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Effects of Volcanic Tuff Use on the Rheological and Mechanical Properties of Self-Compacting Concrete

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ABSTRACT

The rise in demand of concrete products has led to overexploitation of river sand the main fine aggregate in concrete resulting in major environmental degradation. As a result, researchers have focused their efforts on developing eco-friendly concrete using alternative renewable materials like volcanic tuff and other natural pozzolana types. This study therefore, aims at investigating the use of Kenyan, Kitengela volcanic tuff as a partial replacement of river sand in self-compacting concrete, and determining the effects it will have on the rheological and mechanical properties of the self-compacting concrete. The study involved partially replacing river sand with volcanic tuff in percentages of 0%, 2.5%, 5%, 7.5% and 10% and carrying out rheological tests (V-funnel test, L-box test, T-500 test and J-ring test) on fresh concrete and mechanical tests (compressive strength and tensile strength tests) on hardened self-compacting concrete on days 7, 14, and 28 to determine the effects of volcanic tuff on properties of both fresh and hardened self-compacting concrete. There was a general decrease in rheological properties (flow and passing abilities) of self-compacting concrete with increase in volcanic tuff percentage replacement from 0 % to 10%, with least flow and passing abilities recorded at 10% replacement. Similarly, increase in volcanic tuff percentage replacement led to decrease in both compressive and tensile strength of self-compacting concrete with lowest values recorded at 10% volcanic tuff replacement.

1. Introduction

Growth in the construction industry has led to a sharp increase in the demand of concrete products, consequently increasing the demand of aggregates as they form the bulk of concrete. River sand the most common fine aggregate in concrete has been overexploited resulting in major environmental degradation [1]. Globally over 50 billion tonnes of sand are harvested annually for use in the construction industry, hence there is need to find an alternative or complimentary fine aggregate in order to offset the high demand of river sand [2]. Self-compacting concrete (SCC) refers to concrete that flows under its own weight and fills the required space or formwork completely without needing any form of compaction [3]. Since its invention in the late 80s, self-compacting concrete use has been on a steady rise in Kenya. Volcanic tuff is a pyroclastic, consolidated rock

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which is mostly composed of compacted and cemented ash that come from volcanic eruptions, it’s readily available in most parts of Kenya and widely used as a substitute of river sand in normal concrete and mortar in the country [4]. With the growing popularity of self-compacting concrete in Kenya, adoption of volcanic tuff as a partial replacement of river sand in self-compacting concrete will help ease the burden on river sand.

Volcanic tuff has found widespread use in concrete due to its availability and structural properties, being lighter than normal aggregates it reduces the weight of concrete while still giving it good structural properties [5]. Volcanic tuff due its wide occurrence and ease of extraction is cheaper than river sand hence it significantly reduces the cost of concrete [6]. Table 1 below shows the physical properties of volcanic tuff in comparison to other aggregates.

Table 1: Physical properties of volcanic tuff compared to normal aggregates [7]

Parameter	Coarse aggregate	River sand	Volcanic tuff
Oven dry specific gravity	2.6	2.55	1.962
Saturated surface dry specific gravity	2.63	2.6	2.02
Bulk density (kg/m^3)	2650	2630	1982
Water absorption ration by weight	1.2%	1.7%	10.1%

Various studies have been carried out on the use of volcanic tuff in both normal concrete and SCC. Daoud [8] investigated the use of volcanic tuff in preparation of self-compacting low-density concrete mix. This study established that volcanic tuff use enables creation of a rheological stable self-compacting concrete mix with compressive strength of the hardened concrete ranging from 24-57 Mpa. Generally, this study concluded that volcanic tuff can be used as an aggregate in the production of self-compacting concrete that is strong, lightweight and of good mechanical strength. Yerlan et al. [9] made similar observations in their study, they observed that volcanic tuff can be utilized in the production of lightweight self-compacting concrete with a compressive strength of 43.5Mpa and an average density of 1750.0 kg/m^3.

Omrane and Rabehi [10] demonstrated that volcanic tuff can be utilized as a suitable filler in the preparation of concrete with average density of 2038 kg/m^3 and compressive strength of 26 Mpa. The study established that volcanic tuff concrete had a lower density than conventional concrete concluding that volcanic tuff was an appropriate material for construction of earthquake resistant structures. Walid et al. [11] observed that volcanic tuff can be used in the production of self-compacting mortar with improved mechanical properties when used as a partial substitution of portland cement up to 10% replacement. They found the long term compressive and flexural strength of the resulting mortar to be close to that of the control mortar made with portland cement.

Further studies by [12] examined the possibility of using volcanic tuff in self-compacting concrete, they subjected volcanic tuff to a series of tests to determine its specific density, water absorption, average density and porosity. These tests were conducted as per ASTM C29/C29M-17a. In the study, volcanic tuff was used to replace limestone aggregate in percentages of 25%, 50%, 75% and 100%. The specimens in this study showed satisfactory porosity. Compressive strength of the resulting concrete was tested and found to be 18Mpa. Studies conducted by [13] on preparation of self-compacting concrete by replacing fine aggregates with quarry dust to assess its effects on water absorption and durability concluded that 10-50% replacement of fine aggregate with quarry dust significantly improved water absorption of self-compacting concrete but decreased its workability.

While various studies have been carried out on the use of volcanic tuff in concrete, there are still many areas yet to be addressed, necessitating the need for more research on this subject. Most studies have focused on the use of volcanic tuff as partial replacement of cement in normal concrete and self-compacting concrete, few studies have focused on the use of volcanic tuff as a partial replacement of fine aggregates in self-compacting concrete [14]. This study will attempt to fill this gap.

Recent studies on the use of lightweight aggregates in self-compacting concrete have mostly focused on artificial lightweight aggregates. Few studies have been done on the use of natural lightweight aggregates like volcanic tuff in the production of self-compacting concrete. Artificial lightweight aggregates while they produce concrete with good mechanical properties are expensive to produce as they involve much heating and sintering [15]. This study therefore, presents an excellent opportunity to study the use of natural lightweight aggregates like volcanic tuff that are readily and cheaply available in Kenya in the production of self-compacting concrete.

The purpose of this study is to investigate the effects of volcanic tuff on the rheological and mechanical properties of self-compacting concrete when used as partial replacement of river sand. This study also aims at determining the suitability of using volcanic tuff as a partial replacement of river sand in self-compacting concrete and determining the ideal volcanic tuff percentage replacement that gives the best self-compacting concrete properties. The study involves partially replacing river sand with volcanic tuff in percentages of 0%, 2.5%, 5%, 7.5% and 10% and carrying out rheological tests (V-funnel test, L-box test, T-500 test and J-ring test) and mechanical tests (compressive strength test and split tensile test) on the resulting self-compacting concrete to establish its properties.

2. Methodology

2.1 Material acquisition

Materials used in this research were cement, river sand, volcanic tuff, coarse aggregates, superplasticizer and potable water. Volcanic tuff was obtained from Kitengela region in Kenya. Superplasticizer SikaViscoFlow®-615KE which is a polycarboxylic ether-based superplasticizer complying with ASTM C-494, is a high range water reducer and a workability enhancing admixture for concrete based on Sika PCE technology. It was obtained from Sika Kenya Limited and has the following properties:

- Works based on a combination of electrostatic adsorption and steric repulsion effects thus, solid particles can be dispersed and a high level of fluidity can be reached with less water.
- Keeps workability for extended time.
- Maintains constant slump flow and smoothness of concrete over hours.
- Extremely powerful water reduction (thereby creating high concrete density and high strengths).
- Controls retarding properties.
- Excellent plasticising effects, resulting in improved flow, placing and compaction characteristics.
- Greatly improves water tightness.
- Reduces creeps and shrinkage.
- Reduces carbonation rate of the concrete.

Portland pozzolana cement (Grade 32.5R) used in this research was sourced from Bamburi Cement Company. This is a portland pozzolana cement manufactured by mixing portland cement clinker with natural pozzolana in accordance to East African Standard KS EAS 18-1 that is in conformity with BS EN197-1. The physical and chemical properties of portland pozzolana cement used are given in Tables 2 and 3 below respectively.

Table 2: Physical properties of Portland cement [16].

Physical property	EN-197-1 specifications
Compressive strength 2-days (MPa)	≥10
Compressive strength 28-days (MPa)	≥32.5 ≤52.5
Initial setting time	≥75
Soundness (expansion)	≤10

Table 3: Chemical proprieties of Portland Cement [16].

