Investigating The Potential Use of Tuff Aggregates to Produce Lightweight Concrete

Sang G. K. [*], Abuodha S. O.[**], Mwero J. N. [**]

[*] Department of Civil and Construction Engineering, University of Nairobi, Kenya

[**] Department of Civil and Construction Engineering, University of Nairobi, Kenya

DOI: 10.29322/IJSRP.10.09.2020.p10555
http://dx.doi.org/10.29322/IJSRP.10.09.2020.p10555

Abstract- Sources of conventional concrete materials such as gravel, granite and limestone rocks are becoming scarce due to overexploitation as Kenya strives to industrialize posing great risks on their availability as well as sustainability. This research sought to assess the feasibility and suitability of tuff aggregates for the production of structural lightweight concrete. Normal-weight concrete (NWC) samples made from granite aggregates were used as control in the experiment. The main primary properties of study and comparison for the two types of concrete were the unit weights and compressive strengths. The mix design process was done according to ACI 211.2-98 Code. The workability of fresh concrete was tested according to BS EN 12350-2. The average slump value of tuff concrete mixed with water-cement ratio of 0.4 was 12 mm while that of conventional concrete was 27 mm. The unit weights of tuff and conventional concretes were determined according to ASTM C138. The results suggest average 28-day dry densities of 2038 kg/m^3 and 2527 kg/m^3 for tuff and conventional concretes respectively. The compressive strength tests were performed at different ages of concrete in accordance with BS 1881-part 116. In particular, the 28-day compressive strengths of 26.0MPa and 30.0MPa were obtained for tuff and conventional concretes respectively when presoaked aggregates were used with water-cement ratio of 0.4. However, an increase in the 28-day compressive strength of tuff concrete up to 25.5MPa while a decline in the compressive strength of conventional concrete up to 20.4MPa were noted at water-cement ratio of 0.6 when oven dry aggregates were used. The results of unit weights and compressive strengths from this study confirmed the concrete produced from tuff aggregates as a lightweight structural concrete as per Euro Code 2. The study further confirmed tuff aggregates to be suitable materials for the production of lightweight structural concrete which can be recommended for high-rise buildings and long-span bridges.

Index Terms- Compressive Strength, Lightweight Concrete, Normal-weight Concrete, Tuff Aggregates, Unit Weight.

I. INTRODUCTION

A lightweight structural concrete can be defined as a concrete having a 28-day air dry density of not more than 2200 kg/m^3 and a compressive strength of at least 17 MPa as per Euro code 2 [22] whereas a normal-weight concrete (NWC) density ranges from 2200 kg/m^3 to 2600 kg/m^3 [13]. Due to its high density, the conventional concrete becomes a structurally inefficient material for a number of applications such as high-rise buildings and long span bridges. Many attempts have therefore been made to reduce the self-weight of concrete thus increasing its structural efficiency. Minimal research has been done in which the properties of tuff and normal-weight concrete have been compared despite substantial tuff deposits being found across many parts of Kenya including Bahati and Kedowa areas of Rift Valley Province where volcanic eruptions are known to have been prevalent. Tuff is a type of extrusive igneous rock that is formed from the products of an explosive volcanic eruption [9]. Tuff rocks in Kenya are mainly used to produce dimension stones for walling in buildings and erection of perimeter walls. However, expanded polystyrene wall panels are slowly being embraced by designers and builders to replace the use of tuff rock dimension stones in the building industry.

Two classifications of lightweight aggregates (LWA) include natural and artificial aggregates. The natural lightweight aggregates (NLWA) are produced by crushing volcanic natural rocks while the artificial lightweight aggregates (ALWA) are produced by expanding materials such as perlite, clay, shale, slate and vermiculite through heating in a rotary kiln. Lightweight aggregate concretes (LWAC) are produced by using porous aggregates with a specific gravity lower than 2.6 [11]. The production of artificial lightweight aggregates is a very costly process requiring a lot of energy for heating the aggregates. Similarly, the production of conventional aggregates is an expensive process which contributes to the destruction of roads during transportation as well as an increase in carbon emissions due to heavy crushing and blasting operations at quarry sites. Increased construction activities in Kenya has put conventional materials for making concrete at risks of depletion. An investigation on the use of natural tuff aggregates to make lightweight concrete, therefore, becomes relevant. The current research sought to investigate and assess the suitability of tuff aggregates for the production of a low-density concrete while comparing its properties with those of conventional concrete. This study explored the performance of LWAC incorporating tuff coarse aggregates while comparing its properties with those of normal-weight concrete made using granite aggregates. Other than increased structural efficiency, up to 489 kg/m^3 by weight of concrete reduction in structures can be achieved if tuff concrete is used instead of normal-weight concrete according to the current research. This translates into a reduction of 19.0% weight of structures constructed with tuff concrete compared with similar structures done with conventional concrete. In the rush to meet the Millennium Development Goals (MDGs) and the Vision 2030 [12], the Kenyan government has initiated a number of flagship projects which have increased the consumption of cement from a low of 154,781 tonnes in January 2005 to a high of 564,000 tonnes in January 2017 [14]. Consequently, the consumption of conventional coarse aggregates was estimated to have increased from 619,124 tonnes to 2,256,000 tonnes in the same year. This necessitates the investigation of alternative materials to avert early depletion of conventional materials.

II. MATERIALS AND EXPERIMENTAL PROGRAM

The borrow site for tuff aggregate material was in Bahati area in Nakuru County, Kenya. Nakuru County is in Rift Valley Province located between longitudes 35°28' and 35° East and Latitude 0°13' and 10°10' South at an altitude of about 1912 meters above the sea level. Masonry blocks are normally extracted from tuff rock deposits for constructing walls of buildings in the area. The borrow site for the conventional aggregate material was Ongata Rongai quarry located in Kajiado County, Kenya. Kajiado is situated 17 km south of Nairobi Central Business District at an altitude of 1,731 above the sea level. Fine aggregate for the study was river sand obtained from Kajiado river beds. Kajiado is a town in Kajiado County, located 80 km south of Nairobi, along the Nairobi – Arusha Highway. The samples were collected using gunny bags and taken to the University of Nairobi laboratory for storage, analysis, and testing. Figure 2.1 shows a sample of sand harvested from Kajiado river which was used as fine aggregate. Figures 2.2 and 2.3 show sampled tuff aggregate borrow site and tuff aggregate in Bahati area. Tuff rock formation in the area is found at an average depth of 1.5m beneath the ground level and extends several kilometers in the area of coverage. Figures 2.4 and 2.5 show the borrow site and a sample of conventional aggregate material respectively found in Ongata Rongai in Kajiado county. The materials used to produce tuff concrete include; water, Type 1 cement, sand, and crushed coarse tuff aggregate while conventional concrete was prepared for control experiment using crushed granite aggregates, water, Type 1 cement and sand. Commercially available polycarboxylic ether based superplasticizer complying with requirements of ASTM C-494 Type F and G [4] was incorporated into concrete mixtures. Potable water was obtained from the University of Nairobi laboratory for mixing and curing of concrete. Ordinary Portland cement with class strength of 32.5N complying with EN 197 Standards [7] was used for this investigation

Figure 2.1: A sample of sand used as fine aggregate

Figure 2.2: Tuff aggregate heap and borrow site in Bahati quarry

Figure 2.3: A sample of tuff aggregates from Bahati quarry

Figure 2.4: Conventional aggregate borrow site from Ongata Rongai

Figure 2.5: A sample of conventional aggregates from Ongata Rongai quarry

The process of grading the aggregates and determination of physical properties such as bulk densities and specific gravities were done according to BS EN 882 [19]. Concrete mix design process for tuff and normal-weight concrete was done according to ACI 211.2 Code [1] while targeting 28-day compressive strengths of 25 N/mm^2 with w/c ratio of 0.4. Batching was done by weight of constituent materials to give a unit volume of concrete. The density of tuff fresh concrete was estimated from the constituent mix materials to be 1974.2 kg/m^3. This density is less than the maximum density of LWC of 2200 kg/m^3 as defined by Euro Code 2 [22]. The density of fresh normal-weight concrete was estimated to be 2453.2 kg/m^3 from the combination of the constituent mix materials according to

Table (1) below. The mix proportions for tuff aggregate concrete by weight were determined to be 1: 2.3: 2.2 representing cement, sand and tuff aggregates respectively. The corresponding mixture proportions for the conventional concrete were 1: 2.3: 3.7 by weight of the cement, sand and granite aggregates respectively in a concrete mixture. Coarse aggregates of tuff and granite materials occupying the same volume of about 63% in a unit volume of concrete but having different weights gave the above mix proportion. The mixtures were prepared based on a water-cement ratio of 0.4 to produce a unit volume of concrete as per their respective weights according to the table below.

