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An Experimental Study on Stabilization of Expansive Soil using Metakaolin and Ground Granulated Blast Furnace Slag

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***Abstract:** Expansive soils pose significant challenges to civil engineering structures due to their high shrink–swell behavior under varying moisture conditions. This study investigates the stabilization of expansive soil using metakaolin and Ground Granulated Blast Furnace Slag (GGBS) as sustainable stabilizing agents. Metakaolin and GGBS were initially added individually at proportions of 5%, 10%, 15%, and 20% by dry weight to evaluate their influence on engineering properties. Based on laboratory results, the optimum metakaolin content was identified as 15%. Subsequently, GGBS was incorporated at 10%, 15%, 20%, and 25% along with the optimum metakaolin content to examine the combined effect. Laboratory tests included Atterberg limits, compaction characteristics, unconfined compressive strength (UCS), and California Bearing Ratio (CBR). The results showed a reduction in plasticity and a significant improvement in strength characteristics. The optimum performance was observed at 15% metakaolin and 15% GGBS. The study* **demonstrates that the combined use of metakaolin and GGBS is an effective and sustainable approach for improving expansive soil.**
***Keywords:** Expansive soil, Soil Stabilization, Metakaolin, Ground Granulated Blast Furnace Slag, Unconfined Compressive Strength.*

I. INTRODUCTION

Expansive soils present significant challenges in geotechnical engineering due to their pronounced shrink–swell behavior under varying moisture conditions. These soils undergo substantial volume changes during wetting and drying cycles, leading to differential heave, settlement, cracking, and reduced structural stability, which adversely affects the performance of pavements, foundations, and lightweight structures. Therefore, proper identification and treatment of expansive soils are essential to ensure long-term stability and safety of civil engineering structures. The expansive nature of these soils is primarily attributed to the presence of swelling clay minerals that absorb water and expand during wet conditions and contract upon drying. Conventional stabilization methods using lime and cement are effective; however, the need for sustainable and cost-efficient alternatives has led to the use of industrial by-products such as metakaolin and Ground Granulated Blast Furnace Slag (GGBS). Metakaolin improves strength and reduces plasticity through pozzolanic reactions, while GGBS enhances durability due to its cementitious properties.
The present study aims to evaluate the effectiveness of metakaolin in stabilizing expansive soil, determine the optimum percentage for improving engineering properties, investigate the combined effect of metakaolin and GGBS, assess changes in index properties, compaction characteristics, UCS and CBR values, and identify the most suitable mix proportion for sustainable soil improvement.

II. LITERATURE REVIEW

A. Previous Studies on Metakaolin

1) Rao and Venkatarama Reddy (2010) reported that the addition of metakaolin reduced plasticity index and swelling potential, while improving strength due to pozzolanic reactions.
2) Davidovits (2015) observed improvement in compressive strength and stiffness of soil stabilized with metakaolin, with microstructural evidence of geopolymeric compound formation.
3) Sharma and Gupta (2016) found that the combined use of metakaolin and lime significantly enhanced strength and durability due to the formation of cementitious compounds.
4) Karim et al. (2018) reported a decrease in liquid limit and plasticity index, along with an increase in strength with curing time, recommending metakaolin as a sustainable stabilizer.

5) Wang et al. (2019) showed that metakaolin forms cementitious products that fill voids, resulting in improved soil structure, higher strength, and reduced permeability.
6) Previous Studies on GGBS
7) Pathak et al. (2014) reported that increasing GGBS content decreased OMC and plasticity index, while increasing MDD and compressive strength.
8) Abhijit et al. (2015) observed that GGBS and sisal fiber improved MDD, UCS, and CBR values, with optimum performance at specific proportions.
9) Al-khafaji et al. (2017) reported reduction in plasticity index and improvement in strength, highlighting the latent hydraulic nature of GGBS.
10) Rasool et al. (2017) found that UCS and CBR values increased with GGBS content, with optimum performance around 18%.
11) Sravanthi et al. (2017) reported improvement in Atterberg limits, compaction, UCS, and CBR values with the combined use of GGBS and RBI Grade-81.

Previous studies have primarily focused on the individual use of metakaolin and GGBS for soil stabilization. However, limited research is available on their combined effect and synergistic interaction in improving the engineering properties of expansive soils.

III.MATERIALS AND METHODOLOGY

A. Materials Used

1) *Expansive Soil*: The expansive soil used in this study was collected from Gajulamandyam area, Tirupati district. The soil was air-dried, pulverized, and sieved through a 4.75 mm sieve to obtain a uniform sample. Preliminary characterization indicated high plasticity and swelling potential, classifying it as highly expansive clay. The untreated soil exhibited high liquid limit, high plasticity index, and low strength, making it suitable for stabilization studies. The properties of the soil are presented in Table I.

