

# AN EVALUATION OF EXPANSIVE SOIL STABILIZATION WITH SAND AND COAL BOTTOM ASH: A COMPARATIVE STUDY

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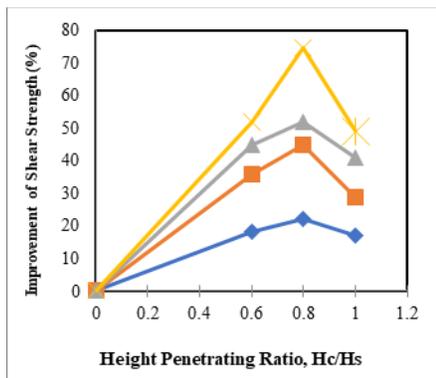
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## Graphical abstract



## Abstract

Expansive soils pose significant challenges in geotechnical engineering due to their tendency to swell and shrink with moisture variation, often leading to structural damage. Traditional stabilization techniques have limitations in addressing the volume change behavior and the insufficient strength of such soils. This study investigates the effectiveness of granular columns composed of sand and coal bottom ash (CBA) in improving the shear strength characteristics of expansive soil. While granular column techniques have been studied previously, limited attention has been paid to the comparative performance of CBA and sand columns with varying geometries, particularly in small-scale laboratory conditions. The research involved 19 batches of soil samples, including a control sample and six batches each of sand and CBA columns with diameters of 16 mm, 19 mm, and 25 mm, and penetration depths of 60 mm, 80 mm, and 100 mm. The unconfined compression strength (UCS) test was employed to evaluate the mechanical performance of the treated soils. Results revealed that sand columns enhanced the shear strength of expansive soil by 25% to 76%, while CBA columns demonstrated an improvement of 30% to 88%, depending on the diameter and penetration depth. This study contributes to the understanding of the mechanical behavior of expansive soils treated with alternative sustainable materials like CBA, offering a cost-effective and environmentally friendly solution for ground improvement. The novelty of this research lies in the systematic comparison of sand and CBA column performance under varied geometric configurations, expanding current knowledge on the stabilization of problematic soils.

Keywords: Granular column, coal bottom ash, sand, expansive soil and soil stabilization

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## 1.0 INTRODUCTION

Expansive clay soils, known for their poor bearing strength, high plasticity, and water absorption capacity, require stabilization before construction to prevent structural damage due to swell-shrink behavior. Chemical and mechanical stabilization methods are commonly used to improve key soil

properties such as compressive and shear strength, permeability, and durability [1]. Swelling in such soils is primarily influenced by the type and amount of clay minerals present, their surface area, particle arrangement, and pore water chemistry [2], [3].

Ground improvement methods can be categorized into ground improvement, treatment, and reinforcement. The use of inert materials like sand has

been explored for mechanical stabilization, while coal bottom ash (CBA), a by-product of coal combustion, presents a more sustainable alternative to natural sand [4]. CBA is a weak pozzolanic material containing approximately 10% lime, 30% silica, and 15% alumina, with a particle size between 2–4 mm and specific gravity ranging from 2.1 to 2.7. It is more porous than sand but similar in texture [5].

Sand, being a naturally occurring granular material, has demonstrated effective load-bearing behavior in confined conditions. It can serve as a filler and admixture to improve the plasticity, compaction, and strength of cohesive soils [6], [7]. Meanwhile, the improper disposal of coal ash, including bottom ash (BA) and fly ash (FA), poses environmental risks, such as air pollution and respiratory hazards [8]. Utilizing CBA as a soil stabilizer offers a dual benefit of waste utilization and soil improvement [9], [10].

Field studies, such as those in Mauritius, have confirmed CBA's effectiveness as a mechanical stabilizer. A full-scale road project using CBA-treated saprolite subgrade reported that 30–40% CBA addition significantly increased California Bearing Ratio (CBR) values and drastically reduced swelling potential [11]. These results affirm the potential of CBA for safer and more reliable geotechnical applications.