Table 1: Concrete mix proportions targeting concrete grade M25 to give 1m^3 of concrete

Type of concrete	Tuff concrete	Granite concrete
Mixing water for concrete	133kg/m^3	133kg/m^3
Cement content	333kg/m^3	333kg/m^3
Fine aggregate content	768kg/m^3	768kg/m^3
Coarse aggregate content	740kg/m^3	1219kg/m^3
Air content	2%	2%
Water-cement ratio	0.40	0.40

The workability tests were performed according to BS EN 12350-2 [8]. The effects of superplasticizer (SP) on the workability of concrete mixtures were investigated by varying the SP dosages from 0%, 0.5%, 1.0%, 1.5%, 2.0% and 2.5% by weight of cement while keeping the water-cement ratios constant at 0.4. In the experiment, presoaked aggregates were used for the concrete mixtures in order to ensure minimal absorption of both water and the superplasticizer by dry aggregates especially the tuff aggregates. The compaction factor test for concrete was conducted in accordance with BS EN 12350-2 [8]. The densities of NWC and LWAC in fresh states were measured in accordance with ASTM C138/C138M-16a [5]. The average unit weights of concretes were measured at the ages of 14 and 28 days according to ASTM C642 [6]. The compressive cube strength tests were carried out according to BS 1881: Part 116 [17] at the ages of 7, 14, 21, 28, 35 and 42 days. Although 35 and 42 day strengths are not common, this study sought to assess the influence of internal curing on compressive strength of concrete in service. The strength to weight ratio of concretes were also determined and compared at the age of 28 days. The 28-day splitting tensile strengths of concretes specimens were determined and compared having been prepared from the concretes samples based on w/c of 0.4 without adding superplasticizer. The tuff aggregates were presoaked before mixing to ensure minimal absorption of mixing water. Three concrete cylinder specimens cast from each type of concrete on 150 mm diameter x 300 mm long moulds were investigated for 28-day splitting tensile strengths. The tensile strengths were determined according to equation (1) below which was formulated by Timoshenko and Goodier [21].

$$\sigma_x = \frac{2P}{\pi LD} \qquad (1)$$

Where;

