CJES
Caspian Journal of Environmental Sciences
Online ISSN: 1735-3866
Print ISSN: 1735-3033

# Geotechnical improvement of soils by rice husk ash in Caspian Region, Northern Iran

**Maysam Salimzadehshooiili**

*Assistant Professor, Department of Civil Engineering, Faculty of Engineering, University of Guilan, Rasht, Iran*

** Corresponding author's Email: m.salimzadehshooiili@guilan.ac.ir*

## ABSTRACT

Soil stabilization using additive materials is a fundamental technique in geotechnical engineering. Common stabilizers include lime, cement, rice husk ash (RHA), pozzolans, micro-silica, aluminum sulfate, and fly ash. Given the increasing emphasis on sustainable materials, this study focuses on RHA—a pozzolanic material widely available in northern Iran as a promising soil stabilizer. RHA's abundant supply, ease of processing, and cost-effectiveness make it suitable as a partial or complete replacement for cement in various soil stabilization applications. The research outlines RHA's production process using different curing methods by altering the time and temperature of combustion and the rate of cooling process, while the chemical characterization was determined through X-ray florescence (XRF) and scanning electron microscopy (SEM) analysis. Furthermore, to assess the capability of RHA in soil stabilization, unconfined compressive strength (UCS) test was performed on the treated sandy clay soil specimens after 7 and 28 days curing period. The findings revealed that the RHA obtained from burning at 500 °C for 12 hours and rapidly cooled shows the highest pozzolanic activity while gradual cooling has a negative effect on it. The UCS test results showed that adding 15% of RHA-cement, with equal proportions, to the sandy clay soil could enhance the compressive strength by over 2.7 MPa. Results indicate that incorporating RHA not only improves soil stabilization and reduces cement usage, but also offers environmental benefits by repurposing an agricultural byproduct that would otherwise go to waste. These findings provide practical guidelines for implementing eco-friendly soil stabilization practices in the Caspian region and similar ecological zones.

**Keywords:** Rice husk ash (RHA), Soil stabilization, Environmental sustainability, Cement replacement
Article type: Research Article.

## INTRODUCTION

The growing population and limited availability of suitable land for construction have necessitated the use of weak or soft soils for civil engineering projects. Consequently, various soil stabilization and improvement techniques are employed depending on the project type and desired geotechnical properties (Ghorbani & Salimzadehshooiili, 2019). Many infrastructure projects—such as irrigation and drainage networks, road construction, embankments, and earth dams—often face shortages of suitable soil materials, making it essential to enhance the strength and performance of locally available soils. One effective soil improvement method is the addition of stabilizing agents, which enables the use of weak or marginal soils while avoiding the high costs associated with transporting materials from distant sources. Common additives include lime, cement, rice husk ash (RHA), pozzolans, micro silica, aluminum sulfate, and fly ash. Lime stabilization, dating back to ancient times, became widely adopted in the United States after 1945 (Ingles & Metcalf 1972; Ghorbani & Salimzadehshooiili 2019). The key chemical reactions triggered by these additives are ion exchange, pozzolanic reactions, and hydration, with the pozzolanic

Caspian J. Environ. Sci.
DOI:
Received:
Article type: Research

reaction being the most significant. This reaction—occurring between lime, water, and silica/alumina-rich soil components—produces cementitious compounds that enhance soil shear strength. The process is time-dependent and ceases in the absence of moisture (Mallela *et al.* 2004).

Lime stabilization is widely used in construction to create stable foundations. Produced by calcining limestone ($CaCO_3$) at 1289 °C, quicklime (CaO) effectively stabilizes clayey soils but has limited impact on organic soils (Alrubaye 2016). Key reactions include cation exchange, flocculation, and pozzolanic reactions, which form cementitious compounds, enhancing strength and durability over time (Little 1987). Lime increases soil pH, dissolving silicates and aluminates to form strength-boosting hydrates, though excess lime reduces effectiveness. Carbonation, an undesirable reaction with $CO_2$, can also occur. Design methods based on AASHTO & ASTM standards optimize lime-stabilized mixtures for improved compressive, tensile, and flexural strength (Milad 2020). Zivari *et al.* (2023) investigated the "Effect of Lime-Rice Husk Ash on Geotechnical Properties of Loess Soil in Golestan Province, Iran". Their experimental results demonstrated that a 5% L-RHA admixture represents the optimal dosage, and delivering. Throughout history, civilizations have used soil stabilization methods, mainly for road construction. After the Roman era, Europe saw limited progress until horse-drawn vehicles increased demand for durable roads, prompting engineers to develop stabilization techniques later adopted in other fields (Ingles 1972). Today, chemical stabilization improves soil properties by enhancing strength, reducing plasticity, and controlling permeability. Common methods include cement, lime, bitumen, and fly ash. Recently, eco-friendly stabilizers like rice husk ash have gained attention for reducing environmental impact while maintaining performance, offering sustainable solutions for geotechnical applications. The production of cement saw significant advancements in the 18th century. During this period, John Smeaton discovered that the best mortar was obtained by mixing pozzolan with limestone containing a considerable percentage of clayey materials. Later, Joseph Aspdin, an English architect, developed a specific method for cement production and patented this product in 1824, naming it Portland Cement. In this manufacturing process, a mixture of clay and finely crushed limestone is heated in a kiln to drive off $CO_2$, producing clinker. The first Portland cement in the United States was manufactured in 1872 **(Ingles1972).**

