

Stabilization of Peat Soil Using Cement and Rice Husk Ash: Strength and Microstructural Evaluation

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Abstract: Peat soil is a highly compressible and weak geomaterial with high water content and low shear strength, making it unsuitable for the support of engineering structures without stabilization. This study investigates the effectiveness of Ordinary Portland Cement (OPC) and Rice Husk Ash (RHA) for enhancement of engineering and strength properties of peat collected from Ziro Valley, Arunachal Pradesh, India. Different percentage OPC and RHA were used to treat the peat soil and the effects of the percentage of the binder and curing periods on the compaction characteristics and Unconfined Compressive Strength (UCS) were investigated. Standard Proctor compaction and UCS tests were performed after 0, 7, 14 and 28 days curing. The results showed that the strength of peat soil significantly increased as a function of both the amount of OPC and RHA added to the soil, and the curing time. The optimum mixture of 15% OPC + 12% RHA resulted in the highest UCS value of 819 kPa, an improvement of 333% from the value of 189 kPa of the untreated peat soil. The microstructural analysis also revealed the improvement in strength, as SEM images displayed a more compact and cohesive soil matrix after stabilization, fewer pore spaces and stronger bonding between particles. XRD analysis determined the mineral phases of silica bearing minerals and other mineral phases related to RHA and stabilized soil matrix. The main findings of this research are that the use of OPC and RHA concurrently can significantly improve the strength and microstructural properties of peat soil, indicating its potential as a stabilization of weak organic soils, and the use of RHA as an agricultural by-product.

Keywords: Peat soil, cement, rice husk ash, OMC & MDD.

Introduction

The demand for soils, even those with subpar geotechnical qualities, is increasing due to urbanization, a shortage of land, and population growth. Peat is defined as a highly organic soil that contains a substantial amount of decomposing plant or animal matter, which accumulates over time in an anaerobic environment. [1]. Significant strength growth requires the production of calcium silicate hydrates (CSH), calcium aluminates (CAH), and calcium aluminum silicate hydrates (CASH), which are produced when cement is hydrated in soil-cement treatment [2]. Soils rich in organic matter exhibited a much slower strength gain compared to those with lower organic content. Peatlands cover approximately 4.23 million km² globally [3], whereas in India, peat deposits are distributed across several regions, particularly the southwestern, eastern, and northern parts of the country. However, comprehensive surveys and systematic characterization of Indian peatlands remain limited, with relatively few regions having been investigated in detail.

The recent studies have further shown how challenging it is to enhance the peat due to its high organic matter, low density, high compressibility, and poor load-carrying capacity. Paul and Hussain [4] have studied the cement stabilization of Indian peat, extracted from various places in northeast India, and found that the cementation process enhanced the properties of peat significantly. The research study also revealed how the organic content affects the densification and strength formation process of peat and how the cement treatment process could counteract the negative impacts of the organic matter and acidity. The microstructural study revealed the presence of various cementitious products such as C-S-H, C-A-H, C-A-S-H, and ettringite.

Worldwide, various stabilization methods have been studied for the improvement of the unsatisfactory engineering behavior of peat soils. In Malaysia, which is known for its large deposits of tropical peat soil resulting in great difficulties in infrastructure construction, cement and lime stabilizations have been extensively studied, whereas, recently, there have been more studies on the use of wastes from industries and agriculture as part-substitutes for binders. In a recent study on tropical peat soil stabilization, it was observed that cement and lime are still the most frequently studied traditional stabilizers despite their strong dependence on peat properties [25].

In Indonesia, efforts to examine other stabilization options apart from the use of normal cement stabilization have also been made. One such alternative technique is the biopolymer stabilization which has been used in recent

times to stabilize the peat soil from Palangka Raya where the introduction of biopolymer based on chitosan resulted in higher values of the shear strength of the peat soil at higher dosages and cure periods [26].

Apart from chemical stabilization of soils, deep mixing and mass stabilization methods have been used internationally to enhance the bearing capacity and deformation properties of very soft organic soils. The deep mixing technique was first developed in Japan and Sweden and has been adapted to other countries due to its ability to increase strength and decrease the compressibility of soft ground. Deep mixing entails the process of mechanically mixing in-situ soils with cementitious binders to produce stabilized soil masses or columns. The use of deep mixing is especially important for the improvement of peat soil when excavation and total replacement of the thick organic layer is not possible .

Other researchers in other countries have shown the possibility of stabilizing the peat using by-products from industries and agriculture. In Estonia, the use of oil shale ash together with pozzolanic additives for the stabilization of peat and organics soils, including its use in road embankments, has been evaluated. Recent studies on field scale showed that calcareous ash and pozzolanic additives could be used for improving the bearing capacity of peat, which at the same time underlined the significance of counteracting the retarding effect of humic substances on the cementation reactions [27]. This study shows that the choice of stabilizer depends highly on the chemical composition of the peat and composition of the binder.

Other researchers have studied blended cementitious binders instead of solely Portland cement. For instance, the research done on peat stabilization using cement, fly ash, and polypropylene fiber showed the improved UCS and CBR values while decreasing the use of Portland cement . In addition, recently, the geopolymerization process of Indian peat using RHA as binder and various activators showed a good improvement in strength of stabilized peat depending on the organic content, binder dosage, activator concentration, and curing period [28].

There has not been any research on peat in Arunachal Pradesh yet, but Abhinaba Paul and Monowar Hussain's study concentrated on peat from three northeastern Indian states: Assam, Tripura, and Manipur. Peat can be treated in several ways, but the most effective ones include chemical binders like fly ash, cement, and lime [4]. For example cement is known to enhance the geotechnical characteristics of soil and is commonly applied as a binding agent in ground improvement practices [5].

While cement has proven to be efficient, its excessive application in peat stabilization is known to be connected with relatively high binder demands and environmental problems related to the production of cement. This has resulted in an increased interest of recent studies in using the waste products as partial replacement for cement. In particular, Paul and Hussain [7] examined the possibility of applying ground-granulated blast furnace slag (GGBS) and rice husk ash (RHA) as partial substitutes for cement in Indian peat. It was shown that these waste products have the ability to contribute to improving the performance properties of peat without excessive usage of conventional cement. Different peat types characterized by varying levels of organic matter content were tested in the course of the study, which were taken from three northeastern states of India.

