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An Experimental Study on the Engineering Behavior and Performance of Cement-Stabilized Pond Ash–Rice Husk Ash–Clay Mixture for Highway Construction

Avinash Singh[1], Ravi Kumar[2]

[1]PG Students, Department of Civil Engineering, Suyash Institute of Information Technology, Hakkabad Gorakhpur, Uttar Pradesh 273016

[2]Asst. Prof., Department of Civil Engineering, Suyash Institute of Information Technology, Hakkabad Gorakhpur, Uttar Pradesh 273016

[1]aviisingh37@gmail.com

ABSTRACT: The present study investigates the engineering behavior and performance of cement-stabilized pond ash–rice husk ash–clay mixtures for highway construction applications. Clay soils are characterized by high plasticity, low strength, and significant volume change behavior, which adversely affect pavement performance. To overcome these limitations, stabilization using cement in combination with industrial and agricultural waste materials such as pond ash and rice husk ash has been explored. Laboratory investigations were conducted using varying proportions of cement (3–10%), pond ash (10–30%), and rice husk ash (5–20%). The engineering properties of the stabilized soil were evaluated through compaction, strength, plasticity, durability, and permeability tests. The results indicate that the Optimum Moisture Content increased by approximately 43%, while Maximum Dry Density decreased by about 17%. The strength characteristics improved significantly, with California Bearing Ratio increasing by approximately 248% and Unconfined Compressive Strength by about 200% at the optimum mix proportion. The Plasticity Index reduced from 24% to 6%, indicating improved soil consistency and reduced moisture sensitivity. The stabilized soil exhibited enhanced durability with strength retention up to 95% under wet–dry cycles and a significant reduction in permeability. The study concludes that the combined use of cement, pond ash, and rice husk ash provides an effective, sustainable, and cost-efficient solution for improving clay soil for highway subgrade applications.

KEYWORDS: Soil stabilization; Pond ash; Rice husk ash; Cement; CBR; UCS; Subgrade; Sustainable materials

1. INTRODUCTION

Clayey soils are commonly encountered in geotechnical and highway engineering projects and are often associated with unfavorable engineering properties. These soils typically exhibit high plasticity, low shear strength, and significant volume changes with variations in moisture content. Such characteristics lead to issues such as excessive settlement, cracking, and reduced pavement life, making untreated clay unsuitable for direct use as a subgrade material [1], [2]. To address these challenges, soil stabilization has been widely adopted as an effective technique to improve the engineering performance of problematic soils. Among various stabilizing agents, cement is extensively used due to its ability to enhance strength and durability through hydration reactions. These reactions produce cementitious compounds such as calcium silicate hydrate (C–S–H), which improve inter-particle bonding and reduce void spaces within the soil matrix [3], [4]. In

recent years, increasing emphasis on sustainable construction has encouraged the use of industrial and agricultural waste materials as supplementary stabilizing agents. Pond ash, a by-product of coal-based thermal power plants, is abundantly available and has demonstrated potential in improving soil properties while reducing environmental disposal concerns [5], [6]. Similarly, rice husk ash (RHA), an agricultural waste rich in reactive silica, exhibits strong pozzolanic properties and has been successfully utilized in stabilization systems [7], [8].

Previous studies have shown that the incorporation of such materials can significantly enhance soil strength, reduce plasticity, and improve durability [9]–[11]. The pozzolanic interaction between silica and calcium hydroxide generated during cement hydration results in the formation of additional cementitious compounds, which further strengthen the soil structure and decrease permeability [12]. Moreover, the use of these materials supports environmentally sustainable construction practices by reducing reliance on conventional resources and promoting waste utilization [13]. Earlier research has also demonstrated that stabilization techniques can effectively reduce swelling behavior, decrease plasticity, and improve load-bearing capacity of clay soils under varying environmental conditions [14]–[16]. However, most existing studies have focused on individual stabilizing agents, and limited research has been carried out on the combined use of cement, pond ash, and rice husk ash for soil stabilization [17]. Therefore, the present study aims to experimentally investigate the engineering behavior and performance of cement-stabilized pond ash–rice husk ash–clay mixtures for highway construction applications. In this research, systematic laboratory investigations were carried out to evaluate the compaction characteristics in terms of Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), along with strength properties using California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) tests. The study further examines the influence of curing period on strength development, as well as the modification in plasticity behavior through Atterberg limits. In addition, durability performance was assessed under wet–dry cyclic conditions to simulate environmental effects, and permeability characteristics were analyzed to understand water flow behavior through the stabilized soil. A comparative evaluation of compaction and strength parameters was also performed to identify the optimum mix proportion. The overall objective is to assess the suitability of the stabilized soil as a sustainable, durable, and efficient subgrade material for highway construction [18].

