

# OPTIMUM SHELL LIME AND METAKAOLIN FOR STABILIZATION OF AN EXPANSIVE SUBGRADE

K. Venkata Bhargav<sup>1</sup>, V. Priyanka<sup>2</sup>, K. Mallikarjuna Rao<sup>3</sup>, S. Vijaya Bhaskar<sup>4</sup>

<sup>1</sup>PG Student, Department of Civil Engineering, S.V.U College of Engineering, Andhra Pradesh, India

<sup>2</sup>PG Student, Department of Civil Engineering, S.V.U College of Engineering, Andhra Pradesh, India

<sup>3</sup>Professor, Department of Civil Engineering, S.V.U College of Engineering, Andhra Pradesh, India

<sup>4</sup>Academic Consultant, Department of Civil Engineering, S.V.U College of Engineering, Andhra Pradesh, India

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**Abstract** - This study investigates the stabilization of expansive clayey soil using metakaolin and shell lime to improve its geotechnical properties for subgrade applications. Expansive soils exhibit significant volume changes due to moisture variation, causing structural instability and pavement distress. Soil samples collected from Gajulamandam, Tirupati, were classified as highly plastic clay (CH) with high liquid limit and free swell index. Laboratory tests including Atterberg limits, Standard Proctor compaction, Unconfined Compressive Strength (UCS), and California Bearing Ratio (CBR) were conducted on untreated and treated soil samples. Metakaolin was added in varying percentages of 5–20%, while shell lime was introduced in proportions of 2–10%. Combined stabilization was also carried out using the optimum metakaolin content. The results showed that metakaolin reduced the liquid limit and plasticity index while improving strength characteristics, with optimum performance observed at 15% replacement. Shell lime further enhanced soil properties through cation exchange, flocculation, and pozzolanic reactions, with significant strength improvement at 6–8% addition. The combined use of metakaolin and shell lime produced higher strength and stiffness due to the formation of cementitious compounds. The study concludes that metakaolin and shell lime are effective, sustainable, and economical stabilizing agents for expansive soils and can be successfully used in pavement subgrade applications.

**Key Words:** Expansive Soil, Highly Plastic Clay, Metakaolin, Pavement Subgrade, Shell Lime.

## 1. INTRODUCTION

Expansive soils, commonly known as black cotton soils, undergo significant swelling and shrinkage due to changes in moisture content. These soils are highly plastic, fine-grained, and possess low stability, which causes damage to pavements and foundations. The volume change behavior mainly depends on the mineralogical composition of the clay particles.

Soil stabilization is necessary to improve the engineering properties of expansive soils. Metakaolin is a highly reactive pozzolanic material produced by calcination of kaolin clay at temperatures between 650°C and 800°C. In the presence of moisture, it reacts with calcium

compounds to form cementitious products such as calcium silicate hydrates (C–S–H), which improve the strength and stability of soil. Therefore, metakaolin can be effectively used for stabilization of expansive soils in subgrade applications.

### 1.1 Objectives of the Study

- To determine the engineering properties of untreated expansive soil.
- To study the effect of metakaolin and shell lime on expansive soil.
- To determine the optimum percentage of metakaolin and shell lime for stabilization.
- To evaluate the improvement in strength characteristics using UCS and CBR tests.
- To assess the suitability of stabilized soil for subgrade applications.

### 1.2 Literature Review

#### 1.2.1 Previous Studies on Metakaolin

Previous studies reported that metakaolin effectively improves the engineering properties of expansive soils. The addition of metakaolin reduces liquid limit and plasticity index while increasing UCS and CBR values through pozzolanic reactions and formation of cementitious compounds. The stabilized soil exhibits improved strength, durability, and reduced compressibility, making metakaolin a sustainable stabilizing material for expansive soils.

#### 1.2.2 Previous Studies on Lime

Studies on lime stabilization showed significant improvement in expansive soil properties. Lime treatment reduces swelling potential and plasticity characteristics while enhancing compaction, UCS, and CBR values. The improvement is mainly due to cation exchange, flocculation, and pozzolanic reactions. Lime stabilization also increases the bearing capacity and durability of subgrade soils, making it suitable for pavement applications.

