Properties of Lightweight Concrete made with Volcanic Scoria from Kenya, as Coarse Aggregates

Tejiona Tangomo Frank Roland, Ochieng Abuodha Silvester, Shitote Stanley Muse, Poh'Sie Guillaume Herve

Abstract: Lightweight concrete (LWC) is a specific type of concrete developed when the need to reduce dead load becomes relevant in structures, such as high-rise buildings and bridge decks. This type of concrete can offer a good strength to weight ratio, good insulating properties and costs benefits due to reduced sections of bearing elements in a structure (columns, beams, foundations). It is commonly made using artificial lightweight aggregates like expanded shales and clays; however, the manufacturing process of those aggregates is linked to a great amount of energy consumption, natural resources depletion, and large amount of emission of CO_2 gas in the environment, and finally high costs. This experimental study investigated the use of volcanic scoria aggregates from Lukenya in Kenya to produce structural lightweight aggregates concrete (SLWAC). Scoria stones were collected, crushed into particle sizes 4.75-19 mm, conforming to the grading requirements of ASTM C330, and used to produce lightweight concrete designed using the three different methods prescribed by the standard ACI 211.2-98 for proportioning structural lightweight concrete. The design strength was 30 MPa and the aim was not only to investigate the feasibility of producing structural lightweight concrete with locally available scoria aggregates, but also to find out the best mix design approach out of the three prescribed by the standard, namely the weight method, the absolute volume method and the damp loose method. Physical and mechanical tests were carried out on the scoria aggregates to classify them as suitable for structural lightweight concrete production. Similar tests were also carried out on the lightweight concrete. The results showed that the absolute volume method of mix design was the one giving the best results as regards to the dry density, the slump, and the strengths (compressive, splitting tensile and flexural strength); This lead to the conclusion that volcanic scoria can be used as an alternative to artificial lightweight aggregates for structural lightweight concrete production, and proved the efficiency of the absolute volume method as the best mix design approach.

Keywords: Absolute Volume Method, Artificial Lightweight Aggregates, Lightweight Concrete, Structural Lightweight Concrete, Volcanic Scoria Aggregates

I. INTRODUCTION

The use of Lightweight concrete (LWC) has been investigated in the construction industry for centuries and currently, good performance is expected for a consistent and reliable material with predictable characteristics. There are several classifications of lightweight concrete depending, either on their method of production where we have lightweight aggregate concrete, aerated or cellular concrete, and No-fines concrete; or on the purpose for which the concrete is to be used, where we distinguish structural lightweight concrete, concrete used in masonry units and insulating concrete.

Structural lightweight aggregates concrete is a specific type of lightweight concrete, made with lightweight aggregates conforming to the requirements of ASTM C330 standard, and strong enough to be used as structural concrete. Lightweight aggregates can be artificially processed by expanding, or calcining diverse products such as shale, slate, blast furnace slag, clay, or diatomite. The resulting product is called artificial lightweight aggregates which are the most commonly known. However, we also have naturally occurring lightweight aggregates such as pumice, tuff or scoria aggregates [1], [11]. Their physical properties are almost similar to the artificial aggregates, but with lower mechanical properties [3]. For this reason, the production of structural lightweight aggregate concrete has been long commonly done using the artificial lightweight aggregates even if the manufacturing process is related to many environmental issues such as depletion of natural resources, great amounts of energy consumption, and emission of dangerous gases (such as CO_2); and finally, aspects of high costs.

In Africa, like various other parts in the world, there are a lot of natural resources from volcanic eruptions which are almost waste, including volcanic scoria aggregates. Scoria is relatively darker and heavier than other natural lightweight aggregates and mostly used by cement companies to make clinker for cement production, around the world. The other common use is in road construction where it can constitute the sub-base material. However, they are light and porous like artificial aggregates with many other similar properties. It can therefore be used as a cheaper alternative. The advantage of lightweight aggregates (LWA) as compared to the normal weight aggregates (NWA), is through conferring to the concrete a lower density (around 25% lighter), leading to size reduction of load bearing elements in structures, as well as less structural steel reinforcements. Induced seismic loads are also decreased, thereby reducing the risk of damages due to earthquakes on the structure. Finally these advantages, lead to cost savings [7], [8], improves sound and thermal insulation, as well as fire resistance [6], [9].