Therefore, the present study aims to experimentally investigate the engineering behavior and performance of cement-stabilized pond ash–rice husk ash–clay mixtures for highway construction applications. In this research, systematic laboratory investigations were carried out to evaluate the compaction characteristics in terms of Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), along with strength properties using California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) tests. The study further examines the influence of curing period on strength development, as well as the modification in plasticity behavior through Atterberg limits. In addition, durability performance was assessed under wet–dry cyclic conditions to simulate environmental effects, and permeability characteristics were analyzed to understand water flow behavior through the stabilized soil. A comparative evaluation of compaction and strength parameters was also performed to identify the optimum mix proportion. The overall objective is to assess the suitability of the stabilized soil as a sustainable, durable, and efficient subgrade material for highway construction.

2. MATERIALS AND METHODOLOGY:

2.1. MATERIALS

The materials used in this study include clay soil, Ordinary Portland Cement (OPC), pond ash, rice husk ash (RHA), and water. Each material was selected based on its role in improving the engineering performance of soil and its contribution to sustainable construction practices.The clay soil used in the study represents a typical subgrade material exhibiting moderate plasticity and expansive behavior. The soil showed a liquid limit of 43%, plastic limit of 19%, and plasticity index of 24%, indicating its susceptibility to moisture-induced volume changes. The specific gravity of the soil was found to be 2.7. Due to its low strength and high plasticity, untreated clay soil is not suitable for direct use in pavement subgrade and requires stabilization. Ordinary Portland Cement (OPC 43 grade) was used as the primary stabilizing agent. Cement improves soil properties through hydration reactions, which produce cementitious compounds such as calcium silicate hydrate (C–S–H). These compounds enhance inter-particle bonding, increase strength, and reduce compressibility of the soil. Pond ash, a by-product of coal-based thermal power plants, was used as a supplementary stabilizing material. It is a non-plastic material with relatively low specific gravity and consists mainly of silica and alumina. The addition of pond ash improves particle packing, reduces void spaces, and contributes to better compaction

behavior while also promoting waste utilization. Rice husk ash (RHA), obtained from controlled combustion of rice husk, is rich in amorphous silica and exhibits strong pozzolanic properties. When combined with cement, RHA reacts with calcium hydroxide to form additional cementitious compounds, thereby enhancing strength and durability. It also helps in reducing plasticity and improving the overall stability of the soil. Potable water was used for mixing and sample preparation. Water plays a crucial role in activating hydration and pozzolanic reactions and ensures uniform mixing of all components.

2.1.1 CEMENT

Cement is an important part of construction project with Portland cement being one of the most widely used types that are often used in the construction of concrete and mortar. The basic base of numerous structures including buildings, bridges, and roads is concrete, which is a composite material that includes aggregates, sand, water and cement. The hydration process of OPC 43 aids the hardening process and also enhances strength when the material comes in contact with water.

Table 3.1 Physical Properties of Cement

Fineness	Specific gravity, G	Standard consistency (%)	Initial setting time (min)	Final setting time (min)	Soundness (mm)
3	3.07	37	30	600	3

2.1.2 FINE AGGREGATE (SAND

Fine aggregates are mostly composed of natural sand particles which are obtained through mining processes. These particles are 1/4th inch or less and these particles consist of natural sand, and crushed sand particles. They are characterized by their particle sizes, which are less than 4.75 mm. The fine aggregates play a crucial role in the formulation of concrete since they play a significant role in determining the hardened properties of the material. The measurement of the particle size structure is done with the aid of sieve analysis, in which the aggregates that pass through the sieve with a diameter of 4.75 mm would be considered fit to be used in the production of concrete.

Table 3.2 Physical Properties of Sand

Fineness	Specific gravity, G	Water Absorption (%)	Particle Size (mm)	Bulk Density (kg/m^3)
2.2 - 3.2	2.5 - 2.9	0.5 -2	0.075 - 4.75	1400 - 1600

2.1.3 POND ASH (PA)

Pond ash is the by-product that is produced by coal-fired thermal power plants. The material has a rough texture and contains a lot of silica, alumina and other substances. The use of pond ash in the construction industry can help alleviate land pollution and conserve natural resources like sand and soil. It is also a cheaper alternative to the traditional building materials.

Table 3.2 Properties of Pond Ash

Silt + clay (micro m)	Fine sand (micro m)	Medium sand (mm)	Coarse sand (mm)	Colour	Shape	Specific gravity, G
41.6	44.6	12.2	1.6	Light Gray	Rounded/subrounded	2.1

2.1.4 RICE HUSK ASH (RHA)

The development of rice husk ash (RHA) is developed by the controlled burning of rice husks. This material has a high concentration of silica, about 80 90 percent and portrays the properties of a pozzolanic compound, which makes it useful in cement, concrete and refractory material applications. RHA is used to enhance strengths and durability of construction materials, and also finds application in steel, rubber and ceramic industries. Rice husk and its ash can find uses in construction industry, energy and agricultural industries, which can lead to a sustainable environment and decrease industrial waste.

