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Sustainable Stabilization of Expansive Soil for Subgrade Applications Using Waste Glass Powder and Steel Slag

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Abstract

Expansive soils pose a significant challenge to civil engineering practice, frequently causing structural damage and constraining road infrastructure development in Ethiopia. Pavements and light structures constructed on such soils are particularly vulnerable to premature failure due to excessive settlement and recurring volume changes. This study investigated the improvement of expansive soil for subgrade applications through stabilization using steel slag (SS) and waste glass powder (WGP). Laboratory experiments were conducted with glass powder and steel slag contents ranging from 5% to 20% at 5% increments. Waste glass powder, sourced from discarded drinking glass and construction waste, was finely ground and evaluated for its chemical composition and pozzolanic activity prior to use. Although steel slag is an effective stabilizing agent, its limited availability and high cost restrict its widespread application; therefore, a blended SS–WGP stabilization approach was examined as a more economical and sustainable alternative. Soil samples were collected from a road section at a depth of 1.5 m, and comprehensive laboratory tests were performed to determine the physical and mechanical properties of both untreated and treated soils. According to the AASHTO classification system, the natural soil was classified as A-7-5, while the Unified Soil Classification System (USCS) categorized it as CH. The results demonstrated that increasing SS and WGP contents significantly enhanced the maximum dry density (MDD), California Bearing Ratio (CBR), and unconfined compressive strength (UCS), while reducing the liquid limit (LL), plasticity index (PI), free swell index (FSI), optimum moisture content (OMC), California Bearing ratio (CBR), CBR swell Unconfined compressive Strength (UCS). Specifically, the PI decreased from 39.52% to 8.40%, FSI from 102.7% to 35.5%, and OMC from 25.82% to 21.05%. Conversely, MDD increased from 1.385 g/cm³ to 1.65 g/cm³, CBR improved from 2.26% to 9.35%, CBR swell drops 9.74% 1.58% and UCS rose from 24.26 kPa to 125.38 kPa at the optimum blend of 20% SS and 15% WGP. Overall, the combined use of steel slag and waste glass powder proved to be an effective and sustainable method for enhancing the engineering performance of expansive soils for subgrade applications.

Keywords: Expansive soil; Stabilization; Steel slag; Waste glass powder; Subgrade improvement

Introduction

Engineering structures founded on expansive soils often suffer from serviceability and durability problems due to the pronounced volume changes of the subsurface material. These soils swell significantly when exposed to moisture and shrink upon drying, resulting in differential ground movements. In areas dominated by expansive soils, the subgrade is typically stiff, which increases the susceptibility of lightly loaded structures to cracking caused by uneven settlement [1]. Consequently, infrastructure such as buildings, bridges, and pavements is particularly vulnerable to damage. This challenge is well documented in Ethiopia [2] and in many other regions worldwide.

To mitigate the adverse behavior of expansive soils, soil stabilization techniques are widely employed to ensure that subgrade materials meet required engineering performance criteria. Soil stabilization involves the modification of soil properties through mechanical or chemical means to improve strength, durability, and volumetric stability [3]. The primary mechanisms governing stabilization include cation exchange, flocculation, agglomeration, and pozzolanic reactions, which collectively alter soil structure and behavior. Various stabilizing agents have been used, such as recycled gypsum [4], cement [5], lime [6], [7], [8],[9], bitumen [10], modified drilling waste materials [11], oil palm kernel shell and cockle shell derivatives [12], limestone powder waste [13], and laboratory-developed binders such as the SEU-2 binder [7], [14]. Although effective, these additives are often associated with high production costs and adverse environmental impacts [8], [15], [16]. As a result, increasing attention has been directed toward low-cost and sustainable alternatives, including household and agricultural wastes [17], fly ash [14], bagasse ash, and rice husk ash [18-19].

Stabilization generally reduces soil plasticity, enhances strength, improves workability, and minimizes volume changes induced by variations in moisture and temperature. In some cases, it may also alter soil permeability [16]. Based on Atterberg limits and particle-size distribution, clayey soils can be categorized as having low, medium, high, or very high swelling potential. According to the Unified Soil Classification System (USCS), soils classified as CL or CH [20] and as A-6 or A-7 under the AASHTO system, are typically considered expansive soils [1], [2]–[21]. Expansive clay soils are particularly problematic due to their inherent tendency to undergo excessive swelling and shrinkage in response to moisture fluctuations [22].

Chemical stabilization of clay soils commonly occurs through cation exchange and pozzolanic reactions. Pozzolanic materials are defined as substances containing silica (SiO_2), alumina (Al_2O_3), and ferric oxide (Fe_2O_3) in combined proportions equal to or exceeding 70% by weight [23-24]. The incorporation of such materials reduces soil porosity and pore size while enhancing strength through the formation of calcium silicate hydrate (C–S–H) in the presence of calcium hydroxide and water [23]. Despite these advantages, the construction of stabilized roads remains costly due to continued reliance on industrial stabilizers such as cement and lime [21]. Therefore, the use of industrial and solid waste materials—such as waste glass powder (WGP) and steel slag (SS)—as alternative stabilizing agents presents a promising and sustainable solution.

Waste glass powder is widely available worldwide, originating from households, hotels, and construction activities, where discarded glass is crushed and disposed of as solid waste. Since glass is non-biodegradable, its accumulation poses environmental challenges and adversely affects soil quality and ecosystem health. Consequently, WGP has gained recognition as a viable soil stabilizing material [25]. Globally, glass production is estimated at approximately 130 million tons annually, yet only about 40% is recycled [26-27]. In Addis Ababa City alone, municipal solid waste generation is estimated at about 5,612.73 m^3 per day, of which glass waste constitutes approximately 0.5% (28.1 m^3/day) [28]. Chemically, WGP is rich in silica and alkali compounds and exhibits high crushing resistance, relatively high permeability, and small-strain stiffness, making it suitable for geotechnical applications such as soil stabilization and embankment construction [29].

Steel slag is another significant industrial by-product generated during steel manufacturing, accounting for approximately 15–20% of crude steel production. It is produced during steelmaking processes such as basic oxygen, electric arc, and open-hearth furnaces and is available in substantial quantities worldwide. Global steel slag generation is estimated to range between 170 and 250 million tons annually (USGS, 2018). Asia alone contributes nearly 60% of global steel slag production. In Ethiopia, the Ethiopian Iron and Steel Factory in Addis Ababa produces approximately 1.5–3 tons of steel slag per day, which can accumulate to more than 548 tons annually if not properly managed. Steel slag contains hydraulic compounds such as C_2S, C_3S, C_3A, and C_4AF, which exhibit behavior similar to cement and lime, making it a promising binder for road construction applications. Consequently, numerous studies have focused on enhancing the

utilization of steel slag powder, with current applications primarily centered on road base and subgrade layers. This study seeks to encourage the utilization of waste glass and steel slag to improve the engineering performance of weak subgrade soils while reducing greenhouse gas emissions.

2. Materials and Methods

The aim of the research was to investigate the effects of glass powder, steel slag, and their combination on the properties of expansive subgrade soil. Clay soil, glass powder and Steel slag were utilized as the study's ingredients.

2.1. Materials

2.1.1. Soils. The soil sample used for this study was collected from road side around Sanka, Amhara Reginal State, Ethiopia. The disturbed sample soil was collected by digging trial pits at a depth of 1.5m below the ground level, as the top soil is likely to contain organic matter and other foreign materials. As preliminary investigations revealed that the soil was exceedingly broken, flexible, and had a greyish black color. The physical characteristics of the natural soil is shown in Table 1 and Figure 1.

Table 1. Physical characteristics of the sample soil.

Properties	**Soil**
Gravel (%)	0.00
Snad (%)	6.1
Silt (%)	38.00
Clay (%)	55.9
Liquid Limit (%)	78.35
Plastic Limit (%)	38.83
Plasticity Index (%)	39.52
Specific gravity	2.71

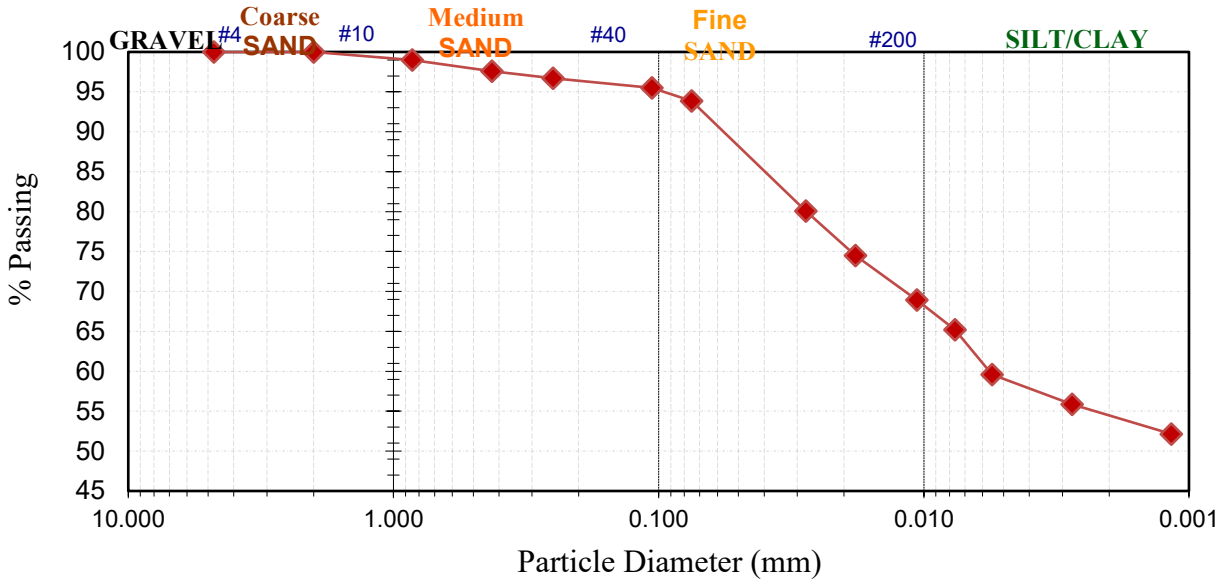


Figure 1: Particle size distribution cure of the soil sample

2.1.2. Glass powder. The glass powder was gathered from local drinking vessels; there were a lot of glass bottles which are broken and thrown. The glass was collected and deposited in a certain location, since, they occupy space, and they are challenging to dispose. Glass is a non-crystalline, amorphous substance that is transparent to the light and usually fragile. Cleaning the waste glass to remove the dirt and crushing. The glass was crushed by Los Angeles Abrasion Test Machine and sieved through sieve number 200 (75µm) to be mixed with soil. Glass is totally inert and non-biodegradable material. The rate at which waste material is being produced has significantly increased as a result of the growth of industrial activity. In the world the production volume glass was estimated around 130 million tons, whereas only 40% were recycled [27]. In Addis Ababa City, solid waste is estimated at about 5,612.73m^3/day from these glasses constitutes around 0.5% (28.1m^3 /day) of municipal solid [28]. But till now there is no such use of recycled waste glass in Ethiopia. The Glass powder is composed of silicate and alkali which exhibit high crushing resistance, high permeability, and small strain stiffness, these properties could enhance its usage for soil stabilization in geotechnical engineering works, embankment constructions [27], 28], [30]. These industrial pozzolana materials was mixed with steel slag to reduce the thickness of flexible pavement layers with increased strength. Table 2 presents the chemical composition of WGP.

