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SUSTAINABLE SOIL IMPROVEMENT USING BAKERY WASTE: A STUDY ON EGGSHELL POWDER AS A STABILIZING AGENT

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ABSTRACT
The growing generation of solid waste, particularly from the bakery sector, presents considerable environmental and disposal challenges in India. The use of eggshell powder (ESP), a calcium-rich byproduct of bakery waste, as a sustainable stabilising agent for clayey soils is examined in this study. To assess the geotechnical performance of clay samples, different amounts of ESP (15%, 20%, and 25% by dry weight) were applied. The soil's index properties, compaction behaviour, Unconfined Compressive Strength (UCC) and California Bearing Ratio (CBR) were evaluated in a laboratory. According to the findings, adding ESP improved the CBR and UCC values while considerably lowering the liquid and plastic limits. Optimal performance was observed at 20% ESP, where the CBR increased by approximately 20% and the UCC improved by nearly 90% compared to untreated clay, indicating enhanced load-bearing capacity and durability. According to these results, ESP may be a more economical and environmentally friendly substitute for traditional stabilisers while also encouraging waste reduction and long-term soil enhancement. This approach aligns with circular economy principles and encourages environmentally responsible construction practices.
Keywords: Eggshell Powder (ESP), Soil Stabilization, California Bearing Ratio (CBR), Unconfined Compressive Strength (UCC), Waste Utilization, Sustainable Construction.
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INTRODUCTION

Global solid waste generation has significantly increased as a result of the fast expansion of industrialisation and urbanisation. Among these, food-related wastes—particularly eggshells from bakeries, restaurants, and households—constitute a major portion of biodegradable waste that is often discarded in landfills. Globally, billions of eggs are consumed each year, producing large quantities of eggshell waste. Improper disposal of this material contributes to environmental pollution and potential health hazards due to odour and microbial activity. This situation raises an important question: can this abundant biowaste be utilised effectively for sustainable construction applications? Eggshells, primarily composed of calcium carbonate ($CaCO_3$) and trace organic matter, exhibit chemical and mineralogical similarities to industrial lime and limestone[1]. Hence, they possess potential for use as a low-cost and environmentally friendly stabilising material. Chemical stabilisers like bitumen, cement, and lime have historically been widely used to increase soil strength; however, their use is linked to significant expense and high energy consumption [2,3]. Substituting such stabilisers with natural or waste-derived materials can reduce costs and the carbon footprint associated with soil stabilization[4]. Eggshell powder (ESP), according to earlier studies, can significantly improve the mechanical and geotechnical characteristics of poor soils [5]. According to studies, adding ESP enhances compaction properties, lowers soil flexibility, and boosts load-bearing capacity [6]. Other researchers have investigated its application as a partial cement replacement, reporting enhanced durability and reduced permeability in concrete mixes[7–9]. When combined with clayey soils, the high calcium concentration of ESP promotes the creation of cementitious compounds such as calcium silicate hydrates (C–S–H),

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which increases strength [10,11] . Few studies have systematically investigated the combined effects of eggshell powder (ESP) on important soil properties, such as Index Properties, California Bearing Ratio (CBR), Compaction characteristics and Unconfined Compressive Strength (UCC), despite extensive research on the potential of ESP in construction applications. Thus, by experimentally assessing the application of ESP as a sustainable stabilising agent for clay soils, this study aims to close this gap[12]. By promoting resource-efficient building techniques and repurposing bakery waste as a valuable engineering material, this study also advances Sustainable Development Goals (SDGs) 9: Industry, Innovation, and Infrastructure and SDGs 12: Responsible Consumption and Production. The geotechnical characteristics of clay soil supplemented with eggshell powder (ESP) at dry weight percentages of 15%, 20%, and 25% were assessed in the current study using standard laboratory procedures [13] . The findings aim to aid in the creation of low-carbon, sustainable infrastructure by determining the optimal ESP concentration that enhances strength and workability.

Methodology

The research method was developed to completely assess eggshell powder's (ESP) efficacy as a stabilising factor for clayey soil. The study was carried out in five main stages: collection and processing of eggshell waste, preparation of ESP–clay mixtures, laboratory evaluation of geotechnical properties, analysis of the experimental data, and interpretation of the findings.

