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A Comparative Study on Soil Stabilization Relevant to Transport Infrastructure using Bagasse Ash and Stone Dust and Cost Effectiveness

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Abstract

Soft ground improvement to provide stable foundations for infrastructure is national priority for most countries. Weak soil may initiate instability to foundations reducing their lifespan, which necessitates the adoption of a suitable soil stabilization method. Amongst various soil stabilization techniques, using appropriate admixtures is quite popular. The present study aims to investigate the suitability of bagasse ash and stone dust as the admixtures for stabilizing soft clay, in terms of compaction and penetration characteristics. The studies were conducted by means of a series of laboratory experimentations with standard Proctor compaction and CBR tests. From the test results it was observed that adding bagasse ash and stone dust significantly upgraded the compaction and penetration properties, specifically the values of optimum moisture content, maximum dry density and CBR. Comparison of test results with available data on similar experiments conducted by other researchers were also performed. Lastly, a study on the cost effectiveness for transport embankment construction with the treated soils, based on local site conditions in the study area of Assam, India, was carried out. The results are analyzed and interpreted, and the relevant conclusions are drawn therefrom. The limitations and recommendations for future research are also included.

Keywords: Soil Stabilization; Admixtures; Stone Dust; Bagasse; California Bearing Ratio; Compaction.

1. Introduction

Reducing long-term settlement of infrastructure and providing cost-effective foundations with sufficient load-bearing capacities are national priorities for infrastructure development in most countries. In particular, transport infrastructure build on soft soil can cause excessive settlement, initiating the undrained failure of a super-structure if proper ground

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improvement is not carried out [1]. Adequate ground improvement techniques can be adopted to prevent unacceptable excessive and differential settlement and increase the bearing capacity of the foundations at low cost [2, 3]. Over several decades, various ground improvement techniques have been undertaken around the world, which include the use of admixtures, chemical stabilization, and dynamic compaction, as well as preloading with vertical drains and stone columns, among others [4, 5].

The most common and easily implementable soil improvement techniques for transport infrastructure are carried out either through mechanical stabilization or by using cementitious or non-cementitious additives, known as admixtures, in general, with the objectives of reducing compressibility, while enhancing the capacity and serviceability of the soil sub grade supporting the transport corridors.

The existing literature indicates that there are several methods of soft ground improvement using admixtures, including natural pozzolana, soil-quarry dust mixture, bagasse ash, granite dust, and lime, along with the use of marble dust, stone dust, and fly ash, with blends of wheat husk ash and sugarcane straw ash [6-8]. The suitability of various admixtures for ground improvement have been studied previously, including the use of bagasse ash with lime, cement stabilized soil with stone dust, and rice husk ash with polypropylene fiber [9-11]. However, the sole assessment of these additives to fulfill the strength and serviceability criteria of the treated soil implies that such admixtures are unsuitable for pavement subgrades [12-15]. Furthermore, when rice husk ash was used alone, an increase in vertical displacement took place [16]. Several researchers investigated the use of various other materials with bagasse ash, namely hydrated lime, amalgamated quarry fines, cement kiln dust, dolomite powder, and ordinary Portland cement, and found that such additions initiated curtailing of the soils' plasticity index, although increases in soil bearing capacity were insignificant [17, 18].

In some cases, particle segregation and decreased soil strength were reported, especially when the addition of the stone dust as admixture was beyond 20-30% of the virgin soil's dry weight, although its influence on the CBR values were not studied [19-21]. Zaika and Soeharjono [22] found that reduction in the value of soaked CBR took place while using bagasse ash alone as an admixture and suggested blending lime, Portland cement, and gypsum to enhance the CBR. Chen et al. [23] stated that the use of 2% lignosulphonate improved the shear strength of sandy silt and its ductile behavior. Blending the existing poor soil sub-grade with hydrated lime and bagasse ash managed environmental concerns through waste reduction [24]. Application of fly ash and quarry dust as admixtures exhibited significant decreases in void ratio, plasticity index, and swelling potential with shear strength increments of virgin soil [25].

The use of stone slurry containing lime as an admixture at a proportion of 4 to 5% enhanced the shear strength of virgin soil, although its influence on the soil's bearing capacity was not studied [26, 27]. Ogila [28] investigated the decrease in swelling pressure and heave with the addition of ornamental limestone dust in samples of expansive soils, although alterations in the treated soil's strength parameters were not observed. Hasan et al. [29] found that the presence of montmorillonite clay in soil treated with lime and bagasse ash was likely to initiate shrinkage cracks; in such cases, the use of geomembrane or an emulsified cushion was recommended.

1.1. Significance of the Research

For transport corridors, compaction and penetration characteristics are the two vital sub-grade soil properties to support transport infrastructure, such as the highways and railways. Although various admixtures to improve soft soil are available, as per the literature, the use of bagasse ash and stone dust have been quite effective, owing to local availability in large quantities, as well as low cost, besides satisfactory performance in soft soil stabilization. However, the available literature has yet to provide insight into a comparative investigation on the suitability of bagasse ash and stone dust as admixtures in terms of the compaction and penetration characteristics of treated soft soils, or a study on the cost effectiveness of such a soil stabilization technique, specifically for transport infrastructure. This present study aims to bridge this knowledge gap by conducting a comprehensive laboratory experimental program, followed by cost computations.

2. Experimentations

In this section, the materials used, their engineering properties, and the experimental approach and plan are described briefly in sequence.

2.1. Materials

The soft soil sample was stabilized by applying admixtures, i.e., bagasse ash and stone dust in target quantities. The material properties are described below.

2.1.1. Soft Soil

The soil sample used in this study for the laboratory tests was collected from Guwahati, Assam, India by means of an auger boring technique from a depth of about 1-2 m below the ground's surface. The natural moisture content of the soil was measured about 31%. The sample was air-dried, and thereafter, used in the laboratory for investigation. The particle size distribution (PSD) performed by sieve analysis and hydrometer tests indicated that the soil could be classified as well-graded silty clay; the PSD curve is presented in Figure 1. The geotechnical properties are shown in Table 1. The soil may be classified as CL, after the unified soil classification system.

Limited research was carried out previously by other researchers with virgin soil at the study area around the Deepor Beel at Guwahati, Assam, India, including subsoil characterizations and groundwater quality assessment [30, 31], although any investigations on chemical stabilization with the virgin soil is yet to be conducted.

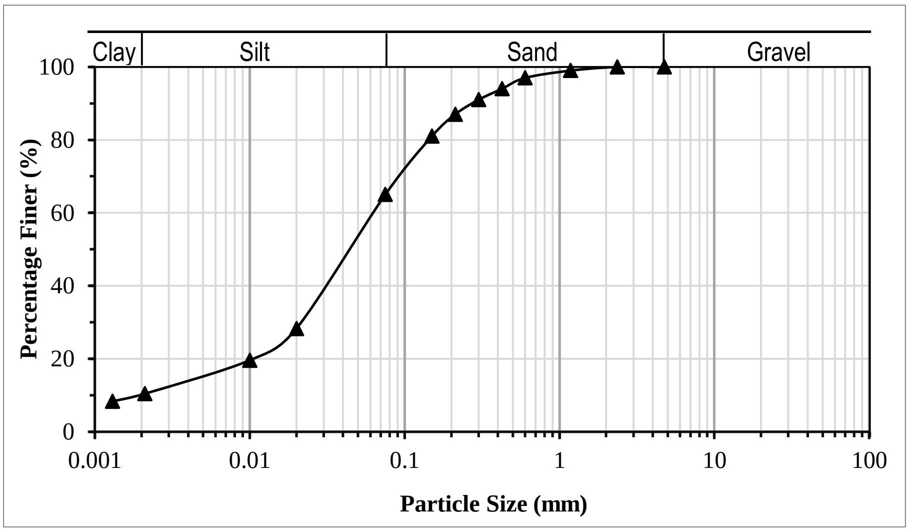


Figure 1. Particle size distribution of untreated soft soil sample

Table 1. Geotechnical properties of untreated soil sample

Geotechnical properties		Values
Uniformity coefficient (C_u); Coefficient of curvature (C_c)		27.5; 5.68
Atterberg limits *	Liquid limit	52%
	Plastic limit	19%
	Plasticity index	33%
Specific gravity of soil particles, G **		2.64
Standard Proctor compaction test #	Optimum moisture content	19.34%
	Maximum dry density	15.95 kN/m^3
California bearing ratio (CBR) ##	Un-soaked sample	4.92%
	Soaked sample	2.66%