The use of pozzolanic materials like fly ash enhances and accelerates the effects of additives such as lime. Lime significantly improves the engineering properties of fine-grained clayey soils, including swell potential, shear strength, water absorption capacity, and plasticity characteristics (Atterberg limits). However, lime application has certain limitations - its addition to soil may lead to detrimental effects through destructive reactions including carbonation, sulfate attack, organic matter interference, sulfide reactions, and salt effects . When sulfate ions are present in soil or when stabilized soil is exposed to sulfate-rich water, lime not only fails to reduce swelling but conversely increases expansion while decreasing strength (Sherwood 1962;  Sata 2007). This phenomenon occurs due to chemical reactions between clay minerals, lime and sulfates that form expansive minerals like ettringite and thaumasite. These minerals demonstrate considerable water absorption capacity leading to severe swelling e(Hunter,1988). Fly ash primarily consists of silicon, aluminum, iron and calcium oxides. Its addition increases soluble calcium content, thereby enhancing pozzolanic activity. Fly ash incorporation also significantly elevates pH levels. At higher pH values, silica is released from its tetrahedral sheet structure and alumina from its octahedral sheet structure, accelerating pozzolanic reactions (Sezer *et al.* 2006;  McKennon 1994e).

Rice husk ash (RHA) contains abundant silica with high specific surface area, making it particularly effective for activating soil-lime reactions. RHA is produced through controlled combustion of rice husks at 600 °C (Della 2002), with approximately 20% yield by weight (Anwar 2001). Composed mainly of silica and alumina, RHA qualifies as a pozzolanic material according to ASTM C618-2012a standard. While abundantly available in countries like China and India (Sata 2007), its lightweight nature and low density make it prone to airborne dispersion. With its high pozzolanic activity and specific surface area (Ramakrishna 2006), RHA can be effectively combined with lime to reduce Portland cement requirements in soil stabilization (Smith 1986; Zhang 1996; Sata 2007). The cement production process is costly and environmentally damaging. Rice husk, a byproduct of rice milling, is often disposed of as waste or used as fuel in some countries, contributing to environmental pollution. Given that global rice production reaches approximately 500 million tons annually, with husks accounting for 20% of this weight (~100 million tons), finding sustainable uses for rice husk ash (RHA) is of great significance. Research on the pozzolanic properties of RHA and its application in concrete began in the late 1960s. Today, advancements in controlled combustion techniques and chemical purification methods have enabled the production of high-quality RHA with minimal impurities, renewing interest in its use as a sustainable

Received:
Article type: Research

construction material (Salas 2009). Rice husk ash (RHA) possesses the highest silica content among agricultural byproducts. The rice plant absorbs orthosilicic acid from groundwater, which undergoes biochemical transformation into amorphous silica within the husk structure. Properly controlled combustion of rice husk yields approximately 20% highly reactive hydrated amorphous silica (Nair 2008). When used as a partial cement substitute, RHA demonstrates significant economic advantages while enhancing the material mechanical properties through optimal processing and application (Ghorbani 2019).The pozzolanic reactivity of RHA is strongly influenced by combustion temperature, with optimal results achieved between 500-700 °C where complete carbon removal occurs without crystalline silica formation. Recent studies show that 15-20% cement replacement with ultrafine RHA (particle size $< 10$ μm) can increase 28-day compressive strength by up to 18% compared to conventional mixes.

This study conducts a comprehensive review of soil stabilization techniques, with a focus on evaluating rice husk ash (RHA) as a sustainable alternative to cement. The research examines RHA production methods, including processing and activation techniques, along with detailed material characterization using X-ray fluorescence (XRF) and scanning electron microscopy (SEM). Additionally, the thermal behavior of rice husk and its associated chemical reactions are analyzed. The mechanical performance of RHA-stabilized soils is assessed through unconfined compressive strength (UCS) testing, while environmental considerations are discussed to evaluate its ecological benefits. The findings aim to establish optimal mix designs that meet both engineering performance and sustainability requirements for practical geotechnical applications.

## MATERIALS AND METHODS

### Mechanism of soil stabilization with cement and soil-cement chemical reactions

In geotechnical engineering, cementation describes the bonding of soil particles into a stronger cohesive mass through cementitious stabilization. While coarser materials like gravel naturally possess good geotechnical properties, research has mainly focused on improving fine sands and fine-grained materials through artificial cementation (Clough 1981). The addition of cement initiates important chemical reactions including cation exchange and flocculation-agglomeration, which begin immediately upon contact with clay particles. These reactions rapidly enhance the soil's plasticity by modifying its particle size distribution and fabric structure as particles aggregate, ultimately increasing soil strength. Chemically, clinker consists of four principal compounds according to cement nomenclature:

- Tricalcium silicate ($C_3S$)
- Dicalcium silicate ($C_2S$)
- Tricalcium aluminate ($C_3A$)
- Tetracalcium aluminoferrite ($C_4AF$)

The grinding process reduces particle size to enhance cement hydration rate and completeness. In soil-cement stabilization, calcium-rich phases ($C_3S$ and $C_2S$) are particularly crucial, comprising about 75% of Type I/II Portland cements, as they facilitate cation exchange and soil particle aggregation (Bhattacharja 2003). Finer cement particles achieve more complete hydration, a process that can continue for years. While Portland cement requires months to years for full hydration, initial hydration occurs as particles coalesce around soil particles, forming partial membranes that delay inner component hydration (Ismail 2002). Fig. 1 illustrates cement particles within a soil matrix after the curing process.