Component	% composition before mixing	% composition after milling
Limestone CaO	60	Clinker 65%
Kunkur (SiO2)	35	
Mullscale, Iron ore, (Fe2O3)	2	
Bauxite, Alumina dust (Al2O3)	3	
Pozzolana (SiO2)		30
Gypsum (CaSO4)		5

2.2 Self-Compacting Concrete Mix preparations

Physical tests including; particle size distribution, moisture absorption, bulk density, fineness modulus was carried out on the aggregates. Self-compacting concrete mixes were prepared by fixing the coarse aggregate volume at 50%, and to achieve the performance criteria of self-compatibility, water/powder ratio was restricted to 0.42 and river sand was partially replaced with volcanic tuff by weight in the proportions of 0%, 2.5%, 5.0% 7.5% and 10%. The mix proportions for SCC are given in table 4 below.

Table 4: Self-compacting concrete mix proportions

SCC mix	Water content (kg/m^3)	Cement (kg/m^3)	SikaViscoFlow-615KE % by weight of cement	Coarse aggregate (kg/m^3)	Natural river sand (kg/m^3)	Volcanic tuff (kg/m^3)	Volcanic tuff as % replacement of river sand	Water cement ratio W/C
SCC mix 1	160	375	1%	870	435	0	0%	0.42
SCC mix 2	160	375	1%	870	424.13	10.87	2.5%	0.42
SCC mix 3	160	375	1%	870	413.25	21.75	5%	0.42
SCC mix 4	160	375	1%	870	402.37	32.63	7.5%	0.42
SCC mix 5	160	375	1%	870	391.50	43.50	10%	0.42

2.2.1 Rheology tests

In order to determine the effects of the Kenyan, Kitengela volcanic tuff on the flow properties of self-compacting concrete, filling ability and passing ability tests were conducted. Filling ability refers to the rheological property of SCC to flow into all spaces in densely reinforced structures by gravity. Slump flow Test, T500 test, and V-funnel test were conducted as per BS EN 12350-2:2009 specifications to assess the filling ability of SCC. Slump flow and T500 Test procedure followed specifications provided by BS EN 12350-2:2009. A slump cone was used in these tests and carried out at 0%, 2.5%, 5.0% 7.5% and 10% volcanic tuff replacement. The average of both diameters of flow was recorded and time for SCC to reach 500mm diameter mark was recorded as T500 time. V-funnel test was conducted to assess viscosity and filling ability of SCC. The tests complied with BS EN 12350-9:2009; EFNARC, 2005 standards. Time taken for concrete to flow out of the funnel was measured for 0%, 2.5%, 5.0% 7.5% and 10% volcanic tuff replacement of river sand.

Passing ability of SCC is the ability to flow through tight openings like spaces between steel reinforcing bars without undergoing segregation or blocking. Passing ability was assessed using L-box test apparatus and J-ring test apparatus.

L-Box tests were carried out in accordance to BS EN 12350-10 (2010) and EFNARC (2005) specification for 0%, 2.5%, 5.0% 7.5% and 10% volcanic tuff replacement of river sand. J-ring tests were performed as per BS EN 12350-12 (2010) and EFNARC (2005) specifications for 0%, 2.5%, 5.0% 7.5% and 10% volcanic tuff replacement of river sand.

2.2.2 Mechanical tests

Compressive strength test and split ring tensile test were conducted to assess the mechanical properties of SCC. Compressive strength test was done in accordance to BS EN 12390-3:2009. Standard cubes of 150 mm × 150mm × 150mm were used. The crushing strength of the cubes was used to determine the load bearing capacity of the hardened SCC at days (7, 14, 21 and 28) for 0%, 2.5%, 5%, 7.5% and 10% volcanic tuff replacement of river sand. The split tensile strength test was used to determine the tensile strength of the harden SCC. Cylindrical concrete samples measuring 150mm diameter and 300mm length were prepared and split tensile test done at days (7, 14, 21 and 28) for 0%, 2.5%, 5%, 7.5% and 10% volcanic tuff replacement of river sand.

3. Results and discussion

3.1 Physical properties of aggregates

3.1.1 Gradation of aggregates

Normal S-curves are obtained for both river sand and volcanic tuff aggregates as shown in Figure 1 below, this indicates well-graded aggregates. Considering the gradation and particle size characteristics, volcanic tuff aggregates and natural river sand show striking similarities since particle distribution of both aggregates fitted into zone 2 grading of BS 882-1992. The particle size distribution of the two aggregates fell within the lower and upper bounds which is in compliance with ASTM-97 recommendations.

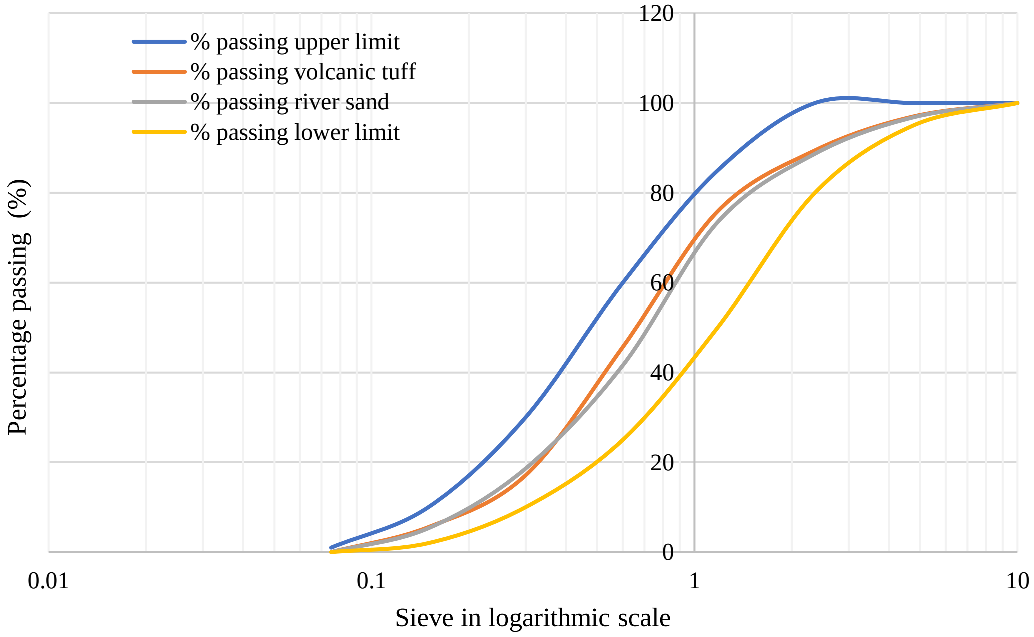

Figure 1. Gradation curves for volcanic tuff and river sand

From the semi-log plot, volcanic tuff aggregates were predominantly made of intermediate particles (2-4mm) and filler in the proportion (>2mm) of 89.45% and 10.55%, respectively. Similarly, for the case of natural river sand, the proportion of intermediate size particles is observed to be 88.69% this significantly contributes to the workability of the SCC.

3.1.2 Fineness modulus

The fineness modulus of river sand and volcanic tuff were obtained to be 2.75 and 2.69 respectively. This shows that volcanic tuff aggregate was made of finer particles than river sand. Fineness modulus affects many properties of concrete like workability and the quality of finish. As smaller particles will have a higher surface area increasing the water demand of the aggregate [17]. Higher fineness modulus decreases the fresh property of SCC due to increase in coarser particles. Hence it is necessary to do proper gradation of both fine and coarse aggregates in order to obtain adequate properties of SCC.

3.1.3 Bulk density

Bulk density refers to the mass of material per unit volume, for volcanic tuff the bulk density was calculated to be 1389kg/m^3, for river sand it was 1530 kg/m^3 and coarse aggregate was 1410 kg/m^3. Bulk density plays a crucial role in properties of SCC. Higher bulk density will lead to concrete with higher strength and durability [18]. Higher bulk density implies concrete has fewer voids, hence more compact and stronger. On the other hand, lower bulk density may reduce the strength of concrete, but increase workability as a lower bulk density makes concrete easier to work and place.

3.2 Filling ability

Filling ability of SCC was tested using slump cone test and T500 test to determine if the SCC was able to flow and fill the narrow gaps in reinforced concrete formworks.