## 2. MATERIALS AND METHODOLOGY

Table -2: Properties of Metakaolin

### 2.1 Materials Used

#### 2.1.1 Expansive Soil

Expansive soils exhibit significant swelling and shrinkage behavior due to variations in moisture content under constant stress conditions. These soils are commonly found in semi-arid regions and are highly problematic for pavement and foundation construction. In the present study, expansive soil was collected from Gajulamandyam Industrial Area, Tirupati, to evaluate its geotechnical properties and suitability for stabilization using metakaolin and shell lime.

Table -1: Properties of Expansive Soil

S.No	Property	Value
1	Specific Gravity	2.57
2	Atterberg Limits <ul style="list-style-type: none"> <li>Liquid Limit</li> <li>Plastic Limit</li> <li>Plasticity Index</li> </ul>	115.5% 27.8% 87.5%
3	Light Compaction Test <ul style="list-style-type: none"> <li>Optimum Moisture Content</li> <li>Maximum Dry Density</li> </ul>	17% 1.69 g/cc
4	Unconfined Compressive Strength	160.78(kPa)
5	Free Swell Index	410%
6	Hydrometer Analysis <ul style="list-style-type: none"> <li>Gravel</li> <li>Sand</li> <li>(Silt + Clay)</li> </ul>	6.2% 37.0% 56.8%
7	Soil Classification	CH
8	California Bearing Ratio <ul style="list-style-type: none"> <li>Un soaked</li> <li>Soaked</li> </ul>	6.39 5.47

#### 2.1.2 Metakaolin

Metakaolin is a highly reactive pozzolanic material produced by the controlled calcination of kaolin clay at temperatures ranging from 650°C to 800°C. During heating, the crystalline structure of kaolinite loses chemically bound water and transforms into an amorphous reactive material known as metakaolin. In this study, metakaolin was collected from FNZ Laboratory, Bangalore, and used as a stabilizing agent for expansive soil.

Sl No.	Parameters	Test Results
1.	SiO <sub>2</sub>	52.0%
2.	Al <sub>2</sub> O <sub>3</sub>	46.0%
3.	Fe <sub>2</sub> O <sub>3</sub>	0.60%
4.	TiO <sub>2</sub>	0.65%
5.	CaO	0.09%
6.	MgO	0.03%
7.	Na <sub>2</sub> O	0.10%
8.	K <sub>2</sub> O	0.03%
9.	LOSS OF IGNITION	0.50%

#### 2.1.3 Shell Lime

Shell lime is a calcium-based material obtained by burning snail shells rich in calcium carbonate (CaCO<sub>3</sub>). It acts as a natural and sustainable source of lime and is widely used for soil stabilization due to its cementitious properties. In the present study, shell lime was obtained from Antony Cool Tile, Chennai, and used to improve the engineering properties of expansive soil.

Table -3: Properties of Shell Lime

S.NO	Analysis (As per IS1540/1978)	Results Obtained
1	Purity of Calcium Hydroxide as Ca(OH) <sub>2</sub>	98.20%
2	Moisture Content	0.005%
3	Acid Insoluble Matter as SiO <sub>2</sub>	0.01%
4	MgO	0.01%
5	Iron as Fe <sub>2</sub> O <sub>3</sub>	0.001%
6	Alumina as Al <sub>2</sub> O <sub>3</sub>	0.01%
7	CO <sub>2</sub>	1.1%
8	Mn <sub>2</sub> O <sub>3</sub>	0.001%
9	95% Material Pass Through 75 micron mesh	Passed

## 2.2 Experimental Methodology

This study investigates the stabilization of expansive soil collected from Gajulamandiyam Industrial Area, Tirupati using metakaolin and shell lime. The untreated soil was first tested for its basic geotechnical properties, including Atterberg limits, compaction characteristics, UCS, and CBR as per IS standards. Metakaolin was then added in varying proportions (5%–20%) to identify the optimum content. Based on this, further stabilization was carried out by adding shell lime (2%–10%) along with the optimum metakaolin content. All soil mixtures were compacted at their OMC and MDD and tested to evaluate improvements in engineering behavior. The results of treated soils were compared with untreated soil to determine the most effective combination for stabilization.

