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Evaluation Studies on Marine Clay Stabilized with Foundry Sand and Geopolymer as Subgrade for Flexible Pavement

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Abstract: Marine clay deposits prevalent along coastal corridors present significant geotechnical challenges due to their low shear strength, high compressibility, and volumetric instability under fluctuating moisture conditions. This research proposes an advanced stabilization strategy for marine clay subgrades through the synergistic use of foundry sand (FS) and alkali-activated geopolymer (AAG) binders formulated from sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The objective of present investigation is to develop a sustainable and high-performance subgrade material suitable for flexible pavement applications in coastal environments. A comprehensive experimental program was carried out to investigate the effects of foundry sand content and activator molarity on the mechanical and durability performance of the stabilized marine clay. Laboratory tests including Atterberg limits, compaction characteristics, unconfined compressive strength (UCS), and California Bearing Ratio (CBR) tests were conducted. The inclusion of 10% FS and 1.5% AAG reduced plasticity index by 71%, increased maximum dry density from 1.58 to 1.72 g/cc, and improved soaked CBR from 1.34% to 8.07%. These findings confirm the potential of FS–AAG blends as sustainable, high-performance stabilizers for marine clay subgrades in flexible pavement applications.

The optimized formulation exhibited substantial gains in Compaction and CBR values with improved moisture resistance, confirming its suitability for sustainable pavement foundation systems. This study contributes to the advancement of eco-efficient soil stabilization techniques by utilizing industrial by-products and minimizing dependence on conventional cementitious materials in coastal infrastructure development.

Keywords: Marine clay, Foundry sand (FS), Alkali-activated geopolymer (AAG), Subgrade stabilization, Coastal pavements, Sustainable materials.

I. INTRODUCTION

The formation of marine clay soils along India's coastline is the result of prolonged geological, sedimentary, and geochemical processes spanning thousands of years. Extending nearly 7,500 kilometers, India's coast bounded

by the Arabian Sea to the west, the Bay of Bengal to the east, and the Indian Ocean to the south represents a highly dynamic transition zone where terrestrial and marine processes continuously interact. Over geological time, these interactions have led to the deposition, accumulation, and consolidation of fine-grained sediments, resulting in the development of soft, highly compressible marine clays that characterize many coastal regions today.

The origin of these deposits dates back to the Quaternary period, particularly the Holocene epoch (approximately 6,000–10,000 years ago). During this period, alternating glacial and interglacial cycles triggered sea-level fluctuations, causing repeated phases of marine transgression and regression. Rising sea levels inundated coastal lowlands, creating tranquil depositional environments where fine sediments transported by rivers settled out of suspension. Subsequent sea-level retreat exposed these sediments, which gradually consolidated under self-weight and overburden pressure to form extensive marine clay beds along India's coastal belt.

Within the Visakhapatnam–Chennai Industrial Corridor (VCIC), which traverses the coastal plains of Andhra Pradesh and Tamil Nadu, marine clay deposits are particularly prominent near Kakinada, Machilipatnam, and the Chennai region. Fine-grained sediments carried by the Godavari and Krishna rivers were deposited in deltaic and estuarine zones under low-energy hydrodynamic conditions. The influence of saline seawater induced cation exchange reactions, enhancing soil plasticity and compressibility, while the accumulation of decomposed organic matter contributed to high moisture content and reduced shear strength. In several VCIC localities, natural water content exceeds 100%, reflecting the extremely soft and weak nature of these soils. Over time, secondary processes such as oxidation, leaching, and desiccation further altered their mineralogical and mechanical characteristics.

From an engineering perspective, these marine clay deposits pose significant challenges to infrastructure development along the VCIC. Their high compressibility, low bearing capacity, and poor drainage properties can lead to excessive settlement and structural instability. To mitigate these issues, various ground improvement methods including lime or cement stabilization, preloading with vertical drains, the use of industrial by-products such as foundry sand, an geosynthetic reinforcement are adopted. Understanding the genesis and behavior of these clays is essential for designing sustainable, resilient, and durable coastal infrastructure within this rapidly developing industrial corridor connecting Visakhapatnam and Chennai.