3.2.1 Slump cone test

Results in Figure 2 show that slump flow decreased with increase in Kenyan, Kintegela volcanic tuff percentage replacement. Largest slump flow of 745mm was attained at 0% replacement and the least slump flow of 640mm at 10% replacement. The decrease in slump with increase in volcanic tuff percentage replacement can be attributed to volcanic tuff absorbing more water leaving less water for lubrication of the self-compacting concrete mix, this reduces the fluidity of the SCC mix hence lowering slump flow. Volcanic tuff is more porous and has a high surface area than river sand hence it absorbs more water than river sand. These findings are in line with studies done by [19], they observed that volcanic tuff when used as an aggregate in self-compacting concrete absorbs more water, leading to reduction in the lubrication water. This results to stiffer and less workable SCC reducing its slump flow. Studies done by [20] found that when the water/cement ratio is held constant, volcanic tuff reduces the workability of SCC as it absorbs more water due to its porosity and high surface area. At 0% replacement, with no volcanic tuff, river sand absorbs less water hence more water is available for lubrication resulting in the highest slump of 745mm. At 2.5% replacement the content of volcanic tuff increased and absorbed more water resulting in decrease in slump. At 5% and 7.5% percentage replacements there’s further decline in slump since the content of volcanic tuff increased and more water was absorbed leaving less and less water for lubrication. 10% replacement had the highest content of volcanic tuff and absorbed the most water leading to the smallest slump flow. From the results it can be projected that higher percentages of volcanic tuff replacement may not achieve self-compacting concrete with acceptable slump since more water will be absorbed leaving little or no water for lubrication of the concrete mix, which may negatively affect the workability of the SCC mix. The effect of volcanic tuff on water demand at a given slump value largely depends on the type of the pozzolan. While some natural tuffs increase the water demand like zeolite and diatomite due to their high-water absorption others like volcanic ash and pumice only moderately increase the water demand when used in high percentages.

The reduction in slump flow with increase in volcanic tuff replacement can also be attributed to finer particles in volcanic tuff increasing the paste volume of the SCC mix sine finer particles have a higher water demand. Fine aggregates play an important role in determining properties of SCC, during gradation particle size fractions smaller than 0.075 mm are in fine aggregate content and should be taken into account when calculating the water powder ratio, good particle size distribution is therefore important when it comes to workability of SCC. While the increase in paste volume caused by finer particles in volcanic tuff implies more water demand, this does not necessarily lead to a disadvantage. Zeyad and Almalki [21] point out that the increase in water volume will result to a more stable mix and hence better conditions necessary for design of self-compacting concrete maybe achieved.

The third possible explanation for the decrease in slump flow with increase in volcanic tuff percentage replacement is the particle shape of volcanic tuff which were more angular and flakier shaped as opposed to river sand that were more round-shaped. The angularity and flaky shape of the volcanic tuff may increase friction due to increased particle interlock between the protruding ends of volcanic tuff, this greatly reduces flow ability of SCC leading to decrease in slump flow. Similar observations were made in research done by [22], the researchers found out that increase in angularity and flakiness of aggregates greatly contributed towards the decrease of concrete workability, since the increased angularity increases specific surface area of concrete due to the irregular shape, this in turn increases particle interlocking effect and friction between aggregates, this greatly reduces the flow ability of the concrete.

Figure 3, shows the average flow diameter of SCC decreases linearly (R^2 = 0.991202) with increase in volcanic tuff percentage. These findings are a true reflection of how volcanic tuff affects the yield stress and plastic viscosity of SCC. Holding other constituents of SCC constant and varying the volcanic tuff percentage from 0% to 10% correspondingly increases the yield stress and plastic viscosity of the SCC, this results in a linear decrease in average slump flow diameters. These findings are in line with studies conducted by [23], they observed that volcanic tuff when used as fine aggregate gradually reduces the flow of concrete and a linear relationship can be deduced.

