

## ABSTRACT

Foamed concrete is a lightweight material with self-compacting rheological properties. Conventionally, it is produced from mixture of cement, fine aggregates (dredged sand) and mechanically entrained foam. Research findings have shown that the foam degenerates to create evenly distributed macro and micro air pores after 45 minutes; also, that other fine aggregates could be used as partial replacement of the dredged sand. In this respect, it has been established that laterite which is usually available near project sites and less expensive to procure is suitable as partial replacement of dredged sand in concrete. The particle size distribution of dredged sand contains inter-particle voids that contribute to the formation of macro air pores. These macro pores are defects that reduce structural properties of foamed concrete. In addition, non-application of foamed concrete made with available local materials in developing countries is due to dearth of information on its structural properties and the structural strengths of elements made with it. Thus, the application of laterite as partial replacement of dredged sand in foamed concrete to reduce macro pores with minimal impact on the rheological properties was examined. This study consists of two parts namely, preliminary and main investigations. During the preliminary investigation, the effects of replacing dredged sand with laterite on the rheological property (measured as spread diameter) and compressive strength of cube specimens at 28<sup>th</sup> day were examined. The variables were curing periods, methods of curing and proportions of laterite (0-100 % replacement of dredged sand by weight at interval of 10 %). In the main experiment, the structural properties of foamed concrete made with laterite between 0 and 25 % and the strengths of reinforced concrete beams made with the specimens were examined. Also, three curing methods namely; air, water, and initial curing in water for seven days before exposure to air curing for the remaining curing days were used. The results obtained at the preliminary stage showed that foamed concrete samples with laterite between 0 and 25 % as partial replacement of dredged sand satisfied flow consistency requirement and self-compacting rheological criterion: the spread diameters obtained which are between 532 mm and 642 mm are according to established specifications. The compressive strength of foamed concrete at 28<sup>th</sup> day increased with increases in proportions of laterite for specimens cured in all curing media. These results formed the basis for the main investigation using laterite in the proportions of 0, 5, 10, 15, 20 and 25 %. The results obtained from the main investigation, showed that specimens made with 25 % laterite content and cured initially in water for seven days before exposure to air curing developed the maximum 28<sup>th</sup> day structural properties: compressive strength (17.2 N/mm<sup>2</sup>), split tensile strength (2.38 N/mm<sup>2</sup>) and modulus of rupture (3.72 N/mm<sup>2</sup>). These structural properties are greater than the minimum values recommended in ACI 213R (2014) for structural lightweight concrete. Therefore, the foamed lateritized concrete with laterite as partial replacement of dredged sand between 0% and 25% in this investigation fit properly into the range of specifications for lightweight structural concrete and thus has the potential of application in such areas as load bearing walls, short span beams and slabs, low volume drain and infill in ribbed floor system. The differences in cost benefit analysis between 0% foamed lateritized concrete and specimens with 5, 10, 15, 20 and 25 % laterite were 1.75, 3.5 110, 111 and 113 % respectively. These values justify the application of laterite as partial replacement of sand in foamed concrete production but with an optimum value of 25 % partial replacement of dredged sand with laterite.

**Keywords:** Foamed concrete, Laterite, Rheology, Structural properties

## TABLE OF CONTENTS

CERTIFICATION	i
SIGNING OFF OF OWNERSHIP RIGHT OF THESIS	ii
ABSTRACT	iii
DEDICATION	iv
ACKNOWLEDGEMENTS	v
LIST OF TABLES	vi
LIST OF FIGURES	vii
LIST OF SYMBOLS	viii
<b>1.0 INTRODUCTION</b>	<b>1</b>
1.1 Background of the Study	1
1.2 Statement of the Problem	5
1.3 Research Aim and Objectives	6
1.4 Scope and Delimitation of Study	7
1.5 Significance of Study	7
1.6 Operational Definition of Terms	9
<b>2.0 LITERATURE REVIEW</b>	<b>12</b>
2.1 Foamed Concrete Formation Mechanism	13
2.1.1 Cement-Sand Matrix Formation Mechanism	15
2.1.2 Pores Formation Mechanism	18
2.2 Rheological Property of Foamed Concrete	24
2.3 Compressive Strength	34
2.4 Tensile Strength	42