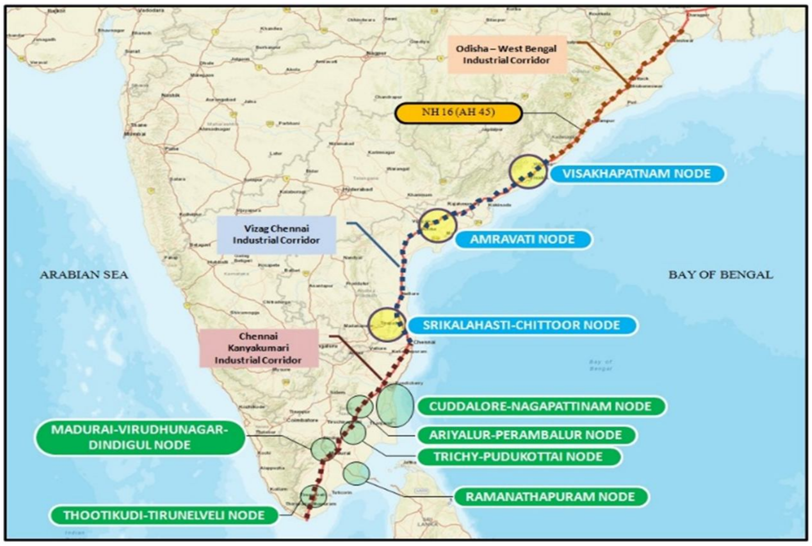


Figure 1 Map showing the Visakhapatnam–Chennai Industrial Corridor (VCIC)

II. MATERIALS AND METHODS

A. Marine Clay

The soil used in this study is marine clay, collected from Kakinada Sea Ports Limited at a depth of 1.5 meters below ground level. Kakinada Port is located on the east coast of India at a latitude of 16°56′ N and longitude of 82°15′ E. The region lies within the Godavari deltaic plain, where marine clay is typically soft, highly plastic, and compressible. This soil type is geotechnically challenging due to its low shear strength and poor drainage, making it suitable for studies on soil stabilization and improvement.

B. Foundry Sand

Foundry sand (FS) is a specialized engineered material widely used in metal casting industries such as automotive, aerospace, and heavy machinery manufacturing. It mainly consists of high-purity silica sand, known for its excellent thermal stability, uniform grain size, high permeability, and superior reusability. These characteristics ensure accurate mould formation, enhanced surface finish, and the structural integrity of cast products. In the present study, foundry sand was collected from Sri Bhavani Castings Ltd., Kakinada, a reputed foundry industry in Andhra Pradesh, India, which employs conventional green sand-casting methods. The process generates considerable quantities of foundry sand (FS), which can be reused effectively in geotechnical and construction applications.

In addition to this, several other metal casting and steel industries are located in the Dhavaleswaram industrial region, near Rajahmundry, Andhra Pradesh. Prominent among them are Shiva Shakti Steel and SS Engineering, both contributing significantly to local casting and fabrication sectors by producing ferrous and non-ferrous components for infrastructure and machinery.

Different types of FS include green sand (silica sand with bentonite and water), resin-coated sand for precision castings, and chromite sand for high-temperature applications.

