

Circular Utilization of Locally Sourced Aggregates for Stabilizing Expansive Soils: Experimental Evidence from Ambo Sandstone and Cinder Gravel

Leevesh Kumar

leevesh.amou@gmail.com

Gudeta Midkesa

Research Article

Keywords: Ambo sandstone, Cinder gravel, Circular construction, Mechanical stabilization, Sustainable subgrade

Posted Date: May 19th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-8356915/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Circular Utilization of Locally Sourced Aggregates for Stabilizing Expansive Soils: Experimental Evidence from Ambo Sandstone and Cinder Gravel

Gudeta Midkessa ¹, Leevesh Kumar ^{2*}

¹Department of Construction Technology & Management, Ambo University, Ambo, Ethiopia

²Department of Civil Engineering, World University of Bangladesh, Dhaka, Bangladesh-1230

* Corresponding author, Email address: leevesh.amou@gmail.com

Abstract

This research assesses the future prospects of using locally found sandstone and cinder gravel as a sustainable and resource-conserving stabilizer of expansive subgrade soil, which is also based on the principles of the circular economy to encourage the valorization of the local material and the minimization of reliance on chemical supplements that are carbon-laden. Mechanical stabilization of expansive soil samples of Ginchi, Ethiopia was done with different proportions (0-80%) of the Ambo sandstone and cinder gravel. Atterberg limits, compaction characteristics, California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) were laboratory tests performed in compliance with AASHTO and ASTM standards to evaluate the variations in the plasticity, the density, strength, and the bearing capacity. Both stabilizers enhanced engineering performance as it was most optimal at 60 percent replacement. In this level, PI dropped to 27% to 10.5% (sandstone) and 5.8% (cinder gravel), MDD rose to 1.68 g/cm³ to 1.81-1.85 g/cm³, UCS rose to 195 kPa to 487-520 kPa, and soaked CBR grew to 0.79% to 6.25-7.18%, which were below minimum requirements of ERA subgrade. Cinder was found to have better improvement than sandstone in most of the parameters. Indigenous Ambo sandstone and cinder gravel are used to increase the soil strength besides minimizing the environmental effects of cement- and lime-based stabilization. Their implementation helps in circularity, through the encouragement of the use of local resources, lowering the emissions of transport, and decreasing the injuries of using externally obtained materials. The results show a viable, inexpensive and sustainable road construction route through expansive soils areas.

Keywords: Ambo sandstone, Cinder gravel, Circular construction, Mechanical stabilization, Sustainable subgrade.

1. Introduction

Expansive soils are considered to be the most troublesome geomaterials in the civil and transportation engineering science because of the large proportion of clay minerals, especially montmorillonite, which leads to high swelling and contraction under wetting and drying processes (Nelson and Miller, 1992; Chen, 2012). Such volumetric variations frequently result in cracking of the pavement, settling of the foundation at different rates, early structural failure and higher maintenance expenses particularly in under loaded infrastructure like road undercarriage. Ethiopia holds vast soils mostly scattered in the central highlands and the lowlands that continues to bring challenges to the sustainable development of roads (Zewdie, 2004; Hunde, 2014; Bibiso, 2017). Also, they do not pose good advantages to be used as subgrade material unless suitable stabilization measures are put in place due to their low shear strength, high level of plasticity and low bearing capacity. Traditional methods that are used to stabilize soil are usually based on the use of those chemical binders that include cement, lime, and industrial by-products which are effective to enhance the plasticity, strength, and compressibility properties (Senol et al., 2006; Ghosh and Dey, 2009; Castro et al., 2011). These stabilizers are however linked to high energy consumption, large CO₂ emissions in the production process, and high construction costs, especially in developing areas where the access and transportation of such materials are restricted (Castro et al., 2011; Vincent et al., 2020; Ifediniru and Ekeocha, 2022). Consequently, there is an increased concern on their environmental impact and their sustainability in the long run, leading to a quest to find alternative methods of stabilization that have a low embodied energy input and dependency of carbon-intensive binders.

Resource-efficient and circular construction practices nowadays are getting more of attention, with the focus placed on the use of locally available resources, the decrease of virgin resource mining, and the decrease of emissions related to transportation. In the framework of geotechnical engineering, mechanical stabilization with the help of the native granular material that can enhance the performance of soils but minimise the environmental effects can be considered such approaches (Senol et al., 2006; Universal Rural Road Access Program, 2009). Local aggregate technology is consistent with the sustainability goal by reducing the distance of resources transportation, valorizing the resource at

the region, and developing cost-efficient infrastructure in the low-income and rural environment (Hunde, 2014; Hailu et al., 2015). Other indigenous resources in Ethiopia especially in the Oromia region are ambo sandstone and cinder gravel (red ash). These are non-plastics and angular materials that are in granular form, and thus they are good candidates to be used in the mechanical stabilization of expansive soils. It has already been proved that granular additives, including sand, gravel, crushed rock, and volcanic cinders, could be effectively used to lower clay activity, enhance particle gradation, improve compaction properties, and enhance the strength and bearing capacity of weak soils (Indiramma & Sudharani, 2017; Balkis, 2019; Senol et al., 2006). Nevertheless, with this potential, available Ethiopian literature has mostly concentrated on chemical stabilization processes or individual assessments of the traditional materials, and little comparative analysis of local sourced aggregates has been conducted (Zewdie, 2004; Bibiso, 2017).

Furthermore, sustainability is also not addressed (reduced embodied energy, less transportation emission, and long service life of stabilized subgrades); this is not common to expansive soil stabilization research in the Ethiopian setting. This exclusion is significant upon the national policy directions that promote use of local materials in order to have economical, robust, and environmentally friendly road infrastructure (Universal Rural Road Access Program, 2009). To fill these gaps, the current research paper will examine the engineering performance of the expansive soils with limitations in the proportion of Ambo sandstone and cinder gravel using a set of laboratory experiments in the context of AASHTO and ASTM guidelines. Besides evaluating the plasticity, compaction, strength, and bearing capacity, the research brings into focus the role of locally sourced aggregates in resource-efficiency and circular building to lessen relying on carbon-intensive stabilizers and increase the sustainability of the subgrade construction of roads. The current study seeks to offer a practical advice on the implementation of the low-cost low-carbon stabilization measures that could be applied in Ethiopia among other regions with similar geotechnical and environmental constraints.