Table 3.4 Properties of Rice Husk Ash

Calcium oxide (CaO)	Silica (SiO2)	Alumina (Al203)	Iron oxide (Fe2O3)	Magnesia (MgO)	Sodium oxide (Na2O)	Potassium oxide (K2O)	Specific gravity
2.4	91.3	1.4	0.6	2.1	0.3	1.9	1.98

2.1.5 CLAY

We work with the metakaolin clay in this study which is a highly reactive pozzolanic material that is produced by the calcification of the kaolin clay. This material is usually employed to substitute cement or fine aggregate in concrete, increasing the strength, durability, and resistance to chemical degradation. It helps to reduce the quantity of cement required and creates a smooth and homogenous mixture as well as reduces the CO2 emissions. Furthermore, it helps to reduce efflorescence.

2.1.6 COARSE AGGREGATE

Course aggregate usually composes 65 -70 percent of the total volume in concrete mixtures. It's essential to recognize that smaller aggregates can enhance the strength of concrete. Further, the greater the strength of aggregates, the greater the overall strength of the concrete, which explains why aggregate sizes of between 20 mm up to 4.75 mm are commonly preferred in concrete mixes.

2.2 EXPERIMENTAL METHODOLOGY

2.2.1 Mix Proportioning

The stabilization of clay soil in the present study was conducted by addition of cement, pond ash and rice husk ash in different proportions. The mix proportions were determined on the basis of literature review and preliminary tests to determine the individual and combined effects of stabilizing agents on the soil behavior.

The percentage of stabilizing materials was taken with respect to the dry weight of soil. The variety of proportions estimated in the research is as follows:

a. Cement: 3% to 10%

b. Pond Ash: 10% to 30%

c. Rice Husk Ash: 5% to 20%

A set of trial mixes was prepared to determine the optimum combination. The mix design adopted for experimental investigation is presented in Table 3.1.

Table 3.7 Mix Proportions Used in the Study

Mix ID	Soil (%)	Cement (%)	Pond Ash (%)	RHA (%)
M0	100	0	0	0
M1	100	3	10	5
M2	100	5	15	10
M3	100	7	20	15

2.2.2 Preparation of Stabilized Mixtures

The stabilized soil mixtures were prepared in an organized way in order to achieve uniformity and consistency. The collected soil sample was air-dried and pulverized then sieved through a 4.75 mm sieve to remove coarse particles. The necessary amounts of soil, pond ash and rice husk ash were weighed to the accuracy based on the chosen mix proportions. First, the soil and additives were dried and mixed together to gain a uniform distribution of the particles. The mixture was then mixed with cement and then thoroughly blended. Water was added slowly to the dry mixture in order to get the moisture content within closer limits of the Optimum Moisture Content (OMC). The whole mixture was mixed properly until the homogeneous mass was achieved. The precautions were taken not to segregate and create lumps.

2.2.3 Specimen Preparation

The prepared mixtures were used to prepare test specimens for different laboratory tests. The samples were compacted as per standard procedures in order to attain homogeneity. In compaction tests, soil samples were compacted in standard Proctor molds in three layers with known compaction energy. The samples of the CBR tests were compacted in CBR molds and kept under controlled conditions. UCS tests were done on cylindrical specimens with standard dimensions. The preparation of all specimens was done soon after mixing to reduce the loss of moisture.

2.2.4 Compaction Test Procedure

According to the Standard Proctor compaction test, the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of the soil and stabilized mixtures were determined. The test implies compressing the soil in layers with the help of a standard hammer. Different moisture contents were calculated to determine the OMC, and MDD, the compaction curve was plotted.

2.2.5 California Bearing Ratio (CBR) Test

CBR test was done in accordance to the requirements given in ISO: 2720 (Part 16) to assess the load bearing capacity of the stabilized soil. The test material was put into the CBR mold and pressed. The experiment was conducted on a soaked and unsoaked environment. The specimen was placed in water and left to stand in the

water within the time range of 96 hours before the test. The penetration test was carried out at a rate of 1.25 mm per minute and the values of the load were recorded. The standard formula was used to determine the CBR value:

$$CBR = \frac{\text{Test Load}}{\text{Standard Load}} \times 100$$

3. Results and Discussion:

The compaction characteristics of soil play a vital role in determining its suitability for use as a subgrade material in highway construction, as they directly influence strength, stability, and deformation under applied loads. These characteristics are mainly controlled by factors such as particle size distribution, specific gravity, moisture content, and surface properties of the soil. In the present investigation, the soil was stabilized using cement (3–10%), pond ash (10–30%), and rice husk ash (5–20%). The inclusion of these stabilizing materials resulted in noticeable changes in the compaction behavior of the soil. The detailed compaction results are presented in Table 4.1, which indicate a systematic variation in both Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) with increasing stabilizer content. It can be observed from Table 4.1 that the OMC increases from 18.3% for untreated soil (M0) to 26.2% for the stabilized mix (M4), corresponding to an increase of approximately 43%. In contrast, the MDD decreases from 18.6 kN/m³ to 15.5 kN/m³, showing a reduction of about 17%. This trend clearly reflects the influence of the added materials on the moisture–density relationship. The graphical trends further validate these observations.