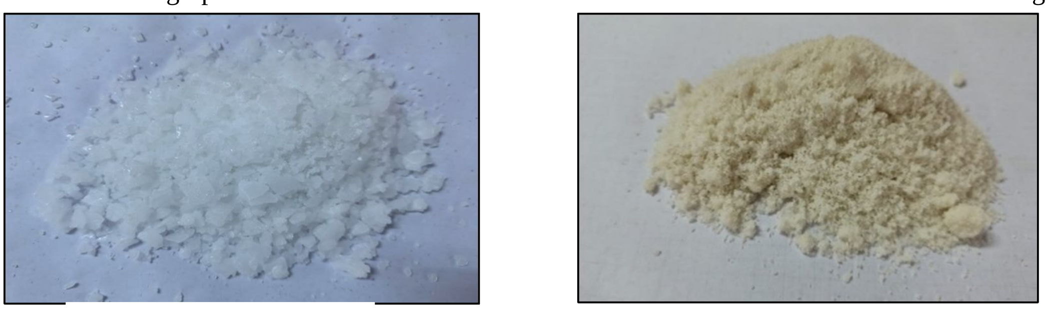
Beyond casting, recycled foundry sand serves as an eco-friendly alternative in sustainable construction, used in road subgrades, concrete, asphalt, and embankments. Its reuse helps minimize industrial waste, conserve natural resources, and support sustainable development and circular economy initiatives in coastal Andhra Pradesh.

Figure 2 Foundry Sand Sample

C. Alkaline Activators Geopolymers (AAG)

Geopolymers are inorganic alumino-silicate materials formed by reacting alkaline activators such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) with alumino-silicate-rich sources like fly ash or slag. This reaction creates a three-dimensional Si–O–Al network, producing materials with excellent strength, durability, and resistance to heat and chemicals. In this study, geopolymers synthesized using NaOH and Na_2SiO_3 serve as sustainable binders and an eco-friendly alternative to Portland cement. They reduce carbon emissions, utilize industrial by-products, and require less energy during production.

In construction and geotechnical engineering, geopolymers enhance the durability and load-bearing capacity of concrete and stabilized soils. They are also used for waste encapsulation, soil stabilization, and heavy metal immobilization in environmental applications. The combination of NaOH and Na_2SiO_3 allows control over setting time and strength development, making geopolymers a sustainable and high-performance material for modern infrastructure and soil stabilization technologies.



Sodium hydroxide

Sodium silicate (Na_2SiO_3)

Figure 3 Sodium hydroxide (NaOH) & Sodium silicate (Na_2SiO_3)

D. Objective of Study

The objectives of the present experimental study are

1) Comprehensively characterize the engineering, physical, and chemical properties of the marine clay soil collected from the Kakinada coastal region.
2) To investigate the effectiveness of Foundry Sand (FS) and Alkaline Activator-Based Geopolymers (AAG) as sustainable stabilizing agents for improving the geotechnical performance of marine clay.
3) To optimize the mix proportions of FS and AAG through systematic laboratory experimentation in order to achieve maximum strength, durability, and load-bearing capacity of the treated soil.
4) To perform California Bearing Ratio (CBR) and Cyclic Plate Load Tests on both untreated and treated marine clay samples to quantitatively evaluate the enhancement in stiffness, resilience, and deformation characteristics.

This Study investigates the potential of Foundry Sand (FS) combined with Alkaline Activator-Based Geopolymers (AAG) as a sustainable soil stabilizer for marine clay (MC) in coastal regions.

III. LITERATURE REVIEW

(Mohammed Riyadh Hayder, 2025) This research investigated the stabilization of poorly graded sand subgrade soils using metakaolin-based geopolymers as an environmentally friendly alternative to Portland cement. The study demonstrated significant improvements in mechanical properties, including unconfined compressive strength, California Bearing Ratio (CBR), and modulus of subgrade reaction, with optimal metakaolin content typically between 10% and 15%. Microstructural analysis revealed a denser, more homogeneous structure and the formation of new crystalline phases, contributing to enhanced strength and durability. The findings confirm that metakaolin-based geopolymers are highly effective for subgrade soil stabilization, offering a sustainable solution for construction projects.