While lime has long been a standard chemical stabilizer [12], its performance is linked to ion exchange and the neutralization of the electrical imbalance in clay particles [13]. However, recent efforts focus on identifying more cost-effective and eco-friendly alternatives such as sand and CBA. For example, incorporating 30% CBA has been shown to improve compressive strength beyond that of untreated soils [14].

Studies have also examined the role of sand in modifying soil plasticity. Sand addition reduces the plasticity index, helping shift clay classification from medium to low plasticity according to the Unified Soil Classification System [15]. Almuathir [16] and Srikanth & Mishra [17] reported that sand significantly lowers soil flexibility. Furthermore, research indicates that a sand content above 30% leads to substantial improvements by decreasing soil suction, swelling, and compressibility, while enhancing permeability and strength [18].

In addition, recent studies have proposed innovative, eco-friendly materials and methods for soil stabilization. de Medeiros [19] evaluated the mechanical behavior of soil stabilized with asphalt emulsion under multi-stage loading. Their results showed that even a 2% emulsion content, after a seven-day curing period, significantly improved the soil's resilient modulus and reduced permanent deformation. Koestoer [20] explored a downstreaming technique to convert small-scale green ammonia into nitrogen-phosphorus fertilizer tablets for rural applications, promoting the concept of using localized and sustainable chemical additives. Al-Dalain [21] performed a numerical and laboratory analysis of palm oil fuel ash (POFA)-stabilized soils and found that a mixture of 30% POFA with 10% MgO achieved

unconfined compressive strengths of 3.18 MPa at 7 days and 3.89 MPa at 28 days, representing a 64% strength gain over traditional cement stabilization. These studies emphasize the growing trend of incorporating low-cost, regionally available materials to enhance soil performance. However, direct comparisons between these approaches and sand or CBA column-based stabilization in expansive clay remain limited, identifying a gap that the present research aims to address.

This research addresses the gap in comparative studies on sand and CBA columns for expansive soil stabilization. It investigates their effects on swelling behavior, strength, and sustainability, aiming to identify the most effective and environmentally responsible proportions for practical geotechnical applications.

## 2.0 METHODOLOGY

### 2.1 Selection of Ground Improvement Technique and Materials

With the increasing demand for stable ground conditions in urban development, especially on problematic soils like expansive clay, effective and economical soil stabilization techniques are essential. Among various ground improvement methods, granular columns have gained attention due to their simplicity, cost-effectiveness, and ability to enhance drainage and strength characteristics of soft or expansive soils.

This study explores the use of sand and coal bottom ash (CBA) columns as reinforcing inclusions in expansive soil. Sand, due to its non-cohesive granular nature, helps reduce the plasticity and swell potential of clay soils while improving drainage. CBA, a coarse residue from coal-fired power plants, exhibits pozzolanic behavior and can improve the mechanical properties of clayey soil. The use of CBA not only enhances soil strength but also promotes sustainability by reusing industrial by-products and reducing environmental burdens associated with waste disposal.

The natural soil used in this research is clayey in nature, exhibiting high plasticity, significant moisture sensitivity, and fine particle size ( $<2 \mu\text{m}$ ). The physical characteristics of the soil include a high surface area, flaky structure, and substantial capacity for water retention. The stabilizing materials—sand and CBA were selected based on their contrasting grain characteristics and ability to function as column inclusions within the soil matrix. Sand consists of coarser mineral particles and provides structure and permeability, while CBA, being angular and porous, contributes to strength gain and improved stabilization through chemical and physical mechanisms.