2. Materials and Methods

2.1 Study Area and sample collection

In Ginchi, Ethiopia a region where montmorillonite clay prevalence is high and shrink-swell is great (Nelson & Miller, 1992; Chen, 2012), expansive soils were taken at various sites along an under-construction road section. Samples pits were dug to a depth of between 0.5 m 3 m. The mobile GPS was used to capture the geographic positions of every location, and plotted on the master plan of Ambo town, as shown in Figure 1. Similar to previous soil surveys of Ethiopian expansive soil areas (Zewdie, 2004; Bibiso, 2017), the samples that were collected were dark clayey in nature that was characteristic of high-plasticity Vertisols. Sandstone of Ambo was procured at Sankalle Faris quarry, in the north west of Ambo, and cinder gravel (red ash) at Tulu-Dimtu, some 10 km south west of Ambo. Both of them are local aggregates that are commonly used in the construction of a region (Hunde, 2014).

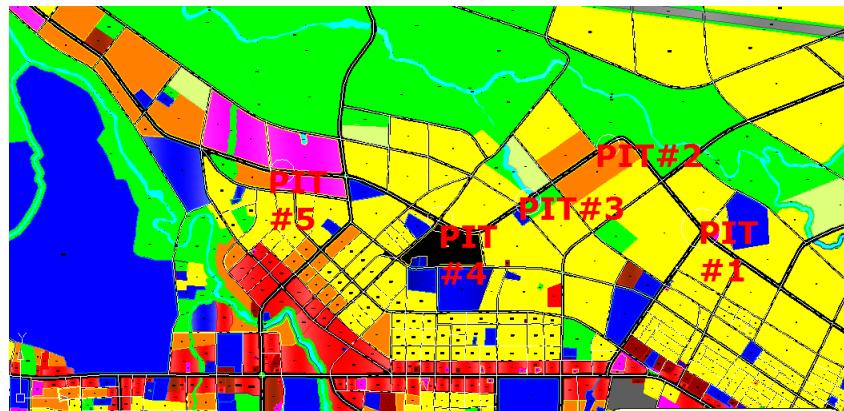


Fig. 1 Soil sampling locations and GPS coordinates in the Ginchi–Ambo area

2.2 Materials Description

2.2.1 Expansive soil

The native soil was mainly fine-grained clay and the ability to swell and plasticity typical of black cotton Ethiopian soils (Hailu et al., 2015; Jones, 2018). The soil was air-dried, crushed and sieved before testing in accordance with AASHTO T87-86.

2.2.2 Sand stone and Cinder gravel

Air drying of the two granular stabilizers followed, then they were crushed (manually where necessary) and sieved to the right gradation to be mechanically stabilized. The sandstone and cinder gravel used in this study are shown in Figure 2 and 3, respectively. They are not plastic and receive angularity, which predisposes them to changing the clay soil structure (Indiramma & Sudharani, 2017; Balkis, 2019).



Fig. 2 Sand stone



Fig. 3 Cinder gravel

2.2.3 Sample preparation and mixing protocol

Each stabilizer was mixed with natural soil at 0, 20, 40, 60 and 80 percent replaced in terms of dry weight, as summarized in Table 1. These ratios were chosen regarding the past studies that indicated that the highest performance was achieved before the segregation of particles at high aggregate contents (Senol et al., 2006; Ghosh and Dey, 2009). The samples were mixed well so that the stabilizers could be evenly distributed. The soil-stabilizer mixtures were prepared as per the AASHTO, ASTM and ERA standards in each category of the tests, and this correlates with other studies of stabilization in the past in Ethiopia and elsewhere (Castro et al., 2011; Ifediniro & Ekeocha, 2022).

Table 1 Proportions of soil-stabilizer mixtures used in this study

Mix ID	Soil (%)	Ambo sandstone (%)	Cinder gravel (%)
M0	100	0	-
M20	80	20	-
M40	60	40	-
M60	40	60	-
M80	20	80	-
C20	80	-	20
C40	60	-	40
C60	40	-	60
C80	20	-	80

2.3 Experimental setup

To determine the influence of sandstone and cinder gravel on plasticity, compaction, strength and bearing capacity, a systematic series of geotechnical tests were carried out.

2.3.1 Grain size analysis

AASHTO T11-96 wet sieve and hydrometer analyses were conducted to establish the fractions of gravel, sand, silt and clay. The content of Clay was of great interest because it is directly related to the swelling potential of Vertisols (Nelson & Miller, 1992). Particle-size classification followed AASHTO and USCS standards, where gravel, sand, silt, and clay were defined based on the size thresholds shown in Table 2.

Table 2 Grain-size classification ranges according to AASHTO and USCS standards

S.N.	Description	AASHTO	USCS
1	Gravel	>2 mm	>4.75 mm
2	Sand	0.075-2 mm	0.075-4.75 mm
3	Silt	0.002-0.075 mm	0.002-0.075 mm
4	Clay	<0.002 mm	<0.002 mm

2.3.2 Atterberg limits

The standard methods involving the determination of liquid limit (LL), plastic limit (PL), and plasticity index (PI) were similar to the methods used in other similar expansive soil research (Bibiso, 2017; Vincent et al., 2020). The results of this test for untreated soil are presented in Table 3. These measurements helped to measure the losses in plasticity due to the addition of stabilizers. Measurement of shrinkage limit and linear shrinkage was under IS:2720 guidelines, which are more commonly used to test the behavior of expansive soils (Khemissa and Mahamedi, 2014).

$$PI = LL - PL \quad (1)$$

Table 3 Atterberg limits of natural soil prior to stabilization

Sample	LL (%)	PL (%)	PI (%)	Shrinkage limit (%)
Pit 1	86.12	35.38	50.74	17.27
Pit 2	96.83	31.2	65.63	16.4
Pit 3	102.61	36.66	65.95	17.14
Pit 4	89.51	32.63	56.88	17.14
Pit 5	89.21	35.95	53.26	15.71