Table 2: Chemical composition of WGP

Constituent	Percentage (%)
Silica (SiO2)	71.44
Aluminum (Al2O3)	1.70
Ferric Oxide (Fe2O3)	0.73
Calcium Oxide (CaO)	10.81
Magnesia (MgO)	1.65

Source: [31].

2.1.3. Steel Slag. Steel slag is a waste by-product generated during the manufacturing of iron and steel. The steel slag used in this study was collected from the Ethiopian Iron and Steel Manufacturing Company in Addis Ababa. In Ethiopia, the Ethiopian Iron and Steel Factory, located in Addis Ababa, generates a large amount of steel-making slag as the main waste byproduct of iron and steel production. The factory produces over 548.25 tons of slag each year. This slag would typically be disposed of in a landfill if not used as a construction material, leading to the occupation of farmland and the pollution of groundwater, air, and soil. The basic characteristics of pozzolana, such as density, surface area, and chemical composition, influence the rate at which the pozzolanic reaction occurs. For this study, the steel slag passing through a #4 sieve (4.75 mm) was used for laboratory tests. According to the USCS, the steel slag is classified as well-graded sand. Chemical test results indicated that the steel slag was free of cadmium (Cd) and copper (Cu), which are typically used for stabilization through cation exchange, flocculation, and agglomeration processes to improve the engineering properties of clay soils. Additionally, external factors such as mix ratios, water content, reaction temperature, curing conditions, and time may affect the reaction rate. The main oxide composition of the slag consisted of 71.89% SiO_2, Al_2O_3, and Fe_2O_3, which exceeds the 70% minimum required by ASTM (C618) for an acceptable pozzolan. The steel slag sample had a specific gravity of 3.32. The results of the chemical composition test on the maize steel slag are shown in Table 3 Figure 2 illustrates the particle size distribution curve of the steel slag.

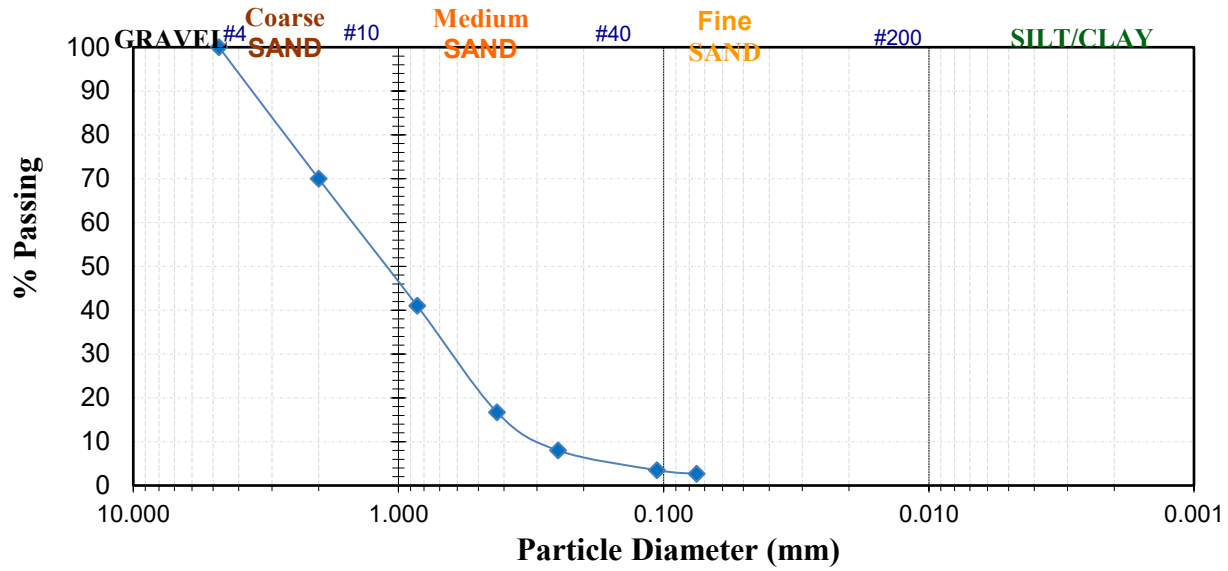


Figure 2: Shows the grain size distribution of the used aggregate.

Table 3: Chemical properties of steel slag

Chemical Composition								
Oxide	SiO2	Al2O3	FeO3	MgO	CaO	K2O	NaO	MnO
Steel slag	52.14	16.96	13.52	2.00	4.48	0.88	<0.01	0.16

2.2 Methodology

2.3. Research Design. In this study, steel slag and glass powder mixtures were used as additives in the expansive soil mixture. The experimental research methodology was applied in this study to answer the research questions and achieve the objectives based on experimental results, using quantitative, qualitative, and comparative analysis approaches. The study involved the identification of the problem in the study area, collection of materials, and preparation of samples for laboratory testing. Both glass and steel slag were crushed to convert them into powder form and prepare them for testing. Laboratory tests were conducted on subgrade soil with glass powder and steel slag separately, as well as in combination, to determine the optimum percentage of additives. The proposed stabilizer composition percentages ranged from 0-20% for SS and 0-20% for WGP by dry weight of the soil. The required laboratory tests were performed, as shown in Figure 3.

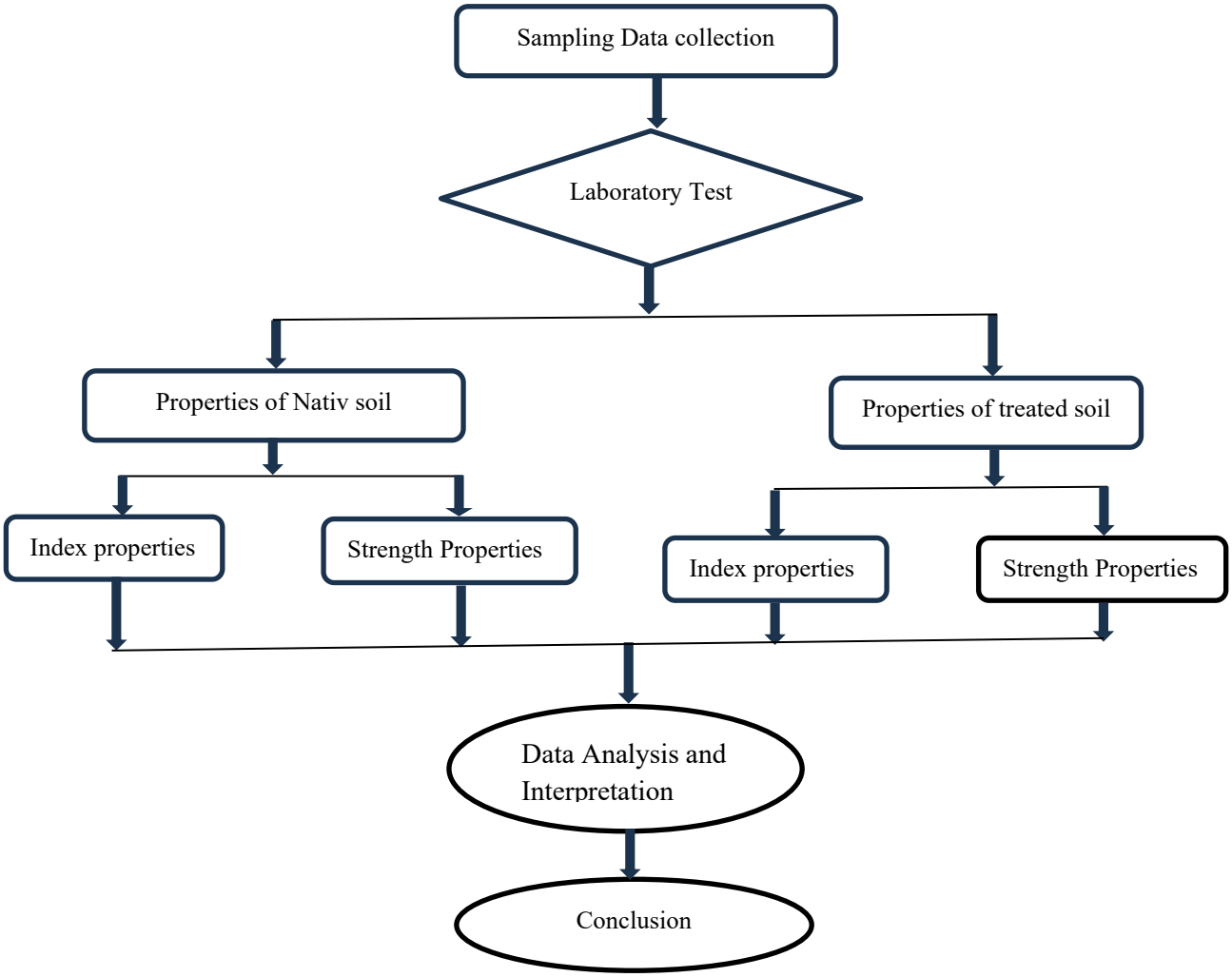


Figure 3: Test flow chart.

2.3. *Sample Collection and Sampling Techniques.* The sampling technique used in this study is purposive sampling, which is based on the specific objectives and information needed to determine the properties of expansive soil. As a result, the samples were selected through visual inspection and engineering judgment. The research focuses on the impact of SS and WGP on the expansive properties of the soil. For this study, the samples were collected from an area with a high abundance of expansive soil, specifically from Sanka, Amhara Reginal State, Ethiopia. The soil was dark in color and consisted of highly plastic clay. Glass waste was gathered from hotels, where numerous glass bottles were crushed and discarded. These glass bottles were collected and deposited in designated areas, taking up land space and posing disposal challenges. Additionally, glass powder was observed as a common household waste from residential buildings and as

construction residue during finishing works. The steel slag utilized in this study was obtained from the Ethiopian Iron and Steel Manufacturing Company located in Addis Ababa. This factory, a major producer of iron and steel in Ethiopia, generates large amounts of steel-making slag as a primary byproduct of its manufacturing process.