2.5 Flexural Capacity of Reinforce Concrete Beam	48
2.6 Foamed Concrete: Conventional and Innovative Mix Composition	59
2.7 Cost-Benefit Analysis	66
<b>3.0 MATERIALS AND METHODS</b>	<b>68</b>
3.1 Theoretical Frame Work	68
3.2 Materials Preparation and Methods	70
3.2.1 Preliminary Investigation	70
3.2.1.1 Materials	70
3.2.1.2 Mix design	72
3.2.1.3 Trial mix: determination of actual foam quantity	77
3.2.1.4 Effect of replacing sand with laterite on plastic density, spread diameter	78
3.2.1.5 Effect of replacing sand with laterite on compressive strength	79
3.2.1.6 Effect of curing duration in water on compressive strength	80
3.2.2 Main Investigation Phase I	80
3.2.3 Main Investigation Phase II	83
3.3 Cost Benefit Analysis (CBA)	87
<b>4.0 RESULTS AND DISCUSSION</b>	<b>89</b>
4.1 Preliminary Investigation	89
4.1.1 Fine Aggregate characteristics	89
4.1.2 Analysis of Setting Times and Consistency of Cement	91
4.1.3 Mix Composition of Foamed Concrete	92
4.1.4 Effect of Replacing Sand with Laterite on Rheological Properties of Foamed Concrete	94
4.1.5 Hardened State Properties	98

4.2	Main Investigation Phase 1	106
4.2.1	Compressive Strength of Foamed Concrete Specimens	106
4.2.2	Split Tensile Strength	114
4.2.3	Modulus of Rupture	123
4.3	Main Investigation Phase II	132
4.4	Cost Benefit Analysis (CBA)	138
4.5	Summary of Findings	144
<b>5.0</b>	<b>CONCLUSIONS, CONTRIBUTIONS TO KNOWLEDGE AND RECOMMENDATIONS</b>	147
5.1	Conclusions	147
5.2	Contributions to Knowledge	148
5.3	Recommendations	149
	<b>REFERENCES</b>	150
	<b>APPENDICES</b>	157
Appendix A	Preparation of Materials and Production Process of Foamed Concrete	157
Appendix B	Estimation of Moment Capacity and Shear Force of Concrete Beam at Ultimate Load Using Equations of Equilibrium	168
Appendix C	Test Results of Foamed Laterized Concrete Specimens in Hardened State	173
Appendix D	Determination of Moment and Shear Capacities of Reinforced Foamed Laterized Concrete Beams at Ultimate Load Using Equations of Equilibrium	183

## LIST OF TABLES

Table 1.	Major groupings of foamed concrete areas of applications	14
Table 2.	Compound composition of ordinary Portland cement	15
Table 3.	The different stages of hydration reaction	16
Table 4.	Rheological characterization and ranking of concrete	25
Table 5.	Slump and spread test values of different types of concrete	29
Table 6.	Foamed concrete classification based on modified Marsh cone flow	31
Table 7.	Classification of lightweight concrete	36
Table 8.	Numerical relationship between tensile strength and compressive strength	43
Table 9.	Approximate values of tensile strength of concrete expressed as a fraction of the compressive strength	44
Table 10.	Quality control measures for the design and production of foamed concrete	61
Table 11.	Base mix composition of foamed concrete in $\text{kg/m}^3$ with w/c ratio of 0.7	74
Table 11.	Base mix composition of foamed concrete in $\text{kg/m}^3$ with w/c of 0.5	75
Table 13.	Procedures for the determination of density of the base mix	76
Table 14.	Proportions of materials in different batches	79
Table 15.	Maximum reinforcement required to achieve ductile failure mode	84
Table 16.	Minimum reinforcement required to achieve ductile failure	85
Table 17.	Comparison between the limits and reinforcement provided	85
Table 18.	Shear stress and shear reinforcement provided at ultimate load	86
Table 19.	Comparison between the physical properties of sand and laterite	90
Table 20.	The initial and final setting times, consistency of two brands of OPC	91
Table 21.	Effects of foam concentrate quantity on the density of foamed concrete	93