* As per ASTM D4318 [53]; ** As per ASTM D5550 [54];
# As per ASTM D698 [35]; ## As per ASTM D1883 [36]

2.1.2. Bagasse Ash

The dry pulpy fibrous residue of sugarcane after juice extraction is termed as bagasse. It is extensively used as a building material, as well as for manufacturing biofuel [32]. The raw bagasse collected from sugar mills is oven dried, and thereafter burnt to ashes, which are used as an admixture for soil stabilization. The bagasse ash is dark black in wet conditions, and gray in dry conditions, consisting of Silica, as well as oxides of Magnesium, Calcium, Iron, Sodium, Potassium and Aluminium [22]. The bagasse is locally available in bulk quantities for utilization in ground improvement for transport infrastructure. The physical and chemical properties of the bagasse ash used for experimentation were obtained from the laboratories, and presented in Table 2. A representative photographic view of the bagasse ash is shown in Figure 2(a).

2.1.3. Stone Dust

Stone dust, which is used as a civil construction material, is a waste material generated while crushing stones in a stone crusher that produces angular aggregates in different sizes. Stone dust is mostly reduced into powdered form after the breakdown of boulders and rocks and appears grayish in color. It is largely available in Guwahati and in other parts of Assam, India. A representative photographic view of the stone dust used in the experiments is shown in Figure 2(b). The particle size distribution curve (see Figure 3), obtained from sieve analysis data, indicated sand and gravel contents of 90 and 10% respectively. The geotechnical properties of the stone dust obtained from laboratory tests are given in Table 3.

Table 2. Properties of bagasse ash

Properties		Values
Physical	Specific Gravity	2.51
	Blaine surface area	512 m^2/kg
	Particle size (D_{50})	27.3 μm
	Colour	Reddish Grey
Chemical	SiO_2	64.73
	Al_2O_3	5.96
	Fe_2O_3	7.56
	CaO	12.67
	MgO	3.23
	SO_3	1.89
	K_2O	3.96

(a) (b)

Figure 2. Photographic views of: (a) bagasse ash, and (b) stone dust

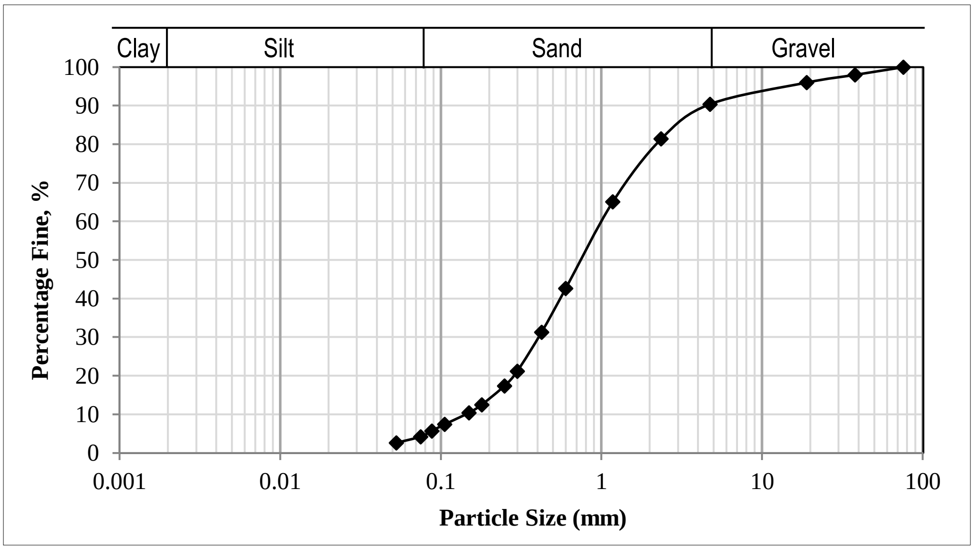


Figure 3. Particle size distribution of stone dust

Table 3. Geotechnical properties of stone dust

Geotechnical properties		Values
Specific gravity of soil particles, *G* **		2.71
Grain size Distribution $	Gravel	10 %
	Sand	90 %
	Silt and Clay	0 %
Maximum Dry Unit Weight		19.1 kN/m^3
Shear Parameters $$	Angle of shearing resistance	4.1°
	Cohesion, *c*	0.00

** Pycnometric method (ASTM D55550) [54]; $ Sieve analysis (ASTM D6913) [55]

$$ Direct shear test (ASTM D3080) [56]

2.2. Test Approach and Plan

The virgin soil collected was first oven dried for 48 hours, and thereafter, manually ground and uniformly mixed with the above-mentioned admixtures at selected proportions by weight. Two different categories of stabilized soil samples (remolded), one with bagasse ash and the other with stone dust, were separately tested and comparative studies were carried out. While a standard Proctor test is suitable for ordinary transport infrastructure, pavements for heavier traffic loading, especially aircraft and frequent truck traffic, demand a modified Proctor test, following the procedure included in ASTM D1557 [33]. In the study area in Assam, India, the measured traffic loading is much lighter [34]. Hence, the standard Proctor test was followed.

The compaction characteristics of the stabilized soil samples were determined by a standard Proctor test following the procedure described in ASTM D698 [35]. On the other hand, the penetration characteristics of treated soil samples were determined by CBR tests for un-soaked and soaked samples, as per recommendation of ASTM D1883 [36]. To carry out the tests, the proportion of admixtures was varied between 2-10% by weight of the dry virgin soil sample and mixed separately with the soil. A total of 33 sets of tests were performed, including the untreated soil, as detailed in Table 4. To minimize the experimental error, three separate experiments were conducted for each set of tests, and the average values of the results were taken for analysis and interpretation. In the laboratory, the CBR specimens were prepared at the optimum moisture content for each test category. It is acknowledged the field CBR values may differ if the field moisture content is different from the optimum moisture content.

Table 4. Test program

Soil samples	Test category		Set of tests *
Untreated soil sample (i.e., no admixtures)	Standard Proctor compaction		1
	CBR	Un-soaked	1
		Soaked	1
Bagasse ash proportion by weight of untreated soil: 2, 4, 6, 8 and 10%	Standard Proctor compaction		5
	CBR	Un-soaked	5
		Soaked	5
Stone dust proportion by weight of untreated soil: 2, 4, 6, 8 and 10%	Standard Proctor compaction		5
	CBR	Un-soaked	5
		Soaked	5
Total set of tests =			33

* For each set, 3 separate tests were conducted to minimize the error, if any (variation in results in all test sets were observed to be less than 5%)

Both the bagasse ash and stone dust are largely available in bulk quantities around the entire study area in Assam, India at cheap rates because of the large number of sugar mills and rock quarries existing in the region [37, 38]. Previous studies revealed that the optimization of compaction and penetration characteristics was achieved when their quantities vary between 4-12% of the dry soil's weight [10, 21, 29]. In order to ensure adequate enhancement of the treated soil's compaction and penetration characteristics, while limiting the transport cost to ensure cost-effectiveness, the maximum quantity of admixtures was restricted to 10% in this paper.