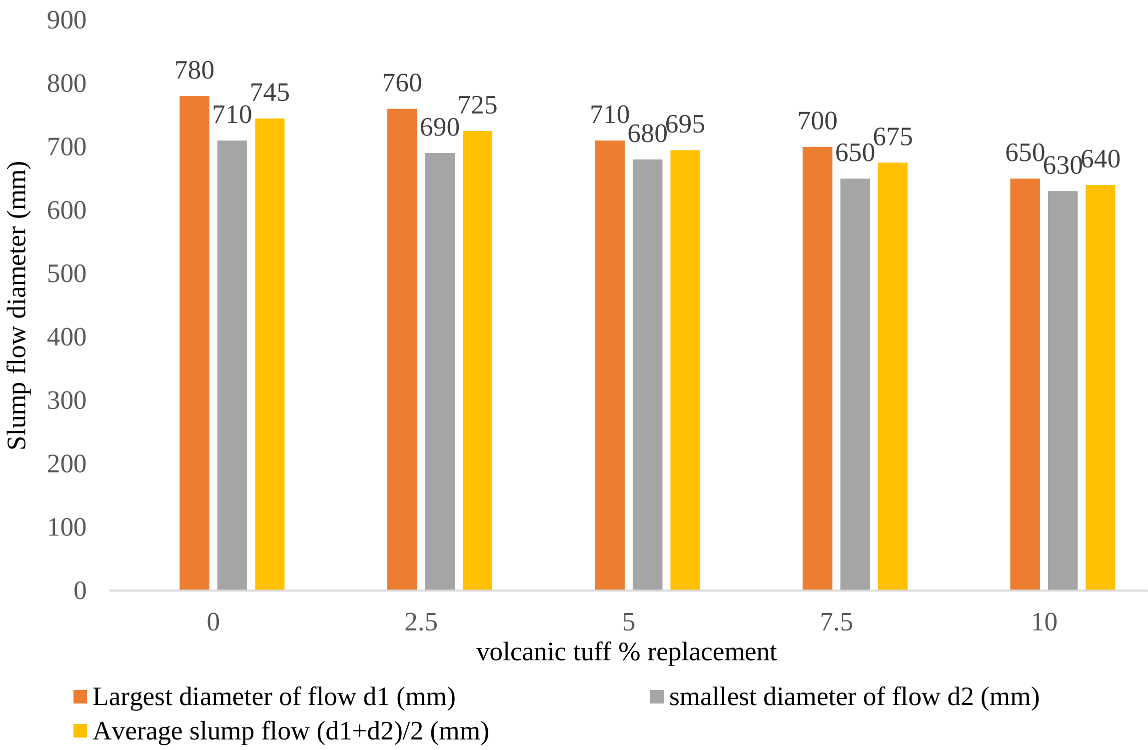

Figure 2. Slump flow test results

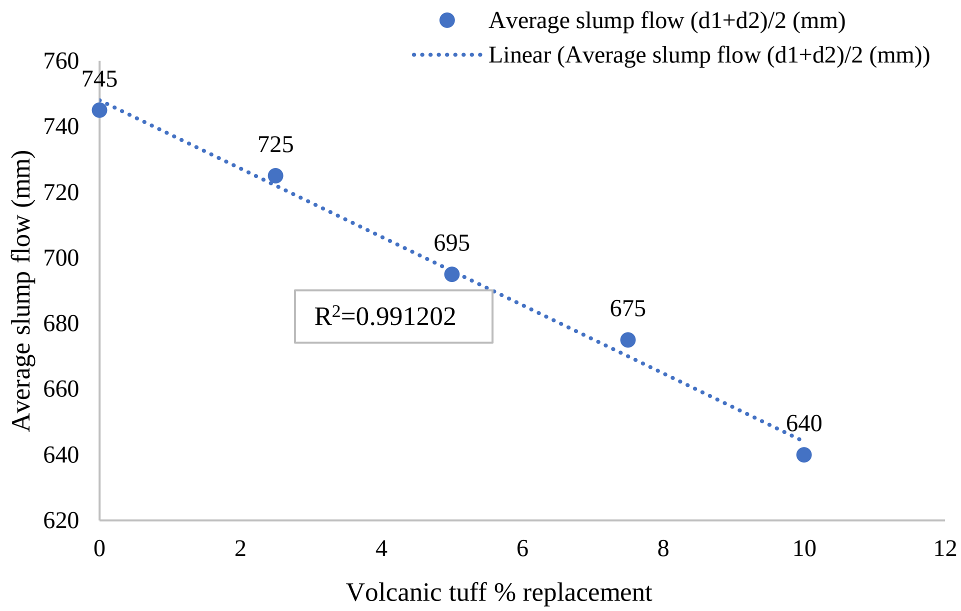

Figure 3. Linear plot of average slump flow

3.2.2 T500 results

From the results in Figure 4 below, T500 flow times increased with increase in Kenyan, Kitengela volcanic tuff percentage replacement. Increasing volcanic tuff percentage decreased the flow ability of SCC, thus the slowest T500 flow time of 5.25 seconds was recorded at 10% replacement and the fastest flow time of 2.25 seconds was recorded at 0% replacement. The T500 test was carried out simultaneously with the slump cone test, with the T500 test measuring the time it takes for the SCC to reach the 500mm-diameter mark on the slump plate. The increase in T500 time with increase in volcanic tuff percentage can be attributed to the increased water absorption of volcanic tuff reducing water available for lubrication of the SCC mix, this increased the yield stress of the SCC mix making it harder for it to flow. These finding are in line with studies done by [24], they made similar observations that volcanic tuff when used as an aggregate in self-compacting concrete affects the workability of concrete as it absorbs high amount of mix water due to its porous nature reducing the amount of free water in the concrete mix that could be used to lubricate the concrete. Similar observations were made by [25] in their study, they investigated the effects of volcanic tuff on the workability of cement mortar, and observed that volcanic tuff while it enhanced properties of fresh concrete, it considerably reduced the workability of the mortar due to its high-water absorption. Zeyad and Almalki [21] made similar observations that workability of self-compacting concrete is greatly affected by water, hence decrease in water for lubrication greatly decreases the workability of SCC. At 0% replacement the SCC mix had no volcanic tuff hence less water was absorbed by the aggregates as river sand absorbs less water than volcanic tuff leaving more water for lubrication of the SCC mix resulting in shortest time for the SCC mix to reach the 500-diameter mark. As the percentage of the volcanic tuff increased to 2.5%, 5%, 7.5% and 10% the content of volcanic tuff increased and so did the water absorption rate hence the water available for lubricating the SCC mix kept decreasing with subsequent increase in volcanic tuff percentage replacement causing the SCC mix to be less fluid and increasing the time needed to reach the 500-diameter mark. The slowest T500 time 5.25 seconds was recorded at 10% replacement since at this percentage the content of volcanic tuff was at its highest and most water was absorbed. These findings are a clear indicator that volcanic tuff may not be a suitable for higher percentage replacements greater than 10% since the water absorption maybe too much and negatively impact the workability of the SCC.

The particles shape of volcanic tuff could also be slowing down the flow of the SCC mix with higher percentages of volcanic tuff since it has more angular and irregular particles than river sand which are more rounded. The angular shape of volcanic tuff increases particle interlocks and friction within the SCC hence increasing the flow time to reach the 500mm-diameter mark. These findings concur with studies done by [26], they observed that particle shape of aggregates greatly affect fresh properties of the concrete mix, as angular and irregular particles increase friction and particle interlocks increasing flow time.

In order to validate the effects of volcanic tuff on filling ability, regression analysis was conducted on data for filling ability (V-funnel flow times) and percentage replacement, the root square value correlation between the flowing ability and percentage replacement of R^2 = 0.990468 shows a linear correlation between percentage replacement of natural river sand with volcanic tuff aggregates and V-funnel flow times as shown in Figure 5. The linear relation depicts a steady increase in flow times with the increase in volcanic tuff percentage replacement. A clear testament how percentage of volcanic tuff affects flow ability of the SCC mix.

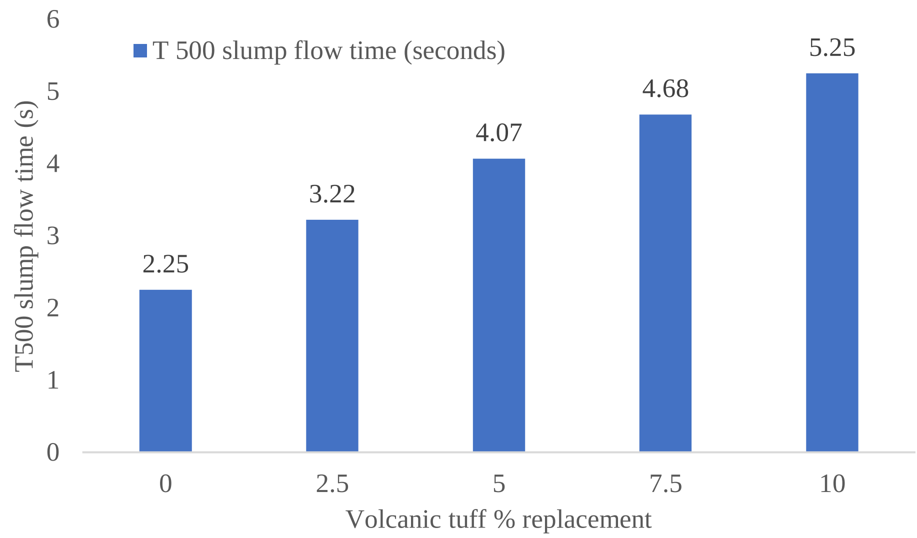

Figure 4. T500 test results

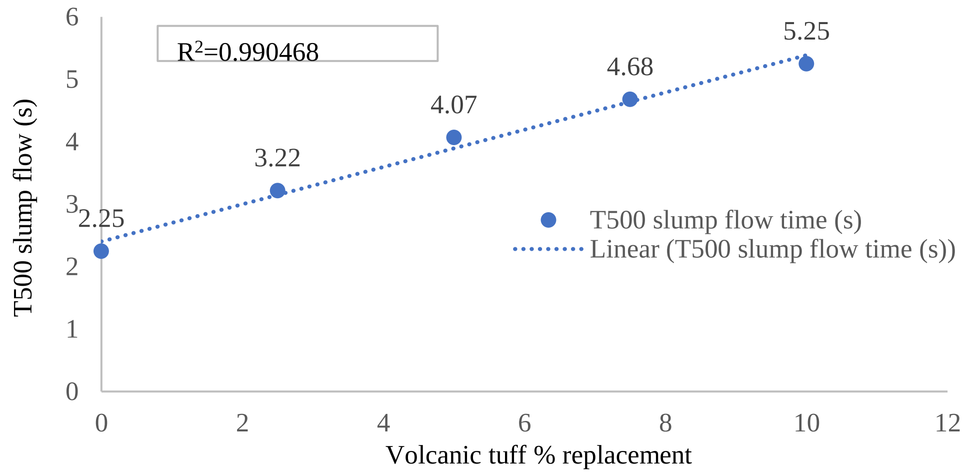

Figure 5. Linear plot of T500 results

3.3 Passing ability

J-ring and L-box tests were used to measure the passing ability of the SCC mixes. The aim of determining the passing ability of SCC is to ensure that the resulting concrete mix is able to pass through narrow gaps of reinforcing bars in structures.

3.3.1 J-ring

J-ring test results are shown in Figure 6 below. The passing ability was computed using the formula below:

$$\text{J -ring flow} = \frac{d1+d2}{2} \quad (1)$$

Where: d1 = the largest diameter of the circular spread of SCC, d2 = the diameter perpendicular to the largest diameter (d1)

Passing ability= No-J-ring/slump flow - J-ring flow (2)

The passing ability results obtained are in compliance with the acceptable criteria for self-compacting concrete and criteria for viscosity for SCC as outlined in BS-EN 206-9(2010). The results also comply with the requirement of the difference between the no J-ring and J-ring being less or equal to 5cm. Sample 5 with 10% volcanic tuff percentage had the lowest passing ability of 5.83. Sample 1 with 0% volcanic tuff percentage had the highest passing ability of 9.67. There is a general decrease in passing ability with increase in volcanic tuff percentage from 0% to 10%. This can be attributed to the particles shape of volcanic tuff which are angular and irregularly shaped compared to rounded sand particles. The angularity of volcanic tuff greatly increased internal friction within the SCC mix thus affecting its passing ability through the narrow gaps between bars of the J-ring apparatus. The angular shape of volcanic tuff also increases particle interlocks within volcanic tuff thus interfering with its passing ability around obstacles as particle interlocks increase blockages with obstacles like bars of the J-ring apparatus. These findings are in line with [27] they found a clear relationship between particle shape of aggregates and passing ability of SCC mix. In their study they established that mixes that had higher contents of volcanic tuff experienced reduced workability as a result of increased friction and particle interlocks within the SCC mix due to the irregular shape of volcanic tuff.

