Journal of Engineering and Sustainable Development
Vol. 30, No. 06, November 2026
https://jeasd.uomustansiriyah.edu.iq/index.php/jeasd
ISSN 2520-0917
Research Article
https://doi.org/10.31272/jeasd.2918

The Behavior of The Tunnel Reinforced by Additives in Soft Soil

Zahraa H. Faleih, Husam H. Baqir, Ahmed S.A. Al-Gharbawi*

Civil Engineering Department, University of Technology, Baghdad, Iraq

*E-mail: ahmed.s.algharbawi@uotechnology.edu.iq

Article Info

Received	**08/09/2024**
Revised	**23/10/2026**
Accepted	**24/10/2026**

Abstract

Tunnels play a vital role in reducing traffic congestion and enhancing safety. However, constructing tunnels in soft clay soil poses a significant challenge due to low tensile strength and susceptibility to deformation. To overcome this issue, additives such as cement and rice husk ash can strengthen the soil and increase its load-bearing capacity. Traditionally, Portland cement has been used as a binding material in soft soil improvement projects. However, its high cost and carbon footprint have raised concerns about its financial and environmental impact. Therefore, researchers are exploring alternative and environmentally friendly binding materials that utilize industrial by-products as new "green" cementitious materials to address this issue. This study compares the effectiveness of cement and rice husk ash as additives in improving soft clay. Such materials can create a more environmentally friendly and cost-effective solution for soil improvement projects. Three ratios of rice husk ash (2%, 4%, 6%) were used and compared with a single cement ratio equivalent to 5%. This ratio was selected for comparison with the results of using rice husk ash, which showed that the ash used provided a good and environmentally suitable improvement ratio.

Keywords: Axial load, Cement, Rice husk ash, Soft Soil, Soil Improvement with Additives, Tunnel.

1. Introduction

Soil improvement can be achieved by modification, stabilization, or combining both. Soil amendment involves the addition of an amendment such as cement or lime to change the index properties of the soil. On the other hand, soil stabilization is a method of treating soils to make them stronger and more durable for construction applications beyond their original classification. Lime and cement have been used for years to provide more active soils. However, as energy prices have risen since the 1970s, they have gone up. It is acknowledged that clay soil has limited bearing capacity and is too often settled, which can pose significant challenges to construction projects. Experts have investigated many strategies for enriching such soils. According to studies, adding lime to stabilize the sand column stiffens the surrounding soil, lowering the initial soil moisture content. This information could lead to the development of long-lasting clay soil, greatly impacting the construction sector. These strategies have been studied [1].

Using nano-silica materials to enhance the functionality of clay soils. The examination covered conducting laboratory experiments with one-of-a-kind concentrations of nano-silica (0, 0.1, 0.2, 0.4, and 0.8). These assessments can detect Atterberg limits, optimal moisture content (OMC), maximum dry density (MDD), and microscopy. Studies have proven that the use of 0.4-0.6% nano-silica in soils yields proper effects. In particular, the maximum liquid limit (LL) and plastic limit (PL) have decreased at 0.6% nano-silica addition, resulting in the lowest plasticity index. This shows that incorporating nano-silica in soil samples at their maximum limits is feasible and has reduced these limits [2].

Different ratios of organic material were mixed with kaolinite to make artificial soils, specifically animal manure, which accounted for 5%, 10%, 15%, and 20% of the dry weight of the soil. The physical and mechanical characteristics of the soil were assessed by some standardized procedures, including the analysis of grain size distribution, determination of Atterberg limits, measurement of soil compaction, vane shear testing, and oedometer testing. The experiment was carried out on soil samples, both with and without organic matter. The findings demonstrated that organic waste exerts a substantial impact on the physical characteristics of soil, including its liquid limit, plastic limit, and plasticity index [3]. Furthermore, organic waste has a substantial impact on both the coefficient of secondary compression and the compression index. The assessments were conducted using two scenarios: In the first

Work of This Research is Licensed under CC BY

scenario, a consistent value of undrained shear strength was employed by varying the water content of the artificial soils. In the second scenario, both the dry unit weight and the water content of the soil were maintained.

In the work of Salim and Lafta [4], the consequences of the driven pile were examined when it was inserted and loaded into an already-existing tunnel that was buried in sand. The effects of driving and loading a pile on the transfer of stresses to the tunnel are found to depend on the horizontal separation distance between the pile's tip and the tunnel. Additionally, the stresses created by loading a pile are greater than the stresses created during the construction phase, and the presence of a tunnel increased the pile's ultimate bearing capacity.

The soft clay is mixed with sulfate-resistant Portland cement (PC) and quicklime (LQ), causing it to solidify and harden. In contrast, the soft clay remains in its original state. Laboratories conducted tests to measure specific gravity, Atterberg limits, and the standard Proctor test when introducing 2% and 4% dry-weight LQ. The main objective of this research is to examine the compression ratio (CR), rebound ratio (RR), and stiffness of both treated and natural soils by utilizing elasticity parameters (Es) through cohesion tests. The laboratory tests indicated a significant improvement in the soil after treatment. This resulted in a decrease in the plasticity index and an increase in efficiency. Moreover, it caused a drop in the compression ratio (CR), a reduction in the recoil ratio (RR), and an increase in the elasticity modulus. Differences in hydraulic relationships led to decreased maximum humidity, improved water quality, and smaller fluctuations in humidity compared to larger diffusion rates [5].

Liu et al. [6] used fiber-reinforced concrete and conventional reinforced concrete for tunnel lining samples. The goal was to compare the structural behavior of steel-reinforced and fiber-reinforced concretes. The failure mechanism of conventional reinforced concrete and fiber-reinforced concrete tunnel linings was compared in the study. The findings indicated that using synthetic fibers to minimize the quantity of steel reinforcement in the tunnel lining improves the lining design. Synthetic fibers may delay the onset of failure and boost load-carrying performance compared to regular RC samples. The differences between fiber-reinforced concrete and standard reinforced concrete tunnel linings and their impact on cracking, toughness, durability, and other mechanical properties were also investigated. The findings revealed that fiber-reinforced concrete tunnel lining construction outperforms traditional tunnel lining construction and has a unique failure mechanism, with a 47% decrease in reinforcing steel in lining sections.

In the studies of Basha et al. [7] and Behak [8], the source of silica was unspecified. Rice husk ash may react with calcium hydroxide (pozzolanic reaction), forming a gel known as CSH gel (calcium silicate hydrate). CSH gel is the main product of the cement hydration process. The shrine plays a crucial role in its construction Intensity. When cement is used in treatment and renewal, Soil production, or concrete, the C2S and C3S components in cement react with water according to reactions (1) and (2) (water reactions) to form CSH gel products and free calcium hydroxide. When mixing, add rice husk ash, rice husk ash, and transparent non-crystalline silica. It will react with free calcium hydroxide. Reaction (3) forms more CSH gel. The addition of these gelatinous CSH materials will help improve the Strength and durability of soil or cement concrete mix. Thus, it can be considered to assist in enhancing strength, and rice husk ash must be used together. Compatible with cement or lime to improve soil.

$$2(3CaO.SiO_2) + 6H_2O \rightarrow 3CaO.2SiO_2.3H_2O + 3Ca(OH)_2 \quad (1)$$

$$2(2CaO.SiO_2) + 2H_2O \rightarrow 3CaO.2SiO_2.3H_2O + 3Ca(OH)_2 \quad (2)$$

$$2SiO_2 + 3Ca(OH)_2 \rightarrow 3Ca1.5.2SiO_3.5.2H_2O \quad (3)$$

Nsaif [9] studied the improvement of soft soil. This study was carried out to improve the problematic soils with waste materials. Different percentages of plastic waste materials were used to improve the cohesion and angle of internal friction of the soil. The results showed that the use of plastic waste materials increased the cohesion and the maximum dry density of the soil.