2.4 *Sample preparation.* Before conducting the laboratory tests, the soil samples were air-dried, pulverized, and mixed with the additives based on the dry weight of the soil. The sample preparation procedure included the following steps: air-drying the samples or oven-drying them at 60°C or lower, disintegrating the soil aggregates using a rubber-covered mallet, and performing sieve analysis on the dried soil samples. After disintegration, mold specimens were prepared, and an experimental design was developed to create a hybrid mixture of different admixtures with the soil. The proportions of glass powder and steel slag were fixed. The glass powder-stabilized sample was combined with the weak subgrade soil in proportions ranging from 5% to 20%, in 5% intervals based on the weight of the soil used for each test. Similarly, the steel slag-stabilized sample was combined with the weak subgrade soil in proportions ranging from 5% to 20%, in 5% intervals by dry weight of the soil. As illustrated in Figure 4, the soil samples, WGP, and SS were prepared in accordance with the AASHTO T87-86 sample preparation procedure.



(a) (b) (c)

Figure 4: Prepared sample: (a) soil, (b) glass powder, (c) steel slag.

2.5. Grain Size Analysis. This test is used to determine the proportion of different grain sizes present in a soil sample. Grain size analysis is commonly used to classify soils and to specify suitable soils for road construction and other embankment projects. Sieve analysis is the procedure

used to determine the distribution of course or larger-sized particles. The distribution of course, larger particles is assessed using mechanical (sieve) analysis, while the distribution of finer particles is determined using the hydrometer method. Particle-size analysis may involve either mechanical (sieve) analysis or sedimentation analysis. When analyzing fine-grained soils (such as clay and silt) with particle sizes smaller than No. 200 (0.075 mm), sedimentation analysis is applied. In this study, both sieve analysis and hydrometer analysis were conducted according to the AASHTO T-88 test method for particle size analysis of soils [21].

2.4 Specific Gravity. A soil sample that was oven-dried at 110°C and passed through a 2 mm sieve was used to determine the specific gravity, which measures the particle weight of the soil using a pycnometer. Determining the specific gravity of soil is important for understanding the density of the soil solids and the relationship between air voids, water, and solids within the sample. Specific gravity is defined as the ratio of the mass of a unit volume of soil at a given temperature to the mass of an equal volume of gas-free distilled water at the same temperature. This test includes the determination of specific gravity for the native soil and was conducted in accordance with the AASHTO T100 testing procedure.

2.5 Atterberg Limits. This test was intended to determine the plastic and liquid limits of the soil. Liquid limit (LL) is the percentage of water content at which a portion of soil in a standard cup cut by a standard-diameter groove will flow together at the base of the groove for a distance of 13 mm (1/2 in.), after being subjected to 25 shocks from the cup being dropped 10 mm in a standard liquid limit apparatus that is operated at a rate of two shocks per second. The percentage of moisture in a soil that causes it to lose its ability to be shaped into 3.2 mm (1/8 in.) diameter threads without disintegrating is known as the plastic limit. The same procedure is also carried out for the treated soil with the mixing of steel slag and glass powder content. AASHTO T 90s test procedures were followed to conduct experimental tests.

2.6 Free Swell Tests. The test includes the determination of the free swell index for both the natural soil and the soil–slag–cement mixture. The tests are conducted in accordance with the IS: 2720 (Part 40) – 1977 testing procedure. Two 10 cc samples of oven-dried soil are collected and sieved through a 425-micron mesh. One sample is placed in a 100-cc graduated glass cylinder containing kerosene, while the other is placed in a similar cylinder filled with distilled water. After being left undisturbed for 24 hours, the volumes of both samples are recorded. The same procedure is also

carried out for the treated soil with varying increments of steel slag and waste glass powder content. The free swell test provides an approximate estimation of the soil's degree of expansiveness.

2.6 Compaction. A modified compaction test was conducted for each sample containing glass powder, steel slag, and their combination, in order to determine the OMC and MDD. The test was performed in accordance with the AASHTO T-180 procedure and was repeated with varying water contents until the OMC and MDD were established using modified compaction. The density and moisture content of each compacted soil sample were measured, and the relationship between dry density and moisture content was then determined.

2.7 California Bearing Ratio. The CBR tests were conducted in accordance with the AASHTO T193-93 standard procedures on natural soil samples modified with glass powder, steel slag, and a combination of both additives. These materials were compacted at their respective OMC and MDD. Three-point CBR tests were carried out to evaluate the strength of both untreated and treated soil samples and to assess their behavior under loading conditions.

A total of 15 kg of natural soil passing through a #4 (4.75 mm) sieve was used. The soil-steel slag-WGP mixtures were prepared at their respective OMC and compacted into a 2250 cm^3 mold. The sample was divided into three representative portions, each weighing approximately 5.0 kg, and compacted using 10, 30, and 65 blows per layer, respectively, for five equal layers in one CBR mold.

The compacted samples were then soaked in a water bath for 96 hours with a 4.5 kg surcharge load to determine the soaked CBR value. After soaking, the mold was removed from the water and allowed to drain for 15 minutes before the penetration test. The CBR penetration was conducted at a strain rate of 1.25 mm per minute. CBR values were recorded at penetrations of 2.54 mm and 5.08 mm, with the higher value being reported.

2.7. Unconfined Compressive Strength. The unconfined compressive strength is defined as the compressive stress at which the unconfined cylindrical specimen of soil will fail in a simple compression test. The unconfined compressive strength tests were conducted on Expansive soil, Expansive soil with steel slag, Expansive soil with glass powder and Expansive soil, steel slag and glass powder mixtures as per AASHTO T 208. All the samples are prepared by modified

compaction using split mold at OMC and MDD to maintain same initial dry density and water content.

3. **Result and Discussion**

In order to provide insight into the research about the engineering properties of expansive soil in relation to its use, the results are examined and discussed. The investigation involved the evaluation of both natural and stabilized soil samples separately and by combining the stabilizers. To assess gradation, specific gravity, and Atterberg limits, a 24-hour-soaked sample was utilized to attain the required chemical interaction between the constituents. CBR was evaluated using a sample that had been soaked for 96 hours.

3.1. Properties of untreated Subgrade Soil

3.1.1 Grain Size Distribution. Grain size analysis provides the grain size distributions, and it is required to classify the soil using wet and hydrometer method as per AASHTO T 88. From the grain size analysis result, the distribution of particle sizes larger than 75μm is determined using sieving, while the distribution of particle sizes smaller than 75μm or passed on the No. 200 sieves is determined by a hydrometer analysis was used to classify silt and clay soils. Sodium hexametaphosphate is used as a dispersing agent. As shown in Figure1 the sample subgrade soil contains 0.00% of gravel, 7.5% of sand, 40.2% of silt particles, and 52.3% of clay particles. Therefore, more than 50% of the soil particles pass through the 2-micrometer sieve, indicating that the soil is clayey in nature and possesses low strength [2], [21].

3.*4 Soil classification.* AASHTO and USCS were applied to classify the natural soil based on index properties and grain size analysis. Table 4 demonstrates that the untreated soil sample utilized in this study, the percentage of LL is 78.35%, the percentage of PI is 39.2%, and the percentage of particles passing the No. 200 sieve is 92.09%. According to standard classifications, soils with a liquid limit below 35% are considered to have low plasticity, 35–50% indicate medium plasticity, 50–70% high plasticity, and 70–90% extremely high plasticity [32]. Thus, the studied soil was categorized as A-7-5 asper AASHTO and CH according to USCS as shown in Figure 5 and 6. This shows that the subgrade soil is clay, which is highly expansive and considered a weak foundation material [21],[33]. According to its engineering properties, this soil is soft and fragile, unable to

withstand heavy loads and prone to expansions, cracks, and settling. Therefore, the soil needs to be improved to use as subgrade material.

Table 4: Properties of natural soil.

Properties	Value
Specific Gravity	2.71
Atterberg's Limit	
Liquid limit (%)	78.35
Plastic Limit (%)	38.83
Plastic Index (%)	39.52
Grain Size Distribution	
Gravel (%)	0.00
Sand (%)	6.1
Silt (%)	40.2
Clay (%)	52.3
Soil classification (AASHTO and USCS)	A7-5 and CH
Water content (%)	42.32
Differential free swell (%)	102.72
PH value	
Optimum moisture content (%)	25.82
Maximum Dry Density (gm/cm^3)	1.385
Soaked CBR (%)	2.26%
CBR swell	9.35%
Unconfined compressive strength (KN/m2)	24.26

