

Improvement of Soil Stability and Strength by Integrating Industrial Waste Materials Fly Ash and Steel Slag

Arushi Sharma¹, Rasmeet Kour²,

¹PG student Dept. of Civil Engineering Sri Sai College of Engineering and Technology, Badhani, Punjab, India

²Assistant Professor Dept. of Civil Engineering Sri Sai College of Engineering and Technology, Badhani, Punjab, India

arushi.1331@gmail.com

Abstract – Soil acts as the primary supporting medium for all civil engineering structures. The performance of foundations, pavements, and embankments largely depends on the strength and stability of the underlying soil. However, clayey soils often exhibit low bearing capacity, high plasticity, and significant volume changes due to moisture fluctuations, making them unsuitable for direct construction use, while conventional stabilizers such as cement and lime are effective, their production is costly and environmentally intensive. Industrial by-products like fly ash and steel slag offer a sustainable alternative. Fly ash contributes to strength development through pozzolanic reactions, whereas steel slag improves particle interlocking and stiffness. The utilization of these materials not only enhances soil performance but also supports eco-friendly waste management.

The rapid growth of industries residue should be large quantity of waste material in form of slag and ashes. These materials can be used for soil stabilization due to containing some useful elements like Silica oxide (SiO_2), Calcium oxide (CaO), Iron Oxide (Fe_2O_3) and Steel and other element needed for the soil's gripping Waste material like Steel slag and Fly ash Class F (produced from burning anthracite or bituminous coal, having low amount of calcium fly ashes with carbon contents less than 10%) can add with Clayey Soil in proportion ratio to improve soil behavior and its strength. The mix proportion of industrial waste material i.e. Steel Slag is taken in the ratio of 10%, 15% & 20 % and Fly Ash are taken in ratio of 7%, 14 % 21% respectively.

The examinations conducted to assess geotechnical properties include tests for water content, specific gravity, sieve analysis, liquid limit, and plastic limit. These tests show the results of Steel slag and Fly ash that it improves the geotechnical properties of the soil samples with the waste material Steel slag and fly ash of Class F is useful for clayey soil. The optimum values of mixed material for higher California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) value are achieved in mix ratio 69 % Clayey Soil, 21 % Fly Ash and 10 % Steel Slag

Keywords: California Bearing Ratio (CBR), Free Swell Index, Grain Size Analysis, Standard Proctor Density, Optimum

Values, Specific Gravity, Unconfined Compressive Strength (UCS), Waste Material, Steel slag.

1. INTRODUCTION

The soil forms an important determinant of the strength and stability of the surface of the earth, and it provides the basis for the construction process, farming, and several other activities of man. Several soils have very bad engineering characteristics such as being highly compressible and poor drainage characteristics, which make them not suitable for civil works. This cannot be overcome; hence, the physical attributes of the soil have to be improved to make it stronger. The use of the industrial waste materials can become a sustainable alternative among several soil stabilizers which are used in soil improvement. These consist of industrial effluents like slag from steel mills and fly ash. They not only improve soil mechanics, but also provide an environmentally-friendly approach towards reusing materials which, otherwise, might have posed problems for the environment. Soil stabilization using industrial waste residue has become an important concern in the present times. Soil stabilization with these waste products is cheap and locally available compared to other conventional methods.

It helps to minimize the environmental impact caused by the waste and the process of soil stabilization. Poor soil conditions in various areas demand the investigation of waste-based stabilization techniques. Incorporating industrial waste materials into soil can enhance engineering characteristics and aid in promoting sustainable construction.

To determine the effect of agent stabilizer on soil strength and stability, its potential application for field and extensive construction projects would be assessed.

2. LITERATURE REVIEW

Dwivedi S. et al. (2026): The objective of this investigation is to investigate the behavior of silt soil found in the alluvium by using Rice Husk Ash (RHA) and Ground Granulated Blast Furnace Slag (GGBS). Response Surface Methodology (RSM) will be adopted for determining the optimum blend of the

added material.. Experimental findings reveal that the soil sample shows better compaction characteristics, strength, and stability after the addition of the two materials. It is concluded that RHA and GGBS are economically sustainable techniques for soil stabilization.

Aggarwal V. et al. (2026): In this study, machine learning models have been employed to predict the UCS of clayey soil mixed with waste paper sludge and fly ash. It is clearly observed from the experiments conducted in the laboratory that the use of stabilizers plays a very crucial role in enhancing the mechanical properties of the soil in question. The results provide precise estimations of the UCS of the soil and an explanation of the relationship between different stabilization factors. The findings reveal the ability of artificial intelligence methods in determining properties of stabilized soils.

Chandana B. et al. (2026): In this research study focuses on the application of waste materials like fly ash, lime, and quarry dust for soil stabilization. In order to determine their influence on the engineering behavior of soil, various laboratory experiments such as Atterberg limits, compaction, and (CBR) tests were carried out. The experimental findings have shown that these improvements in the engineering properties through microstructure analysis, it has been found that cementitious phases are developed due to this process.