### 2.2 Laboratory Work

The laboratory investigation was divided into two main phases. The first phase focused on characterizing the

basic properties of the clay, sand, and CBA through standard tests to determine their grain size distribution, plasticity, and other geotechnical parameters. This characterization helped in understanding the interaction potential between the clayey soil and the column materials according to Table 1

In the second phase, a series of unconfined compression strength (UCS) tests were conducted to assess the improvement in strength due to the insertion of encapsulated sand and CBA columns. A total of 19 samples were prepared, including one untreated

control sample and 18 reinforced samples. The columns were installed centrally in each soil sample, with diameters of 16 mm, 19 mm, and 25 mm, and penetration depths of 60 mm, 80 mm, and 100 mm, corresponding to replacement and penetration ratios of 0.6, 0.8, and 1.0 respectively. Each soil specimen had a fixed diameter of 50 mm and a height of 100 mm. The UCS test results were then analyzed to evaluate the effectiveness of sand and CBA in enhancing the shear strength of expansive clay.

**Table-1** Sample Size and Penetration Ratio

$D_c$ (mm)	$A_c/A_s$ (%)	$H_c$ (mm)	$H_c/H_s$	$H_c/D_c$
16	10.24	60	0.6	3.75
16	10.24	80	0.8	5.00
16	10.24	100	1.0	6.25
19	14.44	60	0.6	3.15
19	14.44	80	0.8	4.21
19	14.44	100	1.0	5.26
25	25.00	60	0.6	2.4
25	25.00	80	0.8	3.2
25	25.00	100	1.0	4.0

### 3.0 RESULTS AND DISCUSSION

#### 3.1 Properties of Soil

A thorough description of clay is given in Table 2, emphasizing its geotechnical characteristics, which are crucial for comprehending its applicability in building applications. The clay has a plasticity index of 21%, which indicates moderate plasticity, with a

liquid limit of 49% and a plastic limit of 28%. The clay has an ideal moisture content of 20.5%, which is optimum for compaction, and a specific gravity of 2.68 with a maximum dry density of 2 KN/m<sup>3</sup>. The clay is classified as A-7-6 by the AASHTO and as a clayey soil with restricted engineering performance under load by the Unified Soil Classification System, where it is classified as CL.

**Table-2** Summary on the properties of clay

Properties	Value
Liquid Limit %	49%
Plastic Limit %	28%
Plasticity Index %	21%
Specific Gravity (G)	2.68
Maximum Dry Density (KN/m <sup>3</sup> )	2%
Optimum Moisture Content OMC (%)	20.50%
AASHTO Classification System	A-7-6
Unified Classification System	CL

**Table-3** Properties of Sand and Coal Bottom Ash

Properties	Sand	Coal Bottom Ash
Specific Gravity	2.65	2.1
Maximum Dry Density (KN/m <sup>3</sup> )	2.05	1.37
Optimum Moisture Content OMC (%)	10.27	23%
Liquid Limit %	-	30%

A comparison of the key physical properties of sand and coal bottom ash (CBA) is provided in Table 3. Sand, with a specific gravity of 2.65 and maximum dry density of 2.05 kN/m<sup>3</sup>, demonstrates good compactability and is suitable for structural applications. Its low optimum moisture content (OMC) of 10.27% indicates that it requires less water for compaction, which is beneficial for ease of handling and field efficiency. Sand is non-plastic, lacking a liquid limit, which contributes to its stability and resistance to volumetric changes under moisture variation.

In contrast, CBA has a lower specific gravity of 2.1 and maximum dry density of 1.37 kN/m<sup>3</sup>, indicating its lighter and more porous nature. Its higher OMC of 23% suggests a greater water demand during compaction. The 30% liquid limit of CBA reflects its moderate plasticity, which may influence its behavior under wet conditions. These distinctions highlight that while sand is more mechanically stable, CBA may provide additional chemical stabilization benefits and is a more sustainable option due to its origin as an industrial by-product.

### 3.2 Effect of Encapsulated Sand and CBA Column on Shear Strength of Expansive Clay

The incorporation of sand and coal bottom ash (CBA) columns into expansive clay soils leads to a noticeable improvement in their mechanical behavior, particularly in terms of undrained shear strength. To quantify this enhancement, unconfined compressive strength (UCS) tests were conducted on each treated and untreated specimen. The undrained shear strength ( $S_u$ ) was calculated by dividing the UCS values by two, following conventional geotechnical practice for cohesive soils.