Table 4.1: Compaction Results for Stabilized Soil

Mix ID	Cement (%)	Pond Ash (%)	RHA (%)	OMC (%)	MDD (kN/m³)
M0	0	0	0	18.3	18.6
M1	3	10	5	20.5	17.8
M2	5	15	10	22.8	17.0
M3	7	20	15	24.5	16.2
M4	10	30	20	26.2	15.5

As illustrated in Fig. 4.1, the OMC shows a consistent increasing trend with the increase in stabilizer content, which can be attributed to the higher water absorption capacity of pond ash and rice husk ash. Similarly, Fig. 4.2 demonstrates a decreasing trend in MDD, mainly due to the replacement of relatively heavier soil particles with lighter and more porous ash materials. The increase in OMC is primarily due to the porous structure and high surface area of pond ash and rice husk ash, which require additional moisture for proper compaction. On the other hand, the reduction in MDD can be explained by the lower specific gravity of these materials, which decreases the overall bulk density of the soil mixture. These findings are consistent with established principles of soil compaction, where the introduction of lightweight and porous materials increases moisture requirement and reduces dry density.

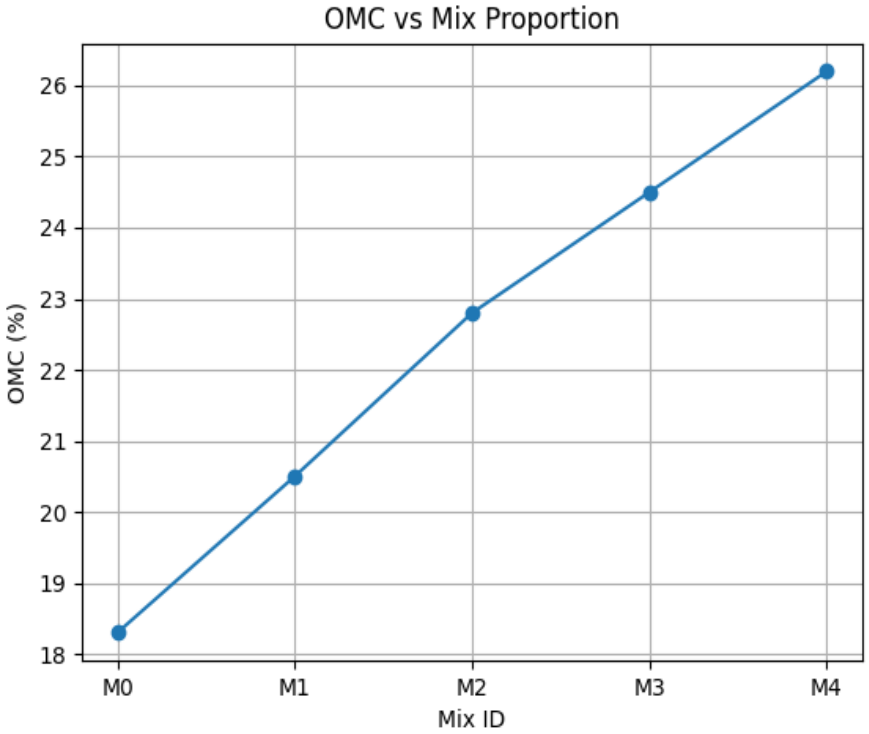

Fig. 4.1: The graph shows a continuous increase in Optimum Moisture Content (OMC) from M0 to M4 due to the higher water absorption capacity of stabilizing materials such as pond ash and rice husk ash.

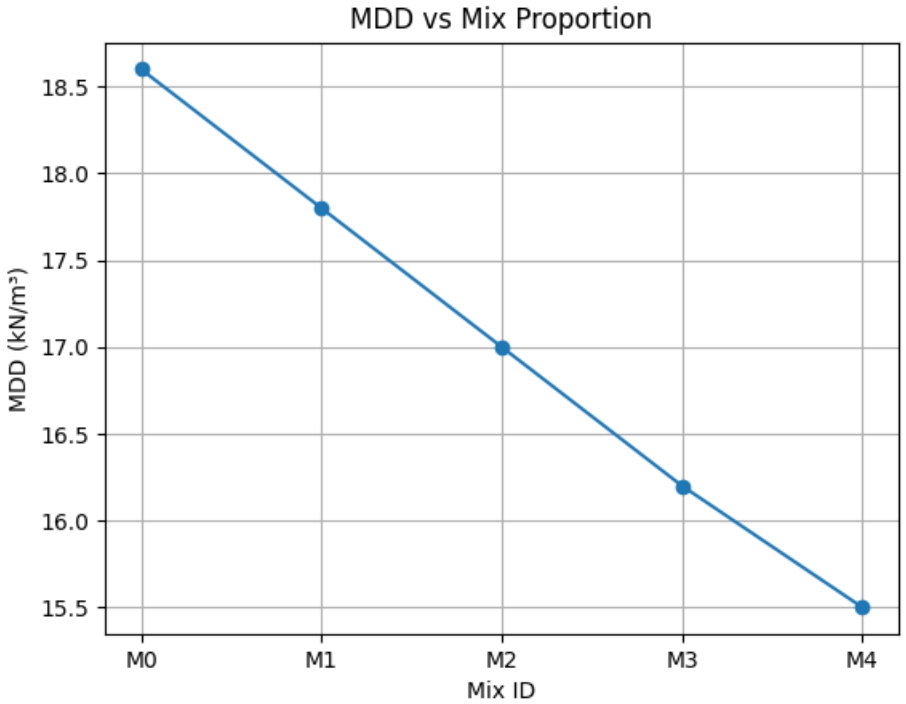

Fig. 4.2: The graph shows a decreasing trend of Maximum Dry Density (MDD) with increasing stabilizer content due to the replacement of heavier soil particles with lightweight ash materials.