TABLE I
Properties of Tested Expansive Soil

Sl. No.	Property	Value	IS Codes
1	Specific Gravity	2.57	IS: 2720 (Part III) – 1980
2	Grain Size Distribution		IS: 2720 (Part IV) – 1985
	• Gravel	6.2%	
	• Sand	37.0%	
	• Fine fraction (Silt + Clay)	56.8%	
3	Liquid Limit	115.45%	IS: 2720 (Part V) – 1985
4	Plastic Limit	27.82%	IS: 2720 (Part V) – 1985
5	Plasticity Index	87.63%	IS: 2720 (Part V) – 1985
6	Free Swell Index	410%	IS: 2720 (Part XL) – 1977
7	Soil Classification (IS)	CH	IS: 1498
8	Optimum Moisture Content (OMC)	16.43%	IS: 2720 (Part VII) – 1980
9	Maximum Dry Density (MDD)	1.75 g/cm³	IS: 2720 (Part VII) – 1980
10	Unconfined Compressive Strength (UCS)	160.78 kPa	IS: 2720 (Part X) – 1991
11	CBR (Unsoaked)	6.39%	IS: 2720 (Part XVI) – 1987
12	CBR (Soaked)	5.47%	IS: 2720 (Part XVI) – 1987

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Volume 14 Issue V May 2026- Available at www.ijraset.com

2) *Metakaolin*: Metakaolin is a highly reactive pozzolanic material obtained by calcination of kaolin clay at temperatures ranging from 650°C to 800°C. It is an amorphous aluminosilicate material that improves soil strength through pozzolanic reactions. In this study, metakaolin was used as a fine powder procured from Fnz Laboratory, Bangalore. The chemical composition of metakaolin, as provided by Fnz Laboratory, is presented in Table II.

TABLE II
Chemical Composition of Metakaolin

Sl. No.	**Parameter**	**Value (%)**
1	SiO_2	52.0
2	Al_2O_3	46.0
3	Fe_2O_3	0.60
4	TiO_2	0.65
5	CaO	0.09
6	MgO	0.03
7	Na_2O	0.10
8	K_2O	0.03
9	Loss on Ignition	0.50

3) *Ground Granulated Blast Furnace Slag (GGBS)*: Ground Granulated Blast Furnace Slag (GGBS) is a by-product of the iron and steel industry, obtained by rapid cooling and grinding of molten slag. It is a calcium-rich cementitious material that enhances soil strength and durability through hydration reactions. GGBS is widely used as a sustainable stabilizing agent due to its ability to enhance strength and durability of soil. The GGBS used in this study was procured from GOGGA Minerals and Chemicals, Bangalore. The chemical composition of GGBS, as provided by GOGGA Minerals and Chemicals, Bangalore, is presented in Table III.

TABLE III
Chemical Composition of GGBS

Sl. No.	**Parameter**	**Value (%)**
1	SiO_2	35.20
2	Al_2O_3	18.80
3	CaO	35.38
4	MgO	6.93
5	Fe_2O_3	1.30
6	MnO	0.37
7	Chloride	0.022
8	Total Alkalis	0.58
9	Sulphide Sulphur	0.28
10	Insoluble Residue	1.90
11	Loss on Ignition	0.20
12	Glass Content	93.25
13	Free Moisture	12.00

B. *Experimental Methodology*

In this study, laboratory tests were conducted to determine the index and engineering properties of the soil. Index properties were evaluated using grain size distribution, specific gravity, and Atterberg limits tests. Engineering properties were determined using standard Proctor compaction, unconfined compressive strength (UCS), and California Bearing Ratio (CBR) tests under both soaked and unsoaked conditions.

The soil was stabilized using metakaolin and GGBS, both individually and in combination. Stabilized samples were prepared at different proportions and tested after appropriate curing periods to evaluate the effect on strength, compaction characteristics, and load-bearing capacity.