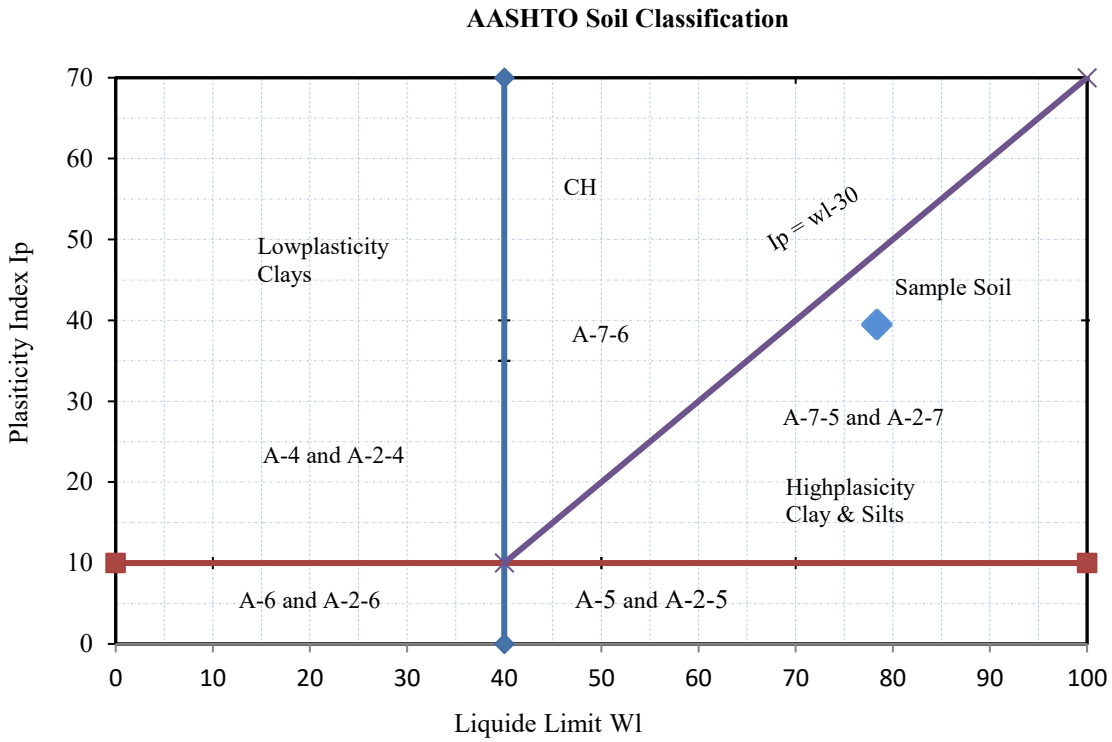


Figure 5: AASHTO classification of natural soil

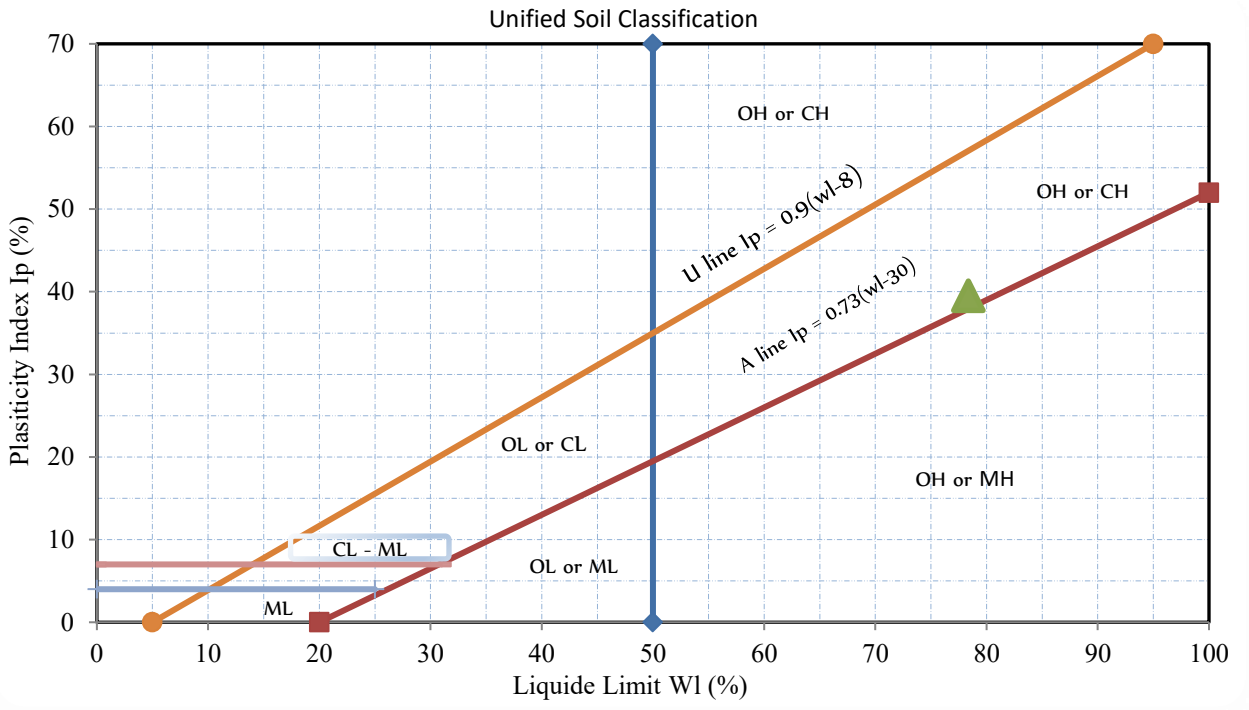


Figure 6: USCS classification of natural soil

3.5 CBR and CBR Swell of Natural Soil. The CBR test is a measure of the resistance of a material and also it is used to evaluate the subgrade strength of flexible pavement. After soaking the soil samples, for 4 days the CBR and CBR swelling values were measured, giving results of 2.26% and 9.74%, respectively. The tested soil exhibits high thermal sensitivity and low bearing capacity, rendering it susceptible to cracking and structural failure under heavy loads.

To address this, chemical stabilization is necessary to improve the soil's properties. Moreover, the measured CBR 2.26% and swelling 9.35% values fall below the Ethiopian Roads Authority (ERA) standards, which require a CBR greater than 5% and swelling below 2%. This indicates that the soil has low load-bearing capacity and a high potential for expansion, making it unsuitable for use as a subgrade material without treatment. In conclusion, the soil does not meet ERA requirements and must be improved using appropriate stabilization methods before being used in road construction. Therefore, soil sample need to improve the engineering properties to use as a subgrade material by using additives.

3.6. *Unconfined Compressive Strength.* The UCS test is one of the most widely used methods for evaluating soil shear strength because it is quick and economical. In this study, UCS tests were carried out on untreated expansive soil following the AASHTO 208 standard. The native soil recorded a UCS value of 24.26kN/m², showing that Expansive soil has very low shear strength. This result highlights the need to improve its engineering properties with suitable additives before it can be effectively used as a subgrade material.

3.2 Experimental Test Results of Stabilized Expansive Soil

3.2.1. Effects of Glass powder on the properties of sample soil. LL and PL tests were conducted on samples prepared with 5%, 10%, 15%, and 20% WGP additives. The Atterberg limits results indicate that the LL were reduced and PL were increased as the glass powder content increases. The glass powder content ranged from 5% to 20% in increments of 5%. As shown in Figure 7, the PI decreased from 39.52% to 18.79%. Due to WGP acts as an internal filler with a lower water absorption capacity than clay [34]. Data from Table 2 indicates that WGP is predominantly composed of silica (approximately 71.44%). Because this non-plastic material replaced a portion of the expansive soil, the Liquid Limit (LL) dropped from 78.35% to 58.93% [35]. Figure 7 presents the results obtained from the study.

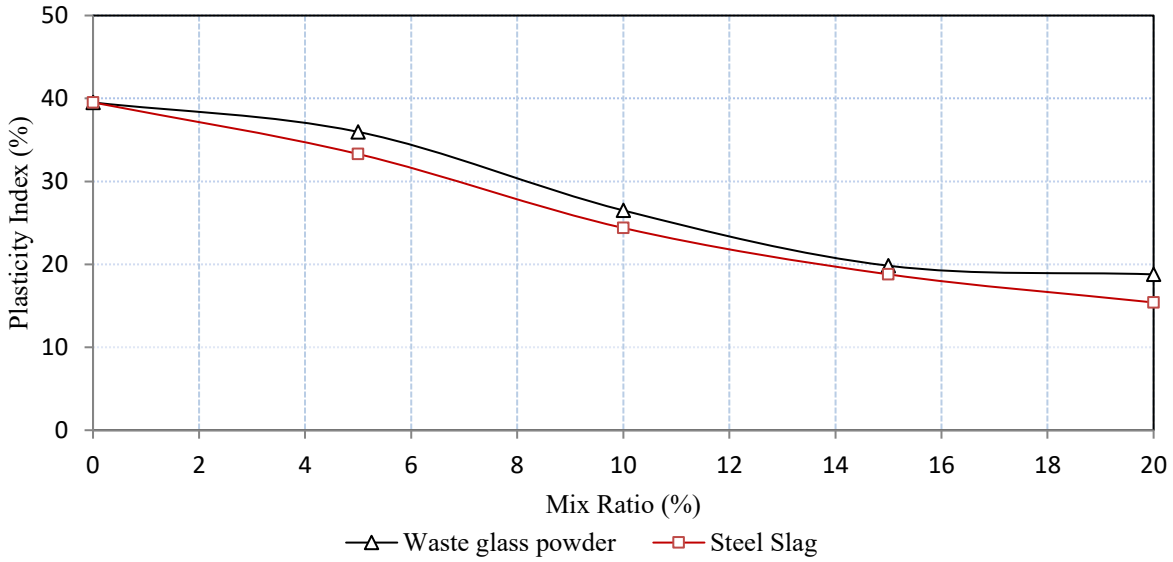


Figure 7: Effects SS and WGP on PI of the sample soil.

The AASHTO T-180 standard test procedure was applied to determine the moisture-density relations. Different percentages of glass powder (5%, 10%, 15%, and 20%) were added to the subgrade soil, and laboratory tests were conducted. Figure 11 presents the relationship between WGP content and dry density, showing that the dry density increases from 1.385 g/cm³ to 1.576 g/cm³ as the glass powder content rises from 0% to 15%, after which it decreases with further WGP addition. The reason is that adding more than 15% WGP increases water absorption, which in turn reduces the soil density [34]. Meanwhile, the OMC decreases from 25.82% to 22.976%. The improvement in dry density is due to cation exchange and pozzolanic reactions (the gradual formation of cementitious compounds) between the glass powder and soil particles, which lead to flocculation and agglomeration of clay particles, resulting in textural changes [36]. The reduction in OMC is because WGP has lower water absorption capacity compared to expansive soil, which aligns with findings from [34]. Figure 8 illustrates the variation of OMC with the percentage of additives.

