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Formulation and Evaluation of an Aloe Vera–Based Hybrid Soil Stabilizing Agent Incorporating GGBS and Cement for Base Course Improvement

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ABSTRACT: This study evaluates a sustainable hybrid stabilizer—cement, GGBS, and Aloe vera—for improving pavement base courses while lowering carbon emissions. Lab and field testing on well-graded A-2-4(0) soil assessed physical and mechanical properties, with data analyzed via one-way ANOVA and Tukey's HSD. Higher stabilizer concentrations improved particle packing in four mixtures (T0 to T3), increasing maximum dry density while decreasing optimum moisture content. Visual monitoring revealed that while increased GGBS content led to desiccation in T1 and T2, the additional 0.2% Aloe vera dosage in T3 successfully maintained a moist matrix through enhanced moisture retention. Consequently, one-way ANOVA and Tukey's HSD confirmed statistically significant CBR leaps across all design transitions ($p<0.05$). CBR values escalated from 36.23% in untreated soil (T0) to a peak of 205.05% in T3, driven by high dosage sensitivity between T1 and T2 (Δ=61.97%) and moisture-retention efficacy between T2 and T3 (Δ=57.96%). Ultimately, both T2 (147.10%) and T3 cleanly exceeded the DPWH 100% minimum base course requirement. Although the T3 mixture demonstrated the best overall performance, the T2 mixture is the best option for real-world projects, reducing standard cement consumption by 21% to maximize material efficiency.

KEYWORDS: Soil stabilization, GGBS, Aloe vera, CBR, sustainable construction, base course

I. INTRODUCTION AND REVIEW OF RELATED LITERATURE

In pavement engineering, a roadway's longevity depends fundamentally on the base course layer beneath it. While soil-cement mixtures offer a cost-effective stabilization solution by utilizing local materials and reducing expensive imports (Solihu, 2020; Choudhary et al., 2023), widespread Ordinary Portland Cement (OPC) use carries negative environmental impacts due to high energy consumption and CO2 emissions (Gupta & Chaudhary, 2020). This study addresses these issues by incorporating sustainable materials, reducing cement consumption, and lowering CO2 emissions. This hybrid treatment uses cement for early strength, Ground Granulated Blast Furnace Slag (GGBS) for long-term pozzolanic reactions, and Aloe vera for moisture regulation and enhanced particle contact to create a dense, strong soil matrix.

To counter excessive emissions, this research adopts a fixed inclusion of 5% cement in every mixture. Prior literature justifies this exact baseline concentration; Arshad et al. (2018) showed that soil stabilized with 5% cement by weight achieved an unconfined compressive strength (UCS) greater than 0.8 MPa for subgrade applications, and Owamah et al. (2023) demonstrated that 5% cement boosted soil California Bearing Ratio (CBR) values from 15% to 27%, significantly improving load-bearing ability.

GGBS, an industrial byproduct of the iron and steel blast furnace process, is highly valued for its natural pozzolanic properties. In soil-cement stabilization, GGBS interacts with calcium compounds produced during cement hydration to generate extra cementitious products, particularly Calcium Silicate Hydrate (C-S-H). This reaction improves the treated soil's strength, density, and long-term stability by reducing soil porosity, improving particle bonding, and increasing resistance to deformation under load. According to Park et al. (2016), GGBS features a glassy, amorphous calcium aluminosilicate structure formed by rapid cooling. This structure controls its reactivity but causes slow hydration when mixed with water alone because the dissolution of its amorphous components is limited. Consequently, chemical activators like cement are needed to improve reactivity. Raghuvanshi and Singh (2024), GGBS's chemical composition is quite similar to PC, with different amounts of lime, silica, and alumina. It has also been widely employed as a component in concrete. Kumar and Ojha (2025) experimentally demonstrated that adding controlled percentages of GGBS to problematic soils significantly improves key engineering properties. Their study showed that optimal GGBS content increases soil stability under loading, reduces plasticity, and improves workability. Prasad et al. (2018) states that combining GGBS with other stabilizing agents enhances the effectiveness of soil treatment, resulting in stronger and more durable soil. GGBS improved compaction, reduced plasticity, and increased bearing capacity.

GGBS is also an effective soil stabilizing agent that improves the engineering properties of expansive soils. According to Prasad et al. (2018), its pozzolanic and hydraulic properties catalyze chemical changes within the soil matrix, leading to improved compaction, reduced plasticity, and enhanced bearing capacity. However, literature emphasizes determining optimal GGBS content because excessive amounts may decrease performance due to incomplete activation or particle imbalance.