σx; represents the splitting tensile strength, MPa or N/mm^2

P; is the maximum applied point load, N

L; is the length of the specimen, mm

D; is the diameter of the specimen, mm

III. RESULTS AND DISCUSSIONS

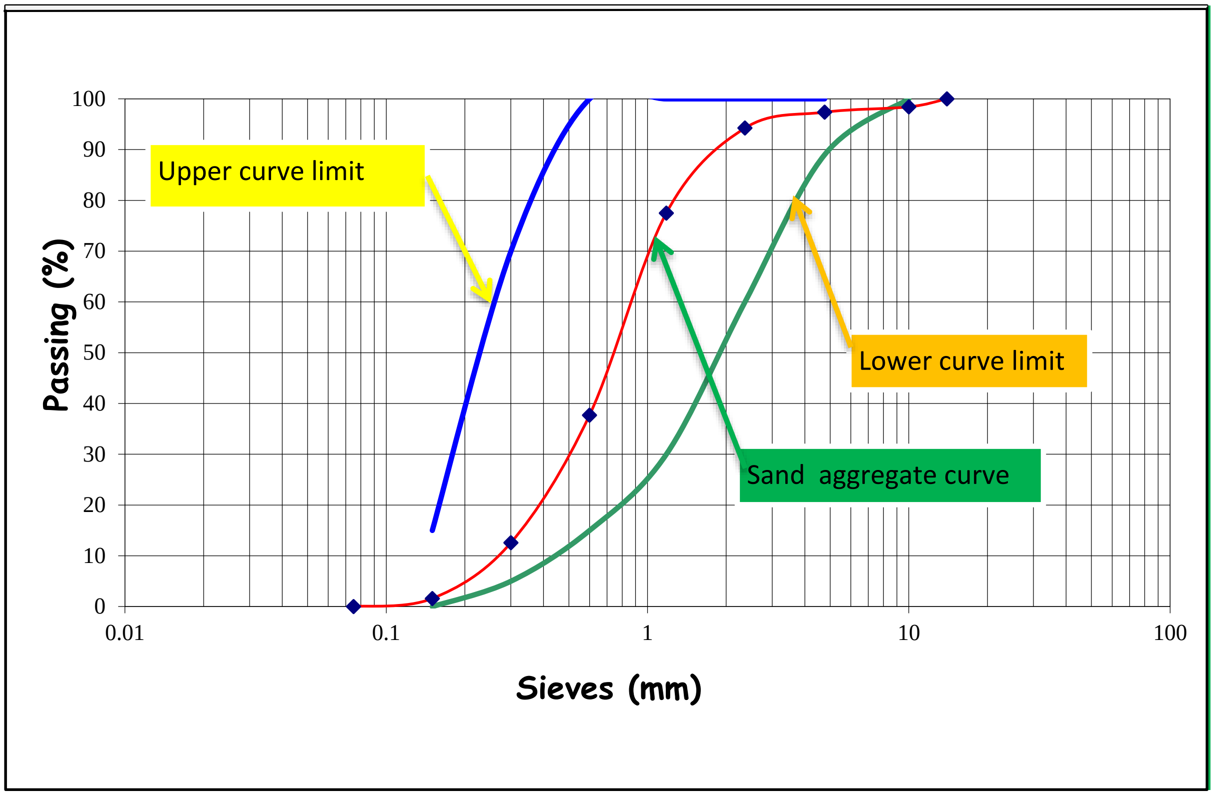

Figure 3.10: Grading limits for Sand

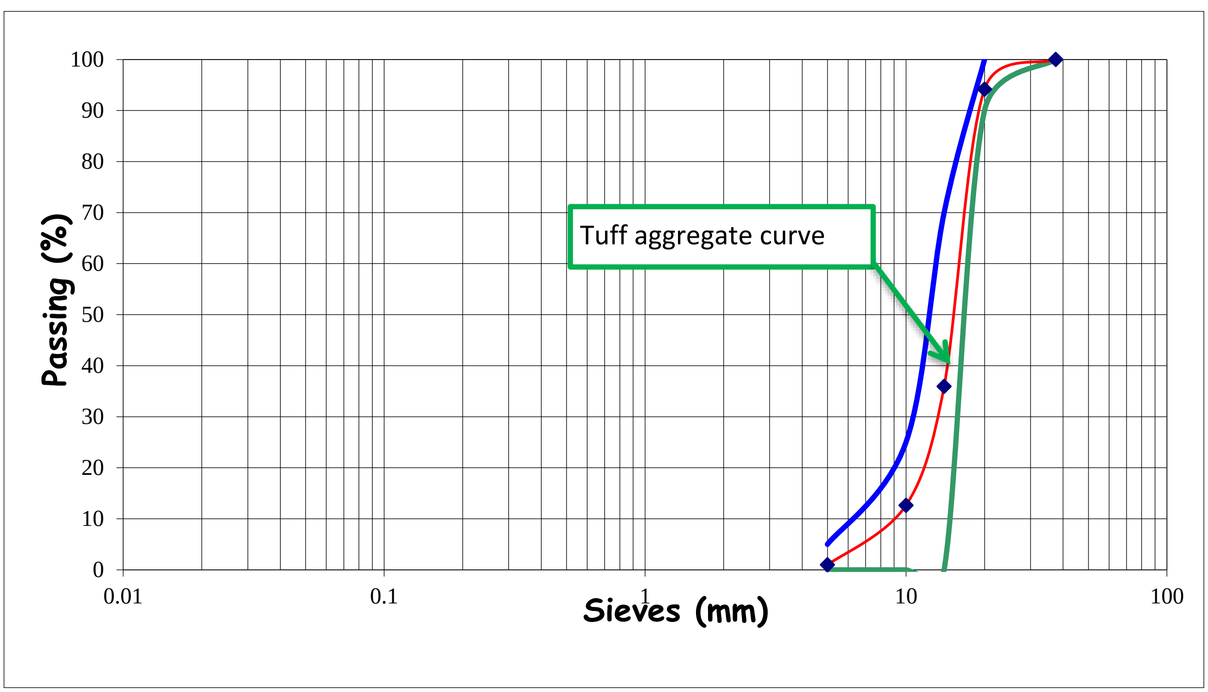

Figure 3.11: Grading curve for tuff aggregate from Bahati area in Nakuru

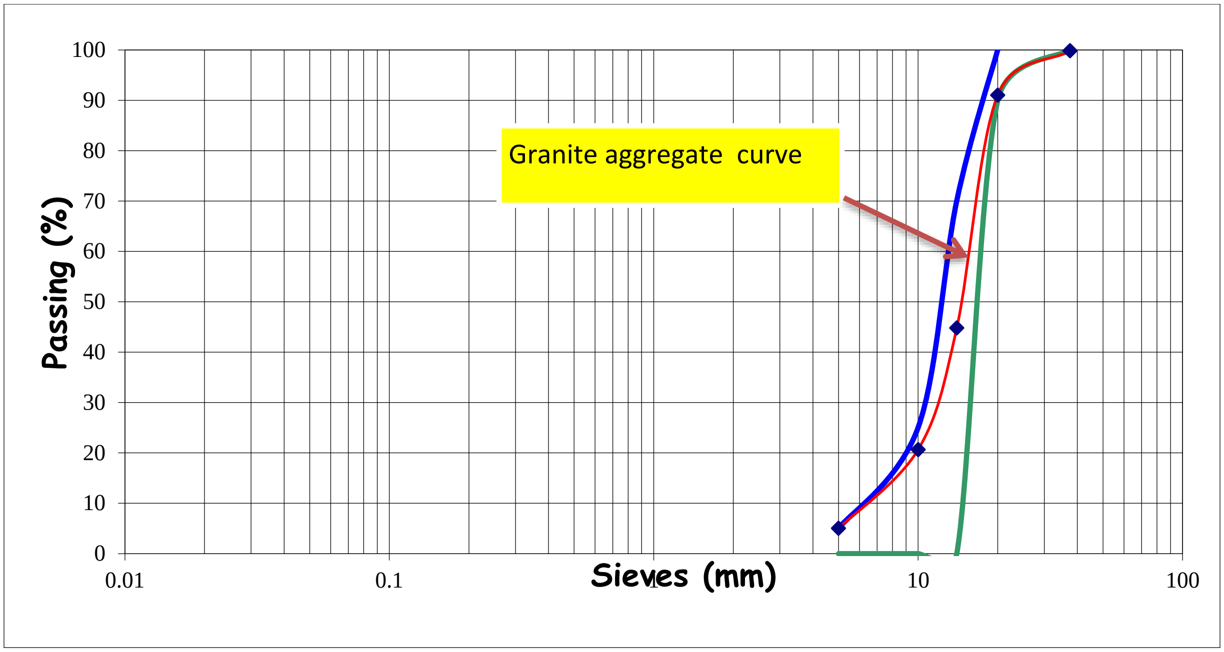

Figure 3.12: Grading curve for coarse granite from Birika in Kajiado County

As shown in the Figures 3.10, 3.11 and 3.12 above, the gradation for the sand, tuff and granite aggregates were found to fall within the acceptable limits of the BS 812-103.1 [18]. The effective sizes of the particle size distribution (PSD) (D_{10}), (D_{30}) and (D_{60}) passing were 0.27 mm, 0.50 mm, and 0.90 mm respectively for fine aggregates. The fine aggregate belonged to zone-II. Similarly, the effective sizes (D_{10}), (D_{30}) and (D_{60}) passing were 7.0 mm, 10.10 mm and 10.50 mm respectively for tuff coarse aggregates. The effective size (D_{10}), (D_{30}), and (D_{60}) passing were 6.0 mm, 10.10 mm, and 10.70 mm respectively for normal coarse granite aggregates. The coefficients of uniformity, Cu, given by the ratio of (D_{60}) to (D_{10}) for fine, tuff, and granite aggregates were determined to be 3.3, 1.5, and 1.8 respectively. The coefficients of curvature, Cc, calculated from equation (2) below, were found to be 1.02, 1.38, and 1.6 for sand, tuff and granite aggregates respectively. These results were checked against AASHTO classification which provides that Cu should be greater than 4, i.e.$C_U > 4$ while C_C should be greater than 1 but less than 3, i.e. $1 < C_C < 3$ for aggregates to be considered well-graded. It follows therefore, all the aggregates being lower than 4 were not well graded but uniformly graded. This means the cement paste and fine aggregate required to fill the void spaces between aggregates in the mix were more in quantity increasing the cost of producing the concretes than the case would be if the aggregates were well-graded. The amount of cement and fine aggregate also has an effect on the unit weight and the compressive strength of the hardened concrete.

Well-graded aggregates enhance the workability, placement, degree of compaction, and durability of concrete. In contrast, aggregates that are poorly graded result in underfilling of voids in particles resulting in entrapped air and can negatively affect the workability and strength concrete. A concrete made from poorly graded materials does not protect the reinforcement from corrosion due to possible leakages. The coefficient of curvature, Cc, of aggregate is given by equation (2) below;

$$\text{Coefficient of curvature, } \mathrm{C_c} = \frac{((\mathrm{D_{30}})^2)}{(\mathrm{D_{10}})(\mathrm{D_{60}})} \qquad (2)$$

Where;

D_{10} is the effective size of particle size distribution at 10%

D_{30} is the effective size of particle size distribution at 30%

D_{60} is the effective size of particle size distribution at 60%

Table 2: Physical Characteristics of Aggregates and Cement

Type of concrete	Tuff concrete	Granite concrete
Coarse aggregate maximum size	20.0mm	20.0mm
Dry rodded unit weight of aggregate	1180kg/m^3	1600kg/m^3
The specific gravity of OD coarse aggregate	1.55	2.65
The specific gravity of SSD coarse aggregate	1.89	2.66
Flakiness Index of aggregate	20%	31%
Elongation Index of aggregate	15%	22%
Coarse aggregates water absorption	21.9%	0.25%
The specific gravity of fine aggregates	2.63	2.63
The specific gravity of Portland cement	3.15	3.15
Maximum size of fine aggregates	5mm	5mm
Fineness modulus of sand	2.7	2.7

Table 2 above presents the physical properties of constituent materials of concretes. The fineness modulus of the sand was found to be 2.70. A fineness modulus of 2.70 indicates that the sand was of medium-range and zone-II. It was not too fine nor too coarse. A medium-range sand has fineness modulus ranging from 2.6 – 2.9. Fineness modulus values in the range of 2.40 to 3.00 are common in Portland cement concrete (PCC) mixtures. A fineness modulus value of 2.7 is fairly good for workability and finishing of concrete. It is important for good texture and finishes in concrete works.

The specific gravity (SG) of a substance is a measure of its density. Samples of tuff and granite aggregates gave average specific gravities of 1.55 and 2.65 respectively. The low specific gravity noted for tuff aggregates is attributed to higher internal porous microstructure for the aggregates compared with granite aggregates. A lower specific gravity of tuff aggregates indicates that these aggregates are more porous due to the presence of air voids. Conversely, a higher value of specific gravity for granite aggregate means higher values of abrasion and attrition necessary to withstand extreme exposure conditions of weather. The specific gravity of aggregate affects the proportioning of concrete materials as given in ACI 211.2-98 [1] when carrying out mixed designs.

Figure 3.13: A sample of saturated surface dried tuff aggregate

Figure 3.13 shows a sample of tuff aggregates being surface dried after presoaking to saturated surface dry (SSD) condition to determine and compare its water absorption with that of conventional aggregates. After presoaking, the specific gravity of tuff aggregates improved from 1.55 to 1.89 while that of conventional concrete increased from 2.65 to 2.66. The tuff aggregates were found to have gained on average a weight by 21.9% while granite samples weight increased on average by 0.25%. From the results of water absorption, tuff aggregates were found to absorb more water than granite aggregates due to the presence of numerous larger size of pores within their cellular structure. The crystal structures forming granite rocks are tightly interlocked leaving tiny pore spaces to store water. The absorption capacity and rate of absorption are especially important for mixed design calculations to correctly establish the water-cement ratio which controls the workability, strength and permeability characteristics of concrete. Due to the high water absorption by tuff aggregates, the actual and effective water-cement ratio required to produce good workability mix is usually lowered resulting in slump loss during mixing. Many factors affect the actual water-cement ratio of lightweight concrete mixtures. The most important ones include; water absorption, the state of moisture content, and the amount of porous aggregate in a concrete mix. The reduction of water-cement ratio in fresh concrete is usually considered a negative phenomenon that can lead to loss of concrete workability. Therefore, tuff aggregates require high water-cement ratio to produce a workable mix than conventional concrete. Its therefore recommendable to presoak these aggregates before they can be used to produce a lightweight concrete mix with good workability.