The load-bearing capacity of soil is an important parameter in assessing its suitability for subgrade applications, as it reflects the ability of soil to withstand traffic loads without excessive deformation. The California Bearing Ratio (CBR) test is widely used to evaluate the strength and stiffness of soil under penetration loading conditions. In the present study, the soil was stabilized using cement (3–10%), pond ash (10–30%), and rice husk ash (5–20%). The addition of these materials significantly improved the strength characteristics of the soil. Cement hydration produces calcium hydroxide, which reacts with silica present in rice husk ash to form calcium silicate hydrate (C–S–H), thereby enhancing inter-particle bonding. Pond ash further improves particle gradation and packing, resulting in increased load-bearing capacity. The CBR results are presented in Table 4.2, which clearly indicate a substantial

increase in strength with the addition of stabilizers. The CBR value increases from 3.5% (M0) to 12.2% (M3), representing an improvement of approximately 248%. However, a slight reduction to 10.8% (M4) is observed beyond the optimum mix due to excess ash content.

Table 4.2 CBR Results for Stabilized Soil

Mix ID	Cement (%)	Pond Ash (%)	RHA (%)	CBR (%)
M0	0	0	0	3.5
M1	3	10	5	6.8
M2	5	15	10	9.5
M3	7	20	15	12.2

The graphical representation further confirms these trends. As shown in **Fig. 4.3**, the CBR value increases steadily from M0 to M3 due to improved bonding and strength resulting from cement hydration and pozzolanic reactions. Beyond the optimum mix, **Fig. 4.3** also reflects a slight decline in CBR at M4, which can be attributed to excess ash content reducing cohesion and bonding efficiency

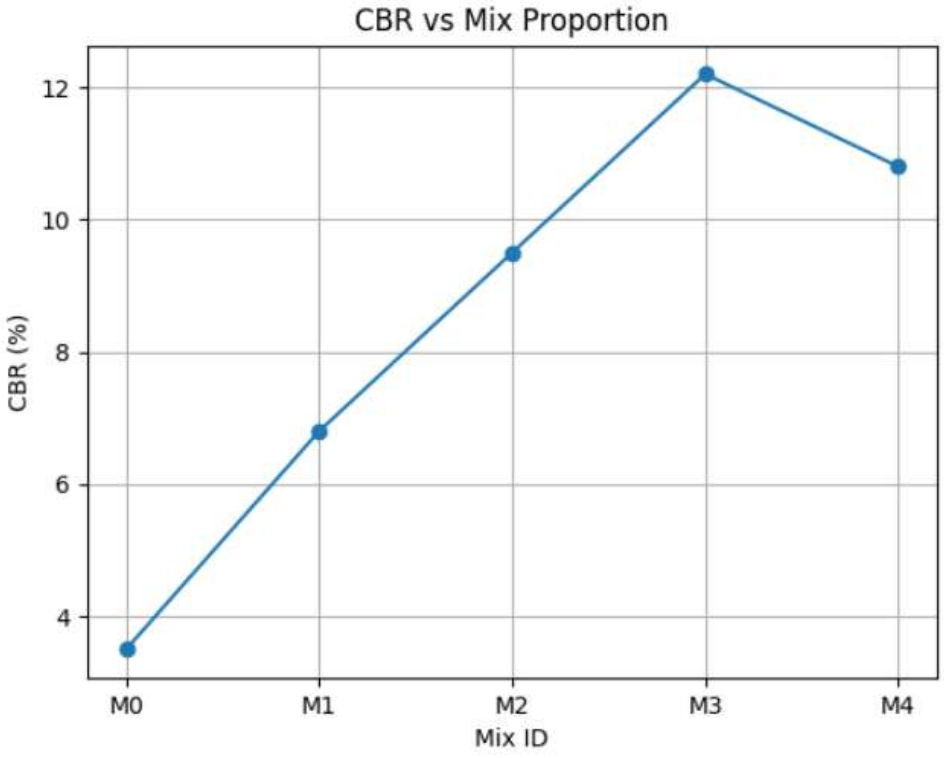

Fig. 4.3 The graph shows a steady increase in CBR from M0 to M3, reaching a maximum at M3 due to improved strength from stabilization.