The existing tunnel lining when a new pile is constructed nearby. This is done to evaluate the safety against the extra forces and moments caused by pile driving and loading and to determine the minimum distance required for constructing any structures near the tunnel. Mohammed et al. [10] explains that an experiment was conducted to study the effects of inserting and loading driven piles on an existing tunnel set in sand-filled ground. The impact of pile driving and loading on stress transfer to the tunnel is determined by the horizontal separation distance between the pile's tip and the tunnel. The stresses created by the loading of a pile are greater than the stresses during the building stage. Furthermore, the inclusion of a tunnel boosted the pile's final bearing capacity. When the tunnel was positioned at a distance of 0 or 0.6 depth, the stresses rose with increasing insertion depth due to the pushing of the pile; however, at 1.6 depth, the stresses would grow to a certain depth before experiencing a major reduction. That is accurate for the loading phase as well, when the piles reach their maximum weight.

Ahmed [11] studied the impact of excavating a shallow tunnel on the settlement of a two-story building on different types of soil, such as medium to stiff clayey soil with Young's moduli of 50, 75, and 100 MPa. Eight central tunnel locations ("diameter = 4 m") were positioned beneath the building strip foundation ("width = 2 m") at various depths and locations to identify the critical tunnel location at each depth. A total of 24 FEM analysis solutions were carried out at eight locations for each soil using ANSYS software. The FEM analysis revealed that tunnel excavation increased surface settlement and caused differential settlement at different locations. When the tunnel center was at both depths below the foundation's centerline, that was the crucial tunnel location.

Rice husk is a popular fuel for boilers that process paddy and create energy by combustion or gasification. This produces around 20 million tons of Rice Husk Ash (RHA) each year, providing a substantial environmental concern to the surrounding area and where it is disposed of. There are

numerous methods for disposing of RHA, including commercial uses. One such use is to replace some cement with RHA (15 to 25%). This article investigates how various levels of RHA in concrete impact its physical and mechanical qualities. The researchers tested sample cubes with varied amounts of RHA and w/c ratios, substituting cement by mass. The compressive strength, water absorption, and slump retention were tested [12].

According to Jayanthi and Singh. [13], Kuntikana and Singh [14], and Varaprasad et al. [15], waste materials may successfully minimize landfill trash, reduce demand for natural aggregates such as sand, gravel, and Portland cement, and, ultimately, lower building costs. However, present applications for rice husk ash (RHA) as a pozzolanic material in civil engineering are restricted. According to Hossain et al. [16], RHA is a prevalent agricultural byproduct in emerging nations such as India, China, the United States, Brazil, and Southeast Asia. RHA is permeable and lightweight, containing more than 70% silica and, in certain circumstances, up to 98%. Despite its advantages, RHA is often thrown as trash, harming the environment, human health, and air and water quality. Increasing the use of waste materials in civil engineering may lessen the environmental impact of building and, eventually, cut construction costs.

Najm et al. [17] examined the impact of tunneling and seismic activity on a tunnel model and the adjacent clay and sand soil layers, utilizing data from the AL Mafraq junction project in Diyala. A finite element study using PLAXIS 3D demonstrated a substantial drop in soil stress levels as the distance from the tunnel increased. A safe distance, equivalent to twice the diameter of the tunnel, was determined. The top section of the tunnel, consisting of clay, was seen to be less susceptible to seismic shocks and had minor settlement during excavation in comparison to dynamic settlement rates. In summary, the research highlights the need to take into account both tunneling and seismic impacts when designing tunnels to improve their stability.

Many soils encounter substantial geotechnical difficulties, which are impacted by characteristics such as soil type, composition, and mineralogy. These factors notably impact the mechanical and physical qualities of the soils. Several studies have investigated ways to address these problems by integrating conventional additions such as cement and lime, or by mixing soils with manufactured or chemical ingredients. There has been a recent trend in employing additives made from industrial, agricultural, residential, and mineral wastes, which are considered sustainable resources. Al-Naje et al. [18] focused on the particular effects of several sustainable materials on compaction properties, California bearing ratio, and unconfined compressive strength.

Almashhadany and Albusoda [19] conducted a series of shaking table experiments to investigate the impact of tunnel model depth and ground acceleration direction on the tunnel model's horizontal acceleration, the surrounding soil, surface settlement, and dynamic earth pressure on the tunnel walls. The experiments included a square tunnel model that was placed within both dry and saturated Karbala Sand. The tunnel model was then exposed to sinusoidal movements at acceleration levels of 0.05g, 0.1g, and 0.2g. The upper layer of the sand had a relative density of 30%, while the bottom layer had a relative density of 70%. The results indicate that the direction of seismic loading has a substantial effect on the horizontal acceleration of the tunnel model. Furthermore, the acceleration decreases as the depth increases. It was observed that surface settlement increases as the tunnel depth and ground acceleration rise, especially at 0.2g. In addition, the seismic loading direction had no impact on the settlement of dry soil, whereas the dynamic earth pressure (DEP) was positive in dry soil and negative in saturated soil. The impact of ground acceleration direction and tunnel depth on dynamic earth pressure (DEP) was negligible in saturated soil subjected to a 0.2g load.

Nugroho et al. [20] examined the potential of using fly ash, a byproduct of coal combustion, as a sustainable material for stabilizing soils with high plasticity. An experiment was conducted to evaluate the effect of different concentrations (up to 30%) of a mixture of fly ash and 5% lime on soil compressibility and void ratio. The specimens were made at the ideal moisture content and examined both with and without the process of curing. The findings indicated that increased density leads to a decrease in void volume, and the process of curing has a substantial impact on reducing both the void ratio and compressibility of the soil. The study revealed that the compressibility index demonstrates enhancement with time, especially when using a 25% fly ash combination, as a result of the progressive development of robust molecular connections between fly ash and lime.

Yousif and Mustafa [21] focused on addressing the issue of saline soil, which is widespread in many urban areas. The goal is to improve the stability of saline soil by using various additives. In this study, the main focus is on the utilization of polypropylene fiber (PPF) along with different proportions of cement. Direct shear experiments were carried out on both untreated and treated soil samples, which were soaked for 24 hours to simulate real environmental conditions. The results showed a significant decrease in the soil's strength after saturation, with a 48.6% decrease in cohesiveness and a 67.8% decrease in the angle of internal friction. However, the inclusion of PPF greatly improved these characteristics. Specifically, soil treated with 1.5% PPF and varying amounts of cement showed significant increases in both cohesiveness and internal friction angle. These improvements were more noticeable as the amount of cement used increased.

In this study, the tunnel is inserted at different depths, 1.5d and 2.5d (i.e., d is the diameter of the tunnel), with improvement of the soil above the tunnel with varying percentages of rice husk ash and cement to study the behavior of clayey soil with a tunnel and to reduce the pressures above the tunnel crest.