(Shriram Marathe, 2025) The study investigates using fly ash (FA) and calcium carbide residue (CCR) geopolymers to stabilize soft marine clay (Coode Island Silt, Melbourne). Results show that higher FA content and NaOH concentration improve unconfined compressive strength, with optimum performance at a Na_2SiO_3/NaOH ratio of 70:30 and liquid-to-FA ratio of 1.0. Adding 12% CCR increased strength by up to 1.5 times compared to FA-only geopolymer, and also enabled strength gain at room temperature. Strength development trends were similar to cement stabilization but with much lower environmental impact. Overall, FA–CCR geopolymers proved to be an effective and sustainable alternative to traditional cement binders for soil stabilization.

(Tiwary, 2023)The study examines the use of waste foundry sand (WFS) and terrazyme as eco-friendly soil stabilizers for clayey soil. Experimental results showed that adding 15% WFS reduced soil swelling to 10% and lowered plasticity limits, while terrazyme further improved soil strength by binding clay particles. Compaction tests revealed that a mix of 10% WFS with 0.4 ml terrazyme gave optimal maximum dry density and moisture content. Unconfined compressive strength increased significantly, reaching 508 kPa at 28 days for the combined mix compared to untreated soil. The California Bearing Ratio (CBR) also improved by nearly 80%, making the soil suitable for use as a subgrade material in road construction.

IV. RESULTS & DISCUSSION

Table -1 Chemical Properties of FS & AAG

S. No.	Constituent	Chemical Formula	Foundry Sand (%)	Sodium Hydroxide (NaOH)	Sodium Silicate (Na_2SiO_3)
1	Silica	SiO_2	85.40	-	36
2	Alumina	Al_2O_3	4.25	-	-
3	Iron Oxide	Fe_2O_3	2.10	-	0.05
4	Calcium Oxide	CaO	1.85	-	-
5	Magnesium Oxide	MgO	0.95	0.10	-
6	Sodium Oxide	Na_2O	0.60	77.48	12
7	Potassium Oxide	K_2O	0.45	-	-
8	Loss on Ignition (LOI)	—	4.40	-	3.50
9	Water	H_2O	-	22.52	68

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Table - 2 Properties of Untreated Marine Clay Soils

Sl.No	Properties		Symbol	Untreated Marine Clay
	Partical Size Distribution	Gravel (%)		0
		Sand (%)		5.76
		Silt (%)		28.24
1		Clay (%)		66
2	Differential free swell (%)		DFS	82
3	Nature Moisture Content (%)			82.56
4	Specific gravity		G	2.25
5	Liquid Limit (%)		W_L	
5	Plastic Limit (%)		W_p	38.54
6	Plasticity Index (%)		Ip	32.39
7	Soil Classification			CH
8	Maximum Dry Density (gm/cc)		M.D. D	1.58
9	Optimum Moisture Content (%)		O.M.C	30.02
10	CBR Value (soaked) (%)			1.52
11	cohesion (kN/m$^{2)}$		C	1.48
12	Angle of internal friction		ø	3.28

A. Differential Free Swell

Table - 3 Mix Proportions used for testing

S. No	Mix Proportion	DSF
1	100 % MC	95
2	89.5% MC +10% FS+ Soil+ 0.5	50.00
3	89% MC +10% FS + Soil + 1	45.00
4	88.5% MC +10% FS+ Soil + 1.5	40.00

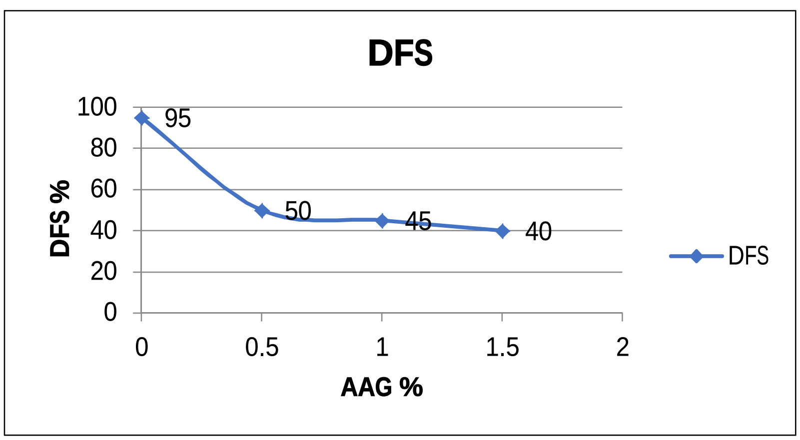

Figure 4 Variation of DFS of MC Treated with 10% of FS with Different Percentages of AAG