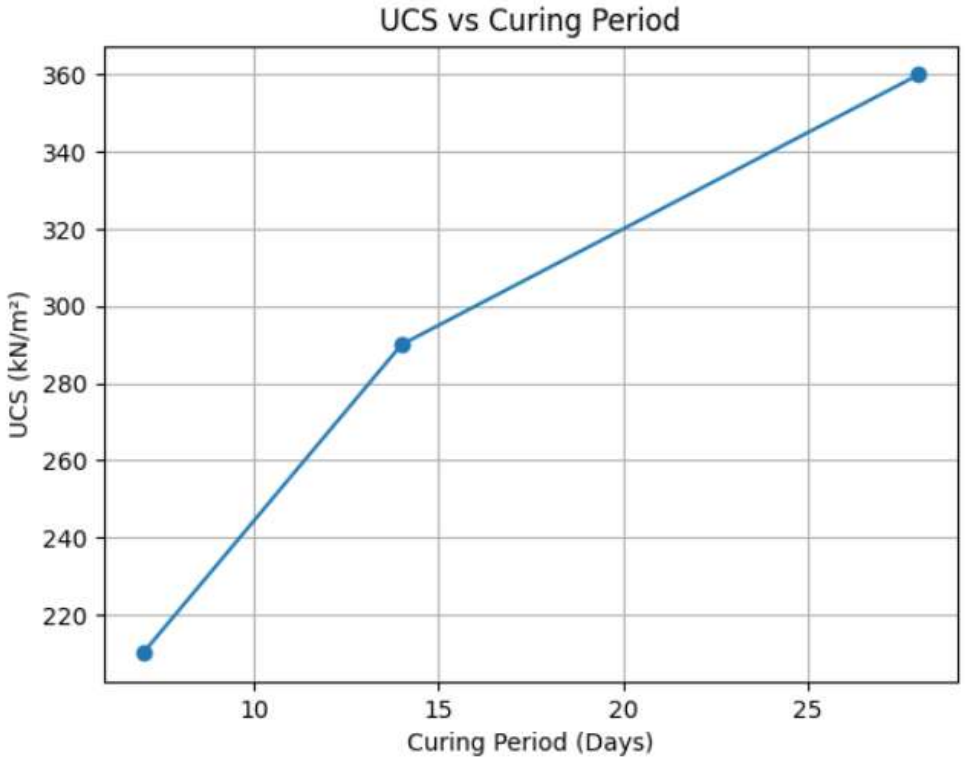

Fig. 4.4 The graph shows a steady increase in UCS from 7 to 28 days due to continued hydration and improved bonding

The strength behavior of soil is a key parameter for evaluating its suitability in subgrade applications, as it governs load-carrying capacity and resistance to deformation. The Unconfined Compressive Strength (UCS) test is widely used to assess the compressive strength of cohesive soils and the effectiveness of stabilization. In the present study, the soil was stabilized using cement (3–10%), pond ash (10–30%), and rice husk ash (5–20%). The addition of these materials significantly enhanced the strength characteristics of the soil. Cement hydration produces calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H), which improve inter-particle bonding. In addition, the silica present in rice husk ash reacts with calcium hydroxide to form additional cementitious compounds through pozzolanic reactions, further contributing to strength development. Pond ash improves particle packing and reduces voids, thereby increasing overall strength. The UCS results are presented in Table 4.3, which clearly show a substantial increase in strength with the addition of stabilizers. The UCS value increases from 120 kN/m² (M0) to 360 kN/m² (M3), indicating an improvement of approximately 200%. A slight reduction to 330 kN/m² (M4) is observed beyond the optimum mix due to excess ash content.

Table 4.3 UCS Results for Stabilized Soil

Mix ID	Cement (%)	Pond Ash (%)	RHA (%)	UCS (kN/m²)
M0	0	0	0	120
M1	3	10	5	210
M2	5	15	10	290
M3	7	20	15	360

The graphical representation further supports these observations. As shown in **Fig. 4.5**, the UCS increases steadily from M0 to M3 due to improved bonding and formation of cementitious compounds. Beyond the optimum mix, the graph shows a slight decline in UCS at M4, which is attributed to excess ash content reducing effective bonding.