It is true that based-on previous studies the bagasse ash needs to be treated with lime or cement as an activator, especially when the soil is expansive or very soft compressible clay [39]. In the present study, the virgin soil is silty clay. Thus, additional activators might enhance the cost significantly, compared to the relative benefits in the enhancement in the compaction and penetration characteristics. Hence, considering the local soil's characteristics, an activator was not used for soil stabilization.

3. Results and Discussions

The plot of maximum dry density versus moisture content for untreated soil (i.e., without any admixture), obtained from the standard Proctor test data, is shown in Figure 4, from which the optimum moisture content and dry density were evaluated as 19.2% and 15.95 kN/m^3, respectively. For the CBR test for un-soaked and soaked untreated soil, the plot of applied plunger load versus the penetration is shown in Figure 5. After incorporating correction in the load-axis, the CBR values for un-soaked and soaked specimens were evaluated as 4.92 and 2.66 %, respectively.

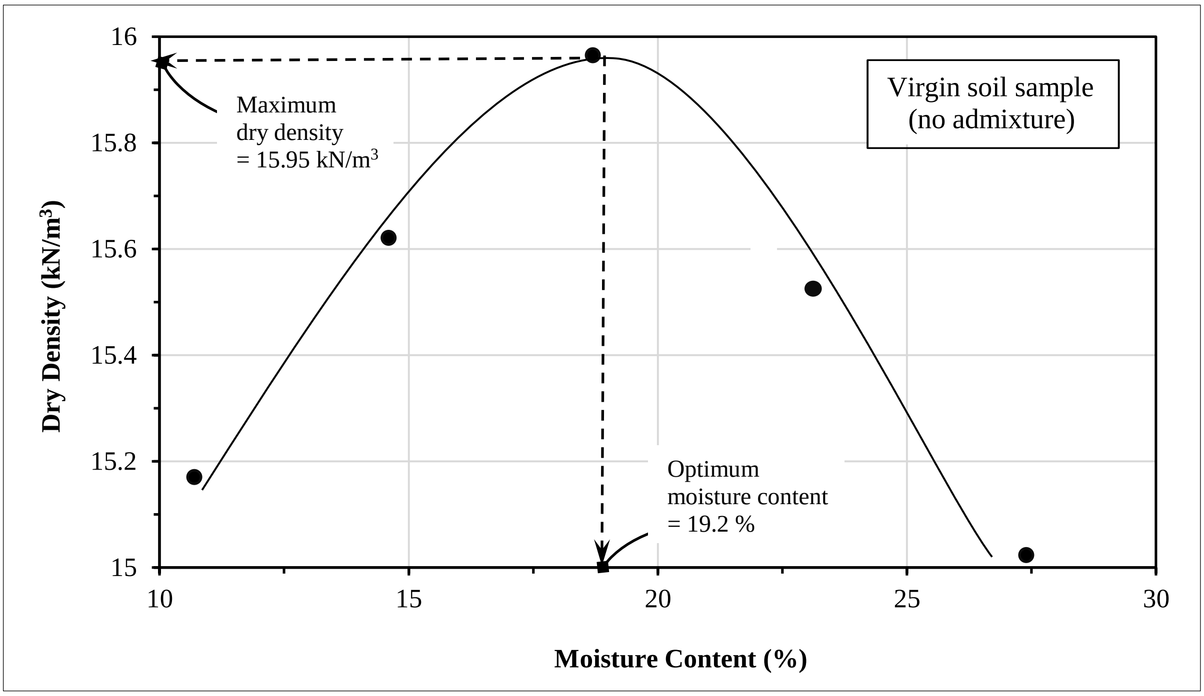


Figure 4. Compaction curve for untreated soil

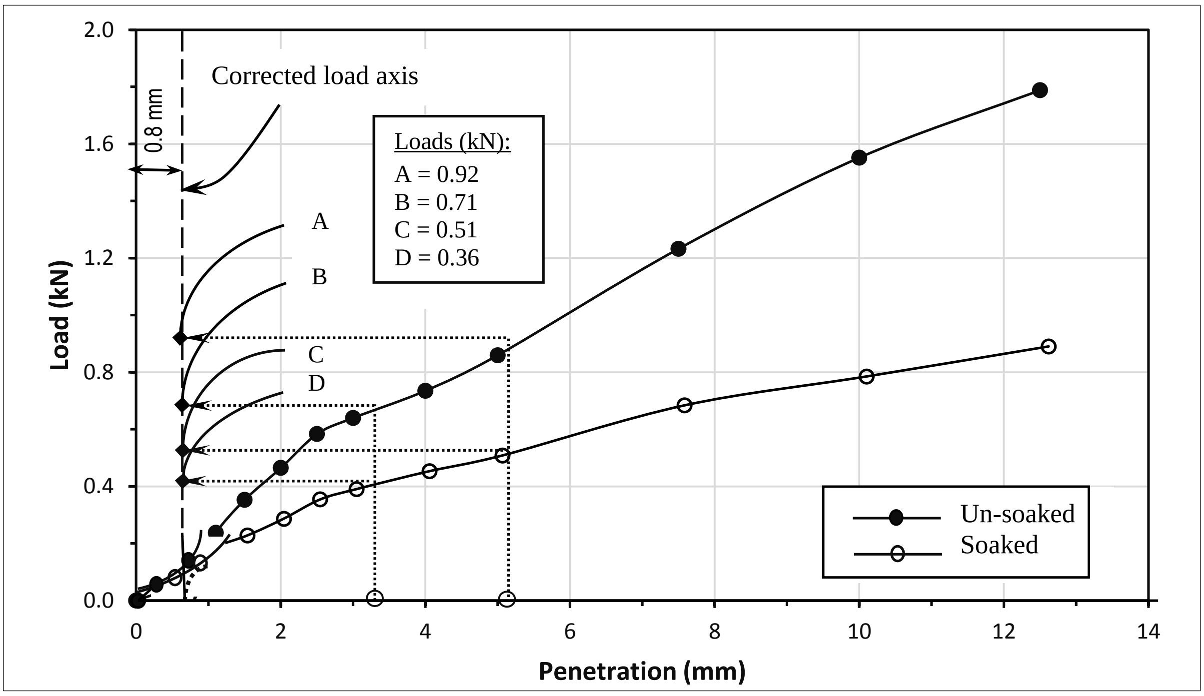


Figure 5. Load-penetration data for CBR tests of untreated soil

The Proctor test results for the treated soil are presented in Figure 6. The CBR test results for un-soaked and soaked treated soil are shown in Figure 7 (with corrected load axis). The optimum moisture content, maximum dry density, and CBR values for the untreated and treated soils are included in Table 5.