The formation of calcium silicate hydrate (C-S-H) during cement hydration drives strength development, representing a fundamental cementitious property. In cement-stabilized soils, additional C-S-H forms through pozzolanic reactions between soil silica and cement-derived $Ca(OH)_2$, with calcium also reacting with aluminum to form calcium aluminate hydrate (C-A-H; Herzog 1963). These processes involve: (i) immediate flocculation-agglomeration and (ii) long-term pozzolanic cementation creating permanent bonds. Microstructural analyses show C-S-H grows in fractal patterns, initially nucleating at clay edges before filling spaces. The primary cement hydration process increases pore water pH, producing highly reactive $Ca(OH)_2$. During secondary reactions, clay minerals decompose, allowing calcium ions to bind with clay particles while silica/aluminum form supplementary C-S-H and C-A-H (Bhattacharja 2003). This creates first a reinforced granular structure, then cohesive bonds between aggregates. Carbonation further enhances long-term strength through reaction with $CO_2$, forming insoluble $CaCO_3$ that densifies the matrix (Geiman 2005).

Received:
Article type: Research

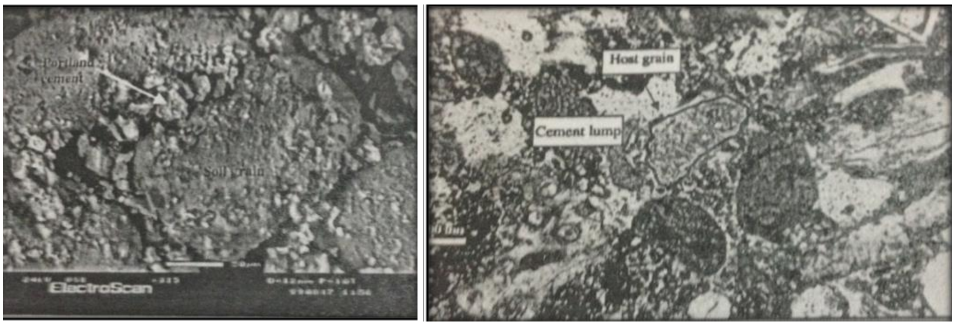


**Fig. 1.** Scanning Electron Microscope (SEM) image of sand stabilized with 8% cement content (Ismail 2002).

Field specimens show greater strength than lab samples due to atmospheric carbonation progressing inward at 0.1-0.5 mm year$^{-1}$. Table 1 systematically summarizes these stabilization mechanisms. Microstructural analyses reveal that the carbonation front progresses inward from exposed surfaces at a rate of 0.1-0.5 mm year$^{-1}$ depending on environmental conditions. This phenomenon explains why field specimens often demonstrate higher long-term strength than laboratory-cured samples when properly exposed to atmospheric carbonation.

**Table 1.** Mechanisms effective in soil stabilization with cement (Geiman 2005), Degree of importance description of mechanisms effective in soil stabilization with cement

| Effective mechanisms in soil stabilization with cement | Description | ےDegree of importance |
|---|---|---|
| Hydration | -Creates strong cohesive forces between particles<br>-The cohesion created is strong, hard material is formed and includes soil networks<br>-Shrinkage, swelling and shrinkage are reduced and resistance to moisture changes is increased Hydration | Very high |
| High Exchange of positive ions | High Exchange of positive ions with the effect of improving the tolerance of electrical charges and reducing plasticity and consequently causing aggregation of soil particles | High |
| Carbonation | Ion exchange<br>Low During the hydration process, cement reacts with carbon dioxide in the air to form a cementing agent. | Low |
| Pozzolanic reaction | The $Ca(OH)_2$ released during the hydration process reacts with the silica and aluminum of the clay particles in the presence of moisture to form a cementitious material | Low |

The primary distinction between cement and lime stabilization methods lies in the time-temperature-strength relationship. Numerous studies confirm that higher cement content enhances compressive strength in stabilized soils, with strength plateauing at approximately 20% cement content. In contrast, lime-stabilized soils achieve optimal strength at lower additive percentages (typically 8%; Ingles 1972). Furthermore, lime stabilization relies on silica released from decomposed clay particles, whereas cement stabilization depends primarily on hydration reactions requiring only water, making it less sensitive to soil composition (Geiman 2005).

### Preparation of rice husk ash

The rice husk used in this study was obtained from Rasht City, Guilan Province, Northwest Iran. First, it was dried naturally under the sun for three days. Then it was burned to turn into ash (this operation lasted three days). Then, the rice husk is burned in the open air and transferred to the furnace for decarbonization. After decarbonization and preparation of rice husk ash, the prepared ash is ground in order to increase the specific surface area and increase the packing effect.

## RESULTS

### Properties and processing of rice husk

Research shows that agricultural waste consists of organic materials such as cellulose, lignin, fiber and small amounts of crude protein and fat, and in addition to minerals such as silica, aluminum oxide and iron oxide.