Another possible explanation for the decrease in passing ability with increase in volcanic tuff replacement can be attributed to the high-water absorption of volcanic tuff due to its high porosity and large surface area which reduces the water available for the lubrication of the SCC mix. This considerably increases friction between the SCC mix and with J-ring bars significantly slowing down the rate at which the SCC mix passes the narrow gaps between J-ring apparatus. Al-Swaidani et al. [18] made similar observations in their study. They observed that volcanic tuff reduced the passing ability of concrete due to its high porosity that causes it to absorb water that could be used for lubrication of the concrete mix, this reduces the fluidity of the concrete affecting its passing ability. At 0% replacement there is no volcanic tuff in the SCC mix hence no angular shaped particles to interlock, this leads to high passing ability. As the percentage of volcanic tuff increased to 2.5%, 5% 7.5% to 10% the volume of volcanic tuff in the SCC also increased, this increased the angular shaped particles in the SCC mix resulting in more particle interlocks and friction which significantly slowed the passing ability of the SCC as the interlocked particles increased blockage with the J -ring bars slowing down their motion as they collided with the bars. This clearly explains why there is a decrease in passing ability with increase in volcanic tuff replacement with 10% replacement recording the least passing ability of 5.83mm.

Regression analysis of passing ability against volcanic tuff percentage replacement gave the value of R^2=0.986792 as shown in Figure 7. The R^2 value shows an infinitesimally marginal deviation from the target value of 1.0. The correlation from the regression analysis shows a linear agreement between the passing ability with the percentage of volcanic tuff aggregate in SCC mixes. Tayeh et al. [28] made the same findings, they deduced a linear relation between increase in pozzolanic material in concrete and steady decline in its passing ability.

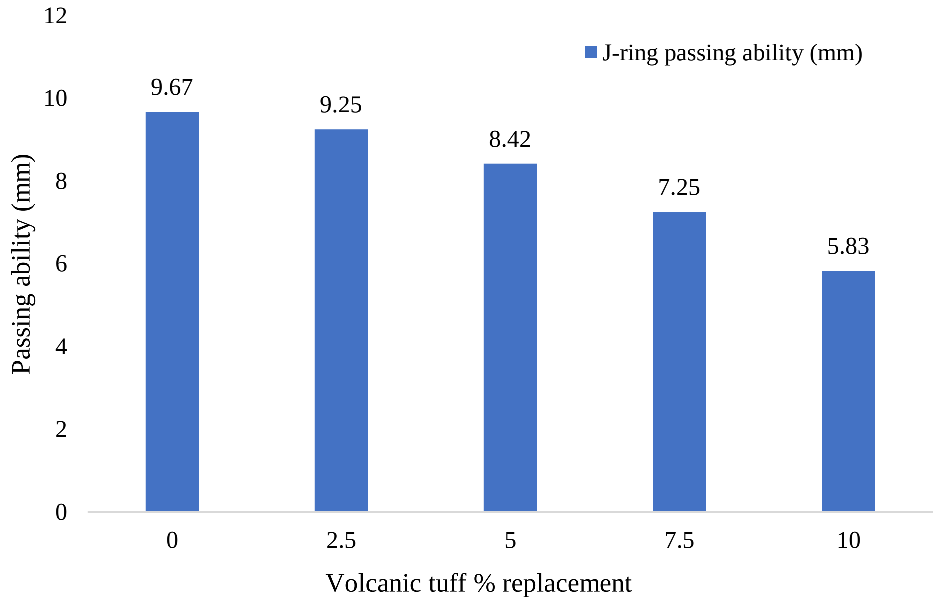

Figure 6. J-ring test passing ability results

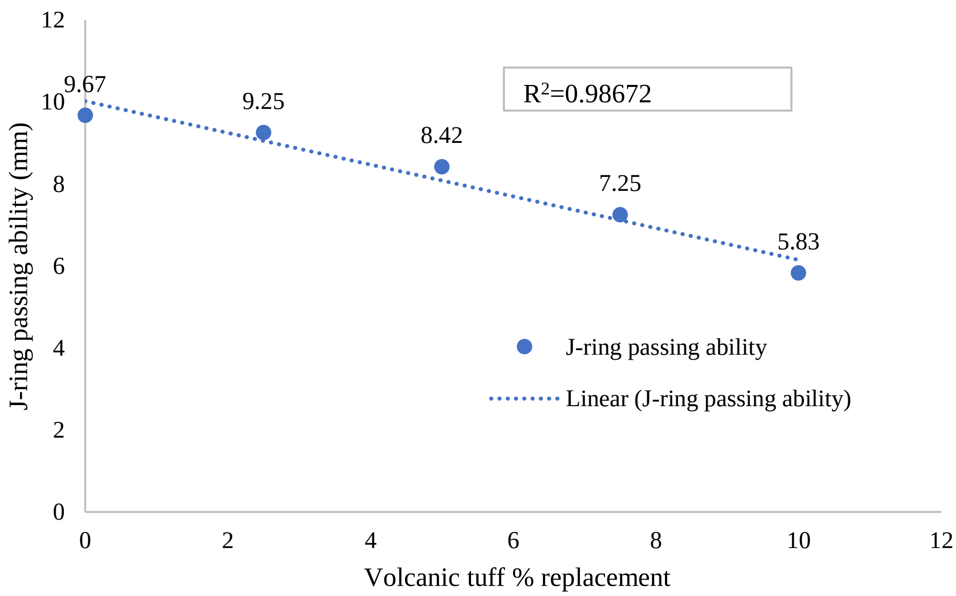

Figure 7. Linear plot of J-ring passing ability

3.3.2 L-box

L-box results are presented in Figure 8 below, from the results, there is noticeable decrease in passing ability with increase in volcanic tuff percentage replacement. At 0% percent replacement, the passing ability (H2/H1) was found to be 0.96. At 10% replacement, the passing ability is 0.68 this value is slightly below the accepted criterion of 0.8 to 1.0, marking a noticeable decrease in the passing ability as the percentage of volcanic tuff aggregates increased. L-box test is used to evaluate the flow properties and the passing ability when the SCC mix is confined by formwork hence forced to flow around reinforcing steel. The decrease in passing ability H2/H1 ratio with increase in volcanic tuff dosage can be attributed to the decrease in the hydration process as a result of volcanic tuff absorbing most water. The high-water absorption by volcanic tuff reduces the chemical water available for the hydration process these results in formation of less cementitious particles that are necessary for binding the SCC mix together to form a uniform mix. This in turn reduces the passing ability as the resulting SCC mix lacks the uniformity to smoothly flow around confinements. Kaleem et al. [29] observed that natural pozzolana significantly reduced the fluidity of SCC due to its high-water absorption leaving little water for hydration hence resulting in a non-uniform SCC mix that is unable to smoothly flow around confinements.

The L-box test measures passing ability through confinements; hence aggregates particles shapes and sizes play a significant role. Volcanic tuff being more irregular and angular shaped is likely to cause blockage due to particle interlocks and friction as the SCC mix passes through the confinement of the L-box this will significantly slow down the passing ability as opposed to the control mix with 0% replacement that has rounded sand particles which are unlikely to experience blockage as they flow to through the L-box confinements. These findings are in agreement with research work by [30], they found out that the irregular shape of natural pozzolana greatly influenced the passing ability of SCC through confinements due to blockages caused by the angular particles interlocking with each other. There's a general decrease in passing ability from 0%, 2.5% 5%, 7.5% to 10% replacement. For 0% the passing ability is 9.67 and reduces steadily to 5.83 for 10% replacement, this is brought about by the combination of high-water absorption of volcanic tuff and its irregular shape. For passing ability, the shape of volcanic tuff is more significant, as the content of volcanic tuff increases the irregular, angular shaped particles of volcanic tuff interlock more greatly increasing in the SCC mix causing blockage within the SCC.

Figure 9 below presents regression analysis conducted on the data for passing ability and $R^2 = 0.9242$ was obtained. The R-square value is closer to 1.0 showing a linear correlation between the volcanic tuff percentage replacement and passing ability of the SCC mixes. Hossain et al. [31] found a similar linear relationship between percentage volcanic tuff replacement and decrease in percentage ability of concrete mix. They observed that volcanic tuff increased friction within the SCC mix significantly reducing its passing ability and a linear relationship between the two variables can be deduced.