2.3.3 Free swell index

Free swell index of the natural soil was calculated in line with the most commonly accepted standard of IS:2720 (Part 40), which is a technique of assessing swelling potential of expansive soils containing montmorillonite. Table 4 shows the measured value of the free swell index of the natural soil sample, and gives necessary background data of the expansive behavior of the soil before undergoing stabilization.

$$FSI = \frac{V_f - V_o}{V_o} \times 100 \quad (2)$$

Table 4 Free swell index and specific gravity of natural soil sample

Sample	Free swell index (%)	Specific Gravity
Pit 1	107.33	2.75
Pit 2	114.33	2.75
Pit 3	103.67	2.71
Pit 4	104	2.78
Pit 5	101.33	2.73

2.3.4 Specific gravity

Specific gravity of the natural soil and stabilized mixtures were determined according to AASHTO T100-93. This parameter is necessary in the computation of void ratio and degree of saturation, which form a basis of interpreting

compaction and strength properties (Sindelar 2015). Table 4 summarizes the results of a measurement of the specific gravity of the natural soil sample.

2.3.5 Compaction characteristics

Proctor compaction testing followed AASHTO T99-94 in order to find out the maximum dry density (MDD) and optimum moisture content (OMC) of the natural soil. The compaction properties thus obtained were summarized in Table 5 and it offers some baseline against which the effect of mechanical stabilization on soil density can be evaluated. Density characteristics developed with the help of mechanical stabilization have been proven to increase the gradation of soil and particle packing, which results in enhanced engineering performance (Indiramma & Sudharani 2017; Balkis 2019).

$$\gamma_d = \frac{\gamma}{1 + w} \quad (3)$$

Table 5 Compaction characteristics (MDD and OMC) of natural soil

Pit	MDD (g/cm ³)	OMC (%)
1	1.47	27.13
2	1.5	26.89
3	1.49	26.15
4	1.49	26.69
5	1.5	27.14

2.3.6 Unconfined compressive strength (UCS)

AASHTO T208 was used to test unconfined compressive strength (UCS) to determine the undrained shear strength of both the natural soil and stabilized mixtures. The remodeled specimens were made at maximum dry density (MDD) and optimum moisture content (OMC). UCS test is a popular method of testing soil stabilization methods (Senol et al., 2006; Ghosh and Dey 2009). Figure 4 represents the stress-strain behavior of the natural soil obtained in UCS test.

$$q_u = \frac{P}{A} \quad (4)$$

$$C = \frac{q_u}{2} \quad (5)$$

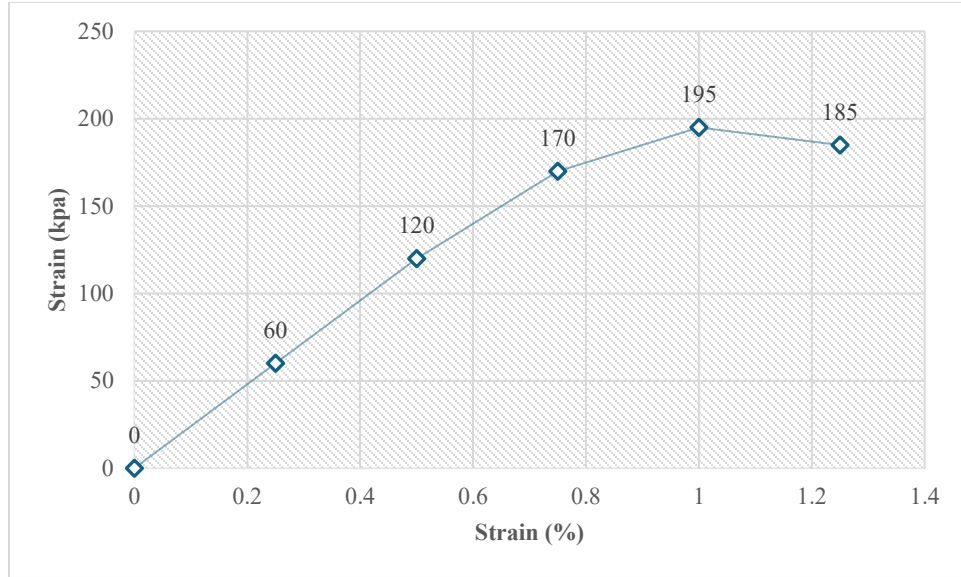


Fig. 4 UCS stress–strain (Natural soil)

2.3.7 California bearing ratio (CBR)

Both wet and dry CBR testing was performed according to the AASHTO T193-93 which is in agreement with the ERA standard of subgrade material. CBR is an important measure of the road subgrade suitability, which is mostly applied in expansive soils (Universal Rural Road Access Program, 2009). The findings of these tests are presented in Table 6 and the related load-penetration behavior of the natural soil is shown in Figure 5. Also, values of swell in the soaking process were observed to ascertain the efficiency of stabilization in the volumetric expansion minimization.

$$\text{CBR} = \frac{\text{Total Load}}{\text{Standard Load}} \times 100 \quad (6)$$

Table 6 Soaked and unsoaked CBR values of natural soil

Sample	Soaked CBR (%)	Unsoaked CBR (%)	Swell (%)
Pit 1	0.79	0.84	3.353
Pit 2	0.75	0.85	3.496
Pit 3	0.75	0.86	3.676
Pit 4	0.74	0.89	3.652
Pit 5	0.76	0.92	3.627