C. *Mix Designation of Soil Samples*

TABLE IV
Mix Proportions

Mix Type	% Admixtures
Soil + Metakaolin	5%, 10%, 15%, 20%
Soil + GGBS	5%, 10%, 15%, 20%, 25%
Soil+ Optimum Metakaolin + GGBS	Optimum % of Metakaolin + 10%, 15% ,20%, 25% GGBS

TABLE V
Mix Designations for (Soil + Metakaolin) Mixes

Mix Designation	Mix Details
MK0	100% Soil
MK5	95% Soil + 5% Metakaolin
MK10	90% Soil + 10% Metakaolin
MK15	85% Soil + 15% Metakaolin
MK20	80% Soil + 20% Metakaolin

TABLE VI
Mix Designations for (Soil + GGBS) Mixes

Mix Designation	Mix Details
G0	100% Soil
G5	95% Soil + 5% GGBS
G10	90% Soil + 10% GGBS
G15	85% Soil + 15% GGBS
G20	80% Soil + 20% GGBS

TABLE VII
Mix Designations for (Soil + Optimum Metakaolin + GGBS) Mixes

Mix Designation	Mix Details
MK0G0	100% Soil
MKoptG10	Soil + Optimum MK + 10% GGBS
MKoptG15	Soil + Optimum MK + 15% GGBS
MKoptG20	Soil + Optimum MK + 20% GGBS
MKoptG25	Soil + Optimum MK + 25% GGBS

IV. RESULTS AND DISCUSSION

A. *Soil Treated with Metakaolin*

1) *Consistency Characteristics*: The Atterberg limits of untreated soil and soil treated with metakaolin were determined as per IS: 2720 (Part 5)–1985. The liquid limit decreases, while the plastic limit increases with increasing metakaolin content, resulting in a reduction in plasticity index (Figs. 1–3).

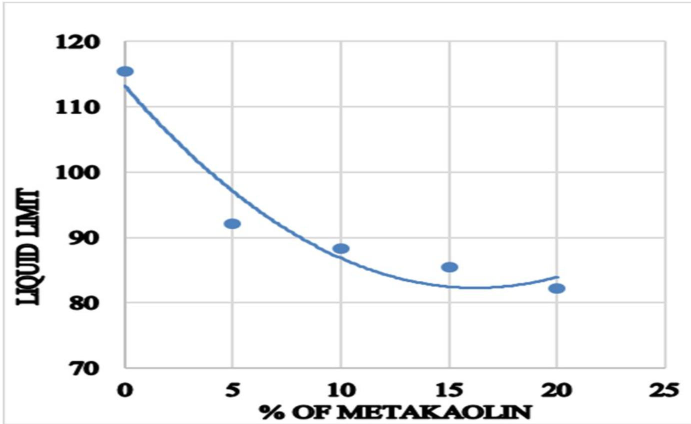

Fig. 1 Variation of Liquid Limit with Metakaolin %

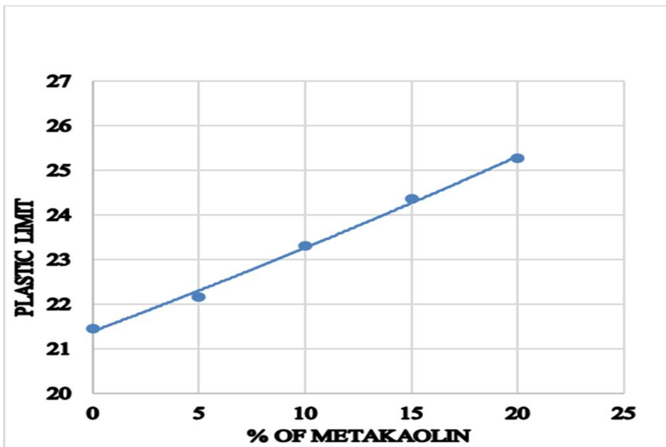

Fig. 2 Variation of Plastic Limit with Metakaolin %

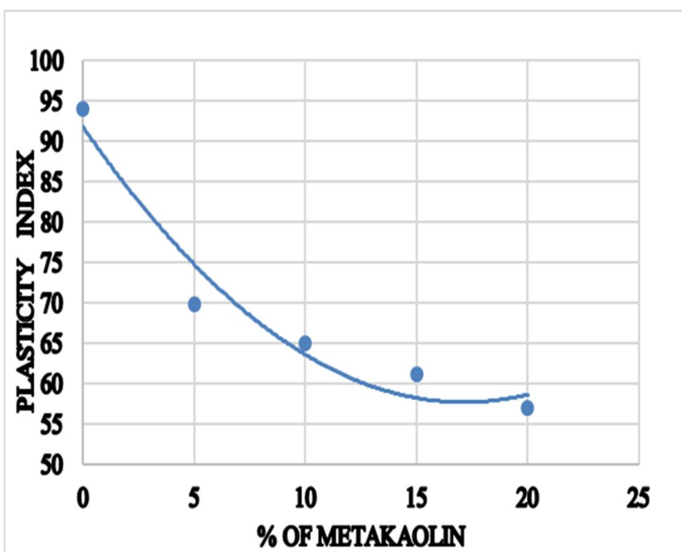

Fig. 3 Variation of Plasticity Index with Metakaolin %

The liquid limit decreases from 115.5% to 82.2%, while the plastic limit increases from 21.5% to 25.3%, reducing the plasticity index from 94% to 56.9%. This indicates improved workability and reduced swelling potential. The behavior is attributed to cation exchange and flocculation–agglomeration, which transform the soil structure from dispersed to flocculated.