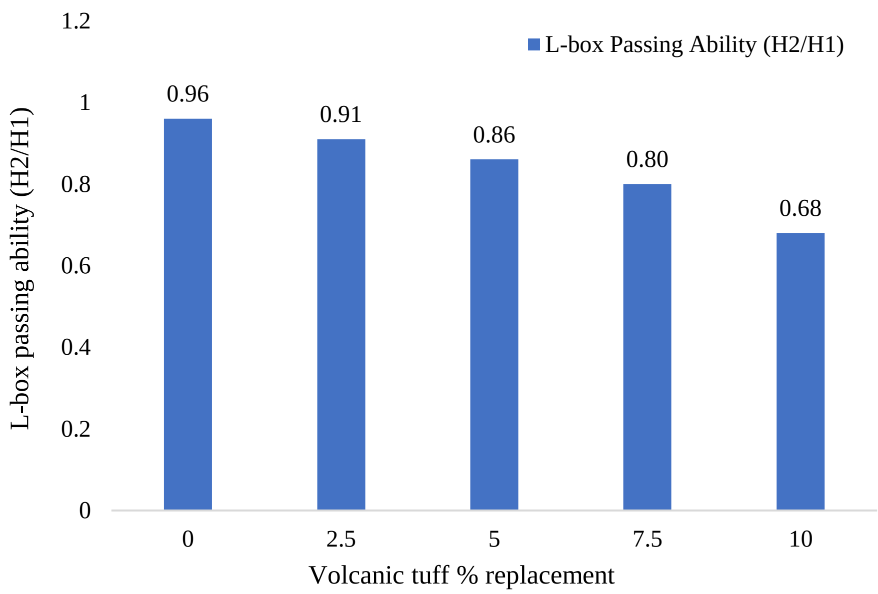

Figure 8. L-box data results

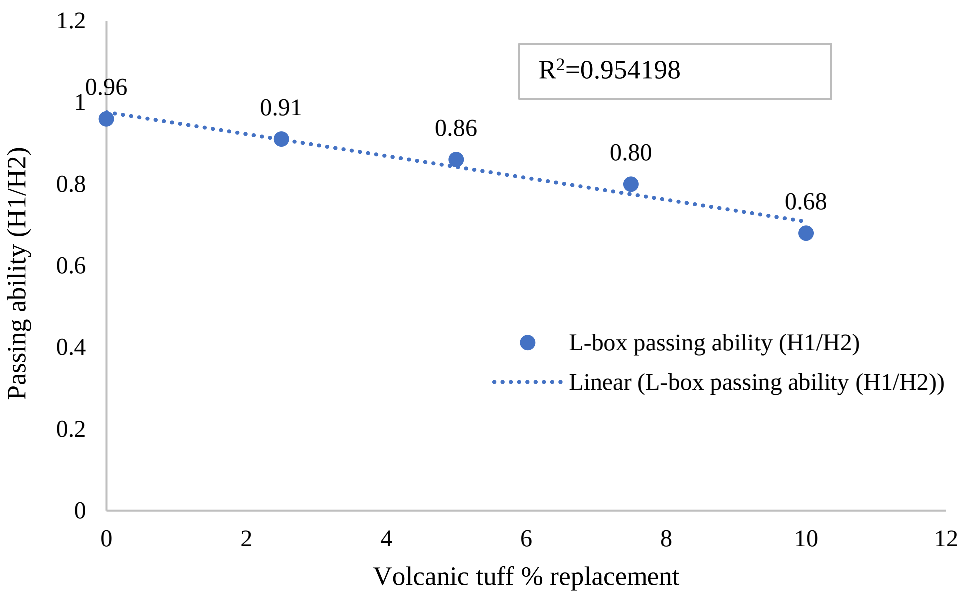

Figure 9. Linear plot L-box passing ability

3.4 Segregation resistance

3.4.1 V-funnel data analysis

From the results in Figure 10 below there is an increase in flow times as volcanic tuff percentage replacement increases. SCC containing higher percentages of volcanic tuff shows reduced passing ability hence longer flow time. Mix 1 with 0% volcanic tuff has considerably shorter flow time of 7.05 seconds and mix 5 with 10% volcanic tuff has the longest flow time of 11.13 seconds. The increase in flow time with increase in volcanic tuff percentage replacement can be attributed to the high specific surface area and internal porosity of volcanic tuff which significantly increases the plastic viscosity, apparent viscosity and the yield stress of the SCC mix hence slowing down SCC as it moves through the V-funnel. Kaleem et al. [29] found out that volcanic tuff has large amounts of micropores giving it large surface area that increases the viscosity of fresh concrete, which significantly reduced its workability but improved its pumpability. At 0% replacement SCC has no volcanic tuff hence has the least viscosity and yield stress, but as the percentage of volcanic tuff increases to 2.5%, 5%, 7.5% and 10% the content of volcanic tuff also increases in the SCC increasing the surface area and porosity, which in turn increase the viscosity and yield stress of the SCC resulting to increase in flow time. V-funnel flow time depicts the viscosity of the concrete mix, implying that viscosity increases with increase in the V-funnel flow time. While V-funnel flow time can be used to estimate the apparent viscosity of the SCC mixture, there are several factors that influence the results of the V-funnel test, like the amount, shape and size distribution of the aggregates, another factor is the viscosity and the amount of paste. Hence in most cases the V-funnel may not necessarily correspond with the viscosity of the concrete mix. Studies by [32] point out that apart from the high surface area and internal porosity of volcanic tuff being the main reason for increase in yield stress and plastic viscosity of the SCC mix, other factors like increased interaction between fine particles can also lead to increase in yield stress and viscosity. This implies that higher amounts of superplasticizer may be needed to reduce both the yield stress and plastic viscosity for SCC mixes containing higher percentages of volcanic tuff.

From Figure 11, regression analysis on the data gives $R^2 = 0.999565$ which is approximately equal to 1. The positive correlation from the regression analysis shows a linear agreement between the average V-funnel flow times and the percentage replacement of volcanic tuff aggregates.