Figure 4 show that the DFS values decreases from 95% to 40% on addition of optimum percentage FS and AAG addition of AAG from 0.5 to 1.5%.

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B. *Atterberg Limits*

Table - 4 Show LL, PL, PI treated MC soil

S. No	Mix Proportion	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
1	100 % MC	67.92	31.38	36.54
2	89.5% MC + 10 % + 0.5 Geopolymer	61.30	44.21	17.09
3	89% MC + 10% FS + 1 Geopolymer	58.46	45.33	13.13
4	88.5% MC + 10% FS + 1.5 Geopolymer	57.49	47.12	10.37

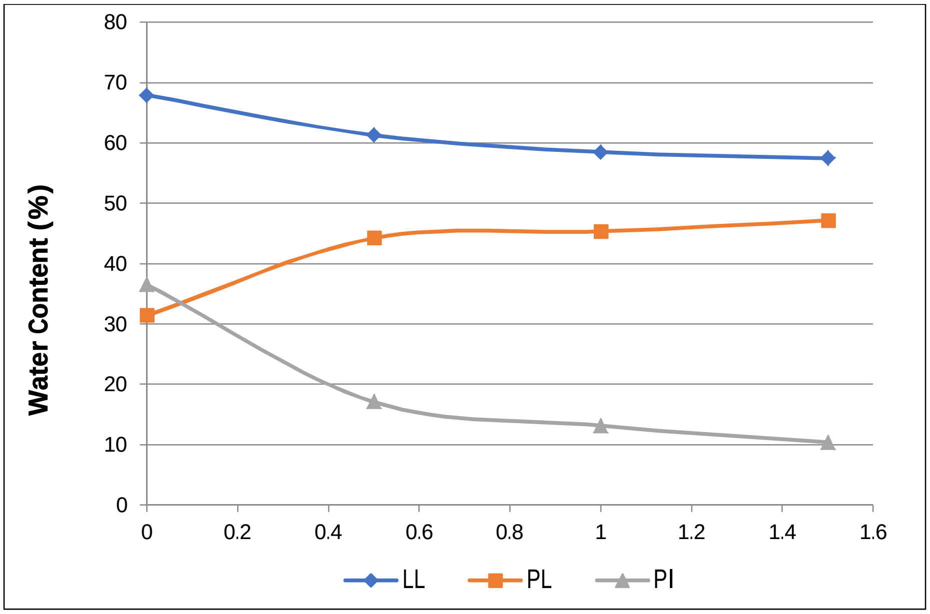

Figure 5 Variation of LL, PL and PI of MC Treated with 10% of FS with Different Percentages of AAG

Figure 4 show that the PL, LL, PI values decrease from 36.54% to 10.37% on addition of optimum percentage FS and AAG addition of AAG from 0.5 to 1.5%.

C. *OMC & MDD*

Table-6: OMC and MDD values of treated MC soil

S.No	Mix Proportion	OMC (%)	MDD (kN/m^3)
1	100 % MC	30.91	13.538
2	89.5% MC + 10 % + 0.5 Geopolymer	26.38	1.67
3	89% MC + 10% FS + 1 Geopolymer	22.7	1.70
4	88.5% MC + 10% FS + 1.5 Geopolymer	14.33	1.72
5	88% MC + 10% FS + 2% Geopolymer	19.16	1.65