### 2.2.1 Mix Designation of Soil Samples

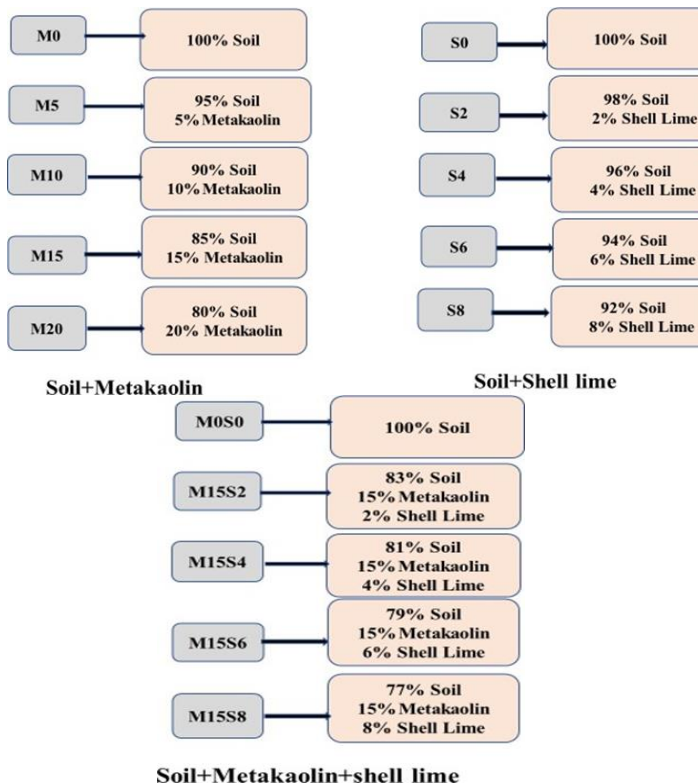


Chart -1: Mix Designation of Soil Samples

## 3. RESULTS AND DISCUSSION

### 3.1 Soil Mixed with Metakaolin

#### 3.1.1 Atterberg Limits

Atterberg limits of the treated soil were determined as per IS: 2720 (Part 5) – 1985. The liquid limit shows variation with the increase in percentage of metakaolin. The plastic limit also changes with the addition of stabilizers. The

variation of liquid limit with percentage of stabilizers is shown in Fig. 1, and the variation of plastic limit is shown in Fig. 2. The plasticity index of soil with varying percentages of metakaolin is presented in Fig. 3.