2. Materials

2.1. Soil

The study used soil from a location north of Baghdad. Standard tests were performed to determine the soil's physical and chemical properties. The test results are shown in Table 1. The particle size distribution of the soil indicates that it contains no gravel, 3% sand, 44% silt, and 53% clay, as shown in Fig. 1.

The soil classification for the Unified Soil Classification System (USCS) is CL

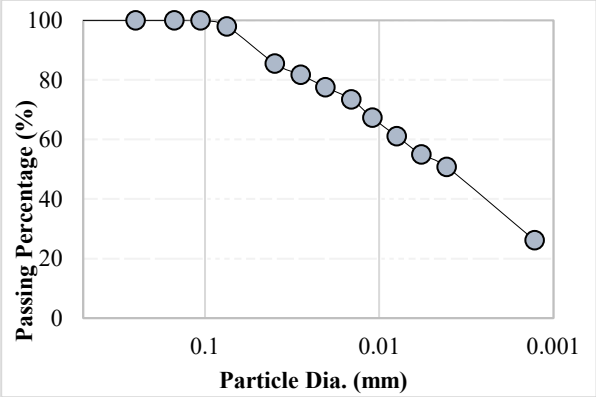

Figure 1. Grain size distribution of the soil used in the study.

Table 1. Physical Properties of The Soil Used

Index Property	Value
Liquid Limit (L.L) %	43.3
Plastic Limit (P.L) %	24.6
Shrinkage Limit (S.L) %	10.7
Plasticity Index (P.I) %	18.8
Specific Gravity (Gs)	2.68
Gravel %	0
Sand %	3
Silt %	44
Clay %	53
Classification (USCS)	Cl
Organic Matter (O.M) %	<0.002
Total Dissolved Salt (TDS)%	2.23
Ph Value %	7.3

This study gently compacted seven soil samples into three layers using a special hammer to remove trapped air in the CBR molds. The undrained shear strength values obtained from the samples were relied upon during all tests. Fig. 2 shows the extracted values and adopts a value of cu=14 kPa.

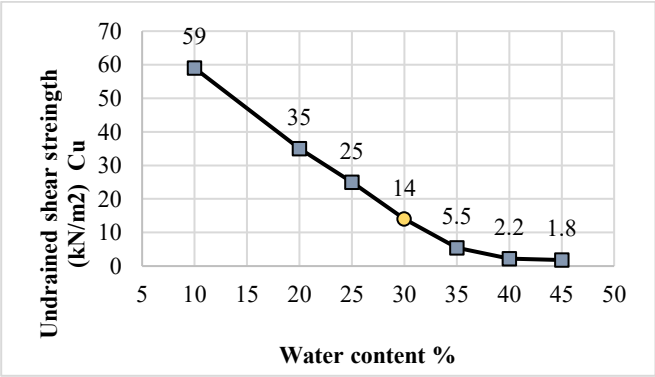

Figure 2. After 48 hours, the remolded clay's undrained shear strength varies with its water content.

2.2. Tunnel (PVC Pipe)

The tunnel used in this study was a PVC pipe manufactured by Amal Al-Sharif Company. The pipe was 58 cm long, 10.16 cm in diameter, and 3 mm thick. Fig. 3 depicts the tunnel used, and Table 2 contains the specifications for the PVC tunnel pipe used.

Figure 3. Tunnel and contains sensors that are used for monitoring.

Table 2. The general specifications of the PVC pipe used.

No.	Specifications
1.	Raw Material: PVC
2.	The thickness of the wall depends on the pressure rating (for example, Sch 40 or Sch 80).
3.	The Maximum Operating Pressure Depends on The Wall Thickness and Pressure Rating.
4.	Corrosion Resistance: The Maximum Operating Temperature Varies Per Rating but Ranges Typically From 0 To 60 Degrees Celsius.
5.	Compliance With Standards: Depending on Its Application, The Pipe May Comply with ASTM D1785 Or ASTM D2665 Standards and Other Standards.

2.3. Cement

Cement improves soil by mixing cement into clayey or sandy soil to improve its mechanical and engineering properties. This is often done in areas where soil has to be improved to support infrastructure such as highways, dams, and industrial facilities. The primary advantages of cement in improving soil include greater load-bearing capacity, which means it can sustain stresses from traffic or structural loads. Cement promotes soil stability by minimizing deformation and settling over time. Cement can be used to improve soil resistance to moisture and chemical erosion. The properties of the cement is shown in Table 3.

2.4. Rice Husk Ash (RHA)

When rice is milled, a by-product called husk is produced. This husk, which makes up about 22% of the weight of the paddy is used as fuel in rice mills to produce steam for boiling. During the burning process, the husk turns into Rice Husk Ash (RH), which contains about 85% - 90% amorphous silica. When added, this ash is produced at high temperatures and can enhance soft soil's load-bearing capacity and stability. The study used three different proportions of rice husk ash (2%, 4%, and 6%) based on previous research. Fattah et al. [22] burned

rice husks in a special oven at 650℃ for 5 hours. Fig. 4 shows the SEM Test of rice husk ash.

Table 3. Properties of sulfate-resistant cement

Test Type	Sample lab.No. Cement trademark and field No. Property	CPCH 333 Resistant Cement Test results	Specification Limits Normal/Salt resistant cement
Physical tests			
Setting time	Initial (mins)	110	Min. 45
	Final (mins)	4.83	Max. 10
Compressive strength (Mpa) at age	3day	16.31	Min. 15
	7day	24.56	Max. 23
Chemical tests			
SiO_2 (%)	21.84	No limited	No limited
Al_2O_3 (%)	4.23	No limited	No limited
Fe_2O_3 (%)	5.32	No limited	No limited
CaO (%)	62.46	No limited	
L.S.F (%)	0.87	0.66-1.02	
MgO (%)	2.83	Max.5	
SO_3 (%)			
Max.	2.23	2.5	2.5
C3A<5%	Not	2.8	2.5
C3A>5%	applicable		
Loss on Ignition (%)	1.39	Max. 4	
Insoluble residue (%)	0.83	Max. 1.5	
C_3S (%)	45.84	Not limited	
C_2S (%)	27.65	Not limited	
C_3A (%)	2.22	Not limited Max.3.5	
C_4AF (%)	16.16	Not limited	

Scanning electron microscopy (SEM) [23] was used to analyze the picture of the ground RHA, as illustrated in Fig. 4. This is accurate for the loading phase as well, when the piles achieve their maximum load. The majority of the silica-containing RHA particles were discovered to be solid with amorphous forms, similar to cristobalite, and trace amounts of crystalline quartz. Only when calcined at elevated temperatures does crystalline RHA transform into amorphous forms. The high combustion temperature of RH was the cause of the irregular particle size. After being ground, the RHA particles were discovered to be considerably finer and to have a more uniform distribution. It has been observed that reactivity increases with finer particle size during mixing and curing. Due to the high surface energy and free OH groups on the silica surface, some particles can also be seen as clumped together and adhered to one another. When the dispersed silica was separated from the solvent, the hydrogen bond that had been formed with the water molecules was likewise broken, creating a Si–O–Si link [24],[25]. The chemical and geotechnical properties of rice husk ash are illustrated in Tables 4 and 5, respectively.