When rice husks are burned to produce electricity, a byproduct known as rice husk ash (RHA) is created. It is regarded as an agricultural and industrial waste. Disposing of rice husks is difficult due to their rough texture, woody character, high silica content, and abrasiveness [6]. According to a study, burning rice husk instead of coal to generate one megajoule of energy has a 34-fold lower impact on global warming [7]. India ranks second only to China in rice husk production, generating roughly 20 million tons each year [8]. Large quantities of RHA can pose environmental risks if not properly managed [9]. One practical and economical approach, particularly in the context of increasing environmental concerns, is to utilize rice husk as a fuel for power generation [8]. The resulting rice husk ash (RHA) is rich in amorphous silica, with silica content reported to exceed 90–95% by weight, making it a potentially valuable supplementary material for soil stabilization [10].

The suitability of the RHA for the stabilization of peat is further proved by the results of recent experimental studies. The stabilization of Batu Pahat peat with RHA proves the opportunity of modification of the engineering properties of the peat with the help of RHA [15]. In addition, as stated in the recent article in Journal of Materials in Civil Engineering, the stabilization of Indian peat with the help of RHA is another method of stabilization of peat where the waste-derived binders can act as an alternative to the cement.

Acting as the primary stabilizer, cement significantly boosts the soil's strength and load-bearing capacity. By creating a stable matrix within the soil, its strong binding and adhesive properties reduce compressibility and improve overall structural integrity [2]. Cement also helps control volumetric changes caused by moisture variations, minimizing the soil's tendency to swell or shrink. Through hydration reactions, it creates strong compounds that make the treated soil more durable over time. Beyond these mechanical advantages, cement provides a dependable foundation for construction on peat soils, which are far more challenging to work with than conventional soils.

This study addresses the challenge of stabilizing peat soil in Ziro Valley for use in construction projects. The work is driven by the absence of previous research focusing on the stabilization of peat soils in this specific region for building purposes.

2. Materials and methods

2.1 Test materials

2.1.1 Peat

The stabilization tests were conducted using soil taken from the depth of 0.5 m-1 m, representing the OH soil layer detected in the profile of the investigated soil. The profile had clearly defined layers with different engineering properties, such as OH layer overlying CI/CL layer. Since soil properties change significantly with depth, the soil used for the current stabilization tests was only taken from the OH layer.



Fig. 1a: Open pit excavation

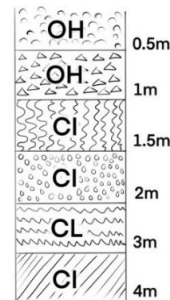


Fig. 1b: Soil profile

The soil sample was collected using the open-pit method, as shown in Fig. 1a. A pit measuring 2 m × 2 m was excavated to a depth of 4 m, followed by a detailed examination of the soil profile, as shown in Fig. 1b. The excavation was carried out in January, during which the groundwater table was observed at a depth of approximately 2 m. The peat soil was collected from the identified peat layer and transported to the laboratory for sample preparation.

For sample preparation, the collected peat soil was initially air-dried and subsequently oven-dried at 105 ± 5 °C for 24 h, following the procedures reported by Kolay et al. (2011) and Fernández-Delgado Juárez et al. (2020). The dried soil was gently ground and passed through the appropriate sieve before testing. Twigs, roots, and other visible coarse organic fragments were manually removed to obtain a relatively uniform soil sample. The same preparation procedure was followed for all specimens used in the investigation. Unless otherwise specified by the relevant testing standards, tap water was used throughout the experimental programme.

It should be noted that oven drying at elevated temperatures may alter the characteristics of highly organic soils. The process can cause the loss of volatile organic constituents and induce structural changes, such as shrinkage or collapse of the soil matrix, which may affect measured density and mechanical properties. Although oven drying is a widely adopted laboratory procedure, this potential alteration represents a limitation of the present study. Therefore, the results should be interpreted with consideration of the possible effects of thermal drying on the natural structure and composition of the peat. Alternative low-temperature drying procedures or testing under near in-situ conditions may provide a more representative assessment of the natural properties of peat.

Table 1 presents the general geotechnical properties of the untreated peat soil used in this study.

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content with silica being in an amorphous state as evident from the broad diffuse region on the XRD pattern.

2.1.2b Cement

Ordinary Portland Cement (OPC) of grade 53 was used in the study, meeting the requirements of IS:12269-1987 specified by the Bureau of Indian Standards (BIS). This grade is characterized by its high compressive strength and durability, making it appropriate for diverse construction purposes. All test specimens were carefully prepared and subjected to a standardized curing process using ordinary water. The use of BIS-compliant OPC of grade 53 ensured uniform cement quality and maintained consistency throughout the experimental program.

2.2 Methodology

2.2.1 Sample Preparation and Selection of Binder Dosages

Peat soil was taken from the Ziro valley area in Arunachal Pradesh. The peat soil was air-dried and gently disaggregated without any significant modification of the natural soil structure. Roots, twigs, or any other impurities in the soil were manually cleaned up and sieved with a 4.75 mm sieve and mixed. The Ordinary Portland Cement (OPC) of 53 grade and Rice Husk Ash (RHA) were used as a primary and secondary stabilizer, respectively.]

The dosages of the cement and RHA were chosen based on the ranges reported in some past experimental investigations on soil stabilization and then were experimented to determine the appropriate dosages of the Ziro valley peat soil. Different binder contents of 5%, 10%, and 15% by the dry weight of soil were considered to represent low, moderate, and relatively high contents of binder, respectively. Similarly, different contents of RHA of 6%, 8%, and 12% by the dry weight of soil were chosen to evaluate the effect of increasing contents of pozzolan material. The chosen percentages were considered experimental dosages.

The choice was also made with respect to the results of previous researches into Indian peat, especially those proving that both cement and RHA are capable of improving peat's engineering properties as a result of hydration and pozzolanic reactions. Lower and intermediate dosages were chosen in order to see the onset and further development of this effect while higher dosages were chosen to find out if the addition of more binder can help in increasing peat's strength or vice versa. The optimum dosage was found on the basis of experiment rather than being assumed theoretically.

All the percentages in this study were calculated taking into account the weight of dried parent peat soil. Dried peat constituents were first thoroughly mixed with the required amount of water according to optimum moisture content (Proctor).

Three specimens for each mix ratio and curing time (0, 7, 14, and 28 days) were tested. The total number of UCS specimens was calculated accordingly considering the number of mixes and curing times. Replicate specimens were made in the same conditions to obtain reliable experimental results.