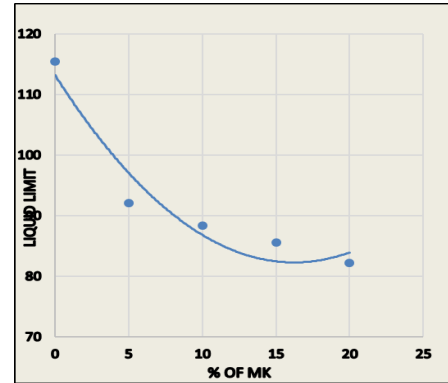


Fig -1: Variation of Liquid limit with addition % MK

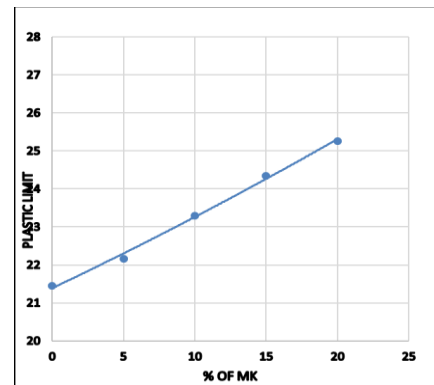


Fig -2: Variation of Plastic limit with addition % MK

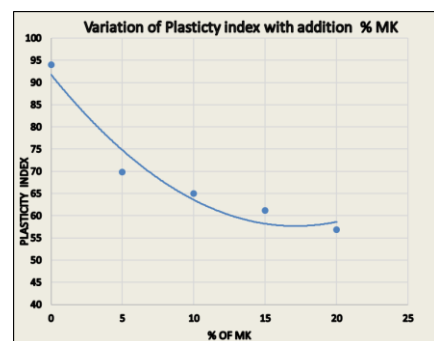


Fig -3: Variation of Plasticity Index with addition % MK

The Atterberg limits show notable improvement with increasing metakaolin content. The liquid limit decreases from 115.5% to 82.2%, while the plastic limit increases from 21.5% to 25.3%, leading to a reduction in plasticity index from 94% to 56.9%. This improvement is attributed to cation exchange, flocculation–agglomeration, and reduced diffuse double layer thickness, which modify the soil structure and lower its water affinity.

### 3.1.2 Compaction Characteristics

The Compaction characteristics of natural soil and stabilized soil mixtures were determined in accordance with IS: 2720 (Part 7) – 1980. Standard Proctor tests were conducted to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) for soil blended with varying percentages of Metakaolin (MK).

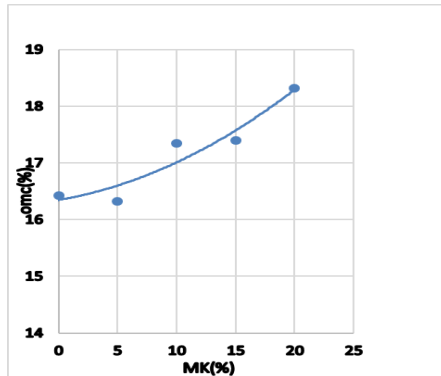


Fig -4: Variation of OMC with addition of % Metakaolin

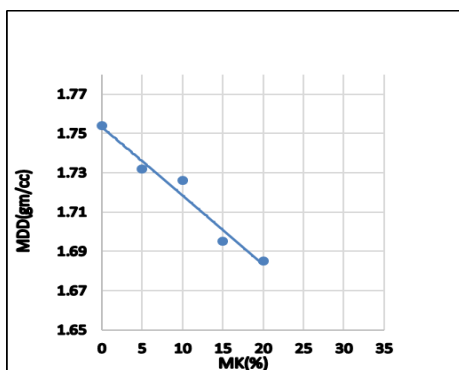


Fig -5: Variation of MDD with addition of % Metakaolin

The compaction results show that with increasing metakaolin content, the Optimum Moisture Content (OMC) increases from 16.43% to 18.32% due to higher water demand caused by its large surface area and pozzolanic activity. At the same time, the Maximum Dry Density (MDD) decreases from 1.754 g/cc to 1.685 g/cc because of the lower specific gravity of metakaolin and formation of a flocculated soil structure. Overall, metakaolin modifies soil behavior by increasing moisture requirement and reducing dry density.

### 3.1.3 Unconfined Compressive Strength

To evaluate the strength characteristics and effectiveness of stabilization, the Unconfined Compressive Strength (UCS) test was conducted on natural soil and soil stabilized with varying percentages of Metakaolin in accordance with IS: 2720 (Part 10) – 1991.

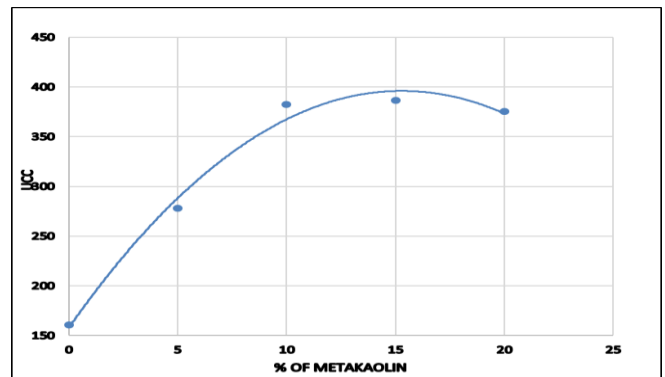


Fig -6: Variation of UCC of soil mixed with addition of Metakaolin in different percentages

The UCC increased from 160.78 kPa for natural soil to a maximum of 386.61 kPa at 15% metakaolin, indicating significant strength enhancement due to pozzolanic reactions. A slight reduction at 20% suggests excess stabilizer beyond the optimum level. Therefore, 15% metakaolin is identified as the optimum dosage for strength improvement.

