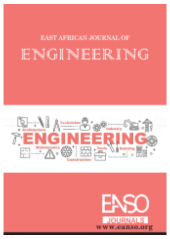

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Original Article

Characteristics of Cinder Gravel as Road Pavement Construction Material in Meru County, Kenya

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ABSTRACT

The availability of suitable road construction materials that meet the specification requirements is becoming scarce, therefore the use of marginal materials presents challenges during construction and performance when used in the construction of road projects. This study exploited the gap that existed by investigating the engineering properties of cinder gravel sourced from Meru County in Kenya. The objectives of the study were to evaluate the engineering characteristics of neat and blended cinder gravel for suitability as road pavement construction material of Low Volume Sealed Roads (LVSRs). The study evaluated the strength and grading properties of the material at different levels of compaction and investigated the relationship between the shear strength of cinder gravel and particle size using a shear box test. The methodology involved both fieldwork and laboratory tests of the material on grading, Atterberg's limits, compaction tests, strength (CBR), repetitive sample compaction tests, and shear box tests. The study established that neat cinder gravel in its natural state was non-plastic and poorly graded due to deficiency in fine particles <0.075 mm (μm) and was blended with locally available fine material. The optimum blending ratio of 90% cinder + 10% weathered rock met the requirements for natural subbase and base materials for LVSRs. The study showed that the MDD of the blended material increased with the level of compaction, indicating better interlocking of the particles of the material. Similarly, the strength (unsoaked CBR) of blended cinder gravel increased with the level of compaction. There was a gradual increase in the Plasticity Index with the number of compaction cycles of the material due to the breakage of cinder gravels and the blending of material into finer particles with compaction. For the soaked specimen, the CBR decreased as the cycles of compaction increased because with the ingress of water, the finer particles of cinder gravel dispersed and lost the interlocking properties. The shear strength of cinder gravel decreased with compaction cycles due to the decrease in the angle of shearing resistance (φ). In conclusion, cinder gravel sourced

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from Meru County blended with fine material improved its engineering properties including cohesiveness.

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INTRODUCTION

Naturally, occurring gravels are abundant sources of road construction materials, but the majority require improvement with cement or lime to be suitable for high-traffic pavement layers. These treatments are expensive and large financial and environmental benefits can be achieved if properties of locally available materials such as cinder gravels can be improved through mechanical stabilisation (blending) to improve the engineering properties (Berhanu, 2009). This study explored the option of blending cinder gravel sourced from Meru County, Kenya with locally available fine material before resorting to treatment. Blending (mechanical stabilisation) refers to the process of combining two or more granular materials to obtain a material of better engineering properties (usually bearing strength and, sometimes, improved plasticity index) (Ethiopian Roads Authority, 2018).

Volcanic cinders are deposits of granular materials from past volcanic activity (Ermias, 2019). It is a porous material ranging from black to dark red in colour and is formed from volcanic eruption as gases escape from the residual rock (Geology Science, 2021). The material is found around the vents of volcanoes inform of cone-shaped hills known as volcanic ash cones. Cinder gravel being readily available and abundant material in certain areas of volcanic occurrence, offers potential for use in low-volume road construction and rehabilitation (Gareth et al., 2018). The challenge has been to mitigate or control the variability in its engineering characteristics, particularly grading, plasticity, porosity, and strength, to meet specification requirements for pavement construction layers (Gareth et al., 2018).

According to the Geological Survey of Kenya by Pulfrey and Walsh (1969), the Northern part of the Eastern Province of Kenya consists of recent lava plains and volcanoes, which was confirmed by Gareth et al. (2018) that cinder materials are found in Marsabit. This calls for the prospecting of volcanic materials like cinder gravels for suitability for road construction in Kenya to complement the depleting gravel sources. The study evaluated the engineering characteristics of neat and blended cinder gravel for suitability as road pavement construction material. The strength and grading properties of the material at different levels of

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compaction were evaluated and the relationship between the shear strength of cinder gravel and particle size using a shear box test was investigated.

According to Lupini et al. (2015), cohesion is the component of the shear strength of soil that is independent of interparticle friction. It was established from the study that the cohesive properties of the cinder gravel material improved with compaction. As the material became finer because of compaction, the particles became more cohesive and plastic to resist shear failure. According to Alias et al. (2014), the angle of friction is dependent on the particle size; the particle-to-particle contact provides an interlocking surface that resists the shearing resistance. In repeated cycle compaction as the cycles of compaction increased, the angle of shearing resistance (φ) decreased. The result was consistent with the findings by Wang et al. (2013), which concluded that larger size particles produced a higher effective internal friction angle and developed high shear strength. Even though it was observed in the study that the MDD of cinder gravel increased with compaction cycles it did not contribute to higher shear strength for cinder gravel.

MATERIALS AND METHODOLOGY

Cinder gravels and Blending Materials

Cinder gravel for the study was sourced from material sites that had not been fully exploited by contractors due to the detrimental properties of the material. The sampling procedure was carried out in accordance with BS 1377 part 1 and the Kenyan Road Design Manual Part III, 1987. The red soil blending material was sampled in a location adjacent to the cinder gravel material site, while the weathered rock was sampled from material sites within the confluence of the same area. The samples of the three materials were air-dried prior to testing in the laboratory, as shown in *Plate 1*. This was in preparation for particle size distribution, Atterberg's limits, compaction, and strength tests.

Plate 1: Sampling preparation of cinder gravel and blending material for testing

Air drying cinder material sampled from Thanantu BP in the laboratory in preparation for standard tests

Air drying red soil blending material in preparation for standard tests

Air drying weathered rock blending material in preparation for standard tests

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The three materials were subjected to laboratory tests for analysis of the properties at their natural state and the results are presented in *Table 1*. Neat cinder gravel was non-plastic and did not meet specification requirements for natural gravels for subbase and base material for LVSRs due to deficiency in fine particles < 0.075 mm (µm).

Table 1: Analysis of neat cinder gravel and blending material

Type of Test	Specifications for LVSRs	Test Results		
		Neat cinder gravel	**Weathered rock**	**Red soil**
Grading	Uniformity Coefficient (C_u) Min. 5	8	40	6
MDD (Kg/m^3)	1400	1455	1505	1382
Plasticity Index (PI) (%)	**Material** — **Specs** G25 — Max 15 G30 — Max 12 G50 — Max 10 G80 — Max 10	NP	21.8	36.1
Plasticity Modulus (PM)	Max 250	NP	336	220

Legend: G25 - denotes natural or blended (mechanically stabilised) granular materials of minimum CBR strength of 25% measured after 4 days soak and so on for G30, G50 & G80.

From the results, cinder gravel was non-plastic, while red soil and weathered rock were plastic. Therefore, cinder gravel was blended with either of the two finer materials to improve its plasticity, thus improving its mechanical properties.

METHODOLOGY

Particle Size Distribution

Three samples weighing 1500 g each for neat cinder gravel and blending material were subjected to particle size distribution to check the limits of gradation. All standard sieve sizes; 50 mm, 40 mm, 28 mm, 20 mm, 14 mm, 10 mm, 6.3 mm, 5 mm, 2 mm, 1 mm, 600 µm, 425 µm, 300 µm, 212 µm, 150 µm and 75 µm were used and a stopper to capture finer particles passing 75 mm sieve size. The mass retained in each sieve was weighed in a digital weighing balance and the percentage weight retained in each sieve was determined; thereafter percentage weight passing each sieve was calculated.