A detailed analysis was conducted by plotting undrained shear strength versus axial strain for each specimen. The peak shear strength from each curve

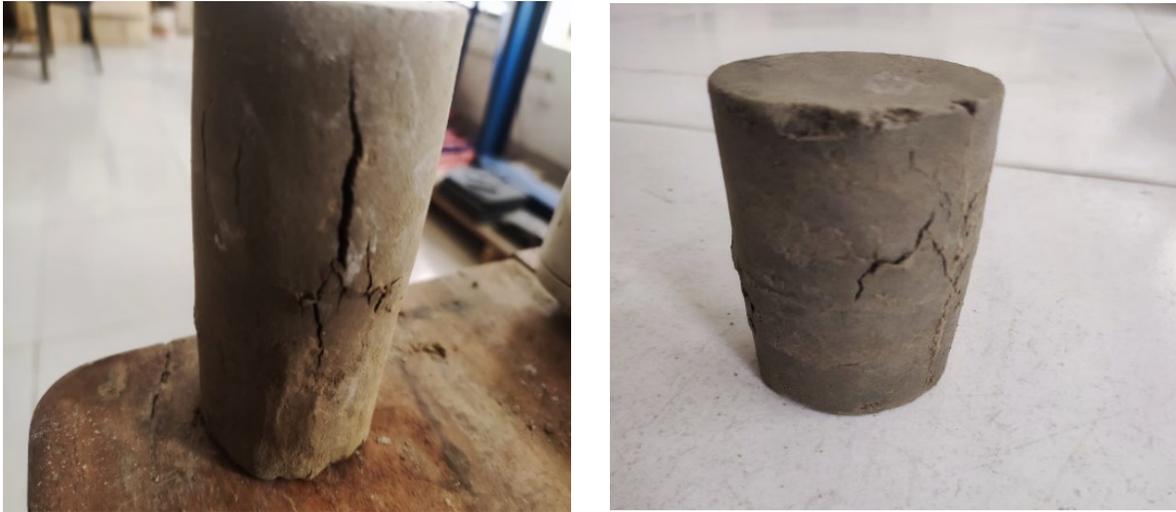
was considered as the representative  $S_u$ . Average values were derived from triplicate tests to ensure repeatability and statistical reliability. A comparative assessment was then performed to evaluate how variations in column parameters (diameter, length, material type, and area replacement ratio) influenced the resulting  $S_u$ .

The data reveal that increasing the column diameter ( $D_c$ ) or column height ( $H_c$ ) leads to a proportional increase in shear strength, indicating improved load transfer and confinement effects. The area ratio ( $A_c/A_s$ ), representing the proportion of reinforcement relative to the treated soil mass, emerged as a critical parameter. Higher ratios corresponded with greater strength gains, emphasizing the benefit of more extensive column inclusion.

Furthermore, failure mode analysis reveals distinct differences between treated and untreated specimens. As shown in *Figure 1*, untreated expansive clay samples predominantly exhibited barreling failure—a localized shear failure originating from the mid-height of the sample. This is indicative of high lateral expansion due to swelling and low confinement.

The results clearly indicate that column diameter has a significant effect on the improvement of shear strength (*Figure 4*). 19 mm diameter columns consistently showed the highest strength improvement, reaching up to 76% at 80 mm height (penetration ratio 0.8). 16 mm columns also improved strength notably (up to 51%), but were less effective than 19 mm columns. 25 mm columns, surprisingly, yielded lower improvement, with a maximum of only 34%.

All CBA-reinforced samples showed marked improvement in shear strength compared to the control sample (0.09 MPa). The best-performing configuration (Ca 19-80) achieved a shear strength of 0.169 MPa, which is an 88% improvement, the highest recorded in this series (*Table 5*).