3.1. Main Findings: Analyses and Interpretations

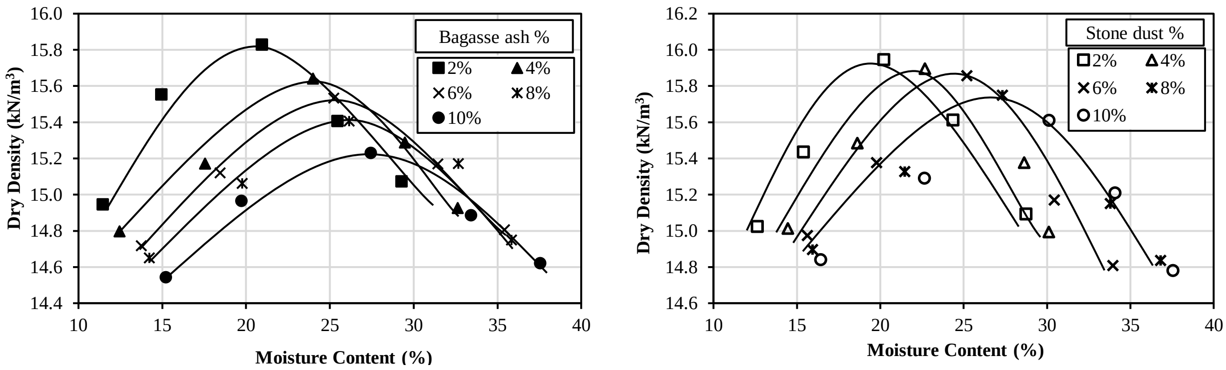
To study the influence of admixtures on the compaction and penetration characteristics of the virgin soil, the optimum moisture content, maximum dry density, and CBR value were normalized as follows (Equations 1 to 3):

$$\alpha_o = \frac{Optimum\ moisture\ content\ of\ stabilized\ soil}{Optimum\ moisture\ content\ of\ untreates\ soil} \quad (1)$$

$$\alpha_m = \frac{Maximum\ dry\ density\ of\ stabilized\ soil}{Maximum\ dry\ density\ of\ untreates\ soil} \quad (2)$$

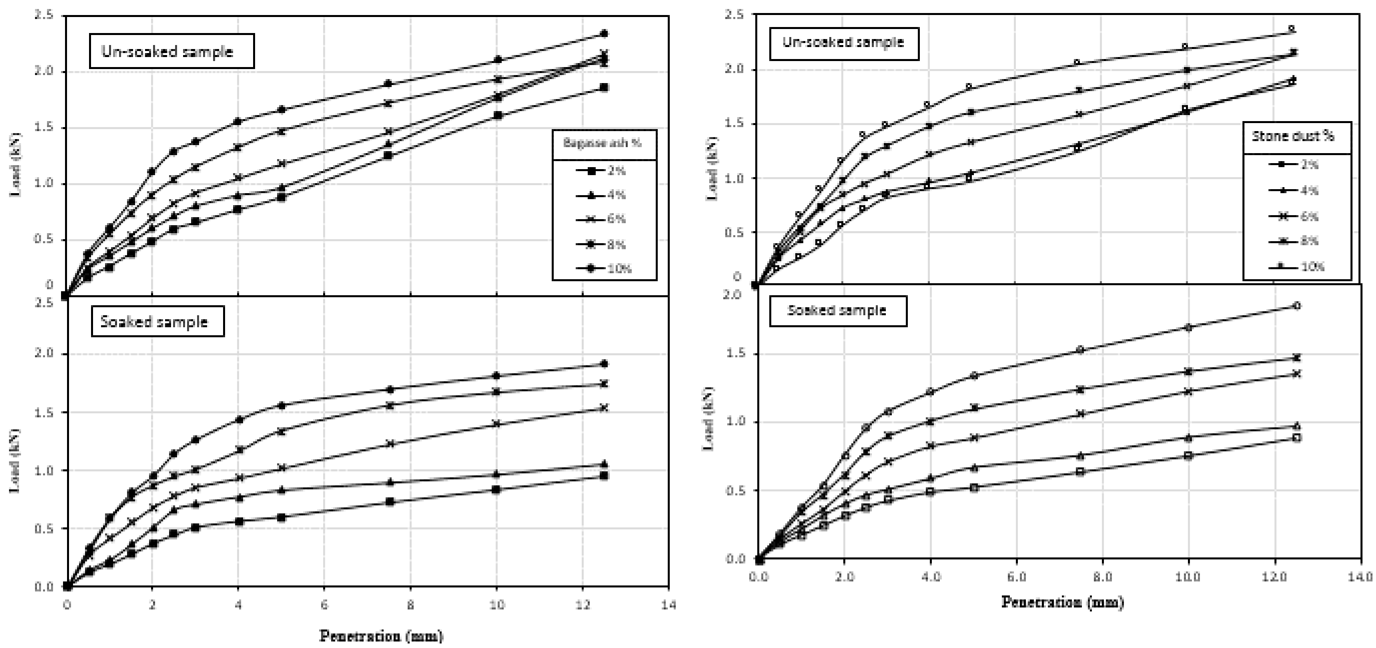
$$\alpha_c = \frac{CBR\ of\ stabilized\ soil}{CBR\ of\ untreates\ soil} \quad (3)$$

where, α_o, α_m, and α_c are the normalized values of optimum moisture content, maximum density, and CBR, respectively.



(a) (b)

Figure 6. Compaction curves for treated soil: (a) bagasse ash, and (b) stone dust



(a) (b)

Figure 7. Load-penetration curves for CBR tests for treated soil: (a) bagasse ash, and (b) stone dust

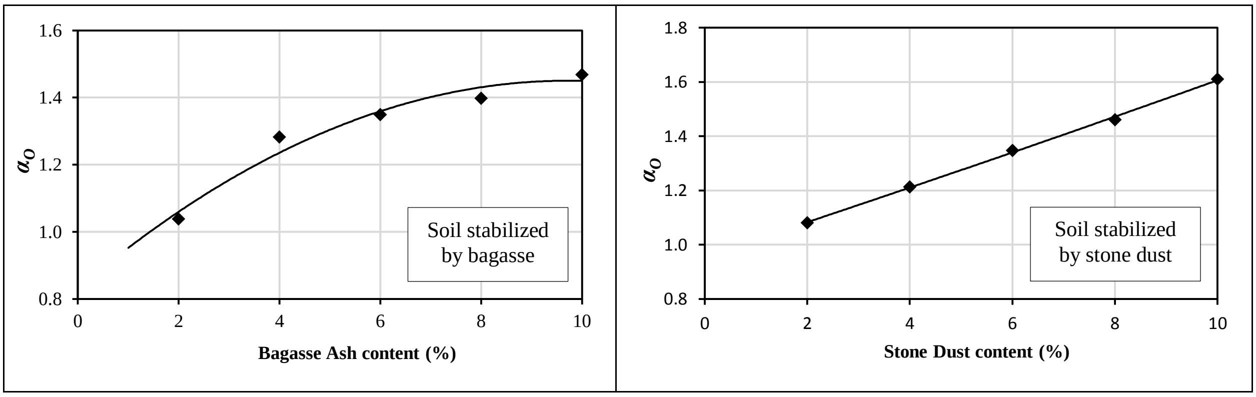
3.1.1. Optimum Moisture Content

The variation of normalized optimum moisture content (α_o) with bagasse ash content is portrayed in Figure 8(a). As the bagasse ash content increased from 2 to 10%, the parameter α_o was observed to increase from 1.12 to 1.47. The pattern of variation was found to be curvilinear with a descending slope. Figure 8(b) depicts the variation of α_o with increasing the content of stone dust. The normalized optimum moisture content was observed to increase in the range of $1.09 < \alpha_o < 1.61$ as the content of stone dust increased from 2 to 10%, the pattern of variation being relatively linear.

The value of α_o greater than unity indicated increases in the optimum moisture content due to the addition of admixtures, the value being slightly higher in the case of stone dust. The above observations may be justified by the possible occurrence of ion exchange between the admixtures and soil particles [40]. In addition, the admixture particles probably reduced the free silt and clay fractions in the soil, thereby occupying larger void spaces for water retention.