Collection and Processing of Eggshell Waste

Eggshells were gathered as bakery waste from nearby bakeries and eateries. The shells were thoroughly cleansed with clean water to remove any remaining organic waste, and then they were oven-dried for four days at one hundred five degrees celcilous to remove any moisture. The dried shells were pulverised using a mechanical grinder until a fine powder of approximately 300 µm particle size was obtained. The powder was sieved to ensure uniformity and stored in airtight containers. This preparation ensured that the ESP used in testing was free from impurities and consistent in particle size, facilitating accurate comparison among samples. The ESP was also calcined by 13 for one to two hours at temperatures between 700 and 900 °C in a muffle furnace[14]. A fine, chalky-white powder was produced once the calcination process was finished. The steps involved in producing ESP from leftover eggshells (Fig.-1) and eggshell powder (Fig.-2).

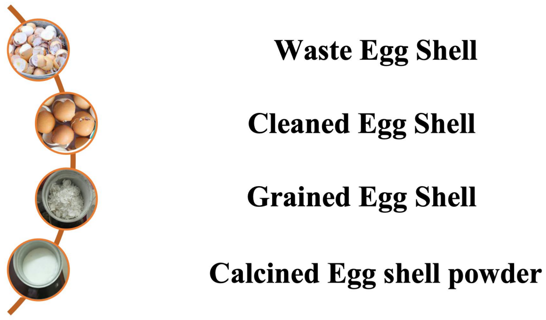

Fig.-1: Process of Eggshell Powder

(A) (B)

Fig.-2: Eggshell Powder (A) Specimens of the White Eggshell, (B) ESP after Farming

ESP-Clay Mix Proportion

Locally available clay soil was crushed, air-dried, and passed through a 425 µm IS sieve before being combined. As shown in Fig.-3, eggshell powder (ESP) was added to the clay in percentages of 15%, 20%, and 25% by dry weight, with the untreated clay acting as the control (S_0). The treated samples were designated as S_1 (15% ESP), S_2 (20% ESP), and S_3 (25% ESP). Each blend was carefully homogenised in the dry state to ensure uniform distribution of ESP before adding moisture for compaction and strength testing.

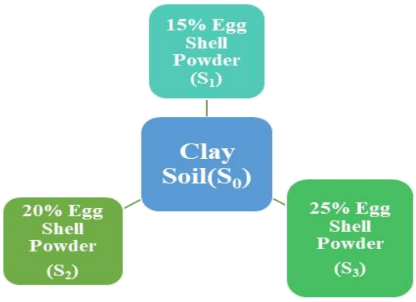

Fig.-3: Mix Proportions ESP-Clay

Various geotechnical properties were examined and tested by ore in accordance with IS Code provisions to determine the ideal percentage, as shown in Fig.-4.

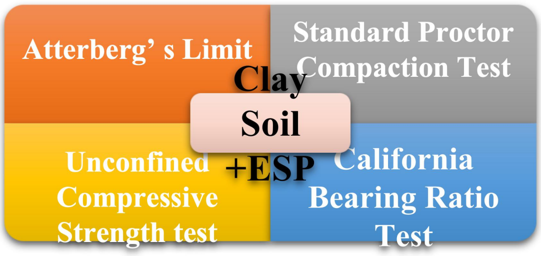

Fig.-4: Analytical Study of ESP-Clay Soil Test

EXPERIMENTAL

Index Properties

To assess changes in soil consistency, the liquid and plastic limits of the soil–ESP combinations were established in compliance with IS: 2720 (Part 5)–1985 and IS: 2720 (Part 6)–1972, respectively, as shown in Fig.-5.


(A)


(B)


(C)


(D)

Fig.-5: Liquid & Plastic Limit Test (A) Soil Sample with ESP, (B) Setting up Apparatus, (C) Threading of Soil, (D) Oven-Drying

Compaction Properties

As shown in Fig.-6, the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) for each soil–ESP mix were ascertained using the Standard Proctor Test (IS: 2720 Part 8–1983).


A


B


C


D

Fig.-6: Standard Proctor Test (A) Soil Sample with ESP, (B) Compacting, (C) Cutting, (D) Levelling

California Bearing Ratio (CBR) Test

As shown in Fig.-7, the tests were conducted in both soaked and unsoaked conditions in accordance with IS: 2720 (Part 16)–1987 to evaluate the stabilised soil's load-bearing capacity.