Received:
DOI:
Article type: Research

Noteworthy, agricultural waste cannot be used as a substitute for cement, but must be converted into a useful material for use through a process (burning). Two factors should be considered in the burning of agricultural waste: the resulting ash, which is the amount of waste required to burn on site, and the chemical elements formed. In fact, there is a large amount of silica in the ash, which reacts with lime and forms hydrated calcium silicate with adhesive properties. Table 2 shows the amount of ash and silica found in some plants such as rice husk, rice stalk and bagasse (sugarcane stalk).

**Table 2.** Ash and silica content in agricultural byproducts.

| **Plant** | **Plant part** | **Ash content (%)** | **Silica ($SiO_2$) content (%)** | **Pozzolanic activity class** |
|---|---|---|---|---|
| Wheat | Leaf sheath | 10.48 | 90.46 | High (≥90%) |
| Corn | Leaf midrib | 12.15 | 64.32 | Moderate (60-80%) |
| Bamboo | Nodal core | 1.49 | 57.40 | Low-Moderate |
| Sugarcane | Bagasse | 14.71 | 73.00 | Moderate-High |
| Sunflower | Leaf & stem | 11.53 | 25.32 | Non-pozzolanic (<50%) |
| Rice | Husk | 22.15 | 93.00 | Very High |
| Rice | Straw | 14.65 | 82.00 | High |

The data reveal that rice husk yields the highest ash content (22.15%), with its silica ($SiO_2$) concentration reaching ~93%. Approximately 200 kg of rice husk ash (RHA) is produced per ton of combusted husks. These properties make RHA the most effective agricultural byproduct for partial cement replacement in stabilization applications.

### Thermal behavior of rice husk ash

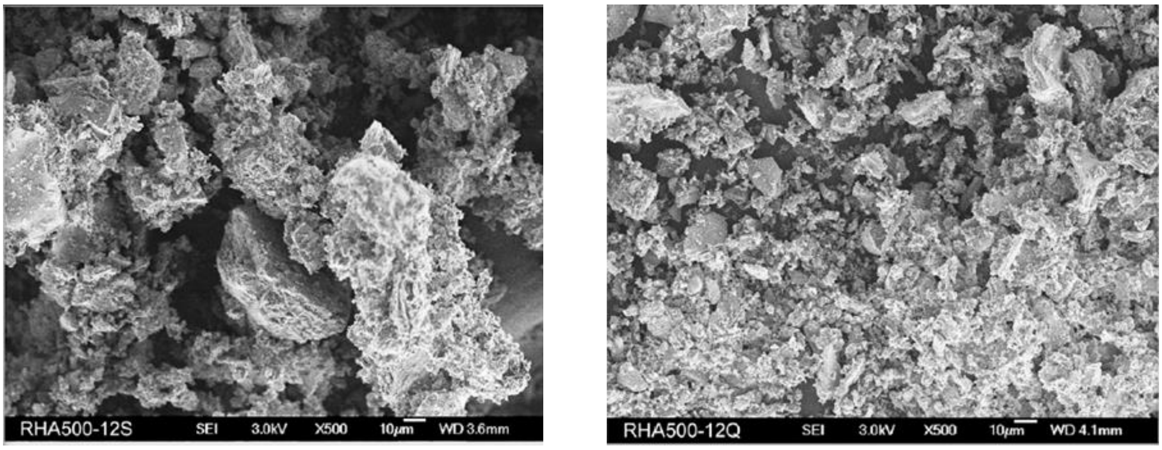
To convert rice husk into ash, burning removes organic matter, leaving silica. Heating to 100 °C evaporates absorbed water, while 350 °C burns volatile matter. Between 400–500 °C, carbon oxidizes, leaving crystalline silica. Above 600 °C, quartz forms; higher temperatures produce cristobalite and then tridymite. Below 500 °C, incomplete roasting leaves unburned carbon, weakening mortar strength if carbon exceeds 30%. Pozzolanic activity rises with temperature as carbon reduces, but above 750 °C, less active cristobalite forms, and at 900 °C, inactive tridymite appears. X-ray diffraction shows silica remains non-crystalline at 450–700 °C, but at 850 °C, it crystallizes into quartz. Burning duration also matters: 2 hours at 500 °C is optimal, as longer times reduce pore structure and surface area, harming reactivity. Cooling methods significantly impact pozzolanic activity. The results are supported by the results of a research conducted by Nair *et al.* (2008) who conducted research on rice husk ash at different temperatures (500, 700, and 900) and different burning times (15 minutes, 6 hours, 12 hours, and 24 hours) and different slow and fast cooling conditions. Then, they measured the effect of different burning conditions on the level of pozzolanic activity of rice husk ash by measuring changes in electrical conductivity. First, the electrical conductivity of 200 mL of saturated lime solution was determined at a temperature of 40 °C. Then 5 g was added to the solution and after a certain time, its electrical conductivity was measured again. The difference between these two values was reported as changes in electrical conductivity. This method, which is a rapid method for determining the amount of pozzolanic activity, is based on the principle that the electrical conductivity of a solution of water and lime depends on the amount of Ca and OH ions and that a decrease in the amount of these ions due to chemical interactions with lime will lead to a decrease in the electrical conductivity of the solution. The results of the pozzolanic activity test are shown in Table 3.