Given the widespread use of gums for soil stabilization, nature-based admixtures are developing as environmentally acceptable alternatives to synthetic additives, encouraging sustainable construction methods and minimizing reliance on finite resources. (Tadesse 2023). In order to enhance the engineering characteristics of the mixture, the researchers included aloe vera powder as an additional stabilizing element. Its natural gel-forming and hygroscopic (moisture-retaining) properties to the soil matrix. It is also stated that higher dosages of the natural ingredient enhanced long-term drying shrinkage; nevertheless, the resulting change in length was minor and within acceptable limits. Another application of aloe-vera used to improve compressive strength of concrete states that as the concentration of aloe vera juice increases, there is a slight and steady decrease in the compressive strength and in terms of workability, it is observed that as the concentration of aloe vera juice increases, the workability of the concrete increases (Shalini et al., 2021). Accordingly, they incorporated 0.5%, 0.7% and 1% of aloe-vera juice and it is observed that the highest compressive strength attained is at 0.5% proportion of aloe vera gel. Tirado et al. (2024) reported that Aloe vera cuticle exhibited a high water-holding capacity, retaining up to 18 times its weight in water, while maintaining stability in the presence of calcium ions. In hybrid stabilization approaches, the inclusion of Aloe vera may influence compaction behavior by improving moisture availability during hydration, potentially affecting OMC and MDD.

In the construction industry, cement initiates hydration to connect particles, while GGBS gradually adds calcium silicate hydrates (C-S-H) to increase strength and durability. Polysaccharide-rich Aloe vera acts as a water-retention and viscosity-modifying agent. Combining these elements, a hybrid treatment using cement for early strength, GGBS for long-term pozzolanic reaction, and Aloe vera for enhanced particle contact and moisture regulation can produce a denser, stronger soil matrix.

Due to practical limitations, each test condition will use two samples. This aligns with standard laboratory protocols, where the second sample serves as a mandatory check-test to validate results and ensure reliability. Treated specimens will be prepared using specific percentages of the hybrid agent and evaluated for standard compaction and soaked California Bearing Ratio (CBR). To assess strength development over time, CBR testing is performed after a 7-day curing period. According to ACI 308R-16 (American Concrete Institute, 2016), hydration proceeds rapidly during the first week of curing and slows down as the internal structure becomes denser. Concrete strength testing at 7, 14, and 28 days is widely practiced because these ages correspond to key points in the hydration and strength-development process. ASTM C39/C39M-21 (ASTM International, 2021) notes that early-age strength data are essential for detecting batching errors, curing deficiencies, or unexpected mix behavior. Additionally, when a stabilized specimen achieves extreme stiffness, it may reach a state of "piston refusal." This occurs when the material’s surface hardness exceeds the penetration capacity of the standard 50 mm diameter piston, potentially leading to eccentric loading or equipment instability, such as piston tilting (Ferdez et al., 2021).

Several studies validate the reliability of limited-scale testing and alternative materials in field density evaluations. Research published in the International Journal of Engineering Trends and Technology (IJETT) demonstrated that small-scale compaction results closely agree with laboratory Proctor compaction, showing a minimal dry density variance of just 0.03g/cm^3. This finding is supported by Park et al. (2021), who confirmed that adhering to strict testing procedures on a limited soil bed yields accurate dry density values that closely approximate actual in-situ conditions. Furthermore, regarding the sand cone calibration material, Sangiamsak et al. (2021) established that standard Ottawa sand is merely a reference material rather than an absolute requirement; consequently, thoroughly calibrated and validated local, non-standard sands can be successfully utilized instead without compromising test integrity.

This study utilizes a one-way ANOVA to determine if differences between untreated and stabilized soil specimens are statistically significant rather than the result of random variation. To complement this, a post hoc test is employed to identify the specific concentrations that yield significant improvements in strength, compaction, and bearing capacity. This study evaluates an Aloe vera-GGBS-cement hybrid soil stabilizing agent designed to enhance the bearing capacity and engineering performance of base course materials.

This study advances key UN Sustainable Development Goals (SDGs) for sustainable infrastructure. It supports SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities) by introducing an innovative material that improves pavement bearing capacity, durability, and safety. Additionally, replacing cement with GGBS aligns with SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) by enhancing resource efficiency, minimizing waste, and cutting CO2 emissions.

By integrating ecologically beneficial materials, the research provides sustainable, practical solutions for real-world pavement construction that reduce reliance on conventional cement while contributing to durable, high-performance base courses.

Statement of the Problem

This study aims to develop an effective hybrid soil stabilizing agent using Aloe vera gel, Ground Granulated Blast Furnace Slag (GGBS), and cement to enhance the bearing capacity of soils used as base course. Specifically, it seeks to answer the following questions:

1. What are the index properties of the untreated soil sample?
   a. Grain Size
   b. Atterberg Limits (LL, PL, and PI)
   c. Engineering classification based on the AASHTO Soil Classification System
2. What are the compaction characteristics (OMC and MDD) of the treated and untreated soil samples?
3. What are the mechanical performance outcomes of different stabilizer proportions ranging from untreated soil (T0), and to soils incorporating varying percentages of GGBS and Aloe vera (T1 to T3)?
   a. T0: 100% Soil
   b. T1: 89.5% Soil + 5% Cement + 5% GGBS + 0.5% Aloe vera
   c. T2: 84.5% Soil + 5% Cement + 10% GGBS + 0.5% Aloe vera
   d. T3: 83.3% Soil + 5% Cement + 10% GGBS + 0.7% Aloe vera
4. What is the influence of the hybrid soil stabilizing agent to the stabilization and strength development of the treated soil after 7 days of curing, as evaluated using CBR tests?

