Cyclic Effects on Low-Cost Grades Stabilized with CaO and Class 'F' Fly Ash

Emmanuel Emem-Obong Agbenyeku, Edison Muzenda, and Innocent Mandla Msibi

***Abstract*—In the current global trend for greener engineering practices, a number of environmentally friendly, sustainable and lean engineering approaches are constantly initiated. Among which is the identification, transformation and utilization of available waste for environmental, economic and social benefits. Soil stabilization is often required in engineering and research on the effective use of wastes as chemical and cement blenders/stabilizers are increasingly channeled in these directions. Recycling has become the first best option of dealing with waste before landfilling is considered in cases of handling difficulties. In South Africa, 41,000 tons of solid waste is destined for landfills daily which does not include the huge amounts of ash waste from power plants dumped in ash dams. This paper describes the use of commercially available Lime (L) and Fly ash (FA) in stabilizing Berea Soil (BS). Series of tests to study the strength properties of stabilized BS grade under cyclic effects common to tropical and sub-tropical regions were conducted and certain indicators were used to track the degradation pattern of the stabilized product. Batches of BS mixed with 6 and 9 % L stabilizers and 0, 6, 12 and 18 % FA additives were compacted and hydrated for 7 days at relative humidity (RH) of 95-100 % and temperature (T) of 22-25 ^{o}C. The specimens were immersed in distilled water for 12 hours and dried at 40 °C for 36 hours to depict a complete single wet-dry cycle. 4, 6 and 10 cycles were initiated herein. After designated cycles, masses of the specimens were measured prior testing for Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR) and Liquid Limit (LL). L-FA stabilized BS resulted in significant improvement in strength and bearing properties. CBR of the stabilized mixes increased with increased L-FA content and decreased with increased cycles. In the long run defined by 10 cycles only the 6 % L + 12 % FA mix had adequate strength under the operative drainage conditions capable of sustaining stresses from low traffic loadings and may only be suitable for re-compacted grades of low-cost rural road projects. LL was found as the best indicator for the degradation pattern having the highest determinant coefficient (R^2 = 98.6 %) in correlation with other indicators.

***Keywords*—Fly ash, Lime, Berea sand, Stabilizers, Degradation

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I. INTRODUCTION

CHALCEDONIC and opaline silica are non-crystalline or poorly crystalline forms of silica found in flints, sandstones and dolomites. These are reactive aggregates that cause alkaline silica reaction (ASR) expansion. Low alkaline chemical/cement used to prevent ASR often contains FA and ground granulated blast furnace slag (GGBFS). Class-F and class-C FA are effective in preventing ASR when used in large quantities. The benefits of industrial wastes such as; GGBFS, FA, and silica fume (SF) in stabilizing soil have been fairly well recorded by [1, 2, 3, 4]. South Africa's power stations dispose FA by either dry dumping or by hydraulic deposition into ash dams [5]. Successive chemical and mechanical tests on FA collected from one of the stations showed the presence of significant amounts of free lime, quartz, alumina and iron oxide. This indicated high likelihood of pozzolanic hardening of the ashes [6, 7] and are thus classified as class-C FA. On the other hand, most stations produce FA with low self-cementing potential and are classified as class-F FA [8]. Formation of BS as recorded by [9] is a result of underlying calcarenite leaching action. It is part of a recent formation of unconsolidated red dune ridges along most of the Indian Ocean coastal plain. Texturally, it is composed of iron oxide coated quartzite sand weakly bonded mainly by kaolin clay. BS is known to exhibit collapsible behaviors due to its natural delicate macro structure and profile heterogeneity. Embankment failures, moisture induced slope failures, pavements and buildings have failed from this soil as such [10, 11] considered this soil as one of the problem soils of Southern Africa whose engineering properties may benefit from appropriate stabilization technology. The abundance and accessibility of FA as residual waste in ash dams in South Africa paved way for its use with residual sands of Southern African semi-arid environments of seasonal rainfall intensity and sunshine. Excellent performance of base courses of collapsible Durban BS stabilized with L, Bitumen seals and Cement have been reported by [12, 13]. The northern region of Kwazulu Natal with annual rainfall of 900 mm and Weimert number of less than 2 is classified wet for pavement design purposes. There have been investigations by [12] detailing the failure of unpaved and graveled top municipal roads and settlement of old black tops in these regions. Whereas [13] investigated various low traffic volume surfaced road pavement carrying less than 400 vehicles per day. The road was constructed with L and Cement stabilized BS mixed with other aggregates and they recorded low relative maintenance cost and higher durability of the product. In addition, the beneficial effects of stabilizing residual tropical soils with Cement, Cement and FA, Hydrated Lime

(HL), L and Rice Husk Ash (RHA) are well documented. For some residual soils, it was observed that higher strength was developed by the L-RHA mixtures at all stages of the curing period than Cement-RHA mixtures. Stabilization of soils and their behaviour in harsh climatic conditions as well as their durability are a major concern in recent times [14, 15]. Herein however, the effect of FA blending of cement with L stabilizers in BS of the Durban bluff in Kwazulu Natal province under cyclic effect was investigated and certain indicators such as; LL, UCS, CBR, Cyclic effects, Residual mass and percentage FA replacements were used to monitor the degradation of the stabilized product.