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Volume 14 Issue V May 2026- Available at www.ijraset.com

2) *Compaction Characteristics*: Compaction characteristics were determined as per IS: 2720 (Part 7)–1980. The variation of OMC and MDD with metakaolin content is shown in Figs. 4 and 5.

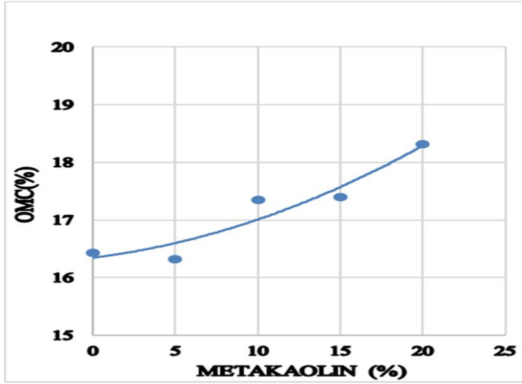

Fig. 4 Variation of OMC with Metakaolin %

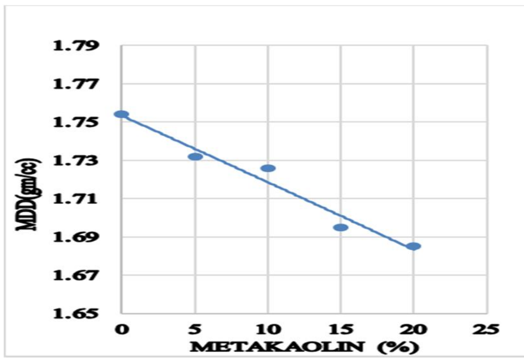

Fig. 5 Variation of MDD with Metakaolin %

The OMC increases from 16.43% to 18.32%, while the MDD decreases from 1.754 g/cm³ to 1.685 g/cm³. This is due to the high surface area and water absorption capacity of metakaolin. The decrease in MDD is attributed to its lower specific gravity and flocculated structure, leading to increased voids.

3) *Unconfined Compressive Strength Test*: The UCS tests were conducted as per IS: 2720 (Part 10)–1991 (Fig. 6).

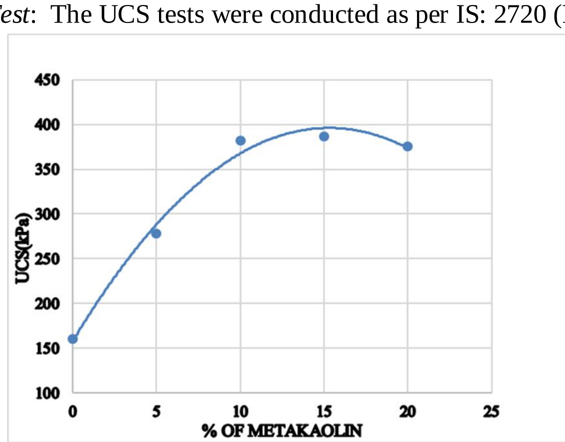

Fig. 6 Variation of UCS of soil treated with Metakaolin %

The UCS increases from 160.78 kPa to a peak of 386.61 kPa at 15% metakaolin, followed by a slight decrease at higher content. The improvement is due to pozzolanic reactions forming cementitious compounds, while the reduction beyond 15% is attributed to excess unreacted metakaolin and increased voids.

B. Soil Treated with GGBS

1) Consistency Characteristics: Atterberg Atterberg limits were determined as per IS: 2720 (Part 5)–1985 (Figs. 7–9).