Table 5. Test results

Admixture type	Admixture content (%)	Standard Proctor compaction test		CBR (%)	
		Optimum moisture content (%)	Maximum dry density (kN/m^3)	Un-soaked	Soaked
None (i.e., untreated soil)	0	19.2	15.95	4.92	2.66
Bagasse ash	2	19.41	15.82	4.44	3.31
	4	23.98	15.64	5.29	4.94
	6	25.22	15.53	6.12	5.79
	8	26.14	15.41	7.7	7.04
	10	27.45	15.23	9.62	8.53
Stone dust	2	20.21	15.95	5.28	2.79
	4	22.67	15.90	6.02	3.45
	6	25.19	15.86	7.13	4.55
	8	27.32	15.75	8.85	5.82
	10	30.12	15.61	10.2	7.05



(a) **(b)**

Figure 8. Variation of normalized optimum moisture content, α_o with: (a) bagasse ash content, and (b) stone dust content

3.1.2. Maximum Dry Density

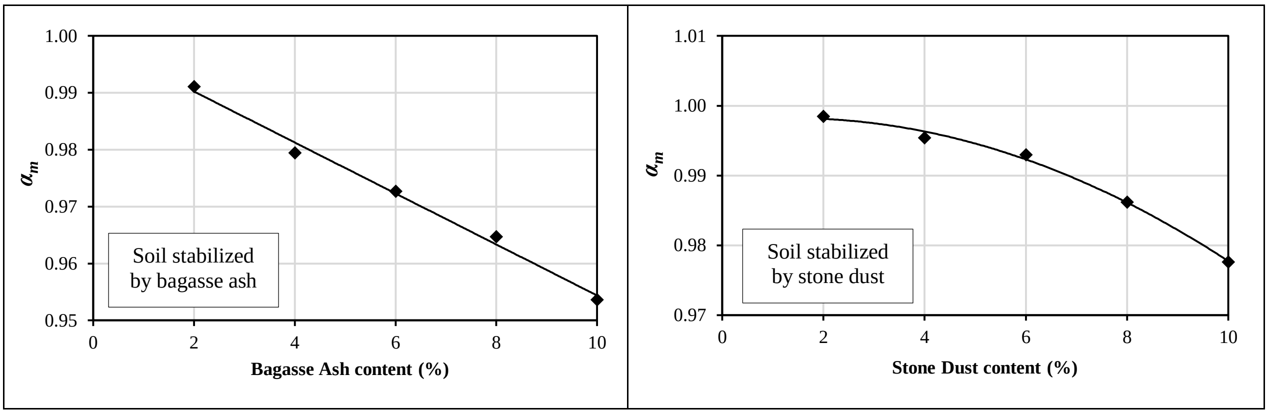
Figure 9(a) presents the variation of normalized maximum dry density with bagasse ash content. As observed, the parameter α_m decreased fairly linearly in the range of $0.95 < \alpha_m < 0.99$ as the bagasse ash content increased from 2 to 10%. In the case of stone dust, on the other hand, as shown in Figure 9(b), α_m decreased following a curvilinear pattern with a descending slope with increasing stone dust content; the range of variation being $0.97 < \alpha_m < 1.0$. The values of αm less than unity indicated a reduction in the value of maximum dry density due to admixture addition. This is advantageous in terms of the decrease in the self-weight of the subgrade with stabilized soil at optimum moisture content. Considering the findings of Kaniraj and Havangi [41], the above observation may be justified with the possible accumulation and flocculation of virgin soil particles with ion exchange between the admixture molecules, which probably initiated the weight-volume ratio reduction.

3.1.3.California Bearing Ratio

The variation of the normalized CBR against increasing bagasse ash content is plotted in Figure 10(a). The increasing bagasse ash content from 2 to 10% initiated the parameter α_c to increase in the ranges of $1.0 < \alpha_c < 2.2$ and $1.25 < \alpha_c < 3.25$ for the un-soaked and soaked tests, respectively. The patterns of variation in both the cases were observed to be curvilinear with ascending slopes; for the un-soaked tests, a reverse curvature was noted with a point of inflection at a bagasse content of about 5%.

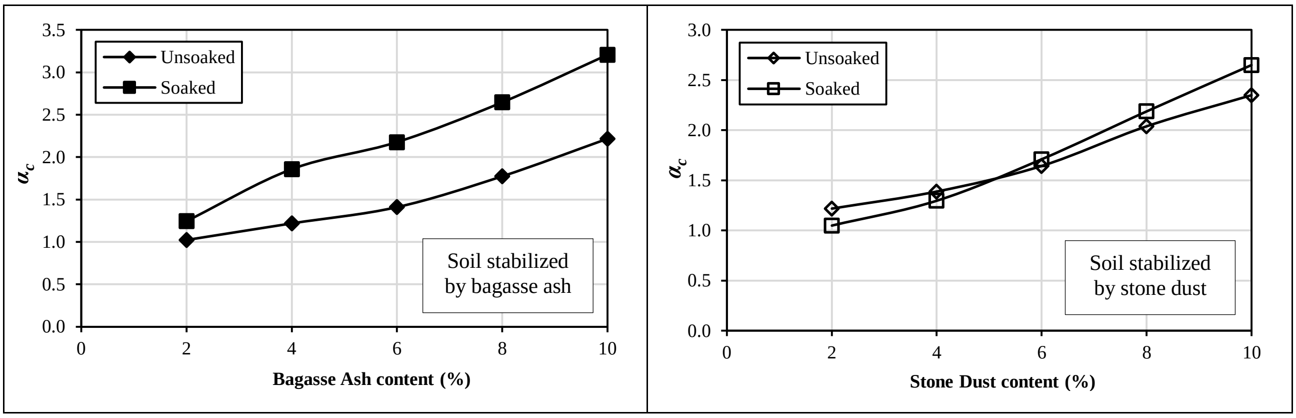
Figure 10 (b) depicts the variation of the parameter αm with the stone dust content. The range of variation of α_c was found to be $1.0 < \alpha_c < 2.7$ and $1.25 < \alpha_c < 2.3$ for the un-soaked and soaked tests, respectively. The pattern of variation was observed to be curvilinear with ascending slopes.

For both of the above cases, the value of the parameter αc was found to be greater than unity, indicating enhancement in the CBR with respect to the untreated soil, due to addition of admixtures. Furthermore, the values corresponding to those with the stone dust were higher compared to those with the bagasse ash, which implies that the soil stabilized with stone dust produced lower penetration-susceptibility.



(a) **(b)**

Figure 9. Variation of normalized maximum dry density, α_m with: (a) bagasse ash content, and (b) stone dust content



(a) **(b)**

Figure 10. Variation of normalized CBR, α_c with: (a) bagasse ash content, and (b) stone dust content

Considering the findings of Mousavi and Karamvand [42], the above observation may be justified with the possible chemical reaction between the soil particles and admixtures. The admixtures probably attributed to cementing effects on the soil, increasing their penetration resistance, thereby increasing the CBR; such cementing efficiency appeared to be more in the case of stone dust. The untreated virgin soil had a specific gravity of 2.64, whereas the bagasse ash and stone dusts had specific gravities of 2.51 and 2.71, respectively. Therefore, mixing the virgin soil with the admixtures at various proportions altered the specific gravity of the treated soil. This factor attributed to the alteration in the treated soil's CBR values [43, 44].

3.2. Comparison with Previous Studies

The test results obtained from the present study were compared with the previous experimental results of Sharma and Kaushik [10] and Zaika and Soeharjono [22] for bagasse ash test data, and Agarwal [20], Kumar and Bishnoi [26] and Venkateswarlu et al. [27] for stone dust test data, as shown in Figures 11 and 12.

