BAUET Journal

BAUET JOURNAL
Published by
Bangladesh Army University of Engineering & Technology (BAUET)
Journal Homepage: https://journal.bauet.ac.bd/
DOI: https://doi.org/10.59321/BAUETJ.V4I2.8

Evaluation of Sugarcane Bagasse Ash as a Subgrade Stabilizing Material: A Case Study in Bangladesh

Md. Rashedul Haque[1], Md. Mahbubul Hasan Hriday[1], Rakibul Hasan[1], Shahjahan Miah[1]

[1]Department of Civil Engineering, Faculty of Engineering and Technology, Pabna University of Science and Technology, Pabna 6601, Bangladesh

Abstract: Soil stabilization is crucial for improving subgrade performance in road construction, enhancing durability, and reducing maintenance costs. Sugarcane Bagasse Ash (SBA), a by-product of sugarcane processing, shows promise as a cost-effective and environmentally friendly stabilizer due to its pozzolanic properties. This study evaluates the effectiveness of SBA as a subgrade stabilizer in Bangladesh. Soil samples collected from the Hatikumrul-Bonpara highway were treated with varying percentages (5%, 10%, 15%, and 20%) of SBA by weight. Laboratory tests including Atterberg Limits, Standard Proctor, and Unconfined Compressive Strength (UCS) were conducted to assess changes in soil properties. Results indicate that SBA reduces Plasticity Index (PI), increases Maximum Dry Density (MDD) up to 15% SBA content, and significantly enhances UCS, peaking at 204.5 kPa with 15% SBA. Optimal stabilization effects were consistently observed at 15% SBA content. This study demonstrates that SBA can effectively improve subgrade soil properties in Bangladesh, suggesting its potential as a sustainable alternative to conventional stabilizers like lime and cement.

Keywords: *Sugarcane Bagasse Ash, Subgrade, Stabilization, Unconfined Compressive Strength*

Introduction: Soil stabilization techniques can significantly enhance the strength and durability of the subgrade, thereby improving the overall lifespan of the pavement. There is a lot of study being done worldwide on the economical use of wastes for engineering applications because of the need to reduce the rising costs of soil stabilizers and subgrade building. Aprianti et al. (2015) defined Sugarcane Bagasse Ash (SBA) as the residues left over after sugar cane bagasse is co-generated and burned at certain temperatures [1]. The term 'ash' in this context refers specifically to the inorganic mineral residue that remains after the organic components of the bagasse are burned," is a synthesized definition based on common scientific knowledge and descriptions found in multiple sources. SBA stands out as a suitable stabilizer for soil due to its pozzolanic properties, improvement in soil characteristics, cost-effectiveness, and environmental advantage. This contributes to the overall performance and longevity of pavements and other infrastructure, ultimately supporting economic development through reduced maintenance needs and enhanced infrastructure resilience.

GRT (2021) characterized soil stabilization is the process of modifying the mechanical, chemical, or biological components of soil engineering qualities. Soil stabilization is a process used in civil engineering to enhance and optimize the engineering qualities of soils. Mechanical quality, permeability, comprehensibility, durability, and plasticity are some of these attributes. While it is normal practice to enhance soil qualities physically or mechanically, other schools of thought prefer to refer to chemical changes brought about by the addition of chemical admixtures as "stabilization" [2]. A study by researcher Osinubi (2000) on stabilized black cotton soils in Nigeria found that the rise in MDD may be caused by the agglomeration and flocculation of clay particles as a result of ion exchange, as well as by Bagasse Ash (BA) filling in holes up the soil matrix [3]. Mansaneira, E. et.al (2017) in their study verify potential use of SBA as a partial replacement of Portland cement. The study found that SBA displays the physical and chemical characteristics of a pozzolanic material as demonstrated by pozzolanic activity, physical and chemical tests, and the thermogravimetry test, which verified SBA's pozzolanicity. The study also shown that in order for calcined ash to have pozzolanic action, it must be ground [4]. In a 2018 review study, researcher Behnood explored the challenges, approaches, and techniques of soil and clay stabilization, discovering that calcium-based stabilizers like cement and lime typically cause the modified soil system to exhibit more brittle behavior [5]. In 2021, Sarosh et al. examined how to improve the compressive strength of laterite soil, known for its high iron and aluminum content and commonly found in hot, wet tropical areas. They used lime and SBA for stabilization and compared these methods to lime alone. Their results showed that the PI of the natural soil, originally 29%, was reduced by 7% with the optimal soil-lime mix [6]. A critical review by Khandelwa, et al. (2022) showed that Using bagasse ash instead of traditional methods is more cost-effective and environmentally friendly [7]. Desmond et al., 2022 has conducted a study on improvement of the geotechnical properties of Calabar subgrade soil which is clay with low plasticity using limestone dust (LSD) and SBA and found that LSD performed better as a standalone stabilizer and in conjunction with SBA than it did when used alone SBA. This investigation determined the strength characteristics both before and after the additions were applied [8]. Mahmoud et al. (2020) conducted research on enhancing soft clay with a low Bearing capacity value and high plasticity. From an environmental perspective, the study suggested using sugar cane ash and lime for clay stabilization to create materials with cementitious properties. The dirt utilized