Li et al. (2025): The current study explores the effect of industrial by-products on the stabilization of expansive soils, using experimental procedures and microstructure analysis. The study evaluates the effects of industrial waste products on the behavior of the expansive soils regarding its engineering and mechanical characteristics. Experimental results have shown significant improvements in strength, reduced swelling ability, and increased stability in soils after stabilization. This analysis indicates formation of cementing phases as well as improvement in bonding of particles. Hence, findings from this study reveal the potentiality of industrial wastes in enhancing expansive soil behavior sustainably.

Wang et al. (2025): In this study, the effect of steel slag and fly ash on the stabilization of subgrade soils for pavement construction is evaluated. Laboratory tests prove that the incorporation of industrial by-products results in improved compaction behavior, higher shear strength, and increased CBR values in the soil. Moreover, the treated soil displays lower plasticity and better resistance against moisture deformations. It can be concluded that the combined use of steel slag and fly ash significantly improves the stability and durability of subgrade soils and may be effectively used as sustainable stabilizers in transportation engineering works.

Gautam N et al. (2025): This paper presents the evaluation of the process of stabilization of expansive subgrade soil with the help of Rice Husk Ash (RHA), Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBS). Several proportions of stabilizing materials have been used to increase the performance of soil. The results revealed improved performance in terms of increasing strength and load carrying capacity while decreasing the swelling properties of soil. The paper highlights the possibility of the use of industrial wastes for sustainable stabilization of soils.

Suresh T et al. (2025): This work explores the improvement of expansive subgrade soil using Fly Ash along with Microbially Induced Calcite Precipitation (MICP). Different proportions of Fly Ash have been used to investigate soil strength and stability. It was observed that there were improvements in soil strength and decreased expansion. The paper clearly highlights that the combination of Fly Ash and MICP is useful and sustainable technology for the improvement of expansive subgrade soils.

Sneha Rathod et al. (2024): study the impact of fly ash, steel slag, and coconut shell as efficient stabilizers in black cotton soil. The test outcomes demonstrated that inclusion of those materials increases the density of soil up to a maximum percentage of 15% mixture.

Sultan Almuaythir et al. (Oct 2024): The study is about SF, CKD, CCR, RHA, and GGBS as sustainable stabilizers for clay soil. With the addition of 3% to 9% of additives, there is an increment in the behavior of soil and reduces the swelling potential plasticity of soil, along with considerable enhance its strength. After 30 days of curing, the UCS increases from 114.64 kPa to 1582.91 kPa with 9% of GGBS content. Analysis of microstructure shows strong bonding materials in the soil.

Alemshet et al. (2023): In this particular study, the objective was analysing the effect of Fly Ash (FA) and Phosphogypsum Steel Slag (PGSS) on the stabilization of expansive soil. The results of this research show the reduction in the Free Swell Index (FSI) by 80.04 percent. Further, there was an increase in the value of Maximum Dry Density (MDD), from 1.46 to 1.93 kg/cm³. There is no clear mention of (OMC), but there was a decrease in this too. The value of CBR has improved; in the case of 20% FA and 10% PGSS, the soaked value was 13.8%, and the unsoaked value was 16.21%. The value of CBR Unconfined Compressive Strength (UCS) increased to 97.47 percent in 14 days curing period.

Worku Firomsa Kabeta et al. (2023): This study highlights the use of steel slag as an additive in enhancing the high expansive clay soils. For the sample containing 25% steel slag, liquid limit reduced from 90.8% to 65.2%. Furthermore, plasticity index has been reduced from 30.5% to 22.7%. Moreover, the swelling was reduced from 104.6% to 58.2%. Mass gravity is 3.05, MDD increased from 1.504 to 1.69g/cm³ and OMC was reduced to 12.01%. (UCS) was increased from 94.3 to 170.6 kPa and (CBR) also increased from 3.64% to 6.82%.

Eilei Guet al. (2023): This study looks at the use of steel slag powder as a partial substitute for cement in enhancing fluidic silty sand. Cement to steel slag ratio of 9:6 produced a strength of >100 kpa and sustainable results. Steel slag provides early strength development while temperature provides enhancement in the formation of CSH/CAH gel. With time, soil structure compacts which confirms.

Witold Waciński, et al. (2023): This research focuses on the use of waste-based additives for soil stabilization with the aim of strengthening its properties such as strength, sealing, frost resistance, and cost-effectiveness. The most effective soil stabilizers based on EPW from WPEF in combination with

waste H_2SO_4 , tire pyrolysis oil emulsion, and NaOH-based ones for sandy soils. The best way to increase the strength of clay soils is through the use of EPW from WPEF with NaOH and waste H_2SO_4 . Soils that met the light traffic stabilisation criterion (1.6 MPa) were EPW from WMP and ash "by-pass" CBPD, other materials meet the subbase material criterion (1.25 MPa). It was found that there is a relationship ($R^2=0.8904$) between frost resistance and capillary rise in control samples but not in the treated soils.