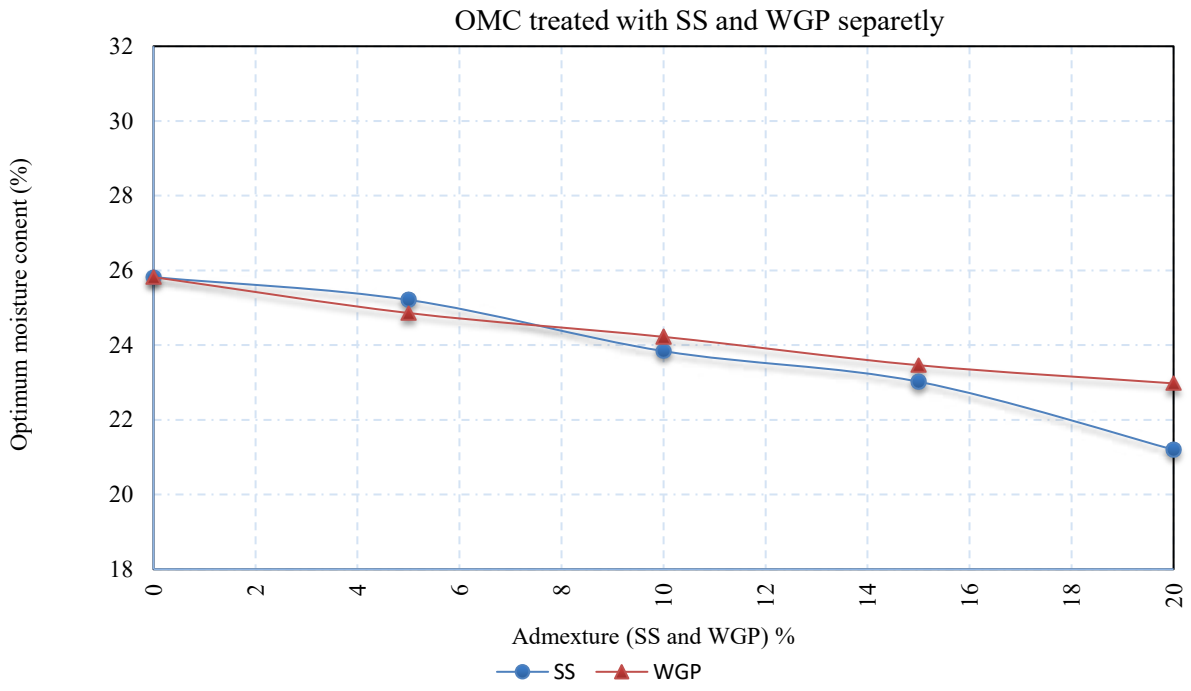


Figure 8: Effects SS and WGP on OMC of the sample soil.

The laboratory CBR test results indicate that the addition of WGP significantly improves the strength of the soil while reducing its swelling potential. The soil samples were tested with varying WGP contents of 5%, 10%, 15%, and 20%. As illustrated in Figure 9, the CBR value increased from 2.26% for untreated soil to a maximum of 5.74% at 15% WGP content. With further addition of WGP, the CBR slightly decreased to 5.12% at 20%. In contrast, the CBR swell value decreased markedly from 9.74% to 1.28% as the WGP content increased from 0% to 15%, indicating that 15% WGP is the optimum content for enhancing soil performance. These results indicate that 15% glass powder significantly improves the soaked CBR value, making the soil suitable for use as subgrade material for road and pavement design, meeting the ERA's minimum requirement for paved roads (CBR > 5%). The increased CBR values of WGP-treated soils are attributed to the pozzolanic cementitious properties of glass powder, which bind soil particles and enhance soil strength [37]. The addition of WGP fills the voids between expansive soil particles, improving the overall bearing capacity of the sample [34].

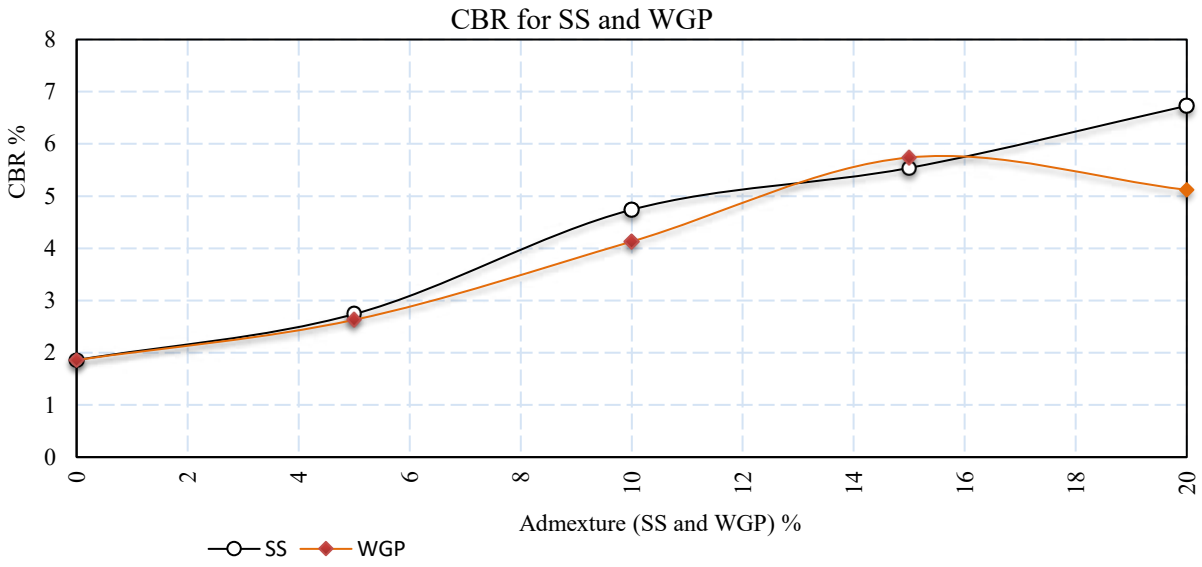


Figure 9: Effects SS and WGP on CBR and CBR swell of the sample soil.

UCS tests were conducted on remolded soil specimens mixed with varying proportions of WGP at 5%, 10%, 15%, and 20% to evaluate the improvement in soil strength. The UCS of the untreated soil was 24.966kN/m², indicating that the expansive soil has very low strength and poor shear resistance. As shown in Figure 10, the UCS values increased with increasing WGP content up to an optimum level. Compared with the untreated soil, the UCS improved to 47.604 kN/m², 56.673 kN/m², and 57.836 kN/m² for WGP contents of 5%, 10%, and 15%, respectively. However, at 20% WGP, the UCS slightly decreased to 51.72 kN/m². Overall, the results demonstrate that the inclusion of WGP significantly enhances the UCS of expansive soil, with the maximum strength gain achieved at an optimum content of 15% WGP. At this level, UCS increased by 57.836% compared to natural soil. The improvement is primarily attributed to reduced cohesion resulting from the decrease in expansive clay content [34], [37], [38].

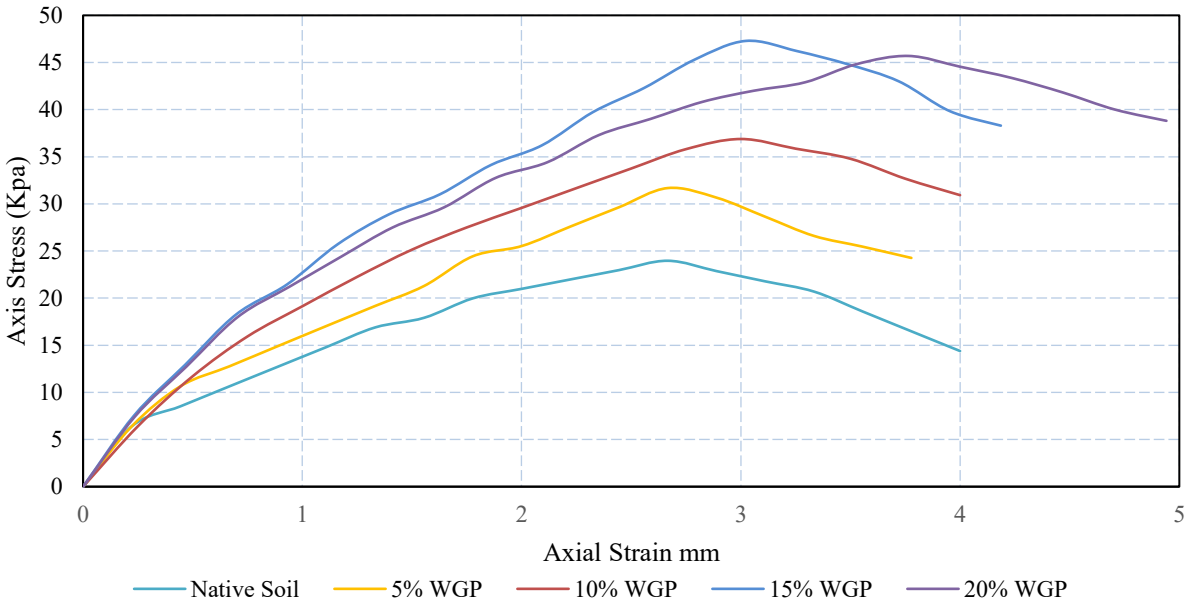


Figure 10: Effects SS and WGP on UCS of the sample soil.

3.7 Effects of Steel Slag on the Engineering properties of Subgrade Soil. The Atterberg limits test was carried out by adding steel slag to expansive soil to investigate its effects on the soil's properties. The experimental test results indicate that the addition of steel slag significantly decreases the LL and PI of the treated soil. Steel slag was added in varying proportions—5%, 10%, 15%, and 20%—to assess its impact.

The test results show that the liquid limit of the untreated soil, initially 78.35%, decreased to 72.13%, 65.81%, 62.57%, and 57.24% with the addition of 5%, 10%, 15%, and 20% steel slag, respectively. Figure 7 shows that the PI reduced to 41.52%, 34.3%, 27.38%, 22.57%, and 16.4% for the corresponding percentages. The reduction in consistency limits is attributed to the properties of steel slag: its low water absorption capacity, non-plastic nature, and the cation exchange process that increases inter-particle attraction and promotes flocculation [39]. When mixed with soil, steel slag increases the overall particle size, thereby reducing the surface area and decreasing the amount of clay minerals in the mixture [40]. As a result, the water-holding capacity of the soil mixture decreases, leading to lower Atterberg limits and reduced PI.

To assess the impact of steel slag on the moisture-density relationship of subgrade soil, compaction tests were conducted in accordance with AASHTO T 98 standards. As shown in Figure 11, the

modified compaction test revealed that increasing the percentage of steel slag enhances the MDD. Figure 7 shows that increasing the percentage of SS results in a reduction in OMC. When 20% steel slag was added, the MDD increased from 1.385 g/cm³ to 1.6183 g/cm³. Conversely, the OMC decreased from 25.8% to 21.2%. This is because steel slag is a dense material with a high specific gravity and low water retention capacity [41]. As more steel slag is added, the soil mixture becomes heavier and less able to hold moisture, resulting in an increased MDD and decreased OMC [42].