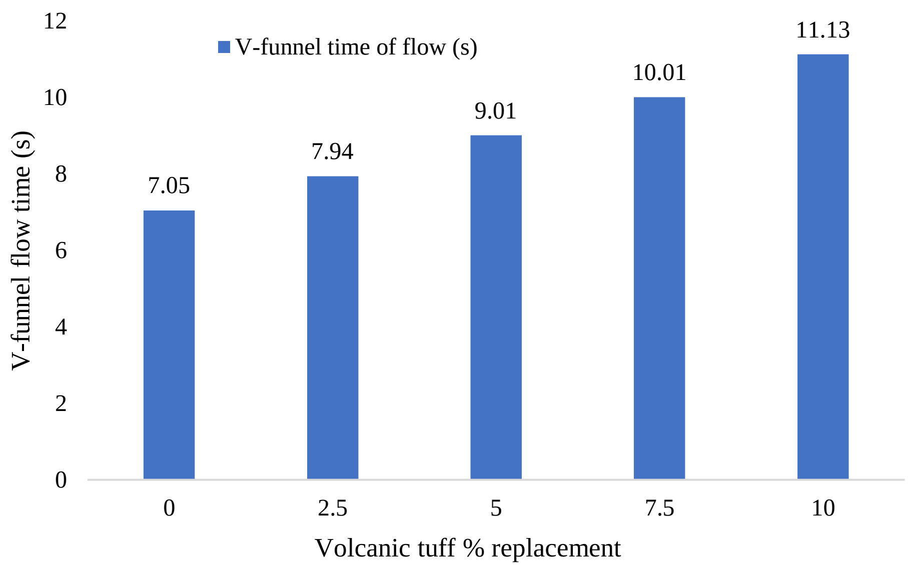

Figure 10. V-funnel test results

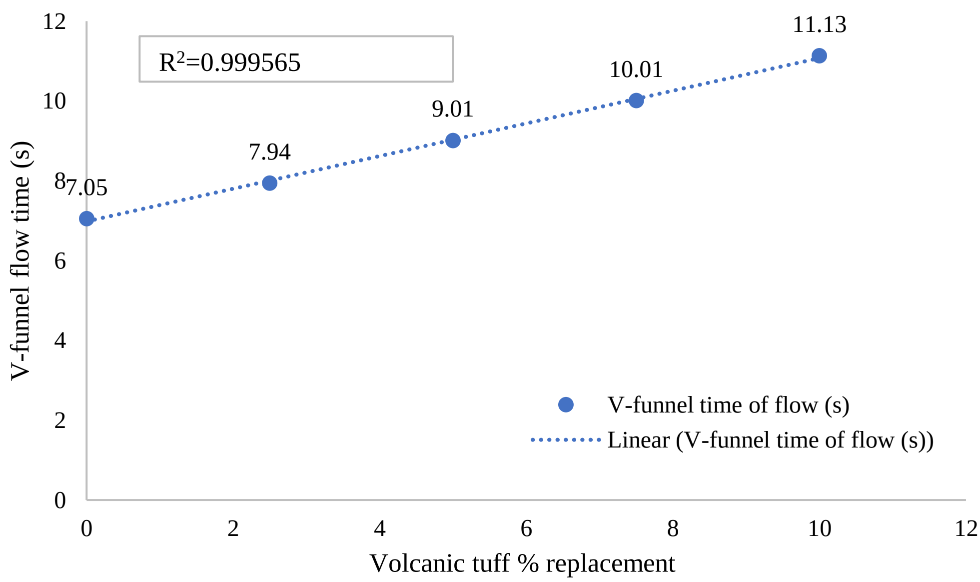

Figure 11. Linear plot V-funnel flow time

3.5 Hardened properties of SCC

3.5.1 Compressive strength test results

Results of compressive strength are shown in Figure 12 below, from the results it can be seen that increase in Kenyan, Kitengela volcanic tuff percentage replacement leads to decrease in compressive strength of SCC mixes. Highest values of compressive strength were obtained at 0% volcanic tuff replacement and there is noticeable decrease in compressive strength with increase in volcanic tuff percentage with 10% volcanic tuff recording the lowest values of compressive strength.

The noticeable decrease in compressive strength of the SCC with increase in volcanic tuff percentage replacement can be attributed to the flaky shape of volcanic tuff particles which led to development of weaker bonds between fine aggregates and cement paste. Bond strength in concrete depends on the strength of the mix and the surface characteristics of aggregates more so for fine aggregates where the surface texture plays an important role as it affects bonding with cement. Since volcanic tuff has a substantial amount of flaky shaped particles, this influences the bond between aggregates and cement paste, leading to a negative effect on the strength of the self-compacting concrete matrix. Aggregates that have flaky-shaped particles have a tendency to orient in one plane thus allowing air voids and bleeding water to form underneath. This adversely affects the compressive strength development of SCC as well as its durability. These findings are in line with studies done by [17], they observed that volcanic tuff particles have a higher flakiness index which negatively affected the compressive strength of concrete as flaky particles formed weaker bonds with cementitious fraction of cement.

Another possible explanation for the decrease in compressive strength with increase in volcanic tuff percentage can be attributed to the porous nature of volcanic tuff which causes it to absorb more water compared to river sand, volcanic tuff also has a high surface area compared to river sand increasing its water demand, this leaves little water for the hydration process, this results in decreased bonding between cement paste and aggregates leading to decrease in compressive strength of the concrete mix. Omrane and Rabehi [10] made similar observation in their study. They established that addition of volcanic tuff to SCC significantly reduced the compressive strength of SCC mix as volcanic tuff absorbed much water that would have been used in the hydration process hence the resulting to concrete with less compressive strength as the hydration process is responsible for bonding of concrete and its strength development. Water is available in concrete in three different forms, namely chemically bonded water, physically bonded water and free water. It is the chemically bonded water that is utilized in the hydration process, this is the same water that volcanic tuff absorbs due to its high porosity and high surface area hence reducing water available for the hydration process. As the percentage of volcanic tuff replacement increased from 0%, 2.5%, 5% 7.5% to 10% so did the content of volcanic tuff in the SCC mix, the more the volcanic tuff in the SCC mix the more the water absorption rate and the higher the flakiness index of the SCC mixes this clearly explains why there is steady decline in compressive strength with increase in volcanic tuff replacement. The high-water demand by volcanic tuff can affect the workability of the self-compacting concrete mix, this makes it harder for the SCC to achieve proper consolidation and compaction. As a result, measures should be taken like optimizing the mix design and incorporating chemical admixtures in order achieve the desired workability and to reduce the water content in the SCC mix.

From figure 13, the regression analysis value was obtained as $R^2 = 0.993296$. This clearly shows there is a linear relationship between the percentage of volcanic tuff replacement and the decrease in compressive strength of SCC mixes. Castañeda et al. [16] made similar findings in their study. They found out that the percentage of volcanic tuff replacement was inversely proportional to the compressive strength of SCC resulting mainly from the weak bonds volcanic tuff develops with cement paste in the SCC mix and a linear relationship between percentage of volcanic tuff and compressive strength of concrete could be established.

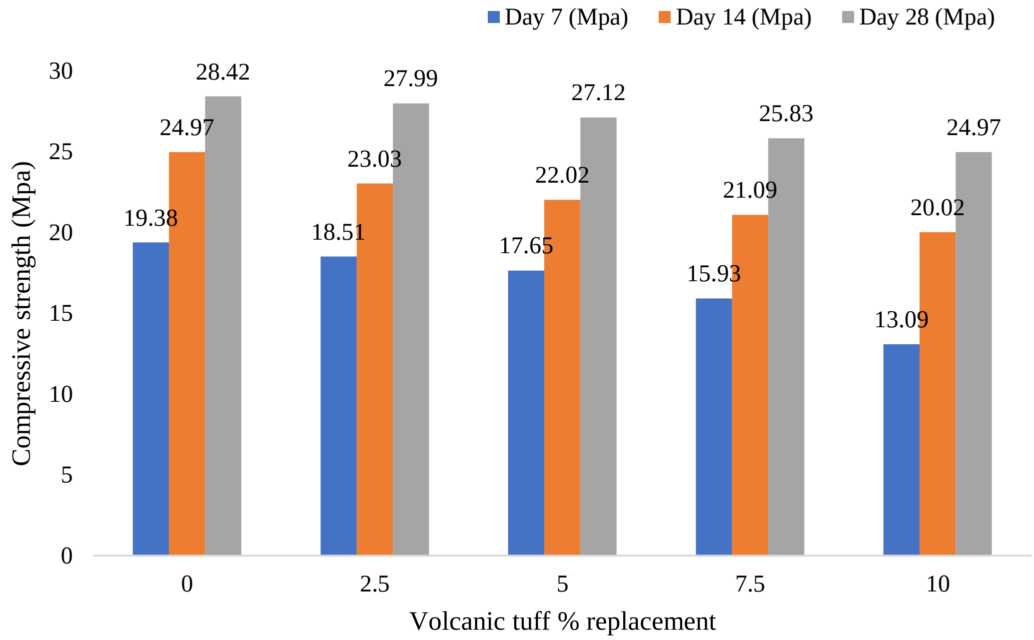

Figure 12. Compressive strength test results

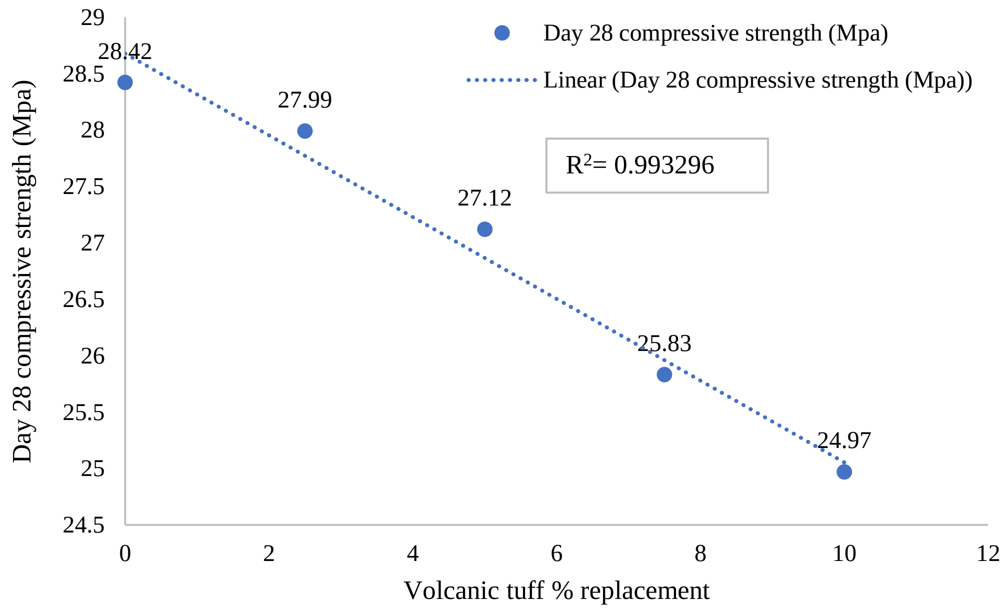

Figure 13. Linear plot compressive strength

3.5.2 Tensile strength results analysis

Figure 14 below shows tensile strength at each volcanic tuff percentage replacement. From the results, there is a fair relation between increase in volcanic tuff percentage replacement and decrease in tensile strength of SCC mixes. Highest values of tensile strength were obtained at 0% volcanic replacement and there is noticeable decrease in tensile strength with increase in volcanic tuff replacement with 10% volcanic tuff percentage recording the lowest values of tensile strength.