The percentage passing in each sample was plotted on a logarithmic scale and compared with the minimum and upper limits for natural gravel requirements for subbase and base material in the Kenyan Road Design Manual Part III and the Kenyan Pavement Design Guidelines for LVSRs. The RDM Part III provides the grading limitation that qualifies the use of natural granular materials like cinder gravel in road construction. It meets the grading requirement when a certain percentage passes the required sieve sizes. The LVSRs guideline provides various categories which cinder gravel has to meet in order to be used in road construction. For this study, natural/blended granular materials (G30) and (G80) grading envelopes specification limitation was used as given in *Figures 1* and *2*. The results are discussed and the grading curves for neat cinder gravel and blending material are provided.

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Figure 1: Specifications requirements for subbase materials for LVSRs

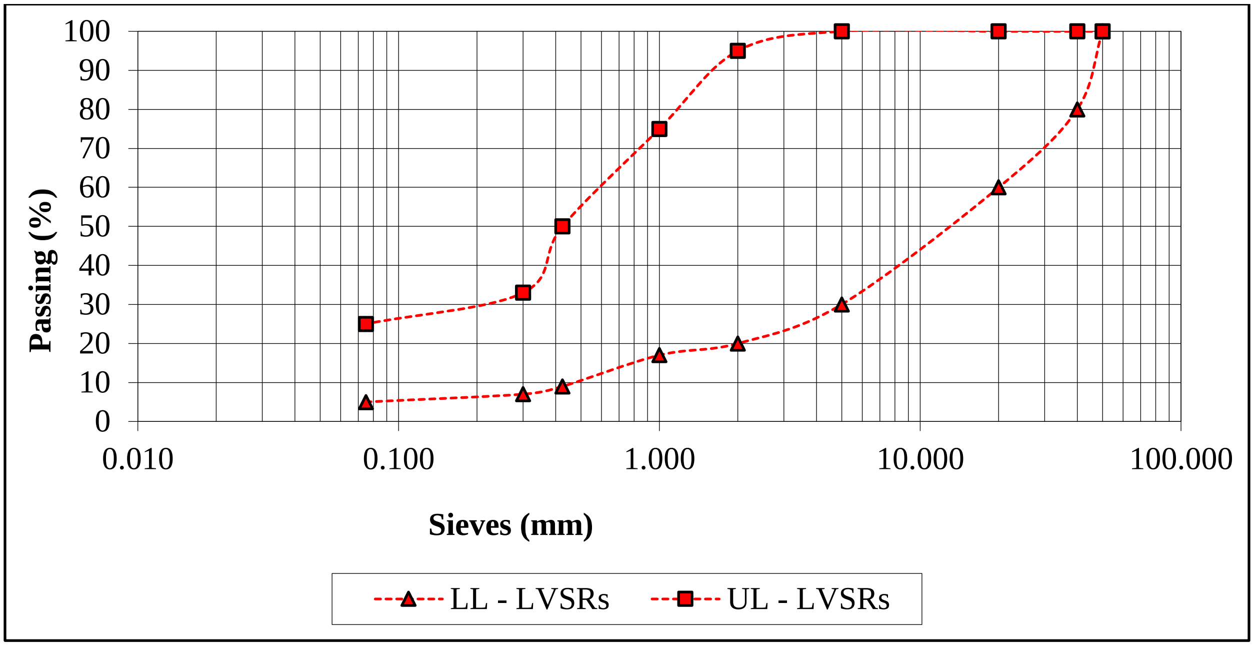
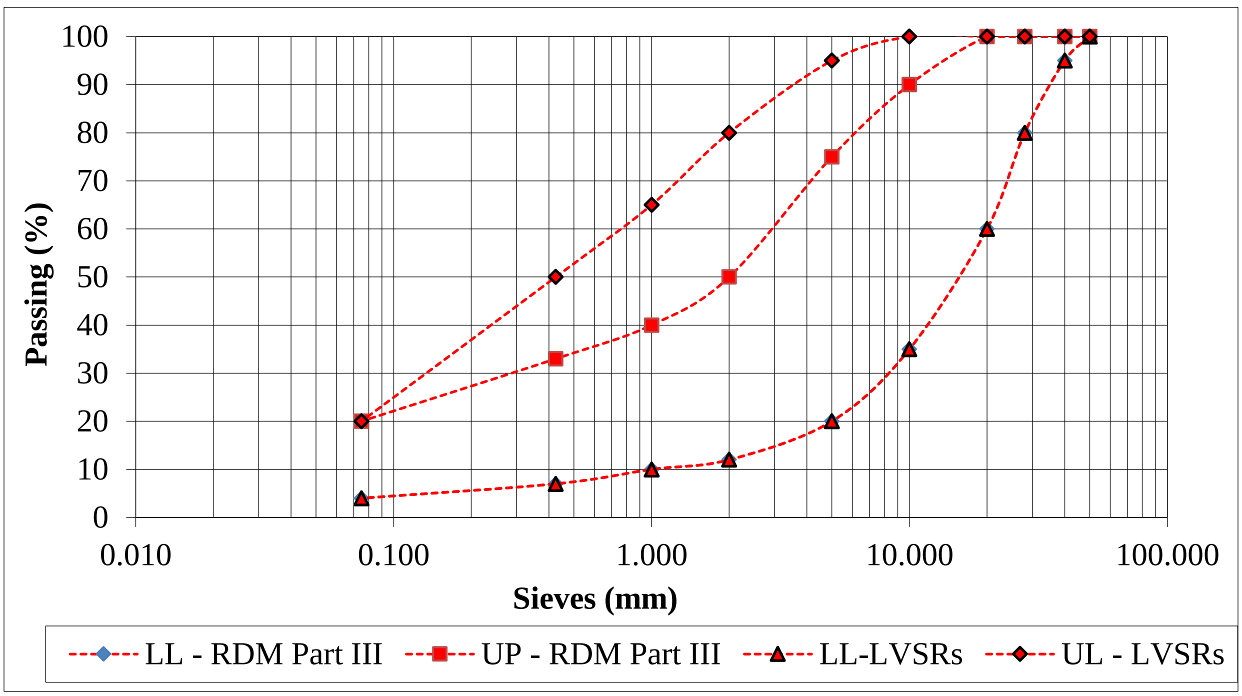


Figure 2: Specifications requirements for base materials for LVSRs



Since natural materials are compacted on site during road construction and cinder gravel breaks into finer material when compacted, it was necessary to determine the grading of cinder after compaction using the wet sieve analysis BS 1377 Part 2 Standard procedure. Wet sieve analysis was carried out for compacted material after MDD and CBR determination and after soaking for 24 hours. To separate silt and clay-sized particles, 2 gms of Sodium Hexameta Phosphate was added to 1 litre of water for each sample and mixed uniformly. Thereafter, the material was oven dried for 24 hours

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at 105 ºC before carrying out dry sieve analysis of material retained on 2.36 mm, 600 µm, and 75 µm sieves.

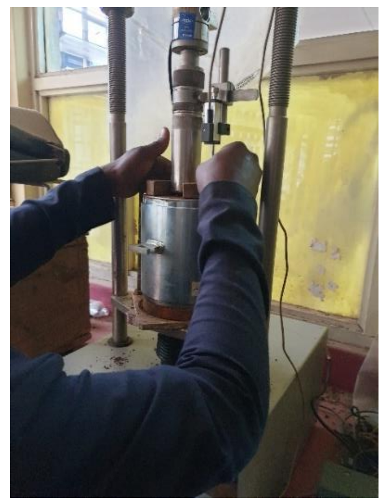
Blending of Cinder Gravel with Weathered Rock and Red Soil

Cinder gravel was blended with weathered rock and red soil of various proportions ranging from 90:10 to 70:30 by weight at increments of 5% of the blending material and subjected to laboratory tests to check on the properties of the improved material. The tests carried out were; Particle size distribution, Atterberg's limits, compaction tests, and CBR strength tests in accordance with BS 1377 and AASHTO T180-D standard testing procedures. Since cinder gravels break into finer material when compacted, grading and Atterberg's limits of blended cinder were determined after MDD and CBR determination. During compaction tests, water was added to the specimen at an increment of 100 ml and covered with aluminium foil for at least an hour for the moisture to dissipate uniformly as shown in *Plate 2*.