There are very few published studies on the use of scoria as aggregates for structural lightweight concrete production; most of the previous studies were on the use of lightweight aggregates for production of blocks [10].

Revised Version Manuscript Received on March 10, 2018.

Msc. Student, Tejiona Tangomo Frank Roland, Department of Civil Engineering, Pan African University Institute for Basic Sciences Technology and Innovation (PAUSTI) hosted by Jomo Kenyatta University of Agriculture and Technology (JKUAT), Juja, Kenya, E-mail: tejionafrank@gmail.com

Dr. Ochieng Abuodha Silvester, Department of Civil Engineering, University of Nairobi, Nairobi, Kenya, E-mail: sochieng@yahoo.com

Prof. Shitote Stanley Muse, Department of Civil Engineering, Rongo University, Rongo, Kenya, E-mail: shitote@hotmail.com

Dr. Poh'sié Guillaume Hervé, Department of Civil Engineering, Higher National School of Public Works, Yaoundé, Cameroon, E-mail: pguillaumeherve.ing@gmail.com

This study investigated the feasibility of using locally available volcanic scoria aggregates for production of structural lightweight concrete. The volcanic scoria aggregates were prepared and their properties checked in accordance with the ASTM C330 requirements. Thereafter, three different methods of mix design as prescribed by ACI 211.2 standard (Weight method, absolute volume method and damp loose method) were used to design lightweight concrete specimens [2], [4]. Physical and mechanical tests were carried out on both scoria aggregates and concrete in a fresh and hardened state such as slump, dry density, compressive strength, splitting tensile and flexural strength. The aim was to develop a structural lightweight concrete made with locally available scoria aggregates while finding out the best mix design approach regarding the requirements of ACI 211.2 standard.

II. MATERIALS

The main constituent materials of this study were Ordinary Portland Cement 42.5, natural river sand as fine aggregates, the volcanic scoria aggregates as coarse aggregates and Water. They are all locally available in Kenya, and the research was conducted at the Structural and Materials Laboratory of Jomo Kenyatta University of agriculture and Technology (JKUAT).

A. Ordinary Portland Cement.

The cement used was Ordinary Portland Cement Type I (CEM I 42.5 N) called "Bamburi Power Plus". It is an early high strength cement, conforming to the specification prescribed by the standard EN 197-1, and is manufactured by "Bamburi Cement Ltd" in Kenya. The cement is safely kept in dry condition. Some important physical properties have been determined in the Laboratory, such as its Bulk density (loose and compacted) and its specific gravity as shown in Table I. Its chemical composition is as shown in Table II.

Table I: Some Physical Properties of Bamburi Power Plus 42.5

Specific gravity	Loose bulk density (Kg/m3)	Compacted bulk density (Kg/m3)
3.197	1162.3	1398

Table II: Chemical Composition of "Bamburi Power Plus 42.5"

Parameters	Percentage (%)
SiO_2	*20.61*
Al_2O_3	*5.05*
Fe_2O_3	*3.24*
CaO	*63.37*
MgO	*0.81*
SO_3	*2.75*
Na_2O	*0.15*
K_2O	*0.52*
Free CaO	*0.63*
Na Eq	*0.49*
Cl-	*<0.01*
LOI	*2.90*
I.R.	*1.00*
C3A	*7.91*

B. Natural River Sand

The sample sand used in this study was from Meru river in Kenya. This sand has a fineness modulus of 2.32 with particles sizes between 0-4.75 mm. The sand equivalent value and silt content value have been found respectively as 94.77% and 5.42%. Its particle size distribution has been determined as shown in Table IV, as well as its bulk density, specific gravity and water absorption summarized in Table V. Its grading curve is shown on Figure I. The sand used was found suitable to produce hydraulic concrete as regard to its properties and according to criteria requirements of ASTM C330.