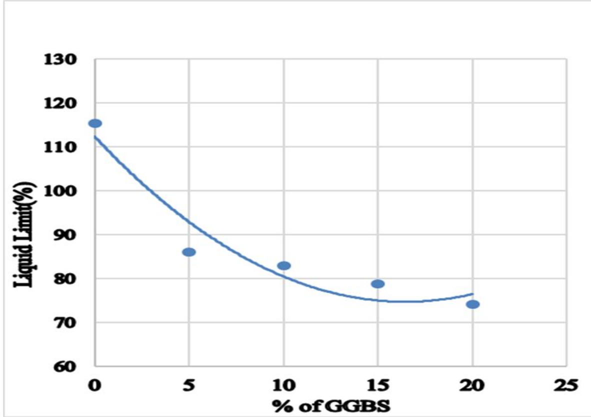

Fig. 7 Variation of Liquid Limit with GGBS %

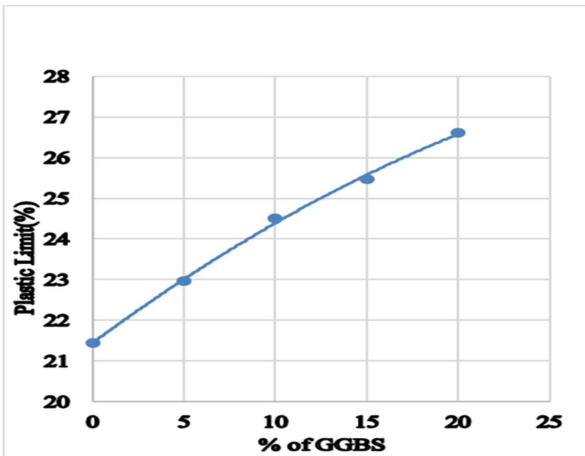

Fig. 8 Variation of Plastic Limit with GGBS %

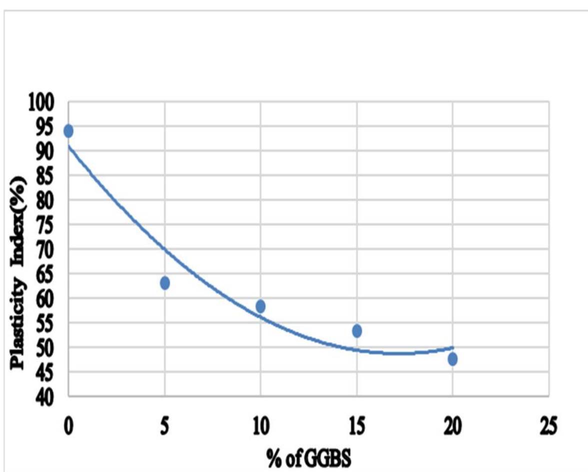

Fig. 9 Variation of Plasticity Index with GGBS %

The liquid limit decreases from 115.5% to 74.2%, while the plastic limit increases from 21.5% to 26.6%, reducing the plasticity index to 47.6%. This behavior is due to flocculation and formation of cementitious compounds such as C–S–H through latent hydraulic reactions.

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2) *Compaction Characteristics:* Compaction characteristics were determined as per IS: 2720 (Part 7)–1980 (Figs. 10 and 11).

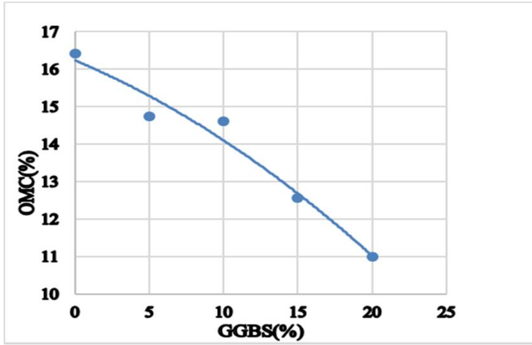

Fig. 10 Variation of OMC with GGBS %

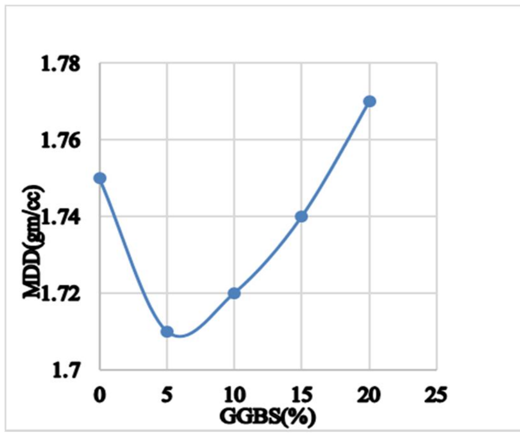

Fig. 11 Variation of MDD with GGBS %

The OMC decreases, while the MDD increases with increasing GGBS content. This is attributed to reduced water affinity, higher specific gravity, and improved particle packing due to cementitious bonding.

3) *Unconfined Compressive Strength Test*: The UCS tests were conducted as per IS: 2720 (Part 10)–1991 (Figs. 12 and 13).