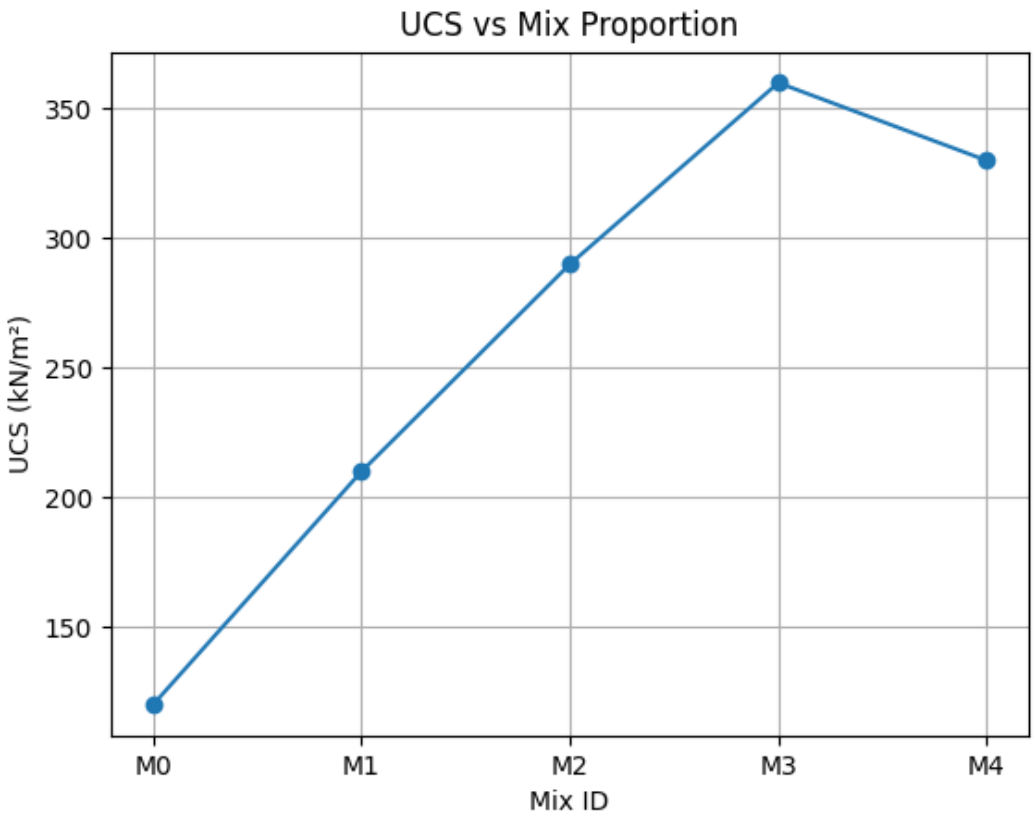

Fig. 4.5: Variation of UCS with Mix Proportion of graph shows UCS increasing from M0 to M3, reaching a peak at M3, and then slightly decreasing at higher stabilizer content.

The engineering behavior of stabilized soil is a key factor in determining its suitability for subgrade applications, as it governs strength, stability, and deformation under loading conditions. Both compaction characteristics, such as Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), and strength parameters, including California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS), play an important role in evaluating soil performance. In the present study, the soil was stabilized using cement (3–10%), pond ash (10–30%), and rice husk ash (5–20%). The addition of these stabilizing agents significantly influenced both compaction and strength behavior. Pond ash and rice husk ash, being lightweight and porous, increase water demand during compaction, while cement and pozzolanic reactions contribute to the formation of cementitious bonds that enhance strength. The comparative trends of engineering properties are illustrated in Fig. 4.10, which clearly shows the variation of OMC, CBR, and UCS with mix proportion. It is observed that OMC increases continuously from 18.3% (M0) to 26.2% (M4), indicating an increase of approximately 43% due to higher water absorption of stabilizing materials. In contrast, strength parameters show a significant improvement up to the optimum mix. The CBR increases from 3.5% to 12.2%, and UCS increases from 120 kN/m² to 360 kN/m², indicating substantial enhancement in strength up to Mix M3. Beyond this optimum level, a slight decrease in strength is observed due to excess ash content.