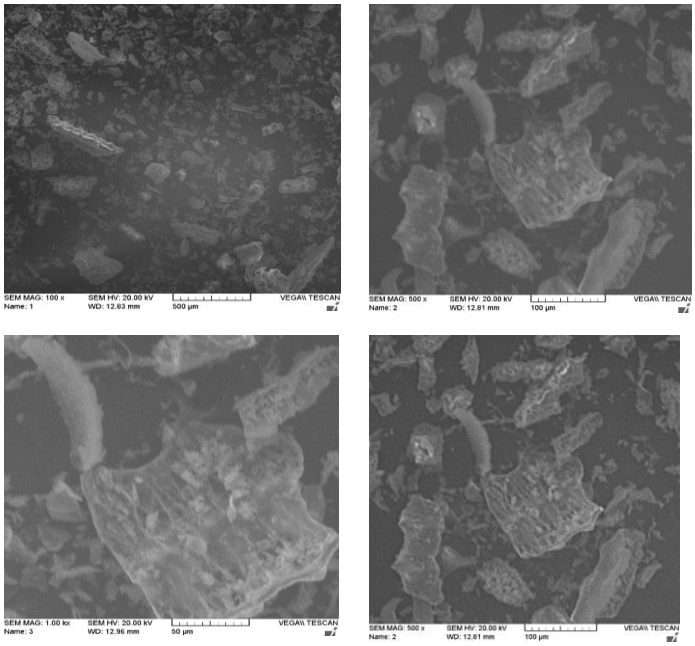

Figure 4. The RHA used in the study under SEM

Table 4. Chemical composition of rice husk.

No.	Index property	Index value
1	SiO2	84%
2	Al2O3	3.1%
3	Fe2O3	1.7%
4	CaO	3.9%
5	MgO	0.28%
6	Loss in ignition	4.5%

Table 5. Geotechnical properties of rice husk.

No.	Index property	Index value
1	Liquid Limit (%)	Non-Plastic
2	Plastic Limit (%)	Non-Plastic
3	Specific Gravity	2.12
4	Maximum Dry Density (kN/m3)	7.05

3. Experimental work.

3.1 Steel container

The studies were conducted in a steel container measuring 600×600×600 mm made from 4 mm thick steel sheets. Fig.5 shows the steel container and loading apparatus.

3.2 Steel footing

The tests used a 4 mm thick and 70 mm wide square steel foundation.

3. 3 Loading assembly

A loading system was designed to apply static vertical loads to the footing model. Fig. 5 depicts the key components of the loading assembly. Furthermore, the sensors used in this investigation include:

- Load cell.

- Pressure cell
- Extensometer (X, Y) Direction
- Strain gauge

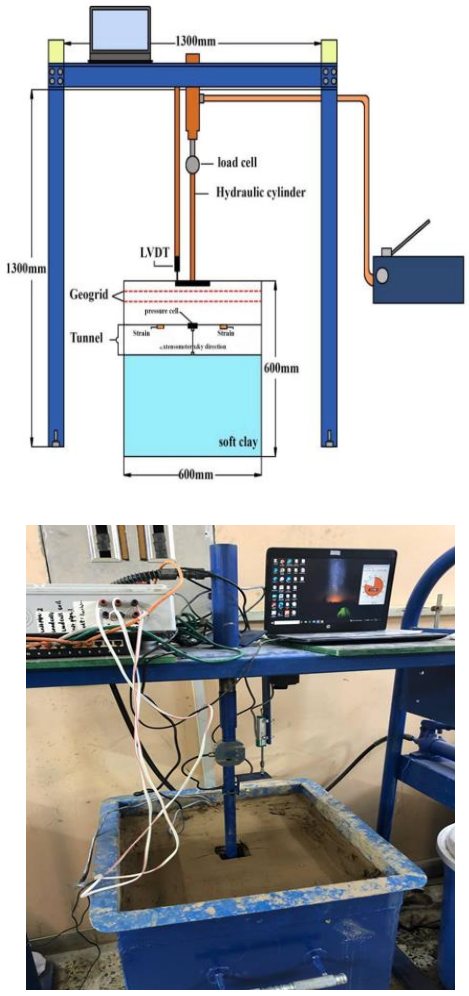

Figure 5. The laboratory model and loading apparatus

4. Testing Program

The testing procedure used is described in the flow chart**.** The testing program flow chart is shown in Fig. 6, and the model preparation is shown in Fig. 7.

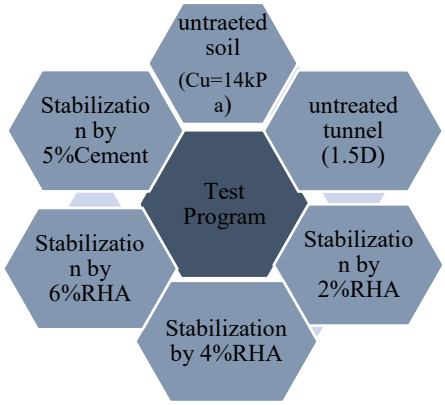

Figure 6. Number of models used to improve tunnel soil

Note/ Cu= undrained shear strength,

TC=clay with a tunnel, D= diameter of pipe

RHA = Rice Husk Ash

Figure 7. Model Preparations

5. Results and Discussion

Failure of model tests is defined as the stress required to cause settlement corresponding to 10% of the footing diameter (width) depending on the proposal given by (Terzaghi, 1947), (as cited by Brand and Brenner,1981), and as cited by Fattah et al. [26] The dimensions employed for the tunnel , specifically the dimensions that have been adopted (1.5D), were derived from prior research conducted by Fattah et al. [27], Slash et al. [28] and Al Khalali [29], as well as the Baghdad Metro project. Hence, it seems that by excavating and reinforcing tunnels at

deeper levels, the stresses that reach the tunnel are reduced due to the decreased applied loads and curing times for all tests with additives (7 days).

5.1 Effect of stabilizing the soil on the sides of the tunnel

The study investigates the impact of different percentages of rice husks and cement on the properties of various soils, focusing on improving the soil's load-bearing capacity. Using additives to enhance soil quality is considered the most effective option. In this case, two materials were used to improve the soil in the tunnel, and the tunnel walls were reinforced by mixing the soil with the additive material. Reinforcing the tunnel from the sides is considered the best choice as it reduces the risks associated with lateral pressures, is more efficient in bearing loads, and is more cost-effective and practical to implement than reinforcing the tunnel from the top. First, rice husk ash material was used to strengthen the tunnel walls at three ratios (2%, 4%, and 6%) as illustrated in Fig. 8, Fig. 9, and Fig. 10, respectively, and the bearing capacity at failure and the improvement ratio are illustrated in Tables 6 and 7, respectively. The study revealed that incorporating 6% rice husk ash with soft soil resulted in a 1.85 improvement in the tunnel soil compared to unreinforced soil. Notably, the pipe used in the research functions as a hard layer, making minimal difference to the soil around it. Then, cement was applied (5%) to enhance the soil, in contrast to rice husk ash as described in Fig. 11. Due to the quick cement reaction and chemical composition, the improvement ratio was (s/B=10%), equivalent to 2.66 compared to the tunnel without improvement.

Hossain [30] and Barwar et al. [31] used rice husk ash with cement to improve the creation of weak clay in India. Research results have shown that rice husk ash helps to increase the strength and durability of the soil-cement mixture. Not only does it increase strength and durability, but rice husk ash can also help reduce the use of at least 1% bamboo shoots. Research conducted by Wibowo et al. [32] on using rice husk ash with cement to improve the soil indicates that, for weak clay (A-7-5), rice husk ash may help increase the strength and bearing capacity of the soil when used as paving materials.

