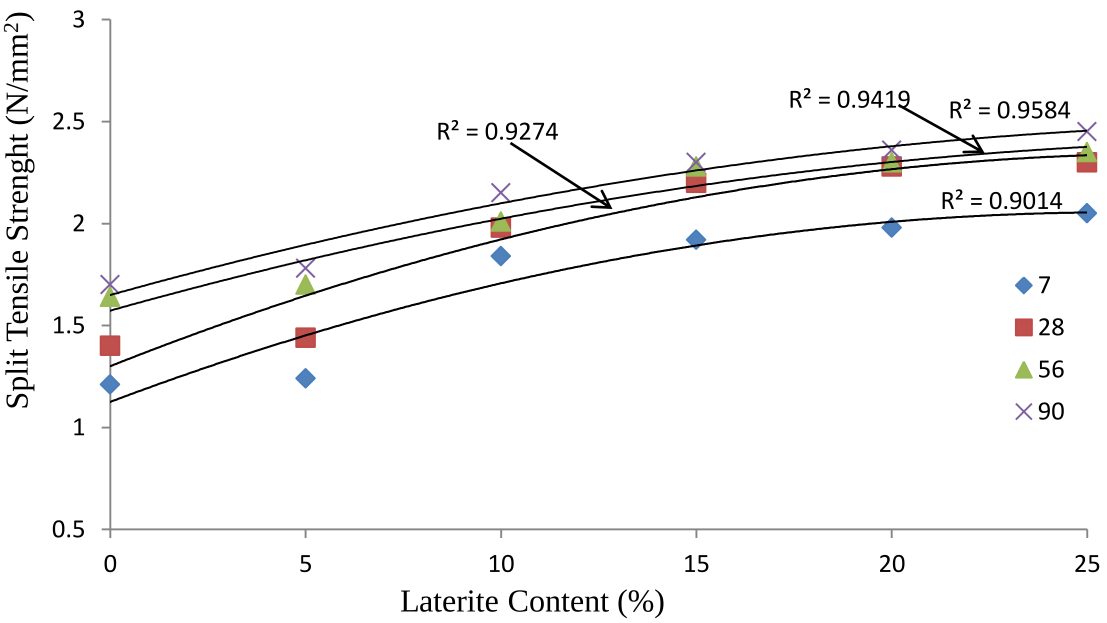


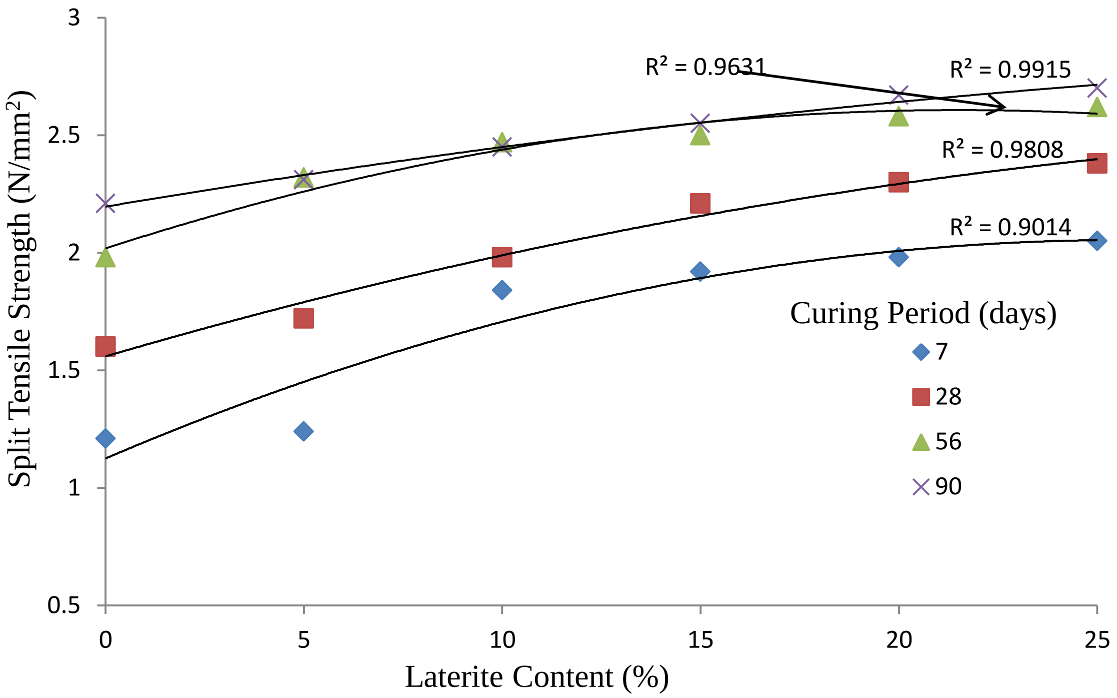
Figure 38. Relationship of split tensile strength to the proportion of laterite at various curing periods of specimens cured in water

Also, in indicates that the split tensile strength of foamed laterized concrete increases with the proportion of laterite at all curing periods. For example, at 28th day curing in water, the split tensile strengths of specimens with 0, 5, 10, 15, 20, and 25 % laterite are 1.40, 1.44, 1.98, 2.20, 2.28 and 2.30 N/mm^2. Also at 90th day curing the strengths developed by the specimens are 1.70, 1.78, 2.15, 2.30, 2.36, and 2.45 N/mm^2. In addition, the split tensile strengths of the specimens increase with curing period. For example, the strengths of specimens with 15 % laterite at 7th, 28th, 56th and 90th days are 1.92, 2.20, 2.28, and 2.30 N/mm^2. Similarly, the tensile strengths of specimens with 20 % laterite at the same curing periods are 1.98, 2.28, 2.30, and 2.36 N/mm^2 respectively (see Appendix C7).

The regression lines of the relationship of split tensile strength to the proportion of laterite are defined by polynomials of second degree. Also, the regression lines of the relationship reveal that much gain in split tensile strength was achieved with 28 days curing period. Beyond this period, continuous curing of specimens in water yielded a little increase in strength. Therefore, long term curing of foamed concrete is not necessary for split tensile strength development. Nonetheless, the results have shown that proper and adequate curing of foamed concrete at early days after production to prevent loss of water from the internal structure is important as it is in normal weight concrete, which was earlier stated in Gambhir (2013).

4.2.2.2 Cylindrical specimens cured in water for 7 days before exposure to air curing.

Figure 39 shows the results of the split tensile strength of specimens cured in water for 7 days and exposed to air curing, and the relationship of split tensile strength with the proportion of laterite.



Figures 39. Relationship of split tensile strength to the proportion of laterite at various curing periods of specimens cured in water for initial 7days

Figure 39 indicates that the split tensile strengths of the specimens increase with the proportion of laterite at all curing periods. For example, for 7 days curing period, the split tensile strength of the specimens with 0, 5, 10, 15, 20, and 25 % laterite content are 1.21, 1.24, 1.84, 1.92, 1.98, and 2.05 N/mm^2 respectively. The same trend also occurred at 28, 56, and 90 days curing periods. Furthermore, the strengths of specimens with different proportions of laterite increase with curing period. Thus, for specimens with 25 % laterite the strengths are 2.05, 2.38, 2.62, and 3.11 N/mm^2 (see Appendix C8).

The regression lines in Figure 39 show uniform increase in split tensile strength of specimens with different proportions of laterite at 7, 28 and 56 days curing periods. With this method of curing, the increase in strengths after 56 days are very small and most cases are insignificant.

Figures 37 to 39 show that the split tensile strengths of the foamed concrete specimens cured in different media increase with the proportion of laterite. For example, the 90th day split tensile strengths of specimens with 0 to 25 % laterite which were cured air are 1.42, 1.58, 1.70, 1.86, 1.92 and 2.15 N/mm^2; in water are 1.70, 1.78, 2.15, 2.30, 2.36 and 2.45 N/mm^2; and in water initially for 7days before exposure to air curing are 2.21, 2.38, 2.45, 2.55, 2.67 and 2.70 N/mm^2 respectively.

Figures 38 and 39 show that the split tensile strength of specimens cured in water for whole curing period and those cured in water initially for 7 days before exposure to air curing increases with curing duration. For example, the split tensile strength of specimens made with 5 % laterite content at 7th, 28th, 56th and 90th days curing periods and cured in water are 1.24, 1.44, 1.70 and 1.78 N/mm^2 respectively, and specimens cured in water for initial 7 days before exposure to air curing are 1.24, 1.72, 2.32 and 2.38 N/mm^2. In Figure 38, specimens cured in air showed different trend because the split tensile strengths of specimens made with 0 and 5 % laterite increase with curing period. For example, the split tensile strengths of specimens with 5% laterite at 7th, 28th, 56th and 90th days curing periods are 1.19, 1.4, 1.53 and 1.58 N/mm^2 respectively. The split tensile strengths of specimens with 10, 15, 20 and 25 % laterite increase with curing duration up to 28th day and subsequently reduces with time. For example, for specimens with 15 % laterite, the split tensile strengths at 7^{th}, 28^{th}, 56^{th} and 90^{th} days are 1.77, 1.98, 1.86 and 1.86 N/mm^2 respectively.

These observations can be attributed to the following: improved fine aggregates particle size distribution with the addition of various percentages of laterite and variation in the moisture content of the specimens. These agree with the conclusions in Civil-Engineering world (2009) that the split tensile strength of concrete increases with increase in compressive strength and also varies with the moisture content of the concrete. They observed that concrete specimens cured in water develop higher split tensile strength than specimens cured in air. Also, Penttala (2009) states that the inside of air cured specimens could dry up due to hydration which causes self-desiccation. This phenomenon generates large pore water tension inside the structure which subsequently reduces the tensile strength of the concrete.

4.2.3 Relationship between Split Tensile and Compressive Strengths

The relationship between split tensile strengths and compressive strengths of specimens with proportion of laterite is reported under the following headings: specimens cured in air, water and initially in water for 7 days before exposure to air curing.