Table 22.	Mix composition of foamed concrete with w/c ratios of 0.7	93
Table 23.	Mix composition of foamed concrete with w/c ratios of 0.5	94
Table 24.	The results of compressive strengths of specimens with 0% laterite content made with different mix proportions	103
Table 25.	Comparison of the compressive strengths developed at 7 <sup>th</sup> and 28 <sup>th</sup> days curing for specimens cured in air	108
Table 26.	Comparison of the compressive strengths developed at 7 <sup>th</sup> and 28 <sup>th</sup> days curing for specimens cured in water	110
Table 27.	Comparison of the compressive strengths developed at 7 <sup>th</sup> and 28 <sup>th</sup> days curing periods for specimens cured in water for initial 7 days before exposure to air curing	112
Table 28.	Structural properties of laterized foamed concrete at 28 <sup>th</sup> day	136
Table 29.	Structural properties of normal weight concrete at 28 <sup>th</sup> day	136
Table 30.	Unit cost of different materials required for foamed concrete production in Lagos, Nigeria as at March, 2016	139
Table 31.	Prices of different grades of normal weight concrete per cubic metre in Lagos, Nigeria as at March, 2016	139
Table 32.	Cost benefit analysis of foamed concrete specimens with 0% laterite content	140
Table 33.	Cost benefit analysis of foamed concrete specimens with 5% laterite content	141
Table 34.	Cost benefit analysis of foamed concrete specimen with 10% laterite content	141
Table 35.	Cost benefit analysis of foamed concrete specimens with 15% laterite content	142
Table 36.	Cost benefit analysis of foamed concrete specimens with 20% laterite content	142
Table 37.	Cost benefit analysis of foamed concrete specimens with 25% laterite content	143
Table 38.	Summary of findings based on specific objectives of the study	144

## LIST OF FIGURES

Figure 1.	Continuous foam generator	19
Figure 2.	Mobile foam generator	20
Figure 3.	Schematic representation of foam production process	22
Figure 4.	Sample of foam produced from a foam generator	23
Figure 5.	Graphical representation of Bingham equation: relationship of stress to shear rate	25
Figure 6.	Schematic representation of spread test	28
Figure 7.	Modified Marsh cone use for flow test	31
Figure 8.	Schematic diagram of Tattersall two-point apparatus	32
Figure 9.	Relationship of shear rate to change in shear stress	33
Figure 10.	Relationship of compressive strength to gel/space ratio of normal weight concrete	38
Figure 11.	Relationship of compressive strength to duration of in water of normal weight concrete at various curing periods	40
Figure 12.	Pore size distribution of binder pastes for cement paste of low heat PC and OPC)	41
Figure 13.	Schematic representation of split tensile test	45
Figure 14.	Schematic representation of third point loading system	46
Figure 15.	Schematic representation of failed beam within the middle third	47
Figure 16.	Schematic representation of failed beam outside the middle third	48
Figure 17.	Distribution of strains and stresses within elastic limit of reinforced concrete beam	49
Figure 18.	Distribution of strains and stresses in a cracked section of reinforced concrete beam	51
Figure 19.	Distribution of stresses and strains in a reinforced concrete beam at ultimate limit load	51
Figure 20.	Schematic drawing of third point load test	52
Figure 21.	Moment diagram at ultimate load	53