5. What is the statistical difference in CBR values between untreated and treated (T1 to T3) soil samples based on ANOVA results?
6. Does the developed hybrid soil stabilizing agent significantly improve the bearing strength of soil intended for use as base course in pavement construction?

Hypothesis of the Study

To address the stated research questions, the following hypotheses were formulated:

H01: There is no significant difference between untreated soil and soil samples treated with varying stabilizer proportions (T1 to T3) in terms of CBR values based on ANOVA.

H11: The treated soil sample with varying stabilizer proportions (T1 to T3) exhibits significantly higher CBR values based on ANOVA compared to the untreated soil.

H02: There is no significant difference among the varying stabilizer proportions (T1, T2, and T3) in terms of their mechanical performance.

H12: There is a significant difference between the treated variations (T1, T2, and T3), allowing for the identification of the optimum hybrid stabilizer proportion for pavement base course construction.

Conceptual Framework

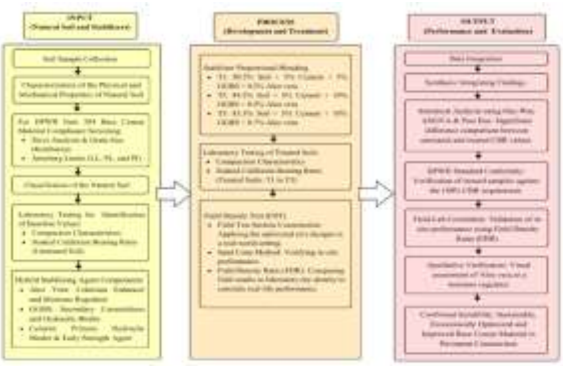

Figure 1. Conceptual Framework of the Study

II. METHODOLOGY

Research Design

This study utilizes an experimental research design to evaluate a sustainable hybrid soil stabilizing agent composed of Aloe vera powder, Ground Granulated Blast-Furnace Slag (GGBS), and cement. Laboratory experiments are conducted to assess and compare the index properties, compaction characteristics, and California Bearing Ratio (CBR) of untreated and treated soil specimens, establishing the stabilizer's efficacy for base course applications.

Materials and Treatments

1. Materials

a. Soil Sample- The soil samples used in this study were particularly collected from Sapang, Cabanatuan City Nueva Ecija.

b. Aloe-vera powder- Extracted from mature Aloe-vera leaves, blended to obtain a uniform gel, dehydrated and powdered. The processed Aloe Vera powder will be sieved to achieve a particle size of approximately 75 µm.

c. Ground Granulated Blast Furnace Slag (GGBS): Industrial by-product sourced from a local supplier. The GGBS will be used in finely powdered form, with a target particle size of approximately 75 µm to enhance reactivity and consistency in the hybrid stabilization mix.

d. Ordinary Portland Cement: Type I cement.

Table 1. Treatments to Be Used and Their Layout

Treatment Code	Description
T0	Control (Untreated Soil)
T1	89.5% Soil + 5% Cement + 5% GGBS + 0.5% Aloe vera
T2	84.5% Soil + 5% Cement + 10% GGBS + 0.5% Aloe vera
T3	84.3% Soil + 5% Cement + 10% GGBS + 0.7% Aloe vera

Table 2. Soil Properties and Test Method

Parameter	Type	Standard
Grain Size	Dependent	ASTM D6913
Liquid Limit	Dependent	ASTM D4318
Plastic Limit	Dependent	ASTM D4318
Plasticity Index	Dependent	ASTM D4318
OMC	Dependent	ASTM D698
MDD	Dependent	ASTM D698
CBR	Dependent	AASHTO T193
Relative Compaction		ASTM D1556
Stabilizer Composition	Independent	

Data Gathering Procedures

The following experimental procedures will follow a systematic workflow based on the conceptual framework to evaluate the formulation and efficacy of the hybrid soil stabilizing agent for improving base course:

1. Soil Sample Collection and Preparation
   a. Soil samples will be collected from the designated base course site.
2. Index Properties Identification
   i. Sieve Analysis
   ii. Casagrande Cup Method
   iii. Rolling Method
3. Preparation of Hybrid Soil Stabilizing Agent
   a. The hybrid stabilizer will be prepared in predetermined proportions.
4. Compaction Test of Treated Mixtures
   a. Determine each mixture's compaction characteristics using Proctor tests.
5. Specimen Preparation for Testing
   a. Soil samples will be mixed with the hybrid stabilizing agent.
   b. Two replicate samples will be cured for 7 days before mechanical testing.
   c. Use the OMC and MDD obtained per mixture to prepare samples for: California Bearing Ratio (CBR) – soaked condition.
6. Laboratory Testing

a. Conduct CBR tests for each mixture.
7. Visual observations
a. Visible changes in soil color, moisture retention, and surface conditions were systematically documented in a controlled laboratory setting. .
8. Field Testing
a. Measure field dry density using a sand cone test. FDT verifies whether the field achieved the lab-defined target.