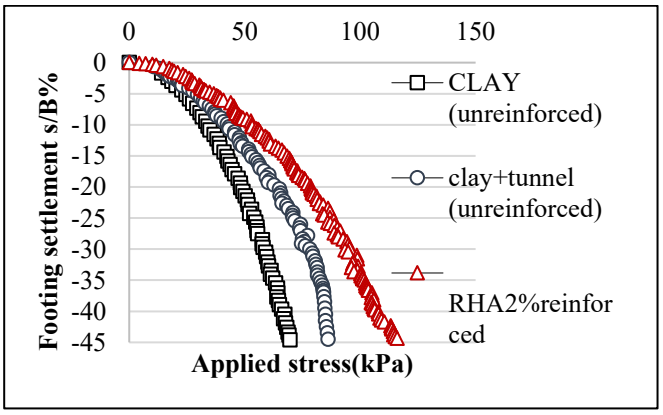

Figure 8. Pressure versus settlement relations of 2% RHA above the tunnel for the tunnel at a depth of 1.5 D.

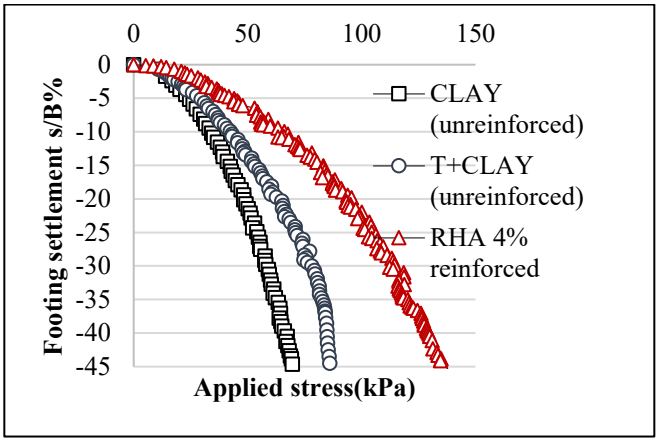

Figure 9. Pressure versus settlement relations of 4z% RHA above the tunnel for the tunnel at a depth of 1.5 D.

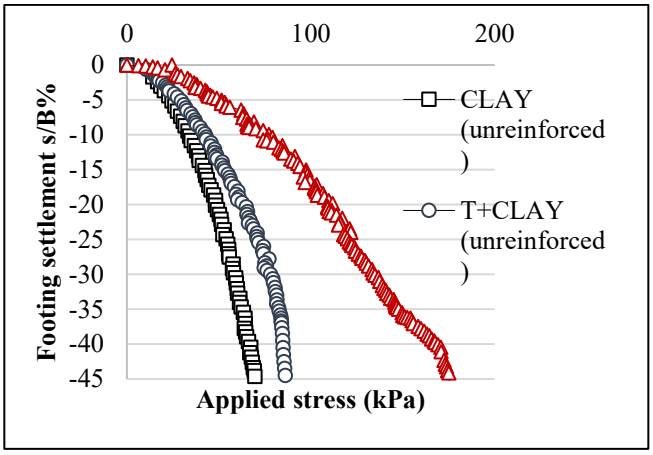

Figure 10. Pressure versus settlement relations of 6% RHA above the tunnel for the tunnel at a depth of 1.5 D.

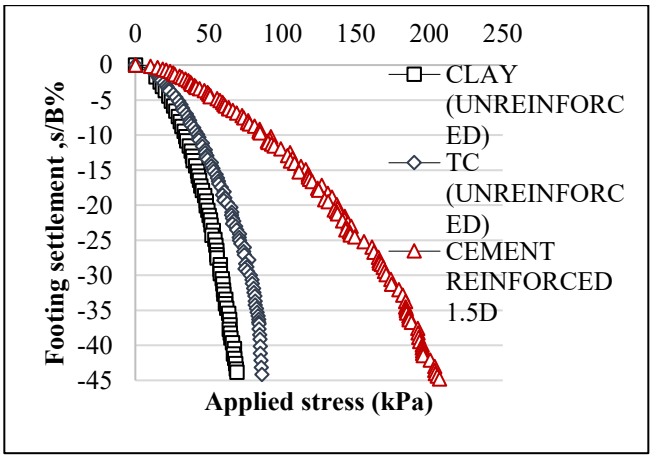

Figure 11. Pressure versus settlement relations of 5% cement above the tunnel for the tunnel at a depth of 1.5 D.

Table 6. Results summaries in bearing pressure q (kPa) versus footing settlement S/B for the tunnel at depth 1.5d.

s/B (%)	Clay only	Clay +Tunnel (1.5D)	RHA 2%	RHA 4%	RHA 6%	Cement 5%
5	24.5	25.7	30.4	37.4	43.4	49.2
10	33.1	40.9	47.4	56.8	66.4	84.5
15	42.3	52.7	64.7	77.5	92.8	108.3
20	49.2	60.1	76.2	93.8	109.8	128.7
25	52.1	71.6	86.7	104.2	121.9	146.1
30	57.8	76.3	94.3	114.3	133.2	169.5
35	62.1	82.4	100.3	117.8	146.1	183.9
40	66	84.9	105.6	128.7	165.5	193.3
45	70.7	86.6	113.5	134.9	174.3	204.1

Table 7. Summary of improvement factors (IF) versus footing settlement S/B for the tunnel at depth 1.5d.

S/B (%)	Clay +Tunnel (1.5D)	RHA 2%	RHA 4%	RHA 6%	Cement 5%
5	1.04	1.16	1.45	1.68	2.09
10	1.24	1.18	1.39	1.62	2.66
15	1.25	1.23	1.47	1.76	2.05
20	1.22	1.27	1.56	1.83	2.14
25	1.37	1.21	1.45	1.7	2.04
30	1.32	1.24	1.50	1.75	2.22
35	1.33	1.22	1.43	1.77	2.23
40	1.29	1.24	1.52	1.94	2.28
45	1.22	1.31	1.56	2.01	2.36

5.2 Effect of stabilizing on the surface pressure above the tunnel

Additives such as rice husk ash and cement enhance tunnel soil stability and reduce pressures on the sides and top of the tunnel. This helps to reinforce the tunnel, improving its safety and sustainability. The applied pressure with the applied surface pressure is illustrated in Figs. 12, 13, 14, and 15 for 2%, 4%, 6% RHA and 5% cement, and 6% RHA and 5% cement, respectively. According to the data, the optimal percentage for reinforcing the tunnel with rice husk ash was found to be 6%, resulting in a reduction of tunnel pressures from 13.6 kPa (in unreinforced tunnel soil) to 6.2 kPa. When reinforced with cement, the improvement in pressure application was significant, with pressures decreasing from 13.6 kPa to 4.2 kPa compared to the unreinforced tunnel. Table 8 shows the improvement in the pressures reaching the tunnel when reinforcing the tunnel sides with additives.

Yoobanpot and Jamsawang [33] and Jongpradist et al. [34] showed that rice husk ash can be used as a substitute. The cementitious part can also be used to increase the strength of the soil-cement mixture (creating a soil-cement mixture with bamboo shoots has high strength). Depending on the content of bamboo shoots and mixed rice husk ash, the compressive strength can reach up to 35%.