Received:
Article type: Research

**Table 3.** Pozzolanic activity variation under different combustion and cooling conditions.

| **Combustion conditions** | **Cooling method** | **Electrical conductivity change (mS/cm)** | **Pozzolanic activity class** |
|---|---|---|---|
| 700 °C for 12 hours | Gradual cooling | 3.2 | Moderate |
| 700 °C for 12 hours | Rapid cooling | 3.6 | Moderate |
| 700 °C for 24 hours | Gradual cooling | 3.0 | Low-Moderate |
| 700 °C for 24 hours | Rapid cooling | 3.5 | Moderate |
| 500 °C for 12 hours | Gradual cooling | 5.3 | High (Optimal) |
| 500 °C for 24 hours | Rapid cooling | 5.4 | High |
| 500°C for 12 hours | Gradual cooling | 5.2 | High |
| 500°C for 24 hours | Rapid cooling | 5.2 | High |

As can be seen, the ash sample obtained from burning at 500 °C for 12 hours shows the highest pozzolanic activity. It is also observed that gradual cooling has a negative effect on the amount of pozzolanic activity. Scanning electron microscope (SEM) photography of rice husk ash particles burned at 500 °C for 12 hours under different cooling conditions shows that gradual cooling increases the size of rice husk ash particles (Fig. 2).



**Gradually cooled RHA (a)** **Rapidly cooled RHA (b)**

**Fig. 2.** The size of rice husk ash particles under different cooling conditions.

Another important parameter that plays a controlling role in the process of rice husk ash formation is air. If sufficient oxygen is not available for the combustion of rice husk, the separation of silica after the initial charring of rice husk may be slow. In addition, when rice husk is burned, it is necessary to remove ambient carbon dioxide from the surrounding particles in order to completely burn the oxygen in the system. Therefore, replacing the generated carbon dioxide with fresh air is one of the important factors that regulate the process of silica precipitation and its subsequent crystallization. The presence of carbon in rice husk ash will change its color to black and reduce the flexibility of mortar made with it. Another method that can improve the pozzolanic activity of rice husk ash is chemical treatment. Studies by Feng *et al.* (Ghorbani 2019) showed that chemical treatment of rice husk with 1 N hydrochloric acid improved the ash (Fig. 3).

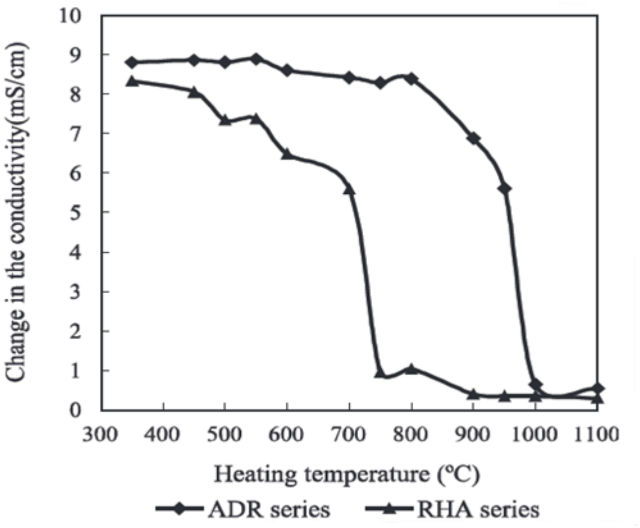


**Fig. 6.** Effect of chemical pretreatment of rice husk at different temperatures on the pozzolanic activity of rice husk ash (RHA: conventional vs. ADR: chemically treated).

For treatment, rice husks are placed in a hydrochloric acid (HCl) solution before burning and immediately washed with water and then dried in air. For burning temperatures above 500 °C, the decrease in pozzolanic activity is intensified, and for burning temperatures above 700 °C, the pozzolanic activity decreases abruptly. However, in the case of treated ash, with an increase in burning temperature to 800 °C, the pozzolanic activity of the resulting ash does not show a noticeable change. It is observed that at the same burning temperatures, the silica content and specific surface area (ADR) of treated ash are higher than that of ordinary ash.

## Characteristics of rice husk ash and preparation of rice husk ash

The most important characteristic of rice husk ash that controls pozzolanic reactions is the presence of amorphous silica content. Due to its highly active pozzolanic properties, RHA is suitable for forming calcium silicate gel, which is actually the product of its reaction with cement. In fact, when RHA and cement are mixed in the presence of water, the pH of the environment increases and the active silica present in RHA reacts with calcium hydroxide and a calcium silicate hydrate gel is produced. The reaction described is shown in equations 1 and 2 (Mallela 2004; Geiman 2005; Salas 2009)

$$CaO + H_2O = Ca(OH)_2 \tag{1}$$

$$Ca(OH)_2 = Ca^{2+} + 2(OH)^- \tag{2}$$

The burned ash was placed in a furnace at 600 °C for two hours to decarbonize and increase the pozzolanic property, then it was ground using a mill for 1.5 hours to prepare it for adding to cement and creating a higher specific surface area. Fig. 4-a shows the RHA used before grinding process and Fig. 4-b after the grinding. Also, the grain size of the RHA used before and after grinding is shown in Fig. 5. In fact, the reason for grinding is to pay attention to the fact that with an increase in the specific surface area of the material, the number of surfaces ready for the reaction increases and, consequently, the probability of the hydration reaction upraises. Therefore, the grinding process of each of the stabilizers can lead to an increase in the specific surface area, an increase in the reactivity potential, and consequently an elevation in compressive strength.