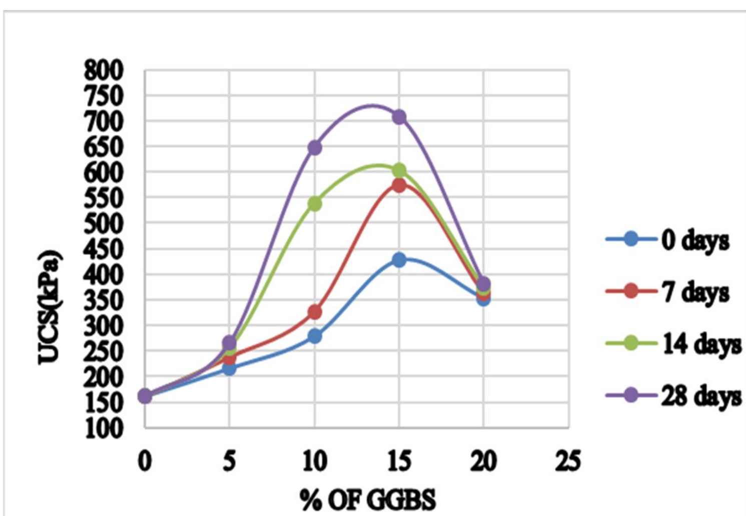

Fig. 12 UCS Values for soil treated with % GGBS

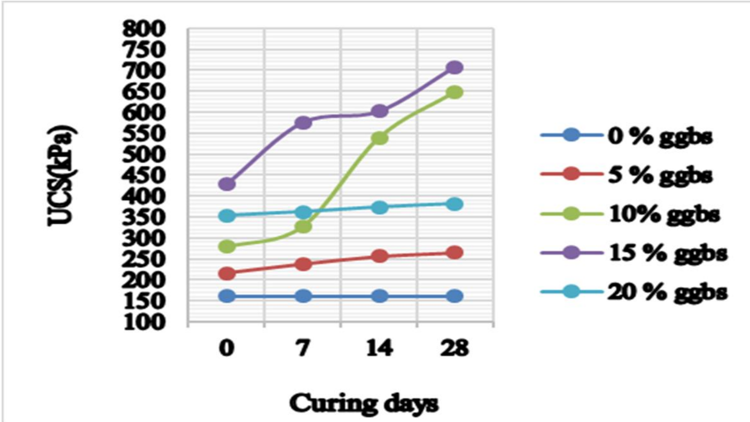

Fig. 13 UCS Values for soil treated with % GGBS and curing days

The UCS increases with GGBS content and curing time due to the formation of cementitious products and improved soil structure.

C. Soil Treated with Optimum Metakaolin and GGBS

1) *Compaction Characteristics*: The Compaction characteristics of soil stabilized with optimum metakaolin (15%) and varying GGBS content were determined as per IS: 2720 (Part 7)–1980 (Figs. 14 and 15).

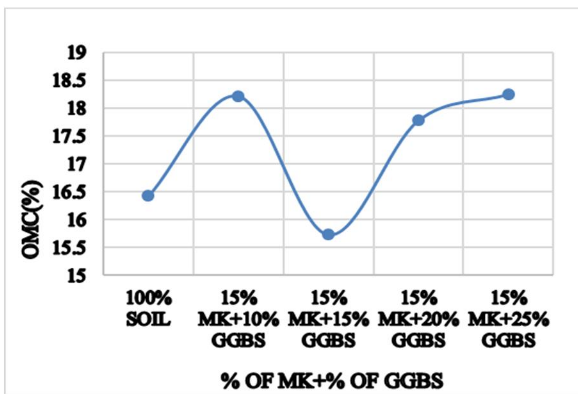

Fig. 14 Variation of OMC at optimum % of MK with GGBS%

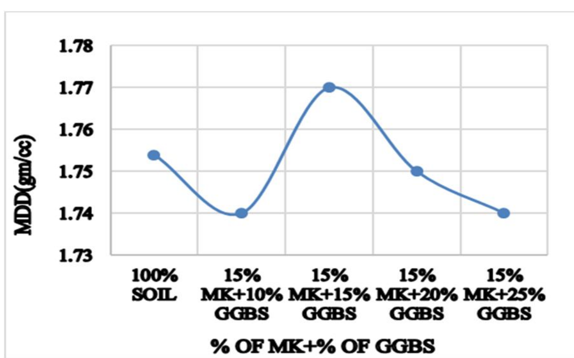

Fig. 15 Variation of MDD at optimum % of MK with GGBS%

The OMC initially increases and then decreases, while the MDD increases to a maximum at MK15G15 and then decreases. This behavior is due to the combined effects of water demand from metakaolin and improved particle packing and cementitious bonding from GGBS.