Specimens with visible defects, including cracks, segregation, or improper molding, were not used for the test and were replaced accordingly. The specimens were prepared, compacted, cured, and tested using the same process.

2.2.2 Compaction Tests

The compaction behavior was done following IS 2720 (Part 7):1992 through the Standard Proctor test. Each mixture prepared was then compacted until it achieved its maximum dry density (MDD) at its respective optimum moisture content (OMC).

2.2.3 Curing Conditions

Immediately after specimen preparation, each specimen was carefully extruded, wrapped with polyethylene film to minimize moisture loss, and placed inside a sealed desiccator maintained at $27 \pm 2^\circ\text{C}$ and relative humidity above 95%. A saturated water environment was maintained inside the desiccator throughout the curing period to prevent evaporation and ensure consistent hydration. Specimens were cured for 0, 7, 14, and 28 days prior to testing. 0-day curing period stands for the UCS that is determined immediately after preparing and compacting the specimen without further curing after the specified period of initial handling.

2.2.4 Mechanical Testing

The strength behavior of both untreated peat and samples stabilized with different proportions of cement and rice husk ash was examined through unconfined compressive strength (UCS) testing. This testing was conducted following the guidelines of IS 2720 (Part 10)–1991 (Reaffirmed 2006). UCS tests were performed on the UCS

specimens, which were fabricated by compaction of the soils mixture at their specific MDD and OMC obtained from the Standard Proctor Compaction Test.

Tests were carried out after curing periods of 0, 7, 14 and 28 days. Curing was done in a controlled environment using a desiccator to maintain uniform conditions. For each curing duration and mix proportion, three specimens were tested to account for natural variability in results. Following the curing period, the specimens were subjected to axial loading until failure occurred, and the UCS was determined by dividing the maximum load by the specimen's cross-sectional area. The mean of the three readings for each mix was reported as the representative value, providing a reliable indication of the material's performance at each curing stage. All specimens were subjected to the same curing process, thereby ensuring consistency in UCS development for all mixtures. The specimens of 0 days were subjected to UCS test right after the completion of mixing and compaction process. It must be noted that the moisture content and matric suction were neither controlled nor measured in this experiment.

3. Results and discussion

3.1 Effect of cement with peat on Compaction

The parent peat soil's OMC and MDD in the subsequent Standard Proctor Compaction test were 29.88 percent and 13.47 kN/m³, respectively. Fig. 3a , Fig. 3b and Fig. 3c shows that the MDD reduces and the OMC increases when 5% cement is added to blends that contain 6% and 8% RHA. We observe the same feature when we mix 10 and 15 percent cement with 6 and 8 percent RHA .The RHA's high porosity likely caused the increase in OMC by improving its capacity to absorb water compared to other materials[11]. It might be due to the difference between the specific gravity and porous nature of RHA as compared to the mineral content in soil. Thus, addition of higher amounts of RHA will lead to the presence of lightweight and porous soil particles. It will thus reduce the measured dry density of the soil. However, it should be noted that the reduction in MDD is not an indication of deterioration in the effectiveness of soil stabilization. Compaction density and microstructure formation after the curing process are two different properties of soils. While the addition of RHA leads to reduction in compaction density, it also helps fill the interstices between soil particles due to their small size [12]. OPC contains components that have calcium which reacts with the reactive silica contained in RHA. In an appropriate moisture condition, this reaction is expected to enhance the production of other cementitious products such as C-S-H. The combined impacts of OPC on particle packing, hydration, and pozzolanic reaction may, therefore, explain why there was improvement in mechanical behavior despite the decrease in MDD noted in the process of compaction [11,12].

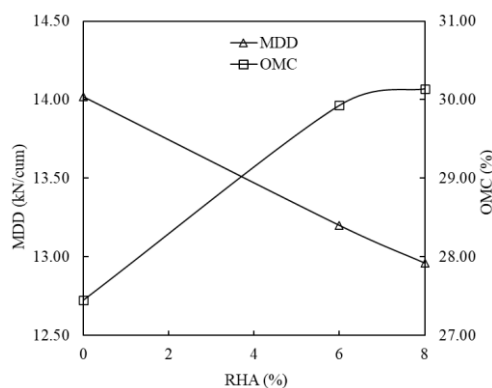


Fig. 3a :Trend of MDD and OMC for S+5C+different % RHA

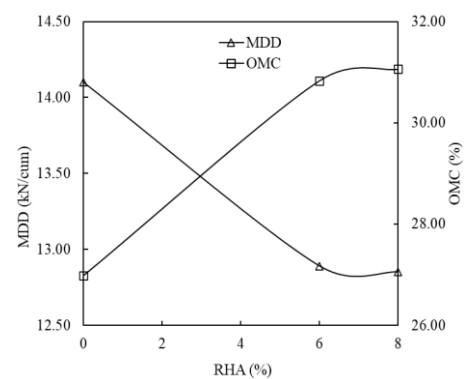


Fig. 3b: Trend of MDD and OMC for S+10C+different % RHA

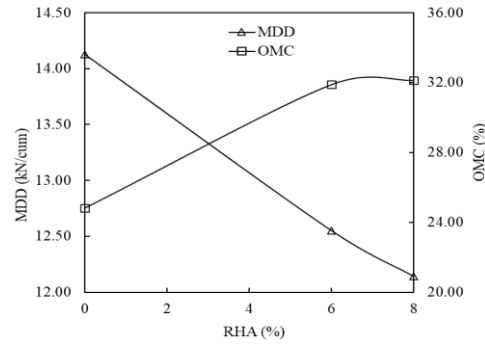


Fig. 3c: Trend of MDD and OMC for S+15C+different % RHA

3.2 Effect of cement with peat on unconfined compressive strength

Table 2 shows the unconfined compressive strength (UCS) values and failure strains of the peat-cement mixes as determined by the UCS tests. The untreated peat exhibited a UCS of 189 kPa after 28 days of curing. However, adding various amounts of cement (5%, 10%, and 15%) led to a range of UCS values after 0 days of curing, with values of 113 kPa, 155 kPa, and 264 kPa, respectively.

UCS readings showed a significant improvement after 28 days of curing. For the aforementioned cement percentages, the UCS values climbed to 235 kPa, 432 kPa, and 528 kPa, respectively. These findings show that the strength of the parent soil-cement mixtures significantly increased during the curing process. As the curing duration increases, the cementitious materials within the soil matrix undergo further reactions, contributing to improved cohesion and interparticle bonding.