Z. Zhanget al. (2023): The use of MSWI fly ash and FFA in stabilizing a pavement containing expansive clays is discussed in this study. As compared to the FFA which has lower CaO content, the MSWI fly ash has shown a good stabilizing effect on poor clay by reducing its dry density and increasing compressive strength (up to 2 MPA within 28 days). Additionally, fly ash stabilized the poor clay making it durable and resistant to moisture. It was found through the micro structural analysis that they have attained good bonding. The test for heavy metals proved that there is no threat. The ratios of 15-20% MSWI worked perfectly fine in all conditions but 10% MSWI and FFA worked well in dry conditions. As an alternate material, MSWI fly ash may serve better as compared to the conventional materials. Nevertheless, such material requires caution due to its variable compositions.

RESEARCH GAP

Gaps identification is a critical part of every dissertation study and research work. Some gaps identified in the literature review for stabilization of clayey soil using steel slag and fly ash include the following:

1. Partial Awareness of Synergy or Antagonism of Steel Slag and Fly Ash: The study of the stabilization of soil using these two materials separately has been carried out before, but no research has been done on the selected proportions used in this study to evaluate their synergy or antagonism which will give critical insights into the stabilization of clayey soil.

2. Variation in Material Properties: There may be variations in properties of steel slag and fly ash like strength, workability and bonding due to difference in origin. Impact of variation of these properties on their capability to stabilize soil has not been adequately researched yet.

3. Long Term Effect: Most of the studies have been conducted on the laboratory behavior of soil stabilization while the long term behavior of soil stabilized by steel slag and fly ash has not been investigated yet.

4. Environmental Impact Assessment: Use of industrial byproducts processes has an environmental advantage. But there are limited works on metal leaching study of steel slag and fly ash in the stabilized soil. It is important that there should be a proper environmental impact assessment of these materials in terms of their sustainability.

5. Standardization and Engineering Practices: Currently, there is no standardized practice of stabilization of clayey soil using steel slag and fly ash. For the standardization of engineering practices, mixing design guidelines, performance standards and their research are necessary.

6. Economic Feasibility and Cost-benefit Analysis: Though these materials are relatively economical compared to other conventional stabilizers, but still the studies regarding their economic feasibility are lacking. It will help in assessing the economic feasibility and advantages of these materials.

7. Case Studies and Pilot Projects: Mostly all the studies are performed in controlled environment, that means there is no study performed in actual field conditions. Thus it is necessary to perform extensive case studies and pilot projects.

3. MATERIALS AND METHODOLOGY USED

3.1.1 SOIL

Soil samples were obtained from the nearby region at a certain depth below ground level from the locations Jammu city, Jammu & Kashmir. The sample is kept open to the surrounding atmosphere and is exposed to sunlight throughout the day. The soil samples were packed and placed in water-resistant bags, which will ensure that the soil remains dry.

After the collection of the soil sample, we break the soil into small pieces by hammering them in the laboratory. The sieving of the crushed soil is done through 4.75mm sieve and this will be the untreated soil sample for the next experiment.

Soil sample was collected from the Jammu region of Jammu & Kashmir, India and analyzed according to Indian Standard IS 2720. In this study, the soil should be free from any contaminants and lumps are removed after analyzing the soil sample. To increase the stability and strength of the soil, the stabilizing agents such as fly ash and steel slag are added



Fig 3.1 Clayey soil sample

Table 3.1 Engineering Characteristics of Untreated Clayey Soil

SrNo	Properties	Values
1	Clay Content	87.5 %
2	Silt Content	4.3%
3	Fine Sand	5.4%
4	Medium Sand	2.8%
5	Liquid Limit	42.85%
6	Plastic Limit	32.45%
7	Plasticity Index	10.40
8	Specific Gravity	2.64

3.1.2 FLY ASH

Fly ash is one form of pozzolanic waste that is produced by Class F fly ash is produced from coal combustion in thermal power plants consists of a smaller quantity of 10% calcium oxide. Fly ash possesses both cementitious and pozzolanic properties. Silica and alumina in the fly ash require the presence of a binder such as Portland cement, quicklime and hydrated lime along with water to react and form cementitious compounds. It is a powdery material which consists of unburned carbon and metal o.