## 3.2 Soil Mixed with Shell Lime

### 3.2.1 Atterberg Limits

The Atterberg limits of the treated soil were determined as per IS: 2720 (Part 5) – 1985. The liquid limit shows variation with the increase in percentage of shell lime. The plastic limit also changes with the addition of stabilizers. The variation of liquid limit with percentage of stabilizers is shown in Fig. 7, and the variation of plastic limit is shown in Fig. 8. The plasticity index of soil with varying percentages of shell lime is presented in Fig 9.

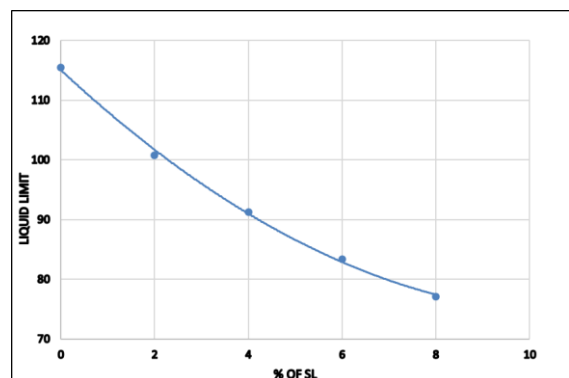


Fig -7: Variation of Liquid limit with addition % Shell Lime

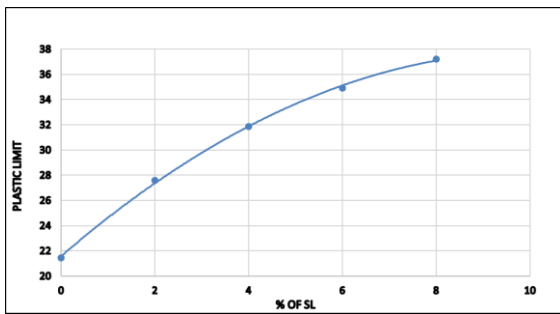


Fig -8: Variation of Plastic limit with addition % Shell Lime

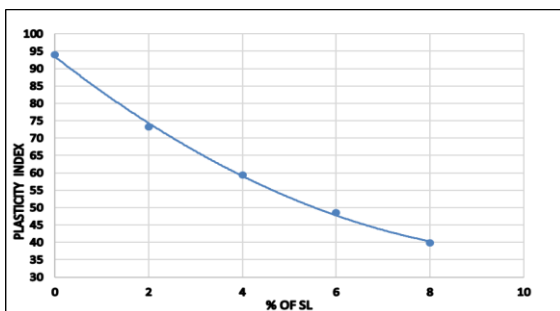


Fig -9: Variation of Plasticity Index with addition % Shell Lime

The addition of metakaolin resulted in a progressive decrease in liquid limit and plasticity index, while plastic limit increased with dosage. The plasticity index reduced from 94.00% to 39.90% at 20% metakaolin, indicating significant reduction in soil plasticity due to pozzolanic reactions and flocculation mechanisms.

### 3.2.2 Compaction Characteristics

Compaction characteristics of natural soil and stabilized soil mixtures were determined in accordance with IS: 2720 (Part 7) – 1980. Standard Proctor tests were conducted to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) for soil blended with varying percentages of Shell Lime.