Plate 2: Compaction and strength tests of the various blends

Mixed specimen covered with aluminium plastic foil for 1 hour before compaction for homogeneity of moisture

AASHTO T180-D standard compaction test of sample in a mould



Mounting compacted specimen for CBR Testing

Repeated Cycle Compaction of Blended Cinder Gravel

Cinder gravel was investigated to check if the material increased or decreased in strength as the breakdown of the particles into finer particles during compaction. This breakdown is achieved through repeated cycles of moulding-compaction (Newill et al., 1987). To determine this variation, repeated cycle compaction on the same specimen was done for moulded samples at MDD and OMC for the optimum blending ratio of 90% cinder gravel + 10% weathered rock. The first specimen was compacted in accordance with AASHTO T180-D standard procedure and MDD, CBR, moisture content, and Atterberg's limits were determined. For the second specimen, the compacted material was extracted from the mould, mixed thoroughly and re-compacted (without the addition of water) to represent two mould-compaction cycles. A similar procedure was carried out for three, four and five mould-compaction cycles. For every compaction cycle, the MDD and CBR test at OMC was determined, then followed by grading and

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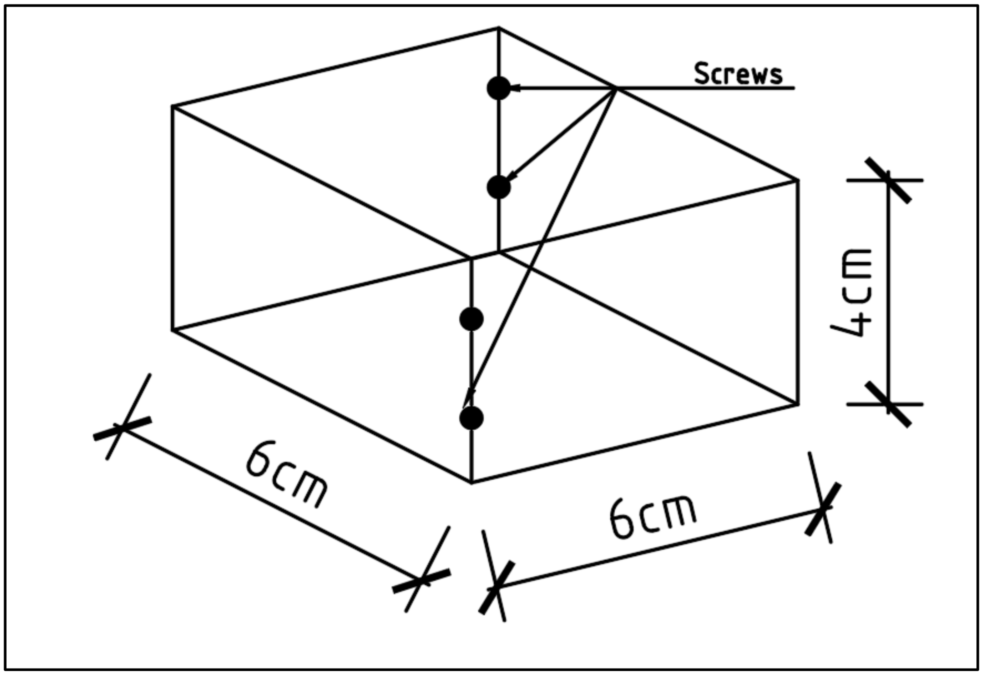
Atterberg's limit determination. Neat cinder gravel, one, three and five repeated cycle compactions were prepared in a CBR mould in accordance with AASHTO T193 and soaked for 4 days, after which the swell and soaked CBR were determined.

Relationship between Shear Strength of Cinder Gravel and Particle Size Using Shear Box Test

To enable the shear box test to be carried out, a 6 cm x 6 cm x 4 cm mould was fabricated as shown in *Figure 3*.

Figure 3: Detachable prefabricated shear box mould



The methodology comprised compacting five (5) specimens of the optimum blending ratio at different compaction cycles of five (5) factorial and thereafter extracting a specimen in a shear box mould for shear value determination. The samples were remixed after each compaction cycle to ensure uniformity of the material before remoulding. A 6 cm x 6 cm x 4 cm mould was fabricated and samples were moulded at MDD and OMC of the optimum blending ratio determined in accordance with the AASHTO T180-D standard test procedure. During compaction, a split mould was used for ease of extruding the cutter from the sample. The prefabricated shear box mould was driven into the compacted mould using a hydraulic jack and the sample in the cutter was trimmed using a sharp straight edge and the mould sides were unscrewed to remove the specimen for the shear box test. The specimen for the shear box test was extracted from the bottom surface of the sample because it is the surface of higher compaction.

Upon extrusion from the mould, the specimen was covered with a cling film foil paper to prevent moisture loss from the sample and also allow excess water to dissipate into the sample for 24 hours in readiness for the shear box test. The procedure for extrusion of compacted specimen for shear box test is shown in *Plate 3*.

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Plate 3: Extrusion of compacted specimen for shear test

Trimming and extracting specimens from compacted samples extruded from the split mould

Extracted specimen being covered with a cling film foil paper for 24 hours before testing

The specimens were soaked for a few minutes prior to shear box testing

Three specimens per test for each cycle of compaction were moulded for the three loads applied; 32.2 kg, 68.9 kg, and 105 kg.

RESULTS AND DISCUSSION

Cinder Gravel Blended with Weathered Rock

The maximum dry density of blended cinder gravel increased with an increment in the blending ratio, indicating improved compaction and binding properties of the material. Similarly, the strength (CBR) of blended cinder increased slightly with an increment in the blending ratio of weathered rock, indicating improved interlocking of particles. However, with a further increase in the blending ratio above 25%, the high quantity of fines reduces the contact area between large particles to large particles of cinder gravel. The strength of the blend is significantly derived from the contact between large particles to transfer the load. Therefore, if this contact is reduced by the presence of a large quantity of fines, then the strength of the blend is consequently reduced. The plasticity properties of blended cinder increased with the blending ratio as the material became finer, as shown in *Table 2*.

Table 2: Test results of cinder gravel blended with weathered rock for various proportions

Blending ratio	Test results			
	MDD (Kg/m3)	OMC (%)	Unsoaked CBR (%)	Plasticity Index (%)
Cinder + 30% weathered rock	1512	22.9	148	19.2
Cinder + 25% weathered rock	1463	25.5	160	15.8
Cinder + 20% weathered rock	1487	25.1	149	14.9
Cinder + 15% weathered rock	1451	25.9	152	15.5
Cinder + 10% weathered rock	1409	26.9	123.5	13.1

It is deduced from *Table 2* that MDD increased with the blending ratio while OMC decreased. This is because an increase in finer particles in the mixture provides a large surface area for more moisture absorption in bonding the particles together.

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The correlation between the blending ratio and maximum dry density in *Table 2* is presented graphically in *Figure 4*. It is observed that a linear relationship exists between the blending ratio and MDD value. As the blending ratio increases, maximum dry density also increases, indicating that a linear relationship exists between these two parameters. The correlation is expressed by the linear trend line equation:

$$MDD = 4.36BR + 1377.2 \quad (1)$$

$$R^2 = 0.7885$$

MDD is the maximum dry density (Kg/m^3), BR is the blending ratio (%) and R^2 is the coefficient of correlation (variation of observed values to the regression line).

In equation (1), the constant (1377.2) is the y-intercept, which is the MDD of a neat cinder material. The equation can be used to predict the MDD of cinder gravel at various blending ratios without carrying out individual MDD as an initial check and save on time.