II. Experimental Approach

A. Test Procedures

Batches of BS were thoroughly mixed with required amount of L, FA and water. Mixtures of 6 and 9 % L stabilizer and 0, 6, 12 and 18 % FA additives were used for the study. The chemical composition of the BS, L and FA were determined by X–ray diffraction analysis in accordance with the requirements of [16]. Table 1 shows the total (SiO_2+AL_2O_3+Fe_2O_3) constitution of the commercially available FA to be exceed 70 % which qualifies it an active pozzolana [8]. Given the low content of pozzolana in the L, the addition of FA is crucial to the BS-L pozzolanic reaction. Mechanical analysis was conducted on the BS and it was found to be uniformly graded. The grain size curve in conformance with [16] is shown in Figure 1.

TABLE I
CHEMICAL CONSTITUENTS OF BS, L AND FA

	SiO_2	AL_2O_3	Fe_2O_3	MnO	MgO	CaO
BS	62.7	19.5	13.6	0.11	0.30	0.83
L	0.19	0.27	1.13	1.65	93.9	0.00
FA	83.0	8.00	2.65	0.55	0.22	0.18
	Na_2O	K_2O	TiO_2	P_2O_5	Cr_2O_3	NiO
BS	0.32	0.85	1.7223	0.013	0.0615	0.0061
L	0.06	0.06	0.0021	0.020	0.0015	0.0000
FA	0.04	0.00	0.2600	0.400	0.0050	0.0000

The plasticity index of the BS was found to be within 6-8 %. Thoroughly mixed samples were left to equilibrate for 24 hours before compaction in order to properly blend. Maximum Dry Density (MDD) and Optimum Water Content (OMC) for each mix were determined according to the standard AASTHO compaction method [16]. Compacted specimens were cured for 7 days at RH of 95-100 % and T of 22-25 ^{o}C in a curing chamber before compression test was done. Permeable hessian bags were used to cover the samples and water was constantly sprinkled on the cover over the seven day period as specified in [16]. The specimens hydrated for 7 days were completely submerged in distilled water for 12 hours then dried at 40 °C for another 36 hours. These steps completed an entire single wet-dry cycle. The selected numbers of cycles used herein were; 4, 6 and 10 cycles of wetting and drying. After the designated cycles the mass of the specimens were measured before the UCS tests.

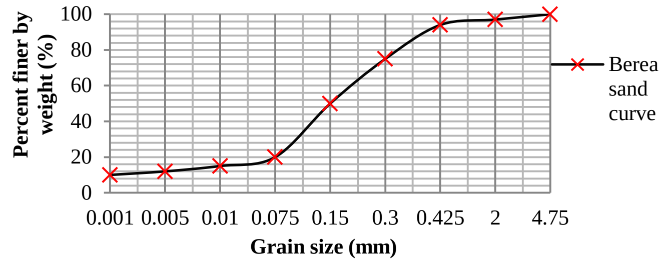

Fig. 1 Particle size curve for BS

The LL and CBR tests were also conducted. A 48 g of the thoroughly mixed soil fines in accordance with the prescribed standard method was weighed and placed in a porcelain dish in consonance with [16]. Distilled water was added, the material was stirred properly and then transferred to the casagrande device which operated at a speed resulting in two taps per/sec applied to the soil until about 10 mm contact was made between the two soil portions. CBR tests were conducted on soils stabilized with combinations of 6 and 9 % L and 12 % FA only. The samples were compacted at the respective OMC to 95 % of the associated Modified AASTHO MDD soaked for 7 days and then subjected to respective cycles. The physical and mechanical properties of the soil are shown in Table 2.

TABLE II
PHYSICAL AND MECHANICAL PROPERTIES OF BS

Specific Gravity	Atterberg Limit	ASSTHO Compaction
$D_{2.0}$ = 2.68	PI = 6 - 8%	MDD = 16.8Mg/m^3
$D_{0.075}$ = 2.71	SL = 2%	OMC = 10.20%

For the implementation of low-cost grades and low traffic road projects in developing countries, CBR of naturally occurring materials is the most commonly used design parameter. It remains a simple and direct parameter for the grade design and can also be correlated with other more complex mechanical pavement parameters. In conjunction with the UCS and other basic physical properties, it has formed the basis of the Catalogue method of Design specified in [17]. The CBR values were determined for all wet-dry cycles of both the 6 % and 9 % L with 12 % FA stabilized soil mixes in accordance with [16]. The soil mixes were compacted to 95 % modified AASTHO MDD and OMC and tested after the 7 days curing. This test was carried out on every compacted sample after been soaked for 7 days.