Article history:
Received 30 April 2024
Received in revised form 17 September 2024
Accepted 08 October 2024
Available online 01 November 2024

Corresponding author details: Dr. Md. Rashedul Haque
E-mail address: rashedul.haque@pust.ac.bd
Tel: +880 1724450396

for this investigation was collected next to the bridge that spans Cairo-Alexandria Road, Egypt [9]. Wubshet and Tadesse (2014) carried out a study to stabilize expansive soil of Addis Ababa with a combination of lime and bagasse ash. This study demonstrated that incorporating lime, as well as a combination of lime and bagasse ash, significantly enhanced the soil's California Bearing Ratio (CBR). The improvements were more pronounced with curing. However, bagasse ash on its own had a limited impact on bearing capacity. The lime-bagasse ash mixture substantially strengthened the expansive soil. They collected soil from a random location, where in this study, the soil was obtained directly from the subgrade, which is unique to this study [10]. In another study conducted by Shimola (2018) in India, lab tests were carried out by supplanting a parcel of sweeping soil with SBA (4%, 8%, 12%, 16%, and 20%). The researcher has conducted his study using black cotton soil where as we have used plastic soil which covers almost everywhere in Bangladesh subgrade soil. The unconfined compressive quality for the initial soil was 0.241 N/mm^2, and the shear quality was 0.1205 N/mm^2. After the expansion of 16% SBA substance, these values rose to 4.355 N/mm^2 and 2.1775 N/mm^2, separately. A diminish within the Versatility List (PI) and an increment in Greatest Dry Thickness were moreover watched, which are positive markers of stabilization [11]. Another comparable consider was carried out by Ali (2014) in Pakistan to examine the impact of marble tidy and bagasse cinder on the stabilization of sweeping soils. In this ponder, the analysts combined marble clean and bagasse cinder to stabilize sweeping soil. They found that the fluid limits, plastic limits, versatility file, and sweeping list were diminished with the expansion of 4%, 8%, and 12% marble tidy and bagasse cinder [12]. Hence, expanded marble tidy and bagasse cinder lower the extending soil's list values. When 12% bagasse ash is added, the soil uplift pressure decreases from 9.02 psi to 4.72 psi, indicating that bagasse ash is more successful in reducing soil uplift pressure than marble dust, which reduces soil uplift pressure from 9.02 psi to 5.56 psi. This demonstrates that bagasse fire debris works better to reduce soil elevation weight. They moreover watched that with the expansion of marble clean and bagasse ash remains, the dry thickness of broad soil moreover developed and remained at a greatest after addition. In Japan, a similar study conducted by Talib (2017) investigated the effectiveness of SBA in stabilizing organic soils. Organic soil samples for this research were collected from Hokkaido, Japan. Different mix designs were prepared to understand the strength improvement. One of the two samples used in this investigation was found to have the highest UCS, 387 kPa, and to be roughly 30 times stronger than the original soil. The other sample, though increased in strength, was not as impressive. They also noticed that when curing time and preloading during curing increased, the UCS of treated soil also increased. Some studies also utilized treated SBA in pursuit of achieving better results [13]. Another study is conducted by Magar (2017) investigated the effectiveness of alkali-activated SBA in the stabilization of soft soils. According to their test results, the alkali-activated binder has a high reactivity in facilitating the development of strength. According to UCS testing, the AB-25-12-0.25 mixture (The AB-25-12-0.25 mixture typically refers to an alkali-activated binder (AB) containing 25% SBA and 12% lime, with an alkali activator solution concentration of 0.25 M) exhibits a maximum strength of 0.41 MPa, which is 78.3% more than raw soil after seven days of curing [15]. Jakhar (2020) also investigated a similar concept. The AB-25-12-0.25 mixture typically refers to an alkali-activated binder (AB) containing 25% SBA and 12% lime, with an alkali activator solution concentration of 0.25 M. In this study, expansive soil from India was stabilized with varying contents of bagasse ash (2.5%, 5%, 7.5%, and 10%) and a fixed amount of lime (3%). All the samples showed improvements in geotechnical characteristics after stabilization, and it was observed that the combination of 7.5% SBA and 3% lime gave the best results. In another recent study carried out by Singh (2020) SBA and rice straw ash were used to stabilize clayey soil. They observed that the maximum value of CBR and UCS was obtained at 16% SBA + 20% Rice Straw Ash (RSA). The CBR value increased by about 117.67% and the UCS value increased by about 28.45% [16]. However, the above-mentioned studies did not show the effects of SBA acting alone.