**Figure 1** Deformation of Expansive Soil Samples Under Compression: (a) Without Column, (b) With Encapsulated Sand and CBA Column

**Table 4** Result obtained from unconfined compression test of clay encapsulated with sand

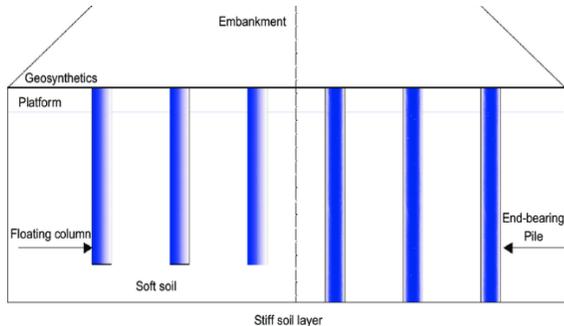
Sample	Column Dia (mm)	Column height (mm)	Height penetration ratio	Shear strength (Mpa)	Shear strength improvement (%)
Controlled Sample					
C	0	0	0	0.09	0
Sand Column					
Sa 16-60	16	60	0.6	0.122	36
Sa 16-80		80	0.8	0.136	51
Sa 16-100		100	1	0.125	39
Sa 19-60	19	60	0.6	0.150	67
Sa 19-80		80	0.8	0.158	76
Sa 19-100		100	1	0.147	63
Sa 25-60	25	60	0.6	0.116	29
Sa 25-80		80	0.8	0.121	34
Sa 25-100		100	1	0.113	25

**Table 5** Findings from the unconfined compression experiment of clay encapsulated with coal bottom ash

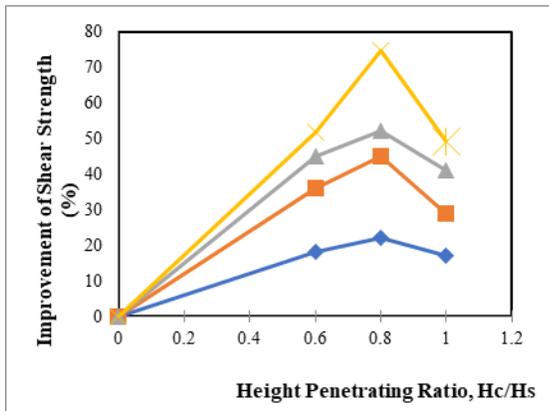
Sample	Column Dia (mm)	Column height (mm)	Height penetration ratio	Shear strength (Mpa)	Shear strength improvement (%)
Controlled Sample					
C	0	0	0	0.09	0
Coal Bottom Ash Column					
Ca 16-60	16	60	0.6	0.126	40
Ca 16-80		80	0.8	0.142	58
Ca 16-100		100	1	0.131	46
Ca 19-60	19	60	0.6	0.154	76
Ca 19-80		80	0.8	0.169	88
Ca 19-100		100	1	0.158	71
Ca 25-60	25	60	0.6	0.119	32
Ca 25-80		80	0.8	0.124	37
Ca 25-100		100	1	0.117	30

### 3.3 Penetration Ratio Effect of to The Undrained Shear Strength Column

Regarding column penetration, two primary column varieties can be distinguished: end bearing columns and floating columns. To put it briefly, an end-bearing column is one that is supported by surrounding of soil but not at the bottom, whereas a floating column is one that is supported by soft clay soil at surrounding and bottom. The 100mm column in this investigation is the only end-bearing column; the 60mm and 80mm columns are considered floating[22].



**Figure 2** Schematic Illustration of Floating and End-Bearing Granular Columns in Soft Clay



**Figure 3** Comparison of Sand and Coal Bottom ash

The graphical representation of Figure 3 the increase in shear strength with varying height penetration ratios are given below. The optimal height penetration ratio, as illustrated corresponds to a height column of 100mm for both diameters of sand and CBA columns. The expansive soil sample, which was subjected to testing using a 19 mm diameter CBA column of 80 mm height, achieved the maximum shear strength of 88 kPa compared to all other samples examined using the same column.