Fig 3.2 Fly ash sample

Table 3.2 Engineering characteristics of Fly Ash (Class F)

Sr.No	Properties	Values
1	Calcium Oxide (Cao)	9.45%
2	Classification of Fly ash	Type F
3	Silica (SiO ₂)	23.08 %
4	Al ₂ O ₃	30.94%
5	Silt Content	26.84%
6	Fine Sand	79.02%
7	Liquid Limit	43.2%
8	Specific Gravity	2.02

3.1.3 STEEL SLAG:

Steel slag is a by-product generated during steelmaking. Steel slag has fine and coarse granular particles. It has a high specific gravity, high internal friction angle, and good drainage characteristics. This material has been extensively used for soil stabilization purposes. Its features makes it suitable for embankment and sub grade. The density and plasticity of steel slag satisfy the requirements to be used in the construction of such.



Fig 3.3 Steel Slag Sample

Table 3.3 Engineering Characteristics of Steel Slag

Sr.No	Properties	Values
1	Calcium oxide (Cao)	50%
2	Silicon dioxide (SiO ₂)	20%
3	Aluminium Oxides (Al ₂ O ₃)	1.21 %
4	Gravel	44.35 %
5	Sand	55.02%
6	Fines	1.63%
7	Maximum Dry Density (MDD) , gm/cc	2.0 gm/cc

3.2 METHODOLOGY ADOPTED

1. To assess the various characteristics indicated in the objectives, the following experiments will be performed on virgin soil as well as soil having proportions of steel slag and fly ash:
2. Calculation of soil Index characteristics
 - a. Liquid Limit Test
 - b. Plastic Limit Test
3. Specific gravity Test
4. Free Swell Test
5. Grain Size Distribution Test
6. Standard Proctor Test
7. CBR Test
8. UCS Test

4. RESULT ANALYSIS

The Result Analysis section is a crucial part of this study, providing insights gained through meticulous experimentation and data interpretation. The empirical evidence thus collected provides a thorough understanding of the importance of our discoveries. By carefully examining the results, we identify patterns, correlations, and key trends that align with our research objectives. This in-depth analysis facilitates meaningful discussions and leads to well-founded conclusions that contribute to academic discourse in the field. The detailed examination of these results is presented in this chapter as outlined below.

- Specific Gravity Test (Pycnometer test)
(IS: 2720 Part III Section I/II-1980)
- Free swell index test (IS: Code 2720,
PART-40-1977)
- Grain size test (IS Code 2720, PART- 4-1985)
- Consistency Limit test (IS CODE 2720,
PART-5-1980)
- Standard proctor test (IS: 2720 Part VII-1980)
- California bearing ratio test (IS: 2720 Part XVI-1987)
- Unconfined compressive strength test
(IS: 2720 Part X-1991)

4.1 SPECIFIC GRAVITY TEST

Table 4.1 Value of Specific gravity test

Container Number	Unit
Mass of the empty pycnometer (M ₁), (M ₁)	37.16
Mass of pycnometer plus mass of dry soil (M ₂)	63.50
Mass of pycnometer plus soil plus distilled water (M ₃)	154.59
Mass of pycnometer plus fill with water only (M ₄)	138.21
Specific gravity G	2.64

4.2 FREE SWELL INDEX OF CLAYEY SOIL

Table 4.2 Value of Free Swell Index of soil

Sr.No	Sample Level in Water (V _d) ml	Sample Level in Kerosen (V _k) ml	FSI in water (V _d -V _k)	FSI % = $\left(\frac{V_d - V_k}{V_k}\right) \times 100$
1	23	16	7	43.75
2	20	14	6	42.85
3	21	15	6	40

4.3 GRAIN SIZE ANALYSIS RESULT OF CLAYEY SOIL

Table 4.3 Value of Grain size analysis

S. No	Sieve (mm)	Weight of sample retained on sieve	Cumulative weight retained on sieve	Percentage of soil retained on sieve	Percentage of soil passed on sieve
1	2.36	0	0	0	100
2	1.18	0	0	0	100
3	0.6	0	0	0	100
4	0.425	11.4	11.4	1.14	98.86
5	0.3	23	34.3	3.43	96.57
6	0.15	18.1	52.4	5.24	94.76
7	0.075	34.6	87	8.7	91.3