4.2.3.1 Specimens cured in air

Figure 40 shows the relationship of tensile strength to compressive strength of specimens cured in air.

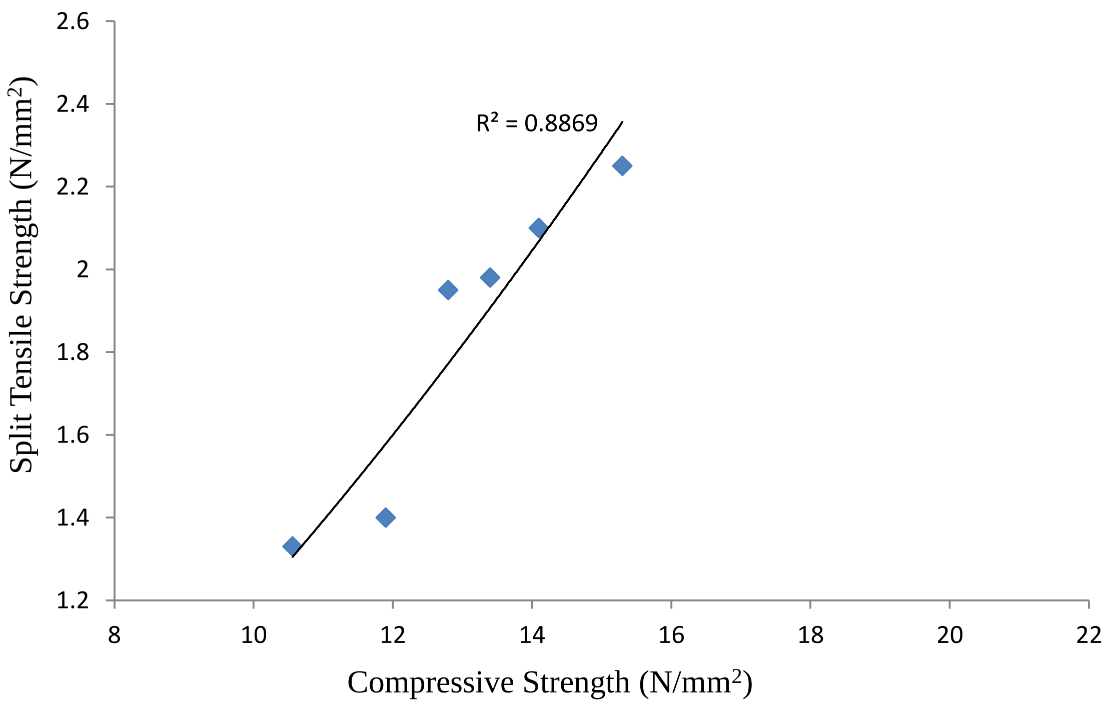


Figure 40. Relationship of split tensile strength to compressive strength at 28th day of specimens cured in air

Figure 40 indicates that tensile strength increases with compressive strength of foamed concrete. The regression line of the relationship is an exponential function which can be expressed as

$$f_t = 0.0288 f_{cu}{}^{1.6} \quad (44)$$

Also, the ratios of tensile strengths to compressive strengths of the specimens (see Appendix C9) show that the tensile strength is approximately between 12 and 15 % of the compressive strength.

4.2.3.2 Specimens cured in water

Figure 41 shows the relationship of tensile strength to compressive strength of specimens cured in water.

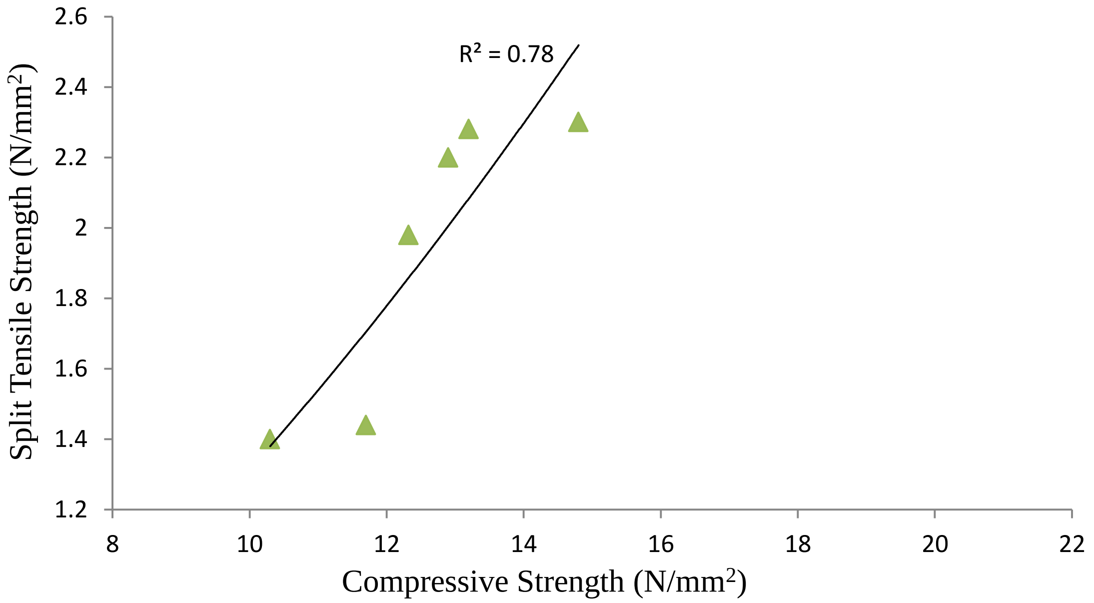


Figure 41. Relationship of split tensile to compressive strengths at 28th day of specimens cured in water

Figure 41 indicates that tensile strength increases with compressive strength of foamed concrete. The regression line of the relationship is an exponential function which can be expressed as

$$f_t = 0.175{f_{cu}}^{0.9} \tag{45}$$

Also, the ratios of tensile strengths to compressive strengths of the specimens (see Appendix C10) show that the tensile strength is approximately between 12 and 15 % of the compressive strength.

4.2.3.2 Specimens cured in water for initial 7 days before exposure to air curing.

Figure 42 shows the relationship of tensile strength to compressive strength of specimens cured in water for initial 7 days before exposure to air curing.

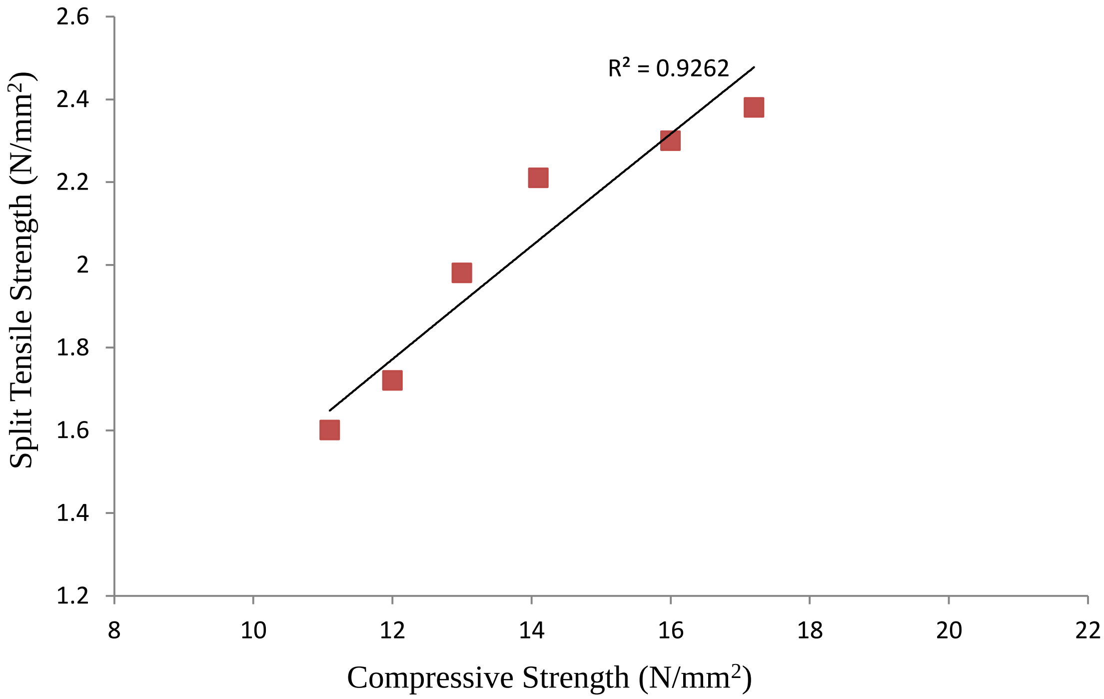


Figure 42. Relationship of split tensile strength to compressive strength at 28th day of specimens cured in water for initial 7-days

Figure 42 indicates that tensile strength increases with compressive strength of foamed concrete. The regression line of the relationship is an exponential function which can be expressed as

$$f_t = 0.0305 {f_{cu}}^{1.6} \tag{46}$$

Also, the ratios of tensile strengths to compressive strengths of the specimens (see Appendix C11) show that the tensile strength is approximately between 11 and 15 % of the compressive strength.

4.2.3 Modulus of Rupture

The results of modulus of rupture (or flexural strengths) of the specimens are reported based on the curing methods used namely air, water and initially in water for 7 days before exposure to air curing.

4.2.3.1 Modulus of Rupture of specimens cured in air.

Figure 43 shows the results of modulus of rupture of unreinforced beam specimens cured in air and the relationship of modulus of rupture to the proportion of laterite as partial replacement of dredged sand.