Figure 4: Correlation between blending ratio with weathered rock and maximum dry density

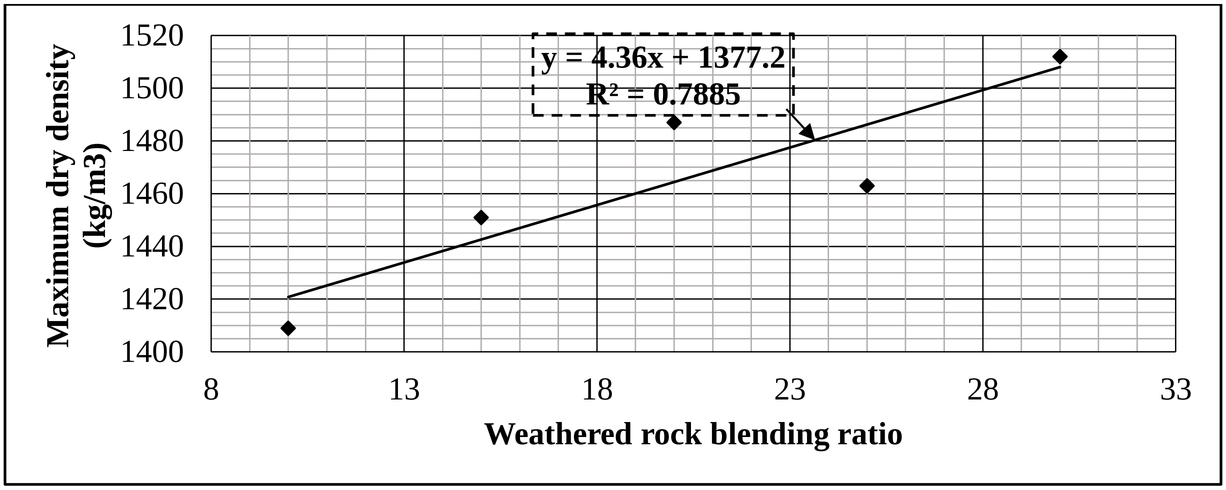
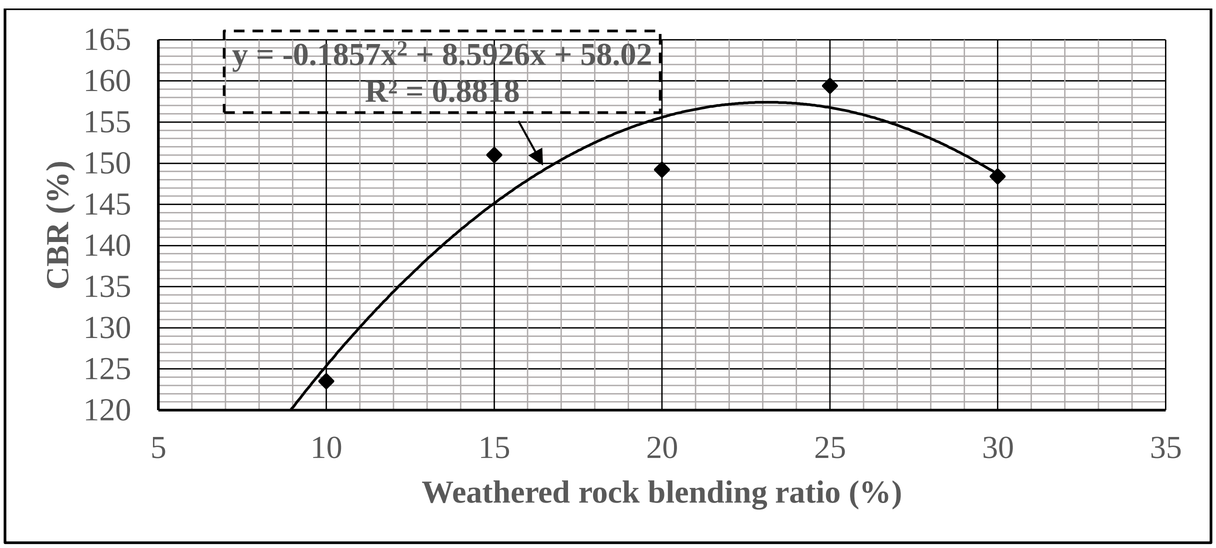


Figure 5: Correlation between blending ratio and unsoaked CBR of blended cinder gravel



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From *Figure 5,* it is observed that the relationship between the blending ratio and unsoaked CBR is a quadratic curve expressed by the equation:

$$CBR = -0.1857BR^2 + 8.5926BR + 58.02 \quad (2)$$

$R^2 = 0.8818$

CBR is the strength (unsoaked), BR is the blending ratio (%) and R^2 is the coefficient of correlation (variation of observed values to the regression line curve).

It was established from the study that the highest strength (unsoaked CBR) value does not occur at the MDD/OMC of the material due to the development of pore pressures at higher moisture contents which negate the pressure /loads impacted on the material with further compaction. This makes the material suitable for road construction in dry areas (ASAL) where the annual rainfall is less than 500 mm.

Cinder Gravel Blended with Red Soil

The results in *Table 3* showed that the MDD and strength of blended material improved significantly with blending with red soil, as was with weathered rock. However, blending with red soil depicted high plasticity. The plasticity of blended material with red soil ranged between 20-30%, while that with weathered rock ranged between 13-20% for the five similar blending ratios because of high fine content < 0.075 mm (μm) in red soil. According to Smith and Smith (1988), the finer the soil, the greater its plasticity index and the results in *Tables 2* and *3* showed that red soil is finer than weathered rock.

Table 3: Tests results of cinder gravel blended with red soil for various proportions

Blending ratio	Test results			
	MDD (Kg/m^3)	OMC (%)	Unsoaked CBR (%)	Plasticity Index (%)
Cinder + 30% red soil	1488	27.3	123.5	27.6
Cinder + 25% red soil	1445	28.2	125.5	23.5
Cinder + 20% red soil	1432	26.4	144	24.1
Cinder + 15% red soil	1449	28.0	150	22.6
Cinder + 10% red soil	1492	25.1	125	18.1

It was concluded from the study that improvement of cinder gravel through mechanical stabilisation (blending) only with red soil did not meet specifications for pavement material for LVSRs. Therefore, chemical stabilisation with lime or cement would be necessary to improve the material, which may not be appropriate or cost-effective for LVSRs where it is preferred that the initial cost of construction is kept low for the project to be viable.

Suitability of Cinder Gravel Blended with Weathered Rock for Road Construction

The particle size distribution after CBR for blended cinder was carried out and compared with specifications and the results are presented in *Figures 6* and *7*. Cinder gravel blended with weathered rock for a 90:10 ratio met specifications requirements for sub-base materials (G30) and base materials (G80) for LVSRs.

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Figure 6: Grading of blending ratios against grading requirements for subbase materials (G30) for LVSRs.