The addition of cement increased the UCS for various percentages of cement at a 28-day curing interval, Fig. 4 demonstrates the experimental values of the unconfined compressive strength (UCS) and their related failure strains. The statistics clearly demonstrate an increase in the failure strain as the cement percentage increases. Additionally, soil samples treated with a higher cement content show a rise in UCS [13].

As shown by the rise in strength with longer curing times across all mix proportions, the curing period is also observed to affect the soil's strength [14]. This demonstrates that soil strength depends not only on the amount of cement present but also on the duration of the curing process.

Fig. 5 provides a thorough visual representation of the interaction between these variables by presenting the fluctuations of UCS concerning cement concentration and curing times. These graphs show how the concentration of cement and the curing time affect the strength of the treated soil. The rearrangement of soil matrix made possible by cement's presence is the mechanism underpinning cement stabilization [15]. Both hydration reactions and pozzolanic reactions are essential to this process [16]. When water is provided, hydration mechanisms involving calcium, silica, and water occur. These reactions lead to the production of calcium hydroxide and calcium silicate hydrate (C-S-H) (CH). Thereafter, pozzolanic reactions occur and more C-S-H, or calcium aluminate hydrate (C-A-H), is produced. The total increase in soil strength after cement treatment is a result of these responses. Therefore, the combined impacts of hydration and pozzolanic processes between the soil and cement content can be used to explain the rise in unconfined compressive strength (UCS). These processes make it easier for soil particles to be restructured and bound together, which ultimately strengthens the stabilized soil's physical properties.

Table 2. UCS and strain values of peat-cement mixes

Mix proportion	Curing period							
	0		7		14		28	
	UCS kPa	Strain (%)	UCS kPa	Strain (%)	UCS kPa	Strain (%)	UCS kPa	Strain (%)
S	78	3.52	92	3.64	154	3.82	189	3.84
S+5C	113	3.64	134	3.71	196	3.84	235	3.98
S+10C	155	3.73	256	3.82	375	3.89	432	4.21
S+15C	264	3.96	349	4.14	462	4.34	528	4.81

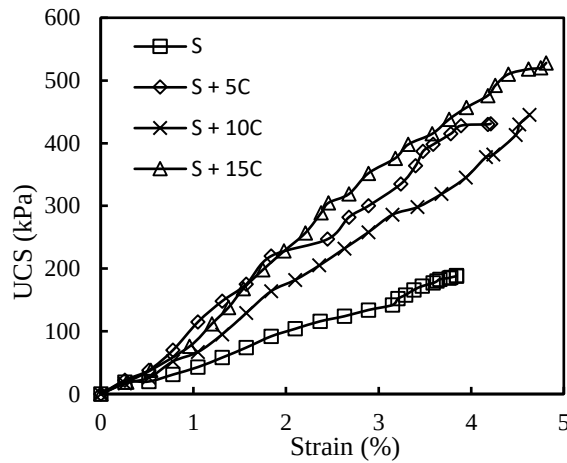


Fig. 4 : Stress-strain curve for peat-cement mixes of 28 days curing

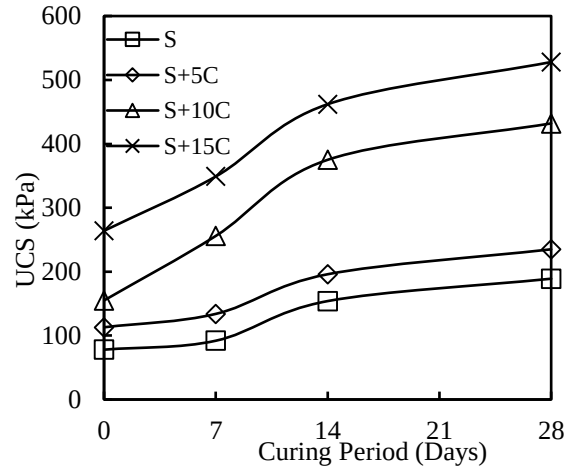


Fig. 5: Trend of UCS for peat-cement mixes



Fig. 6: UCS failure pattern of peat soil For a 28-day curing period



Fig. 7: UCS failure pattern of S+15C for 28-day curing period

The strength development in the parent peat soil over time; this is due to the aging effect, a process involving The untreated peat showed some variation in UCS with increasing curing duration. This change may be related to the redistribution of moisture and gradual changes in the internal structure of the compacted specimens during the curing period. However, because pore-water pressure, organic matter degradation, and microstructural changes were not directly measured, the observed strength development cannot be attributed solely to an aging effect. In contrast, the strength gain observed in the cement-treated specimens can be primarily associated with the progressive development of cementitious bonding during curing [14].

Figures 6 and 7 show the changes in stress-strain behaviour and failure characteristics resulting from OPC addition and curing. The treated specimens generally exhibited a more distinct and abrupt failure response than the untreated peat, indicating increased stiffness and a tendency towards more brittle behaviour with increasing cement content and curing duration.

This change in failure behaviour is associated with the development of cementitious bonds within the soil matrix. In the presence of water, cement hydration produces calcium silicate hydrate (C-S-H) and calcium hydroxide (CH), which contribute to interparticle bonding and increased stiffness. With continued curing, the progressive formation and development of cementitious products increase the resistance of the stabilized soil to deformation. As a result, the treated peat tends to exhibit a less ductile and more brittle response compared with the untreated soil [17,18]. The degree of this transition depends on factors such as cement content, curing duration, moisture conditions, and the inherent characteristics of the peat.

3.3 UCS behaviour of peat-RHA mixes

Table 3 displays UCS and failure strains of the peat-RHA mixtures at 28-day curing age. Unmodified peat yielded UCS value of 189 kPa, while incorporation of 6%, 8%, and 12% RHA gave rise to UCS values of 198, 212, and 238 kPa, respectively. As such, there was an observed gradual enhancement in UCS due to the incorporation of RHA, but the improvement was significantly smaller compared to that achieved using OPC mixture.

The gradual enhancement in UCS value due to RHA may be ascribed to both physical and chemical processes. The small RHA particles can fill up certain interstitial spaces among peat particles and influence the configuration of peat particles. Furthermore, the fact that RHA is rich in silica suggests that pozzolanic reactions may be possible due to availability of calcium sources [19].