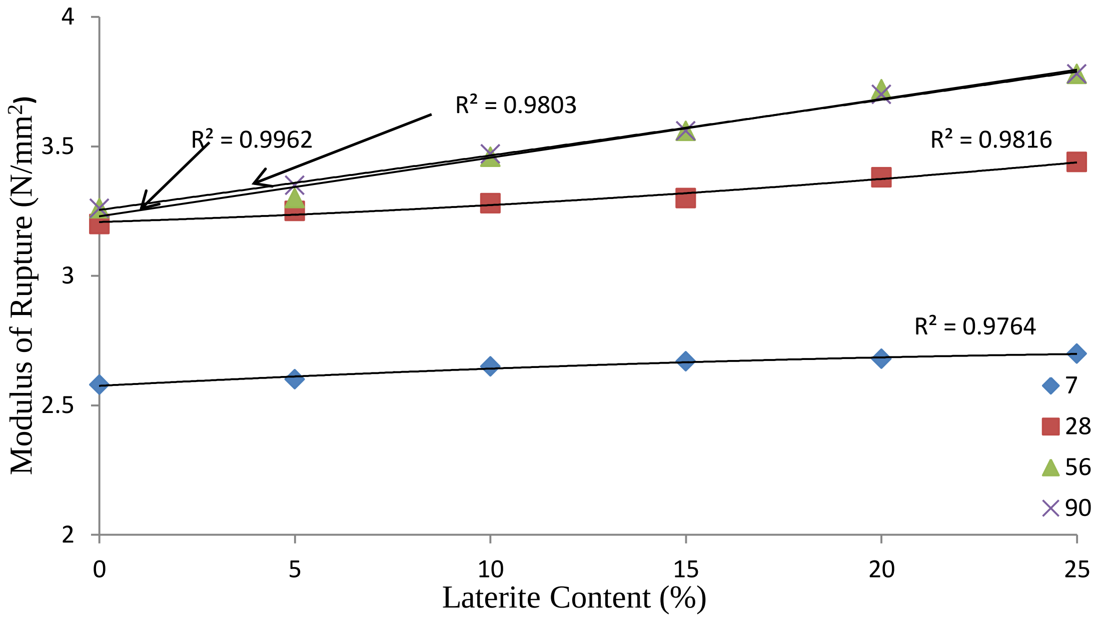


Figure 43. Relationship of modulus of rupture to the proportion of laterite content at various curing periods for specimens cured in air

Figure 43 indicates that the modulus of rupture increases with the proportion of laterite at all curing periods. For example, the modulus of rupture of specimens with 0, 5, 10, 15, 20, and 25 % laterite after 28 days curing period are 3.20, 3.25, 3.28, 3.30, 3.38, and 3.44 N/mm^2 respectively. Also, the results revealed that the modulus of rupture of the specimens increases with curing period. Thus, the modulus of rupture of specimens with 20 % laterite at 7, 28, 56, and 90 days curing periods are 2.68, 3.38, 3.72, 3.72 N/mm^2 respectively (see Appendix C12).

The regression lines of the relationship reveal the rate of flexural strength development in foamed laterized concrete. It indicates that 90 % of the flexural strengths of all the specimens were attained during 28 days curing period. Also the maximum flexural strengths were attained at 56th day curing period. For example, the maximum flexural strengths of specimens with 10, 15, 20 and 25 % laterite which were attained at 56th day curing are 3.47, 3.56, 3.70, 378 N/mm^2, whilst the 28th day curing values are 3.28, 3.30, 3.38, and 3.44 N/mm^2 respectively. The strengths attained at 28th day represent 94, 92, 91, and 91 % of the maximum values.

4.2.3.2 Modulus of rupture of specimens cured in water.

Figure 44 shows the results of modulus of rupture of unreinforced beam specimens cured in water and the relationship of modulus of rupture to the proportions of laterite.

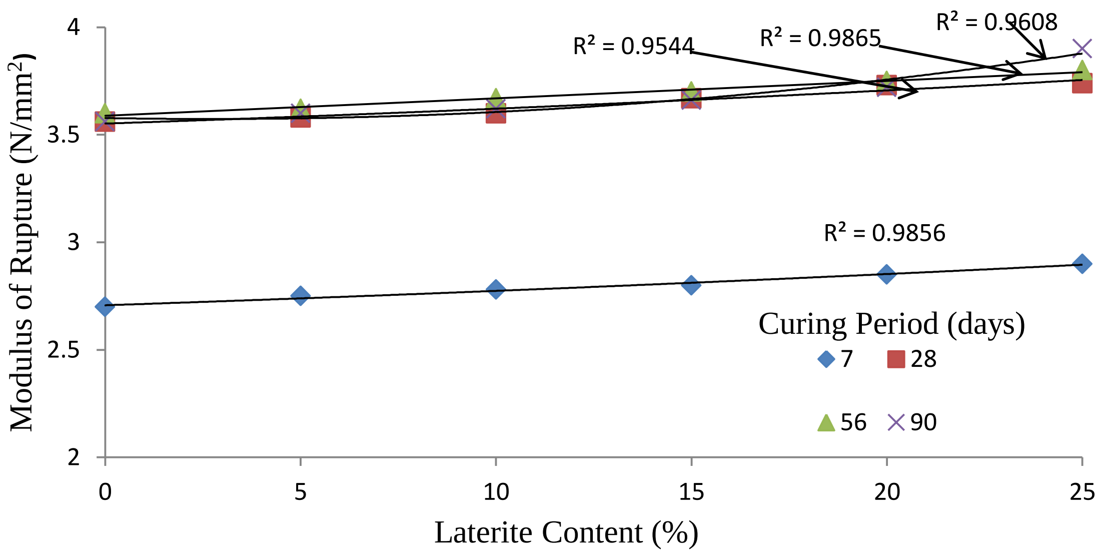


Figure 44. Relationship of modulus of rupture to the proportion of laterite at various curing periods of specimens cured in water

From Figure 44, flexural strengths of the specimens increase with the proportion of laterite. For example, the flexural strengths of specimens with 0, 5, 10, 15, 20, and 25 % laterite at 28th day curing are 3.56, 3.58, 3.60, 3.67, 3.73, and 3.74 N/mm^2. Also, the flexural strengths increase with curing period and maximum values are attained at 56th day curing; and beyond this curing period, further curing of foamed laterized concrete in water results to decreases in flexural strengths. For example, the flexural strengths of specimens with 20 % laterite content at 7th, 28th, 56th, and 90th days are

2.85, 3.73, 3.75, 3.72 N/mm^2 (see Appendix C13). Furthermore, the regression lines of the relationship show that the flexural strengths of the specimens are almost fully attained within 28 days of curing. Therefore, curing of specimens beyond 28 days in water was not necessary.

4.2.3.3 Modulus of rupture of specimens cured in water for initial 7 days before exposure to air curing.

Figure 45 shows the results of modulus of rupture of unreinforced beam specimens cured in water initially for 7 days before exposure to air curing and the relationship of modulus of rupture to the proportion of laterite as partial replacement of dredged sand.

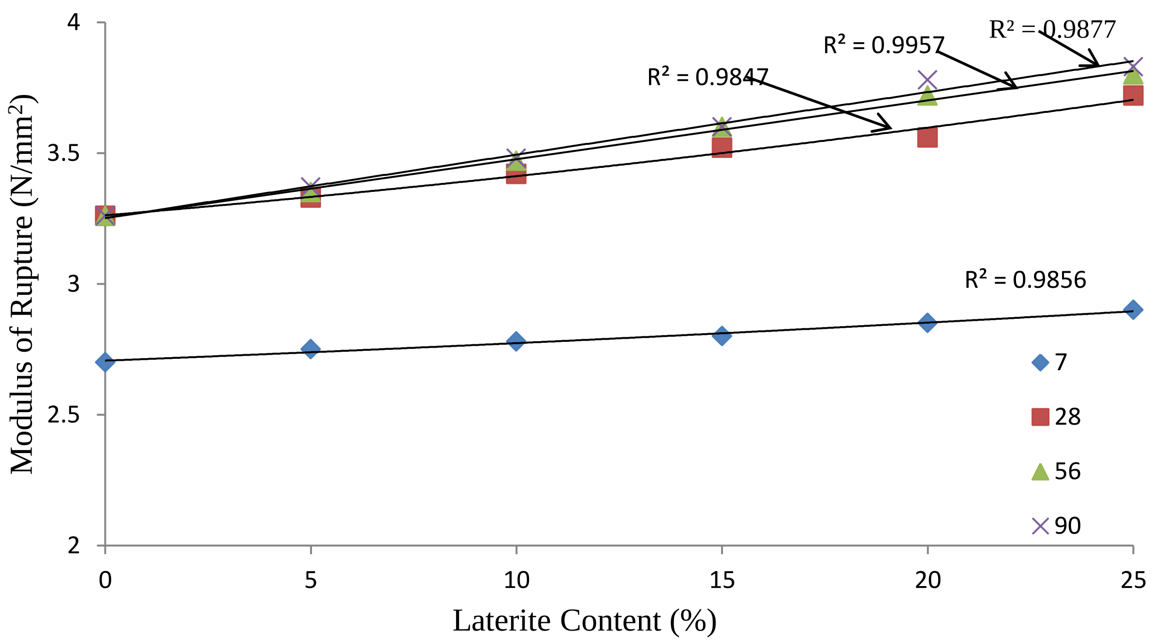


Figure 45. Relationship of modulus of rupture to the proportion of laterite at various curing periods for specimens cured in water for initial 7days

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Figure 45 indicates that the flexural strengths of specimens cured in water initially for 7 days before exposure to air curing increase with the proportion of laterite and with curing period. Also, like other curing media: air and water, over 90% of the strengths were attained within 28 days curing (see Appendix C14).

Figures 43 to 45 show that the modulus of rupture of foamed concrete specimens cured in different media increases marginally with the proportion of laterite, and the increases after 28th day curing in the three media are not really significant. For example, the 90th day modulus of rupture values of the specimens: 0, 5, 10, 15, 20 N/mm^2 respectively; water are 3.56, 3.60, 3.62, 3.70, 3.72 and 3.90 N/mm^2 respectively; water for initial seven days of curing period are 3.26, 3.37, 3.48, 3.66, 3.78 and 3.83 N/mm^2 respectively . The modulus of rupture of specimens with the same proportion of laterite and were cured in different media developed approximately equivalent strength at the curing periods. For example, the flexural strength of specimens with 15% laterite content at 7th, 28th, 56th and 90th days in the different curing media: water for initial seven days are 2.80, 3.52, 3.60 and 3.66 N/mm^2; air are 2.67, 3.30, 3.56 and 3.56 N/mm^2; water are 2.8, 3.67, 3.70 and 3.70 N/mm^2. These values show that curing methods do not significantly affect the development of modulus of rupture of foamed laterized concrete.