BS 812: Part 105 [18] classifies aggregates as flaky when they have a thickness of less than 0.6 of their mean sieve sizes, while aggregate particles with the greatest dimension of more than 1.8 of their mean sieve size are classified as elongated. From Table 2 above, tuff aggregates and the granites had flakiness indices of 20% and 31% respectively. This means conventional aggregates require more fines, cement and water to make a good quality concrete compared with tuff aggregate concrete. This would lead to an increase in the cost of production of conventional concrete than tuff concrete. The elongation indices obtained for tuff aggregate and granite were 15% and 22% respectively. Flaky and elongated aggregates have larger surface areas which resulted in higher demand for cement paste in the concrete mix. This means granite aggregates require more cement to produce a good concrete mix than a similar concrete made from tuff aggregates. BS 882 [19] specifies an upper limit of 50% for uncrushed gravels and 40% for crushed gravel. The shape of aggregate particles influences water absorption, paste demand, placement characteristics such as workability, strength, void content, packing density, and cost as observed by Rached et al. [15].

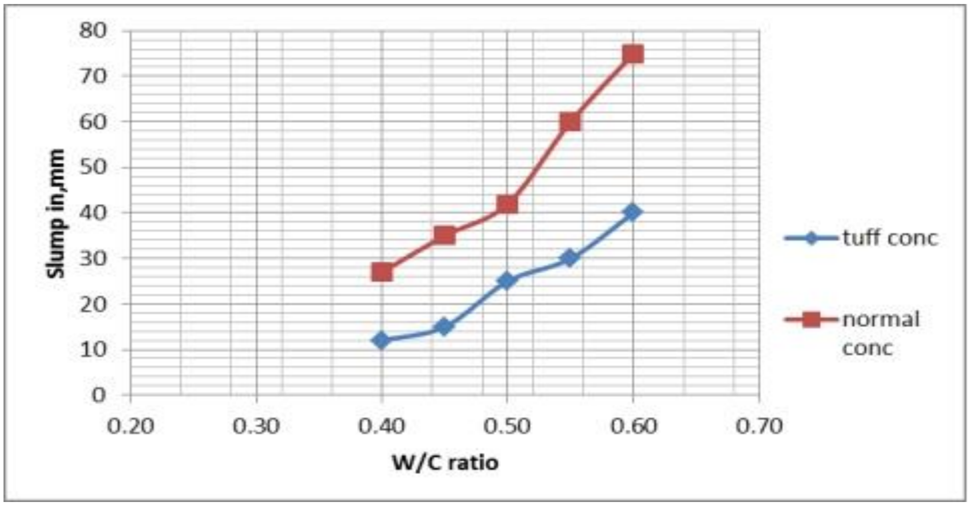

Figure 3.14: Effect of w/c ratio on the slump of the concrete mix

From Figure 3.14 above, the workability of both tuff and granite concrete was enhanced when the w/c ratio in the mix was increased. However, conventional concrete displayed a higher workability than tuff concrete for a given water-cement ratio. This is because tuff aggregates absorbed more water leaving little water for hydration of cement paste and lubrication of aggregates resulting in lower slumps. However, the slump values of both concrete samples were noted to increase with an increase in the mixing water. In the current research, the cement content was kept constant while varying the water content throughout all the mixtures. The aggregates were kept dry before mixing. From the results, a tuff concrete sample mix with a w/c ratio of 0.4 produced a slump value of 12 mm while normal-weight concrete had a slump of 27 mm. A tuff concrete sample with a w/c ratio of 0.4 could not mix thoroughly well as more water was absorbed by porous aggregates making the mixing process difficult and resulting in the harsh concrete with a low consistency. As a result of the inadequate free water, the cement particles failed to fully dissolve and interact with tuff aggregates when the w/c was 0.4 resulting in a low workability mix. It was noted that an increase in w/c ratio from 0.55 to 0.60 produced a slump of 40 mm from 30 mm while normal-weight concrete produced a slump of 75 mm from 60 mm. The increase in the slump of normal-weight concrete was higher as seen in the slope of the curve especially when w/c ratio was increased from 0.5 to 0.6. Increasing w/c ratio to 0.55 resulted in slump values of 30 mm and 60 mm for tuff and normal-weight concrete respectively. A water-cement ratio of 0.6 resulted in slump values of 40 mm and 70 mm for tuff and granite concrete respectively. The normal-weight concrete produced medium workability mixes when mix with w/c ratio of 0.5 and 0.6. Medium workability mixes have slumps in the range of 50mm to 90mm. Tuff concretes produced low workability mixes. Low workability mixes have slumps ranging from 10mm to 40mm. Slump values of tuff aggregate concrete were generally lower than those of normal-weight concrete because tuff aggregates absorbed more water into the pores leaving little water necessary for increased workability of the concrete. The water which was to cause an increase in the slump of tuff concrete was absorbed by the aggregates contributing to slump loss. Subsequently, there was a reduction of tuff concrete workability, unlike granite concrete where the effective free water for workability remains unabsorbed.

However, too much water in the mix resulted in the segregation of concrete. Too much water is therefore not recommended as it reduces the compaction of concrete and increases the chances of concrete bleeding and segregation. This results in the formation of voids and the reduction in strength of the hardened concrete. The segregation occurs when the sand and coarse aggregate components settle at the bottom while the cement paste forms at the top of the concrete mass. Slump values from 25 mm to 75 mm are normally specified for concretes used for floor slabs according to ACI 211.2-98 [1] where the compaction of concrete is necessary.

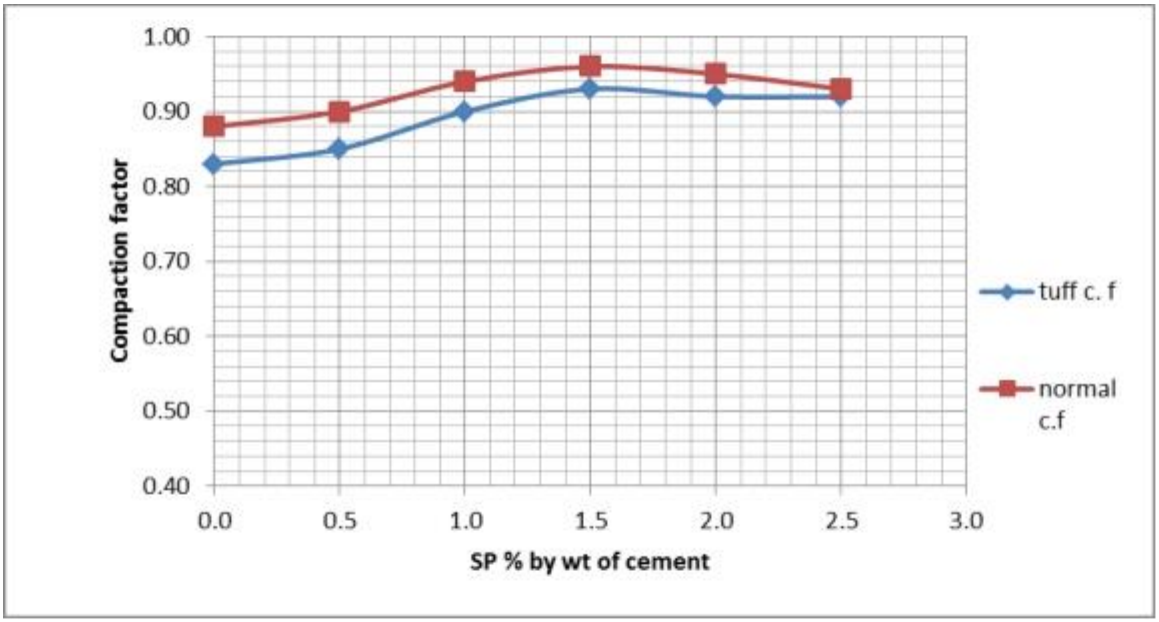

Figure 3.15: Effect of Superplasticizer on compaction of concrete (w/c 0.4)