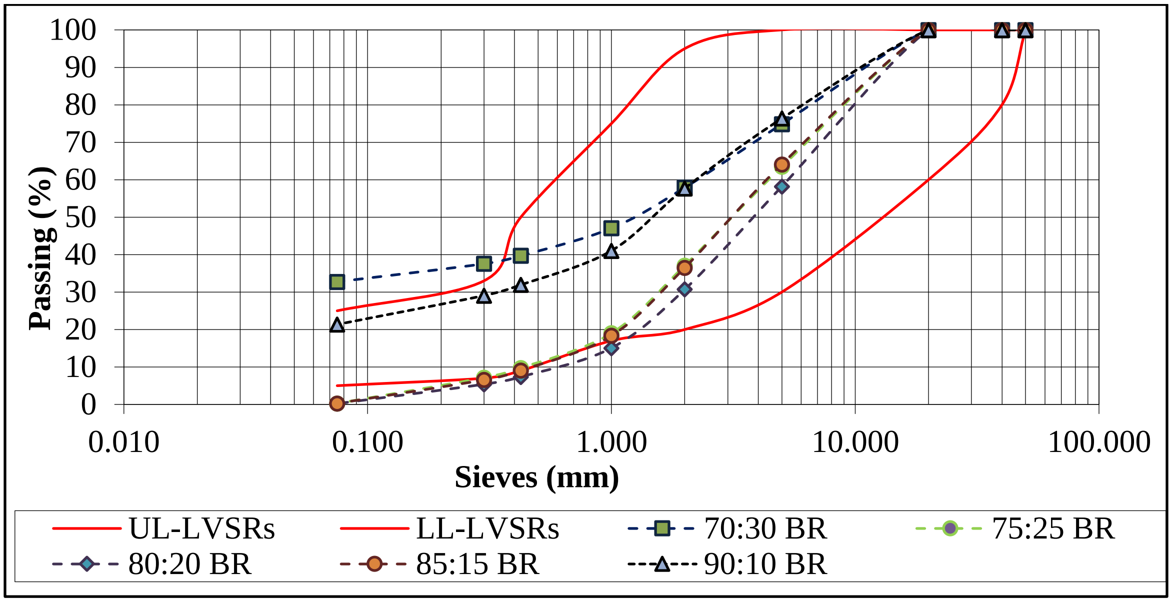
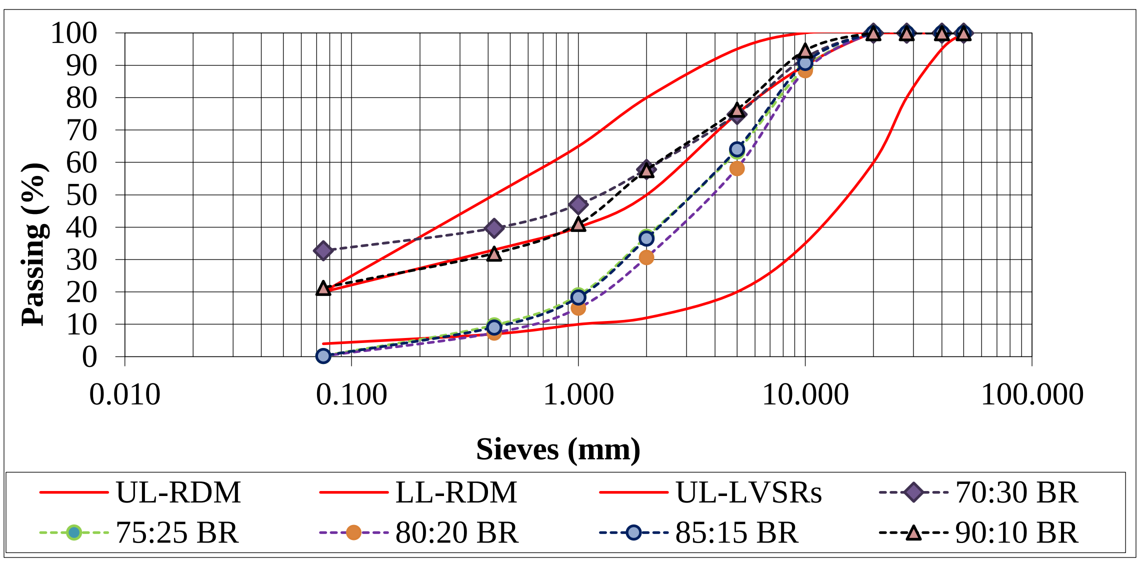


Figure 7: Grading of blending ratios against grading requirements for base materials in RDM-III and (G80) for LVSRs.



The results are consistent with the findings by Berhanu (2009) that the optimum amount of fine soil that makes up for the deficiency of fines in cinder gravel samples from both Alemgena and Lake Chamo areas in Ethiopia was 12%.

Engineering Properties of Cinder Gravel under Repeated Compaction

A comparison was made on the properties of blended cinder gravel for the optimum 90:10 proportion when the material breakdown into finer particles through repeated cycles of moulding-

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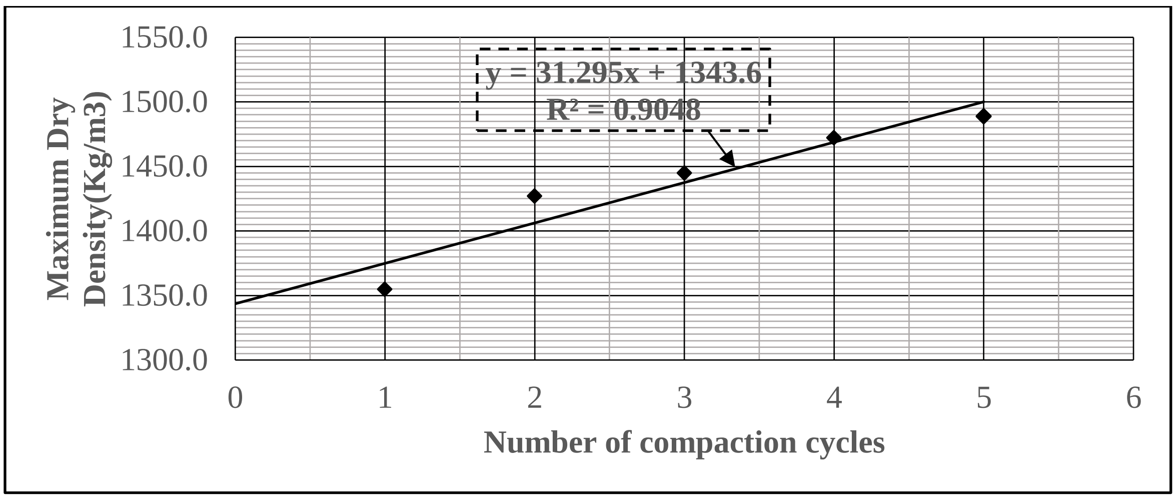
compaction. It is shown in *Table 4* that the maximum dry density of blended material increased with compaction, indicating better interlocking of the particles. Repeated compaction of cinder gravel significantly improved the properties of the material and there should be a balance between having an improved material and the cost to achieve the improvement in the field during the construction of pavement layers.

Table 4: Engineering characteristics of cinder gravel under repeated compaction

Compaction Cycles	MDD (Kg/m^3)	OMC	Unsoaked CBR (%)	PI (%)
One cycle compaction	1355	26.8	115	12.4
Two cycle compactions	1427	25.9	178	13.8
Three cycle compactions	1445	26.0	164	13.7
Four cycle compactions	1472	25.9	179	11.2
Five cycle compactions	1489	24.8	178	15.1

It is observed from *Table 4* that the strength of blended cinder gravel as represented by CBR increased with compaction showing that re-using the specimen is beneficial and therefore repeated scarification and compaction will be beneficial on site. Further analysis of the results showed that there is a gradual increase in the plasticity index with the number of compaction cycles. A graph of MDD (ordinate) versus the number of compaction cycles (abscissae) was plotted, as shown in *Figure 8.*

Figure 8: Correlation between compaction cycles and maximum dry density



From *Figure 8,* it is observed that a linear relationship exists between compaction cycles and MDD value. With the increment in compaction cycles, the MDD increased in a linear relationship expressed by the trend line equation:

$$MDD = 31.295NC + 1343.6 \quad (3)$$

$R^2 = 0.9048$

MDD is the maximum dry density (Kg/m^3), NC is the number of compaction cycles and R^2 is the coefficient of correlation (variation of observed values to the regression line). A graph of the maximum CBR for each compaction cycle was plotted for comparison and is presented in *Figure 9*.