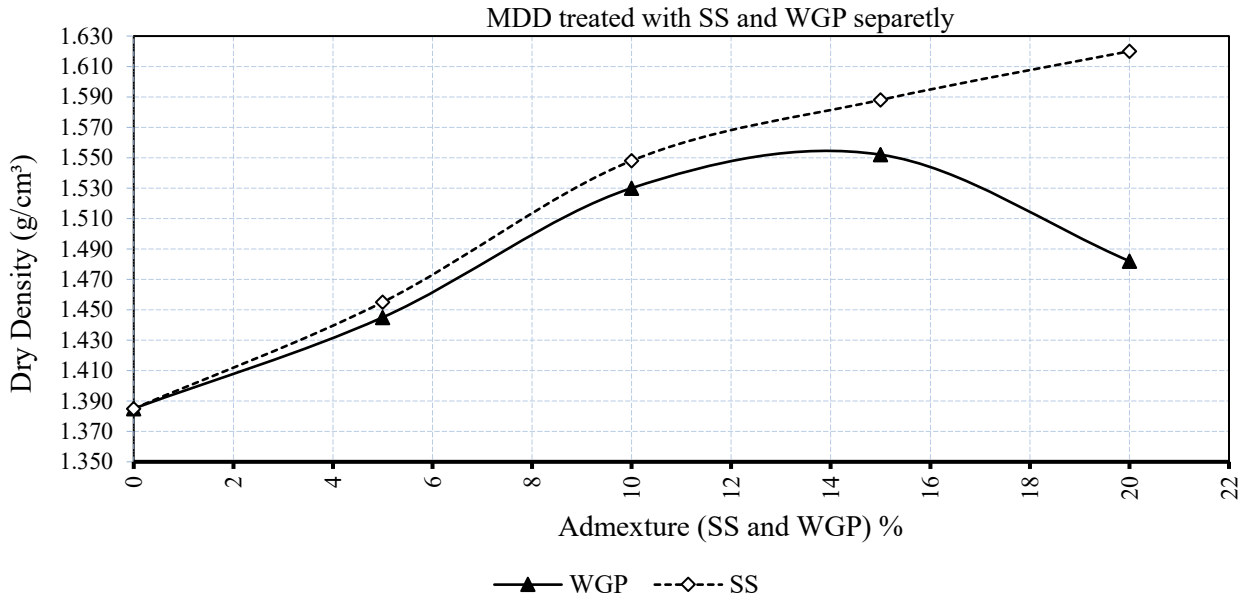


Figure 11: Effects SS and WGP on MDD of sample soil

Soaked CBR tests were also performed on the treated expansive subgrade soil with varying steel slag content. The test results show that adding steel slag significantly improves the strength and reduces the swelling potential of the soil. As illustrated in Figure 12, the CBR value increased from 2.26% to 5.83% with 20% steel slag, while the CBR swell decreased from 9.74% to 1.27%. For all treated samples, the CBR value exceeded 5% and the CBR swell remained below 2%, thereby meeting the Ethiopian Roads Authority (ERA) subgrade specification requirements. The study concludes that a 20% steel slag content yields the highest CBR value and the lowest CBR swell, indicating the optimal improvement in subgrade performance.

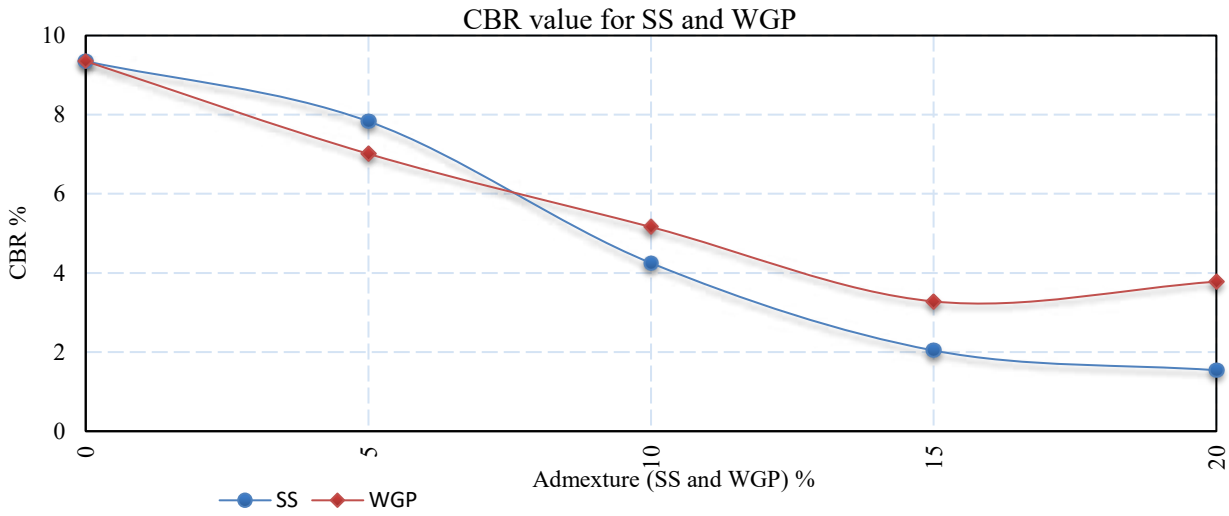


Figure 12: Effects SS and WGP on CBR swell of sample soil

The relationship between UCS and SS content is illustrated in Figure 13. UCS tests were carried out on remolded specimens prepared with different percentages of SS as an additive—specifically 5%, 10%, 15%, and 20%—to evaluate the strength improvement of the treated soil. The UCS of the untreated soil was found to be 24.26kN/m², indicating that the expansive soil has very poor strength and shear resistance. As shown in Figure 13, the UCS values increased steadily with higher percentages of SS. While the untreated soil had a UCS of 24.26 kN/m², treatment with 5%, 10%, 15%, and 20% SS increased the UCS to 29.986, 39.048, 53.107, and 66.855 kN/m², respectively. Overall, the addition of SS significantly improved the UCS of the expansive soil, with 20% SS producing the highest strength value. At this dosage, UCS increased by 175.56% compared to the natural soil. This improvement can be attributed to reduced soil cohesion resulting from a decrease in expansive clay content [37], [43], [44].

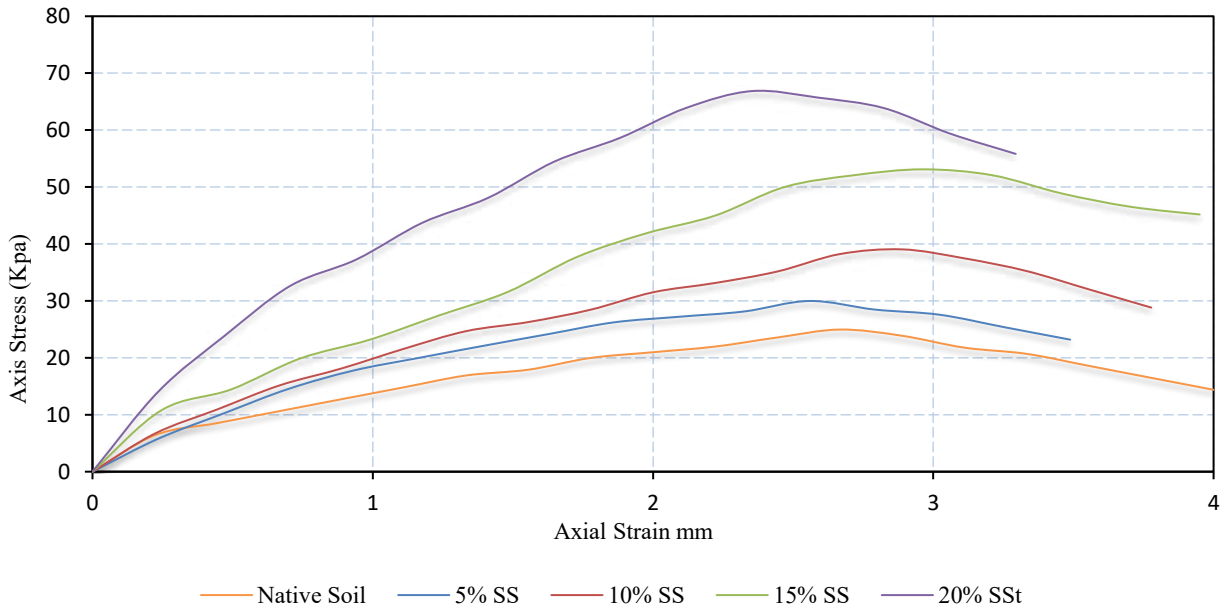


Figure 13: Effects of SS on UCS values of the sample soil.

3.7. Experimental Test Result of Stabilized Expansive Soil

3.7.1. Effects of Glass powder and Steel Slag on the Engineering Properties of Expansive Soil. The objective of this study was to evaluate how steel slag and glass powder influence the engineering properties of expansive subgrade soil, including LL, PL, PI, moisture–density relationship, CBR, and CBR swell and UCS. Laboratory tests were carried out with different proportions of glass powder and steel slag, both individually and in combination. While each additive improved the soil properties on its own, their combined use produced even more significant improvements. Various mix ratios of glass powder and steel slag were tested to analyze their effects, with specific tests on liquid limit, plastic limit, and FSI conducted to observe changes in the natural soil.

The results showed a marked reduction in soil plasticity as the percentage of glass powder and steel slag increased. For example, the liquid limit decreased from 78.35% to 53.16%, while the plasticity index dropped from 39.52% to 8.40% with the addition of 20% glass powder and 20% steel slag. As shown in Figure 14, the combined addition of WGP and SS resulted in a significant reduction in soil plasticity. This improvement is mainly due to the increased calcium availability from the additives, which promotes cation exchange. Furthermore, the non-plastic nature of steel

slag and its interaction with clay particles, combined with the cohesive characteristics of glass powder, help reduce the soil's plasticity [43], [45], [37]. The cation exchange process also enhances particle flocculation, strengthening interparticle attraction.