To simulate a highway base course, a 300 mm thick tub model was constructed following DPWH Item 201 specifications, using dimensions from literature to ensure proper lateral confinement. The Sand Cone Test was conducted within this setup to effectively bridge the gap between laboratory results and field performance.

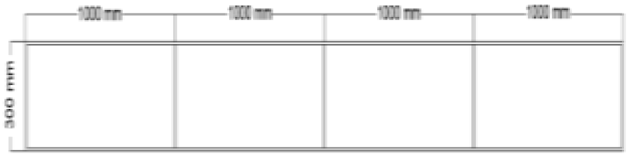

Figure 2.1. Base Course Tub Model Side View

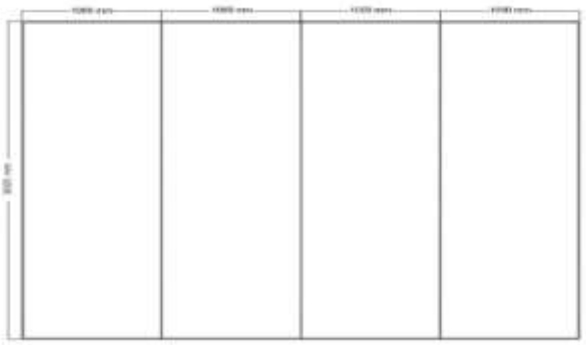

Figure 2.2. Base Course Tub Model Top View

9. Data Comparison, Statistical Evaluation, and Performance Assessment
a. To evaluate the improvement in soil bearing capacity across the various treatment levels, One-Way Analysis of Variance (ANOVA) was utilized. Upon the detection of a significant result in the ANOVA, a Tukey's Honestly Significant Difference (HSD) Post Hoc Test was performed.

Statistical Treatment

The experimental findings were evaluated statistically to determine if variations in soil strength were significant. A One-Way Analysis of Variance (ANOVA) tested whether the hybrid stabilizing agent significantly enhanced the base course material's engineering qualities, analyzing mix performance by testing the null hypothesis that no significant difference exists between control and treated samples.

By calculating the F-statistic, the study determined if differences in CBR performance were due to the treatment, isolating which specific mix compositions yielded significant variations to distinguish the most effective treatments from control samples.

Statistical analyses were conducted at the 0.05 level of significance (α=0.05). If the calculated F-value exceeds the F(crit), the null hypothesis is rejected, indicating a significant treatment effect from the GGBS and Aloe vera additives. And a P-value less than the α level of 0.05 confirms that the improvements in the soil's California Bearing Ratio (CBR) are not due to random variation but are a direct result of the stabilization process.

Graphical representations, such as bar graphs, were also utilized to demonstrate variations between mix formulas and curing times.

III. PRESENTATION ANALYSIS AND INTERPRETATION OF DATA

This chapter aims to provide a clear and systematic presentation of the experimental outcomes, forming the basis for evaluating the effectiveness of the proposed soil stabilization approach.

Table 3. Grain Size Distribution Table

Sieve No.	Weight of Soil Retained (kg)	Percent of mass of soil retained (%)	Cumulative Percent Retained (%)	Percent Passing (%)
2''	0	0	0	100
4	0.849	30.997	30.997	69.003
10	0.376	13.728	44.724	55.276
40	0.638	23.293	68.018	31.982
200	0.552	20.153	88.171	11.829
Pan	0.324	11.829	100	0
Total	2.739	100		

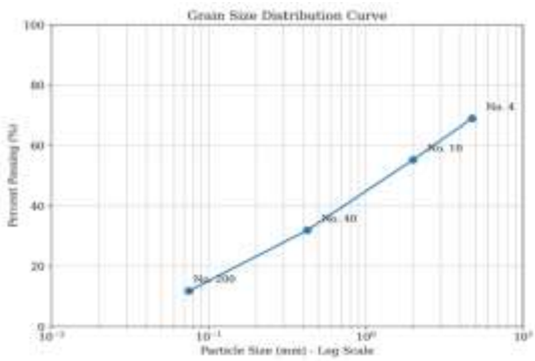

Figure 3. Grain Size Distribution Curve

Presented is the grain size distribution of the untreated soil based on sieve analysis. The results show that the soil consists predominantly of coarse-grained particles with a limited amount of fine material. The soil's mass percent passing values fall completely within the Department of Public Works and Highways (DPWH) Grading B requirements for base course materials, confirming it satisfies the required gradation limits.