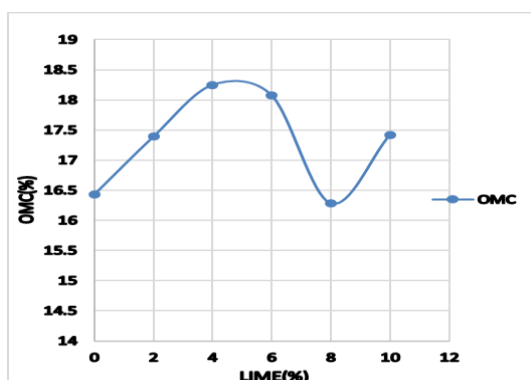


Fig -10: Variation of OMC with addition of % Shell Lime

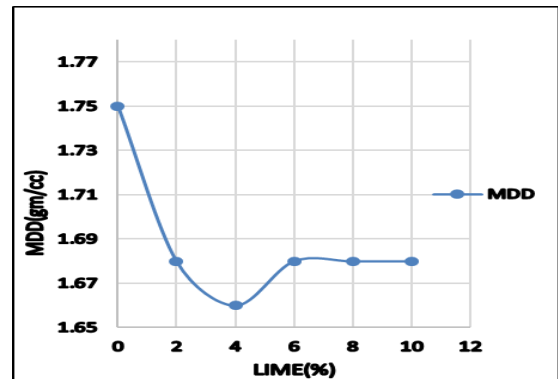


Fig -11: Variation of MDD with addition of % Shell Lime

The OMC increased from 16.43% to 18.25% at 4% lime content due to hydration and flocculation reactions, followed by minor fluctuations at higher dosages. The MDD decreased from 1.75 g/cc to 1.66 g/cc and remained nearly constant thereafter. These results indicate that lime addition increases moisture demand while slightly reducing dry density.

### 3.2.3 Unconfined Compressive Strength

To evaluate the strength characteristics and effectiveness of stabilization, the Unconfined Compressive Strength (UCS) test was conducted on natural soil and soil stabilized with varying percentages of Shell Lime in accordance with IS: 2720 (Part 10) – 1991.

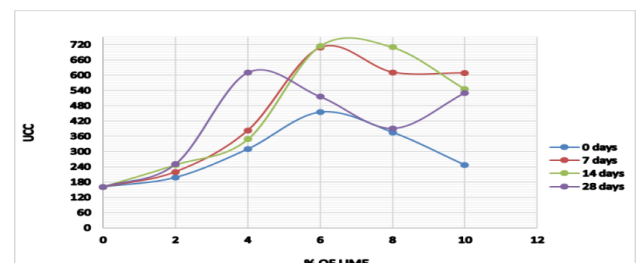


Fig -12: Variation of UCC of soil mixed with addition of Metakaolin in different percentages

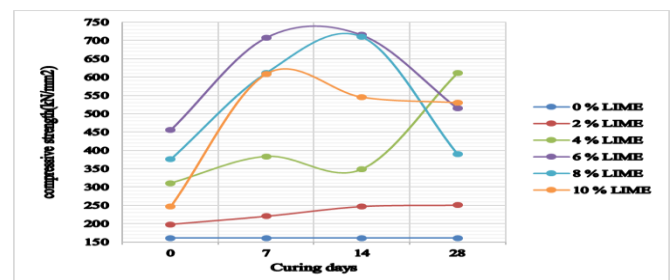


Fig -13: Variation of UCC of soil mixed with % Metakaolin and curing days

The UCS of the soil increases with lime addition and curing time, reaching an optimum at about 6–8% lime content. In this study, strength rose from 160.78 kPa (untreated) to a maximum of 715.07 kPa at 6% lime after 14 days of curing, but decreased at higher lime contents due to excess unreacted lime, increased voids, and carbonation effects. Overall, lime significantly improves soil strength up to an optimum dosage, after which the improvement reduces.