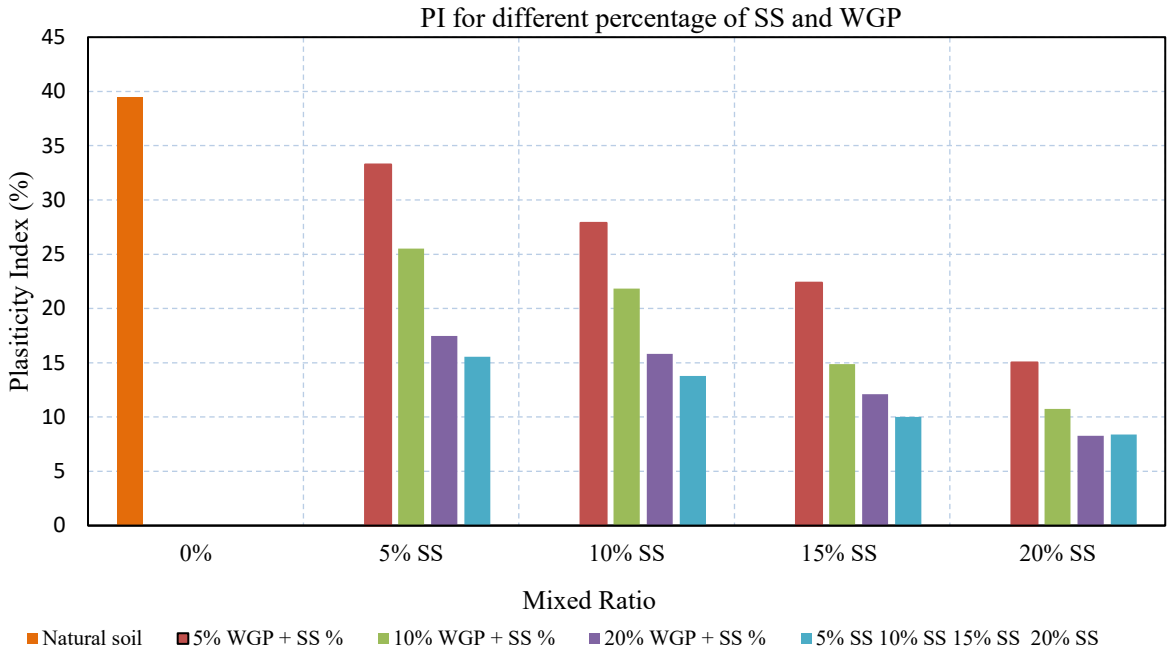


Figure 14: PI with different ratio of SS and WGP

The FSI test was carried out in the laboratory on soil samples treated with different proportions of SS and WGP. The test procedure involved preparing two 10 cc samples of oven-dried soil passing through a while the other was placed in a similar cylinder containing distilled water. After remaining undisturbed for 24 h, the volumes of both samples were recorded. The cylinders were then manually shaken using a rod, covered, and left undisturbed for another 24 h to ensure complete settlement of the soil particles.

The untreated soil exhibited a high FSI value of 102.77%, indicating a strong swelling potential. The addition of SS and WGP significantly reduced the free swell behavior of the soil. The FSI value decreased from 102.77% to 85%, 56%, 35.5%, and 39.54% for soil samples mixed with 5%, 10%, 15%, and 20% SS, respectively, in combination with 15% WGP. The optimum performance was achieved at a WGP content of 20% SS and 15%, beyond which further improvement in FSI

was marginal. The treated samples satisfied the subgrade material requirements specified in IS 2720 (Part 40), which require the FSI to be less than 50%.

The results clearly demonstrate a substantial reduction in FSI with the addition of SS and WGP. The reduction in FSI can be attributed to the non-cohesive nature of SS and WGP and the presence of calcium- and silicate-rich compounds, which reduce the swelling potential of expansive soil. This improvement is primarily associated with cation exchange processes, whereby calcium ions from the additives replace sodium ions within the soil structure. As a result, the FSI values vary with different admixture contents, as shown in Figure 15.

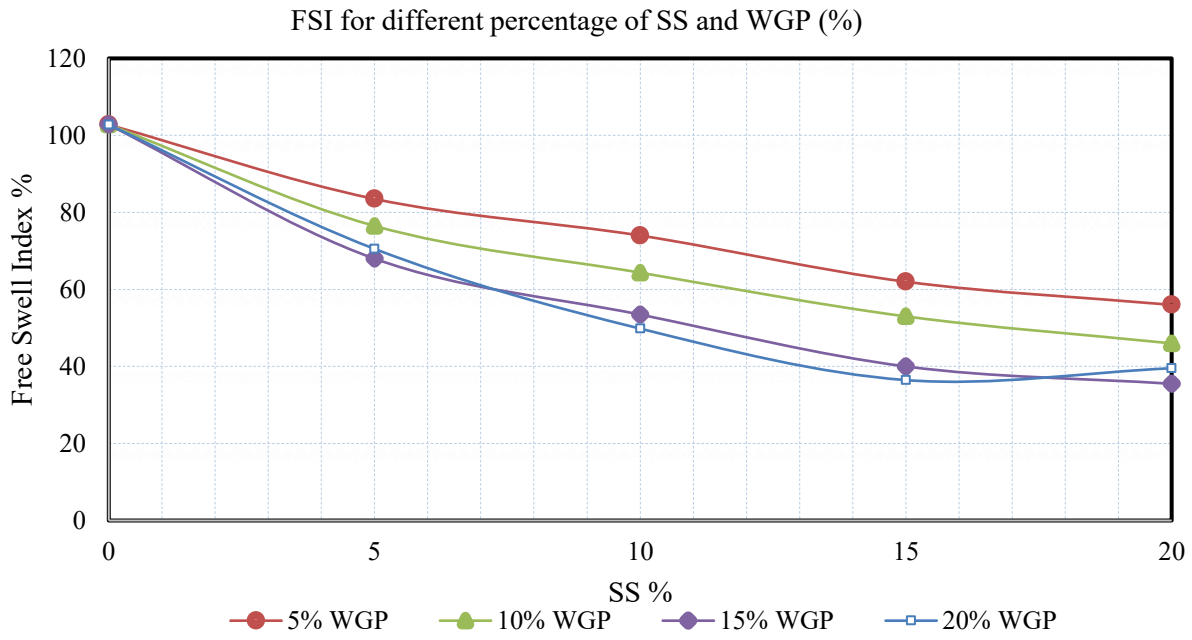


Figure 15: Effects of SS and WGP on FSI of soil.

Figure 16 shows the impacts of various blending percentages of the proposed additives on the maximum dry density and its corresponding optimum moisture content from the compaction curve. In the laboratory using the compaction test the OMC and MDD for natural soil and treated soil can be determined. Compaction is usually used to increase a soil's density and hence it's strength. Additionally, compaction limits the swelling potential of expansive soils, minimizes long-term settlement, promotes stiffness, and reduces the sensitivity of subgrade soil to fluctuations in moisture content. As shown in Figure 16, the natural soil has a maximum dry density of 1.385g/cm^3, and the addition of 5%, 10%,15% and 20% WGP along with 20% steel slag improve

the MDD to 1.576g/cm3, 1.60g/cm3, 1.65g/cm^3 and 1.630g/cm^3 respectively. This increase in maximum dry density of the stabilized soil sample occurred since both glass powder and steel slag has greater specific gravity than the native soil.

The OMC decrease from 25.82% to 21.05% with addition of 15% glass powder and 20% steel slag. The reduction of OMC also due to the water absorption capability of glass powder and steel slag are much less than the studied soil. The optimum moisture content value for un-reinforced soil is 25.82% which decrease to 21.493%, 21.569%, 21.05%, and 21.41% respectively for addition of 3%, 5%, 10%, 15% and 20% glass powder with along 20% steel slag. Therefore, it is concluded that both additives have a significant effect on OMC value. The reduction of OMC in case of glass powder and steel slag has less water absorption capability than the studied soil.

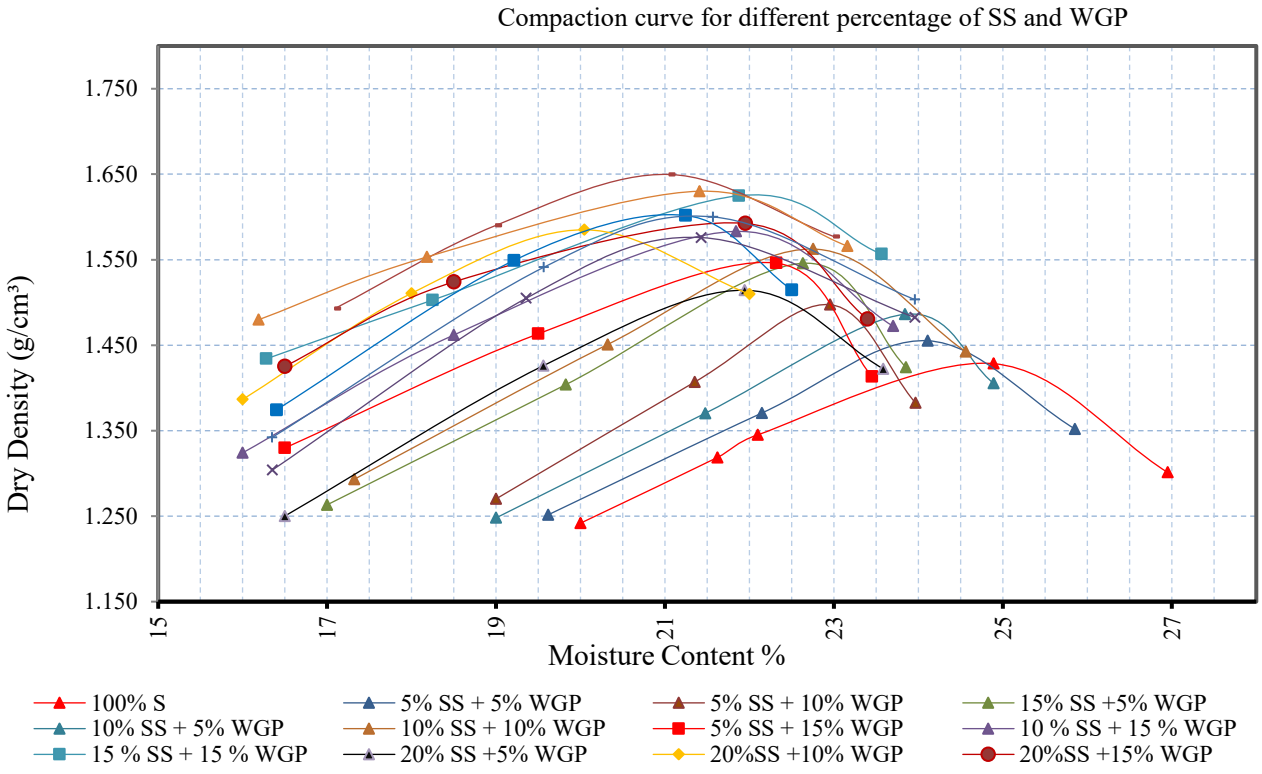


Figure 16: Effects of SS and WGP on MDD of soil.