(A) (B) (C) (D)

Fig.-7: CBR Test (A) Filling of Clay Soil, (B) Cutting, (C) Setting Apparatus, (D) After Testing

Unconfined Compressive Strength (UCC)

The tests were carried out in compliance with IS: 2720 (Part 10)–1991 to assess the soil samples' short-term shear strength. As shown in Fig.-8, each specimen was loaded at a strain rate of 1.2 mm/min, and a 2 kN proving ring apparatus was used to quantify the peak load.

(A) (B) (C) (D)

Fig.-8: UCC Test (A) soil Specimen, (B) testing, (C) deflection of soil, (D) eggshell sample

RESULTS AND DISCUSSIONS

The experimental findings from the geotechnical assessment of clay soils stabilised with varying amounts of eggshell powder (ESP) are compiled in this section. The results are arranged in accordance with the order of tests specified in the protocol. By examining each metric to highlight the variations in performance between treated and control samples, ESP's value as a sustainable soil stabiliser is illustrated.

Index Properties of ESP-Clay Mixes

As the ESP level increased, the ESP–clay mixes' liquid and plastic limits gradually declined. The liquid limit in the control sample was 70%; at 15%, 20%, and 25% ESP, it dropped to 55%, 52%, and 42%, respectively. In a similar vein, the treated samples' plastic limit dropped to 28%, 30%, and 26% from 34% in the control. This decrease in consistency limits is explained by the substitution of coarser ESP particles for finer clay particles, which decreases plasticity and water adsorption. These findings align with those of Kola Veerabrahmam and Prasad (2021), who documented a comparable reduction in soil flexibility with the addition of stabilisers based on calcium. The progressive decline in liquid and plastic limits reflects the reduced water-holding capacity and improved stability of ESP-treated soils, indicating lower plasticity and enhanced workability, as illustrated in Figure 9 and summarised in Tables-1 and 2.

Table-1: Liquid Limit Properties of ESP-Clay Mixes

S. No.	S_0(without ESP)		S_1(15% ESP)		S_2(20% ESP)		S_3(25% ESP)		BIS Standards
	Water (W0) I%	Blows count(N)	Water (W1) %	Blows count(N)	Water t (W2) %	Blows count(N)	Water (W3) %	Blows count(N)	
1	68	85	53	74	50	134	40	148	Liquid Limits greater than 35%.
2	70	58	55	60	52	86	42	85	
3	72	38	57	32	54	35	44	36	
Average Liquid Limit %	70	--	55	--	52	--	42	--	

Table-2: Plastic Limit Values of ESP-Clay Mixes

S.No.	Particulars	S_0 (without ESP)	S_1 (15% ESP)	S_2 (20% ESP)	S_3 (25% ESP)	BIS Standards
1	Empty weight of the container	35.9	32.6	33.8	35.3	*Plastic Limit of clays usually ranges between 20% and 50%*
2	Empty weight of container + Wet soil	45.9	42.6	43.8	45.3	
3	Empty weight of container + Dry soil	42.9	40.3	41.8	42.3	
Plastic Limit %		34	28	30	26	