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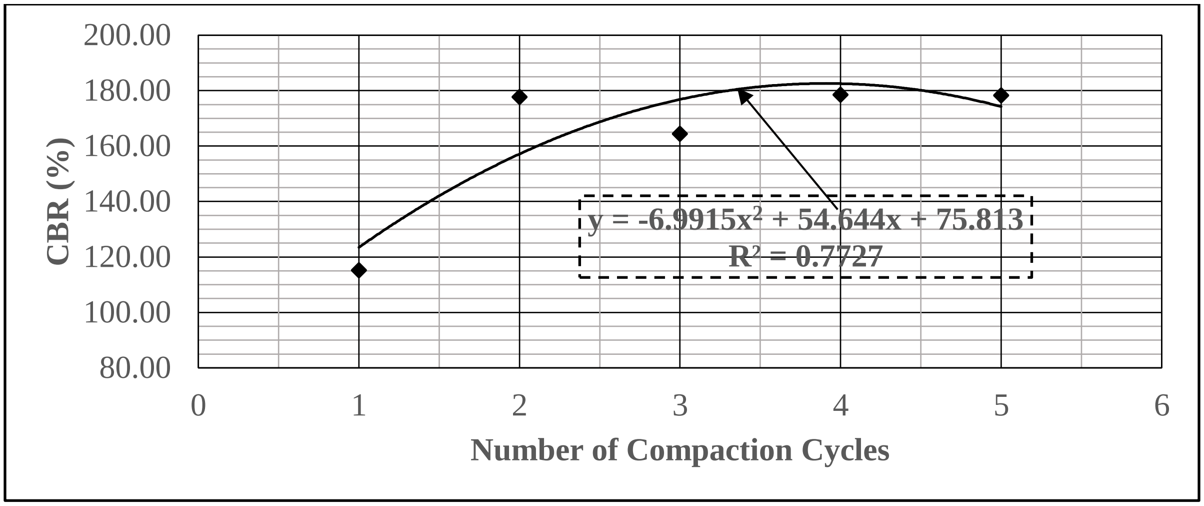
Figure 9: Correlation between the number of compaction cycles and unsoaked CBR



The correlation between the number of compaction cycles and the maximum strength (CBR) of the blended material is expressed by the quadratic curve equation:

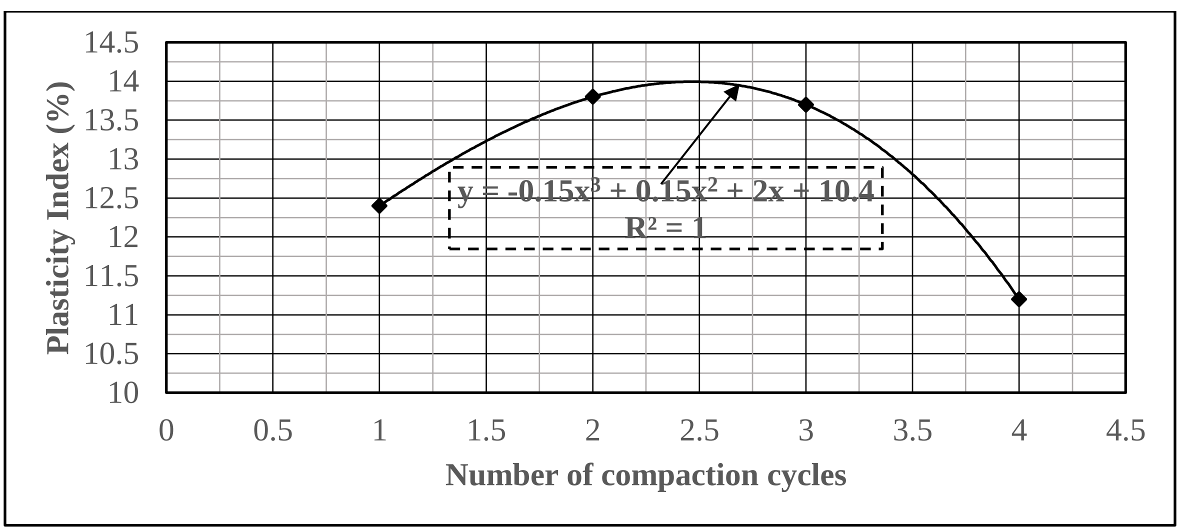
$$CBR = -6.9915NC^2 + 54.644NC + 75.813 \quad (4)$$

$R^2 = 0.7727$

CBR is the strength (unsoaked), NC is the number of compaction cycles, and R^2 is the coefficient of correlation (variation of observed values to the trend line curve).

Analysis of the results in *Table 4* showed that there was a gradual increase in the plasticity index with the number of compaction cycles to a maximum before it dropped from the third compaction cycle, as illustrated in *Figure 10*. This was due to the breakage of cinder gravels into finer particles with further compaction, thus inhibiting the plasticity of the blend. In addition, as the blended material becomes finer, the plastic limit reduces as finer particles absorb more water (moisture). Consequently, this reduces the range of water content at which the material remains plastic (its Plasticity index).

Figure 10: Correlation between the number of compaction cycles and plasticity index



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The correlation between the number of compaction cycles and the plasticity index for the optimum blending ratio is expressed by the parabolic curve equation:

$$PI = -0.15NC^3 + 0.15NC^2 + 2NC + 10.4 \quad (5)$$

$$R^2 = 1$$

PI is the plasticity index (%), NC is the number of compaction cycles and R^2 is the coefficient of correlation (variation of observed values to the trend line curve).

Effects of Soaking on the Strength Properties of Cinder Gravels

Neat and blended cinder gravel blended with weathered rock did not swell when soaked, as shown in *Table 5*. This indicated low moisture susceptibility or porous nature of the material.

Table 5: Comparison of strength for soaked and unsoaked specimen

Specimen	CBR (%)		% Swell after soaking	Remarks
	Unsoaked CBR	Soaked CBR		
Neat cinder Gravel	113.00	16.11	0.04	All specimens depicted low strength when soaked
One mould compaction cycle	115.26	86.30	0.30	
Three mould compaction cycles	164.43	26.05	Nil	
Five mould compaction cycles	178.32	14.80	Nil	

All specimens depicted low strength when soaked and the soaked CBR decreased as the cycles of compaction increased, which was an inverse of the unsoaked CBR. This was because with the ingress of water when soaked, the finer particles of cinder gravel dispersed and lost the interlocking properties. This showed that the material when soaked had higher strength when optimally compacted and weak when over-compacted contrary to the unsoaked properties.

Relationship between the Shear Strength of Cinder Gravel and Particle Size Using Shear Box Test

For the optimum blended cinder gravel 90:10 ratio, a graph of shear stress (ordinate) versus normal stress (abscissae) was plotted for each compaction cycle as shown in *Figure 11*. From the graph, the angle of shearing resistance (φ) and unit of cohesion “c_u” was determined, and values were compared for the five (5) compaction cycles. It was deduced from the graph that the shear stress of blended cinder gravel reduced with increased compaction cycles though not at significant proportions.