From Figure 3.15 above, the compaction factors for both concrete samples improved generally when dosages of superplasticizer were increased in the mixes. The aggregates used for this test were presoaked before mixing to minimize the absorption of water and the superplasticizer, particularly by the tuff aggregates. The compaction factors for tuff concrete were noted to increase at a higher rate than those of granite concrete as the superplasticizer dosage was increased. This was seen as the gap between the two curves reduced gradually until the two curves were close. While the compaction factors increased from 0.88 to 0.96 for normal-weight concrete with superplasticizer dosage of 0% to 1.5%, the compaction factors increased from 0.83 to 0.93 for tuff concrete. The reason for the increase in compaction of the two concretes is that the superplasticizer helped disperse more cement particles to form cement paste which expelled entrapped air from the concretes. The cement paste and the aggregates interlocked after entrapped air was expelled from the voids in the process of compaction producing denser concretes. The compaction of tuff concrete seemed to improve at higher rate as the superplasticizer dosage was increased from 1.0% to 1.5% suggesting that more entrapped air in the concrete was being expelled from the concrete refilling the voids with the cement paste. However, when 2.0% of superplasticizer was added to the mix, the compaction of tuff concrete reduced to 0.92 while that of granite concrete dropped to 0.95. At 2.5% superplasticizer dosage, the compaction of tuff concrete slightly increased to 0.93 while that of granite concrete reduced to 0.93. From these results, an economical optimal percentage dosage of 1.5% to achieve high compaction factors to save on power and cost during mixing and placing can be recommended for the two types of concrete. Since tuff concrete contains air in the pores and between the particles, the superplasticizer forces more films of water and cement paste to expel the air from the pores and fill the void spaces in the aggregates causing an increase in compaction. However, the compaction of both concrete mixes declined when more superplasticizer dosage was increased from 1.5% to 2.5% while keeping the w/c ratio constant. That means more free water was left in the mixes causing segregation and bleeding of concretes and a decline in the compaction factors were noted. However, the compaction of normal-weight concrete was better than tuff concrete due to higher bulk density of granite aggregates than tuff aggregates in the mixes. Optimum superplasticizer dosage of 1.5% is therefore recommended for tuff and normal-weight concrete to achieve high compaction factors of 0.93 and 0.96 respectively.

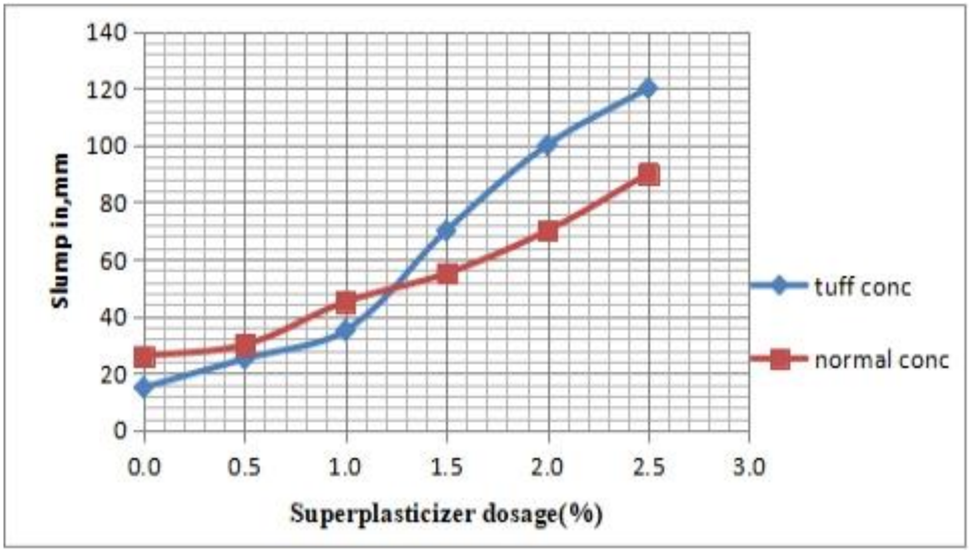

Figure 3.16: Effect of superplasticizer on the slump of concrete having w/c ratio of 0.4

From the results in Table 3.16 above, the concrete samples having water-cement ratio of 0.4 without super plasticizer were observed to have low slumps of 15 mm and 26 mm for tuff and normal-weight concrete respectively. The tuff aggregate samples in the mix absorb more water into the pores of the aggregates leaving little water for mixing and production of a cement paste available to coat the surfaces of aggregates and fill the voids thus making the concrete stiff within a few minutes of mixing. Unlike the tuff aggregates, a small amount of water is absorbed by the conventional aggregates leaving a high amount of water for the hydration of the cement paste responsible for filling the voids and lubrication of the aggregates leading improved slump in the concrete. Superplasticizer causes a transformation of stiff, low-slump concrete into flowing, pourable, and easily placed concrete. When 0.5% superplasticizer dose was added, the slump of tuff concrete increased by 67% to 25 mm while that of normal-weight concrete increased by 15% to 30 mm closing the gap difference at a slump value of 50 mm corresponding to 1.2% superplasticizer in the mixtures. Most of the tuff aggregates could possibly still absorb more water which contributed to lower slumps of tuff concrete than conventional concrete. On reaching a 1.2% superplasticizer dosage addition, the aggregates were possibly wet enough and fully saturated to absorb more water and the superplasticizer. The superplasticizer was increasingly becoming effective in the dispersal and de-flocculation of cement particles by creating like charges on the solid surfaces of the cement particles increasing the concentration of cement paste responsible for the lubrication of aggregates causing an increase in the workability of tuff concrete. The increase in workability of tuff concrete was more rapid surpassing that of normal-weight concrete when the superplasticizer dosage was increased from 1.5% to 2.5%. The gap between the two curves widened with the slump values increasing from 70 mm to 120 mm for tuff aggregate concrete while normal-weight concrete recorded a medium workability slump ranging from 55 mm to 90 mm. At 2.0% dosage, the tuff concrete mix became a high workability mix with a slump exceeding 100mm. This concrete is suitable for use where there is a tight spacing of reinforcement in a concrete structure where vibration of concrete is difficult. On the other hand, the addition of 2.0% superplasticizer dosage increased the slump of normal-weight concrete into a medium workability mix with a slump of 70mm. A medium workability mix has a slump value in the range of 50mm to 90mm. This concrete is suitable for use where there are normal reinforcements requiring vibration during placing.

In essence, an increase in the concentration of superplasticizer from 1.5% to 2.5% in tuff concrete mix contributed to a reduction of bonding and interlocking between the aggregates and the cement paste resulting in an increase in the workability of the mix. The superplasticizer was very effective in deflocculating and dispersing the cement particles causing more increase in fluidity of tuff concrete than the conventional concrete. The increase in slump of tuff concrete continued with increase in superplasticizer in the mix until segregation and bleeding occurred at an addition of 2.5% superplasticizer. The bleed water and superplasticizer which was not absorbed by aggregates nor consumed during the hydration process was responsible for the negative effects in concrete. The bleed water led to the formation of voids thus lowering the compaction of the wet concrete. A negatively affected concrete mix with lot of mixing water produced a high workability mix which sometimes resulted in a collapse slump.

Table 3: Unit weights of tuff and conventional concretes

Age of concrete in days	Unit weight of tuff concrete in kg/m^3	Unit weight of conventional concrete in kg/m^3
1	2031	2510
14	2036	2515
28	2038	2527

From Table 3 above, the densities of tuff and granite concrete when determined in fresh states were 2031 kg/m^3 and 2510 kg/m^3 respectively. The water cement ratio of 0.4 was maintained for all the mixtures. When measured at the ages of 14 days, the densities had increased to 2036 kg/m^3 and 2515 kg/m^3 respectively. When measured after 28 days, the density of tuff concrete increased by 2 kg/m^3 to 2038 kg/m^3 while granite concrete density increased by 6 kg/m^3 to 2528 kg/m^3. The densities of conventional concrete ranged from 2510kg/m^3 to 2527kg/m^3. The 28-day density of normal-weight concrete in particular was found to fall within the range of 2200 kg/m^3 to 2600 kg/m^3 and was in agreement with the study done by Neville et al. [13]. The 28-day density of tuff concrete was 2038 kg/m^3.This was found to be in agreement with the density of lightweight concrete which should not exceed 2200 kg/m^3 as per the definition of Euro code 2 [22]. The difference in unit weights of the two concretes was 489kg/m^3. This means a structure made with tuff concrete will be lighter in weight by 19.0% than a similar structure constructed with a conventional concrete. Consequently, the earthquake forces affecting the structure will be reduced by 19.0% if tuff concrete was used to construct it instead of the conventional concrete. The lower bulk density of the tuff aggregates in the mix contributed to the low density of tuff concrete whereas higher density of the conventional concrete was due to high bulk density of the granite aggregates in the mix. Proper curing provides a moist environment for the development of hydration products. This reduces the voids in hydrated cement paste increasing the density of microstructure in concrete. The hydration products extend from the surfaces of cement grains reducing the volume of voids. The slight gain in the densities of the two concretes therefore was partially because of absorption of water for hydration process and possibly because of expulsion of air from the voids making the concretes denser as they hardened. The increase in a unit weight of tuff aggregate concrete was 0.34% while that of normal-weight concrete was 0.67% within 28 days. These increments were however insignificant since most structural designs consider unit weights of concretes taken after 28 days. The lightweight concrete reduces the failure of structures in earthquake prone areas by lowering the effect of earthquake forces. Reduced dead load also allows the designers to reduce the sizes of structural members and the amount of reinforcement required in structures as compared with conventional concrete.