III. Discussion Of Findings

A. Curing and Cyclic Effects on UCS

In considering lean engineering, simple and low cost structures i.e., artificial embankments, small dams, levees, stabilized and earth retaining walls, the UCS test remains the standard and most common strength test used for estimating material strength. The results of specimens cured for 7 days and subjected to cyclic loads together with their respective determinant coefficients (R^2**)** are shown in Figures 2 and 3 for the 6 and 9 % L stabilizer respectively.

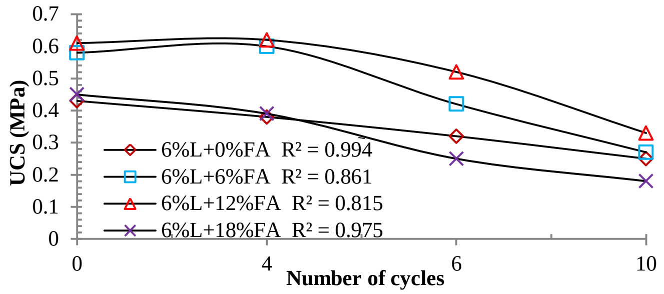

Fig. 2 Cyclic effects on UCS for 6 % L stabilized BS

Figures 2 and 3 also show the effects of FA additives on the strength of specimens subjected to 4, 6 and 10 cycles.

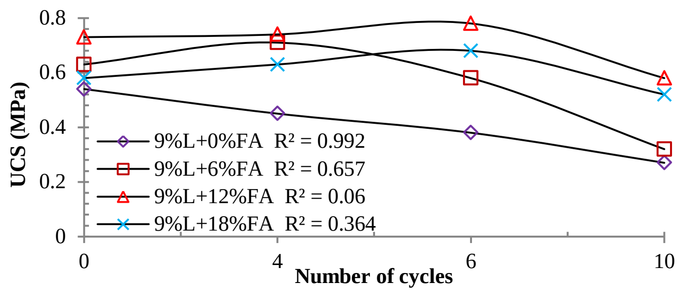

Fig. 3 Cyclic effects on UCS for 9 % L stabilized BS

The trends show an increment in strength development with the addition of FA until 12 % FA for the 6 cycle above which the strength begins to decrease. Generally, the addition of FA from 0 to 18% yielded a high R^2 value with the 12 % FA showing a strong correlation between UCS and the cycles to be as high as 81.5 % for the 6 % L stabilizer. In the case of the 9 % L mix there is a general increase in the R^2 values with the increase in FA up to 18 % although; the 12 % FA indicated a low R^2 value of 6 % between UCS and the cycles. The UCS results show that improvement in strength in the respective L stabilized soil can be enhanced by adding FA. The characteristic strength of the soil is improved by L stabilization whereas the gain in strength comes from the pozzolanic reaction between amorphous silica and or alumina from the soil and L which forms various types of binding agents. Hence, additional amounts of amorphous silica are made available to react with L when FA is added resulting in further increase in strength.

As recorded by [14] the decrease in strength after the optimum is reached as shown in Figures 2 and 3 occurred due to the introduction of excess amount of FA having relatively lower specific gravity to react with the available L. It is observed that the 9 % L mix showed improved strength until 10 cycles above which a reduced strength for consequent cycles occurred. In the case of the 6 % L mix, an increase in strength is also observed and a subsequent reduction right before and at 10 cycles. Consequently, the number of cycles at which the peak is reached depends on the percentage L in the mix. For the 9 % L, the peak is reached at 6 cycles. This may be due to the development of a significant percentage of maximum strength during the curing stage due to the availability of sufficient quantity of L for the completion of the pozzolanic reaction, while the 6 % L stabilizer had a slight reduction in strength at 6 cycles up to 10 cycles. This reduction may be due to the deterioration caused by the cyclic impact.

B. Effect of Waste FA on UCS for the Various Cycles

The UCS results in Figures 2 and 3 are further illustrated in Figures 4 to 6; showing that improvement in strength in the respective L stabilized soil can be enhanced by the addition of FA. It is seen in Figures 4 and 5 that the general trend is a notable increase in strength with the addition of FA until an optimum of 12 % for both the 6 % and 9 % L mixes above which the strength begins to decrease. Therefore, the changes in strength recorded in Figures 2 and 3 came from the additional amounts of amorphous silica made available to react with L when FA is added which accounts for a further increase in strength. While reduction in strength after the optimum/peak is reached is as a result of the addition of excess amount of FA having relatively low specific gravity to react with the available L as noted by [14].