C. Volcanic Scoria Aggregates.

The volcanic scoria aggregates were obtained from a quarry for cement companies in the location of Lukenya in Kenya, in the form of stones. Subsequently, they were manually crushed into particles sizes 4.75-19 mm. Its particle sizes distribution met the grading requirements as shown in Table IV. The grading curve is shown in Figure II. Its chemical composition was determined as shown in Table III, as well as the other physical properties including bulk density (loose and compacted), specific gravity and water absorption as summarized in Table V. The properties make them suitable for lightweight aggregates for structural concrete production according to the criteria requirements of ASTM C330.

Table III: Chemical Composition Volcanic Scoria.

Parameters	Percentage (%)
SiO_2	72.755
Al_2O_3	13.482
Fe	6.082
K_2O	5.129
CaO	1.090
Ti	0.545
Cl	0.333
Mn	0.271
Zr	0.129
Zn	0.048
Nb	0.027
Rb	0.019
Y	0.011
Sr	0.002
Cu	0.002

Table IV: Particle Size Distribution of Fines and Coarse Aggregates.

Sieve size (mm)	***Percentage passing***			
	Sand	Limits (Upper-Lower) as prescribed by the standard ASTM C330-05	**Scoria**	Limits (Upper-Lower) as prescribed by the standard ASTM C330-05
25	-		100	**100**
19	-		99.92	**90-100**

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication Pvt. Ltd.

12.5	-		90.01	**90-100**
9.52	-		35.35	**10-50**
4.75	100	**95-100**	5.23	**0-15**
2.36	97.12	**80-100**	0.46	**0-15**
1.18	84.22	**50-85**	0.14	**0-15**
0.6	49.9	**25-60**	0.14	**0-15**
0.3	28.05	**10-30**	0.14	**0-15**
0.15	3.2	**2-10**	0.14	**0-15**

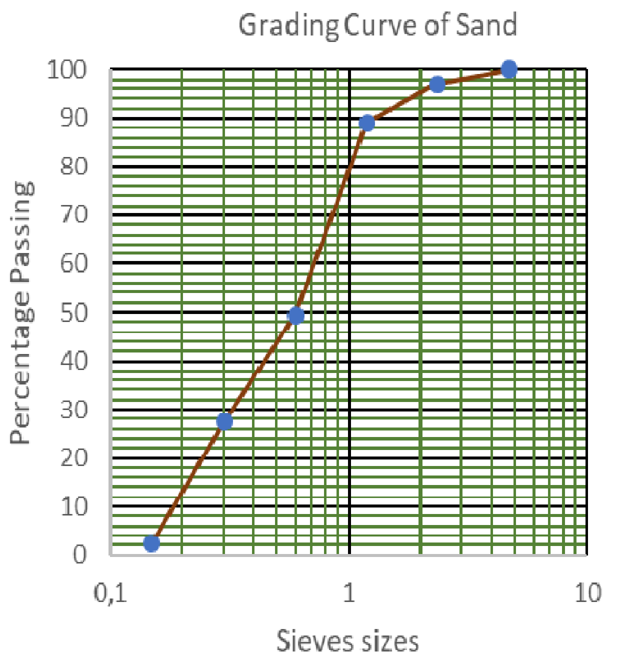

Figure I: Grading Curve of Sand Aggregate.

D. Water

The water used in the study, was potable water obtained from the public water system. The water was clean with no strange materials in it that can disturb the hydration process of cement.