Additionally, the **liquid limit (LL)** of the untreated soil was determined at **20.99%**. And the average **plastic limit (PL)** was determined at **13.56%**. The plasticity index (PI) is **7.43%.** According to the **Department of Public Works and Highways (DPWH)** standards for base course materials, the acceptable plasticity index range is **4–10%**. The computed PI value falls within this specified range, indicating that the soil satisfies the DPWH plasticity requirement for base course applications. The obtained PI value indicates that the soil has low to moderate plasticity, which is desirable for base course materials as it provides adequate workability while minimizing the risk of excessive shrinkage, swelling, and moisture susceptibility. Based on the laboratory results and using the **AASHTO Soil Classification System**, the sample is classified as **A-2-4 with a Group Index (GI) of 0**. According to the **Ohio DOT's Rendition of the AASHTO Classification, an A-2-4(0)** soil is characterized as **Gravel and/or Stone Fragments with Sand and Silt.**

B. Standard Proctor Compaction

Table 4. Compaction Characteristics Values

Compaction Characteristics Values (T0-T3)						
Test No.	1	2	3	4	5	6
T0 (ω)	8.70	9.57	**13.19**	14.62	15.32	17.02
T0 (γdry)	18.83	19.32	**19.58**	18.66	18.5	17.93
T1 (ω)	6.43	8.75	10.61	**11.36**	13.92	16.09
T1 (γdry)	18.84	18.74	19.37	**19.69**	18.65	18.16
T2 (ω)	5.94	7.34	8.24	**10.87**	11.43	13.64
T2 (γdry)	18.56	18.96	19.49	**19.62**	19.16	18.68
T3 (ω)	2.33	3.74	**6.78**	9.38	13.25	13.53
T3 (γdry)	18.50	19.47	**20.05**	19.37	18.35	18.09

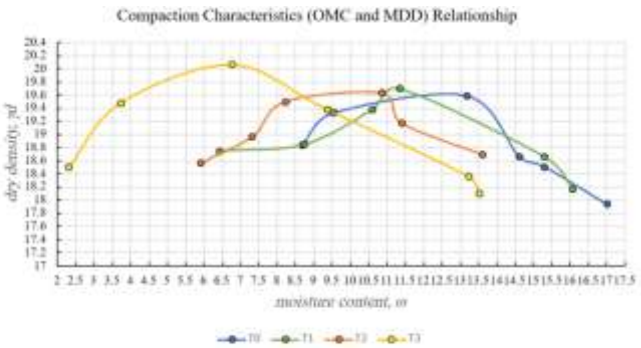

Figure 4. Compaction Characteristics and Relationship

The moisture-density relationships are determined across six compaction trials. The Maximum Dry Density and Optimum Moisture Content of the untreated soil were 19.61 kN/m³ and 12.51%, respectively. T1 reached an MDD of 19.71 kN/m³ at an OMC of 11.20%, mixture T2 achieved an MDD of 19.72 kN/m³ at an OMC of 10.51%, and mixture T3 exhibited the highest compaction performance with an MDD of 20.06 kN/m³ at an OMC of 6.57%.

Table 5. Summary of Compaction Characteristics Values

Mixture ID	OMC	MDD
T0	12.51 %	19.61 kN/m³
T1	11.20 %	19.71 kN/m³
T2	10.51 %	19.72 kN/m³
T3	6.57 %	20.06 kN/m³

The compaction test results demonstrate a clear and significant improvement in the engineering properties of the soil when treated with the hybrid stabilizing agent. Soils with lower optimum moisture requirements are typically less susceptible to volumetric changes.

C. California Bearing Ratio (CBR) Test

California Bearing Ratio (CBR) tests were conducted on the soil sample under soaked conditions to evaluate its bearing capacity in its natural state.

Table 6. California Bearing Ratio (CBR) Values of 7 Days Treated Samples (T0-T3)

Mixture ID	Calibration Factor	CBR Value	CBR Value Adopted	Average CBR Value
T0_1	2.54mm 5.08mm	31.35 % 40.64 %	40.64%	39.06%
T0_2	2.54mm 5.08mm	31.83 % 37.47 %	37.47%	
T1_1	2.54mm 5.08mm	70.46 % 86.76 %	86.76%	85.13%
T1_2	2.54mm 5.08mm	66.32% 83.49%	83.49 %	
T2_1	2.54mm 5.08mm	138.72 % 151.27 %	151.27 %	147.1 %
T2_2	2.54mm 5.08mm	120.03 % 142.92 %	142.92 %	
T3_1	2.54mm 5.08mm	154.13 % 206.92 %	206.92 %	205.05 %
T3_2	2.54mm 5.08mm	175.71 % 203.18 %	203.18 %	

According to ASTM D1883, the CBR value at 2.54 mm is the most commonly utilized value. When the CBR at 5.08 mm exceeds that at 2.54 mm, the test findings should be validated, and if confirmed, it can be recorded.

The untreated control samples yielded an average CBR value of 39.06%, failing to meet the minimum 80% CBR required for DPWH Item 201. Following treatment, the T1 group reached an average CBR of 85.13%, which elevated the bearing capacity but fell slightly below the 100% CBR requirement for DPWH Item 204. T1 serves as a successful proof-of-concept for soil upgrade.

In contrast, the T2 and T3 treatment groups successfully satisfied the minimum 100% DPWH Item 204 CBR requirement. The T2 group achieved an average CBR value of 147.10%, driven by the increased dosage of GGBS which produced extensive Calcium Silicate Hydrate (C-S-H) gels to fill interstitial voids. The highest performance was observed in the T3 group, where samples peaked at an average CBR of 205.05%, significantly influenced by the natural mucilage of the Aloe vera component, which maintains the optimal internal humidity required for consistent GGBS hydration.