Recently, Tesanasin et al. [35] compared and evaluated the effectiveness of using a mixture of cement + rice husk ash Using the above-mentioned mixtures is effective. The uniaxial compressive strength of the reinforced soil is greater than 1000 kPa and meets the requirements of the deep mixing method of Soil-cement by the Thai Highway Committee.

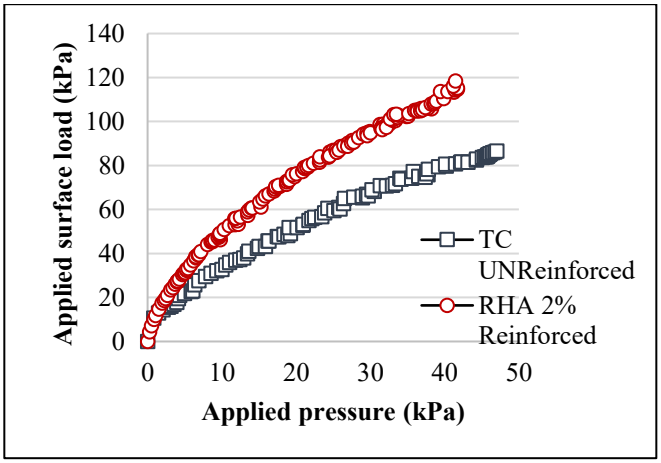

Figure 12. Applied pressure versus the pressure above the tunnel for 2% RHA for the tunnel at a depth of 1.5 D.

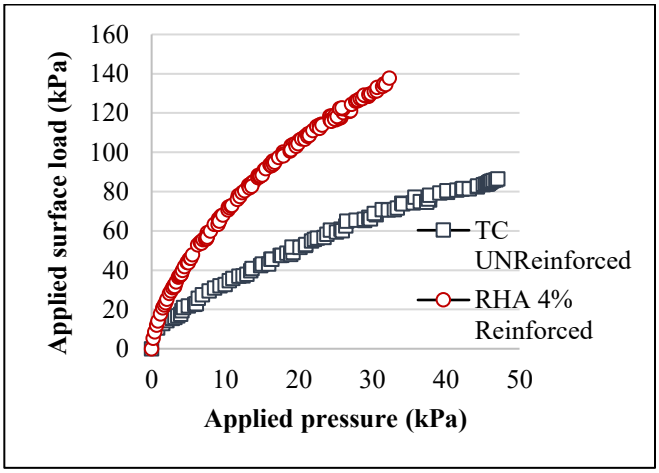

Figure 13. Applied pressure versus the pressure above the tunnel for 4% RHA for the tunnel at a depth of 1.5 D.

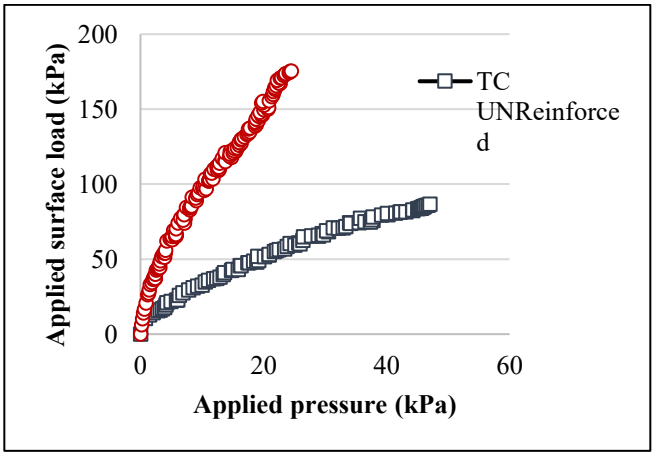

Figure 14. Applied pressure versus the pressure above the tunnel for 6% RHA for the tunnel at a depth of 1.5 D.

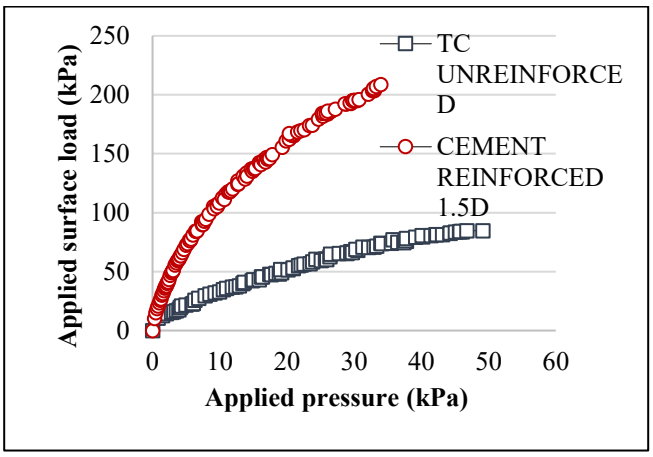

Figure 15. Applied pressure versus the pressure above the tunnel for 5% cement for the tunnel at a depth of 1.5 D.

Table 8. Results Summaries in Pressure (kPa) Versus Footing Settlement S/B for the tunnel at depth 1.5d.

s/B (%)	Clay +Tunnel (1.5D)	RHA 2%	RHA 4%	RHA 6%	Cement 5%
5	6.9	5.2	4.5	3.2	2
10	13.6	10.3	9	5.8	4.1
15	20.9	16.3	12.6	9.4	5.8
20	26.5	21.1	16.3	11.9	7.7
25	32.1	24.5	18.9	14.5	9.8
30	37.8	29.6	22.8	17.6	12.2
35	43.2	33.2	25.2	19.4	14
40	45.9	37.4	28.8	22.2	16.4
45	47	41.4	32.3	24.5	18.3

5.3 The effect of reinforcement when strengthening tunnel sides concerning deflection

Using additives such as rice husk ash and cement to reinforce soft soil around tunnels effectively improves soil stability and reduces deflection and settlement. This method enhances the tunnel's durability and lifespan, making it a sustainable and cost-effective option for construction and infrastructure projects. When creating other models using different proportions of rice husk ash and a curing time of 7 days, effective results were also obtained during the research, as seen in Fig. 16, where deflection and settlement decreased significantly at all three proportions. However, 6% is considered the best in terms of reinforcement. After using 5% cement and allowing the model to cure for 7 days, it was observed from Fig. 17 that there is minimal deviation when loads are applied to the tunnel due to the improved soil durability resulting from the use of cement.

Yang et al. [36] studied the use of a mixture of rice husk ash and cement to improve soil. Weak clay is used in Vinh Long province as a material for roads and bridges. Research results show that when the ash content increases, rice husk will lead to a decrease in MDD value and an increase in the price of treatment or MC. In addition, increasing rice husk ash content will increase some mechanical indicators such as strength, Uniaxial compressive strength, tensile strength, and coefficient of flexibility. A mixture of 75% soil + 20% rice husk ash + 5% cement is considered ideal when it comes to strength values and higher compressive strength.