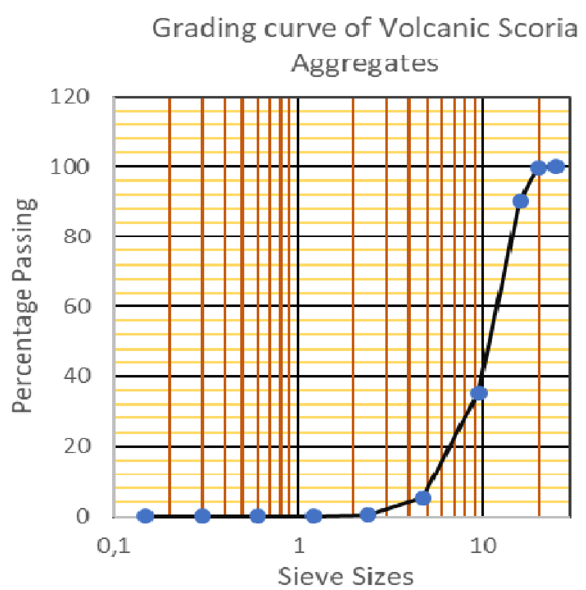

Figure II: Grading Curve of Volcanic Scoria Aggregates

III. EXPERIMENTAL PROGRAM

As prescribed by ACI 211.2-98 (Standard practice for selecting proportion for structural lightweight concrete), three different methods for designing structural lightweight concrete were applied; the weight method or specific gravity pycnometer method, the absolute volume Method and the damp loose method or volumetric method [1], [2]. The target was to produce Grade 30 lightweight aggregates concrete. Before the mix design process, scoria stones were collected and were crushed to make them fulfill the required particles sizes distribution. Thereafter, three mix designs were carried out using the three different methods prescribed by the standard. The scoria aggregates were soaked in water for 24 hours before each mix, to make them in Saturated Surface Dry condition (SSD) as recommended for that type of aggregates with high absorption rate. The main goal was to develop a structural lightweight aggregates concrete using scoria as aggregates, while finding out the best mix design method out of the three. The experimental work was divided into two main phases: the mix designs, and specimen preparation and testing.

A. Mix Designs Proportions

Three experimental programs were adopted in this study each based on one of the three mix design methods prescribed by ACI 211.2-98 standard [1], [2]. The aim was to develop the most suitable LWC mix meeting the requirements for structural lightweight concrete specified in ACI 211.2 standard. The scoria stones were collected, crushed and their physical properties were determined and found to conform to ASTM C330 requirements as shown in Table V, as well as the grading chart in Figure II. Three trial mix specimen types were designed using the three methods with the same w/c = 0.45, and a slump of 25 to 50 cm. At this stage, the main criteria under observations were the workability, the dry unit weight and the compressive strength. The best mix design method was the one giving us the mix with the highest strength to weight ratio with a good workability at the same w/c ratio, conforming to the requirements of ACI 211.2. The mix proportions for the different mix design methods are summarized in the Table VI, as well as the slump values, the dry density the compressive and splitting tensile strengths at 7 days in Table VII.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication Pvt. Ltd.

Table V: Physical Properties of the Scoria Aggregates

Aggregates	Loose bulk density (kg/m^3)	Rodded bulk density (kg/m^3)	Specific gravity (Oven Dry basis)	Specific gravity (SSD basis)	Apparent Specific gravity	Water absorption (%)
Sand	1461	1602.92	2.36	2.51	2.76	4.7
Volcanic Scoria	1013.6	1179.11	1.91	2.16	2.54	13.06

Table VI: Mix Design Proportions for Each Design Method.

Mix design Method	Lightweight Coarse aggregate content (SSD) kg/m^3	Sand content (SSD) kg/m^3	Water cement ratio (W/C)	Water content, kg/m^3	Cement content, kg/m^3
Weight method	848.03	339.12	0.45	187	415.6
Absolute volume method	516	764.64	0.45	187	415.6
Damp loose method	710.36	775.93	0.45	187	374.86

Table VII: 24 Hours Dry Density, Slump, Compressive and Splitting Tensile Strength at 7 days.