D. Relative Percent Difference (RPD)

The validity of the results of the CBR Test was assessed using the Relative Percent Difference (RPD). The RPD is widely utilized in quality control in laboratories to determine the variability of repeated results.

Figure 5. Summary of California Bearing Ratio Values

In this study, the acceptable percent difference between duplicates of each CBR value was considered as 10%. This is based on the standard percentage difference between duplicated measurements in laboratories. As a result, a 10% difference was considered as an acceptable tolerance to make sure that the generated data is valid for subsequent statistical treatments like ANOVA.

Table 7. Relative Percent Difference (RPD) of CBR Values

Mixture ID	CBR Value 1 (%)	CBR Value 2 (%)	Difference (%)	Mean (%)	% Difference
T0	40.64	37.47	3.17	39.06	8.12 %
T1	86.76	83.49	3.27	85.13	3.84 %
T2	151.27	142.92	9.35	147.10	5.68 %
T3	206.92	203.18	3.74	205.05	1.82 %

For the treated samples (T1, T2, and T3), the computed percentage differences are 8.12%, 1.82%, 5.68%, and 3.84%, respectively. Based on the computed Relative Percent Difference (RPD) analysis and the observed CBR results, the 10% acceptable tolerance set for laboratory dependability is well within all of these values. As a result, the T1, T2, and T3 results are regarded as reliable and valid.

E. Comparative Visual Assessment

In conducting this study, while the primary focus remains on quantitative mechanical testing, critical qualitative data can be derived from the physical appearance of the specimens. Distinct visual variations were observed across the different treatment levels, providing initial evidence of the interaction between the soil and the hybrid stabilizing agents. Documenting these visual characteristics complements the numerical data obtained.

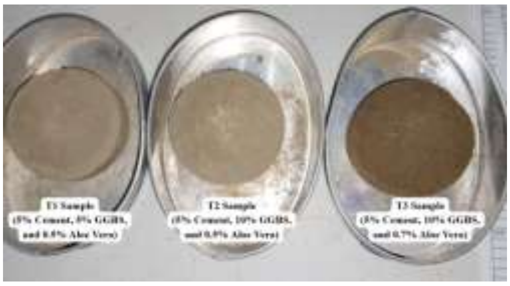

Figure 6.1. Photographic Comparison of the Stabilized Soil Specimens.

Comparing Mixtures T1 and T2 (0.5% Aloe Vera, but 5% and 10% GGBS, respectively). T2 achieved a higher CBR (147.10% mean) than T1 (85.13% mean), but appeared significantly more desiccated after the 4-day curing period. This indicates that increasing GGBS enhances the structural matrix, but increases the chemical demand for water. Furthermore, the "pale" and desiccated appearance aligns with Khattab et al. (2023), noting that without an adequate sealing agent, the high surface area of GGBS particles can lead to rapid "self-desiccation," where water is consumed too quickly or evaporates before pozzolanic bonds mature.

Regarding the robust moisture-regulating agent, more significant comparison is found between T2 and T3, which both utilize 10% GGBS but differ in Aloe Vera dosage (0.5% and 0.7%, respectively). Despite having the same mineral binder content, T3 remained observably moist and dark, whereas T2 showed significant drying.

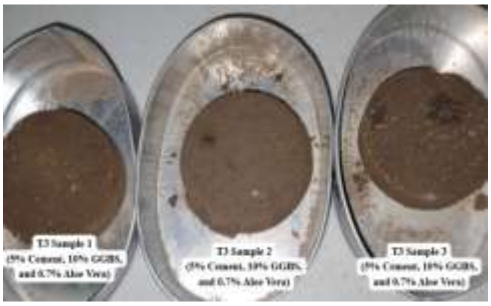

Figure 6.2. Photographic Documentation of Mixture T3 Samples

Figures 8.1 and 8.2 confirm that the additional 0.2% Aloe Vera in T3 was decisive for moisture management. In T2, 10% GGBS likely exhausted available moisture due to the lack of an effective vapor seal. However, natural polysaccharides act as a "molecular bridge" and hydrophobic barrier (Chang et al., 2020), meaning the 0.7% concentration in T3 effectively trapped water within the soil matrix to facilitate prolonged hydration. This explains T3's significantly higher bearing capacity compared to T2, despite both having equal GGBS volumes. Furthermore, T3's lower water content (6.78% OMC) facilitated a more effective stabilization process than T2's higher initial content (10.87% OMC). The contrast between these treatments confirms that the stabilization is a synergistic effect. While GGBS provides the "strength skeleton," the Aloe Vera powder acts as the "curing regulator". The T3 mixture represents the optimal balance, resulting in the most stable and moisture-efficient soil composite.

F. Sand Cone Test

The Sand Cone Test was conducted per ASTM D1556 to validate if the mixtures achieved the Field Density Ratio (FDR), or Relative Compaction (R). These results ensure that CBR improvements are supported by a well-compacted matrix, as proper mechanical compaction is paramount to minimize voids and maximize particle interlocking. The following table compares the field dry density and laboratory maximum dry density (MDD) to determine the percentage of compaction achieved.