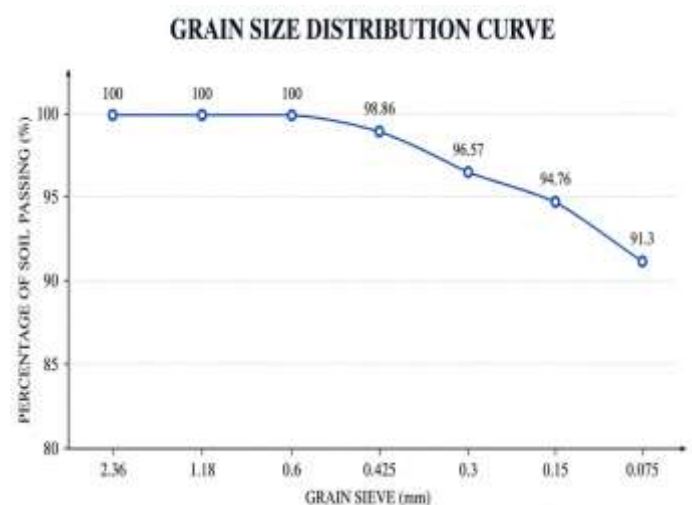


Fig 4.1 Graph of Grain Size

4.4 CONSISTENCY LIMIT (IS: 2720, PART 5 – 1980)

4.4.1 LIQUID LIMIT

Table 4.4.1 Values of Liquid Limit of various mixture

S. No	Mix No	Sample Details	Liquid Limit
1	M1	100% Clayey Soil	42.85
2	M2	93 % Clayey Soil + 7 % Fly Ash	43.50
3	M3	86% Clayey Soil + 14 % Fly Ash	44.10
4	M4	79% Clayey Soil + 21 % Fly Ash	45.05
5	M5	90 % Clayey Soil + 10% Steel Slag	41.09
6	M6	85% Clayey Soil + 15 % Steel Slag	40.12
7	M7	80% Clayey Soil + 20 % Steel Slag	39.15
8	M8	83% Clayey Soil + 7 % Fly Ash + 10 % Steel Slag	37.71
9	M9	78 % Clayey Soil + 7 % Fly Ash + 15% Steel Slag	36.45
10	M10	73 % Clayey Soil + 7 % Fly Ash + 20% Steel Slag	34.15
11	M11	76 % Clayey Soil + 14 % Fly Ash + 10 % Steel Slag	32.41
12	M12	71 % Clayey Soil + 14 % Fly Ash + 15 % Steel Slag	29.44
13	M13	66 % Clayey Soil + 14 % Fly Ash + 20 % Steel Slag	26.36
14	M14	69 % Clayey Soil + 21 % Fly Ash + 10 % Steel Slag	22.80
15	M15	64 % Clayey Soil + 21 % Fly Ash + 15 % Steel Slag	23.60
16	M16	59 % Clayey Soil + 21 % Fly Ash + 20 % Steel Slag	23.30

4.4.2 PLASTIC LIMIT

Table 4.4.2 Values of Plastic Limit of various Mixture

S. No	Mix No	Sample Details	Plastic Limit
1	M1	100% Clayey Soil	32.45
2	M2	93 % Clayey Soil + 7 % Fly Ash	30.96
3	M3	86% Clayey Soil + 14 % Fly Ash	29.64
4	M4	79% Clayey Soil + 21 % Fly Ash	27.35
5	M5	90 % Clayey Soil + 10 % Steel Slag	29.16
6	M6	85% Clayey Soil + 15% Steel Slag	29.79
7	M7	80% Clayey Soil + 20 % Steel Slag	28.90
8	M8	83% Clayey Soil + 7 % Fly Ash + 10% Steel Slag	29.19
9	M9	78 % Clayey Soil + 7 % Fly Ash + 15 % Steel Slag	28.86
10	M10	73 % Clayey Soil + 7 % Fly Ash + 20 % Steel Slag	27.44
11	M11	76 % Clayey Soil + 14 % Fly Ash + 10 % Steel Slag	26.06
12	M12	71 % Clayey Soil + 14 % Fly Ash + 15 % Steel Slag	22.59
13	M13	66 % Clayey Soil + 14 % Fly Ash + 20% Steel Slag	20.57
14	M14	69 % Clayey Soil + 21 % Fly Ash + 10 % Steel Slag	18.16
15	M15	64 % Clayey Soil + 21 % Fly Ash + 15 % Steel Slag	16.79
16	M16	59 % Clayey Soil + 21 % Fly Ash + 20 % Steel Slag	15.67

4.4.3 PLASTICITY INDEX

Table 4.4.3 Values of Plasticity Index of various Mixture

S. No	Mix No	Sample Details	Plasticity Index
1	M1	100% Clayey Soil	10.4
2	M2	93 % Clayey Soil + 7 % Fly Ash	12.54
3	M3	86% Clayey Soil + 14 % Fly Ash	14.46
4	M4	79% Clayey Soil + 21 % Fly Ash	17.70
5	M5	90% Clayey Soil + 10 % Steel Slag	11.93
6	M6	85% Clayey Soil + 15% Steel Slag	10.33
7	M7	80% Clayey Soil + 20 % Steel Slag	10.25
8	M8	83% Clayey Soil + 7 % Fly Ash + 10% Steel Slag	8.52
9	M9	78 % Clayey Soil + 7 % Fly Ash + 15% Steel Slag	7.59
10	M10	73 % Clayey Soil + 7 % Fly Ash + 20% Steel Slag	6.71
11	M11	76 % Clayey Soil + 14 % Fly Ash + 10% Steel Slag	6.35
12	M12	71 % Clayey Soil + 14 % Fly Ash + 15% Steel Slag	6.25
13	M13	66 %Clayey Soil + 14 % Fly Ash + 20% Steel Slag	5.79
14	M14	69 % Clayey Soil + 21 % Fly Ash + 10% Steel Slag	4.64
15	M15	64 % Clayey Soil + 21 % Fly Ash + 15 % Steel Slag	6.81
16	M16	59 % Clayey Soil + 21 % Fly Ash + 20 % Steel Slag	7.6