Mix design Method	7 days compressive strength (MPa)	7 days Splitting tensile strength (MPa)	24 hours-Dry density (kg/m3)	Slump (mm)
Weight method	17.89	1.77	1820	15.5
Absolute volume method	21.81	2.44	1837	50
Damp loose method	18.97	1.95	1832	94

A. Specimen Preparation and Testing

For all the three mix design approaches, during the concrete mixing phase, the aggregates were first mixed with half of mixing water, due to the high absorption rate of volcanic scoria aggregates. Although the fact that those aggregates were soaked in water for 24 hours before the mixing date to reach the SSD condition, it has been proved that they can still absorb water after 24 hours, for a relatively long period of time. So, this measure was to minimize this effect of absorption of the aggregates on the workability of the concrete during the early period of mixing. The other constituents (sand, cement) were then added with the remaining half of mixing water. The mixing was manually done as specified in BS EN 12390, Part 2 (2000).

The slump test was done immediately on fresh concrete after the mixing to measure the workability in accordance with the specifications of BS EN 12350: Part 2 (1999). The lightweight concrete specimens were cast into cylindrical steel moulds of 150 mm of diameter and 300 mm of height, and of 100 mm of diameter and 200 mm of height, respectively for compressive and splitting tensile strengths tests at 7 and 28 days. It was also poured into cubic steel moulds of 150x150x150 mm for use in carrying out the 24 hours air-dry density test. Flexural strength test was also of interest at 28 days and for this purpose, the concrete was cast into steel moulds of size 150x150x560 mm. The moulds were prepared and oiled before, and the concrete was compacted using a vibrator. 24 hours after the casting, the specimens were demoulded and water cured in curing tanks until the dates of testing [1], [2], [3], [4].

IV. RESULTS AND DISCUSSION

A. Physical Properties of Volcanic Scoria Aggregates

With regard to the specifications of ASTM C330 standard, some physical properties of the scoria aggregates were determined, such as bulk density and specific gravity. 2.54 were found as the apparent specific gravity of scoria which is lower than the limit of 2.60 as prescribed by the standard. Also, the oven dry particles density were found to be about 1910 kg/m3 lower than the limit of 2000 kg/m3, as well as the loose bulk density found 1013.6 kg/m3 lower than the limit 1200 kg/m3. The properties led to the conclusion that volcanic scoria aggregates locally available in Kenya, were suitable for the production of structural lightweight aggregates concrete with regard to ASTM C330 standard requirements.

B. Workability of the Lightweight Concrete

The slump test was used to measure the workability of the concrete specimens casted. The slump values varied from 15.5 mm for the weight method, to 50 mm for the absolute volume method and 94 mm for the damp loose method, for the same w/c ratio. It is thus seen that only the absolute volume method gave us a slump within 25-50 mm as defined in the design. The slump values are given for each mix design approach in Figure III.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication Pvt. Ltd.

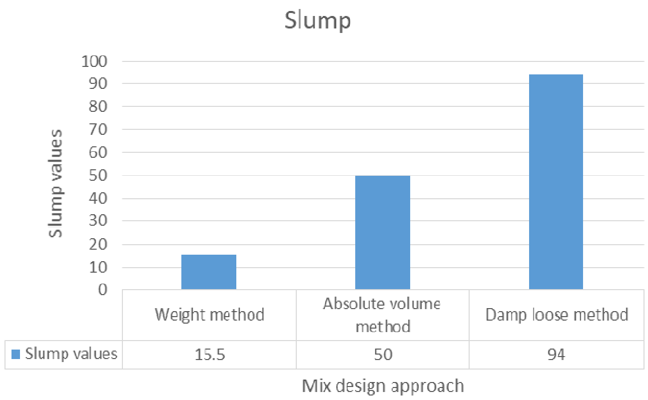

Figure III: Slump values for the Three Mix Design Approaches

C. Air-Dry Density

Air dry density is one of the most important criteria for concrete classification. According to ASTM C567 as well as ACI 211.2-98 specifications, the air-dry unit weight of concrete must not exceed 1842 kg/m^3 to fit one of the requirements for structural lightweight concrete. All the three concrete specimen types fall within the required limits in terms of air-dry density. The absolute volume method shows the highest air dry density. Figure IV shows the different values of air dry concrete density for each mix design approach varying from 1820 to 1837 Kg/m3.