SBA is a waste product and is often disposed of as landfilling. Since SBA is a freely available waste product and has pozzolanic properties, it can be considered a suitable alternative for the full substitution of Lime or Cement as a subgrade stabilizing material. The purpose of this study is to assess SBA's efficacy in Bangladesh as a subgrade stabilizing agent without the need for additional chemical stabilizers. This study sets out to analyze the performance of SBA stabilization by performing several field tests and laboratory tests. The existing subgrade soil sample and the SBA-stabilized soil with different bagasse ash contents (5%, 10%, 15%, and 20%) were tested in the laboratory. The laboratory test results showed that there is a decrease in the PI, a slight rise in the MDD, and a significant increase in the UCS of the soil samples, which have been stabilized by SBA. Furthermore, a great deal of laboratory research and analysis was done to find the ideal ratio for improved soil performance, concentrating on changes in SBA content from 5% to 20% in order to discover the optimal quantity of SBA that gives the highest strength of subgrade soil.

Materials & Method: The methodology began with collecting subgrade soil samples from a site in Bangladesh to represent natural conditions, followed by carrying out the Dynamic Cone Penetration (DCP) test as per ASTM D6951/D6951M (2021) [17]. SBA was obtained from local sugarcane processing facilities, then dried and sieved for uniform particle size. Environmental and economic considerations were evaluated, including SBA's potential for waste reduction and its cost-effectiveness compared to lime and cement. The experimental procedure involved preparing untreated and SBA-treated soils with SBA added at 5%, 10%, 15%, and 20% by weight. To calculate MDD and Optimum Moisture Content (OMC), soil samples that had been treated and those that had not were compacted using the Standard Proctor Test followed AASHTO T 99 (2019) [18]. In order to evaluate the plasticity of the soil, that had not were compacted using the Standard Proctor technique. In order to evaluate the plasticity of the soil, the Atterberg Limits tests, according to AASHTO T 89 (2020) and AASHTO T 90 (2020), were conducted to measure the Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI) [19, 20]. The Unconfined Compressive Strength (UCS) test was performed in accordance with AASHTO T 208 [21] was used to measure the compressive strength of the soil samples with varying SBA percentages. Data analysis compared the results from untreated soil samples with those from SBA-stabilized samples, focusing on changes in PI, MDD, and UCS values. This analysis helped evaluate improvements in plasticity, compaction, and strength. The optimal SBA content was determined by identifying the percentage that maximized strength and other properties. Fig. 1 shows the different steps of the study as below.

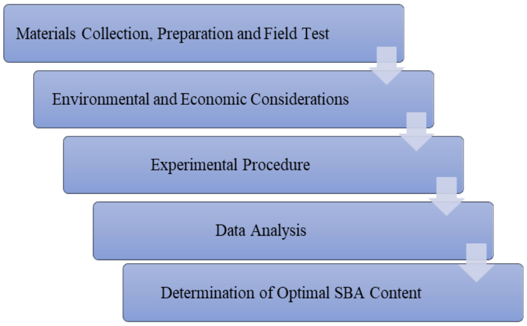

Fig. 1: Flow Chart of the Methodology.

Data collection: Subgrade soil refers to the soil layer beneath a road, railway, or other infrastructure that is designed to support the weight of vehicles and heavy loads. The physical, chemical, and geotechnical properties of subgrade soil are crucial in determining its suitability for construction and ensuring the long-term stability of the infrastructure. The physical properties are of Density, Grain size distribution, Water content, Void ratio, Compaction whereas the geotechnical properties are Shear strength, UCS, Cohesion, Friction angle, Settlement behavior, Permeability, Erosion resistance and the chemical properties are Soluble salts, Organic matter content, Pore water chemistry. During this study we have done DCP-CBR test, Atterberg limits, Density test, Standard Proctor test, UCS test etc. with and without mixing SBA of varying quantity.