Subgrade soil strength is largely governed by the CBR, which directly influences pavement thickness design. In this study, WGP and SS–soil mixtures were compacted in CBR molds at their OMC, and their swelling behavior was evaluated before and after four days of soaking to determine

both CBR and CBR swell values. Figure 17 shows that the soaked CBR value of the soil increases with increasing percentages of both SS and WGP. The natural soil exhibited a very low CBR value of 2.26% and a high CBR swell value of 9.74%, indicating poor suitability as a subgrade material.

The addition of stabilizers significantly improved the soil performance. Incorporating 5%, 10%, 15%, and 20% steel slag in combination with 15% WGP increased the CBR values to 5.25%, 7.19%, 9.35%, and 8.38%, respectively. The maximum CBR value of 9.35% was obtained with 15% WGP and 20% SS, representing an approximate 313.7% increase compared to the untreated soil. At the same time, swelling decreased considerably with increasing stabilizer content. The combined use of 15% WGP and 20% SS reduced the CBR swell to as low as 1.58%. Therefore, the addition of the optimal dosage of WGP and SS meets the requirements of many subgrade strength specifications and satisfies ERA standards.

These improvements are attributed to the optimum proportion of glass powder and the partial replacement of soil by steel slag, which introduces non-plastic materials and promotes flocculation and agglomeration through cation exchange, thereby increasing soil density. The reduced swell potential is also linked to calcium-saturated clay exhibiting lower water affinity and the formation of a cementitious matrix that resists volumetric expansion [42], [46],[47],[48]. Furthermore, the high iron content of steel slag and the non-cohesive nature of both additives contribute to enhanced strength and improved engineering performance of the stabilized soil.

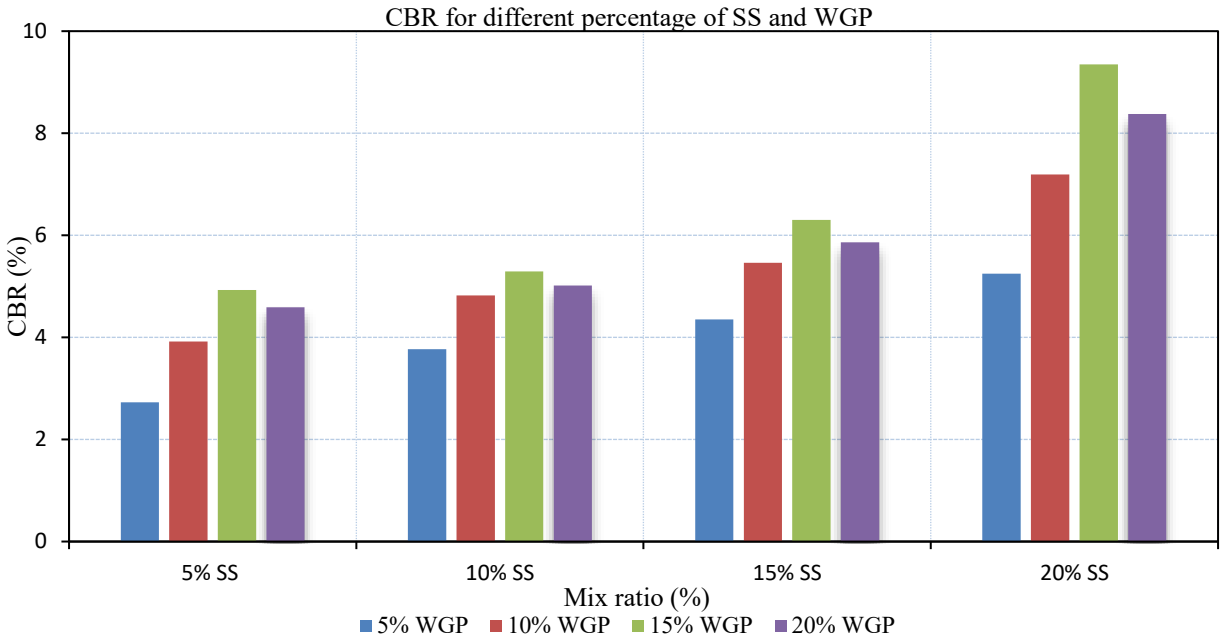


Figure 17: Effects of SS and WGP on CBR of soil.

3.3.5. Effects of SS and WGP on Unconfined Compressive Strength (UCS) Test. The UCS test is a widely used method for evaluating soil shear strength due to its simplicity, speed, and cost-effectiveness. In this study, UCS tests were performed on expansive soil and soil mixtures containing varying proportions of additives, following the AASHTO 208 standards. As shown in Figure 18, the UCS of treated soil gradually increased with the addition of SS and WGP.

Further UCS tests were conducted on soil treated with different proportions of SS combined with 15% WGP. The results indicate that UCS values generally increased with higher contents of both SS and WGP. Specifically, the UCS of the untreated soil was 24.966 kPa, which increased to 48.581 kPa, 56.906 kPa, 67.802 kPa, and 125.379 kPa for 5%, 10%, 15%, and 20% SS, respectively, when combined with 15% WGP. The maximum UCS of 125.379 kPa was recorded for the mixture containing 20% SS and 15% WGP, representing nearly a fourfold improvement over the untreated soil and exceeding the minimum UCS requirement of 50 kPa [31]. The increase in UCS was observed up to the optimum WGP content of 15%, after which further addition of WGP caused a slight reduction, likely due to decreased soil density.

Overall, the results demonstrate that the strength of expansive soil improves significantly with the addition of steel slag and WGP up to their optimum contents. Consequently, both additives are

effective in enhancing the engineering properties of expansive soil. Figure 18 further illustrates that both SS and WGP substantially improve the mechanical properties of clay soil.

The observed increase in UCS is attributed to pozzolanic reactions between the calcium oxide (CaO) in steel slag and the silica and alumina present in the soil [49-50]. In conclusion, increasing the percentages of both steel slag and WGP significantly enhances UCS, confirming that both additives play a crucial role in improving the strength characteristics of expansive soils.

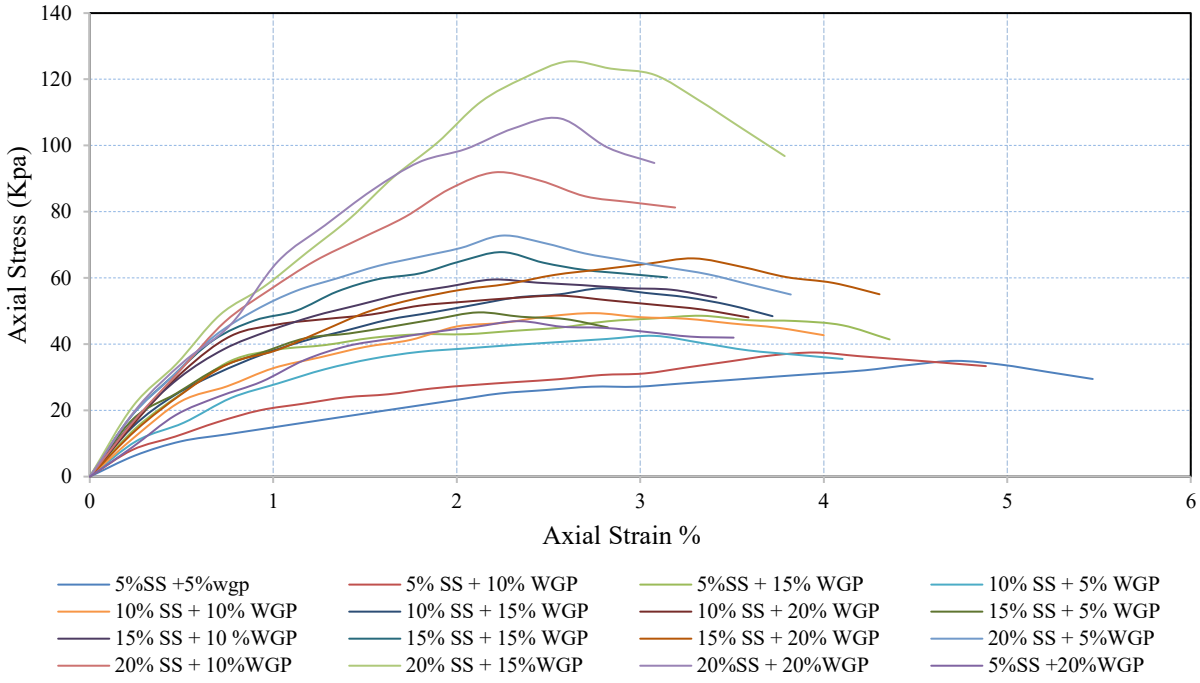


Figure 18: Effects of SS and WGP on UCS of soil.

Conclusion

This study examined the effects of WGP, SS, and their combined application on weak subgrade soil. A comprehensive laboratory testing program, including index and strength tests, was conducted. According to the AASHTO and USCS classification systems, the natural soil was classified as A-7-5 and CH, indicating poor suitability for subgrade use. Following stabilization, the soil exhibited a substantial improvement in bearing capacity and overall performance. The incorporation of SS and WGP proved effective, leading to improvements in MDD and soil consistency. At the optimum mix of 20% SS and 15% WGP, the LL decreased from 78.35% to 53.16%, while the PI was significantly reduced from 39.52% to 8.40%. In addition, the FSI dropped from 102.7% to 35.5%. These improvements are attributed to increased calcium availability from the stabilizers, which promotes cation exchange and introduces non-plastic materials into the soil matrix. Compaction characteristics also improved, with MDD increasing from 1.4385 to 1.65 g/cm^3 and the OMC decreasing from 25.82% to 21.05%. The untreated soil exhibited a low CBR value of 2.26%, rendering it unsuitable for subgrade construction. However, after stabilization, the CBR value increased significantly to 9.35%, meeting subgrade requirements. Similarly, the UCS increased from 24.26 kPa to 125.38 kPa, indicating a marked enhancement in strength. The combined action of SS and WGP reduced plasticity and filled soil voids, resulting in a denser and stronger soil structure. Overall, the stabilized soil satisfied all standard requirements for subgrade materials. The findings of this study provide a basis for selecting appropriate types and proportions of stabilizers based on soil characteristics and targeted strength performance. The use of SS and WGP not only improves expansive soil behavior but also reduces cement consumption, construction costs, and environmental pollution. The optimum mix of 15% WGP and 20% SS by dry weight of soil yielded the best performance across most engineering criteria. Compared to conventional cut-and-replacement methods, this stabilization approach is more economical and environmentally sustainable. Moreover, the effective utilization of WGP and SS contributes to waste reduction and promotes improved environmental conditions.

Data Availability

The data used to support the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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