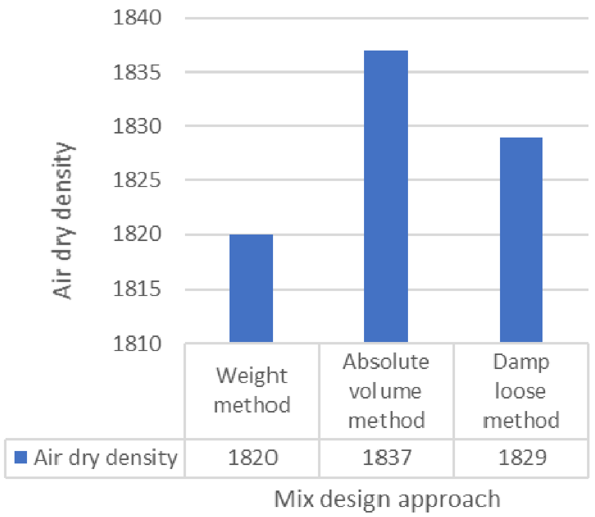

Figure IV: Air-Dry Density of Concrete Specimen Types

D. Compressive Strength

Both ACI and ASTM standard defined structural lightweight aggregates concrete as concrete with lightweight aggregates conforming to ASTM C330, with a compressive strength greater than 17.2 Mpa at 28 days tested as described by the standard. This is one of the most important criteria, together with the dry density. Hence, the concrete specimens for each design approach were tested for the compressive strength at 7 and 28 days, and the results are shown in Figure V. The aim was to find the best mix design approach for structural lightweight concrete using local scoria aggregates. The absolute volume method gave the best results with 21.81 MPa and 32.5 MPa at respectively 7 and 28 days, while the weight method showed the least compressive strength with 17.89 MPa and 26.77 MPa at respectively 7 and 28 days, less than the target design strength. This experiment has shown that local scoria aggregates can be used to produce structural lightweight aggregates concrete, as regard to ACI requirements and absolute volume method is the best mix design approach. It is also noticeable that the early strength which is around 67.1% of the strength at 28 days, exhibited by lightweight concrete with scoria aggregates is good enough, and hence structurally acceptable mostly with the absolute volume method as a mix design approach.

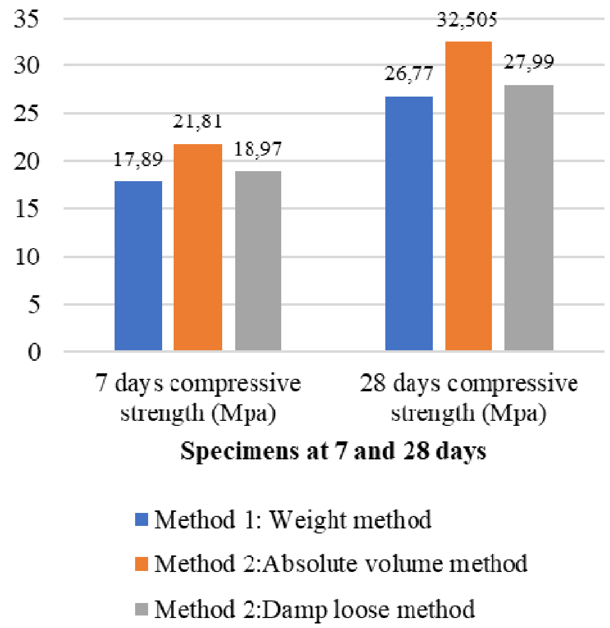

Figure V: Compressive strength for the three Mix Design Approaches at 7 and 28 days.

E. Splitting Tensile Strength

The absolute volume method gave the best results with regard to the splitting tensile strength; 2.44 MPa and 2.74 MPa have been obtained at respectively 7 and 28 days, hence leading to the conclusion that 89.05% of the strength is reached at early age (7 days). The strength at 28 days represents 8.43% of the compressive strength. This value is lower than the range of 10% known for normal weight structural concrete; this could be explained by the cellular structure of the lightweight concrete due to the porous nature of the lightweight aggregates used, which leads to the weakness of the material through enhancing the propagations of microcracks in the material while under loading. However, 1.77 MPa and 2.05 MPa have been obtained with the weight method of mix design at respectively 7 and 28 days, hence representing the worst mix design approach as observed also with the compressive strength. Figure VI shows the splitting tensile strength at 7 and 28 days for each mix design approach.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication Pvt. Ltd.