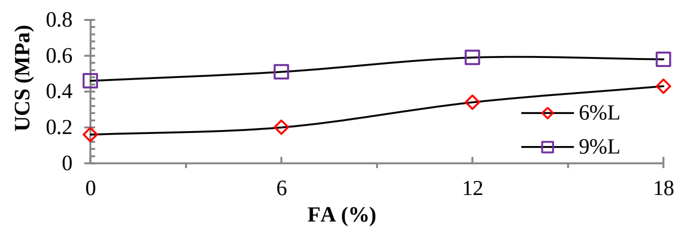

Fig. 4 Effect of FA mixes on UCS for 4 cycles

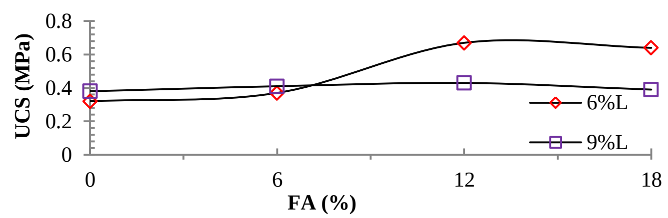

Fig. 5 Effect of FA mixes on UCS for 6 cycles

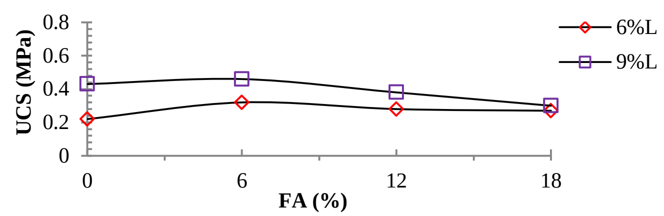

Fig. 6 Effect of FA mixes on UCS for 10 cycles

C. Effect of Cycles on UCS with respect to Mass and LL for 6% and 9 % L-FA Stabilized Specimens

From Figure 7 it can be drawn that for the 6 % L with corresponding FA additives, the number of cyclic loads affects the respective masses which eventually influences the UCS of the specimens. Hence, it reveals that the mass of the specimens after the respective cycles generally led to an increase in the UCS.

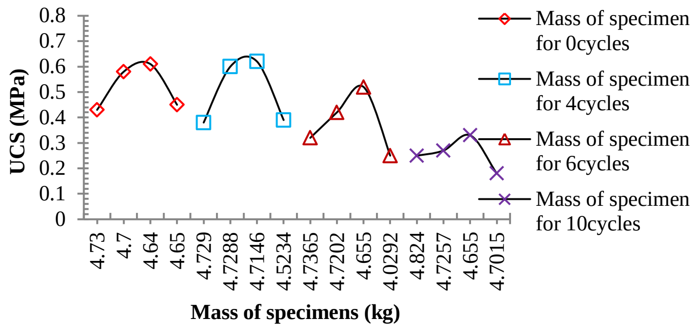

Fig. 7 Cyclic effects on UCS with respect to masses for 6 % L specimens

Here the 4 cycles revealed the highest UCS of 0.62 MPa for a corresponding mass of 4.7146 kg having 12 % FA. The 9 % L with corresponding FA mixes in Figure 8 shows a gradual reduction in the UCS and a corresponding loss in the masses after every cycle. The highest strength value of 0.78 MPa for a mass of 4.72 kg was reached at 6 cycles with 12 % FA content. Beyond 12 % FA and 10 cycles, a general reduction in the respective masses and UCS is recorded. The loss in mass and strength observed may be accounted for by the induced deterioration and material loss caused by the cyclic loading.