Figure 46 shows the relationship of modulus of rupture at 28th day to the proportion of laterite as partial replacement of sand for the specimens in different curing media.

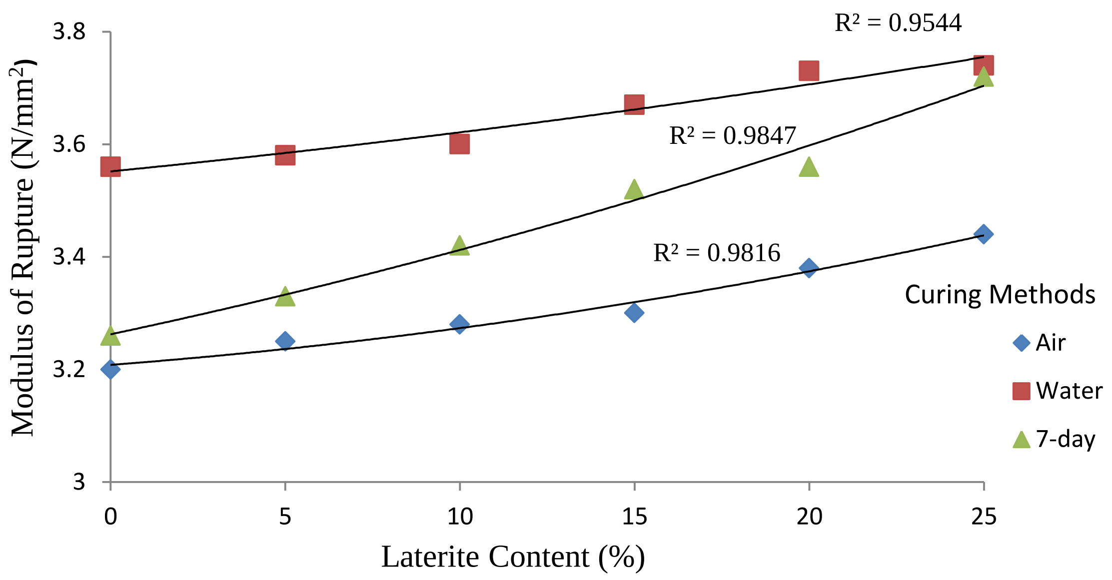

Figure 46. Relationship of modulus of rupture at 28th day to the proportion of laterite of specimens cure in different media

The magnitude of modulus of rupture of the specimens at 28th day are in this order: specimens cured in water, specimens cured in water for initial seven days of curing period; specimens cured in air; For example, at 15 % laterite content, the 28th day modulus of rupture developed by specimens cured in water, water for initial seven days of curing period and air are 3.67, 3.52 and 3.30 N/mm^2 respectively.

4.2.3.4 Relationship between Modulus of Rupture and Compressive Strength

Figures 47 to 49 show the relation of modulus of rupture to compressive strength at 28th day of foamed laterized concrete specimens cured in air, water and initially in water for 7 days before exposure to air curing and they are defined by the equations of the regression lines which are expressed as

$$f_r = 2.0054 f_{cu}{}^{0.2} \tag{47}$$

$$f_r = 2.448 f_{cu}{}^{0.16} \tag{48}$$

and

$$f_r = 1.6623 f_{cu}{}^{0.28} \tag{49}$$

respectively.

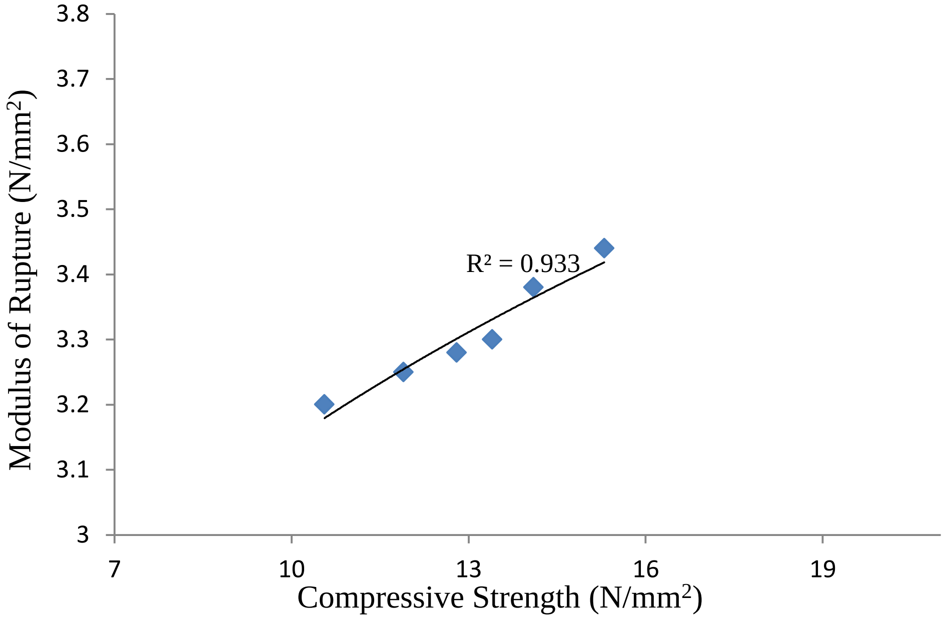

Figure 47. Relationship of modulus of rupture to compressive strength at 28th day of specimens cured in air

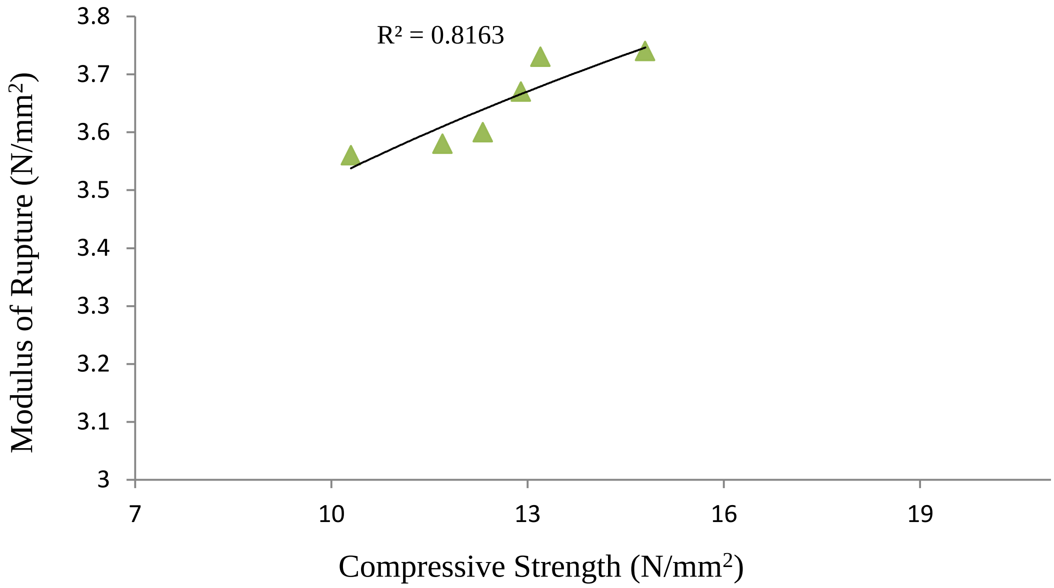

Figure 48. Relationship of modulus of rupture to compressive strength 28th day curing for specimens cured in water

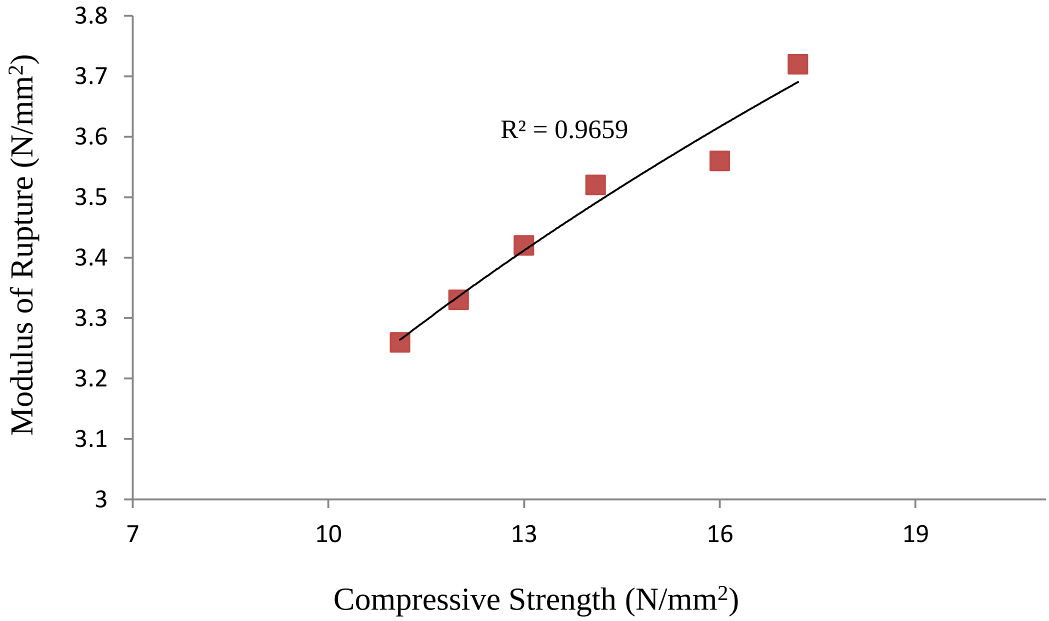

Figure 49. Relationship of modulus of rupture to compressive strengths at 28th day for specimens cured in water initially for 7 days before exposure to air curing

Figure 47 to 49 indicate that the modulus of rupture of foamed laterized concrete is approximately between 20 and 30 % of the compressive strength (see Appendices C15 to C17). These values are more than the values stated in Arthur *et al*. (2010) that the modulus of rupture of light weight concrete is between 10 - 12 % of the compressive strength. Therefore, foamed concrete develops greater flexural strengths than other light weight concrete.