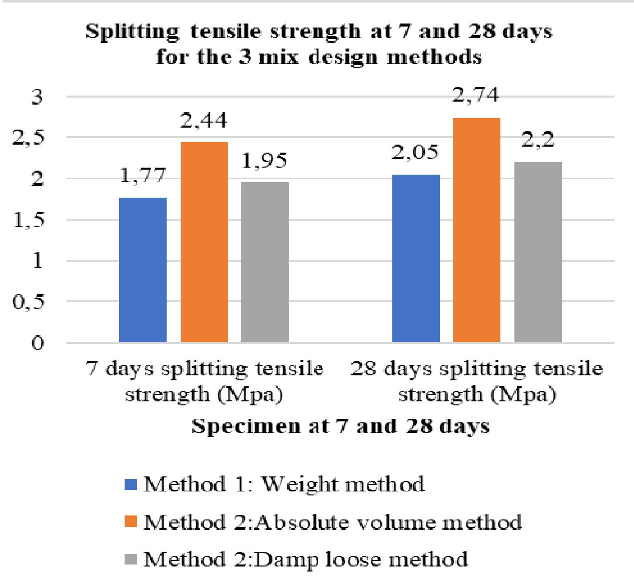

Figure VI: Splitting Tensile Strength for the three mix Design Approaches at 7 and 28 days.

F. Flexural strength

The highest flexural strength of 3.21 MPa has been obtained with the mix specimens designed with the absolute volume method. While, 3.05 MPa has been found as the lowest strength from weight method approach. Figure VII summarizes the values of flexural strength for the three design method approaches.

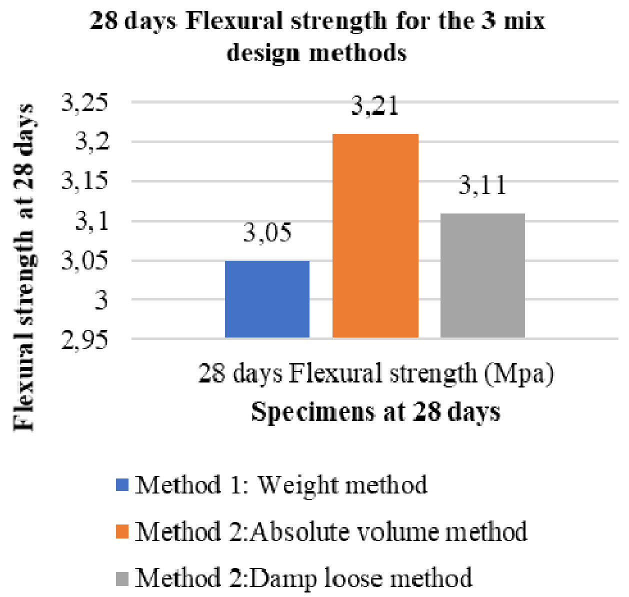

Figure VII: Flexural strength for the three Mix Design Approaches at 7 and 28 days.

V. CONCLUSIONS

As regard to the results obtained from this investigation, some conclusions can be drawn:

- Volcanic scoria aggregates locally available in Kenya, were found suitable as aggregates for the production of structural lightweight aggregates concrete with regard to ASTM C330 standard requirements.
- Volcanic scoria aggregates met the grading requirements in accordance with ASTM C330, for structural lightweight concrete making.
- The absolute volume method gave the best slump value within 25-50 mm as defined in the design, at the same w/c ratio, suitable for general constructions.
- 1820, 1829 and 1837 kg/m^3 have been found as the air-dry density for the concrete specimens designed respectively with the weight method, damp loose method and absolute volume method. All the three concrete specimen types density are suitable. The required limits with regard to the air-dry density must not exceed 1842 Kg/m^3 as for ASTM C567 standard.
- All the three concrete specimen types gave suitable compressive strengths, greater than the required limit of 17.2 MPa as for ASTM C330 at 28 days; and the best compressive strength was obtained with the absolute volume method of mix design. 21.8 MPa and 32.5 MPa were obtained as the compressive strength respectively at 7 and 28 days.
- With the absolute volume method of mix design, the early strength (7days) is around 67.1% of the strength at 28 days, which is good enough to be structurally acceptable.
- The absolute volume method gave the best results as regard to the splitting tensile strength; 2.44 MPa and 2.74 MPa were obtained at respectively 7 and 28 days; The splitting tensile strength at 28 days represent 8.43% of the compressive strength at that age.
- The same observation were done with regard to the flexural strength. The absolute volume method gave the highest values of strength at 7 and 28 days as compared to the two other mix design approaches. 3.21 MPa has been found as the flexural strength at 28 days, representing 9.87% of the compressive strength at that age.
- As regard to those results, a conclusion can be made; structural lightweight aggregate concrete can be produced with locally available volcanic scoria from Kenya as aggregates, and the absolute volume method was found to be the best mix design approach out of the three methods evaluated in the study.

VI. RECOMMENDATIONS

Some recommendations can be made as regard to the results obtained from the study.

- Volcanic scoria aggregates can be used as an alternative to artificial lightweight aggregates; therefore, they should be industrially available in the form of aggregates like the other aggregates types (normal weight aggregates and artificial aggregates).
- The absolute volume method of mix design is highly recommended as the mix design approach for structural lightweight aggregate concrete; mostly with natural aggregates such as volcanic scoria as coarse aggregates.
- With regard to the high absorption rate of volcanic scoria aggregates, they can be pre-coated with a binding material such as asphalt or plastic for instance, in a hot mix process, before the use in the concrete; further investigations should be done in order to assess the physical and mechanical properties of the lightweight concrete made with those pre-coated aggregates.

ACKNOWLEDGMENT

We are sincerely grateful to both the African Union Commission and Pan African University Institute for Basic Sciences, Technology and Innovation (PAUSTI) for their financial support for this research.

REFERENCES

1. ACI 213-87, “Guide for Structural Lightweight Aggregate Concrete”, ACI 213-87, Manual of Concrete Practice, Part 1, American Concrete Institute, Detroit, Michigan, 1995.
2. ACI 211.2-98, “Standard practice for selecting proportions for Structural lightweight concrete”
3. A. M. Neville, Properties of Concrete, John Wiley and Sons Inc., New York, 1996.
4. ASTM C 330-89, “Standard Specification for Lightweight Aggregates for Structural Concrete”, Annual Book of ASTM Standards, 4.02, 193195.
5. ASTM C 33-97, “Standard Specification for Concrete Aggregates”, Annual Book of ASTM Standards, Vol. 4.02, pp.10-16.
6. B. Chen, and J. Liu, "Experimental Application of Mineral admixtures in Lightweight Concrete with High Strength and Workability" Construction and Building Materials, 2008.
7. H.Z. Min, and E. Gjorv, "Characteristics of lightweight aggregate for high strength concrete." ACI Materials Journal, V.88, No.2 , 1990. P150-158.
8. K.F. Meyer, and L.F. Khan, “Lightweight Concrete Reduces Weight and Increases Span Length of Pretensioned Bridge Girders”, PCI Journal, 2002.
9. K.M. Hossain, "Properties of Volcanic Pumice Based Cement and Lightweight Concrete", Cement and Concrete Research, 34, 2004, 283291.
10. Moufti, M. R., Sabtan, A. A., & Shehata, W. M. (2000). Assessment of the industrial utilization of scoria materials in central Harrat Rahat , Saudi Arabia, 57, 155–162.
11. S. Mindess, F. Young, Darwin, Concrete, 2nd edition, New Jersey, Prentice-Hall, 1996.