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2) *Unconfined Compressive Strength Test*: The UCS tests were conducted as per IS: 2720 (Part 10)–1991 (Figs. 16 and 17).

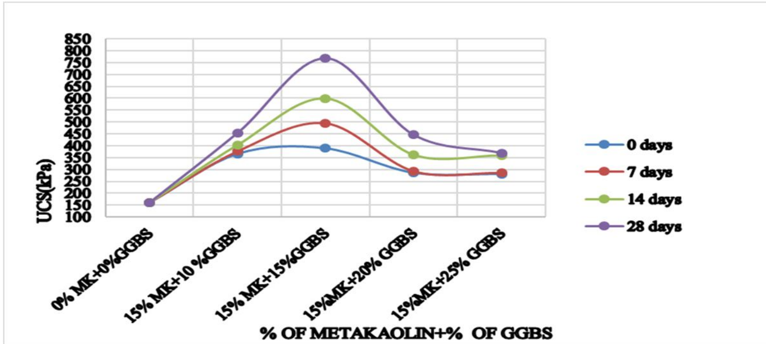

Fig. 16 UCS Values for soil treated with optimum Metakaolin and % GGBS

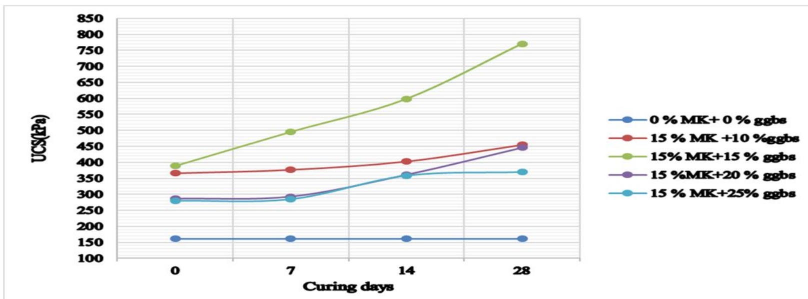

Fig. 17 UCS Values for soil treated with optimum Metakaolin and % GGBS with curing days

The UCS increases significantly from 160.78 kPa to 769.91 kPa at MK15G15 (28 days), followed by a decrease at higher GGBS content. The improvement is due to the formation of C–S–H and C–A–S–H gels, which enhance interparticle bonding and densify the soil matrix.

3) *California Bearing Ratio Test*: The CBR tests were conducted as per IS: 2720 (Part XVI)–1991 (Figs. 18 and 19).

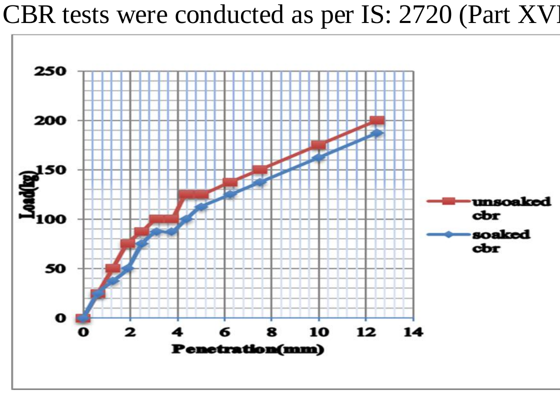

Fig. 18 CBR of Untreated Soil

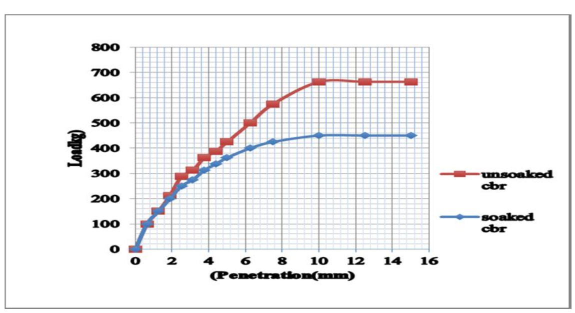

Fig. 19 CBR for Soil Mixed with Optimum Metakaolin (15%) and Optimum GGBS (15%)

The untreated soil shows CBR values of 6.39% (unsoaked) and 5.47% (soaked). After stabilization with 15% metakaolin and 15% GGBS, the values increase to 20.99% and 18.25%, respectively. This improvement is due to the formation of cementitious compounds, enhancing stiffness and load-bearing capacity.