Stress-strain curves of peat-RHA mixtures after curing for 28 days are shown in Fig. 9. For the RHA treated mixtures, the maximum UCS was observed in the specimen with 12% RHA content which showed around 238 kPa of UCS along with failure strain. This suggests that the mixture with 12% RHA content shows the largest strength enhancement in all of the RHA contents tested. However, the relatively small strength enhancement relative to the OPC treated mixtures suggests that RHA has a weak stabilizing ability on the peat.

Table 3. UCS and strain values of peat-RHA mixes.

Mix proportion	Curing period							
	0		7		14		28	
	UCS kPa	Strain (%)	UCS kPa	Strain (%)	UCS kPa	Strain (%)	UCS kPa	Strain (%)
S	78	3.52	92	3.64	154	3.82	189	3.84
S+6RHA	93	3.67	121	3.49	165	4.18	198	4.21
S+8RHA	112	3.94	154	4.24	170	4.46	212	4.58
S+12RHA	141	4.72	174	4.76	195	4.81	238	5

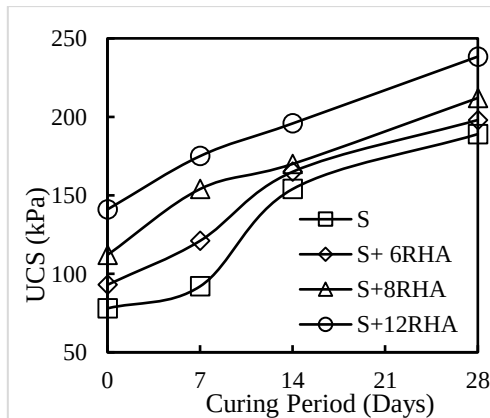


Fig. 8: Trend of UCS for peat-RHA mixes

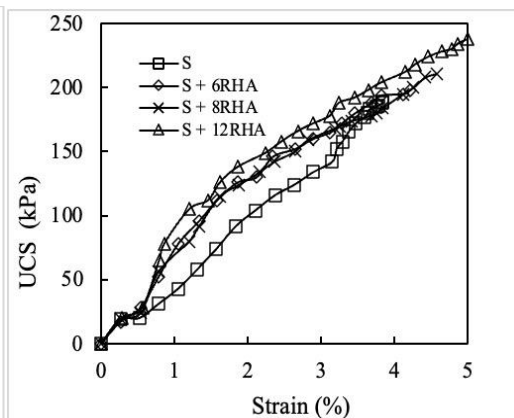


Fig.9: Stress-strain curve for peat-RHA mixes of 28 days curing



Fig. 10: UCS failure pattern of Peat soil for a 28-day curing period



Fig. 11: UCS pattern of S+12RHA for The curing period lasts for 28 days.

For the unconfined compressive strength (UCS) test by modifying natural pozzolan with 6% of rice husk ash (RHA) and curing at 28 days, the failure mode has been changed from ductile to brittle, as present in Fig. 10 and Fig. 11. Initially, the addition of RHA further facilitates cementitious compounds under curing. RHA is rich in silica (SiO_2) that can react with the calcium hydroxide (CH) liberated from cement hydration to form more calcium silicate hydrates (C-S-H). These fillers increase the rigidity and strength of the material. In fact, early in the curing process, it can exhibit ductile behavior [20].

Over time, ongoing chemical reactions influence the development of the material's microstructure. The pozzolanic activity of RHA, together with its particle size and amorphous silica content, plays a key role in these changes. These factors, along with the specific curing conditions, determine the extent to which cohesion, stiffness, and deformation resistance are improved [12].

3.4 Studies on UCS behavior of peat-RHA-cement mixes:

After 28 days of curing, Figure 12 presents the experimental results for the unconfined compressive strength (UCS) and corresponding failure strain of peat–cement–rice husk ash (RHA) mixtures. The findings show that the combined application of cement and RHA produces a substantial improvement in UCS compared with using either stabilizer alone. The figure provides a detailed comparison of UCS and failure strain for the S + 5% C + 12% RHA, S + 10% C + 12% RHA, and S + 15% C + 12% RHA mixtures, highlighting the performance differences among these proportions. The findings indicate that increasing the percentages of cement and RHA from 5 to 15 and 6 to 12, respectively, leads to an enhancement in the UCS value. Following a 28-day curing period, the UCS values for the S+5% C+12% RHA, S+10% C+12% RHA, and S+15% C+12% RHA mixtures were 586 kPa, 672 kPa, and 819 kPa, respectively, as seen in Table 4a, Table 4b, and Table 4c. This illustrates the significant impact of RHA on the strength properties of the peat-cement-RHA mixture.

Table 4a. UCS and strain values of peat-cement-RHA mixes

Mix proportion	Curing period							
	0		7		14		28	
	UCS kPa	Strain (%)	UCS kPa	Strain (%)	UCS kPa	Strain (%)	UCS kPa	Strain (%)
S+5C	113	3.64	134	3.71	196	3.84	235	4.21
S+5C+6RHA	238	4.12	349	4.28	426	4.43	525	4.71
S+5C+8RHA	296	4.39	369	4.39	473	4.78	562	5
S+5C+12RHA	367	4.41	412	4.63	568	4.82	586	5.12

Table 4b. UCS and strain values of peat-cement-RHA mixes

Mix proportion	Curing period							
	0		7		14		28	
	UCS kPa	Strain (%)	UCS kPa	Strain (%)	UCS kPa	Strain (%)	UCS kPa	Strain (%)
S+10C	155	3.73	256	3.82	375	3.89	432	4.21
S+10C+6RHA	312	4.22	378	4.39	468	4.56	554	4.94
S+10C+8RHA	398	4.47	433	4.69	492	5.12	582	5.26
S+10C+12RHA	416	4.72	532	5.15	613	5.28	672	5.41

Table 4c. UCS and strain values of peat-cement-RHA mixes

Mix proportion	Curing period							
	0		7		14		28	
	UCS kPa	Strain (%)	UCS kPa	Strain (%)	UCS kPa	Strain (%)	UCS kPa	Strain (%)
S+15C	264	3.96	349	3.90	462	3.88	528	3.85
S+15C+6RHA	422	4.43	546	4.41	618	4.38	734	4.32
S+15C+8RHA	494	4.74	581	4.67	622	4.54	789	4.51
S+15C+12RHA	541	5.16	642	5.22	768	5.12	819	5.06