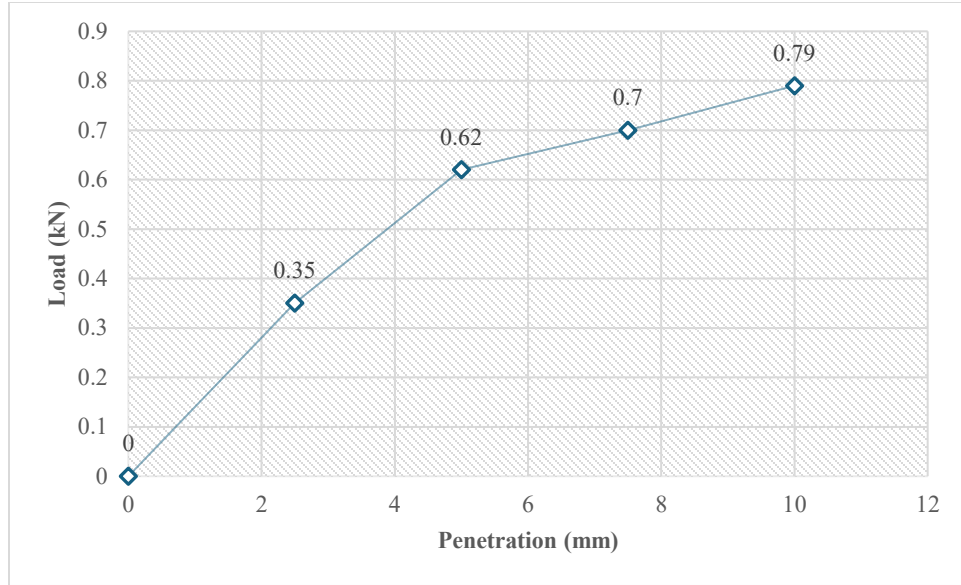


Fig. 5 CBR load–penetration (Natural soil)

2.3.8 Data analysis

Microsoft Excel was used to analyze all the laboratory results. There were comparisons of trends in MDD, OMC, PI, UCS and CBR based on replacement levels. The interpretation of the observations was done based on the existing theories of mechanical stabilization and reinforced by the earlier findings on the sand-, cinder-, and gravel-stabilized clay soils (Castro et al., 2011; Ifediniru & Ekeocha, 2022).

3. Result and Discussion

3.1 Index Properties of Natural Expansive soil

The native soil was of the high-plasticity vertisols that are characteristic of Ethiopia and liquid limit (LL) values of 76.8 to 102.6% and plasticity index (PI) values of 47.1 to 65.9% (see Table 7). These characteristics place the soil under high-plasticity clay (CH) in the USCS and A-7-5 in AASHTO which is consistent with prior research of expansive soils in the area. The free swell index was above 100% which means that it contained high contents of montmorillonite and is prone to volumetric instability, which further underlines the necessity to stabilize the soil before laying the road. Table 8 summarizes the soil properties prior to sand and cinder gravel additions to give a reference point on the possible stabilizers. The high variability and inadequate inherent engineering performance of the soil, according to a circular economy (CE) view, drive the search of low-carbon and locally available additions to the standard chemical stabilizers, mitigating environmental effects and reliance on foreign resources.

Table 7 Basic engineering properties of natural expansive soil

Property	Pit 1	Pit 2	Pit 3	Pit 4	Pit 5
Initial moisture content (%)	48.53	51.02	53.06	51.39	40.67
Specific gravity	2.75	2.75	2.71	2.78	2.73
% Passing No. 200	98.8	99.2	99.87	99.92	99.91
Liquid limit (%)	76.79	78.3	102.61	89.51	89.21

Plastic limit (%)	23.05	31.2	36.66	32.63	35.95
Plasticity index	53.75	47.1	65.95	56.88	53.26
Linear shrinkage (%)	17.27	16.4	17.14	16.7	15.71
Free swell (%)	107.33	114.33	103.67	104	101.33
USCS classification	CH	CH	CH	CH	CH
AASHTO classification	A-7-5	A-7-5	A-7-5	A-7-5	A-7-5
MDD (g/cm ³)	1.47	1.5	1.49	1.49	1.5
OMC (%)	27.13	26.89	26.15	26.69	27.14
Soaked CBR (%)	0.79	0.75	0.75	0.74	0.76
Unsoaked CBR (%)	0.84	0.85	0.86	0.89	0.92
Swell potential (%)	3.353	3.496	3.676	3.652	3.627

Table 8 Soil properties before adding the sand and cinder gravel

Sample No.	Depth	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Specific gravity
1	3.1	0.03	22.88	24.84	43.21	2.75
2	3	0.09	23.12	23.25	48.13	2.75
3	2.9	0.14	21.62	24.68	53.83	2.71
4	3	0.08	21.82	26.92	51.44	2.78
5	3.4	0.09	77.19	26.09	51.37	2.73

3.2 Grain size analysis

The grain size analysis revealed that the natural soil is characterized by the predominance of fine particles and that the clay fraction is 43-53% and very little gravel is present, as Figure 6 indicates. This type of distribution of particles also leads to shrink-swell and low workability. They added Ambo sandstone and cinder gravel to help the gradation because coarser material was added and less clay was dominant. Such a gradation doesn't only boost the engineering performance, but also helps the principles of the circular economy, by requiring less dependency on the imported aggregates, and encouraging the use of the locally available materials.