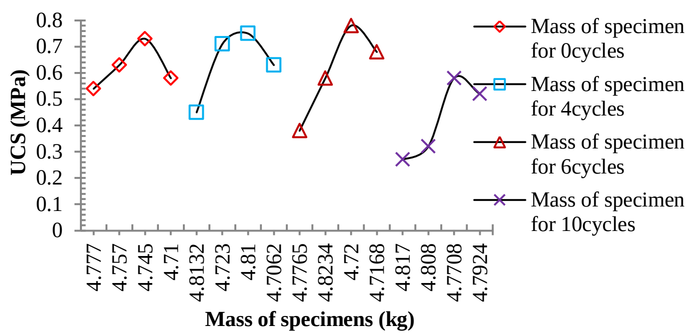

Fig. 8 Cyclic effects on UCS with respect to masses for 9 % L specimens

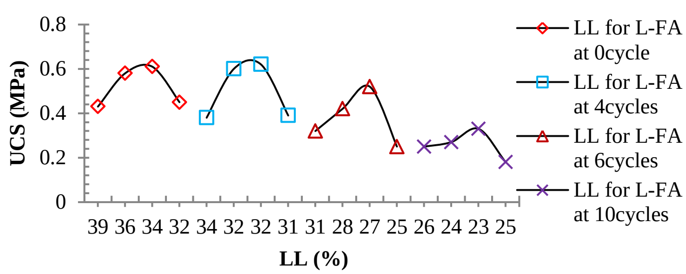

Fig. 9 LL-UCS relationship with respect to masses for 6 % L specimens

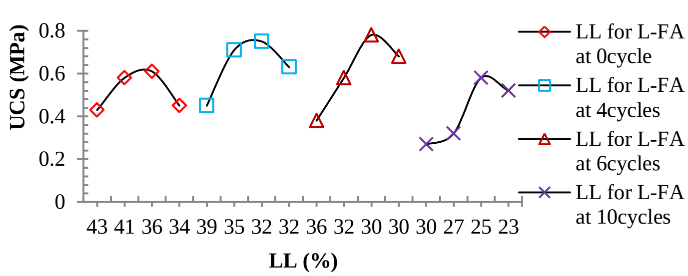

Fig. 10 LL-UCS relationship with respect to masses for 9 % L specimens

There is a general increase in UCS with decreasing LL for all cycles of the 6 % and 9 % L mixes as shown in Figures 9 and 10. It remains the case until it reaches the peak at 12 % FA after which the strength begins to decline. The reduction in strength after the optimum is reached as stated by [14] can be as a result of the introduction of excessive amount of FA having relatively lower specific gravity needed to react with the available L.

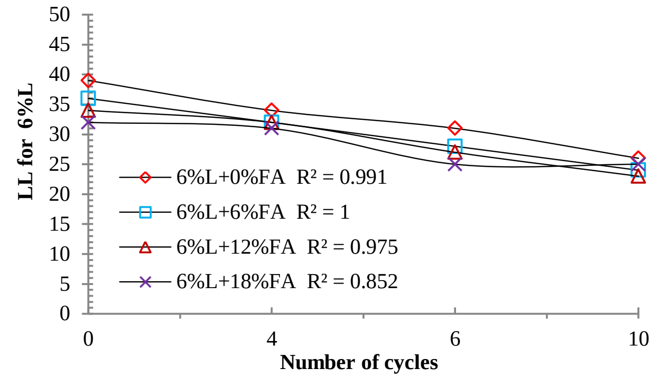

Fig. 11 Cycles-LL relationship with respect to masses for 6 % L specimens

In terms of UCS, Figures 11 and 12 shows a decrease in the LL with subsequent increase in the cycles for both 6 % and 9 % L stabilizers respectively.

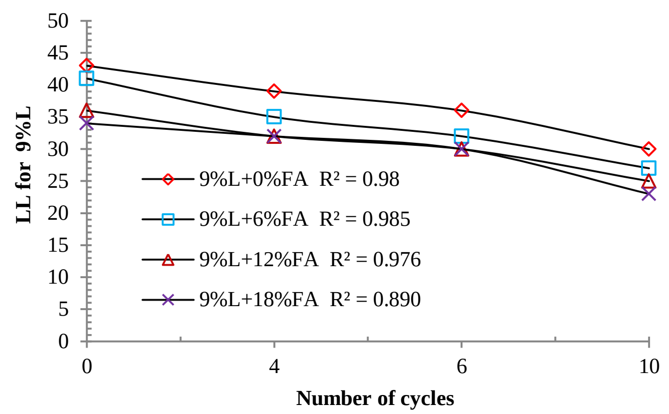

Fig. 12 Cycles-LL relationship with respect to masses for 9 % L specimens

The trends revealed a slight reduction in the R^2 value from 0 % FA to 18 % FA with the 6 % L + 12 % FA having a coefficient of determination (R^2) as high as 97.5 % while the 9 % L + 12 % FA had a 97.6% R^2 value. Hence, it can be said that the LL with relation to cyclic effects decreases with increase in L content.

D. CBR test after Cyclic Impacts on L-FA Mixes in relation to Penetration and LL

From Figures 13 and 14 the relationship established for CBR, penetration depth from all cycles of 6% and 9% L - 12% FA mixes shows that the CBR increases for an increasing depth of piston penetration for all cycles with an exception of the 4 cycles shown in Figure 13; which showed a clear decrease in CBR with increase in piston penetration.