Soil shear strength was improved by 25% to 76% when implanted with a sand column with 16 mm, 19 mm, 25 mm diameter where replacement ratio and penetration ratios of 0.6, 0.8, and 1.0. Meanwhile, soil treated with a 16 mm 19 mm, and 25 mm diameter replacement ratio and penetration ratios of 0.6, 0.8 and 1.0 increased shear strength by 30%, to 88% accordingly [23].



**Figure 4** Unconfined Compressive Strength (UCS) Testing Machine

The findings indicate that the end floating column exhibited superior efficacy in the treatment of the soft soil in comparison to the end bearing column. It is logical given that the floating column can efficiently transmit the load to a stable surface and receive additional resistance, denoted as point bearing load,  $Q_p$ , from the stable base. As an alternative, a floating column can solely rely on the frictional resistance ( $Q_s$ ), which is the force generated when the column's surface interacts with the soil surface. Put simply, the primary source of resistance for the floating column is the friction that occurs between the surface of the column and the soil. The unconfined compression strength result from the UCS machine is shown in Figure 4.

The graph shows in figure 5 that for each level of reinforcement, there is a positive linear relationship between the increase in shear strength and the penetration ratio. The  $R^2$  numbers and linear regression equations show how well the fit is. The improvement rates for the 10.24% and 14.44% reinforcement levels are not as high as those for the 25% reinforcement level, which has a more noticeable effect on improving the shear strength as the height penetration ratio goes up.

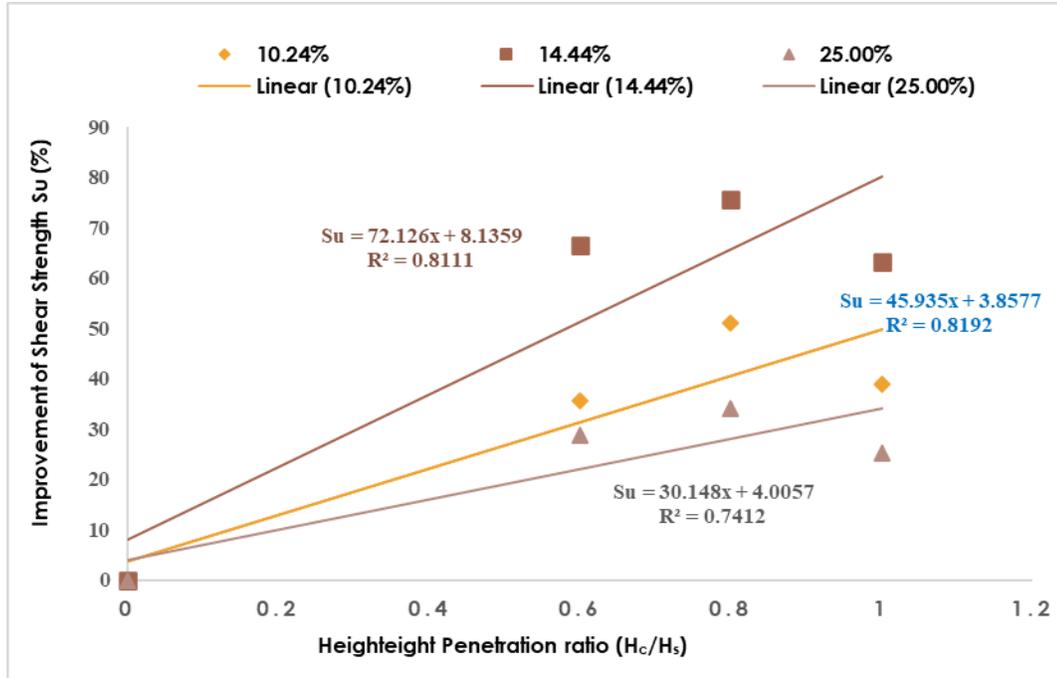


Figure 5 Relationship between undrained shear strength improvement and height penetration ratio (Sand)