4.3 Main Investigation (Phase II)

The results obtained at this stage of the main investigation are presented under the following headings: deflection, modes of failure, moment and shear capacities of the beams.

4.3.1 Deflection and Modes of Failure of Reinforced Foamed Concrete Beams

Figures 50 and 51 show the relationship of deflections to applied load of the specimens tested with third point loading system.

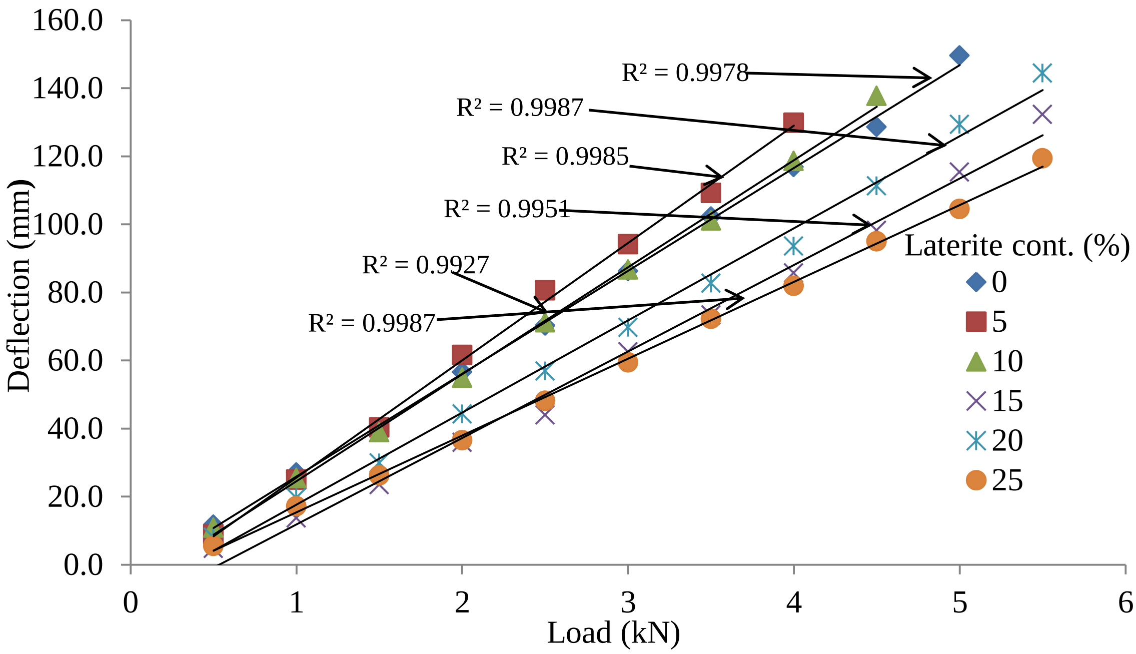

Figure 50. Effect of increase in applied loads on the deflections of specimens reinforced to resist moment and shear forces

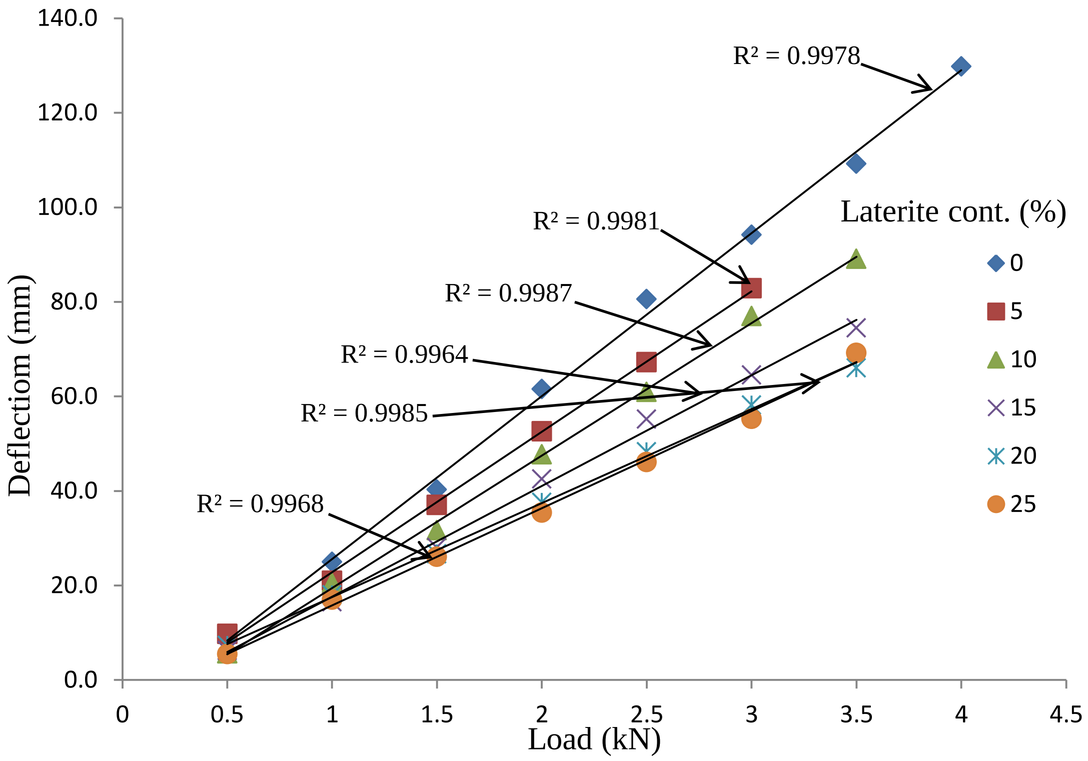

Figure 51. Effect of increase in applied loads on the deflections of specimens without shear reinforced

From Figure 50, expectedly the deflections of the beams increase with applied load. The average deflection value of the specimens that were adequately reinforced to resist shear and flexural stresses before ductile failure occurred is 120 mm. For specimens without shear reinforcement in Figure 51, the average deflection value before they failed without any visible sign of distress (or brittle failure) is 80 mm. The magnitude of deflections of the two sets of specimens within the elastic limit: the deflections when the first cracks were observed are between 36.6 and 52.2 mm. These deflections are high compared with limit of deflection: 20 mm or Span/500 for flexural members as specified in Mosley *et al*. (2008).

Figure 52 shows the shear, flexural-shear and ultimate load capacities of the specimens.

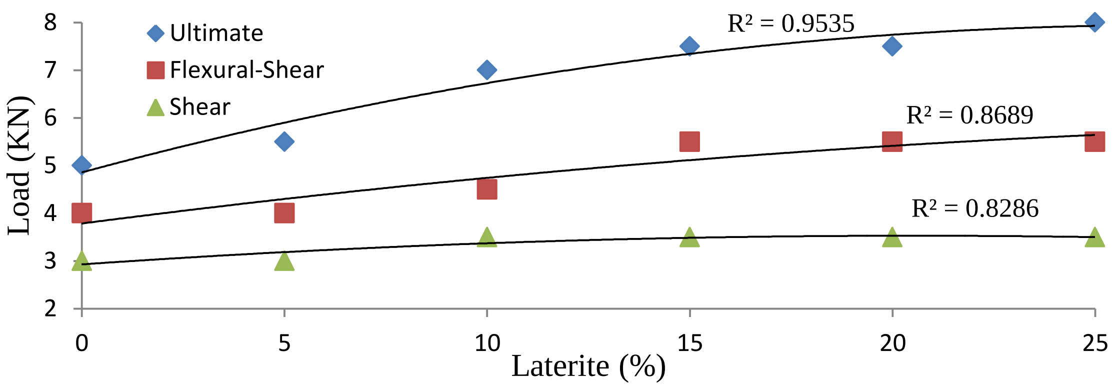

Figure 52. Relationship of applied shear, flexural-shear and ultimate loads to the proportion of laterite in reinforced beams

From Figure 52, the shear loads of the specimens are approximately the same. For example, the shear loads of the specimens with 0, 5, 10, 15, 20 and 25 % laterite are 3.0, 3.0, 3.5, 3.5, 3.5 and 3.5 kN respectively. Also, the flexural-shear load did not change significantly with increases in the proportion of laterite. For example, specimens with 0, 5, 10, 15, 20 and 25 % laterite the flexural-shear loads are 4, 4, 4.5, 5.5, 5.5 and 5.5 kN respectively. Also, after the flexural-shear loads were attained and deflection could no longer be measured, the beams were able to sustained additional applied loads. Therefore, the ultimate failure loads of the beams with 0, 5, 10, 15, 20 and 25 % laterite are 5, 5.5, 7, 7.5, 7.5 and 8 kN respectively.

The beams that were reinforced to resist only flexural stresses failed in shear mode without any visible distress signs and it was accompanied with a loud sound which is a brittle failure. A common feature with all failed specimens was the formation of 45^0 inclined visible cracks close to the supports which spread across the depth of the specimens.

The specimens that were reinforced to resist both flexural and shear stresses failed in flexural-shear mode which were preceded by yielding of the flexural reinforcement and accompanied with visible hair-line cracks within the middle third of the beams is a ductile failure. These actions were quickly followed by the formation of visible 45^0 inclined cracks close to the middle third of the span that propagated through the depth and ultimately caused failure of the beams.

Flexural-shear failure mode can be attributed to low reinforcement-concrete bond strength; because the air voids reduces the net contact surface area between the shear reinforcement and concrete. This assumption is supported in Arthur *et al*. (2010), which had stated that if applied stress in reinforced concrete beams exceeds the concrete-reinforcement bond stresses, shear cracks will propagate without restraint from the shear reinforcement.