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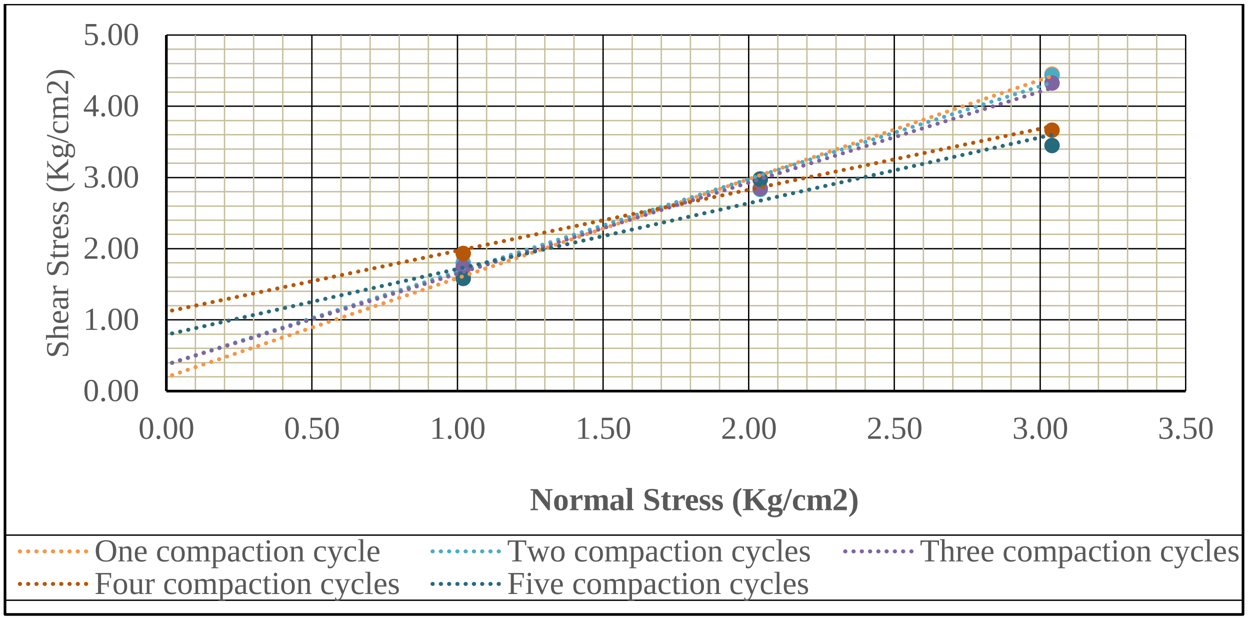
Figure 11: Normal stress (σ) versus shear stress (τ) for various compaction cycles



According to Lupini et al. (2015), cohesion is the component of the shear strength of soil that is independent of interparticle friction (9). Repeated compaction breakdown the larger particles of the material and, when recompacted, results in the densification of the sample hence increase in the cohesion of the soil. Further analysis of graphs of shear stress versus normal stress of optimum blended ratio for the unit of cohesion (c_u) and the angle of shearing resistance (φ) at different cycles of compaction is given in *Table 6*.

Table 6: Comparison of cohesion and shearing resistance of cinder gravel with cycle compaction

Compaction cycles	**Unit of cohesion (c_u) (Kg/cm^2)**	**Angle of shearing resistance (φ)**	**Shear strength (Kg/cm^2)**
One cycle compaction	0.2	54.28	4.43
Two cycle compactions	0.4	52.45	4.35
Three cycle compactions	0.4	51.96	4.29
Four cycle compactions	1.1	40.57	3.7
Five cycle compactions	0.8	42.72	3.61

The results in *Table 6* showed that the unit of cohesion (c_u) of cinder gravel increased with the number of compaction cycles. As the material became finer as a result of the breakdown of large particles of weathered rock into fines, the particles became more cohesive to resist shear failure. Better cohesion was due to mutual attraction existing between fine particles that tend to hold them together in a solid mass. Thus, it indicates that the cohesive properties of the cinder gravel material improve with compaction, as further shown in *Figure 12*.

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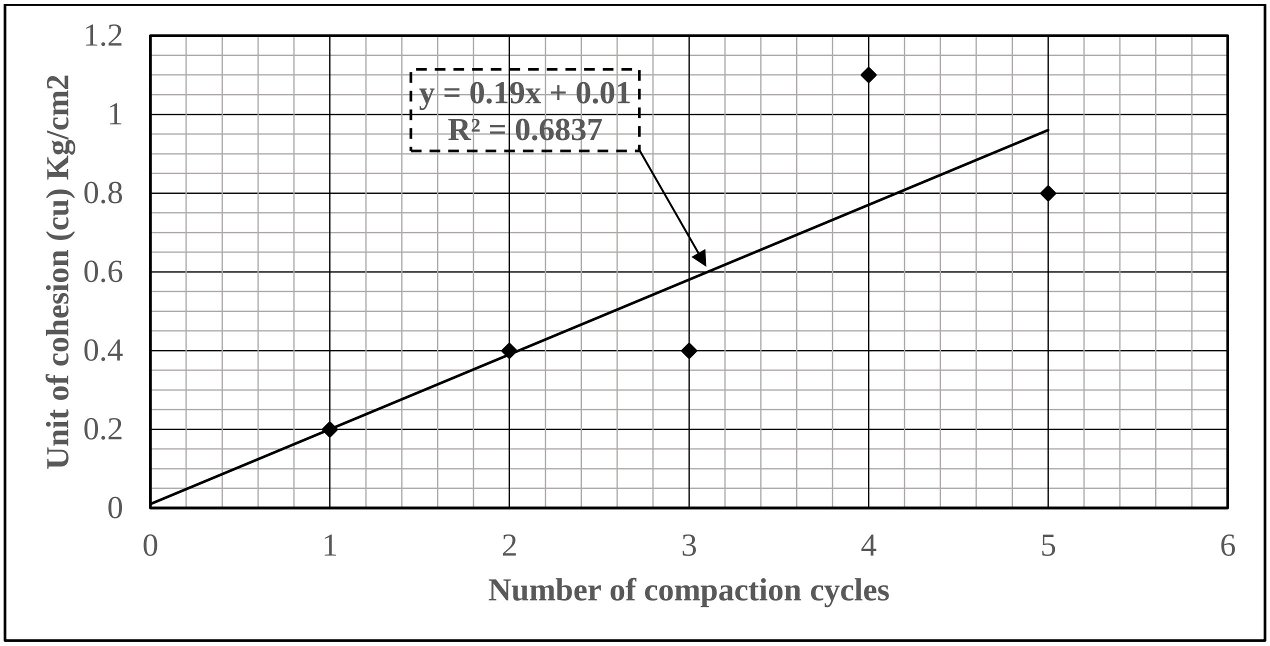
Figure 12: Correlation between the number of compaction cycles with unit of cohesion (cu) of cinder gravels



From *Figure 12*, it is observed that a linear relationship exists between compaction cycles and unit of cohesion expressed by the trend line equation.

$$c_u = 0.19NC + 0.01 \quad (6)$$

$$R^2 = 0.6837$$

c_u is the unit of cohesion (Kg/cm^2), NC is the number of compaction cycles and R^2 is the coefficient of correlation (variation of observed values to the trend line).

Further analysis of the results in *Table 6* showed that the angle of shearing resistance (φ) decreased with compaction cycles. This was also observed graphically in *Figure 11*, where the trend line is steeper for lower compaction cycles. According to Alias et al. (2014), the angle of friction is dependent on the particle size; the particle-to-particle contact provides an interlocking surface that resists the shearing resistance. In repeated cycle compaction as the cycles of compaction increased, the angle of friction decreased. This was a result of the breaking down of larger particles into smaller particles which reduced the surface area for the interlocking of the particles. This showed that the amount of friction between soil particles decreased with compaction and so did the interlocking of particles, as shown in *Figure 13*.

The result was consistent with the findings by Wang et al. (2013) that the angle of shearing resistance is generally increasing with increasing median particle diameter and gravel content. Wang et al. (2013) investigated the effects of particle size distribution on the shear strength of accumulation soil and concluded that larger size particles produced higher effective internal friction angle and developed high shear strength. These results agreed with previous studies by Wang et al. (2013), Charles and Watts (1980) and Nakao and Fityus (2008) that the value of friction angle increases with an increase in particle size.