Received:
Article type: Research

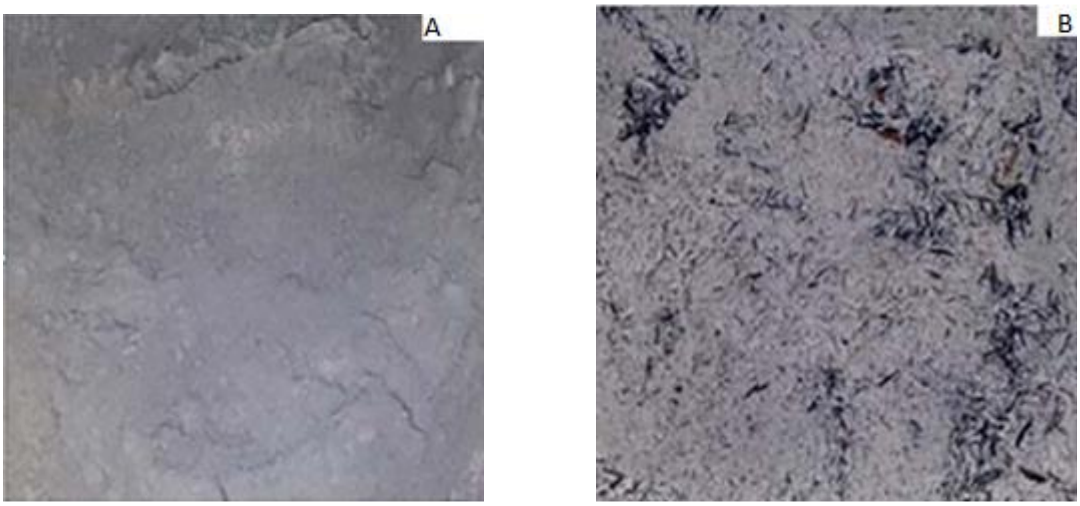


**Fig. 4.** Rice husk ash (RHA) particles: (a) Before grinding-(b) After grinding.

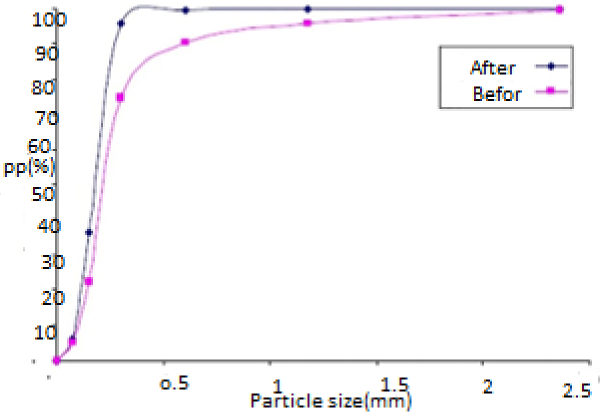


**Fig. 5.** Distribution of rice husk ash particles before and after grinding.

The chemical composition of the RHA, using XRF data is also presented in Table 4.

**Table 4.** Chemical composition of the studied rice husk ash (RHA).

| Component | Content (%) | ASTM C618 classification | Role in pozzolanic activity |
|---|---|---|---|
| **$SiO_2$** | 90.60 | Class F (≥ 70%) | Primary reactive phase |
| **$Al_2O_3$** | 0.49 | - | Minor cementitious contributor |
| **$Fe_2O_3$** | 0.73 | - | Colorant, minimal reactivity |
| **CaO** | 1.51 | - | Supports self-cementing |
| **MgO** | 0.88 | - | Potential expansion control |
| **$Na_2O$** | 0.22 | - | Alkali-silica reaction risk |
| **$K_2O$** | 1.80 | - | Fluxing agent during combustion |
| **$SO_3$** | 0.43 | Max 4.0% (per ASTM) | Sulfate resistance impact |
| **LOI** | 3.34 | Max 6.0% (per ASTM) | Unburned carbon content |

### Unconfined compressive strength (UCS)

The effect of replacing RHA with cement on the UCS of cement-RHA stabilized specimens is shown in Fig. 6. Specimens containing 5%, 10%, and 15% cement, with 50% of the cement replaced by RHA, were prepared and tested after curing periods of 7 and 28 days. According to the results, the UCS initially decreased at 5% and 10% cement replacement levels. However, at 15% cement replacement, as well as in samples made with 7.5% cement and 7.5% RHA, higher strength was observed. This trend can be attributed to the pozzolanic nature of RHA, with its optimal performance depending on both the replacement ratio and the curing period. Further analysis reveals that longer curing durations enhance the pozzolanic reaction, leading to improved strength development in RHA-modified specimens. Additionally, the increased strength at higher RHA replacement levels suggests that the silica content in RHA effectively contributes to secondary hydration reactions with calcium hydroxide. The findings indicate that while partial cement replacement with RHA may initially reduce early strength, the long-term performance can be comparable or even superior due to ongoing pozzolanic activity. This highlights the potential of RHA as a sustainable supplementary cementitious material in soil stabilization applications. Further research could explore the optimal balance between cement and RHA content to maximize both economic and mechanical benefits.