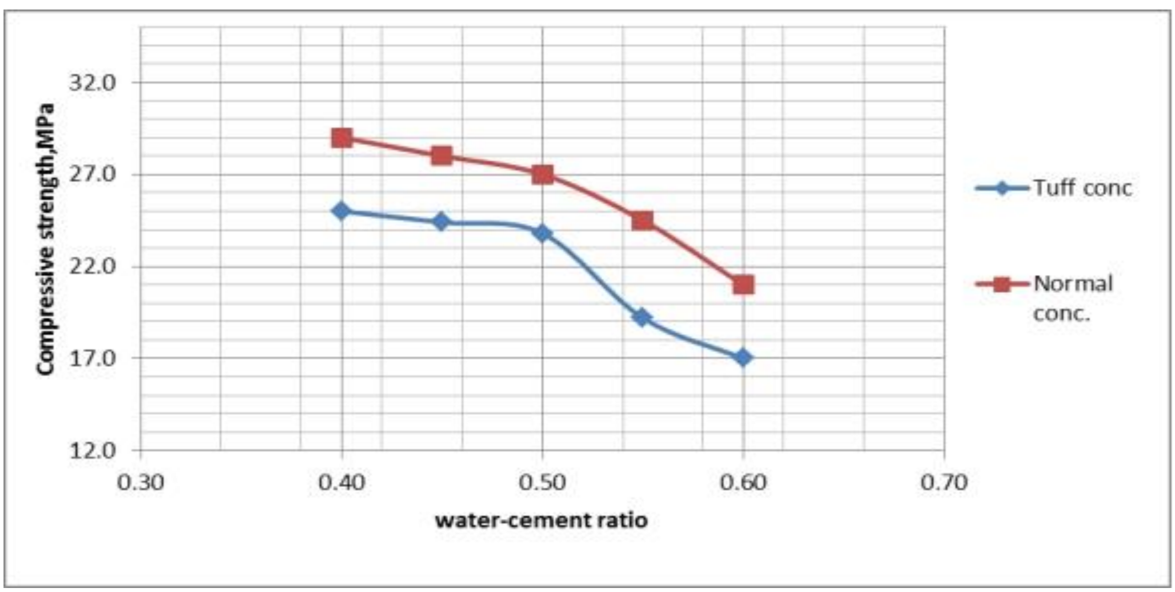

Figure 3.17: Effect of w/c ratio on compressive strength of concretes

From Figure 3.17 above, there was a reduction in the compressive strength of both concretes when the amount of mixing water was increased in the concrete mixes. The amount of cement content was kept constant throughout all the samples. The coarse aggregates of the two concretes were kept in saturated surface dry condition before mixing was done. The compressive strengths were measured on

28-day old concrete cube specimens. It can be observed that the compressive strength of tuff concrete was reduced from 25.0 N/mm^2 to 24.4 N/mm^2 when the w/c ratio was varied from 0.4 to 0.45. When the w/c ratio was further increased from 0.45 to 0.50, the compressive strength of the same concrete was reduced from 24.4 N/mm^2 to 23.8 N/mm^2. A reduction in compressive strength from 23.8 N/mm^2 to 19.2 N/mm^2 was noted when the w/c ratio was varied from 0.50 to 0.55. A further reduction of compressive strength from 19.2 N/mm^2 to 17.0 N/mm^2 was recorded when the w/c ratio was increased from 0.55 to 0.60. By increasing the w/c ratio from 0.4 to 0.6, there was an overall reduction of 32% in the compressive strength of tuff concrete. Any amount of excess free water in the concrete that was not absorbed by the aggregates nor used for the hydration of cement was responsible for the decrease in the compressive strength of the concretes. What happens is that the excess water leaves voids which trap the air pockets and hamper the compaction of concrete. It also increases the drying shrinkage as concrete hardens. Drying shrinkage causes the formation of cracks and weakens the concrete causing a reduction in the compressive strength. Similarly, there was an overall reduction in compressive strength of normal-weight concrete from 29.0 N/mm^2 to 21.0 N/mm^2 when the water-cement was increased from 0.4 to 0.6 representing 27% drop in strength. Excess mixing water in the concrete mix adversely affected the concrete. This is because the air voids in concrete tended to increase with the increase in the amount of water. Excess mixing water contributed to segregation of concrete. This affected the homogeneity and led to uneven hydration process causing a loss in the compressive strength of concrete. This means the cement paste and fine aggregate required to fill the void spaces between aggregates in the mix separated to form a top layer of fine materials and cement paste while the coarse aggregate material settled at the bottom. As a result, the concrete ended up with voids filled with air and lost the compressive strength. Furthermore, the water that was not consumed by the hydration reaction process evaporated as the concrete hardened leaving microscopic pores that reduced the strength of concrete. A concrete mix with too much water also experienced drying shrinkage as excess water evaporated. This resulted in the formation of internal cracks which again reduced the compressive strength of concrete.

However, the reason why the compressive strength of tuff concrete was generally lower than that of conventional concrete was mainly because tuff aggregates are more porous and less rigid than granite aggregates.

In concrete, the mixing water is available in three different forms, namely the chemically bonded water, the physically bonded water, and the free water. The chemically bonded water is utilized during the hydration process. The physically bonded water is the water bonded to the solid concrete materials by adhesive forces. The free water is the water which is beyond the range of solid surface forces and is considered to behave like in bulk water. The chemically bonded water is not lost in drying. It can only be released out when the hydrates decompose on heating up to 1,000°C. The distribution of the physically bonded water and the free water in porous materials strongly depends on the moisture content.

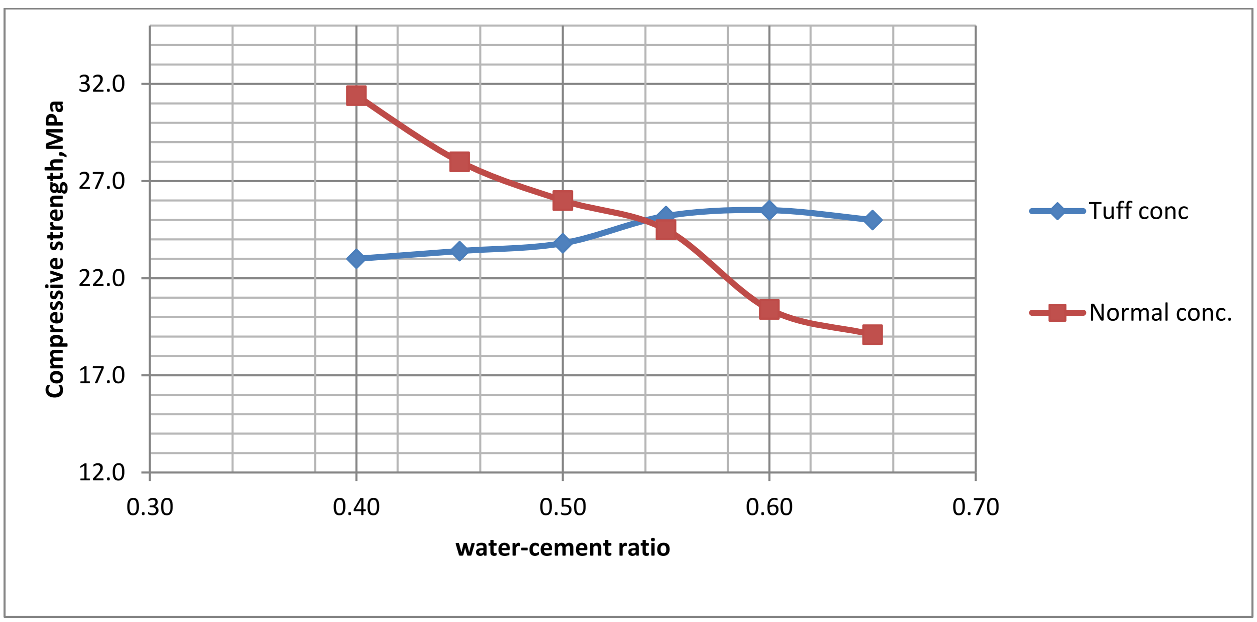

Figure 3.17: Effect of w/c ratio on compressive strength of concrete when dry aggregates are used