Figure 22. Shear force diagram at ultimate load	54
Figure 23. A Section of a beam showing internal equilibrium of forces at ultimate load	54
Figure 24. Actual and equivalent rectangular stress distribution at ultimate load	55
Figure 25. Net tensile strain at ultimate load	55
Figure 26. Schematic representation of failed reinforced concrete beam on flexural-shear mode	58
Figure 27. Schematic representation of failed reinforced concrete beam on web-shear mode	58
Figure 28. Fine aggregates (sand and laterite) particle size distribution	89
Figure 29. Relationship of plastic density to the proportion of laterite	95
Figure 30. Relationship of spread diameter to the proportion of laterite	97
Figure 31. Relationship of density to the proportion of laterite at 28 <sup>th</sup> day	99
Figure 32. Relationship of compressive strength to the proportion of laterite	101
Figure 33. Relationship of compressive strength to curing duration of foamed concrete cured in water at various testing days	104
Figure 34. Relationship of compressive strength to the proportion of laterite at various curing periods for specimens cured in air	106
Figure 35. Relationship of compressive strength to the proportion of laterite at various curing periods for specimens cured in water	108
Figure 36. Relationship of compressive strength to the proportion of laterite at various curing ages of specimens cured in water for initial 7 days	111
Figures 37. Relationship of split tensile strength to the proportion of laterite at various curing periods of specimens cured in air	114
Figures 38. Relationship of split tensile strength to the proportion of laterite at various curing periods of specimens cured in water	115
Figures 39. Relationship of split tensile strength to the proportion of laterite at various curing periods of specimens cured in water for initial 7 days	117

Figure 40. Relationship of split tensile strength to compressive strength at 28 <sup>th</sup> day of specimens cured in air	120
Figure 41. Relationship of split tensile strength to compressive strength at 28 <sup>th</sup> day of specimens cured in water	121
Figure 42. Relationship of split tensile strength to compressive strength at 28 <sup>th</sup> day of specimens cured in water for initial 7-days	122
Figure 43. Relationship of modulus of rupture to the proportion of laterite at various curing periods of specimens cured in air	124
Figure 44. Relationship of modulus of rupture to the proportion of laterite at various curing periods of specimens cured in water	125
Figure 45. Relationship of modulus of rupture to the proportion of laterite at different curing periods of specimens cured in water initially for 7 days before exposure to air curing	126
Figure 46. Relationship of modulus of rupture at 28 <sup>th</sup> to the proportion laterite of specimens cured in different media	128
Figure 47. Relationship of modulus of rupture to compressive strength at 28 <sup>th</sup> day of specimens cured in air	129
Figure 48. Relationship of modulus of rupture to compressive strength at 28 <sup>th</sup> day of specimens cured in water	130
Figure 49. Relationship of modulus of rupture to compressive strength at 28 <sup>th</sup> day of specimens cured in water initially for 7 days before exposure to air curing	130
Figure 50. Effect of increase in applied loads on the deflections of specimens reinforced to resist moment and shear forces	132
Figure 51. Effect of increase in applied loads on the deflections of specimens without shear reinforcement	133
Figure 52. Relationship of applied shear, flexural-shear and ultimate loads to the proportion of laterite in reinforced concrete beams	134

## LIST OF SYMBOLS

$\tau$	=	Shear stress (N/m <sup>2</sup> )
$\gamma$	=	Shear rate (s <sup>-1</sup> )
$\tau_0$	=	yield stress (N/m <sup>2</sup> )
$\eta$	=	Plastic viscosity (Ns/mm <sup>2</sup> )
$S$	=	Slump (mm)
$\rho$	=	Density (kg/m <sup>3</sup> )
$g$	=	Acceleration due to gravity (m/s <sup>2</sup> )
$H_0$	=	Initial (un-slumped) height (mm)
$R$	=	Radius of spread (mm)
$V_s$	=	Volume of sample (m <sup>3</sup> )
$r_1$	=	The smaller radius of the truncated cone (mm)
$r_2$	=	The greater radius of the truncated cone (mm)
$h_c$	=	Height of truncated cone (mm)
$Q$	=	Rate of flow (m <sup>3</sup> /s)
$P$	=	Pressure gradient driving the flow (km/s <sup>2</sup> )
$p$	=	Minimum pressure at which flow begins (N/m <sup>2</sup> )
$L_f$	=	Flow length (mm)
$T$	=	Torque (N.m)
$G$	=	Constant obtained by calibration with Newtonian fluids
$K$	=	Constant obtained by calibration with non-Newtonian fluids
$N$	=	Speed of the impeller (m/s)
$f_{cu}$	=	Compressive strength (N/mm <sup>2</sup> )
$f_0$	=	Compressive strength at zero porosity (N/mm <sup>2</sup> )
$P_0$	=	Porosity (%)