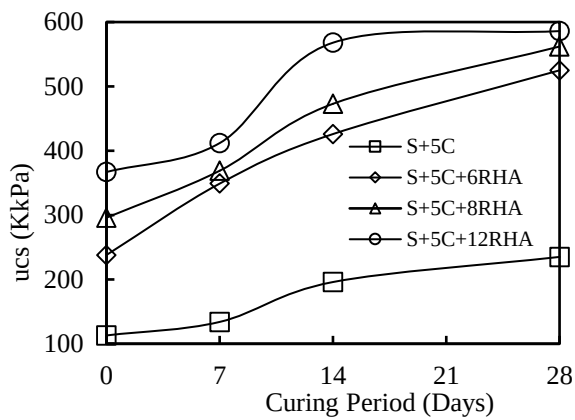


Fig. 12(a): Variation of UCS with RHA content for S + 5% Cement mixes

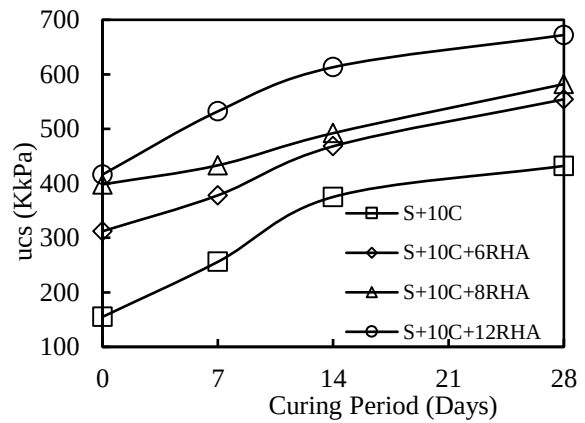


Fig. 12(b): Variation of UCS with RHA content for S + 10% Cement mixes

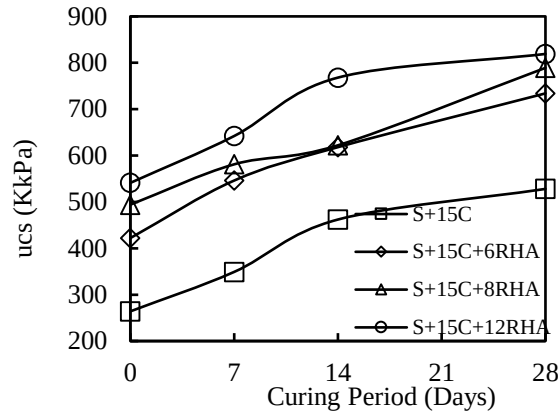


Fig. 12c: Variation of UCS with RHA content for S + 15% Cement

Fig. 12a, 12b and 12c shows how the curing time affects the unconfined compressive strength (UCS) failure pattern of a mixture with cement (C) and peat soil. The UCS test results for 0-day curing show a slight amount of ductile behavior, but not any more ductile than the UCS of pure peat soil. However, after 28 days of curing and the addition of 15% cement and 12% rice husk ash (RHA), the UCS failure pattern tends to become more brittle. When the 15 percent cement and peat soil mixture is tested right away after preparation and before any curing time has passed, it exhibits a modest amount of ductile behavior. Cement increases cohesion and rigidity, increasing the mixture's ability to support loads. When compared to pure peat soil, the ductility is not significantly increased by the addition of 15% cement.

The cement in the mixture goes through hydration after 28 days of curing, creating a sturdy cementitious matrix. The material also experiences further reactions and changes in its microstructure with the addition of 12% RHA. The inclusion of RHA can cause behavior to become more brittle depending on its specific properties, such as its particle size, amorphous content, and pozzolanic activity [12]. As a result, after 28 days of curing, the UCS failure pattern of the combination consisting of 15% C + 12% RHA and peat soil begins to show brittle behavior. The material shows reduced plastic deformation and enhanced vulnerability to abrupt, catastrophic failure, both characteristics of brittle failure as shown in Fig. 13a.



Fig. 13a: UCS failure pattern for S+15C+12RHA for a 28-day curing period.

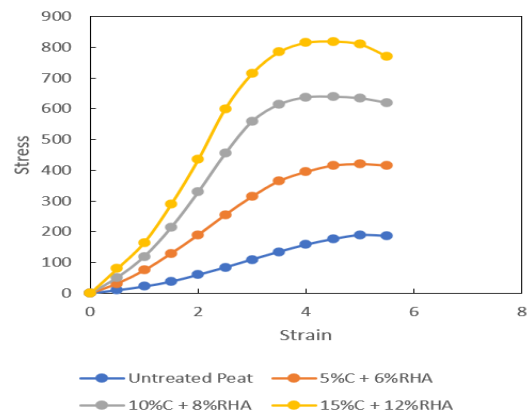


Fig. 13b: Stress-strain response of untreated and treated soil specimens for 28-day curing period.

Fig. 13b demonstrates that the stress-strain curve improved with increasing percentages of cement and RHA in the mixtures. The unamended peat had the weakest stress-resisting capacity, and 15% cement + 12% RHA had the highest peak stress (approximately 810 kPa) compared with other samples, such as 10% cement + 8% RHA

and 5% cement + 6% RHA. This enhanced behavior was due to the formation of cementitious products and pozzolanic reactions that provide enhanced bonding between particles and densification of the matrix [3].

In general, the findings obtained in the current research work follow the trends observed earlier for stabilized peat and organic soils. An increase in binder content enhances the UCS value; however, the longer the curing time, the greater the enhancement in strength due to the continuous development of cementitious materials [23][24].

The addition of RHA causes an increase in OMC and decrease in MDD, and such behaviour is explained by the porous nature and light weight of RHA particles [19]. Experimental works performed recently on the treatment of peat with cement-RHA also reveal the enhancement in UCS values due to the presence of RHA and formation of additional cementitious materials [18,19]. Moreover, the improvement in strength of other organic soils with the increase of cement content and curing time is observed; however, the extent of improvement in strength largely depends on the organic content of the soil [20]. Nevertheless, the extent of changes in the current research is different from the extent of changes observed in previous studies due to the high heterogeneity of peat and the influence of organic content, initial water content, pH, fibre content, binder content and curing conditions.