From Figure 3.17 above, oven dry aggregates of tuff and granite were used at the time of producing the concrete mixes. When the water-cement ratio was increased from 0.4 to 0.65, there was a reduction in the compressive strength of the conventional concrete as the curve kept falling. The compressive strength of the conventional concrete reduced from 31.4 N/mm^2 to 19.1 N/mm^2 representing a drop in strength by 39.0%. This drop is significant as it can alter the whole design and construction of a structure. However, there was an unusual increase in the compressive strength of tuff concrete from 23.0 N/mm^2 to 25.5N/mm^2 when the water cement ratio was increased from 0.40 to 0.60 representing an increase in strength by 10.8%. The compressive strength increased noticeably from 23.8 N/mm^2 to 25.5

N/mm^2 when the water-cement ratio was increased from 0.50 to 0.60. The compressive strength then started to drop from 25.5N/mm^2 to 25.0 N/mm^2 when the w/c ratio was further increased from 0.60 to 0. 65. As can be observed from the curves, there was a striking difference in the behavior of the two concretes. What happened is that a lot of free water was accumulated in the mix as the mixing water was increased in the conventional concrete which contributed to the reduction of the compressive strength. The water which remained unabsorbed by aggregates nor used for hydration of cement was responsible for the negative effects in conventional concrete. This is because the conventional aggregates absorbed very little water during mixing as compared with the tuff aggregates. The excess water in the conventional concrete evaporated and left voids which were filled with air. This created weak linkages and bonds between the cement paste and the aggregate lowering the compaction of concrete. As concrete hardened, drying shrinkage cracks developed. This resulted in the reduction of compressive strength of the hardened concrete.

Unlike the conventional aggregate concrete, tuff aggregates absorbed more water into the pores leaving little water for hydration and lubrication of aggregates when water-cement ratio was 0.4. As a result of low water-cement ratio, the cement in the mix did not hydrate fully resulting in a harsh mix which left the aggregates to segregate. The formation of voids occurred in the concrete contributing to a reduction in the compaction of concrete and loss of compressive strength. As the water-cement ratio was increased from 0.40 to 0.60, the aggregates absorbed enough water and left sufficient water for mixing and hydration of cement particles. Adequate water for hydration, improved workability, interlocking of aggregates, and compaction of concrete was available when the w/c ratio was 0.60. Consequently, the air entrapped in the concrete was expelled during compaction leaving a denser concrete. This gave rise to increase in compressive strength to 25.5N/mm^2. However, with a further increase in the water-cement ratio to 0.65, there was drop in the compressive strength to 25.0N/mm^2. This means the excess water in the mix contributed to the formation of voids and segregation of concrete. The compaction of concrete was thus reduced leading to a reduction in the compressive strength of tuff concrete to 25.0N/mm^2. The compressive strengths were taken on 28-day old concrete cube specimens.

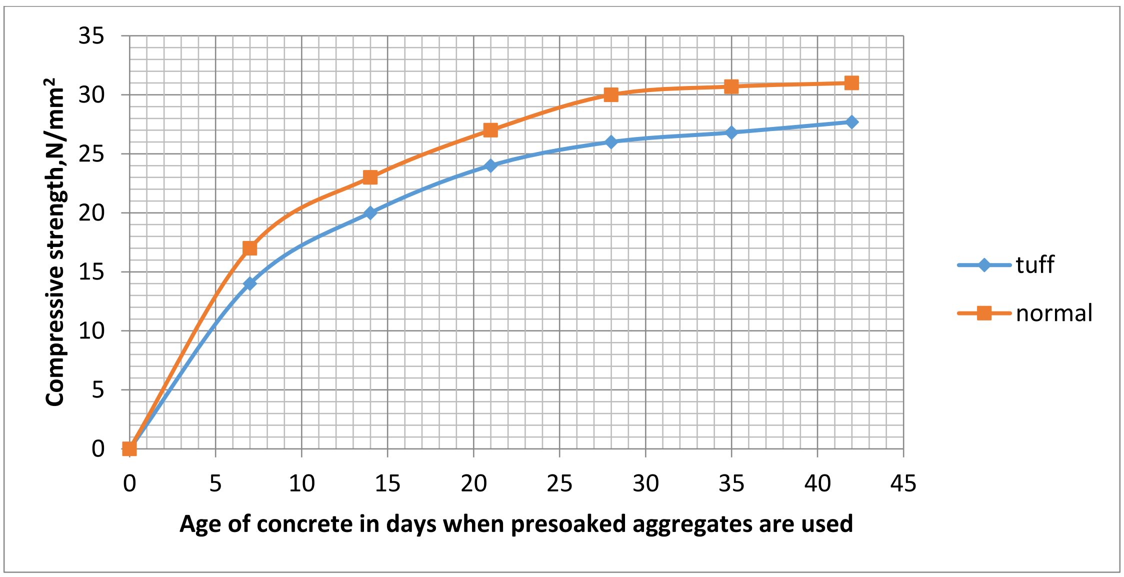

Figure 3.18: Compressive strength of tuff and conventional concrete with age (w/c 0.4)

From Figure 3.18 above, the two concretes registered a sharp increase in compressive strengths within the first 7 days of curing but the rate of increase in strength was noted to slow down as the concretes matured in age. This is because the hydration process is normally faster at early ages of moist cured concrete due to high concentration of tricalcium silicate (Ca_3SiO_5) which is responsible for early strength development in concrete. Tricalcium silicate reacts rapidly with water in a process call hydration to release calcium ions (Ca^{2+}), hydroxide ions (OH^-), and hydro silicate ions ($H_2SiO_4^{2-}$). A large amount of heat is produced during the process as the concrete hardens. This explains why the rate of strength development was higher within the first seven days of the two concretes. Dicalcium silicate (Ca_2SiO_4) reacts more slowly with water and contributes mainly to strength development after 7 days. The process is slower as compared to hydration caused by tricalcium silicate. The hydration of dicalcium silicate leads to formation of amorphous calcium silicate hydrate and calcium hydroxide.

The average compressive strength of tuff aggregate concrete after 7 days was 14.0 N/mm^2 representing a strength gain of 54 % in comparison with 28-day strength of 26.0N/mm^2. The normal-weight concrete was 17.0 N/mm^2 representing a gain of 57% in comparison with 28-day strength which was 30.0N/mm^2. For structural normal-weight concrete, the strength at 7 days should be between 60% to 65% of the 28-day compressive strength depending on several factors which include the type of cement, type of aggregate, grading of aggregates, curing method, compaction of concrete, quality of raw materials, and water-cement ratio. Most concrete strengths are designed for 28 days since concretes are expected to gain 100% maturity in strength. The slow gain in strength of two concretes could be because the aggregates used in the mix were uniformly graded and not well graded. Specifically, the conventional aggregates were uniformly graded, elongated and flaky. This could have contributed to a slow rate of growth in the compressive strength within first 7 days. At the age of 14 days, the compressive strength of tuff concrete increased to 20.0 N/mm^2 representing 77% strength growth in comparison with 28-day strength while that of normal-weight concrete increased to 23.0 N/mm^2 representing 76.6% strength growth compared with the 28-day strength. In well graded normal-weight concrete mix, the strength growth after 14 days should be around 90% of the 28-day strength. After 21 days the compressive strength of tuff concrete was 24.0 N/mm^2 while that of normal-weight concrete was 27.0 N/mm^2. After 28 days, the strength of tuff concrete had increased to 26.0 N/mm^2 while that of normal-weight concrete had reached 30.0 N/mm^2. When measured after 35 days, the strength of tuff concrete was 26.8 N/mm^2 while that of normal-weight concrete was 30.7 N/mm^2. Although the curing of the concrete samples was stopped after 28 days, it was noted that there was a slight increase in strength of both concretes when tested after 35 and 42 days. However, the increments in the compressive strengths of the tuff concrete were higher than those of the conventional concrete. For example, at 42 days, the strength of tuff concrete sample increased by 1.7N/mm^2 to 27.7 N/mm^2 with respect to the 28-day strength while normal-weight concrete strength increased slightly by 1.0 N/mm^2 to 31.0 N/mm^2. When compared, tuff concrete registered a higher increment of strength than conventional concrete after 28 days. The increments are attributed to the continuous hydration of dicalcium silicate due to internal curing in the microstructure of the concretes. The higher increment of strength in tuff concrete than in conventional concrete is attributed to the presence of more water in the pores of tuff concrete which facilitated better internal curing than in conventional concrete. However, the strengths of tuff aggregates were in general lower than those of normal-weight concrete. Tuff aggregates have numerous pores in their cellular structure which contributed to lower strengths of tuff concrete. The presence of either interconnected or disconnected pores within the tuff aggregates served as weak spots that allow for the initiation and propagation of cracks when the concrete was compressed. Granite aggregates on the other hand are more rigid and denser than tuff aggregates causing the conventional concrete to have higher compressive strength.