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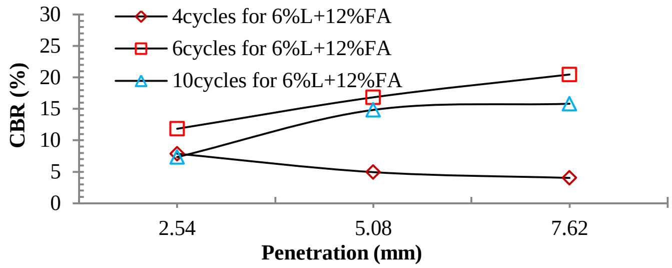

Fig. 13 Effect of 6 % L + 12 % FA mixes with respect to cycles on CBR

As recorded in [18] the CBR number is used to rate the performance of soils primarily for use as bases and sub grades beneath airfields and road pavement. It is a measure of shearing resistance of a soil that is laterally confined under controlled moisture and density conditions.

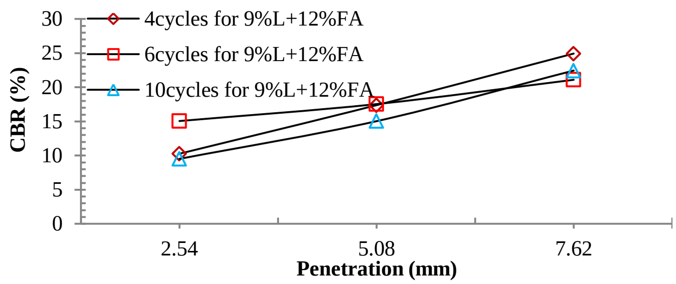

Fig. 14 Effect of 9 % L + 12 % FA mixes with respect to cycles on CBR

The CBR test is relatively simple and cheap and can be ran on standard loading frames. It is therefore widely used for low cost road projects.

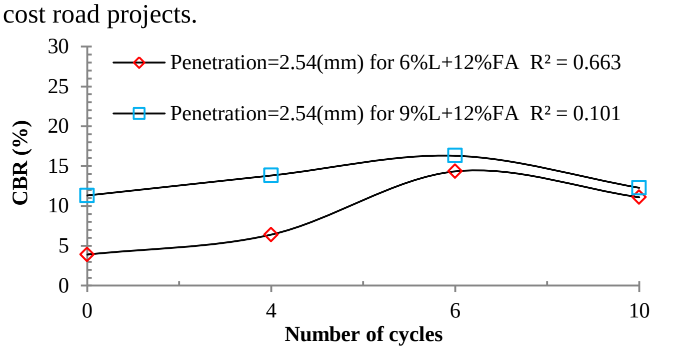

Fig. 15 Cyclic effects on CBR for 6 % and 9 % L + 12 % FA specimen

The result of the CBR tests shown in Figures 13 and 14 reveals a pattern of decreasing CBR with decrease in piston penetration and increasing CBR with increase in piston penetration. The considerable reduction in CBR in Figure 13 exhibited by samples mixed with 6 % L and 12 % FA for the 4 cycles is a manifestation of non-uniform bulk density resulting from the cyclic changes. Also from Figure 15 the CBR increases from 4 cycles to 6 cycles and then decreases at 10 cycles. The 9 % L is seen to have R^2 value of 10.1 % while the 6 % L had 66.3 % direct relationship between the CBR and number of cycles. It also shows that the average CBR of the 9 % L mixes are higher than the CBR of the 6 % L mixes. This tendency is true for all the samples regardless of the L and FA mixes. This indicates that the strength development due to the pozzolanic reaction between amorphous silica and or alumina from the soil and L to form various types of binding agents is reliant on the quantity of FA used up in the reaction. In the case of the 9 % L mixes, 12 % FA supplies adequate additional silica for the reaction while the amount of FA required for optimum reaction in the 6 % L mix is less than 12 % as such, the excess FA led to the strength reduction.

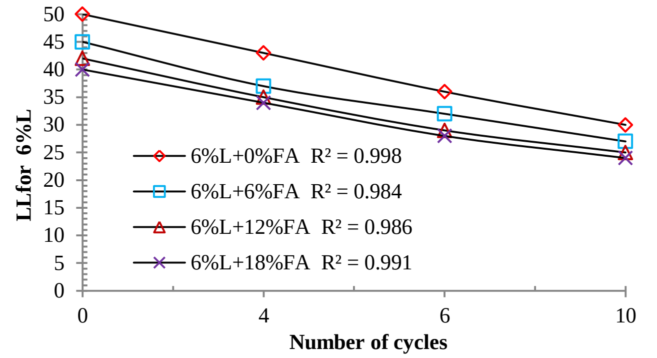

Fig. 16 Cycles-LL relationship for 6 % L specimens

It can also be deduced from Figures 2 to 5 that the lower percentage of FA i.e. 12 % produced stronger and more durable samples than 18 % FA irrespective of the quantity of L in the mix. The strength reduction in mixes containing higher amount of FA is also significant. In the long run, defined by 10 cyclic impacts the difference in strength between the two L mixes is also significant. For the 6 % L and 12 % FA mixes 4 cycles induced similar effect as curing i.e., increased strength development. The results shown in Figures 2 and 3 indicate that the strength of mixes at 10 cycles are very low and can only be used as sub-grades in pavement. However, only the 9 % L and 12 % FA material have adequate shear strength under the operative drainage conditions to sustain the stresses applied by traffic loadings [17]. A decrease in the LL with increase in the cyclic impacts for 6 % and 9 % L stabilizers are shown in Figure 16 and 17 respectively. The R^2 values are seen to be generally high for both.