3.5 Microstructure Analysis:

3.5.1 Scanning electron microscope :

Microstructural analysis of the entire structure of the material gives important information about its composition, especially when it comes to the composition of a composite material like peat soil. The microstructure of peat soil obtained from Arunachal Pradesh has been analysed using the technique of Scanning Electron Microscopy (SEM). Fig. 14(a) is the micrograph of the peat soil as obtained by SEM analysis.

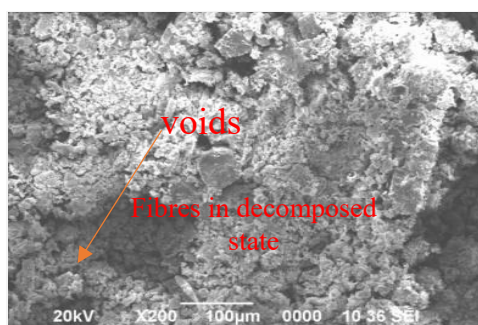


Fig. 14a Untreated Parent Soil

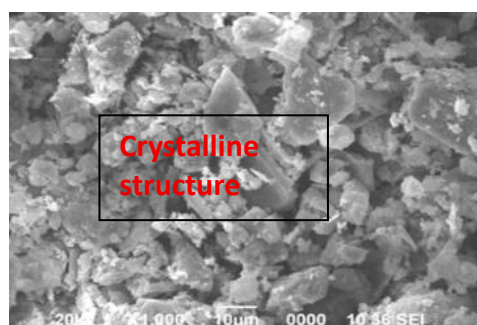


Fig. 14b Parent Soil + 15% OPC + 8% RHA

A close-up look at the peat sample in Figure 14a reveals the presence of degraded fibers. With the fibers appearing to be in a condition of decomposition, the fibrous nature of peat is clearly visible. This finding indicates that the peat has significantly degraded and changed over time.

Fig. 14(b) depicts the SEM micrograph of the optimum stabilised peat soil sample (S + 15% Cement + 12% RHA) at the end of 28 days' curing period. As compared to the untreated peat soil, there is considerable improvement in the microstructure of the stabilised sample. The untreated peat soil consists of a very porous microstructure having interconnected pores and loose soil particles along with partly decomposed organic fibres. The stabilised soil sample has a dense and compact microstructure where the soil particles are tightly bound together by the hydrates. The formation of calcium silicate hydrate (C-S-H) gel and other cementitious products have filled the pores, lowered the void ratio and created a more homogeneous soil structure [21]. In addition, the organic fibres seemed to be encased in the cementitious matrix, thus reducing their decomposition. This is similar to the findings reported by many researchers who observed that cement-rice husk ash stabilisation increases the soil strength by pore filling, particle bonding and matrix densification [3] [5].

The SEM results explain the structural basis for the improvement in UCS of the RHA-amended soil. As compared to the unamended soil, the amended soil was relatively denser, showing good interaction among the particles as well as partial filling of the void space. The fine RHA particles helped fill the void space among the soil particles and enhanced the interactions between soil particles, leading to increased compaction of the soil mass.

3.5.2 X-Ray Diffraction Test

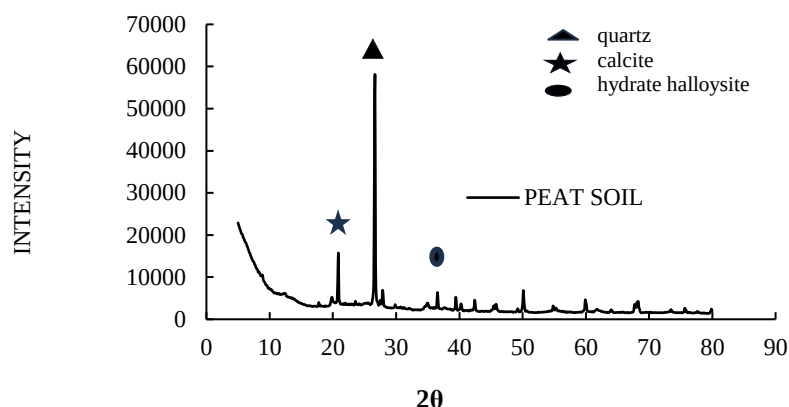


Fig. 15: X-Ray diffraction of Peat soil

When it comes to peat soil, XRD analysis can provide important details on the kinds and relative concentrations of minerals present in the sample. Fig. 15 depicts that peat soil primarily consists of organic matter derived from partially decomposed plant material. The phases present in rice husk ash (RHA) were detected using X-ray diffraction (XRD) by comparing the diffraction pattern against the International Centre for Diffraction Data (ICDD) Powder Diffraction File (PDF-4+) database. Sharp peaks were observed in the diffraction pattern belonging to crystalline silica and other minor minerals. The main peaks seen at $2\theta \approx 21.9^\circ$, 26.6° , 36.5° , and 50.1° were found to be quartz (ICDD PDF No. 46-1045). The peaks at $2\theta \approx 21.9^\circ$ and 36.1° were due to cristobalite (ICDD PDF No. 39-1425). The peaks at $2\theta \approx 29.4^\circ$, 39.4° , and 47.5° were found to be calcite (ICDD PDF No. 05-0586), and peaks around 33.2° and 35.6° were found to be hematite (ICDD PDF No. 33-0664). The minor peaks at 16.4° , 26.2° , and 40.8° were due to mullite (ICDD PDF No. 15-0776). Thus, the presence of quartz and cristobalite signifies the presence of silica in RHA, and the presence of calcite and hematite shows minor crystallinity.

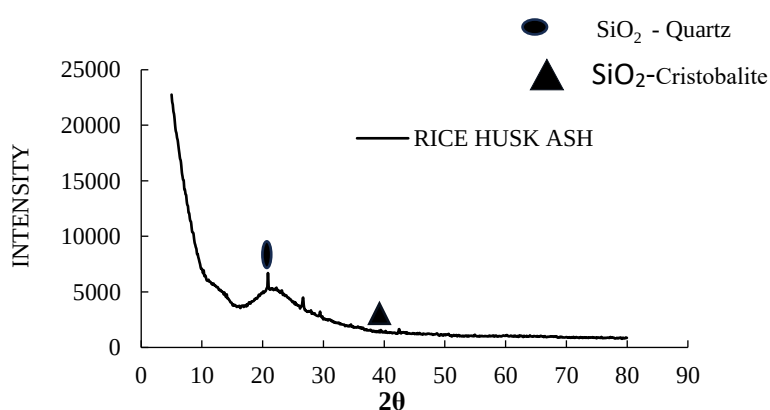


Fig. 16: X-ray diffraction of rice husk ash.