3.3. Implications and Explanations

In the case of the standard Proctor compaction tests, the parameter α_o was observed to vary following a random pattern with increasing admixture content, in the case of previous test data, as opposed to a regularized manner for the current tests, as observed from Figure 11(a). The parameter α_m, on the other hand (see Figure 11b), was observed to decrease with increasing admixture content in the case of previous test data; for bagasse ash, the pattern of variation was regular curvilinear, whereas for stone dust, it was random. In the case of previous test data relevant to the CBR tests, the parameter α_c was observed to vary in a random pattern (see Figure 12) against a regularized pattern for the current tests, as discussed above. The difference in magnitudes, as well as the pattern of variation for the parameters αo, αm, and αc in the case of the previous test data compared to the current test results may be justified with the fact that the soil types were different, collected from various sites, in the cases of previous tests by other researchers. Moreover, the properties of the bagasse ash and stone dust used were also of different properties, compared to the present experiments.

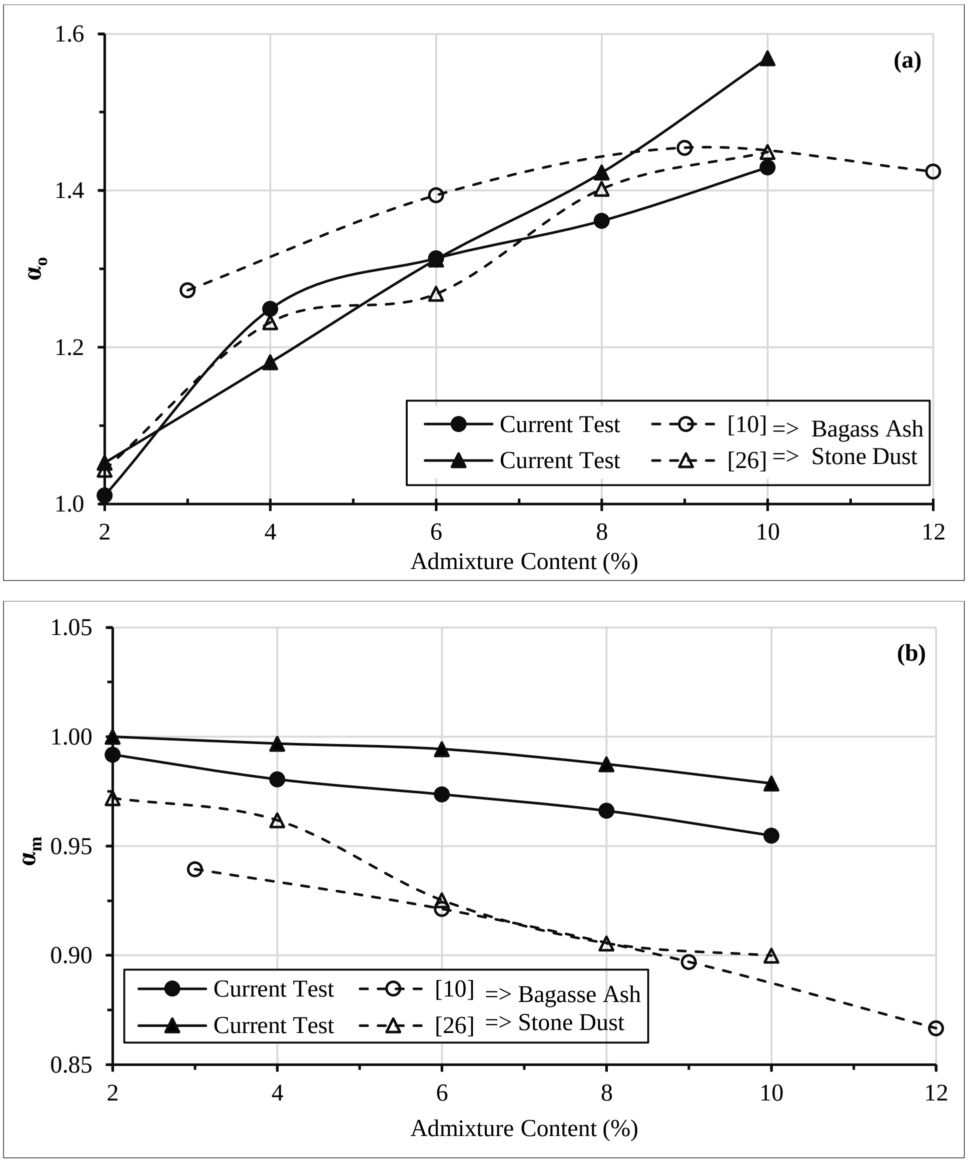


Figure 11. Comparative studies with previous test data for: (a) α_o, and (b) α_m

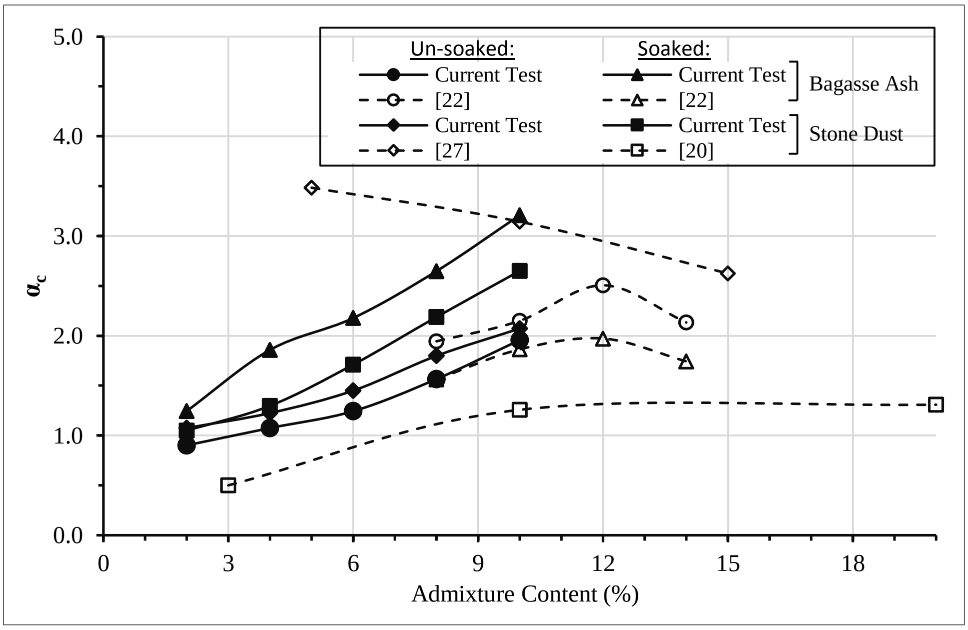


Figure 12. Comparative studies with previous test data for α_c

4. Cost Effectiveness

Highways are considered as nationally important and require periodical maintenance. In rural areas of Assam, India, constructing a pavement requires higher thicknesses of base course and sub-base course to provide adequate drainage facilities, which undoubtedly increases the construction cost. Basack et al. [45] investigated the cost effectiveness of fly ash in pavement construction, and it was observed that using fly ash reduced the cost significantly. The present study is an attempt to estimate the cost of pavement construction with and without additives. From the analysis, it is observed that using soil treated with bagasse ash in pavement construction is more economical in comparison to untreated soil and soil treated with stone dust (see Tables 6 and 7, as well as Figures 13 and 14). The analysis reveals that the cost, compared to the embankment constructed with untreated virgin soil, is reduced by 14.43 and 9.67 % in the cases of bagasse ash and stone dust at 10% proportions, respectively.