V. CONCLUSIONS

The present study demonstrates that stabilization of expansive soil using metakaolin (MK) and Ground Granulated Blast Furnace Slag (GGBS) significantly improves its engineering properties. The addition of MK and GGBS reduces plasticity and enhances soil consistency due to pozzolanic and cementitious reactions.

The unconfined compressive strength (UCS) and California Bearing Ratio (CBR) values show substantial improvement, with optimum performance observed at 15% MK and 15% GGBS. Beyond this optimum level, a slight reduction in strength is observed due to excess unreacted material and increased voids.

Microstructural analysis confirms the formation of cementitious compounds such as C–S–H and C–A–S–H, which enhance bonding, densification, and strength development. Overall, the combined use of MK and GGBS is an effective and sustainable method for improving expansive soil, making it suitable for pavement subgrade applications.

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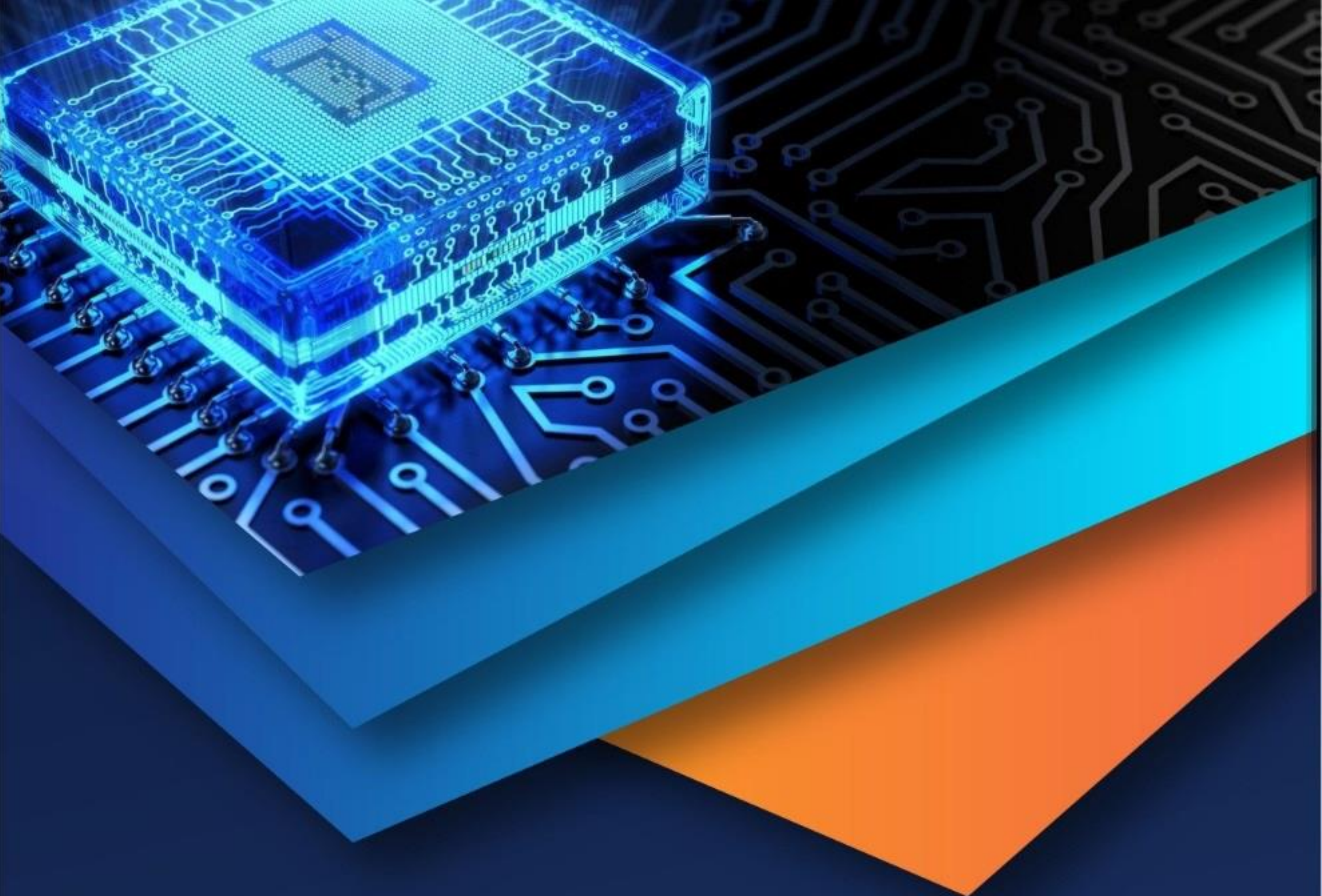

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