4.3.2 Moment and Shear Capacities of Foamed Concrete Beams

Tables 28 and 29 show the 28th day structural properties of foamed laterized concrete derived using Equations (20), (21) and (23) (see Appendix D), and structural properties of normal weight concrete with cement content and w/c ratio of 340 kg/m^3 and 0.5 respectively.

The properties of foamed concrete and the strengths of the beams made with it are low compared with the properties of normal weight concrete as earlier stated by Arthur *et al*. (2010) and Colin (1975). Therefore, foamed laterized concrete can only be applied in areas where the structural properties are suitable and not a direct replacement of normal weight concrete.

Table 28

Structural properties of laterized foamed concrete specimens at 28th day

Laterite cont. (%)	Compressive Strength (N/mm^2)	Split Tensile Strength (N/mm^2)	Modulus of Rupture (N/mm^2)	Moment Capacity (KN-m)	Shear Capacity (N/mm^2)
0	11.1	1.6	3.20	1.75	0.063
5	12.0	1.72	3.33	1.93	0.063
10	13.0	1.98	3.42	2.45	0.063
15	14.1	2.21	3.52	2.63	0.074
20	16.0	2.30	3.56	2.63	0.074
25	17.2	2.38	3.72	2.80	0.075

Cement content = 500 kg/m^3; w/c = 0.5

Table 29

Structural properties of normal weight concrete at 28th day

Compressive Strength (N/mm^2)	Split Tensile Strength (N/mm^2)	Modulus of Rupture (N/mm^2)	Moment Capacity (KN-m)	Shear Capacity (N/mm^2)
25	3.3	5	45.8	1.45

Cement content = 340kg/m^3; w/c = 0.5

Source: Arthur *et al*. (2010); and Colin (1975)

The differences between structural properties of foamed concrete and normal weight concrete can be explained using the concept of geometric and force dimensions, crushing and buckling failure modes of the hydrate structure of concrete. For example, the compressive strength equation for concrete with approximate zero porosity is expressed as

$$f_{cu} = \frac{p_i}{bd} \qquad (50)$$

where b = geometric breadth of member

d = depth of member.

As the porosity approaches unity, that is

ρ approaches 1

Equation (50) can be modified to accommodate entrained air pores and expressed as

$$f_{cu} = \frac{p_i}{b_f d_h} \qquad (51)$$

where $b_f = b - \sum d_p$

$d_h = d - \sum d_p$

b_f = net width of hydrate

d_h = Net depth of hydrate

d_p = average diameter of air entrained pores

ρ = porosity of concrete.

Equations 50, and 51 show that hydrate structure of foamed concrete is subjected to high compressive stress at low compressive force. Also, because the hydrate structure is unrestrained (surrounded by air entrained pores), it could result to buckling failure mode at low applied forces, while a normal weight concrete member fails by crushing failure mode at high applied forces.

4.4 Cost-Benefit Analysis (CBA)

The costs and benefits of foamed laterized concrete are expressed in monetary terms. The costs of production of the different samples of foamed laterized concrete were obtained by substituting the unit costs of the different materials in the general foamed concrete cost equation which can be expressed as

$$C_P = R_c C + R_f F + R_w W_w + R_{wf} W_f + C_l \tag{52}$$

where C_p = total cost of product per cubic metre

R_c, R_f, R_w, R_{wf} = unit rates for cement, fine aggregates, water and enhancing chemical

C, F, W_w, W_f = quantities of cement, fine aggregates, water and foam Concentrate

C_l = labour.

The results of the survey carried out in March, 2016 among concrete vendors and producers in Lagos, Nigeria on the unit costs of the various materials required for foamed concrete production and the prices of different grades of concrete are presented in Tables 30 and 31.

Table 30

Unit cost of various materials required for foamed concrete production in Lagos, Nigeria as at March, 2016.

S/N	Material	Cost/kg (₦)
1	Cement	28
2	Sand	2
3	Laterite	1
4	Foam Concentrate	800
5	Water	0.2

Table 31

Prices of various grades of normal weight concrete per cubic metre in Lagos, Nigeria as at March, 2016.

S/N	Grade of Concrete (N/mm^2)	Price/kg (₦)
1	10	22,000
2	15	25,000
3	20	29,251
4	25	30,700
5	30	32,000

From Table 31, the prices of normal weight concrete varied with its grade. These prices were applied on the different grades of foamed concrete in the CBA of this study. This is because there are no local prices of different grades of foamed concrete in Nigeria. The cost-benefit analysis of foamed concrete with 0, 5, 10, 15, 20, and 25 % of laterite are presented in Tables 32 to 37. The mix composition of materials per cubic metre, before substituting sand with the various proportions of laterite is presented in Table 22.

Table 32

Cost-Benefit analysis of foamed concrete specimen with 0 % laterite content

Cost per cubic metre (C)				Grade of Concrete	Benefit (B) Price (₦)	B – C (₦)	% Increase in Profit
Material	Qty (kg)	Rate (₦)	Amount (₦)				
Cement	500	28	14,000	C11	22,000	2,862	-
Sand	1000	2	2000				
Laterite	-	1					
Foam Conc	1.35	800	1080				
Water	290	0.2	58				
Labour			2000				
Total			19,138				

Table 33

Cost-Benefit analysis of foamed concrete specimen with 5 % laterite content

Cost per cubic metre (C)				Grade of Concrete	Benefit (B) Price (₦)	B – C (₦)	% Increase in Profit
Material	Qty (kg)	Rate (₦)	Amount (₦)				
Cement	500	28	14,000				
Sand	950	2	1,900				
Laterite	50	1	50				
Foam Conc	1.35	800	1080	C12	22,000	2,912	1.75 %
Water	290	0.2	58				
Labour			2000				
Total			19,088				

Table 34

Cost-Benefit analysis of foamed concrete specimen with 10 % laterit content

Cost per cubic metre (C)				Grade of Concrete	Benefit (B) Price (₦)	B – C (₦)	% Increase in Profit
Material	Qty (kg)	Rate (₦)	Amoun t (₦)				
Cement	500	28	14,000				
Sand	900	2	1800				
Laterite	100	1	100				
Foam	1.3	800	1080				
Conc	5			C13	22,000	2,962	3.5 %
Water	290	0.2	58				
Labour			2000				
Total			19,038				

Table 35

Cost-Benefit analysis of foamed concrete specimen with 15 % laterite content

Cost per cubic metre (C)				Grade of Concrete	Benefit (B) Price (₦)	B – C (₦)	% Increase in Profit
Material	Qty (kg)	Rate (₦)	Amount (₦)				
Cement	500	28	14,000				
Sand	850	2	1,700				
Laterite	150	1	150				
Foam Conc	1.35	800	1080	C14	25,000	6,012	110 %
Water	290	0.2	58				
Labour			2000				
Total			18,988				

Table 36

Cost-Benefit analysis of foamed concrete specimen with 20 % laterite content

Cost per cubic metre (C)				Grade of Concrete	Benefit (B) Price (₦)	B – C (₦)	% Increase in Profit
Material	Qty (kg)	Rate (₦)	Amount (₦)				
Cement	500	28	14,000				
Sand	800	2	1,600				
Laterite	200	1	200				
Foam Conc	1.35	800	1080	C16	25,000	6,062	111 %
Water	290	0.2	58				
Labour			2000				
Total			18,938				

Table 37

Cost-Benefit analysis of foamed concrete specimen with 25 % laterite Content

Cost per cubic metre (C)				Grade of Concrete	Benefit (B) Price (₦)	B – C (₦)	% Increase in Profit
Material	Qty (kg)	Rate (₦)	Amount (₦)				
Cement	500	28	14,000				
Sand	750	2	1,500				
Laterite	250	1	250				
Foam Conc	1.35	800	1080	C17	25,000	6,112	113 %
Water	290	0.2	58				
Labour			2000				
Total			18,888				

From Tables 32 to 37 the results show that replacement of sand with varying proportions of laterite in foamed concrete reduces the cost of production and improves its value. The difference between benefits and costs at 15, 20 and 25 % laterite content compared with 0 % laterite content were 210, 211 and 213 %. These values justify the economy of the application of laterite as partial replacement of sand in foamed concrete production.

4.5 Summary of Findings

The summary of findings based on the specific objectives of this study is presented in Table 38.

Table 38

Summary of Findings Based on the Specific Objectives of the Study

s/n	Objectives	Findings
1	Establish the rheological and compressive strength properties of foamed concrete incorporating laterite as a replacement for dredged sand.	i The spread diameter of foamed laterized concrete decreases with increases in the proportion of laterite. ii The compressive strength of foamed laterized concrete increases with the proportion of laterite. i Partial replacement of dredged sand with 25 % laterite was the maximum that satisfied the rheological design criterion with spread diameter between 560 and 760 mm.

2	Determine the structural properties (compressive, flexural and split tensile strengths) of foamed laterized concrete.	i The compressive strength, split tensile strength and modulus of rupture increase with the proportion of laterite. ii The specimens cured in water initially for 7 days before exposure to air developed higher structural properties than specimens separately cured in water and air for the respective curing periods. iii The maximum 28^{th} day structural properties: compressive strength (17.2 N/mm^2); split tensile strength (2.38 N/mm^2) and modulus of rupture (3.72 N/mm^2) were developed by specimens with 25 % laterite as partial replacement of sand.

3	Determine the structural behaviour (deflection and modes of failure) and strengths (flexural capacity and shear capacities) of reinforced foamed laterized concrete beam under flexural load.	i The two sets of beams failed either in shear or flexural-shear modes ii The deflections of the beams within the elastic limit were between 36.60 and 52.2 mm. iii Shear capacity of the beams were between 0.071 and 0.083 N/mm^2 iv The moment capacities of the beams were between 1.75 and 2.80 kN-m.
4	Establish the cost per cubic metre of foamed laterized concrete in comparison to foamed concrete without laterite.	i The replacement of sand with various proportions of laterite in foamed concrete reduced the cost of production and improved the value of foamed concrete. ii The percentage increase in profit on foamed concrete with 5, 10, 15, 20 and 25 % laterite content compared with control (0% laterite) are 1.75, 3.5, 110, 111 and 113 %.