For designing the proposed pavement, the project requirements were established by analyzing the soil properties. The dimensions of the road and design parameters, such as design life and traffic estimations, were considered as per Indian standard technical specifications [46]. The embankment's trial geometry was finalized following the recommended guidelines available [47]. This research is intended to stabilize soil along the stretches of Deepor Beel, a freshwater lake that forms a channel to the Brahmaputra River in Guwahati, Assam, India. As per the sample analysis, as well as the transportation and storage facility available at site, an optimum of 10% bagasse ash and 10% stone dust can be used for securing the banks of Deepor Beel significantly to stabilize the soil. Local availability of both bagasse ash and stone dust in bulk quantity is a major advantage. In addition, the optimum percentage of additives conforms to economic stabilization of pavement sub-grades, thereby curtailing the construction cost significantly.

The components of costs related to bringing additives to the site, time of treatment, and mixing costs are added in the analysis. The optimum time and temperature of the calcinations process to produce bagasse ash with high pozzolanic activity is three hours and a 600°C at 10°C per minute heating rate, respectively [48]. While there are various procedures of mixing of materials at the site, the mix-in-place method, which should be equipped with rotavator and compacting with a smooth wheel roller to achieve the desired density, is recommended from the available information based on the local conditions [49-52].

Table 6. Design criteria of embankments using untreated and treated soils

Embankment Design Components *		**Untreated soil**	**Treated with bagasse ash**	**Treated with stone dust**
C.B.R. value of subgrade (Soaked) **		2.66 %	8.53 %	7.05%
Pavement thickness	Sub-base course	200 mm	70 mm	115 mm
	Base course	150 mm	150 mm	150 mm
Initial traffic (CVPD) #			44	
Design life			10 years	
Growth rate factor			6%	
Projected traffic (CVPD)			$A = P(1+r)^{(n+x)} = 28 \times (1+0.06)^{(0+10)} = 51$	
Top width of embankment			7.5 m	
Carriage way			3.5 m	
Height of embankment			2.0 m.	
Side slope			2H : 1V	
Bottom width of embankment			15.5 m	
Side slope earth over thickness			1.0 m	
Length of embankment			1000 m	

* Design criteria are as per MORTH [46];

Average number of commercial vehicles per day (rural roads);

** The soil samples are to be mixed with additives uniformly in fully submerged condition for 4 days before CBR test.

Table 7. Estimation of cost of construction using untreated and treated soils

Material	Pavement Components	Quantity	Rate * (Indian Rupees ##)	Amount (Indian Rupees)	Total amount (Indian Rupees)
Untreated Soil	Base course	0.15 × 8.0 × 1000 = 1200 m^3	1,608 per m^3	19.3 M **	2.5 M
	Sub-base course	0.10 × 3.75 × 1000 = 375 m^3	1,544 per m^3	0.58 M	
Soil treated with bagasse ash	Base course	0.15 × 8.0 ×1000 = 1,200 m^3	1,608 per m^3	19.3 M	2.1 M
	Sub-base course	0.035 × 3.75 × 1000 = 131.25 m^3	1,544 per m^3	0.2 M	
Soil treated with stone dust	Base course	0.15 × 8.0 ×1000 = 1,200 m^3	1,608 per m^3	19.3 M	2.2 M
	Sub-base course	0.055 × 3.75 × 1000 = 206.25 m^3	1,544 per m^3	0.31 M	
Bagasse ash #	Requirement	0.1×131.25×15.23 = 199.89 kN	51 per kN	10,194	0.01 M
	Transportation and Mixing	200 kN	20 per kN	4,000	
Stone dust #	Requirement	0.1×206.25×14.78 = 304.83 kN	112.96 per kN	10,194	0.01 M
	Transportation and Mixing	305 kN	25 per kN	7,625	

Summarized total cost (Indian Rupees)		
Untreated virgin soil	Soil treated with bagasse ash	Soil treated with stone dust
2.5 M	21,32,250 + 14,194 =2.146 M	22,48,050 + 17,819 = 2.265 M
Saving of cost per 1000 m construction	14.43%	9.67 %

*As per APWRD [51]; ** M stands for million;