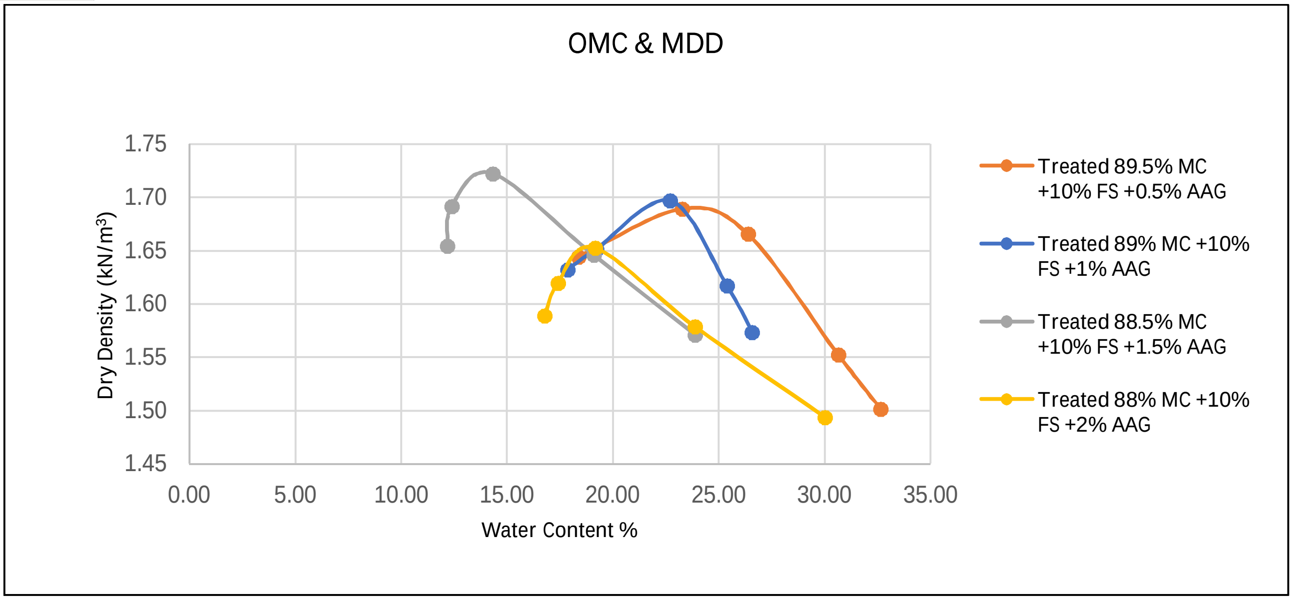

Figure 6 Variation of OMC and MDD of MC treated with 10% FS with various percentages of AAG

Table 6 show that the OMC values decrease from 30.02% to 14.30% on addition of optimum percentage FS and AAG addition of AAG from 0.5 to 2%. The MDD values of the treated MC soil was observed to be increased from 1.58 g/cc to 1.72 g/cc on addition of optimum percentage FS and AAG addition of AAG from 0.5 to 2%. The optimum % of AAG Is 1.5.

D. California Bearing Ratio (CBR)

Table-7: CBR Test Results for different mix proportions

S. No	Mix Proportion	CBR (%)
1	100 % MC	1.34
2	89.5% MC + 10 % + 0.5 Geopolymer	6.27
3	89% MC + 10% FS + 1 Geopolymer	7.62
4	88.5% MC + 10% FS + 1.5 Geopolymer	8.07
5	88% MC + 10% FS + 2% Geopolymer	7.17