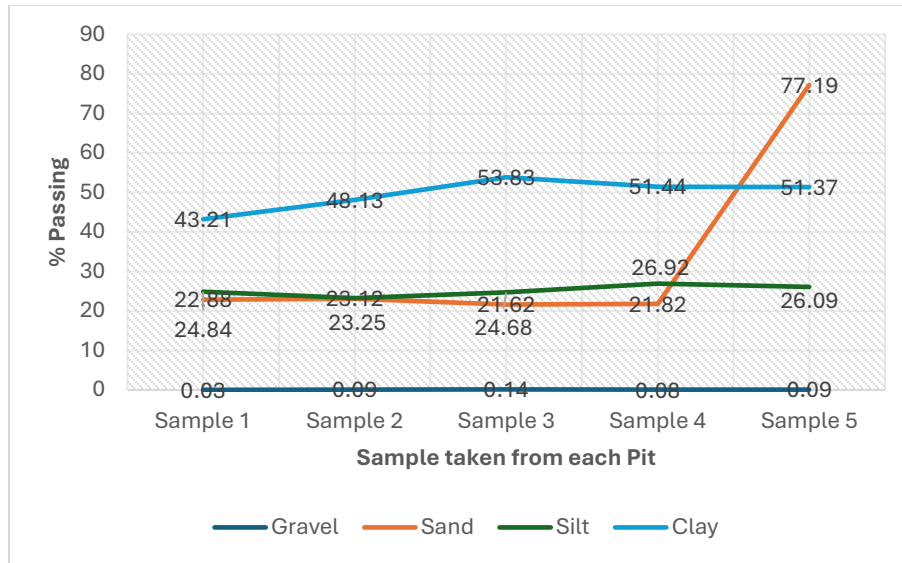


Fig. 6 Grain size distribution curve of natural soil samples

3.3 Atterberg limit and Reduction of Plasticity

3.3.1 Ambo Sandstone Stabilization

The selection of the Ambo sandstone to provide the stabilization was guided by the site conditions and the project aspect of the project, which involved the factor of stability, soil pressure, and availability of the resources. Figure 7 shows that the liquid limit (LL) and plasticity index (PI) of the soil were also greatly decreased with the addition of the sandstone, the Ambo sandstone. The PI dropped to almost half at 60% replacement to 27%, which means that the soil plasticity significantly declined. The said improvement can be explained by the fact that the appearance of non-plastic granular particles dilutes the active clay fraction and breaks the clay-water structure.

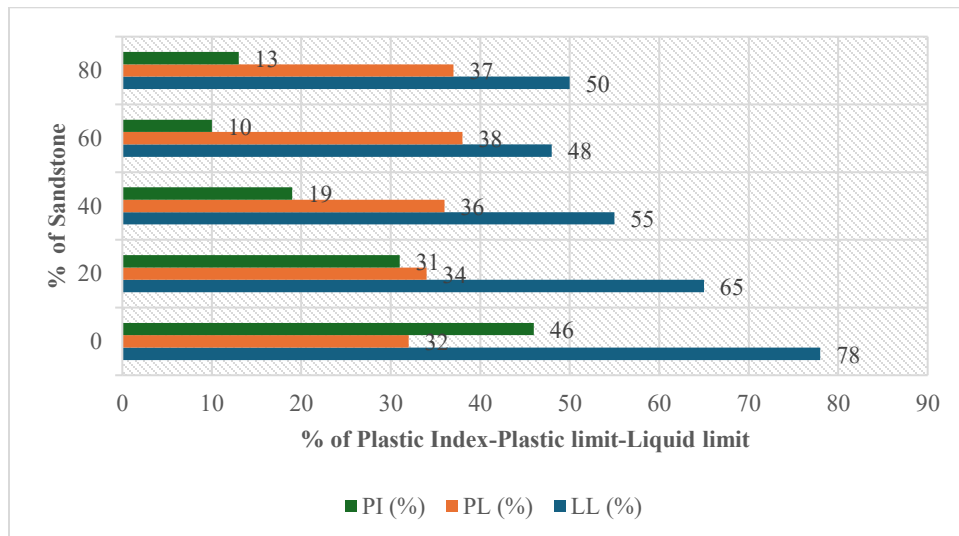


Fig. 7 Effect of Ambo sandstone on Atterberg limits

3.3.2 Cinder gravel stabilization

There was an even stronger effect of cinder gravel on the properties of soils. Figure 8 indicates that the plasticity index (PI) declined to 5.8 percent at 60 percent replacement which was close to near-non plastic behavior at higher contents. Table 9 summarized the results of unconfined compressive strength (UCS) and soaked CBR over different percentages of replacement concluding that there is better mechanical performance. Cinder gravel has a porous and vesicular structure that allows it to absorb excess moisture and as a result, expansive clay minerals become inactive and enhance soil stability.

Table 9 UCS and soaked CBR of Sandstone and Cinder Gravel at varying replacement percentages

Replacement (%)	UCS (kPa) – Sandstone	UCS (kPa) – Cinder Gravel	CBR Soaked (%) – Sandstone	CBR Soaked (%) – Cinder Gravel
0	195	195	0.79	0.79
20	260	310	3.10	3.85
40	365	415	4.85	5.60
60	487	520	6.25	7.18
80	430	470	5.10	6.90

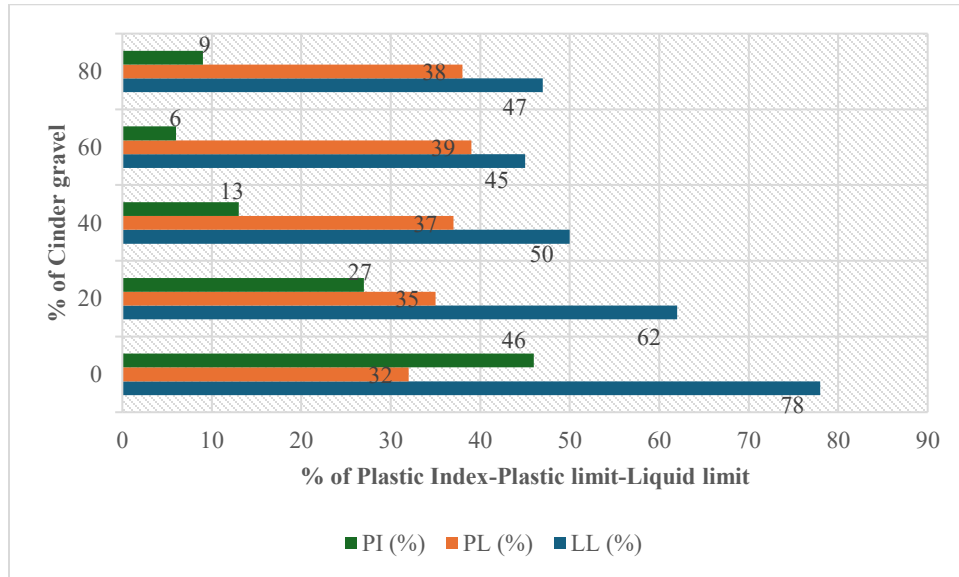


Fig. 8 Effect of cinder gravel on Atterberg limits

3.3.3 Interpretation

Swelling potential will be reduced by a linear relationship to plasticity which enhances the long-term durability of road subgrades. More to the point, this plasticity decrease is attained without the carbon-based binders, which contributes to: decreased embodied energy, cut down on CO₂ emissions, use of cement/lime supply chains and valorization of regionally available materials. Under the CE terms, the mechanical stabilization with local aggregates is the replacement of high-emission products of industries by the low impact local counterparts that underpin the sustainable development of infrastructure.