Fig. 16 shows the Peaks that match the mineral phases found in the sample are frequently visible on the XRD test graph for rice husk ash (RHA). Regarding the crystalline components of RHA, the XRD examination yields important information. The XRD graph shows distinct peaks at specific angles (2θ) that indicate the presence of different crystalline phases. These peaks are typically labeled or indexed according to their corresponding mineral phases.

Conspicuous peaks on the XRD graph represent the principal mineral phases identified in RHA. Other possible phases in RHA include calcite (CaCO_3), hematite (Fe_2O_3), and mullite. Common mineral phases in RHA include silica (SiO_2) in the form of cristobalite or quartz ($\text{Al}_6\text{Si}_2\text{O}_{13}$) [9] [11].

The RHA contains components that are amorphous or imperfectly crystalline, according to XRD examination. Broad humps or the absence of clearly defined peaks in the XRD graph are frequently used to identify these amorphous phases since they do not form distinct peaks.

In the XRD analysis of the stabilized optimum mixture, there was a clear demonstration of mineralogical changes after 28 days of curing. The XRD pattern showed a more prominent peak for both quartz and calcite in addition to the formation of products of cement hydration that were related to calcium silicate hydrate (C-S-H). The decrease in the amorphous organic material and increase in the intensity of the cement hydration product show the efficiency of the pozzolanic reaction between the cement and rice husk ash that contains silicon. These new cementitious materials increased the bonding between particles and led to the improvement of mechanical properties [22].

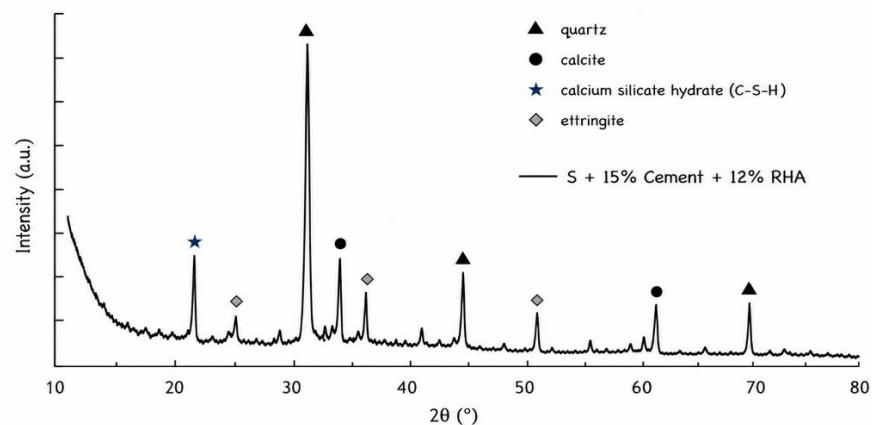


Fig.17: X-ray diffraction (XRD) pattern of the optimum stabilised peat soil specimen (S + 15% Cement + 12% rice husk ash) after 28 days of curing.

XRD pattern for the optimized stabilized sample (S + 15% Cement + 12% RHA) after 28 days of curing is shown in Fig. 17. The diffraction peaks associated with quartz, calcite, and calcium silicate hydrate (C-S-H) indicate the presence of cementitious hydration products. The enhancement in the intensities of calcite and C-S-H peaks reveals more pozzolanic reactions, leading to dense soil structure and better particle bonding, thus contributing to the improvement in the strength of stabilized peat soil. The results are consistent with earlier investigations on cement-RHA stabilized soils [13] [21].

These XRD results help to explain the changes in the mechanical behavior due to the mineralogical properties of the soil modified with RHA. The presence of silica-rich minerals within RHA helps in the possible pozzolanic activity of the material. With the availability of water, the reactive silica may react with the calcium-containing compounds, leading to the formation of cementitious compounds, which enhances the bonding among soil particles. This leads to a denser soil structure, as shown in the increase in UCS of the modified soil samples.

Mineralogical aspects of the RHA were determined by XRD (X-ray diffraction) technique. X-ray diffraction pattern was analyzed to determine the crystalline and amorphous phases of the RHA. The broad diffuse area on the XRD pattern shows that amorphous silica is the major constituent of the ash, and diffraction peaks show crystalline phases of the RHA.

Conclusions:

The current work focused on the stabilization of the highly organic peat soil taken from Ziro Valley of Arunachal Pradesh using OPC and rice husk ash (RHA). The percentages of cement ranging from 5% to 15% and percentages of rice husk ash ranging from 6% to 12% were taken for experimentation. The major findings from the work are stated below:

1. The natural peat had low UCS and poor engineering properties, proving the necessity of stabilizing the peat before using it for construction purposes.

2. The addition of cement usually increased the UCS of peat, and the increment was more pronounced in cases where the content of cement and the curing time were higher. The cement-stabilized samples showed an increase in UCS at curing times of 0, 7, 14, and 28 days, which proves the role of cement hydration and cementitious bonding in strengthening.
3. The addition of rice husk ash further increased the strength of the cement-stabilized peat. The UCS of the S+5C+12RHA, S+10C+12RHA, and S+15C+12RHA samples was 586, 672, and 819 kPa, correspondingly, after 28 days of curing. Therefore, the S+15C+12RHA mixture has the maximum UCS among all analyzed cement-RHA combinations.
4. The increase in UCS is due to the combined effect of cement hydration and the pozzolanic reaction of silica-rich RHA.
5. The findings obtained from the microstructural examination confirm those observed from the mechanical testings. The stabilized samples were characterized by dense matrices and fewer pore spaces, while the XRD findings revealed the existence of cementitious hydrated products which contribute to the strength gain of the stabilized material.
6. The experiment findings reveal the effectiveness of using locally available RHA as a supplementing stabilizing agent in enhancing peat soil.

Author Contributions: The Author Miss Nabam Jumsi (523013@nerist.ac.in) played a significant role in writings the paper and performing all the experimental tests.

The Author, Dr. Ajanta Kalita, an associate professor, played a significant role in completing the investigation in every manner.

The Author, Dr. Ajay Bharti helped in experimental tests that has been carried out.

Corresponding author: Miss Nabam Jumsi

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