### 3.3 Soil Mixed with Optimum Metakaolin and Shell Lime

#### 3.3.1 Compaction Characteristics

The compaction characteristics of natural soil and stabilized soil mixtures were determined in accordance with IS: 2720 (Part 7) – 1980. Standard Proctor tests were conducted to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). In this study, the soil was first stabilized with the optimum percentage of metakaolin and then blended with varying percentages of shell lime (2%, 4%, 6%, 8%, and 10%). The effect of shell lime on the compaction behavior of the metakaolin-treated soil was evaluated by determining the corresponding OMC and MDD values. The variations in OMC and MDD with increasing shell lime content are presented in Table and illustrated in the corresponding figures.

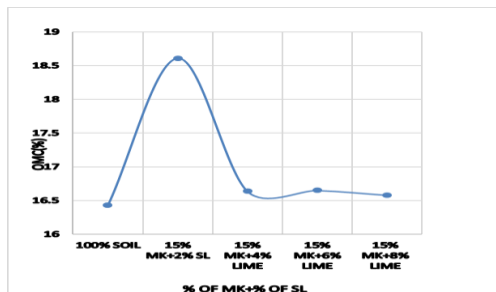


Fig -14: Variation of OMC with Optimum Metakaolin and addition of % Shell Lime

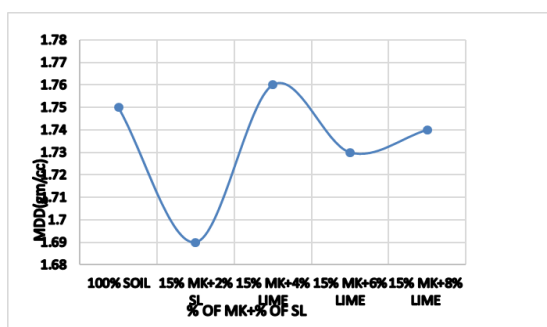


Fig -15: Variation of MDD with Optimum Metakaolin and addition of % Shell Lime

The compaction characteristics of soil stabilized with 15% metakaolin and varying shell lime contents show that the Optimum Moisture Content (OMC) increases from 16.43% (untreated) to 18.61% at 2% lime due to flocculation and hydration effects, with only minor variations at higher lime dosages. The Maximum Dry Density (MDD) decreases initially to 1.69 g/cc at 2% lime and then remains nearly stable between 1.73–1.76 g/cc. Overall, lime addition increases moisture demand and causes slight changes in density due to soil structure modification.

#### 3.3.2 Unconfined Compressive Strength

To evaluate the strength characteristics and effectiveness of stabilization, the Unconfined Compressive Strength (UCS) test was conducted on natural soil and soil stabilized with optimum metakaolin varying percentages of Shell Lime in accordance with IS: 2720 (Part 10) – 1991.

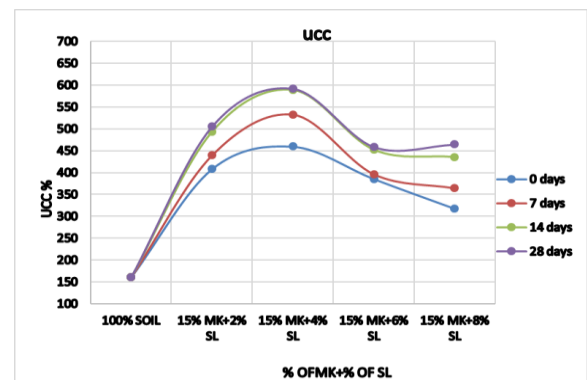


Fig -16: Variation of UCC of soil mixed with addition of Metakaolin in different percentages

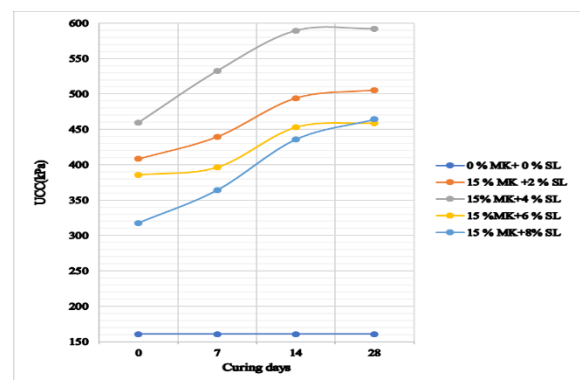


Fig -17: Variation of UCC of soil mixed with addition of Lime at different curing days (0,7,14,28)