As per local market rates; ## 1 Indian Rupee = 0.013 US Dollar

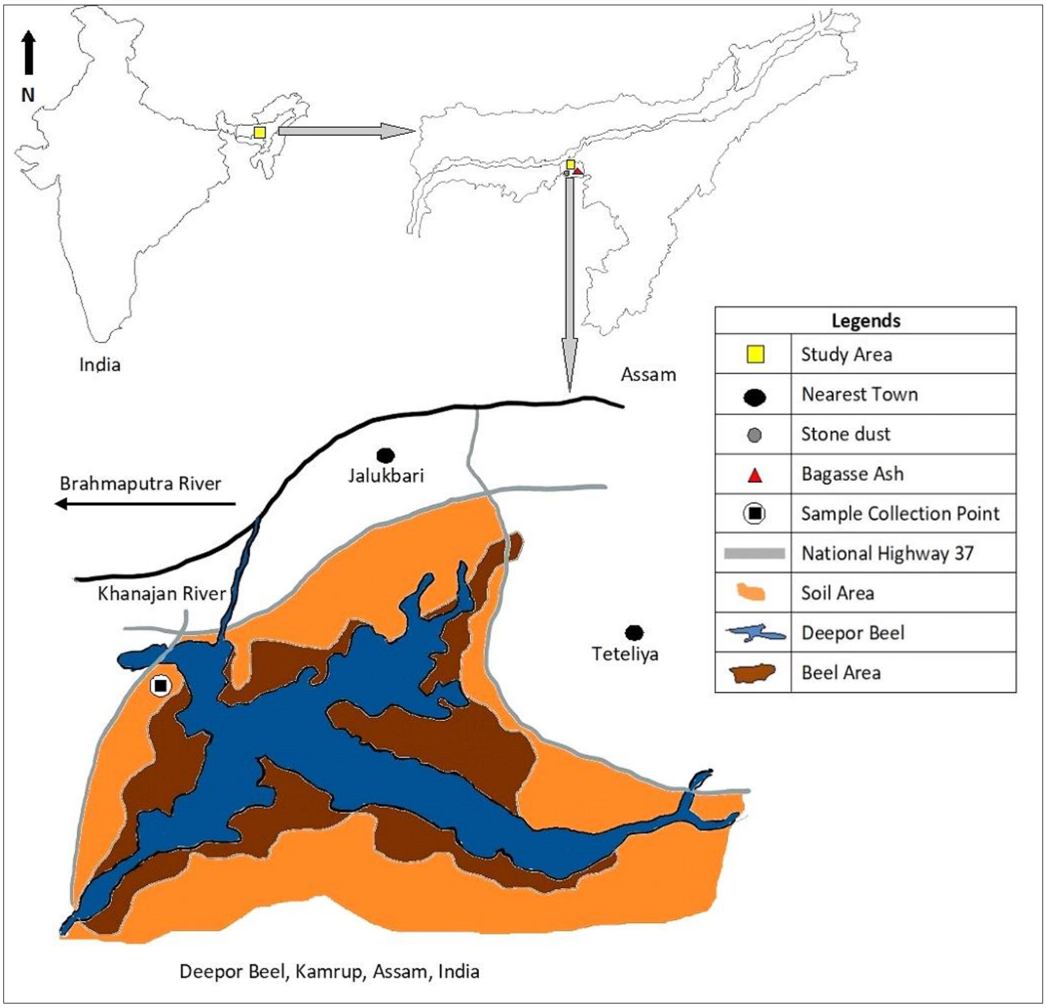


Figure 13. Site location of study area

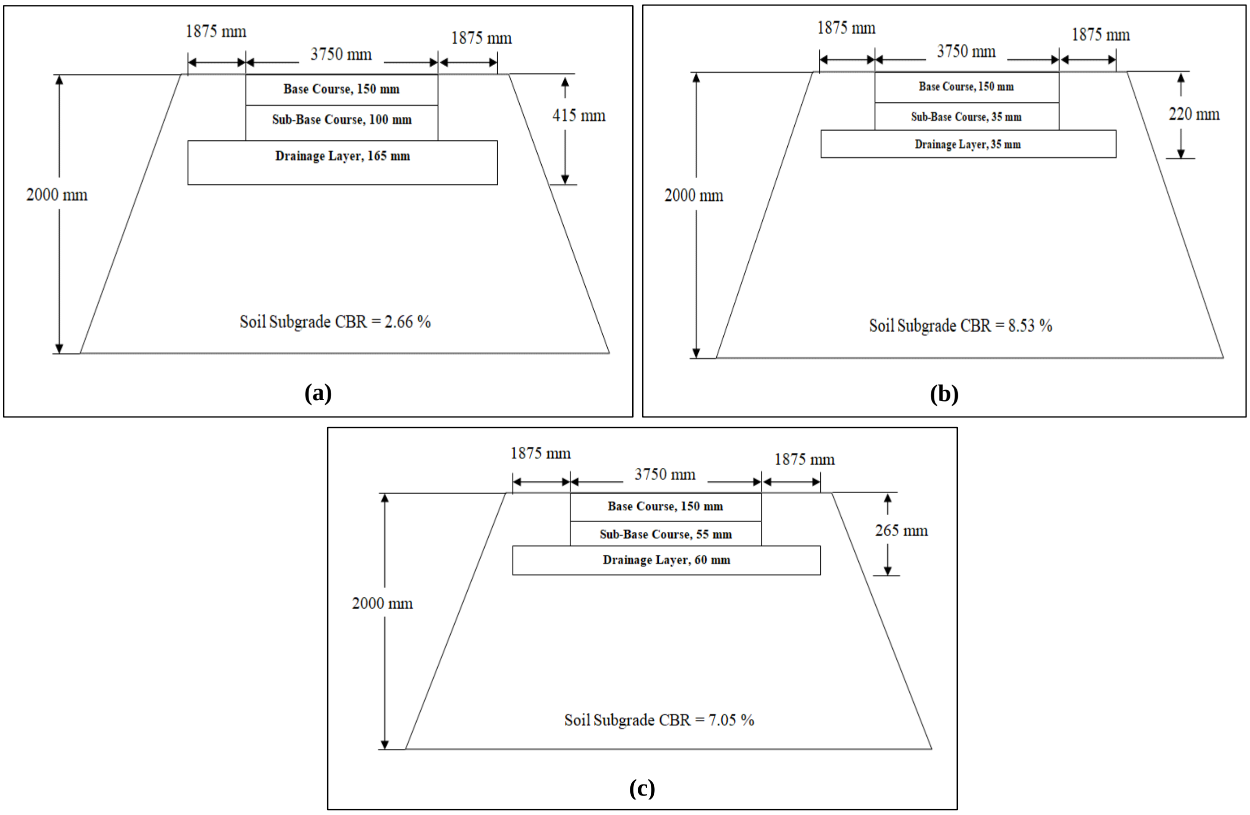


Figure 14. A typical cross section of pavement (a) without admixture (b) with bagasse ash (c) with stone dust (not to scale)

5. Summary and Conclusions

A laboratory-based investigation was performed with the objective of stabilizing soft soil by the addition of admixtures, namely bagasse ash and stone dust; the admixture content was varied from 2-10%. The compaction and penetration characteristics of the treated soil were studied through a series of standard Proctor and CBR tests.

The paper presents a comprehensive study on the suitability of using bagasse ash and stone dust as admixtures for soft ground improvement, in terms of compaction and penetration characteristics. Through extensive laboratory experimentations, the variation of optimum moisture content, maximum dry density, and soaked and un-soaked CBR with admixture content were studied in detail. Through appropriate costing analysis, based on local conditions, the proposed soil stabilization technique was found to be quite cost effective in the case the soft ground supports for transport infrastructure. However, it is essential to conduct a generalized study on the improvement of soft soil in terms of strength, stiffness, and durability [57]. Moreover, the movement of vehicles via transport corridors initiates cyclic loading on the soil sub-grade, altering its strength and stiffness [58]. This study aspect was not covered in the paper.

The study revealed that the optimum moisture content of the stabilized soil increased, in comparison with that of the untreated soil; the increment is up to 47 and 61% in the cases of bagasse ash and stone dust, respectively. While the variation pattern of the optimum moisture content with the admixture content is curvilinear for bagasse ash, the same is observed to be linear in the case of stone dust.

The maximum dry density of the stabilized soil decreased, compared to that of the untreated virgin soil, up to about 5% for bagasse ash and 7% for stone dust. The pattern of variation is linear for bagasse ash and curvilinear in the case of stone dust. The addition of admixtures produced significant enhancement in the soil’s CBR; the increment being as high as 120 and 225% of that of the untreated virgin soil, for un-soaked and soaked samples, respectively, with bagasse ash used as the admixture. In case of stone dust, the increment was observed to be 170 and 120%, respectively. The pattern of variation was observed to be curvilinear.

A comparative study to justify the suitability of the two different admixtures implies that bagasse ash produced relatively less increment in the optimum moisture content, and almost an identical decrease in the maximum dry density, compared to stone dust. This indicates comparatively lower water requirements for initiating compaction in the case of bagasse ash. Additionally, the use of bagasse ash enhanced the soaked CBR significantly, thereby implying a higher penetration susceptibility, compared to the stone dust.

As far as cost effectiveness is concerned, the use of bagasse ash and stone dust can reduce costs significantly. Hence, the appropriate admixture choice would depend on several other factors, including local availability and site treatment procedure costs.

5.1. Recommendations for Future Research Directions

As discussed above briefly, future research should be directed towards a generalized study on the utility of bagasse ash and stone dust as admixtures for chemical soil stabilization. Research should also consider the short-term and long-term enhancement of strength, stiffness, and durability of the treated soil through in-situ and laboratory tests, including plate load tests, vane shear tests, unconfined compressive and tri-axial tests, consolidation tests, etc. In addition, shrinkage and swelling tests and ductility tests should also be conducted for expansive soils. To ascertain the cyclic characteristics of the treated soil in the case of transport infrastructure, cyclic direct shear or tri-axial tests should be conducted. Lastly, a more general cost analysis involving other types of structures may be conducted as well. Such generalized study is currently under progress by the authors, and interesting results are expected.

6. Nomenclature

α_c	Normalized values of CBR	α_m	Normalized maximum dry density
α_o	Normalized optimum moisture content	A	Number of commercial vehicles per day for design
C_c	Coefficient of curvature	C_u	Uniformity coefficient
G	Specific gravity	n	Number of years between the last count and the year of completion of construction
P	Number of commercial vehicles per day at last count	r	Annual growth rate of commercial traffic
x	design life in years		

7. Declarations

7.1. Author Contributions

Conceptualization, S.B. and G.G.; methodology, S.B.; software, G.G.; validation, G.G., P.B. and N.K.; formal analysis, S.B.; investigation, S.B. and G.G.; resources, H.K. and M.K.; data curation, P.B. and N.K.; writing—original draft preparation, S.B. and G.G.; writing—review and editing, H.K. and M.K.; visualization, H.K. and M.K.; supervision, S.B.; project administration, S.B.; funding acquisition, S.B., G.G. and M.K. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in article.

7.3. Funding

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7.5. Conflicts of Interest

The authors declare no conflict of interest.

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