4.5 STANDARD PROCTOR TEST

Table 4.5 Values of Standard Proctor of various Mixture

S. No	Mix No	Sample Details	MDD	OMC
1	M1	100% Clayey Soil	1.945	8.74
2	M2	93 % Clayey Soil + 7 % Fly Ash	1.902	9.62
3	M3	86% Clayey Soil + 14 % Fly Ash	1.862	10.46
4	M4	79% Clayey Soil + 21 % Fly Ash	1.811	11.68
5	M5	90 % Clayey Soil + 10 % Steel Slag	1.874	10.3
6	M6	85% Clayey Soil + 15 % Steel Slag	1.825	11.42
7	M7	80% Clayey Soil + 20 % Steel Slag	1.771	12.55
8	M8	83% Clayey Soil + 7 % Fly Ash + 10 % Steel Slag	1.82	11.9
9	M9	78 % Clayey Soil + 7 % Fly Ash + 15 % Steel Slag	1.726	13.62
10	M10	73 % Clayey Soil + 7 % Fly Ash + 20 % Steel Slag	1.74	13.48
11	M11	76 % Clayey Soil + 14 % Fly Ash + 10 % Steel Slag	1.801	12.1
12	M12	71 % Clayey Soil + 14 % Fly Ash + 15 % Steel Slag	1.68	14.96
13	M13	66 %Clayey Soil + 14 % Fly Ash + 20% Steel Slag	1.583	16.23
14	M14	69 % Clayey Soil + 21 % Fly Ash + 10% Steel Slag	1.740	13.8
15	M15	64 % Clayey Soil + 21 % Fly Ash + 15 % Steel Slag	1.665	15.6
16	M16	59 % Clayey Soil + 21 % Fly Ash + 20 % Steel Slag	1.512	16.75