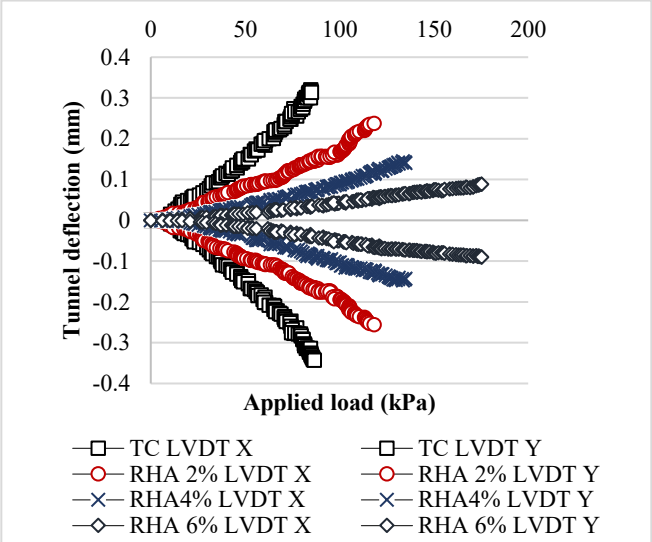

Figure 16. RHA, the Impact of Reinforcement on Deformation Under Loading

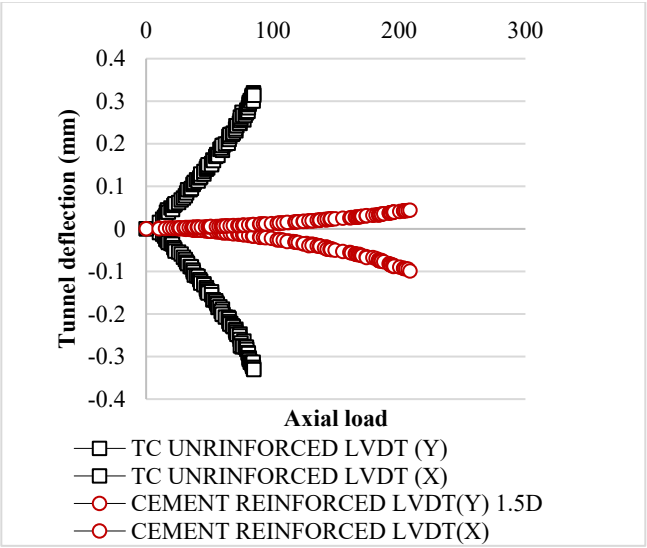

Figure 17. Cement, the Impact of Reinforcement on Deformation Under Loading

6. Conclusion

The utilization of by-products and waste materials for the development of new products has garnered significant interest in recent times. Within this context, rice husk ash (RHA) by-products and waste are considered renewable and sustainable sources of silica due to their high content of amorphous silica. Additives such as cement and RHA play a crucial role in significantly enhancing the bearing capacity and stability of soil in tunnels constructed in soft soil under various loads.

Cement reinforcement increases the load-bearing strength and stiffness of the tunnel by a factor of 2.66, compared to 1.24 for unreinforced tunnels. It also reduces deformations and settlements under loads by approximately 80%, as

demonstrated in Fig. 17. Furthermore, the pressures generated by high loads on the reinforced tunnel decreased to 4.1 kPa, compared to 13.6 kPa for the unreinforced tunnel.

On the other hand, RHA improves the mechanical and chemical properties of the soil, thereby enhancing its long-term load-bearing capacity and reducing permeability. The optimal increase in load-bearing strength and stiffness with a 6% RHA reinforcement was 1.62, compared to 1.24 for the unreinforced tunnel, and the pressure decreased to 5.8 kPa compared to 13.6 kPa. Fig. 16 illustrates the deformations and deviations.

These additives significantly improve the structural performance of tunnels, increase their resistance to deformations, and enhance their stability and safety under various conditions.

Use of LLM and AI

LLM or AI: none declared.

Research funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Data Availability

Most datasets generated and analyzed in this study are included in this submitted manuscript. The other datasets are available upon reasonable request from the corresponding author with the attached information.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contribution Statement

Zahraa Hasoun Faleih: validation, formal analysis, writing the original draft.

Husam Hikmat Baqir and Ahmed Saadalamer Al-Gharbawi: conceptualization, methodology, review, and editing.

References

[1] A. S. A. Al-Gharbawi, M. Y. Fattah, and S. A. Abduhussain, "Behavior of soil reinforced with micropiles," *Open Engineering*, vol. 14, no. 1, Art. no. 20220563, 2024. doi: https://doi.org/10.1515/eng-2022-0563.

[2] N. W. Jassim, H. A. Hassan, H. A. Mohammed, and M. Y. Fattah, "Enhancement consistency and compaction characteristics of clayey soil using nano silica material," *Periodicals of Engineering and Natural Sciences*, vol. 10, no. 6, pp. 77–83, 2022. doi: https://doi.org/10.21533/pen.v10.i6.910.

[3] N. M. Salim and A. A. Hassan, "Effect of organic waste on geotechnical properties of soft clay," *Journal of Engineering and Sustainable Development,* vol. 24, no. 1, pp. 110–123, 2020. doi: https://doi.org/10.31272/jeasd.24.1.8 .

[4] N. M. Salim and S. J. Lafta, "Effect of a driven pile on an existing tunnel," *Journal of Engineering and Sustainable Development*, vol. 24, no. 1, pp. 94–109, 2020. doi: https://doi.org/10.31272/jeasd.24.1.7.

[5] H. Baqir, A. Al-Adili, and A. Sharef, "Compressibility of soft Iraqi soil stabilized with traditional Iraqi stabilizers (cement and lime)," *MATEC Web Conf.,* vol. 162, Art. no. 01015, 2018. doi:https://doi.org/10.1051/matecconf/201816201015 .

[6] X. Liu, Q. Sun, W. Song, and Y. Bao, "Structural behavior of reinforced concrete tunnel linings with synthetic fibers addition," *Tunnelling and Underground Space Technology*, vol. 131, Art. no. 104771, 2023. doi: https://doi.org/10.1016/j.tust.2022.104771.

[7] E. A. Basha, R. Hashim, H. B. Mahmud, and A. S. Muntohar, "Stabilization of residual soil with rice husk ash and cement," *Construction and Building Materials*, vol. 19, no. 6, pp. 448–453, 2005. doi: https://doi.org/10.1016/j.conbuildmat.2004.08.001.

[8] L. Behak, "Soil stabilization with rice husk ash," in *Rice—Technology and Production*, Amanullah and S. Fahad, Eds. InTech, 2017. doi: https://doi.org/10.5772/66311.

[9] M. H. Nsaif, "Behavior of soils strengthened by plastic waste materials," *Journal of Engineering and Development*, vol. 17, no. 4, pp. 182–194, 2013. [Online]. Available: https://jeasd.uomustansiriyah.edu.iq/index.php/jeasd/article/view/981.

[10] S. A. Mohammed, S. Naimi, and A. H. AbdulKareem, "The effect of geogrid reinforcement of embankment over soft foundation," *Periodicals of Engineering and Natural Sciences*, vol. 10, no. 6, pp. 5–27, 2022. doi: https://doi.org/10.21533/pen.v10.i6.904.

[11] A. A. Ahmed, "Effect of tunneling in cohesive soils on existing structures," *Engineering and Technology Journal*, vol. 32, no. 10A, pp. 2475–2490, 2014. doi: https://doi.org/10.30684/etj.32.10A.12.

[12] S. D. Nagrale, H. Hajare, and P. R. Modak, "Utilization of rice husk ash," *International Journal of Engineering Research and Applications*, vol. 2, no. 4, pp. 1–5, 2012. [Online]. Available: https://www.ijera.com/papers/Vol2_issue4/A24001005.pdf.