Table 8.1. Calibration and Determination of the Unit

Descriptions	Symbols	Values	Unit
Unit Weight Bucket	W_1	4.669	kg
Unit Weight Bucket + Sand	W_2	9.068	kg
Weight of Sand	W_3	4.399	kg
Volume of Bucket	V	0.002813	m^3
Density of Sand	ρ	1564.033	kg/m^3
Unit Weight of Sand	Υ_{sand}	15.343	kN/m^3

Weight of Sand Replacement

The Unit Weight of sand used for Sand Cone Test as replacement to Ottawa sand is **15.343 kN/m³**.

Table 8.2. Summary of Relative Compaction Values

Mixture	Hole Number	Relative Compaction	Average Relative Compaction
T0	1	100.770	100.881%
	2	101.00621	
	3	100.867	
T1	1	107.318	107.766%
	2	108.855	
	3	107.125	
T2	1	116.630	115.923%
	2	115.574	
	3	115.563	
T3	1	121.295	121.239%
	2	121.570	
	3	120.852	

These values satisfy the requirement of 100% compaction mandated by DPWH standards. This indicates a direct correlation between laboratory conditions and field performance, confirming that the maximum dry density established during the Proctor test was successfully replicated, strengthening the reliability of the findings.

H. Comparative Statistical Analysis

One-Way Analysis of Variance (ANOVA) was employed to evaluate the effectiveness of the hybrid soil stabilizing agent. Treated soil samples at 7 days curing period were compared with untreated control samples which were presented in the succeeding tables, allowing for the statistical determination of significant improvements in soil properties due to treatment.

Table 9.1. Data Matrix of CBR Results for One-Way

	T0	T1	T2	T3
Sample 1	40.64	86.76	151.27	206.92
Sample 2	37.47	83.49	142.92	203.18

Table 9.2. CBR Results ANOVA Summary

Groups	Count	Sum	Average	Variance
T0	2	78.110	39.065	5.024
T1	2	170.250	85.125	5.346
T2	2	294.190	147.095	34.861
T3	2	410.100	205.05	6.994

Table 9.3. CBR ANOVA Results

Source	SS	df	MS	F	P-Value	F(crit)
Between Groups	31465.25	3	10,488.416	803.311	5.15 × 10^{-5}	6.59
Within Groups	52.226	4	13.056			
Total	31517.47	7				

The ANOVA results from Table 7.3 demonstrate that the hybrid stabilizer (GGBS and Aloe vera) significantly impacts soil strength, as the P-value ($0.00000515 < 0.05$) and F-statistic ($803.31 > 6.59$) firmly reject the null hypothesis. To pinpoint which specific soil mixtures (Control, T1, T2, and T3) drive this variance, a post-hoc Tukey's Honestly Significant Difference (HSD) test was conducted using a Studentized Range q-value of 5.76 (based on k=4 and dfwithin=4 at α=0.05). Comparing the calculated HSD threshold of 14.709 against the absolute mean differences reveals which specific pairs achieved statistically significant strength improvements.

Table 10. Significance Analysis of Pairwise Mixture Comparisons based on Tukey's HSD

Mixtures	Absolute Mean Difference	HSD Value	Significant/ Not Significant
T0-T1	46.070	14.709	*Significant*
T0-T2	108.040	14.709	*Significant*
T0-T3	165.995	14.709	*Significant*
T1-T2	61.970	14.709	*Significant*
T1-T3	119.925	14.709	*Significant*
T2-T3	57.955	14.709	*Significant*

Tukey's HSD analysis confirms all pairwise comparisons are statistically significant because every mean difference exceeds the 14.709 threshold, proving each stabilizer addition enhances bearing capacity. The T0–T1 transition (46.070) shows immediate stabilization; the T1–T2 jump (61.970) highlights dosage sensitivity where 10% GGBS optimizes void-filling; and the T2–T3 increase (57.955) confirms 0.7% Aloe vera improves moisture retention for sustained hydration.
The T0–T2 gap (108.040) marks a critical milestone, elevating the soil from a failed baseline to passing DPWH standards, while the T1–T3 comparison (119.925) shows progression to a fully optimized solution. Ultimately, the T0–T3 pair yields the highest mean difference of 165.995, quantifying the maximum transformative power of the hybrid stabilizer and confirming that the T3 mixture delivers peak structural enhancement.

I. Engineering Applications

According to DPWH Item 204 standards, a base course material must reach a minimum CBR of 100%. Since Treatment 2 achieved an average of 147.095% within 7 days, it significantly exceeds structural requirements. While T3 offers peak performance, T2 represents the Optimal Design Point. Recommending T2 over T3 is rooted in Resource Optimization; selecting a mixture that safely surpasses the 100% threshold maximizes cost-effectiveness and sustainability by minimizing additive volume without compromising the safety factor.
Furthermore, this proves the high potency of the hybrid stabilizer, achieving 'over-compliance' even at mid-range dosages. Therefore, for standard roadway applications where 100% CBR is the benchmark, T2 provides the most balanced solution between mechanical integrity and material economy.