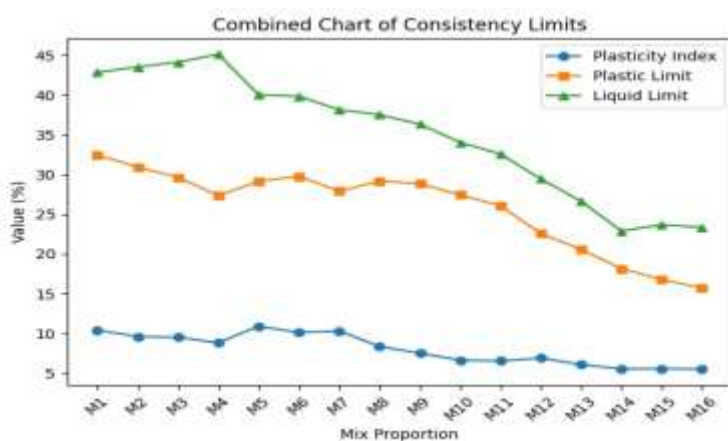


Fig 4.2 Consistency Limit of different value

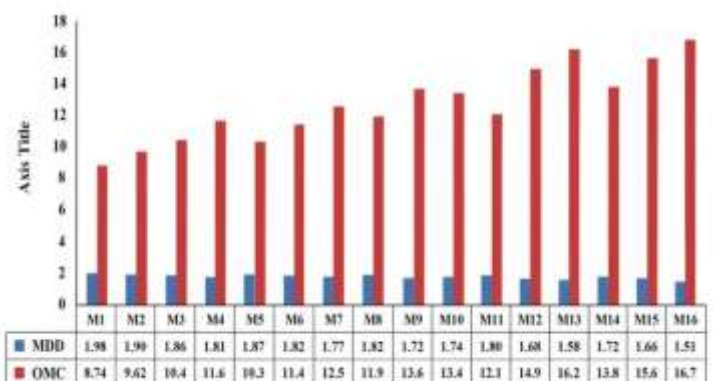


Fig 4.3 Graph of Standard Proctor Test

4.6 CBR TEST

Table 4.6 Values of CBR (Unsoaked & Soaked) of Various Mixture

S. No	Mix No	Sample Details	CBR	
			Soaked	Unsoaked
1	M1	100% Clayey Soil	1.26	3.14
2	M2	93 % Clayey Soil + 7 % Fly Ash	3.19	4.9
3	M3	86% Clayey Soil + 14 % Fly Ash	4.0	6.2
4	M4	79% Clayey Soil + 21 % Fly Ash	6.8	8.2
5	M5	90 % Clayey Soil + 10 % Steel Slag	4.6	7.2
6	M6	85% Clayey Soil + 15 % Steel Slag	6.5	8.0
7	M7	80% Clayey Soil + 20 % Steel Slag	8.2	9.0
8	M8	83% Clayey Soil + 7 % Fly Ash + 10 % Steel Slag	7.9	10.3
9	M9	78 % Clayey Soil + 7 % Fly Ash + 15 % Steel Slag	9.0	11.9
10	M10	73 % Clayey Soil + 7 % Fly Ash + 20 % Steel Slag	9.9	14.5
11	M11	76 % Clayey Soil + 14 % Fly Ash + 10 % Steel Slag	8.9	12.7
12	M12	71 % Clayey Soil + 14 % Fly Ash + 15 % Steel Slag	11.9	15.0
13	M13	66 % Clayey Soil + 14 % Fly Ash + 20 % Steel Slag	13.9	19.4
14	M14	69 % Clayey Soil + 21 % Fly Ash + 10 % Steel Slag	13.4	20.9
15	M15	64 % Clayey Soil + 21 % Fly Ash + 15 % Steel Slag	12.0	20.0
16	M16	59 % Clayey Soil + 21 % Fly Ash + 20 % Steel Slag	12.5	20.2

CBR VALUES

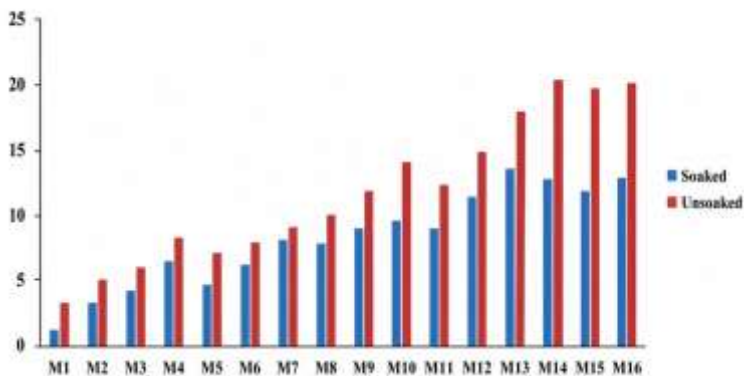


Fig 4.4 Graph of CBR (Unsoaked & Soaked) of Various Mixture

4.7 UCS TEST

Table 4.7 Values of UCS of various mixtures after 7 day & 28 days

S. No	Mix No	Sample Details	UCS	
			7 Days	28 Days
1	M1	100% Clayey Soil	141.42	188.32
2	M2	93 % Clayey Soil + 7 % Fly Ash	151.40	215.60
3	M3	86% Clayey Soil + 14 % Fly Ash	171.25	238.35
4	M4	79% Clayey Soil + 21 % Fly Ash	181.25	263.45
5	M5	90 % Clayey Soil + 10 % Steel Slag	174.45	262.62
6	M6	85% Clayey Soil + 15 % Steel Slag	177.12	258.62
7	M7	80% Clayey Soil + 20 % Steel Slag	180.66	267.66
8	M8	83% Clayey Soil + 7 % Fly Ash + 10 % Steel Slag	181.43	265.43
9	M9	78 % Clayey Soil + 7 % Fly Ash + 15 % Steel Slag	184.66	270.64
10	M10	73 % Clayey Soil + 7 % Fly Ash + 20 % Steel Slag	189.78	278.65
11	M11	76 % Clayey Soil + 14 % Fly Ash + 10 % Steel Slag	188.43	280.38
12	M12	71 % Clayey Soil + 14 % Fly Ash + 15 % Steel Slag	191.69	286.35
13	M13	66 % Clayey Soil + 14 % Fly Ash + 20 % Steel Slag	196.35	291.66
14	M14	69 % Clayey Soil + 21 % Fly Ash + 10 % Steel Slag	198.68	289.88
15	M15	64 % Clayey Soil + 21 % Fly Ash + 15 % Steel Slag	200.16	290.06
16	M16	59 % Clayey Soil + 21 % Fly Ash + 20 % Steel Slag	199.35	289.76