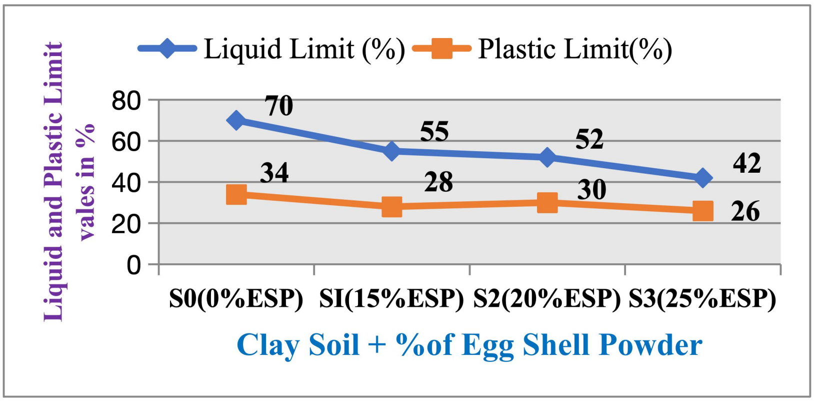

Fig.-9: Liquid and Plastic Limit Properties of ESP-Clay Mixes

Compaction Properties of ESP-Clay Soil Mixes

As shown in Table-3, according to the results of the Standard Proctor Test, adding ESP up to 20% greatly increased the Maximum Dry Density (MDD), which thereafter somewhat decreased at greater concentrations. Conversely, the control sample's Optimum Moisture Content (OMC) dropped from 34% to 28% at 20% ESP. The particle packing effect, in which the small ESP particles cover gaps in the clay matrix to promote increased soil densification, is responsible for the observed increase in MDD. According to Hamada et al. (2020), who noted comparable densification effects in lime-stabilised soils, the 20% ESP mix was found to be ideal, offering the best compaction characteristics. Figure-10 shows the bulk and dry densities of clay soil treated with different concentrations of eggshell powder (ESP). According to the results, both densities first dropped at 15% ESP, then rose at 20%, before marginally declining at 25% ESP. Ideal void reduction and particle packing were indicated by the maximum dry density of 15.59 kN/m³ at 20% ESP. A denser and more stable soil structure is the outcome of the fine ESP particles' effective filling of the gaps in the clay matrix, which explains this improvement. The observed marginal drop in density may be caused by the extra powder's decreased interparticle bonding effectiveness for ESP concentrations exceeding 20%.

Table-3: Bulk and Dry Density for ESP-Clay Mixes

Description	Average of 3 trial values				IS Standards
	S_0(0%ESP)	S_1(15%ESP)	S_2(20%ESP)	S_3(25%ESP)	
Bulk Density(kN/m³)	18.41	17.50	18.40	17.50	Minimum Bulk Density is 14 kN/m³ (typical for soft clay)
Dry Density(kN/m³)	15.72	14.34	15.59	14.83	Minimum Dry Density is 11 kN/m³ (typical for soft clay)

CBR of ESP-Clay Mixes

The CBR values demonstrated a substantial increase upon the incorporation of ESP. In the unsoaked condition, the CBR improved from 2.5% (control) to 5.86% (20% ESP), while in the soaked condition, it rose from 1.44% to 2.42% for the same blend. The trend confirms that ESP enhances the load-bearing capacity of clay soils through improved particle bonding and reduced plasticity.[15] Beyond 20% ESP, a marginal decline was observed, possibly due to the formation of weak zones resulting from excess unreacted powder. Figure-11 illustrates the variation in CBR values for all mixes.