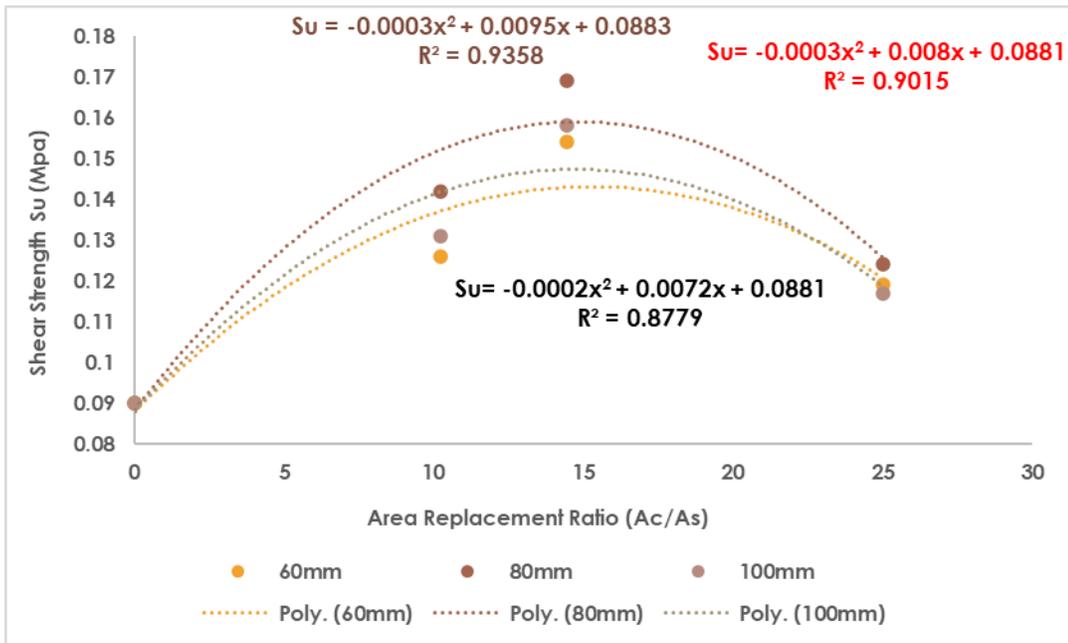


Figure 6 Relationship between undrained shear strength development and Area replacement ratio (Coal Bottom Ash)

Figure 6 displayed the percentage increase in shear strength for various column parameters. The column with a height of 80 mm and a diameter of 19 mm exhibited the highest value of  $R^2$  which is 0.9358. On the other hand, the CBA column with a height of 25 mm and a diameter of 100 mm showed the lowest improvement, whose  $R^2$  value is 0.8779.

Sand mostly improves soil stability mechanically by decreasing flexibility and facilitating drainage, but CBA is rich in silica, which imparts the pozzolanic characteristics in it, and it acts not only as a replacement of sand but a replacement of binding material also up to a certain extent [22], [23].

## 4.0 CONCLUSIONS

This study confirms that both sand and coal bottom ash (CBA) columns can significantly improve the undrained shear strength of expansive clay soils, with CBA performing better due to its chemical reactivity and pozzolanic properties. The optimal height penetration ratio ( $H_c/H_s$ ) was found to be 0.8, consistently yielding the highest strength gains. For sand columns, a 19 mm diameter at this ratio resulted in a maximum shear strength increase of 76%, while CBA columns of the same configuration achieved up to 88%. In contrast, 25 mm columns provided lower improvements, indicating that larger diameters may not always be more effective. The best overall performance was associated with a column slenderness ratio ( $H_c/D_c$ ) of 14.44. These findings highlight CBA as a more effective and sustainable stabilizing agent, especially when optimized column geometry is used. Further field investigations are recommended to support large-scale application and refine design guidelines.

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## Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

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