Sugarcane Bagasse Ash: The bagasse ash obtained from North Bengal Sugar Mills Ltd. was utilized in this investigation at Gopalpur, Natore, Bangladesh. The geographic coordinates of this place is 24°13'39.9"N 88°59'15.3"E. The ash was collected from the disposal site which is outside of the mill area (shown in Fig. 2).

Fig. 2: SBA disposal site of North Bengal Sugar Mills Ltd.

Subgrade Soil: The subgrade soil sample was collected (as shown in Fig. 3) from the Mohishluti Bazar area from the Hatikumrul-Bonpara highway (N507), Tarash, Sirajganj, Bangladesh. The geographic coordinates of this site are 24°22'26.3"N 89°23'02.8"E. The selection of the road section for subgrade soil sample was based on the maintenance history from Roads and Highways database [22].

Fig. 3: Subgrade soil sample collection from Hatikumrul-Bonpara highway (N507).

Field and Laboratory Tests: Researchers Zohrabi and Scott (2003) from the Transport Research Laboratory (TRL) prepared a report investigating the relationship between the CBR, density, and penetrability. The study revealed a robust relationship between CBR and DCP values in different soil types, indicating the efficacy of the DCP device in forecasting in-situ CBR values [23]. The DCP test is becoming increasingly widely used to assess the CBR values of sub-grade soil in the field, as shown by Misra et al. (2005) [24]. Consistent with previous research findings, their study demonstrated a robust association between CBR and DCP for Class C fly ash-stabilized soils. When stabilizing clay soils using Class C fly ash, these correlations may be used to quickly determine the CBR values in the field.

First, Dynamic Cone Penetration (DCP) tests were performed at several locations in the selected area to assess the existing subgrade strength (shown in Fig. 4). After conducting the tests, the DPI (DCP Penetration Index) was correlated with CBR value using the following empirical formula [25].

$$CBR = \frac{292}{DPI^{1.12}} \qquad \text{eq. 1}$$

Fig. 4: Dynamic Cone Penetration test on the Hatikumrul-Bonpara highway (N507) (Coordinates: 24°22'26.3" N 89°23'02.8" E).

Secondly, Atterberg Limits Test, Standard Proctor Test, and Unconfined Compression Test were performed of collected sample to know the physical characteristics in accordance with AASHTO T-90, AASHTO T-99, and AASHTO T-208 codes, respectively. After that, SBA is carefully mixed with the collected soil at stepwise concentrations of 5, 10%, 15%, and 20% of dry soil by weight. The stabilized soil underwent the same laboratory tests once again.

The efficacy of SBA as a stabilizer and the ideal amount of SBA for stabilization to achieve higher density were ultimately determined by analyzing and contrasting the outcomes of all the tests.

Results and Discussion: Three DCP tests were conducted at 100-meter intervals at selected locations on the Hatikumrul-Bonpara highway. The maximum CBR values recorded from the three test pits were 4.82%, 4.69%, and 4.82%, respectively. The average CBR value was calculated to be 4.78%. This CBR value indicated poor subgrade strength, which required economic improvement. Fig. 5 illustrated the impact of SBA on the PI of the subgrade soil sample.

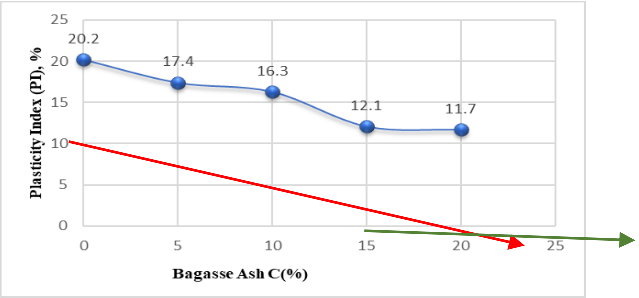

Fig. 5: Change in PI resulting from the addition of various bagasse ash contents.

Fig. 5 showed how the Plasticity Index (PI) progressively dropped as the amount of bagasse ash increased. It was observed that the PI for natural soil was 20.2%. With SBA contents of 5%, 10%, 15%, and 20%, the PI decreased to 17.4%, 16.3%, 12.1%, and 11.7%, respectively. The variation was more pronounced with increases up to 15% SBA, as indicated by the red trend line, but further increases in SBA content led to minimal decline, as shown by the green trend line. This decrease in the subgrade soil's plasticity could be attributed to the replacement of soil particles with pozzolanic ash particles. Cation exchange between the soil particles and the ash particles might also have contributed to this reduction in PI (Salahudeen and Akiije, 2014) [26]. To assess whether these PI variations were significant for sub-grade soil use and whether they met prescribed criteria, it was necessary to refer to guidelines and standards set by various authorities. PI, computed from the difference between the liquid and plastic limits, measures soil plasticity. A higher PI indicated more clay content and a greater potential for expansion and shrinkage with moisture changes, which could affect the soil's stability and strength.