[13] P. N. V. Jayanthi and D. N. Singh, "Utilization of sustainable materials for soil stabilization: State-of-the-art," *Advances in Civil Engineering Materials*, vol. 5, no. 1, pp. 46–79, 2016. doi: https://doi.org/10.1520/ACEM20150013.

[14] G. Kuntikana and D. N. Singh, "Contemporary issues related to utilization of industrial byproducts," *Advances in Civil Engineering Materials*, vol. 6, no. 1, pp. 444–479, 2017. doi: https://doi.org/10.1520/ACEM20160050.

[15] B. J. S. Varaprasad, J. J. Reddy, and J. S. Reddy, "Remediation of expansive soils using mango kernel ash and calcium carbide residue*," Int. J. Environ. Waste Manage.*, vol. 25, no. 2, pp. 220–230, 2020. doi: https://doi.org/10.1504/IJEWM.2020.105351.

[16] Sk S. Hossain, L. Mathur, and P. K. Roy, "Rice husk/rice husk ash as an alternative source of silica in ceramics: A review," *Journal of Asian Ceramic Societies*, vol. 6, no. 4, pp. 299–313, 2018. doi: https://doi.org/10.1080/21870764.2018.1539210.

[17] N. J. Najm, W. A. Zakaria, and M. M. Sreh, "Predicting of seismic performance on tunnel in weak soil," *Diyala Journal of Engineering Sciences*, vol. 16, no. 2, pp. 16–29, 2023. doi: https://doi.org/10.24237/djes.2023.16202.

[18] F. Q. Al-Naje, A. H. Abed, and A. J. Al-Taie, "A review of sustainable materials to improve geotechnical properties of soils," *Al-Nahrain J. Eng. Sci.,* vol. 23, no. 3, pp. 289–305, 2020. doi: https://doi.org/10.29194/NJES.23030289 .

[19] O. Y. Almashhadany and B. S. Albusoda, "Experimental study of seismic response of the square tunnel in granular soil*," Journal of Engineering and Sustainable Development,* vol. 24, no. 2, pp. 80–95, 2020. doi: https://doi.org/10.31272/jeasd.24.2.6 .

[20] S. A. Nugroho, S. P. R. Wardani, and A. S. Muntohar, "Density, load, and fly ash effect on stabilization of high plasticity soil with lime," *Al-Qadisiyah Journal for Engineering Sciences*, vol. 16, no. 2, pp. 102–107, 2023. doi: https://doi.org/10.30772/qjes.v16i2.925.

[21] A. S. Yousif and F. S. Mustafa, "Behavior of saline soil stabilized with polypropylene fiber and cement," *Kufa J. Eng*., vol. 12, no. 1, pp. 29–47, 2021. doi: https://doi.org/10.30572/2018/KJE/120103.

[22] M. Y. Fattah, F. H. Rahil, and K. Y. H. Al-Soudany, "Improvement of clayey soil characteristics using rice husk ash," *Journal of Civil*

Engineering and Urbanism, vol. 3, no. 1, pp. 12–18, 2013. [Online]. Available:https://www.ojceu.com/main/index.php?Itemid=24&id=21&option=com_content&view=article.

[23] D. Hardjito and B. V. Rangan, "Development and properties of low-calcium fly ash-based geopolymer concrete," Faculty of Engineering, Curtin University of Technology, Perth, Australia, Research Rep. GC 1, 2005. [Online]. Available: https://espace.curtin.edu.au/handle/20.500.11937/5594.

[24] P. Chindaprasirt, C. Chotetanorm, and S. Rukzon, "Use of palm oil fuel ash to improve chloride and corrosion resistance of high-strength and high-workability concrete," *Journal of Materials in Civil Engineering*, vol. 23, no. 4, pp. 499–503, 2011. doi: https://doi.org/10.1061/(ASCE)MT.1943-5533.0000187.

[25] V. H. Le, C. N. H. Thuc, and H. H. Thuc, "Synthesis of silica nanoparticles from Vietnamese rice husk by sol–gel method," *Nanoscale Research Letters*, vol. 8, Art. no. 58, 2013. doi: https://doi.org/10.1186/1556-276X-8-58.

[26] M.Y. Fattah, Al-Naemi M.A., Al-Suhaily A.S., "Estimation of bearing capacity of floating group of stone columns," *Engineering Science and Technology, an International Journal*, vol. 20, issue 3, pp. 166 – 172. 2017. https://doi.org/10.1016/j.jestch.2017.03.005

[27] M. Y. Fattah, K. T. Shlash, and N. M. Salim, "Time dependent analysis of tunnels using the finite element method," *Engineering and Technology Journal*, vol. 27, no. 1, pp. 127–151, 2009. doi: https://doi.org/10.30684/etj.27.1.10.

[28] K. T. Shlash, N. M. Salim, and Z. H. Shaker, "Stress analysis around tunnels during construction stages using finite elements method," *Engineering and Technology Journal*, vol. 32, no. 6A, pp. 1562–1578, 2014. doi: https://doi.org/10.30684/etj.32.6A.17.

[29] H. H. M. Al-Khalali, "Using geocell and geogrid reinforcement to improve the performance of buried piles in sandy soil," Ph.D. dissertation, Univ. of Baghdad, Iraq, 2015.

[30] K. M. A. Hossain, "Stabilized soils incorporating combinations of rice husk ash and cement kiln dust," *Journal of Materials in Civil Engineering*, vol. 23, no. 9, pp. 1320–1327, 2011. doi: https://doi.org/10.1061/(ASCE)MT.1943-5533.0000310.

[31] A. Barwar, A. K. Chandrappa, and U. C. Sahoo, "Laboratory investigations on stabilization of weak clay soil using rice husk ash and cement," Innov. Infrastruct. Solut., vol. 7, no. 5, Art. no. 327, 2022. doi: https://doi.org/10.1007/s41062-022-00924-7.

[32] D. E. Wibowo, D. A. Ramadhan, Endaryanta, and H. Prayuda, "Soil stabilization using rice husk ash and cement for pavement subgrade materials," *Revista de la Construcción*, vol. 22, no. 1, pp. 192–202, 2023. doi: https://doi.org/10.7764/rdlc.22.1.192.

[33] N. Yoobanpot and P. Jamsawang, "Effect of cement replacement by rice husk ash on soft soil stabilization," *Kasetsart Journal (Natural Science)*, vol. 48, no. 2, pp. 323–332, 2014. [Online]. Available: https://li01.tci-thaijo.org/index.php/anres/article/view/243266.

[34] P. Jongpradist, W. Homtragoon, R. Sukkarak, W. Kongkitkul, and P. Jamsawang, "Efficiency of rice husk ash as cementitious material in high-strength cement-admixed clay," *Advances in Civil Engineering*, vol. 2018, Art. no. 8346319, 2018. doi: https://doi.org/10.1155/2018/8346319.

[35] T. Tesanasin *et al.*, "Comparison between cement-rice husk ash and cement-rice husk ash one-part geopolymer for stabilized soft clay as deep mixing material," *Transportation Infrastructure Geotechnology*, vol. 11, pp. 1760–1776, 2024. doi: https://doi.org/10.1007/s40515-023-00345-8.

[36] Y. Yang *et al.*, "ZnO nanoparticles loaded rice husk biochar as an effective adsorbent for removing reactive red 24 from aqueous solution," *Materials Science in Semiconductor Processing*, vol. 150, Art. no. 106960, Nov. 2022. doi: https://doi.org/10.1016/j.mssp.2022.106960.