The UCS of soil improves significantly with the combined use of metakaolin (MK) and shell lime (SL), along with curing time, reaching an optimum at MK15+SL4. The strength increases from 160.78 kPa (untreated) to a maximum of 592.07 kPa after 28 days of curing, but

decreases at higher lime contents. This improvement is due to the synergistic reaction between lime and metakaolin, leading to the formation of cementitious compounds (C-S-H and C-A-H) through cation exchange, flocculation, and pozzolanic reactions. Overall, the combined stabilizers significantly enhance soil strength and alter its behavior.

### 3.2.3 California Bearing Ratio

CBR of natural soil and blended mixes were determined as per IS: 2720 (Part XVI) – 1991. The Fig. 18 and Fig. 19 shows the CBR curves of soil mixed with optimum Metakaolin and varying percentages of Shell Lime.

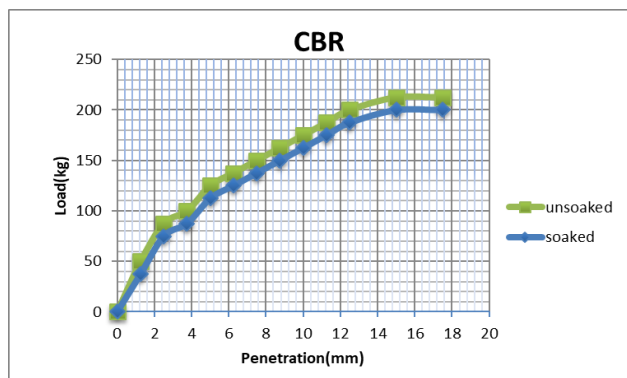


Fig -18: CBR of Untreated soil

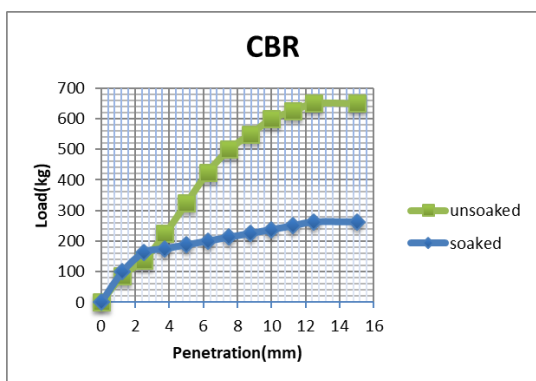


Fig -19: CBR of soil treated with optimum Metakaolin and Optimum Shell Lime

The CBR values show a significant improvement after stabilization with 15% metakaolin and 4% shell lime. The untreated soil has low strength with CBR values of 6.39% (unsoaked) and 5.47% (soaked), indicating poor load-bearing capacity. After treatment, the values increase to 15.82% (unsoaked) and 11.86% (soaked). This improvement is due to pozzolanic reactions between metakaolin and lime, forming cementitious compounds like C-S-H and C-A-S-H, which enhance soil strength.

## 4. CONCLUSIONS

The study shows that stabilization of expansive soil using metakaolin, shell lime, and their combination significantly improves its engineering properties. With increasing metakaolin content, the liquid limit and plasticity index decrease while the plastic limit increases. The OMC increases and MDD shows variation, while UCS improves up to an optimum of 15% metakaolin, reaching about 2.41 times that of untreated soil. Similarly, shell lime treatment reduces plasticity, increases OMC, and improves UCS up to 6% lime, giving a maximum strength of about 4.40 times the untreated soil. For the combined treatment, the optimum mix of 15% metakaolin and 4% lime gives the best performance, with UCS increasing to 3.66 times after 28 days of curing. The same mix also significantly improves CBR values, increasing unsoaked CBR from 6.39% to 15.82% and soaked CBR from 5.47% to 11.86%, confirming enhanced strength and load-bearing capacity of the treated soil.

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