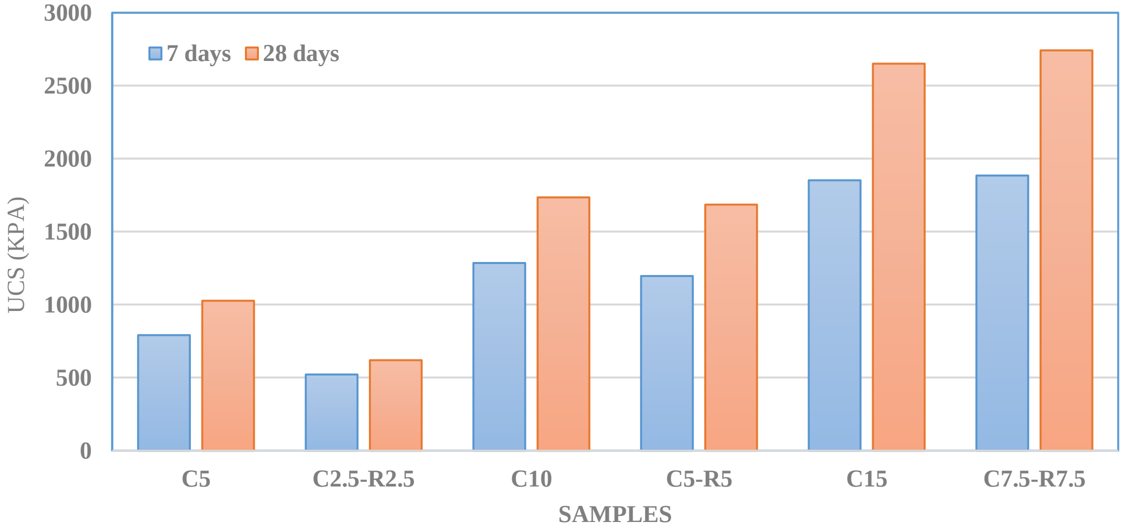


**Fig. 6.** Compressive strength with curing periods of 7 and 28 days.

## DISCUSSION

Soil stabilization has progressively incorporated sustainable materials that optimize both engineering performance and environmental responsibility. Industrial byproducts such as fly ash, silica fume, and particularly rice husk ash (RHA) have gained prominence for their dual value in waste repurposing and geotechnical enhancement (Ingles 1972; Mallela 2004). RHA presents an exemplary circular economy solution, simultaneously addressing two critical environmental challenges: the management of agricultural waste and the substantial carbon footprint of conventional cement production, which emits approximately 1 ton of $CO_2$ per ton of cement produced while consuming 5 TJ of energy per 1,000 tons. The environmental benefits of RHA utilization are multifaceted. First, its production via controlled combustion (600-850 °C for 48 hours) of rice husks - a milling byproduct yielding 200 kg RHA per ton of husk - transforms what would otherwise be an environmental liability into a valuable resource. In rice-growing regions like Northern Iran, where husk disposal often leads to open burning (releasing particulate matter and greenhouse gases) or landfill accumulation, RHA production provides a sustainable waste management alternative. Second, the material composition (85-95% amorphous silica with specific surface area > 50 $m^2\ g^{-1}$) (Sezer 2006; Ghorbani 2019) enables it to directly replace cement, thereby reducing demand for this energy-intensive material. Each ton of cement displaced by RHA avoids approximately 0.4 tons of $CO_2$ emissions,

Received:
Article type: Research

while maintaining 90-95% of the compressive strength in stabilized soils. Beyond carbon reduction, RHA deployment offers additional ecological advantages:

- **Waste stream reduction**: Diverts agricultural waste from open burning (a major source of $PM_{2.5}$ emissions) and landfills
- **Resource conservation**: Decreases quarrying of limestone for cement production, preserving natural landscapes
- **Energy efficiency**: Requires less processing energy than cement clinker production
- **Water protection**: Reduces alkaline runoff associated with traditional cement stabilization

Field applications demonstrate the RHA technical and economic viability, with 25% cement replacement achieving comparable strength while reducing road construction costs by 30-40%. These findings position RHA as a triple-benefit solution: (i) converting waste disposal challenges into valuable resources, (ii) delivering mechanical performance on par with conventional stabilizers, and (iii) advancing sustainable construction through simultaneous carbon reduction and cost savings (Salimzadehshooiili 2023). Future research should investigate optimal application protocols across varied geoclimatic conditions to maximize the RHA environmental and engineering potential as a mainstream stabilization alternative.

## CONCLUSION

This study demonstrates the potential of rice husk ash (RHA) as a sustainable and effective soil stabilizer, particularly in northern Iran, where it is abundantly available. The optimal RHA production conditions—burning at 500 °C for 12 hours followed by rapid cooling—yielded the highest pozzolanic activity, whereas gradual cooling reduced its effectiveness. The unconfined compressive strength (UCS) tests confirmed that a 15% RHA-cement mixture (equal proportions) significantly improved the strength of sandy clay soil by over 2.7 MPa after 28 days of curing. These results highlight RHA ability to enhance soil stabilization while reducing reliance on conventional cement, offering both economic and environmental advantages by repurposing agricultural waste. The findings support the adoption of RHA-based stabilization in the Caspian region-North Iran and similar areas, promoting sustainable geotechnical practices. Further research could explore long-term durability and field-scale applications to validate these laboratory findings.

## REFERENCES

Alrubaye, AJ, Hasan, M, & Fattah, MY 2016, Engineering properties of clayey soil stabilized with lime. *ARPN Journal of Engineering and Applied Sciences*, 11: 2434-2441.