3.4 Compaction Characteristics

3.4.1 Ambo Sandstone

Figure 9 illustrates that the natural soil had an initial dry density of 1.68 g/cm^3 which was changed to 1.81 g/cm^3 with 60 percent substitution using cinder gravel and sandstone. Optimal moisture content (OMC) reduced a little, meaning that there was an increase in packing efficiency and tightness of granules in the stabilized soil matrix.

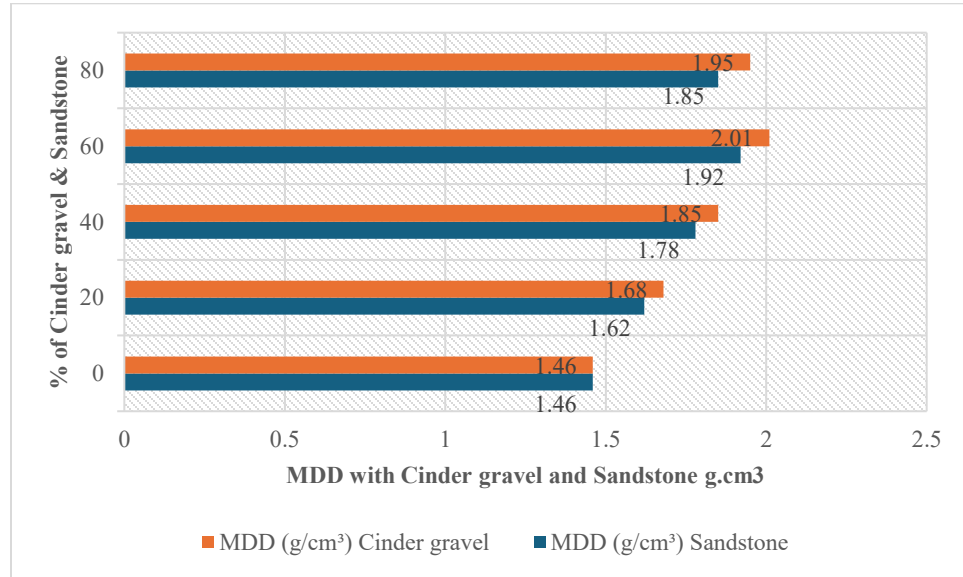


Fig. 9 MDD with cinder gravel & sandstone

3.4.2 Cinder Gravel

The increase in MDD was still higher coming up to 1.85 g/cm^3 at a 60 percent replacement. The OMC reduction suggests that there is enhanced workability and less water requirements- good in water scarce areas.

3.4.3 Sustainability Interpretation

Greater dry densities using local aggregates suggest: Less fuel used in compaction as there are fewer passes, Reduced water usage, taking care of resource efficiency, long subgrade service life, less consumption of maintenance materials. These advantages comply with CE aims to reduce resources input and enhance the lifespan functional.

3.5 Unconfined Compressive Strength (UCS)

3.5.1 Ambo Sandstone

The natural soil with stabilization increased its unconfined compressive strength (UCS) tremendously. Figure 10 presents the results of the increase in the UCS between the natural soil (195 kPa) and the replacement (60 percent cinder gravel and sandstone) (487 kPa) which is an improvement of 149 percent in UCS.

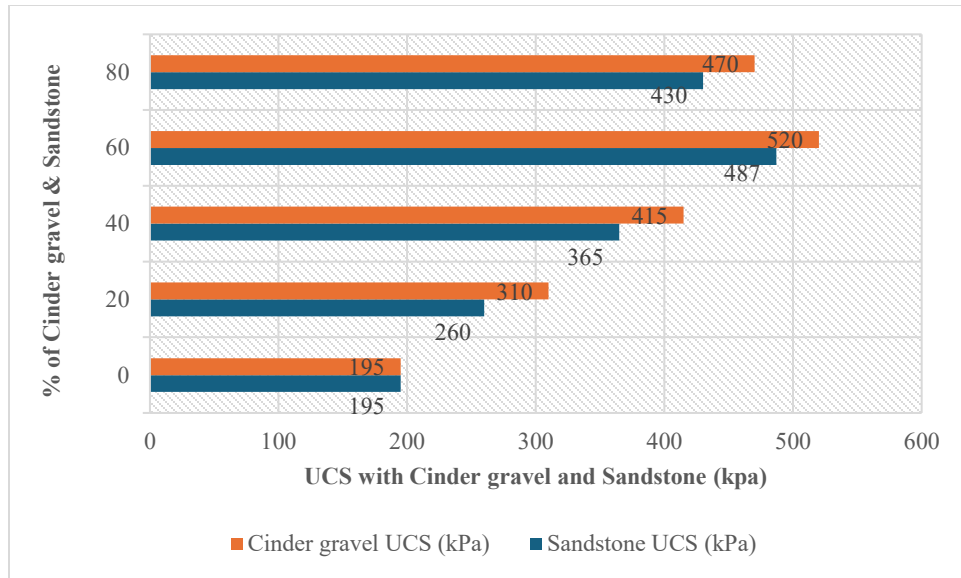


Fig. 10 UCS with cinder gravel & sandstone

3.5.2 Cinder Gravel

At the same replacement ratio, UCS increased 520 kPa at UCS-167 percent that of natural soil. Strength was slightly decreased above 60 by segregation of particles and a lack of cohesion between the matrix.

3.5.3 Mechanistic Interpretation

The benefits of strength are attributed to frictional resistance of granular stabilizers, increased packing density, and less moisture sensitivity. Cinder gravel is superior because it has rough texture and partial interparticle suction.

3.5.4 Sustainability Relevance

These findings indicate that local aggregates can substitute industrial stabilizers with similar or better performance, which enable: reduced infrastructure requirements, resiliency, reduced embodied carbon, use of volcanic resources which are available in large size as part of a circular supply chain.