CHAPTER FIVE

5.0 CONCLUSIONS, CONTRIBUTIONS TO KNOWLEDGE AND RECOMMENDATIONS

5.1 Conclusions

From the results of this investigation the following conclusions are made:

i Laterite can be used as partial replacement of dredged sand up to 25% in foamed concrete without significant impact on the rheological properties.

ii Foamed concrete specimens with 10, 15, 20, and 25 % laterite initially cured in water for 7 days before exposure to air curing exhibited lightweight materials characteristics with properties within the minimum values recommended in ACI 213R(2014) for lightweight structural concrete.

iii Reinforced foamed laterized concrete beams have low moment and shear capacities and these can be attributed to low bond strength between foamed concrete and shear reinforcement.

iv Partial replacement of dredged sand with laterite reduces the cost of production and improves the value of foamed concrete.

v The results obtained herein can be used to develop relevant specifications in Nigeria for the use of foamed laterized concrete.

5.2 Contributions to Knowledge

This study has made unique contributions to knowledge as follows:

i Laterite can be used to improve the particle size distribution of dredged sand in foamed concrete production.

ii Partial replacement of sand with 10 to 25 % laterite can be used to improve the compressive strength of foamed concrete from 10 N/mm^2 (non-structural material) to more than 15 N/mm^2 (structural material), and the lightweight structural material can be used for the construction of structural elements such as load bearing walls, short span beams and slabs, low volume drain and infill in ribbed floor systems.

iii Foamed laterized concrete specimens initially cured in water for seven days before exposure to air curing develop higher structural properties than specimens cured in water and air continuously during the curing periods.

iv The use of laterite as partial replacement of dredged sand between 10 and 25 % will yield cost benefits in the range of 110 to 113 %.

5.3 Recommendations

The findings of this study have shed light into a new construction material with advantages over most traditional construction materials. The results can be applied and used in the construction industry in Nigeria and with worldwide or global application.

But the scope and delimitation of the study covered only the ultimate limit state properties of the material. Also the production process is dependent on the country's currency exchange rate with the dollar because of the importation of foam generator and concentrate. Therefore, to achieve industry application and wider acceptability of foamed laterized concrete among stakeholders in Nigeria and other developing countries, further studies are recommended in the following areas:

a) Investigation gear towards development of local foaming agent and foam generator by multidisciplinary team of engineers and scientists.

b) Investigation of other properties of foamed laterized concrete such as durability, bond strength, shrinkage, water absorption capacity, thermal conductivity, etc.

c) Investigation of the potential introduction of organic and inorganic fibres to further improve the structural properties.

d) Investigation of the potential use of different arrangement and diameters of shear reinforcement to improve the shear and moment capacities of reinforced foamed concrete elements.

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APPENDICES

Appendix A: Preparation of Materials and Production Process of Foamed Concrete

Appendix A1. Laterite mining pit at mowe in ogun state

Appendix A2. Determination of fine aggregate size distribution in a stack of sieves with various aperture in accordance with BS 12620 (2013)

Appendix A3. Mechanical concrete mixing machine in the laboratory

Appendix A4. Mobile foam generator set up in the laboratory

Appendix A5. Foam production and injection foam into concrete mixer

Appendix A6. Measurement of plastic density of foamed on a digital scale

Appendix A 7. Spread diameter (D) of foamed concrete after lifting of the truncate cone.

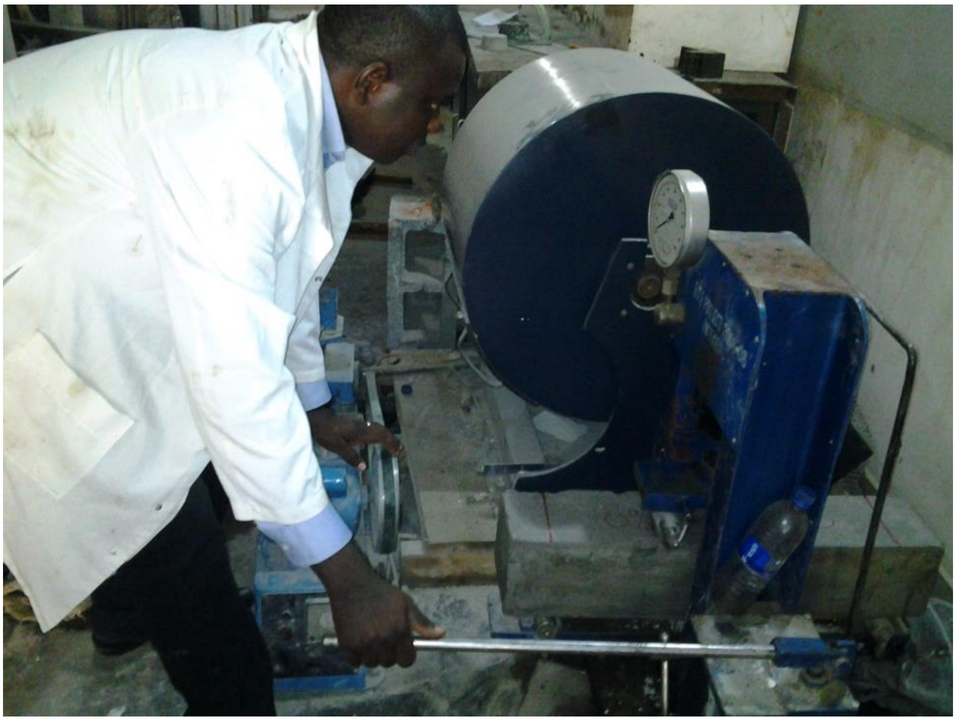
Appendix A8. Filling of prepared steel mould with foamed concrete

Appendix A9. Fresh foamed concrete in steel cube moulds cover with impervious material

Appendix A10. Crushing of foamed concrete cube sample in a compression machine

Appendix A 11. Samples of unreinforced concrete beams and cylinders cured in air

Appendix A12. Placing of concrete beam specimen in curing tank



Appendix A13. Testing of unreinforced concrete beam in a 150kN third point machine

Appendix A 14. Samples of failed unreinforced concrete beams in the middle third

Appendix A15. Testing of unreinforced concrete cylinder in a 600 kN compression machine.

Appendix A16. Samples of failed unreinforced concrete cylinder split along vertical axis

Appendix A17. Samples of prepared steel reinforcement

Appendix A18. Beam specimens covered with damp jute bag in the laboratory

Appendix A19. A typical third point load setup in the laboratory

Appendix A20. Samples of beam specimens that failed in shear

Appendix A21. Samples of beam specimens that failed in flexural - shear

Appendix B: Estimation of Moment Capacity and Shear Force of Concrete Beam at Ultimate Load Using Equations of Equilibrium

The moment capacity and shear stress at ultimate loads of the beams are estimated using Equations (20) to (24). This is achieved by substituting the dimensions of the beams and the compressive strength of the specimens at different stages of the calculation.

Recall;

$$\sum F_y = 0 \tag{20}$$

$$\sum M_D = 0 \tag{21}$$

Therefore, at ultimate load the moment and shear force are 0.35P and 0.5P (see Figures 21 and 22 respectively).

Also,

$$M_u = 0.156bd^2 f_{cu} \tag{22}$$

$$V = vbd = 0.95 f_{\mathrm{yv}} A_{\mathrm{sv}} \tag{23}$$

$$\frac{A_{sv}}{s_v} = \frac{vb}{0.95 f_{\mathrm{yv}}} \tag{24}$$

where,

d = 280 mm

b = 150 mm

f_{cu} – Varies with laterite content

$M_u = 0.156 X 150 X\ 280^2 \mathrm{f_{cu}}\ 10^{-6}$

$M_u = 1.84\mathrm{f_{cu}}$

The estimated moment capacities of concrete beams with various proportions of laterite at ultimate load are shown in Table B1.

Table B1

Estimated moment capacities of foamed laterized concrete beam specimens

Laterite cont. (%)	Compressive Strength- f_c (N/mm^2)	Moment Capacity (KN-m)
0	11.1	20.4
5	12	22.1
10	13	23.9
15	14.1	25.9
20	16	29.4
25	20.9	38.5

Shear Force

From equilibrium of force at ultimate load:

$M_u = 0.35P_i$

$V = 0.5P_i = 1.43M_u$

The shear forces at ultimate load in beams with various proportions of laterite are shown in Table B2

Table B2

Estimated shear force in beam specimens at ultimate load

Laterite cont. (%)	Moment Capacity (kN-m)	Shear Force (kN)
0	20.4	29.2
5	22.1	31.6
10	23.9	34.2
15	25.9	37.1
20	29.4	42.1
25	38.5	55.1

Shear Reinforcement

The shear reinforcement required in the beams at ultimate load that would prevent shear failure is estimated using Equations (23) and (24).

$$V = vbd$$

$$v = \frac{V}{bd}$$

The shear stresses at ultimate load are obtained by substituting the values of shear forces in Table B2 and the beams dimensions into the relationship of shear stress to shear force. Table B3 shows the values of the shear stresses for beams with various proportions of laterite.

Table B3

Estimated shear stress of reinforced beam specimens at ultimate load

Laterite cont. (%)	Shear Force (kN)	Shear Stress (N/mm^2)
0	29.2	0.695
5	31.6	0.752
10	34.2	0.814
15	37.1	0.883
20	42.1	1.002
25	55.1	1.312

The shear reinforcement required is estimated using Equation (24)

$$\frac{A_{sv}}{s_v} = \frac{bv}{0.95 f_{yv}}$$

where:

v = shear stress

A_{sv} = cross-sectional area of the legs of a stirrup

s_v = spacing of the stirrup

b = width of beam = 150 mm

d = effective depth from top fibre = 280 mm

f_{yv} = characteristic strength of the link reinforcement = 460 N/mm^2

The values of area of reinforcement- spacing ratio is obtained by substituting these values into Equation (24). Table B4 shows the values of area of reinforcement-spacing ratio of beams with various proportions of laterite.