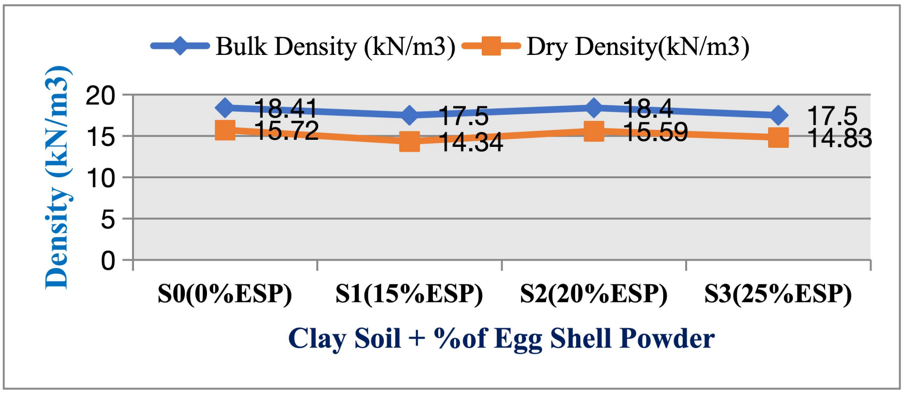

Fig.-10: Bulk and Dry Density for ESP-Clay Mixes

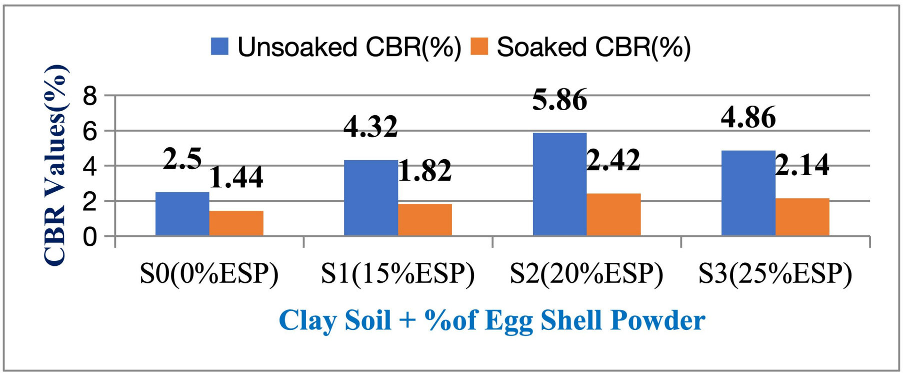

Fig.-11: CBR Properties for ESP-Clay Mixes

Unconfined Compressive Strength (UCC) for ESP-Clay Mixes

Table-4 summarises the findings of the Unconfined Compressive Strength (UCC) test, which showed a considerable improvement in the compressive strength of soils stabilised by ESP. The ESP-treated soils attained 112 kPa, 118 kPa, and 121 kPa for 15%, 20%, and 25% ESP content, respectively, while the control sample showed a UCC of 62 kPa. The creation of cementitious compounds, particularly calcium silicate hydrates (C–S–H), which result from the reaction between calcium in ESP and the silicates in the clay, is the main cause of this improvement. These findings are consistent with observations by Abiodun and Nalbantoglu, who reported comparable strength gains in clays treated with biowaste. Accordingly, a 20% ESP content represents the optimal mix, providing a balance between strength enhancement and workability.

Table-4: UCC Properties for ESP-Clay Soil Mixes

ESP Replacement	UCC Value (kPa)	Possible Observations
0%(Control Clay)	62kPa	Soft clay alone without treatment
15% ESP	112kPa	Significant improvement due to $CaCO_3$ from eggshells
20% ESP	118kPa	Strength increases in this ESP blend are reported in earlier studies
25% ESP	121kPa	May plateau or slightly decrease if excess ESP causes brittleness or poor mixing

Summary of Findings

A comparative summary of soil behaviour for all ESP–clay blends is presented in Table-5. The 20% ESP mix consistently demonstrated superior performance across all tests, achieving reductions in plasticity and moisture demand, coupled with substantial gains in density, bearing capacity, and compressive strength.[16] These results confirm that eggshell powder works well as an eco-friendly stabiliser for soft clay soils while building roads and embankments.

Table-5: Soil Properties of ESP Blends

S. No.	Property	Clay Soil	Clay Soil + 15% Egg Shell powder	Clay Soil + 20% Egg Shell powder	Clay Soil + 25% Egg Shell powder
1	Liquid Limit	70	55	52	42
2	Plastic Limit	34	28	30	26
3	Specific Gravity	2.68	2.92	2.73	2.78
4	Optimum Moisture Content (%)	34	31	28	29
5	Maximum Dry Density (kN/m^3)	15.72	14.34	15.59	14.83
6	CBR (%)	2.5	4.32	5.86	4.86
7	UCC Value (kPa)	62	112	118	121

Contribution to Sustainable Development Goals (SDGs)

SDG 9: Industry, Innovation, and Infrastructure and SDG 12: Responsible Consumption and Production are strongly aligned with this research. The project reduces dependency on energy-intensive binders like cement and lime while promoting the circular economy by turning waste from bakeries into a useful building material. Additionally, the use of ESP in soil stabilisation helps reduce the carbon emissions that are usually linked to traditional stabilising agents, which supports the creation of low-carbon and sustainable infrastructure systems[17].

CONCLUSION

This research examined the feasibility of utilising eggshell powder (ESP), a biowaste generated from bakery operations, as an eco-friendly stabilising agent for clayey soils. The experiment's findings demonstrated that the addition of ESP considerably enhanced the soil's geotechnical behaviour by improving its characteristics while concurrently decreasing its flexibility and moisture sensitivity. Among the tested proportions, the 20% ESP blend demonstrated the most effective balance of strength and workability, increasing the CBR by approximately 20% and UCC by nearly 90% compared to untreated clay. The outcomes of this research confirm that ESP can serve as an eco-friendly and low-cost alternative to traditional chemical stabilisers such as lime and cement. Its use not only improves soil performance but also mitigates environmental issues associated with eggshell waste disposal. By promoting resource-efficient infrastructure development, this study supports SDG 9: Industry, Innovation, and Infrastructure and SDG-12: Responsible Consumption and Production by turning bakery waste into a useful building material. Future studies should concentrate on evaluating ESP-stabilised soils' long-term resilience to cyclic loading and changing environmental circumstances. Moreover, evaluating the performance of ESP in combination with supplementary industrial byproducts, such as mineral admixtures, could provide valuable insights. Extending the large-scale implementation of ESP stabilisation in rural roadway and embankment construction would further substantiate its practical effectiveness and enhance the promotion of sustainable geotechnical engineering practices.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-9: Industry, Innovation and Infrastructure*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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