3.6 California Bearing Ratio (CBR)

3.6.1 Ambo Sandstone

The stability of the CBR of the soil was enhanced significantly. Figure 11 shows that soaked CBR rose to 6.25 percent at 60 percent of substituting the natural soil with cinder gravel and sandstone, which indicates that there was a significant increase in the subgrade strength with the addition of the material.

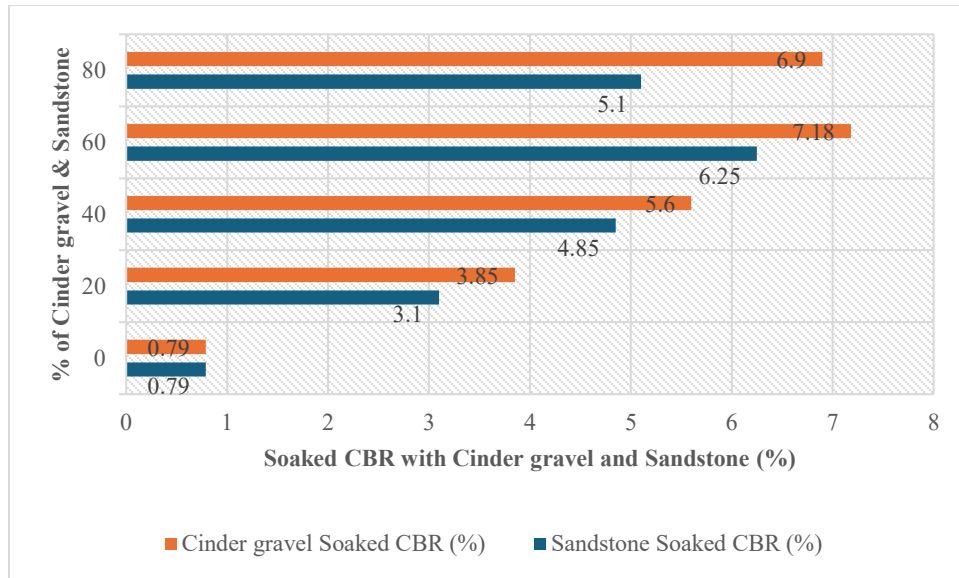


Fig. 11 Variation of soaked CBR % for cinder gravel and sandstone

3.6.2 Cinder Gravel

At 60, maximum CBR was 7.18% which slightly declined at higher contents.

3.6.3 Interpretation

The two stabilizers are above the ERA minimum of 5% of subgrade materials and this indicates its use in the light to moderate traffic roads.

3.6.4 The Perspective of CE

CBR enhancement with local aggregates helps in: decreasing the pavement thickness requirements, reducing material requirement, decreasing rehabilitation cycles, decreasing lifecycle requirements, improving durability, decreasing waste production. This is part of the CE goals through the increased functional life of the service and reduction of rework.

3.7 Performance Comparison of the Two Stabilizers

Table 10 summarizes the comparative performance of both natural soil and the optimum stabilized mixtures. Cinder gravel was found to perform better than Ambo sandstone in all the parameters, recording greater plasticity reductions, high strength, good compaction, and CBR. This high performance can be linked to the fact that it is light in weight and porous in nature with high interlocking capacity. According to the vision of the circular economy, cinder gravel is a good utilization of the volcanic material that is within the area, as it is rather cheap and has low carbon content as a substitute soil stabilizer.

Table 10 Comparative performance of natural soil and optimum stabilized mixers

Parameter	Natural Soil	60% Ambo Sandstone	60% Cinder Gravel
LL (%)	58	35.5	32.7
PI	27	10.5	5.8
MDD (g/cm ³)	1.68	1.81	1.85

UCS (kPa)	195	487	520
Soaked CBR (%)	0.79	6.25	7.18

4. Conclusion and Recommendation

4.1 Conclusion

This paper examined the performance of Ambo sandstone and cinder gravel as a sustainable and locally available stabilizers that can be applied to expansive soils that are prevalent in the Ginchi-Ambo area of Ethiopia. The laboratory findings show that the two materials are important in enhancing engineering properties of the natural soil especially plasticity reduction, compaction behavior, strength and bearing capacity. The optimum was at 60 percent replacement where both stabilizers were at or above the Ethiopian Roads Authority (ERA) standards of subgrade.

Cinder gravel was found to perform best in all the parameters, with a UCS of 520 kPa and soaked CBR of 7.18% which was better than 487 kPa and 6.25% of Ambo sandstone at the same proportion. These benefits are related to the granular, frictional, and porous properties of the materials, which increase the interlock of particles, decrease sensitivity to moisture and minimize the effects of expansive clay minerals.

In addition to the technical performance, the research also describes significant benefits of the circular economy (CE) and sustainability. The application of locally obtained stabilizers will decrease the amount of carbon-intensive chemical additives, decrease the emissions caused by transportation means and will encourage the valorization of the geological potential of the area. This reduces the embodied carbon in roadbuilding, enhancing the efficiency of resources, and extending the subgrade life-cycle- most of the sustainability objectives in the development of sustainable infrastructure in Ethiopia and other low-income countries with similar soil issues.

In general, the results indicate that both Ambo sandstone and cinder gravel are viable, inexpensive, and sustainable, as compared to the conventional stabilization techniques. Their application can be used to promote CE-based geotechnical engineering to increase performance, mitigate environmental effects, and utilize locally available materials.

4.2 Recommendations

4.2.1 Technical Recommendations

- Use 60 per cent of replacement as the ideal stabilizer value of both the Ambo sandstone and cinder gravel in expansive subgrades soils, using the highest UCS and CBR value.
- Where possible, cinder gravel must be preferred because it has better mechanical enhancements and greater resistance to moisture.
- Ambo sandstone is also potential alternative in regions where the availability of cinder gravel is scarce, and much better compared to natural expansive soil.
- Stabilizer gradation must be well regulated to reduce segregation of the particles at a greater level of replacement (>60%).
- The construction process must make sure that mixing is done thoroughly and the compaction is done well to maximize the benefits provided by the process of friction and interlocking.