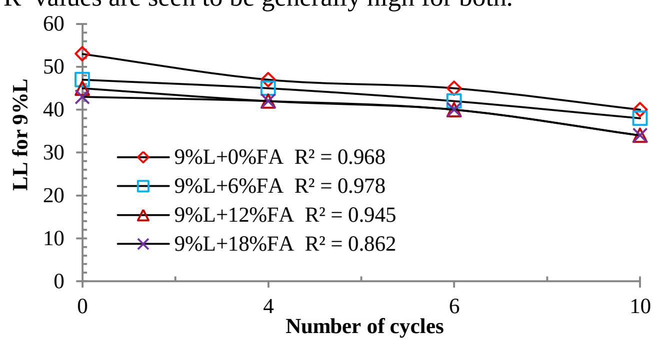

Fig. 17 Cycles-LL relationship for 9 % L specimens

In the 6 % L a slight decrease in the R^2 value was exhibited by the 0 % FA to 6 % FA and a subsequent increase is observed for the 12 % FA and 18 % FA content. A similar trend is also established by the 9 % L. As such, a reduction in correlation between the LL and number of cycles was noticed with the increase in L from 6 % to 9 %. For the 6 % L + 12 % FA a 98.6 % direct relationship was gotten between the LL and the number of cycles. While a 94.5 % direct relationship was gotten for 9 % L + 12 FA.

D. Water Absorption upon Cycles and Residual Mass

After every cycle the samples were weighed. Due to the absorption of water and simultaneous loss of materials the

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mass of the samples at the end of each cycle changed in relation to specimen constitution, curing programme and number of cycles. As shown in Figure 18 there is a general reduction in the mass of the specimens after the cycles. Therefore it reveals that the specimen with 6 cycles caused the highest lose in mass for 6 % L + 18 % FA mix. While the 9 % L + 18 % FA mix suffered the highest mass loss after the 4 and 6 cycles as shown in Figure 19.

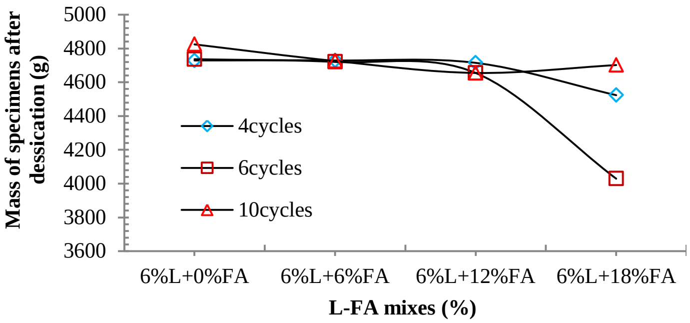

Fig. 18 Residual mass for 6 % L - FA relationship from cycles on specimens

Hence, the general trend of decreasing specimen stability with increasing number of cycles accounts for the loss in mass. The improved sample stability experienced by the specimens with high percentage of FA as shown in Figures 18 and 19 is associated with the changes in the water absorption potentials of the mixes. The samples mixed with 18 % FA shows the least amount of water absorption. This trend follows for both 6 % and 9 % L mixes. It was observed that the moisture absorption at 6 % FA was lesser than 0 % FA but the strength of 6 % FA was higher than 0 % FA thus, an increase in strength with decreasing moisture absorption.

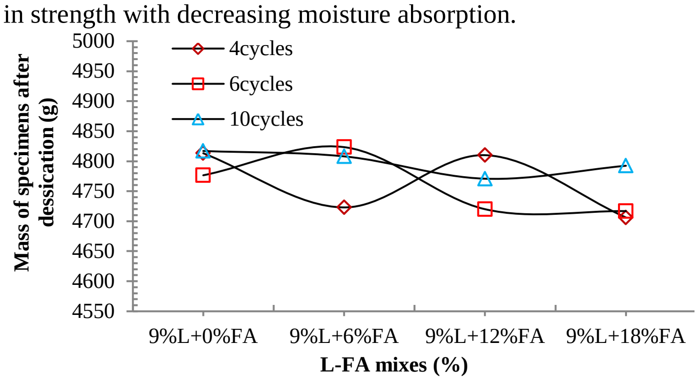

Fig. 19 Residual mass for 9 % L - FA relationship from cycles on specimens

However the trend is not linear as it was also observed that some samples with increased FA content also absorbed more water than samples without FA. This is reflected in Figures 2 to 4 where the UCS results showed that the strength increases up until 12 % FA after which the strength reduces. However, the 7 days curing for mixes containing 6 % L did not have a very strong correlation between strength and loss of mass since negligible material loss was experienced.