Figure 3.19: Failure mode of tuff aggregate concrete cube sample

In Figure 3.19 above, the concrete cube sample for tuff aggregate concrete displayed a non-explosive failure mode. This was a satisfactory failure mode category. Concrete cracking occurs in three stages. In stage one, as the concrete specimen is loaded, the localized cracks are initiated at the microscopic level at isolated points throughout the specimen where the tensile strain concentrations are the largest. In stage two, the crack system multiplies and propagates but in a slow and stable manner. The final stage involves crack system developing and becoming unstable and the release of strain energy is sufficient to make the cracks self-propagate until a failure occurs. The reason for such a failure of tuff concrete can be attributed to the presence of interconnected pores within the tuff lightweight aggregates that served as weak spots for the initiation of micro and large cracks within the aggregate. As the applied stress is gradually increased, the micro cracks extended in length and width until they formed major failure cracks passing through the aggregates and thus causing cracking of the specimen along two planes. The concrete cube specimen developed macroscopic cracks which split the specimen into three sections as loading of the cube was increased gradually. However, the crack on the left of the specimen was wider than the crack on the right side of the specimen, owing to high concentration of stresses on the left side of the specimen during loading.

Figure 3.20: Failure mode of normal-weight concrete cube sample

In Figure 3.20, the failure of the conventional concrete specimen resulted in unsatisfactory failure mode with tensile cracks forming near the extreme edges of the left and right hand side faces of the cube. As the load was increased on the specimen, the formation of a microscopic cracks in a concrete developed. These cracks enlarged into macroscopic tensile cracks which propagated into tensile cracks causing failure of the specimen as loading gradually increased in the specimen. The failure was semi-explosive accompanied by a loud sound produced as the specimen failed in compression. The cracks sizes were smaller in width than those in a failed tuff cube specimen. This is because of the high individual elastic moduli of the aggregates and the paste component in the normal-weight cube specimen. The tensile crack on the left face is smaller than the crack on the right side face of the cube. This means the compressive stresses were more concentrated on the right side edge than on the left side edge of the specimen. The crack on the right hand side edge of the concrete cube was thicker in width than on the left hand edge of the specimen most probably due to uneven cement paste distribution during mixing, compaction and placing of the concrete.

Figure 3.21: Tuff concrete specimen tested for splitting tensile strength

The splitting tensile strengths from three cylindrical tuff concrete specimens were 2.7 N/mm^2, 2.8 N/mm^2 and 3.0 N/mm^2. The average splitting tensile strength for tuff concrete, therefore, was 2.9 N/mm^2. The average 28-day cube compressive strength of tuff concrete from the same mix was 25.6 N/mm^2. The ratio of the tensile stress to compressive strength of tuff concrete was found to be $\frac{1}{9}$.

Figure 3.22: Conventional concrete specimen tested for splitting tensile strength

The splitting tensile strengths from three samples of conventional concrete were 3.5 N/mm^2, 3.6 N/mm^2 and 3.7 N/mm^2. The average splitting tensile strength for the concrete samples was 3.6 N/mm^2. The average 28-day compressive strength of conventional concrete made from the same concrete mix was 34.8 N/mm^2. The ratio of the tensile stress to compressive strength of conventional concrete was found to be $\frac{1}{10}$. One common characteristic of conventional concrete is its increased brittleness more than tuff concrete. The ratio of tensile strength to compressive strength is one the methods used to judge the brittleness of the material. The lower the ratio, the more brittle the material. Conventional concrete therefore from this study was observed to be more brittle. The splitting tensile strength values for both concretes were however found to fall within the range of 2.2 - 4.2 MPa specified in most design standards as acceptable for structural design of concretes. However; the tensile strengths for tuff concrete specimens were lower than those of normal-weight concrete. The reason for low tensile strengths in tuff concrete can be attributed to the presence of more interconnected pores within the tuff lightweight aggregates that serve as weak spots for the initiation of cracks within the tuff concrete. This explain why the tuff concrete specimen on failure developed wider plane cracks than conventional concrete. From Figure 3.21 above, two plane cracks were seen after failure of tuff aggregate concrete whereas one plane crack occurred on the conventional concrete specimen as seen in Figure 3.22. Although the load at which NWC failed in tension was higher, its failure mode was sudden and explosive depicting a more brittle behavior than tuff aggregate concrete. It can therefore be deduced that conventional concrete has a poor capacity to resist vibrational loads and may not be suitable for earthquake structures compared to tuff lightweight concrete. Tuff concrete was observed to develop more irregular internal cracks which appeared to spread to the surface while NWC developed fewer plane cracks with the primary crack developing along the plane of loading. The conventional concrete sample failed suddenly producing explosive sound into two parts through the middle of the cross-section. The formation of two major cracks in the case of tuff concrete allows the tensile stresses to be distributed in the cross section of the concrete. This causes the transfer of tensile stresses to the steel in case of a reinforced concrete. This is because at a cracked section, concrete stress is zero but the steel stress is maximum for a reinforced section. However, more cracks in concrete allow the ingress of water into the concrete causing damage to reinforcement by corrosion and eventual failure to the structure.

IV. CONCLUSION

From the current study, tuff aggregates were found to be suitable materials for the production of structural low-density concrete having a 28-day unit density of 2038 kg/m^3 and compressive strength of 26.0N/mm^2 compared with conventional concrete which was found to have a heavier unit weight of 2527 N/mm^2 and compressive strength of 30.0 N/mm^2 when aggregates are presoaked prior to mixing and concretes prepared in accordance with procedures outlined in the current study. However, the 28-day compressive strength of tuff concrete improves with increase in water-cement ratio attaining a compressive strength of 25.5N/mm^2 at w/c ratio of 0.60 when oven dry aggregates are used unlike the conventional concrete where the compressive strength declines as the water-cement ratio increases registering a strength of 20.4N/mm^2 at w/c ratio of 0.60. The 28-day density of tuff concrete is lower than that of normal-weight concrete by 19.0% making it a suitable material for earthquake structures. The tuff concrete possesses higher strength to weight ratio of 1.3% making it more structurally efficient as compared with conventional concrete which has a ratio of 1.2%. The 28-day tensile strength of tuff aggregate concrete is 2.9 N/mm^2 while that of normal-weight granite concrete is 3.6 N/mm^2.

V. RECOMMENDATIONS

Given the 28-day compressive strength of 25.5N/mm^2 and dry density of 2038kg/m^3, tuff aggregate concrete should be used for the construction of high-rise buildings and long-span bridges particularly those situated in earthquake prone areas. Tuff aggregates were noted to absorb more water than conventional aggregates. This property adversely affects the workability of concrete necessitating presoaking of tuff aggregates and the use of super plasticizers during mixing. The effect of internal curing with respect to change in properties of concrete produced from presoaked aggregates should be investigated up to and beyond 90 days for both tuff and conventional concretes. Further research on the durability characteristics of both tuff lightweight concrete and conventional concretes containing different binder contents and water-cement ratios should be done.

ACKNOWLEDGMENT

This research could not have addressed its intended purpose without God's grace and guidance throughout the years of my study. I am very thankful to my first supervisor Prof. Eng. Silvester Abuodha for his invaluable comments and suggestions throughout the stages of this research. Secondly, I would like to express my sincere gratitude to Dr. Eng. John Mwero who was my second supervisor for his guidance, recommendations, and support throughout the length of this research work. Further appreciation goes to the technicians of the civil engineering laboratory of the University of Nairobi for their cooperation during the preparation and testing of materials in the laboratory. I also thank my friends who in one way or the other contributed to the success of this research. Finally, I would like to thank my family members for their never-ending encouragement, love, prayers and motivation throughout my period of study.

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AUTHORS

First Author – Eng. Geoffrey Kiprotich Sang, BSC. Civil Engineering, JKUAT and jeffsang2@gmail.com.

Second Author – Prof. Eng. Abuodha Silvester Ochieng, PhD Structural Engineering, University of Manchester and sabuodha@uonbi.ac.ke.

Third Author – Dr. Eng. John Mwero, PhD Structural Engineering, University of Nairobi and johnmwero1@gmail.com.

Correspondence Author – Eng. Geoffrey Kiprotich Sang, jeffsang2@gmail.com, jeffsang11@yahoo.com, +254 724 384 923.