4.2.2 Recommendations regarding Sustainability and Circular Economy

- Make regional pavement design standards incorporate locally found materials such as cinder gravel and Ambo sandstone to decrease the use of imported materials and industrial binders.
- Encourage the use of CE strategies through the use of the large amounts of volcanic by-products (e.g., cinder) to cut waste, and create local economic value.
- Promote water and energy saving construction through stabilization technologies that cut water usage and compaction energy hence minimizing the overall environmental footprint.
- The material selection processes should be considered by road authorities in terms of life cycles such as reduction of maintenance during extensive periods of time and carbon saving.

4.2.3 Future Research Recommendations

- Field-scale test of 60 percent stabilizer mixes to determine actual performance of the mixes under different loading and climatic conditions.
- Conduct a microstructural analysis (SEM, XRD) in order to gain a better understanding of the interaction of particles with each other and with their stabilization mechanisms.
- Use Life Cycle Assessment (LCA) to measure savings on carbon and environmental advantage over cement- or lime-stabilized alternatives.
- Explore the stability of stabilized soils in cyclic wetting- drying and freezing- thaw.
- Test other local aggregates or industrial by-products to be used as geotechnical circular material loops.

5. Competing Interests and Funding

The authors of this paper declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

6. Author Contributions

All authors read and approved the final manuscript, participated equally.

References

1. AASHTO Designated, T100-15, (2019). Standard method of test for specific gravity of soil.
2. AASHTO Designated, T193-93, (2019). Standard method of test, the California bearing ratio.
3. AASHTO Designated, T208, (2019). Standard method of test for unconfined compressive strength of cohesive soil.
4. AASHTO Designation, T87-86, (2019). Standard method of test for, dry preparation of disturbed soil samples.
5. AASHTO Designation, T256-01, (2011). Standard method of test for Pavement deflection measurements.
6. Afrin, H. (2017). A review on different types soil stabilization techniques. *International Journal of Transportation Engineering and Technology*, 3(2), 19. <https://doi.org/10.11648/j.ijtet.20170302.12>
7. Balkis, A. (2019). Çimento miktarının farklı toprakların CBR değerlerine etkisi. *European Journal of Science and Technology*, 809–815. <https://doi.org/10.31590/ejosat.588990>
8. Bibiso M. (2017), Assessment of Soil Properties in Some Selected Parts of Ethiopia, *Am-Euras. J. Agric. & Environ. Sci.*, 17 (2), 143-147. <https://doi:10.5829/idosi.aejas.2017.143.147>
9. Castro, F., D., Quesada, D., M., Vega Z., A., Calzada, P., M., (2011). Lime Stabilization of bentonite sludge from tunnel boring, *Applied Clay Science*, (51), 250–257. <https://doi:10.1016/j.clay.2010.11.028>
10. Chen, F., H., (2012). *Foundations on Expansive Soils*, Elsevier Scientific Publishing Company, Amsterdam.
11. Ghosh, A., Dey U. (2009). Bearing ratio of reinforced fly ash overlying soft soil and deformation modulus of fly ash, *Geotextiles and Geomembranes*, (27), 313–320. <https://doi:10.1016/j.geotexmem.2008.12.002>
12. Hailu, H., Mamo, Keskinen, T., R., E., Karlun, E., H., Gebrekidan, H., & Bekele, T., (2015), Soil fertility status and wheat nutrient content in Vertisol cropping systems of central highlands of Ethiopia. *Agriculture & Food Security* (2015) 4-19. <https://doi:10.1186/s40066-015-0038-0>
13. Hunde, B., (2014) Investigation on some of engineering properties of soils found in ambo town, Ethiopia, (M.Sc. Dissertation).
14. Ifediniro, C., & Ekeocha, N. E. (2022). Performance of cement-stabilized weak subgrade for highway embankment construction in Southeast Nigeria. *International Journal of Geo-Engineering*, 13(1). <https://doi.org/10.1186/s40703-021-00166-z>
15. Indiramma, P., & Sudharani, C. (2017). Scanning electron microscope analysis of fly ash, quarry dust stabilized soil. In *Sustainable civil infrastructures* (pp. 284–296). https://doi.org/10.1007/978-3-319-61902-6_22
16. IS 2720, (1977). Methods of test for soil, Part XL, Determination of free swell index of soils.
17. IS 2720-22, (1972). Methods of test for soils, Part 22, Determination of organic matter.
18. Jones, L. (2018). Expansive soils. In *Encyclopedia of earth sciences series/Encyclopedia of earth sciences* (pp. 314–320). https://doi.org/10.1007/978-3-319-73568-9_118

19. Kerrane, J. P. (2004). What are expansive soils? Article on construction defects.
<https://kerranestorz.com/blog/post/what-are-expansive-soils>
20. Khemissa, M., & Mahamedi, A. (2014). Cement and lime mixture stabilization of an expansive overconsolidated clay. *Applied Clay Science*, 95, 104–110. <https://doi.org/10.1016/j.clay.2014.03.017>
21. Nelson, J. D., Miller, D. J., (1992). *Expansive soils, Problems and practice in foundation and pavement engineering*, John Wile & Sons, Inc. New York.
22. Senol, A., Edil, B. T., Shafique, Md. S. B., Acosta H. A., Benson, C.H. (2006). Soft subgrades stabilization by using various fly ashes, *Resources, Conservation and Recycling*, (46), 365–376.
<https://doi:10.1016/j.resconrec.2005.08.005>
23. Sindelar, M. Soils support buildings/infrastructure. *Soil Sci. Soc. America* (2015).
<https://www.soils.org/files/sssaiys/may-soils-overview.pdf>
24. Universal Rural Road Access Program, the Way Forward to Practical Demonstration of Road Construction on Expansive Soil Sub-grade. Ministry of work and urban development. (2009), Addis Ababa Ethiopia.
25. Vincent, E., Dominic, P., & Kure, M. (2020). Assessment of Geotechnical Parameters of Lateritic Soil of Jos and Environs, for Civil Engineering Constructions North Central part of Nigeria. *Nigerian Annals of pure and applied sciences*, 3(3b), 222–239. <https://doi.org/10.46912/napas.209>
26. Zewdie, A., (2004). Investigation into shear strength characteristics of expansive soil of Ethiopia. (M.Sc. Dissertation).