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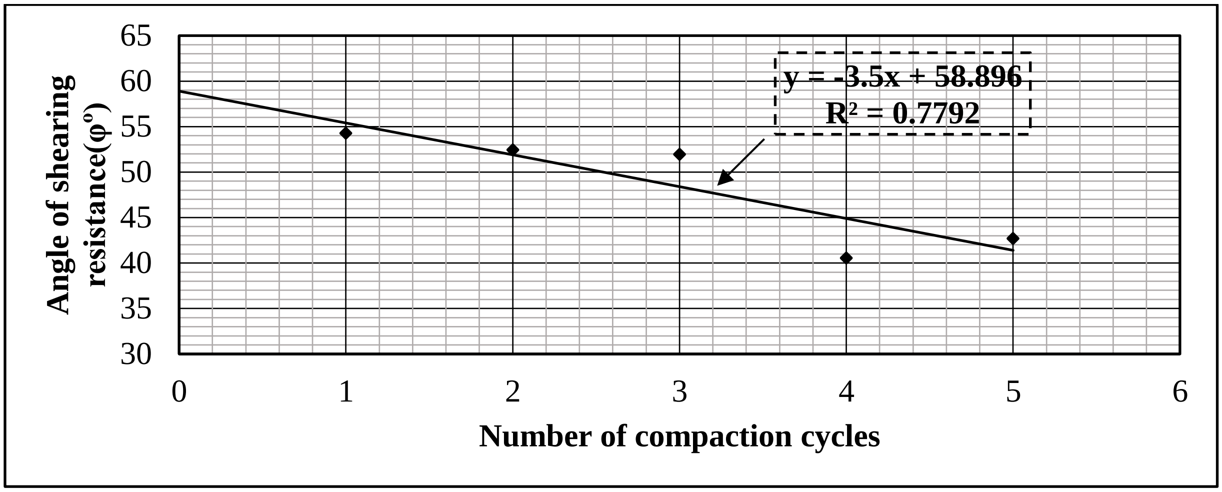
Figure 13: Correlation between the number of compaction cycles with the angle of shear resistance (φ) of cinder gravel



The linear relationship between the angles of shear resistance (φ) with the number of compaction cycles of cinder gravels is expressed by the trend line equation;

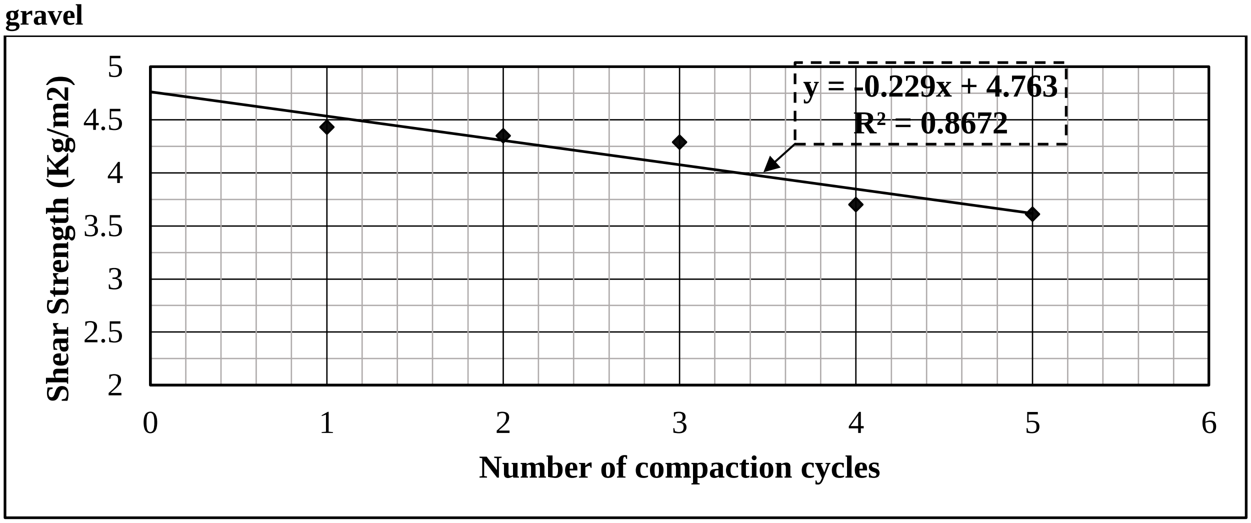
$$\varphi^o = -3.5NC + 58.896 \quad (7)$$

$R^2 = 0.7792$

φ is the angle of shear resistance (°), NC is the number of compaction cycles and R^2 is the coefficient of correlation (variation of observed values to the trend line).

The results in *Table 6* showed that the shear strength of cinder gravel decreased with the number of compaction cycles due to a comparable decrease in the angle of shearing resistance with compaction, as was observed in *Figure 13*. The enhanced cohesive component of the fine particles due to repeated compaction, as illustrated in *Figure 12* was not able to counter the decrease in shear strength due to a decrease in the angle of shearing resistance. Even though it was observed that the maximum dry density of cinder gravel increased with compaction cycles it was established from the study that it did not contribute to higher shear strength for cinder gravel as shown in *Figure 14*.

Figure 14: Correlation between the number of compaction cycles with shear strength (τ) of cinder gravel



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The linear relationship between the shear strength (τ) with the number of compaction cycles of cinder gravels is expressed by the trend line equation;

$$\tau = -0.229NC + 4.763 \quad (8)$$

$$R^2 = 0.7792$$

τ is the shear strength (Kg/cm^2), NC is the number of compaction cycles and R^2 is the coefficient of correlation (variation of observed values to the trend line).

CONCLUSIONS

From laboratory tests carried out on neat and blended cinder gravel sourced from Meru County in Kenya, the following conclusions were made.

- Cinder gravel was suitable for road pavement construction material for LVSRs when blended with weathered rock at an optimum blending ratio of 90% cinder + 10% weathered rock.
- The improvement of cinder gravel through mechanical stabilisation (blending) with red soil did not achieve the specification requirements for road pavement construction for LVSRs because of high plasticity. This requires the use of chemical stabilisation (lime, pozzolans, cement and others) which may not be appropriate or cost-effective for LVSRs where it is preferred that the initial cost of construction is kept low for the project to be viable.
- The higher strength of blended cinder gravel was achieved at lower moistures before the MDD/OMC. It was therefore concluded that cinder gravel was suitable as road pavement construction material in dry areas (ASAL) where the annual rainfall is less than 500 mm.
- The strength of cinder gravel decreased with repeated compaction when soaked due to the dispersal nature of the particles of the material with water ingress. Where the material has been used for pavement construction, the layer should be properly sealed with an impervious overlying material to prevent water ingress.
- Repeated cycle compaction of cinder gravels is not beneficial for slope stability in high embankments due to decreased angle of shear resistance and reduction in shear strength.

Recommendations

Recommendations from the Study

- The research was based on laboratory tests of cinder gravel where conditions are controlled/regulated and there is a need to validate the findings in the field where the material has been used to construct pavement layers.
- Improvement of cinder gravel through mechanical stabilisation (blending) only with red soil did not meet the plasticity specifications for LVSRs. It is recommended that chemical stabilisation with lime or cement be done for the suitability of the blend for road pavement construction for LVSRs.
- Cinder gravel is suitable for use as road pavement construction material in dry areas (ASAL) where the annual rainfall is less than 500 mm.

Recommendations for Further Research

- Conducting undisturbed field tests on the road where cinder gravels have been used as a pavement material to predict the road pavement performance of LVSRs.
- The finding from the study calls for further investigation of the strength and densification properties of cinder gravels before specifying the requirements of the material for pavement construction.

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- Carry out repeated cycle compaction of cinder gravel for higher blending ratios with locally available fine materials to compare the strength properties of the material with soaking.

- During the investigation, it was established that cinder gravel varied considerably in physical properties and characteristics for different quarries. It is therefore recommended that further research be carried out for the suitability of cinder gravels sourced from other parts of the country where the material is readily available for comparison with the findings from this study.

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