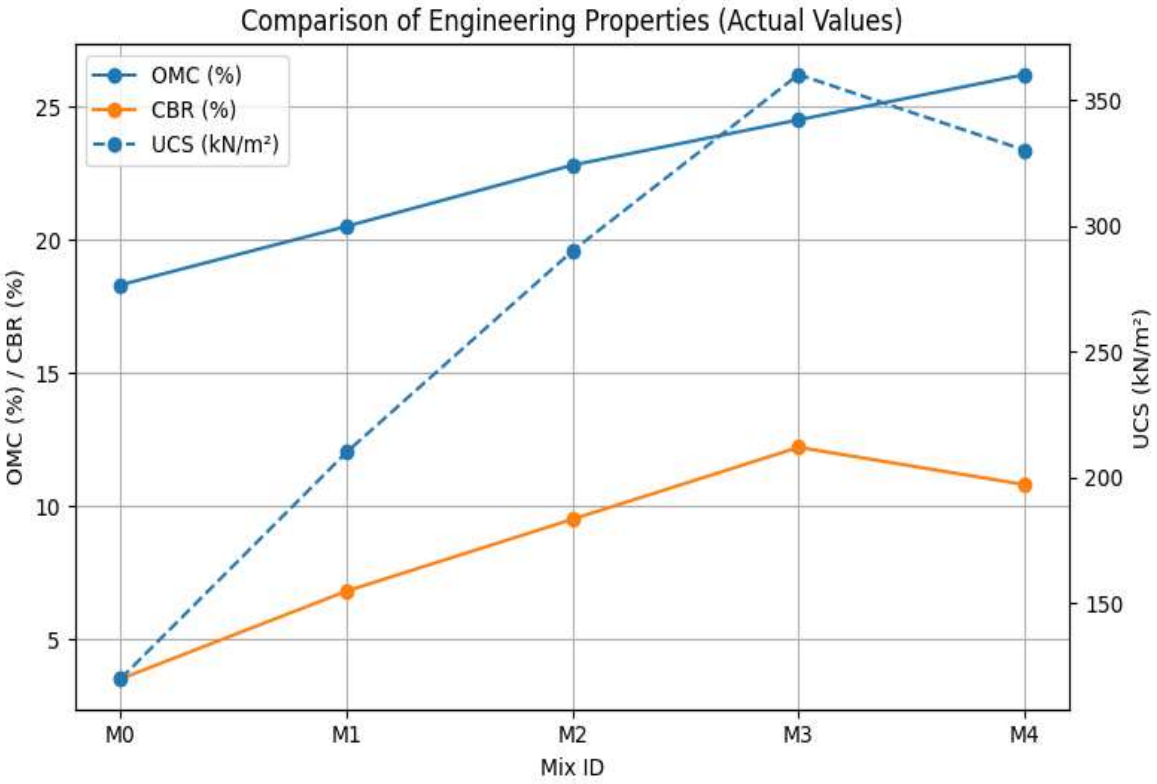

Fig. 4.6: Comparison of Engineering Properties of Stabilized Soil

As shown in Fig. 4.6, while OMC exhibits a continuous increasing trend, both CBR and UCS increase up to the optimum mix (M3) and then show a marginal decline. The increase in OMC is attributed to the porous structure and high surface area of pond ash and rice husk ash. On the other hand, the improvement in strength is due to cement hydration and pozzolanic reactions, which form cementitious compounds that enhance inter-particle bonding and reduce voids. These results are consistent with established soil stabilization principles, which state that the inclusion of cementitious and non-plastic materials improves strength and reduces plasticity up to an optimum level, while increasing moisture requirement.

4. Conclusions:

The Present study explores the engineering behavior and performance of cement-stabilized pond ash-rice husk ash-clay mixtures to their use in highway subgrade construction. The experimental data prove that the stabilization process has a considerable impact on the compaction, strength, plasticity, durability, and permeability of the soil. Improved inter-particle bonding due to hydration and pozzolanic reactions as a result of the addition of cement, pond ash and rice husk ash, and hence results in increased strength and decreased water sensitivity. The research also finds an optimal mix proportion at which the performance is maximum. Generally, stabilized soil has better engineering characteristics than untreated soil, and this attribute is the reason why stabilized soil is a good subgrade material that is both sustainable and durable to be used in construction of highways.

1. The Optimum Moisture Content (OMC) increased 18.3 to 26.2 (or approximately 43 to 25) and Maximum Dry Density (MDD) decreased 18.6 to 15.5 (or approximately 43 to 25) indicating a change in moisture-density relationship because of the addition of lightweight and porous stabilizing materials.

2. The California Bearing Ratio (CBR) not only improved by 3.5% to 12.2% (~248% improvement), but also reflected an enormous increase in the load-bearing capacity and applicability to subgrade applications.

3. Unconfined Compressive Strength (UCS) was improved (120 kN/m 2 to 360 kN/m 2 (~200 percent improvement)) due to the effectiveness of cement hydration and pozzolanic reactions in enhancing soil strength.

4. The stabilized soil had the best performance at the optimal mix proportion (M3), and it was found that the strength would decrease slightly with increase in mix proportion.

5. Stabilized soil strength significantly increased with curing period (7 to 28 days), indicating time-dependence of strengthening of stabilized soil.

6. Plasticity Index (PI) decreased significantly by 24% to 6% which implied that the highly plastic clay was replaced by low plastic material, thus increasing workability and minimizing exposure to swelling and shrinkage.

7. Liquid Limit and Plastic Limit increased and stabilized, and this is indicative of a better consistency and reduced water sensitivity of the soil.

8. The durability test revealed that stabilized soil exhibited an estimated resistance of about 94-95 percent strength to wet-dry cyclic conditions as compared to approximately 85 percent of untreated soil, which proved to be more resistant to environmental factors.

9. The coefficient of permeability decreased to 1.2 x 10 -4 cm/s, which is much better than 1.2 x 10 -4 cm/s, which would suggest the presence of a problem.

10. Cementitious products improve the packing of particles and filling of pores, thus leading to the reduction in permeability.

11. Introduction of pond ash, rice husk ash will help in the utilization of waste materials sustainably so that the country will not rely on natural resources as it will also promote the use of environmentally friendly construction materials.

12. The integrated stabilization strategy improves mechanical and hydraulic characteristics of the soil, which makes it more stable, durable, and applicable in terms of long-term infrastructure development.

13. Correlation analysis between compaction and strength parameters demonstrates that greater moisture demand (OMC) is correlated with better strength properties because of increased chemical reactions within the soil matrix.

14. The research shows that utilizing waste materials in industries and agricultural sectors can be successfully used in order to enhance the performance of soils, and also help in overcoming environmental issues associated with waste disposal.

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