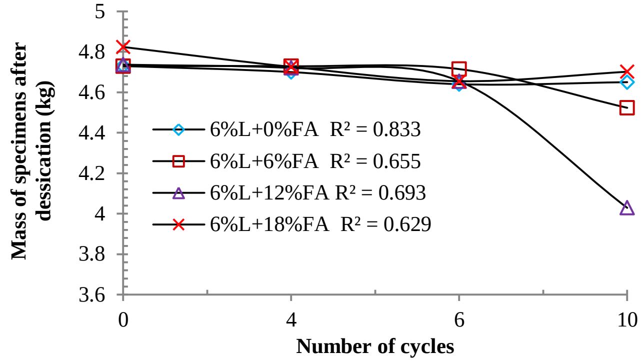

Fig. 20 Residual mass from cycle relationship for 6 % L – FA specimens

Figure 20 shows a general reduction in the mass of specimens of the various FA mixes just after the 4 cycles but with an exception of the 0 % FA and 18 % FA which shows slight increment just at the 10 cycles. This can be accounted for as a result of water absorption. In the case of the 18 % FA, this could have occurred as a result of material loss and a subsequent absorption of moisture. The mass of the 9 % L, 12 % and 18 % FA mixes in Figure 21 show increase at 4 cycles which can be tied to the fact that there was absorption of water and the subsequent reduction in mass of 6 % FA; which was due to the increased specimen instability as a result of the increased number of cycles thereby, leading to a loss in mass. It can be seen that the direct relationship between the mass of the specimens and cycles in Figure 20 decreases with the increase in the FA content. As such, the highest R^2 values were gotten to be 83.3% and 69.3% for the 6 % L, 0 % and 12 % FA mixes respectively.

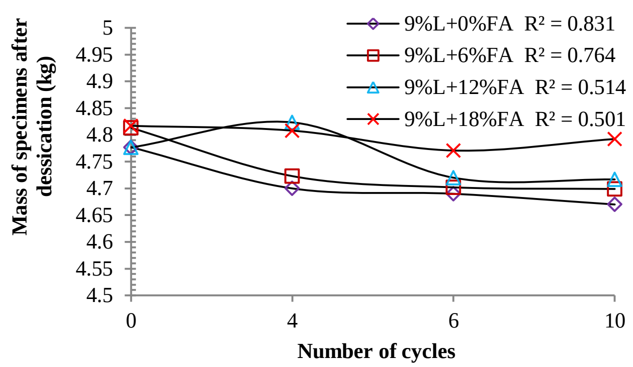

Fig. 21 Residual mass from cycle relationship for 9 % L – FA specimens

On the other hand, Figure 21 shows that the 9 % L exhibits a similar trend. Hence, the highest R^2 values were gotten to be 83.1 % and 51.4 % for the 0 % and 12 % FA mixes respectively. In light of these findings, it can be drawn that the LL is the best indicator of the degradation pattern of the L-FA stabilized BS low-cos grade. This is simply due to the fact that it had a stronger correlation as compared to the other variables and as such, possessed the highest coefficient of determination, R^2 = 98.6%.

IV. Conclusions

Series of tests to determine cyclic effects on BS low-cost grades stabilized with L and FA were conducted. Impact of various cycles and the influence of different percentages of L-FA stabilizers on the strength properties of the stabilized specimens were investigated. The degradation of the stabilized product was monitored by certain indicators and the best indicator was determined. From tests and analysis, the following conclusions were drawn:

The UCS increased after 4 cycles and decreased as the cycles increased.

The UCS decreases with increase in FA with a peak strength from a mix of 6 % L + 12 % FA stabilizer; for FA content higher than 12%, increased cycles led to significant decrease in UCS from excessive FA not used up in the pozzolanic reaction.

Cycles resulted in material loss in specimens; the reduction in mass decreases with increase in FA content.

The CBR of the stabilized mix increases with increase in L-FA content and decreases with increasing cyclic impact.

The significant reduction in piston penetration for samples mixed with 6 % L + 12 % FA was due to non-uniform bulk density of the mixes.

In the long run defined by 10 cycles, only the 6 % L + 12 % FA material mix had adequate strength under the operative drainage conditions to sustain the stresses applied by traffic loadings.

The LL showed the highest coefficient of determination (R^2) thereby, having the strongest percentage correlation between the other variables.

The LL appeared the best indicator to the degradation of low-cost stabilized L-FA BS grade.

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