Table B4

Estimated area of reinforcement-spacing ratio for beam specimens *at ultimate load*

Laterite cont. (%)	Shear Stress (N/mm^2)	A_{sv}/s_v
0	0.695	0.238
5	0.752	0.258
10	0.814	0.279
15	0.883	0.303
20	1.002	0.344
25	1.312	0.450

Appendix C: Test Results of Foamed Laterized Concrete Specimens in Hardened State

Appendix C1

Dry and wet densities of foamed laterized concrete specimens after28 days curing in air and water

Laterite Content (%)	Dry Density (kg/m^3)	28th Day Wet Density (kg/m^3)
0	1550	1785
10	1605	1828
20	1660	1858
30	1725	1887
40	1747	1899
50	1778	1938
60	1880	1987
70	1953	2057
80	1997	2072
90	2000	2091
100	2127	2151

Appendix C2

Compressive strengths of foamed laterized concrete specimens after 28 days curing in air and water

Laterite Content (%)	28^{th} day compressive strength of Specimens cured in water (N/mm^2)	28^{th} day compressive strength of Specimens cured in air (N/mm^2)
0	5.5	4.3
10	6.4	4.5
20	7.2	4.7
30	7.9	4.9
40	8.7	5.1
50	9.2	5.5
60	9.7	5.7
70	10.2	5.9
80	10.7	6.2
90	11.1	7.1
100	12	8

Appendix C3

Compressive strength of foamed laterized concrete specimens cured in air at various curing periods

Laterite cont. (%)	7th Day	28th Day	56th Day	90th Day
0	7.7	10.56	10.74	11.8
5	9	11.9	12.1	13.1
10	10.9	12.8	14.2	14.2
15	11.5	13.4	15.5	15.8
20	12.8	14.1	15.9	16.7
25	14	15.3	17	17.5

Appendix C4

Compressive strength of foamed laterized concrete specimens cured in water at various curing periods

Laterite cont. (%)	7 Days	28 Days	56 Days	90 Days
0	6.8	11.1	12.6	13.5
5	7.7	12	13.5	14.5
10	10.3	13	14.2	15.2
15	11	14.1	16.8	17.5
20	11.72	16	18.4	19.1
25	13.9	17.2	19	20.8

Appendix C5

Compressive strength of foamed laterized concrete specimens cured in water for initial 7 days before exposure to air curing at various curing periods

Laterite cont. (%)	7 Days	28 Days	56 Days	90 Days
0	6.8	11.1	12.6	13.5
5	7.7	12	13.5	14.5
10	10.3	13	14.2	15.2
15	11	14.1	16.8	17.5
20	11.72	16	18.4	19.1
25	13.9	17.2	19	20.8

Appendix C6

Split tensile strength of foamed laterized concrete specimens cured in air at various curing periods

Laterite cont. (%)	7 Days (N/mm^2)	28 Days (N/mm^2)	56 Days (N/mm^2)	90 Days (N/mm^2)
0	1.12	1.33	1.4	1.5
5	1.19	1.4	1.53	1.58
10	1.75	1.95	1.67	1.7
15	1.77	1.98	1.86	1.86
20	1.89	2.1	1.92	1.94
25	1.98	2.25	2.1	2.15

Appendix C7

Split tensile strength of foamed laterized concrete specimens cured in water at various curing periods

Laterite cont. (%)	7 Days	28 Days	56 Days	90 Days
0	1.21	1.4	1.64	1.7
5	1.24	1.44	1.7	1.78
10	1.84	1.98	2.01	2.15
15	1.92	2.2	2.28	2.3
20	1.98	2.28	2.3	2.36
25	2.05	2.3	2.35	2.45

Appendix C8

Split tensile strengths of foamed laterized concrete specimens cured in water for initial 7 days before exposure to air curing at various curing periods

Laterite cont. (%)	7 Days	28 Days	56 Days	90 Days
0	1.21	1.6	1.98	2.21
5	1.24	1.72	2.32	2.31
10	1.84	1.98	2.47	2.45
15	1.92	2.21	2.5	2.55
20	1.98	2.3	2.58	2.87
25	2.05	2.38	2.62	3.11

Appendix C9

Ratio of split tensile strength to compressive strength of specimens cure in air

	28th Day Strengths		
Laterite cont. (%)	Compressive Strength (f_c) N/mm^2	Split Tensile Strength (f_t) N/mm^2	f_t/f_c
0	10.56	1.33	0.13
5	11.9	1.4	0.12
10	12.8	1.95	0.15
15	13.4	1.98	0.15
20	14.1	2.1	0.15
25	18.6	2.25	0.12

Appendix C10

Ratio of split tensile strength to compressive strength of specimens cure in water

	28th Day Strengths		
Laterite cont. (%)	Compressive Strength (f_c) N/mm^2	Split Tensile Strength (f_t) N/mm^2	f_t/f_c
0	10.3	1.40	0.13
5	11.7	1.44	0.12
10	12.3	1.98	0.16
15	12.9	2.20	0.17
20	13.2	2.28	0.17
25	18.0	2.30	0.12

Appendix C11

Ratio of split tensile strength to compressive strength of specimens cure in water for 7 days before exposure to air curing

	28th Day Strengths		
Laterite cont. (%)	Compressive Strength (f_c) N/mm^2	Split Tensile Strength (f_t) N/mm^2	f_t/f_c
0	11.1	1.60	0.14
5	12.0	1.72	0.14
10	13.0	1.98	0.15
15	14.1	2.21	0.15
20	16.0	2.30	0.14
25	20.9	2.38	0.11

Appendix C12

Modulus of rupture of foamed laterized concrete specimens cured in air

Laterite cont. (%)	7 Days (N/mm^2)	28 Days (N/mm^2)	56 Days (N/mm^2)	90 Days (N/mm^2)
0	2.58	3.20	3.26	3.26
5	2.60	3.25	3.30	3.35
10	2.65	3.28	3.46	3.47
15	2.67	3.30	3.56	3.56
20	2.68	3.38	3.72	3.72
25	2.70	3.44	3.78	3.78

Appendix C13

Modulus of rupture of foamed laterized concrete specimens cured in water

Laterite cont. (%)	7 Days (N/mm^2)	28 Days (N/mm^2)	56 Days (N/mm^2)	90 Days (N/mm^2)
0	2.70	3.56	3.60	3.56
5	2.75	3.58	3.62	3.60
10	2.78	3.60	3.67	3.62
15	2.80	3.67	3.70	3.66
20	2.85	3.73	3.75	3.72
25	2.85	3.74	3.80	3.90

Appendix C14

Modulus of rupture of foamed laterized concrete specimens cured in water initially for 7 days before exposure to air curing

Laterite cont. (%)	7 Days (N/mm^2)	28 Days (N/mm^2)	56 Days (N/mm^2)	90 Days (N/mm^2)
0	2.70	3.26	3.26	3.26
5	2.75	3.33	3.35	3.37
10	2.78	3.42	3.47	3.48
15	2.80	3.52	3.60	3.60
20	2.85	3.56	3.72	3.78
25	2.85	3.72	3.80	3.83

Appendix C15

Ratio of modulus of rupture to compressive strength of specimens cure in air

28th Day Strengths			
Laterite cont. (%)	Compressive Strength (f_c) N/mm^2	Modulus of Rupture (f_r) N/mm^2	f_t/f_c
0	10.56	3.20	0.30
5	11.9	3.25	0.27
10	12.8	3.28	0.25
15	13.4	3.30	0.24
20	14.1	3.38	0.24
25	18.6	3.44	0.18

Appendix C16

Ratio of modulus of rupture to compressive strength of specimens cure in water

28th Day Strengths			
Laterite cont. (%)	Compressive Strength (f_c) N/mm^2	Modulus of Rupture (f_r) N/mm^2	f_t/f_c
0	10.3	3.56	0.35
5	11.7	3.58	0.31
10	12.3	3.60	0.29
15	12.9	3.67	0.28
20	13.2	3.73	0.28
25	18.0	3.74	0.21

Appendix C17

Ratio of modulus of rupture to compressive strength of specimens cure in water for 7 days before exposure to air curing

	28th Day Strengths		
Laterite cont. (%)	Compressive Strength (f_c) N/mm^2	Modulus of Rupture (f_r) N/mm^2	f_t/f_c
0	11.1	3.26	0.29
5	12.0	3.33	0.27
10	13.0	3.42	0.26
15	14.1	3.52	0.25
20	16.0	3.56	0.22
25	20.9	3.72	0.18

Appendix D: Determination of Moment and Shear Capacities of Reinforced Foamed Laterized Concrete Beams at Ultimate Load Using Equations of Equilibrium

The moment capacity and shear stress at ultimate loads of the beams are estimated using Equations (20) (21) and (23). This is achieved by substituting the dimensions of the beams and the applied loads when the specimens failed.

Recall;

$$\sum F_y = 0 \qquad (20)$$

$$\sum M_D = 0 \qquad (21)$$

$$V = vbd = 0.95 f_{yv} A_{sv} \qquad (23)$$

Also,

$M_u = 0.35P_i$

$V = 0.5P_i = 1.43M_u$

$v = \frac{V}{bd} = \frac{V}{150*280} = 4.2*10^{-2}V = 2.1*10^{-2}P_i$

The moment capacities of beams with various proportions of laterite are obtained by substituting the values of applied loads that caused the beams with both shear and flexural reinforcement to fail. While the shear capacities are obtained using the fail loads of specimens with only flexural reinforcement. Tables D1 and D2 show the moment and shear capacities of reinforced laterized beams respectively.

Table D1

Moment capacities of foamed laterized concrete beam specimens

Laterite cont. (%)	Applied Load (kN)	Moment Capacity (kN-m)
0	5	1.75
5	5.5	1.93
10	7	2.45
15	7.5	2.63
20	7.5	2.63
25	8	2.80

Table D2

Shear capacities of foamed laterized concrete beam specimens

Laterite cont. (%)	Applied Load (kN)	Shear Capacity (N/mm^2)
0	3	0.063
5	3	0.063
10	3	0.063
15	3.5	0.074
20	3.5	0.074
25	3.5	0.075