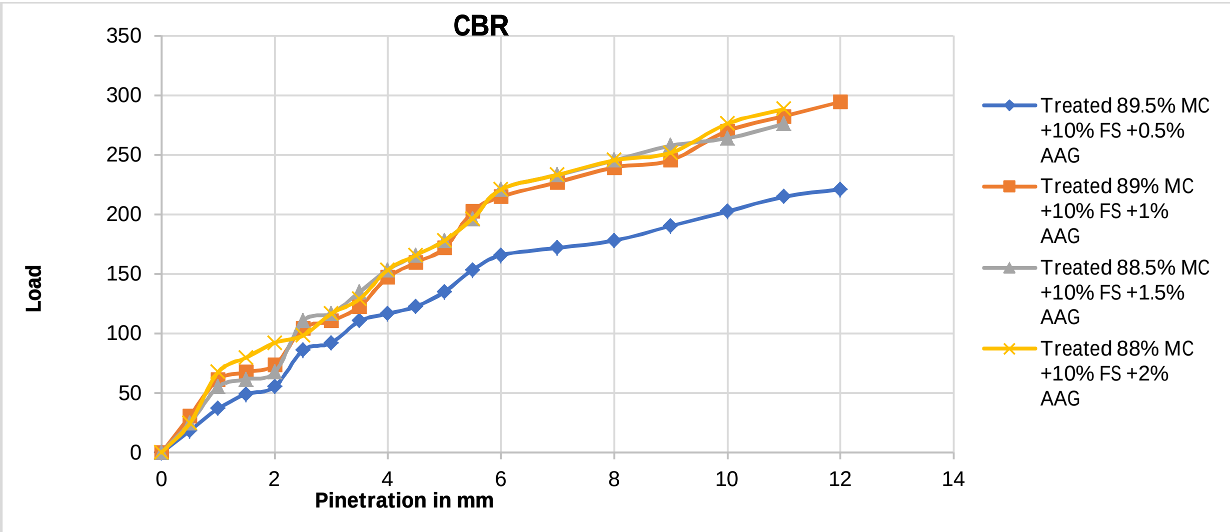

Figure 6 Variation of CBR of MC Treated with 10% FS and Various percentages of AAG

Table-7 shows that CBR is increased from 1.34% to 8.07% after adding Optimum percentage FS and AAG addition of Optimum AAG from 1.5% mix.

V. CONCLUSION

1) It is noticed from the laboratory test results that the Differential Free Swell Index of Marine Clay has been reduced by 42.11% on the addition of 10% Foundry Sand (FS) and it has been further reduced by 27.27% with an addition of 1.5% Alkali-activated geopolymer (AAG) when compared with untreated Marine Clay.
2) It is observed from the laboratory test results that the Liquid limit of Marine Clay has been decreased by 8.81 % on the addition 10% FS of and it has been further decreased by 25.22 % with an addition of 1.5% AAG.
3) It is observed from the laboratory test results that the Plastic limit has been increased by 25.30% on addition of 10% FS and it has been further increased by 3.97% with an addition of 1.5% AAG.
4) It is noticed that the Plasticity Index has been decreased by 33.41% on addition of 10% FS and it has been further decreased by 64.78% with addition of 1.5% AAG.
5) It is observed from the laboratory tests that the OMC of the Marine Clay has been decreased by 48.27% on the addition of 10% FS and it has been further decreased by 7.92 % with addition of 1.5% AAG.
6) It is observed from the laboratory tests that the MDD of the Marine Clay has been increased by 6.96% on the addition of 10% FS and it has been further increased by 2.38% with addition of 1.5% AAG.
7) It is observed that the CBR of the Marine Clay has been increased by 334.33% on the addition of 10% FS and it has been further increased by 38.66% with addition of 1.5% AAG.

The optimized mix of 10% foundry sand and 1.5% alkali-activated geopolymer significantly enhances marine clay subgrade strength and can be adopted for coastal pavement foundation systems.

A. Viability

The treated marine clay exhibited a California Bearing Ratio (CBR) value of **8.07%**, indicating satisfactory strength characteristics for subgrade applications. According to the provisions of *IRC: 37–2018*, the minimum required CBR value for a material to use as a subgrade should poses 8% in flexible pavement construction.

Since, the treated marine clay achieved the CBR value is slightly above this requirement. Hence it fulfills the necessary performance criteria. Therefore, the treated marine clay is suitable as a subgrade in flexible pavement systems.