$\gamma_d$	=	Dry density (kg/m <sup>3</sup> )
$f_t$	=	Split tensile strength (N/mm <sup>2</sup> )
$P_i$	=	Maximum applied load by the testing machine (N)
$l$	=	Length of cylinder specimen (mm)
$d_c$	=	diameter of cylinder specimen (mm)
$f_r$	=	Modulus of rupture (N/mm <sup>2</sup> )
$b$	=	Average width of the specimen (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 (mm)
$A_{s, min}$	=	Minimum area of steel required (mm <sup>2</sup> )
$f_y$	=	Characteristic strength of steel (N/mm <sup>2</sup> )
$A_{s, max}$	=	Maximum area of steel required (mm <sup>2</sup> )
$\rho_m$	=	Maximum reinforcement ratio
$A_s$	=	area of tensile steel
$d$	=	depth of tensile steel from top most compression fibre
$h$	=	overall depth of beam
$\epsilon_{cc}$	=	compressive concrete strain
$\epsilon_{ct}$	=	tensile concrete strain
$\epsilon_{st}$	=	tensile steel strain
$f_{cc}$	=	compressive concrete stress
$f_{ct}$	=	tensile concrete stress
$f_{st}$	=	tensile steel stress
$f$	=	Bending stress at a distance $y$ from neutral axis (N/mm <sup>2</sup> )
$M$	=	Applied bending moment at section (kN.m)
$I$	=	Moment of inertial of cross section about neutral axis (cm <sup>4</sup> )
$y$	=	distance from the neutral axis

$F_{cc}$	=	compressive force
$F_{st}$	=	tensile force
$x$	=	depth of neutral axis from top fibre
$s$	=	equivalent depth of neutral axis from top fibre
$z$	=	lever arm
$M_u$	=	moment capacity of concrete beams
$V$	=	shear force at ultimate load
$v$	=	shear stress
$v_c$	=	ultimate shear stress in concrete
$f_{yv}$	=	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
$D$	=	Plastic density of foamed concrete ( $\text{kg/m}^3$ )
$D_o$	=	Dry density of foamed concrete at 28 <sup>th</sup> day ( $\text{kg/m}^3$ )
$D_B$	=	Density of base mix (mortar) ( $\text{kg/m}^3$ )
$S_D$	=	Spread diameter (mm)
$\phi$	=	Proportion of laterite (%)
$w/c$	=	water/cement ratio
$C$	=	Quantity of cement in the mix (kg)
$W_f$	=	Quantity of foam (kg)
$W_w$	=	Quantity of Water (kg)
$F$	=	Quantity of Fine aggregate (kg)
$V_f$	=	Volume of foam ( $\text{m}^3$ )
$A_{s,prov}$	=	Area of steel provided ( $\text{mm}^2$ )

$b_f$	=	net width of hydrate
$d_h$	=	Net depth of hydrate
$d_p$	=	average diameter of air entrained pores
$C_p$	=	Total cost of product per cubic metre
$R_c$	=	Unit rates of cement
$R_f$	=	Unit rate of fine aggregates
$R_w$	=	Unit rate of water
$R_{ch}$	=	Unit rate of foam concentrate
$C_l$	=	labour cost