IV. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

This study evaluated an Aloe vera-based hybrid soil stabilizing agent combined with GGBS and cement to enhance base course bearing capacity using an experimental design. Sieve analysis of the untreated soil (T0) revealed a well-graded distribution matching DPWH Item 204 Grading B, while its Liquid Limit (20.99%), Plastic Limit (13.56%), and Plasticity Index (7.43%) classified it as A-2-4(0). Duplicate samples for mixtures T1, T2, and T3 were prepared using Relative Percent Difference (RPD) to ensure precision. Compaction testing (ASTM D698) showed the stabilizer effectively reduced the Optimum Moisture Content (OMC) and increased the Maximum Dry Density (MDD) across all treated groups, achieving higher dry density with less moisture.
Performance evaluation after 7-day curing revealed untreated soil averaged a low 36.23% soaked CBR, failing the 80% DPWH requirement for untreated base course. Following treatment, T1 averaged 85.13% CBR, failing the 100% DPWH Item 204 threshold for treated materials, whereas T2 and T3 significantly surpassed it at 147.10% and 205.05%. One-way ANOVA and Tukey's HSD analysis confirmed statistically significant differences in CBR values among groups. The analysis for T3 revealed a key synergistic effect where the bio-polymer acted as a catalyst, retaining the sustained moisture required for the pozzolanic hydration of GGBS. Field Density Tests verified 100% relative compaction compliance, replicating laboratory MDD. Lastly, mixture T2 was determined to be the most economical and practical choice, balancing performance, sustainability, and constructability while providing a substantial margin above the standard.

Conclusion

1. The untreated soil sample is concluded to be a suitable base course material as its index properties align with the DPWH standards, specifically Item 204, where the particle size distribution successfully meets the Grading B requirement and the Plasticity Index (PI) of 7.43% falls within the prescribed allowable range of 4% to 10%. The soil was classified as A-2-4 with a Group Index of 0 under the AASHTO system,

indicating a composition consisting primarily of gravel, stone fragments, sand, and silt.

2. The compaction test results indicate a consistent rise in Maximum Dry Density (MDD) from 19.61 kN/m³ in the control (T0) to a peak of 20.06 kN/m³ in T3, alongside a significant reduction in Optimum Moisture Content (OMC) from 12.51% to 6.57%. This trend demonstrates efficient densification and enhanced mechanical stability, minimizing the soil's susceptibility to volumetric changes like swelling and shrinkage.
3. CBR values increased from 39.06% (T0) to a peak average of 205.05% (T3). While the T1 mixture reached 85.13%, falling below the 100% DPWH Item 204 requirement, the T2 and T3 mixtures significantly exceeded this standard, achieving average values of 147.10% and 205.05% respectively. These results confirm that increasing the proportions of GGBS and Aloe vera effectively upgrades the soil to a high-strength base course.
4. The hybrid stabilizing agent facilitates a synergistic reaction between the GGBS and the Aloe vera. After 7 days of curing, the GGBS produces secondary cementitious products that fill soil voids and create a denser matrix, while the Aloe vera mucilage acts as a moisture reservoir that prevents rapid evaporation and ensures continuous hydration. This process significantly accelerates strength development and bearing capacity, allowing the treated soil to meet rigorous engineering specifications for road construction.
5. The statistical analysis confirms a highly significant difference in CBR values between the untreated and treated soil samples, as evidenced by a P-value of 0.00000515 and an F-statistic of 803.31, which far exceeds the critical value of 6.59. HSD test further validates that every incremental increase in the hybrid stabilizer dosage results in a statistically distinct improvement, with all pairwise comparisons exceeding the HSD threshold of 14.709. Specifically, the T0–T1 (46.070), T1–T2 (61.97), and T2–T3 (57.955) comparisons confirm immediate chemical activation and a "Moisture-Lock Mechanism." Ultimately, the massive leap from T0 to T2 (108.040) and T0–T3 (165.995) demonstrate that this hybrid agent successfully upgrades the soil from a failed baseline to high-performance.
6. The hybrid stabilizing agent significantly improves soil bearing strength, upgrading substandard material into a viable base course. While T0 and T1 fell short of CBR requirements, T2 (147.10%) and T3 (205.05%) exceeded DPWH Item 204 standards within 7 days. T2 is the optimal design point, balancing a robust safety factor while considering resource optimization.

Recommendation

1. Future studies are recommended to investigate the Aloe vera-GGBS-cement hybrid stabilizing agent on a wider range of soil types and classifications.
2. It is recommended that the mixture be tested on soils with varying initial California Bearing Ratio (CBR) values.
3. Further research may investigate a broader range of mix proportions to determine the most optimum mix design.
4. Future studies are recommended to include Unconfined Compressive Strength (UCS) testing to confirm compliance with DPWH Item 204.
5. Future research should look into the performance of stabilized soils during long-term environmental exposure to assess their durability over time.
6. Future research should involve granular sustainability and economic feasibility analysis to prove how the hybrid stabilizer can remain economically competitive.

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