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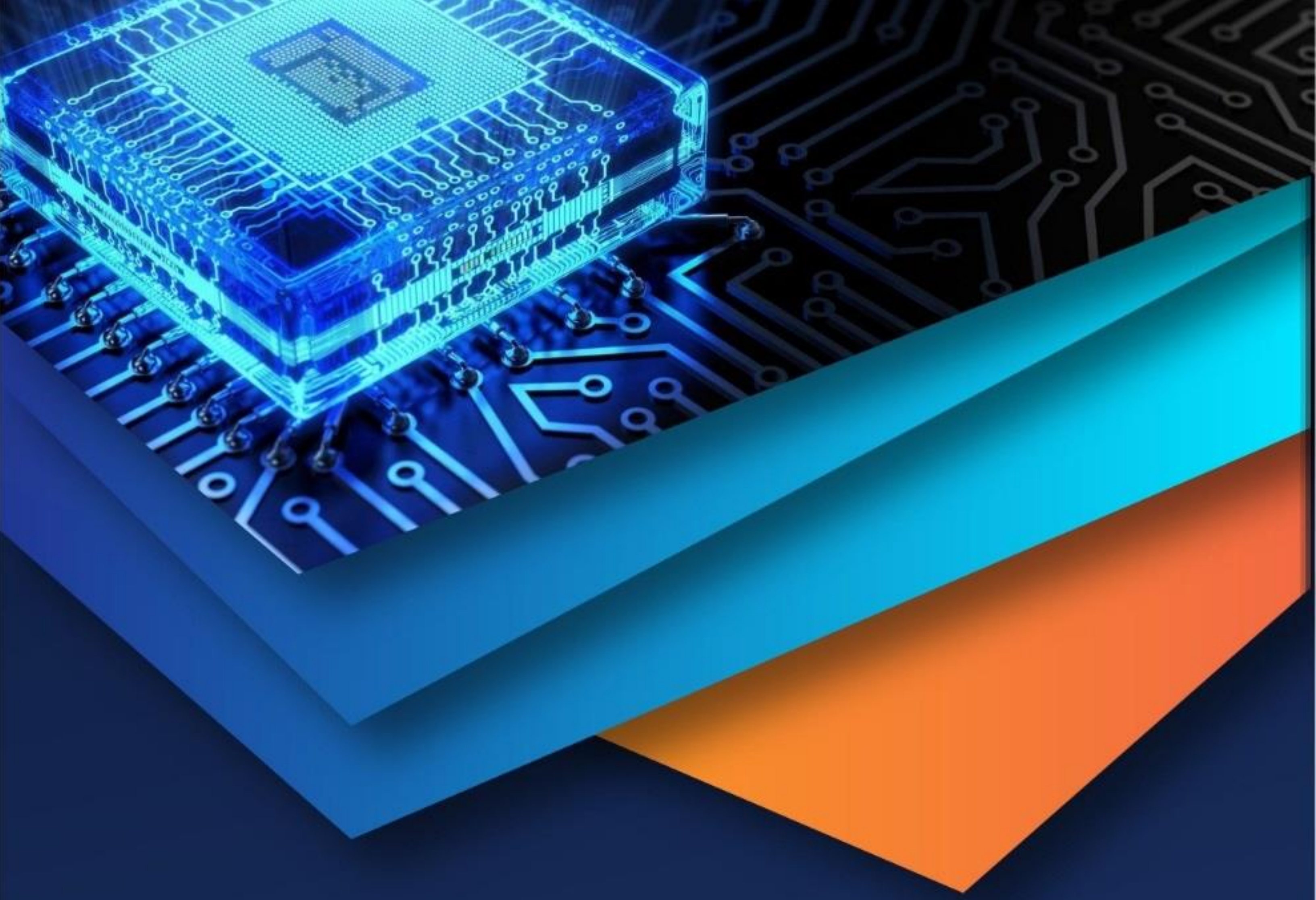

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