Significance of PI Variations:

- Natural Soil PI: 20.2%
- Other Soils PI: 17.4%, 16.3%, etc.

The variations between 20.2% and 17.4% or 16.3% might have seemed small numerically, but even minor changes in PI could have had significant effects on soil behavior and its suitability for sub-grade use.

Different standards and guidelines specify acceptable PI values for sub-grade materials:

- ➢ AASHTO (American Association of State Highway and Transportation Officials):
  - o Soils with a PI less than 10 are typically considered good for sub-grade.
  - o Soils with a PI between 10 and 20 may require stabilization.
  - o Soils with a PI greater than 20 are generally not recommended for sub-grade use without stabilization.
- ➢ TRRL (Transport and Road Research Laboratory):
  - o Similar to AASHTO, generally preferring PI values below 20 for sub-grade materials.
- ➢ Indian Standards (IS 1498-1970):
  - o Sub-grade soils are often categorized based on PI values, where values less than 17 are preferable, and values greater than 20 may need treatment or stabilization.

Given the guidelines, let's evaluate the PI values provided:

- Natural Soil (PI = 20.2%): This value is just above the threshold commonly recommended by AASHTO and TRRL. Stabilization could be necessary for it to function as a sub-grade material.
- Other Soils (PI = 17.4%, 16.3%): These values fall within the range that is typically acceptable for sub-grade use. According to the guidelines, these soils may be used without stabilization or with minimal treatment.

The PI value of 20.2% for the natural soil was marginally higher than the typically recommended maximum of 20% for sub-grade use. This suggested that stabilization might have been necessary to ensure its suitability. The other soils with PI values of 17.4% and 16.3% were within acceptable limits and were likely suitable for use as sub-grade materials without significant stabilization.

According to Das (2010), the UCS test evaluated a soil's capacity to endure axial loads without lateral support, providing valuable information about the soil's shear strength, which was crucial for subgrade performance [27]. Holtz and Kovacs (1981) explained that MDD and OMC, determined through Proctor tests, indicated the soil's compaction properties, essential for ensuring subgrade stability. The Standard Proctor Test yielded the MDD value. For untreated natural soil, the MDD value was 1.50 gm/cc. After incorporating SBA, the MDD value began to increase slowly. Fig. 7 showed how SBA affected the MDD of natural soil. The MDD rose to 1.55 gm/cm³, 1.57 gm/cm³, and 1.61 gm/cm³ for SBA contents of 5%, 10%, and 15%, respectively. The schematic shape of the Standard Proctor Test, as shown in Fig. 6, did not follow a regular test type. Research by Ochepo (2014) and Moyo *et al.* (2024) on soil stabilization indicated similar trends in the Standard Proctor Test curves [29, 30]. The gradual increase in MDD was observed up until the addition of 15% bagasse ash. Beyond this point, further increases in SBA concentration caused the MDD to start decreasing. The initial increase in MDD was primarily due to the finer ash particles occupying voids between soil particles. However, after 15% SBA, the MDD began to decline, possibly due to the substitution of heavier soil particles with lighter ash particles. Higher MDD values typically indicated better compaction and strength. AASHTO recommended an MDD range of 1.75 to 2.2 g/cm³ for sub-grade soils, with the Federal Highway Administration (FHWA) and Indian Standards aligning with this recommendation. Despite this, the increase in MDD up to 15% SBA was a strong indicator of soil improvement. Enhanced compaction had practical implications, as it increased strength and reduced susceptibility to moisture changes, which were critical for sub-grade clay soil performance. Higher MDD values signified better soil qualities, making it more suitable for use in Bangladesh as a sub-grade material for road construction and other projects. The increased MDD values by 7.3% would result in a reduction in the thickness of the improved sub-grade layer. Fig. 6 illustrated how bagasse ash affected the soil-bagasse ash mixtures on UCS.