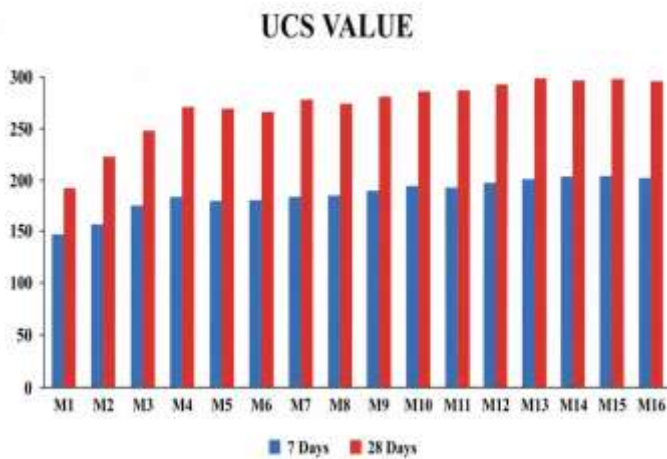


Fig 4.5 Graph of UCS of Various Mix after 7 & 28 days

5. DISCUSSION

5.1 Compaction Characteristics (MDD and OMC)

The addition of fly ash and steel slag influenced the compaction behavior of clayey soil. The Maximum Dry Density (MDD) decreased with increasing stabilizer content, while the Optimum Moisture Content (OMC) increased. This may be due to the lower specific gravity of fly ash and the additional moisture required during compaction.

5.2 California Bearing Ratio (CBR) Characteristics

The CBR values increased significantly under both soaked and unsoaked conditions after stabilization. The improvement indicates enhanced load-bearing capacity and better soil performance. Although soaked CBR values were lower than unsoaked values, the stabilized soil performed considerably better than untreated soil.

5.3 Unconfined Compressive Strength (UCS) Characteristics

The UCS values increased with the addition of fly ash and steel slag and further improved with increasing curing period. The results indicate that the stabilizing materials enhanced the bonding between soil particles, resulting in higher strength.

5.4 Overall Performance of Fly Ash and Steel Slag Stabilization

The combined use of fly ash and steel slag improved the engineering properties of clayey soil by:

- Improving compaction characteristics
- Increasing CBR values
- Enhancing UCS values
- Reducing plasticity characteristics

Among all the mixes tested, **Mix M14 (69% Soil + 21% Fly Ash + 10% Steel Slag)** showed the best overall performance.

5.5 Summary of Discussion

The results demonstrate that fly ash and steel slag are effective stabilizing agents for clayey soil. Their combined use improved strength, bearing capacity, and overall soil performance, making them suitable materials for sustainable soil stabilization.

CONCLUSION

In the tests that were carried out as described above, a thorough analysis was carried out to establish the properties of the clayey soil both in its natural form as well as when Fly Ash (Class F) and Steel Slag had been added to it. The investigation aimed to find out the physical and engineering properties of stabilized clayey soil. The tests were including Consistency Limits, Proctor Density, California Bearing Ratio (Soaked & Unsoaked), and Unconfined Compressive Strength for a period of 7 days to 28 days.

The conclusions drawn from these tests were:

- 1. Soil Properties of Clay Soil:** The soil is made up of more than 90% of particles smaller than 75 microns size sieving, implying that this is a fine grained soil. It has the free swell index of 42.2% approximately, which means that it is slightly swelling. This soil belongs to the category of CI (intermediate plasticity soil) in accordance with the Unified Soil Classification System. This soil cannot be used for embankments and filling purposes because of its properties of clay soil and weak nature.
- 2. Consistency Improvement:** Consistency characteristics of soil get better with the mixing of fly ash and steel slag. Liquid Limit is reduced from 42.85% for natural soil to 22.80% for Mix M14 and Plasticity Index is decreased from 10.4 to 4.64, meaning that soil has become less plastic and easily workable.
- 3. Improvements in Engineering Properties:** Introduction of fly ash and steel slag improved engineering properties of clay soil significantly. There is decrease in Maximum Dry Density (MDD), from 1.945 g/cc for untreated soil to 1.740 g/cc for Mix M14. But an improvement in California Bearing Ratio (CBR) was observed. For soaked condition, CBR value improves from 1.26% to 13.4%, whereas under unsoaked conditions it increased from 3.14% to 20.9%. These results demonstrate a significant enhancement in the load-carrying capacity and overall performance of the stabilized soil.
- 4. Unconfined Compressive Strength (UCS):** The Unconfined Compressive Strength (UCS) increases with the addition of fly ash and steel slag at different proportions. The highest UCS value is obtained at Mix M14, indicating the effectiveness of stabilization in improving soil strength.

5. **Optimum Mix and Strength Behavior:** The mix containing 69% clayey soil, 21% fly ash, and 10% steel slag gives 289.88 KN/m² (Mix M14) after 28 days gives the best performance in terms of strength. The UCS value at 28 days for natural soil is 188.32 kN/m², which increases significantly for stabilized mixes, showing improved strength and reduced compressibility of the soil.
6. **Environmental Impact:** The use of fly ash and steel slag in soil stabilization provides an effective way to utilize industrial waste materials. This approach not only improves soil properties but also helps in reducing environmental pollution and supports sustainable construction practices.

Considering the overall test results, the M14 mixture containing 69% Clayey Soil, 21% Fly Ash, and 10% Steel Slag was found to be the most suitable combination for enhancing soil strength, reducing plasticity, and improving CBR characteristics.

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