The decrease in tensile strength with increase in volcanic tuff percentage can be attributed to the presence of more interconnected pores in volcanic tuff as it is more porous than river sand. These pores act as weak spots for the initiation of cracks within concrete containing higher percentages of volcanic tuff. The development of cracks within the SCC allows for more ingress of water into the concrete mix, excess water interferes with hydration process of concrete thus leading to concrete with lower tensile strength. These findings are in agreement with studies conducted by [21], they observed that there was an inverse relationship between percentage of volcanic tuff in SCC mix and its tensile strength. They attributed this to volcanic tuff being more porous allowing in more water which interferes with the hydration process. Leading to reduction in the tensile strength of concrete.

Secondly, the decrease in tensile strength with increase in volcanic tuff percentage could be attributed to volcanic tuff being more porous and less rigid this results in formation of weak bonds between aggregates and mortar fraction of concrete. The weaker bonding between mortar and aggregates results in concrete with lower tensile strength. Volcanic tuff being more porous than river sand absorbs more water, this free water decreases viscous friction in turn reducing the strength of porous material. Since volcanic tuff has more pre-existing cracks compared to river sand, the absorbed water may act as a lubricant between cracks, this greatly reduces friction between cracks further extending the tensile cracks through inner sliding of particles leading to the SCC mix developing lower tensile strength.

Volcanic tuff with high content of pozzolanic material will exhibit pozzolanic properties, this causes it to react with calcium hydroxide usually (a byproduct of cement hydration) leading to the formation of cementitious materials like calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), these materials contribute to the strength and durability of concrete. Pozzolanic reactivity of volcanic tuff is determined by various factors like the chemical composition of the tuff, amorphous content, as well as the reactive surface area of the volcanic tuff. Chemical composition of the volcanic tuff could vary greatly depending on the volcano the tuff emanated from. Some tuffs contain high percentages of reactive silica, this increases the pozzolanic reactivity of volcanic tuff which may improve the strength development of concrete. However, volcanic tuff with very high levels of alkalis or sulfates could negatively affect the properties of concrete as it may lead to alkali-silica reactions, sulfate attack or both. This alkali-silica reactions forms sodium silicate gel, which can expand as it absorbs water causing cracking as well as spalling of concrete [28]. This contributes to concrete developing lower tensile strength.

Figure 15 shows the regression analysis of tensile strength data, R^2= 0.950256 clearly depicting a linear correlation between split tensile strength and volcanic tuff percentage replacement. It is evident that volcanic tuff presence in concrete has a significant impact on its mechanical properties. The effect of volcanic tuff on the mechanical properties of self-compacting concrete are mainly attributed to the physical and chemical characteristics of volcanic tuff as well as the interaction between the volcanic tuff and the cementitious material in the SCC mix. Volcanic tuff usually consists of fine particles with irregular shapes. These particles can fill voids between coarse aggregates resulting to a denser concrete mix [33]. This increased particle packing may improve the mechanical properties of concrete and its durability holding other factors constant.

In summary, volcanic may have appositive or negative effect on the mechanical properties of SCC depending on various factors of the volcanic tuff like chemical composition, particle size, pozzolanic activity and workability considerations.

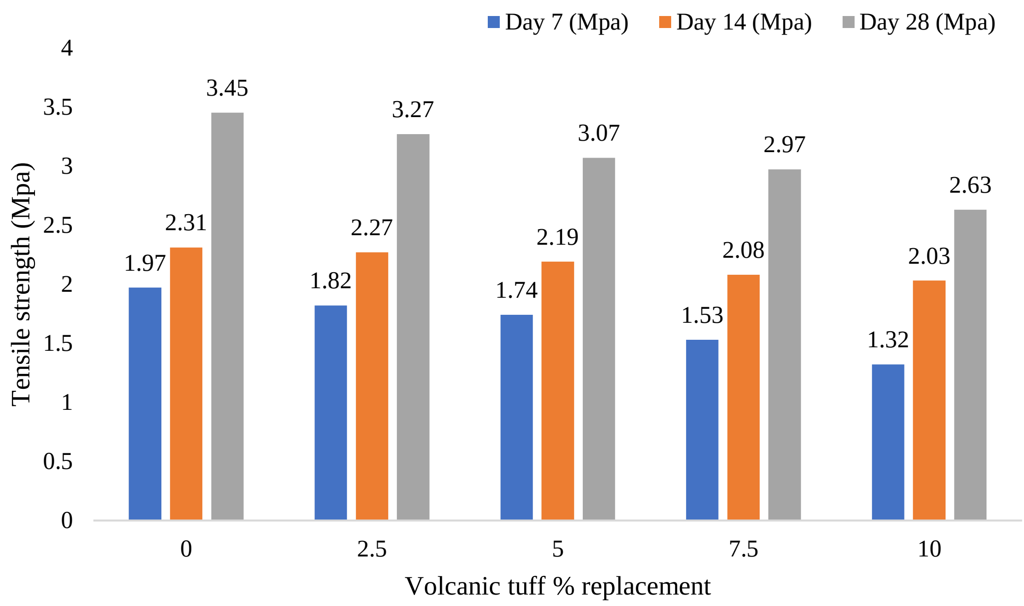

Figure 14. Tensile strength test results

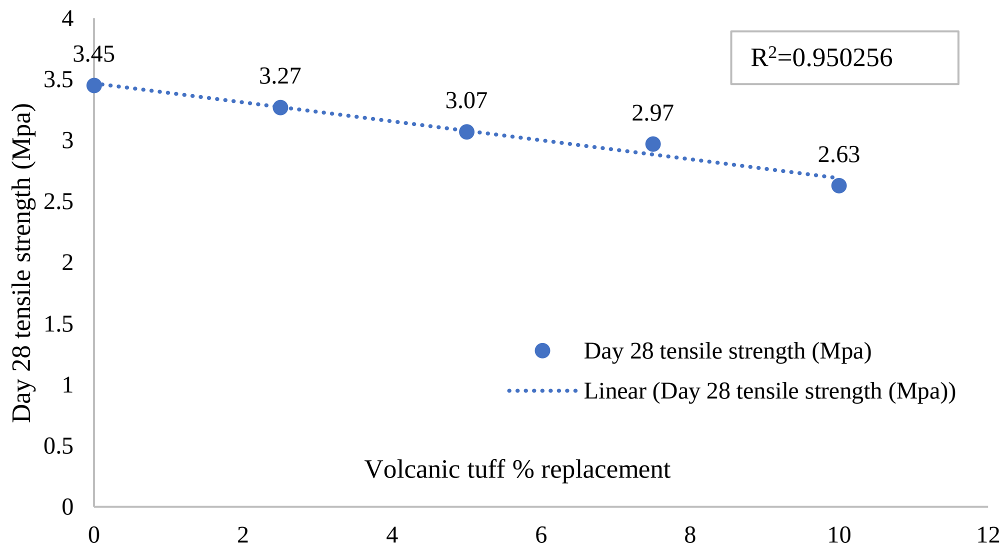

Figure 15. Linear plot tensile strength

4. Conclusions

This research has clearly demonstrated the effects of using volcanic tuff on the rheological and mechanical properties of self-compacting concrete, the following conclusions were established from the study**:**

- Volcanic tuff decreased the filling ability of self-compacting concrete, increase in volcanic tuff percentage led to decrease in the filling ability of SCC.
- Volcanic tuff decreased the passing ability of SCC as shown by the passing ability tests, increase in volcanic tuff percentage led to decrease in the passing ability.
- 10% partial replacement of river sand with volcanic tuff had the lowest flow of SCC.
- Volcanic tuff decreased the compressive strength of SCC. Increase in volcanic tuff percentage led to decrease in compressive strength of SCC.

- Volcanic tuff decreased the tensile strength of SCC. Increase in volcanic tuff percentage led to decrease in tensile strength of SCC.
- Volcanic tuff may not be a suitable replacement of river sand in SCC for higher percentage replacement greater than 10%.

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