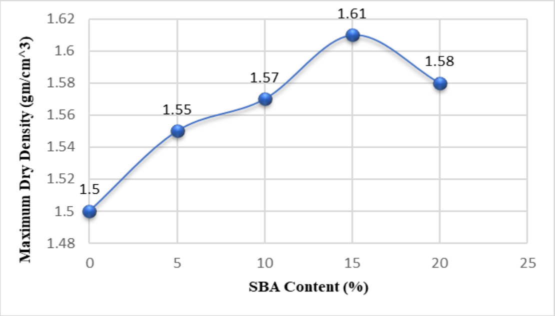

Fig. 6: Variation in the MDD value due to the addition of various bagasse ash compositions.

Fig. 7 indicated that the peak stress for UCS of the natural soil was 100.24 kPa. The soil-ash mixture's ability to withstand stress gradually increased with the addition of SBA up to a 15% bagasse ash level. Beyond 15% SBA content, the strength began to decrease. For 15% bagasse ash content, the UCS peak stress was found to be 204.5 kPa, which was more than double the strength of untreated natural soil. According to AASHTO guidelines, typical UCS values for sub-grade materials ranged from 100 to 300 kPa, with FHWA and Indian Standards also prescribing the same range for sub-grade soil. The untreated soil barely met the minimum requirement and might not have been sufficiently strong for sub-grade use without stabilization. In contrast, the treated UCS value of 204.5 kPa fell comfortably within the recommended range, indicating substantial improvement. The significant increase in UCS from 100.24 kPa to 204.5 kPa clearly demonstrated that stabilizing the sub-grade soil with 15% SBA made it suitable for sub-grade use according to the recommended guidelines by various authorities.

The results of all the aforementioned studies clearly showed that SBA enhanced the strength and other engineering qualities of clay soil. A gradual improvement in soil properties was observed up to the addition of 15% SBA, but with further increases in SBA content, either the rate of improvement decreased or, in some cases, the structural properties deteriorated. Therefore, based on this study, 15% SBA content was considered optimal for soil stabilization.

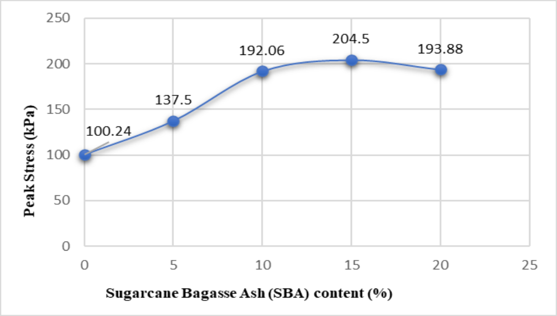

Fig. 7: Variation of UCS test peak value with the addition of different SBA contents.

All the above results and comparisons showed that SBA could be utilized as a subgrade stabilizing agent, but the improvement provided by bagasse ash alone might not have been adequate in all cases. Other traditional stabilizers might have needed to be used when the subgrade condition was particularly poor. From this study, it was further observed that the optimum content of SBA for the stabilization of clay-type soil (as described in this study) was 15%.

Conclusions: The investigation reveals several important conclusions regarding the use of SBA for stabilizing subgrade soil. The subgrade soil's poor quality was evident from its CBR value of 4.78%, highlighting the need for effective stabilization methods. The study found that increasing SBA content led to a consistent decline in the PI of the soil, although the rate of decline did not change significantly with the addition of 15% SBA. This indicates that while SBA influences the PI, the effect stabilizes at higher concentrations. Conversely, the MDD of the soil improved with higher SBA content, reaching its peak at 15% SBA, suggesting a more compact and stable soil structure, essential for road construction. The UCS also showed a notable increase, peaking at 204.5 kPa with the addition of 15% SBA, demonstrating enhanced strength and stability of the subgrade soil. These results point to 15% SBA as the optimal content for subgrade stabilization, offering a cost-effective and environmentally friendly solution. SBA is readily available and incurs mainly transportation costs, addressing waste disposal issues for sugar mills, which could potentially donate the ash for low-budget road construction projects. Overall, SBA proves to be a valuable stabilizer for improving subgrade soil properties, and future research should explore SBA and subgrade soil from various locations to enhance the findings' reliability and applicability in different regions.

Acknowledgements: The authors extend their heartfelt thanks to Executive Engineer Abdur Rahim of the Roads & Highways Department (RHD), Natore, for his invaluable assistance in facilitating the testing and sample collection on the Hatikumrul-Bonpara highway. They also express their deep gratitude to Md. Tarequl Islam, Deputy Manager (Civil) at North Bengal Sugar Mills Ltd., for his support and cooperation in conducting this study.

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