Anwar, M, Miyagawa, T, & Gaweesh, M 2000, Using rice husk ash as a cement replacement material in concrete. In: Waste management series (Vol. 1, pp. 671-684). Elsevier.

Bhattacharja, SANKAR, Bhatty, JI & Todres, HA 2003, Stabilization of clay soils by Portland cement or lime–a critical review of literature. *PCA R&D Serial*, 60: 124-133.

Clough, GW, Sitar, N, Bachus, RC & Rad, NS 1981, Cemented sands under static loading. *Journal of the Geotechnical Engineering Division*, 107: 799-817.

Della, VP, Kühn, I, & Hotza, D 2002, Rice husk ash as an alternate source for active silica production. *Materials Letters*, 57: 818-821.

El Sideek, MAB 2021, Effect of silica fume on the shear strength of cohesionless soil. *Technology (IJCIET)*, 12: 1-16.

Feng, Q, Yamamichi, H, Shoya, M, & Sugita, S 2004, Study on the pozzolanic properties of rice husk ash by hydrochloric acid pretreatment. *Cement and Concrete Research*, 34: 521-526.

Geiman, C M 2005, Stabilization of soft clay subgrades in Virginia phase I laboratory study (Doctoral Dissertation, Virginia Tech).

Ghorbani, A, & Salimzadehshooiili, M 2019, Dynamic characterization of sand stabilized with cement and RHA and reinforced with polypropylene fiber. *Journal of Materials in Civil Engineering*, 31: 04019095.

Herzog, A & Mitchell, JK 1963, Reactions accompanying stabilization of clay with cement. *Highway Research Record*, (36).

Received:
Article type: Research

Hunter, D 1988, Lime-induced heave in sulfate-bearing clay soils. *Journal of Geotechnical Engineering*, 114: 150-167.

Ingles, OG, & Metcalf, J B 1972, Soil stabilization principles and practice (Vol. 11, No. Textbook).

Ismail, MA, Joer, HA, Sim, WH, & Randolph, MF 2002, Effect of cement type on shear behavior of cemented calcareous soil. *Journal of geotechnical and geoenvironmental engineering*, 128: 520-529.

Little, DN 1987, Soil stabilization for roadways and airfields. Engineering & Services Laboratory, Air Force Engineering & Services Center.

Mallela, J, Quintus, HV, & Smith, K 2004, Consideration of lime-stabilized layers in mechanistic-empirical pavement design. *The National Lime Association*, 200: 1-40.

Milad, A, Taib, A M, Ahmeda, A G, Solla, M, & Yusoff, N I M 2020, A review of the use of reclaimed asphalt pavement for road paving applications. *Jurnal Teknologi* (*Sciences & Engineering*), 82(3).

Nair, DG, Fraaij, A, Klaassen, AA, & Kentgens, AP 2008, A structural investigation relating to the pozzolanic activity of rice husk ashes. *Cement and Concrete Research*, 38: 861-869.

Ramakrishna, A N, & Pradeepkumar, A V 2006, Stabilization of black cotton soil using rice husk ash and cement. In: National Conference on Civil Engineering Meeting the Challenges of Tomorrow, GND Engineering College, Ludhiana (pp. 215-220).

Salas, A, Delvasto, S, de Gutierrez, R M, & Lange, D 2009, Comparison of two processes for treating rice husk ash for use in high performance concrete. *Cement and Concrete Research*, 39: 773-778.

Salimzadehshooiili, M 2023, Investigation of the effect of frequency on shear strength and damping of pure sand and sand stabilised with rice husk ash using cyclic triaxial tests. *Advances in Civil and Architectural Engineering*, 14(26): 25-39.

Sata, V, Jaturapitakkul, C, & Kiattikomol, K 2007, Influence of pozzolan from various by-product materials on mechanical properties of high-strength concrete. *Construction and Building Materials*, 21: 1589-1598.

Sezer, A, İnan, G, Yılmaz, H R, & Ramyar, K 2006, Utilization of a very high lime fly ash for improvement of Izmir clay. *Building and Environment*, 41: 150-155.

Sherwood, P T 1962, Effect of sulfates on cement-and lime-stabilized soils. *Highway Research Board Bulletin*, 353.

Smith, RG & Kamwanja, GA 1986, The use of rice husk for making a cementitious material. In: Proceeding of Joint Symposium on the Use of Vegetable Plants and Their Fibers as Building Material, Baghdad.

Tashima, MM, Silva, CAR, Akasaki, JL & Barbosa, MB 2004, The possibility of adding the rice husk ash (RHA) to the concrete. In *the Proceedings of the 2004 International RILEM Conference on the Use of Recycled Materials in Building and Structures* (pp. 778-786).

Zhang, M H, Lastra, R, & Malhotra, V M 1996, Rice-husk ash paste and concrete: some aspects of hydration and the microstructure of the interfacial zone between the aggregate and paste. *Cement and Concrete Research*, 26: 963-977.

Zivari, A, Siavoshnia, M, & Rezaei, H 2023, Effect of lime-rice husk ash on geotechnical properties of loess soil in Golestan province, Iran. *International Journal of Geo-Engineering*, 14: 20.

Caspian J. Environ. Sci.
DOI:

Received:
Article type: Research