

Sustainable Utilization of Waste Materials in Soil Stabilization: A Comprehensive Review on Geotechnical Performance and Environmental Benefits

Vansh Gautam¹, Mr. Atulya Kumar ², Yash Gupta³, Gajendra Yadav ⁴, Dr. Rakesh Kumar Pandey⁵

¹UG Scholar, Department of Civil Engineering, Amity University Chhattisgarh, India

²Assistant Professor, Department of Civil Engineering, Amity University Chhattisgarh, India

³UG Scholar, Department of Civil Engineering, Amity University Chhattisgarh, India

⁴UG Scholar, Department of Civil Engineering, Amity University Chhattisgarh, India

⁵Associate professor, Department of Civil Engineering, Amity University Chhattisgarh, India

Abstract - Soil stabilization has become an important requirement in geotechnical engineering due to increased construction activities on weak and problematic soil deposits. Generally, poor soils are highly compressible, low shear strength, high plasticity and swelling-shrinkage behaviour, and thus, not directly usable in foundations, highway and embankments. At present, soil improvement is carried out using materials such as lime, cement and chemical binders, but these materials are associated with high cost and environmental impact. Recently, the construction industry has focused on sustainable use of industrial, agricultural and municipal waste products for stabilization purpose. Such materials improve the engineering properties of soil and offer an efficient solution to the growing problem of waste disposal. The present paper reviews the use of major waste materials namely fly ash, rice husk ash, waste plastic fibers, ground granulated blast furnace slag (GGBS), steel slag and construction demolition waste for soil stabilization. A comparative interpretation of studies published in journals earlier [1]-[12], shows that these waste materials improve significantly the compaction behavior, California Bearing Ratio, unconfined compressive strength, shear resistance and long-term durability and reduce plasticity and environmental burden. The results of the study show that sustainable waste-based stabilization is economical, eco-friendly and technically reliable method for future geotechnical applications.

Keywords - Soil Stabilization, Sustainable Construction, Fly Ash, Rice Husk Ash, Plastic Waste Fibers, GGBS, Steel Slag, Construction Demolition Waste, Geotechnical Engineering

1. INTRODUCTION

In any civil engineering project, the soil is the principal load-bearing medium. The behaviour of the soil underlying structures such as buildings, pavements, retaining walls, bridges and earth embankments largely controls their performance. Poor engineering properties of the soil may lead to excessive settlement, cracking, tilting and even total failure of the entire structure. Many soils in nature, especially clay and expansive soils, are not suitable for construction due to their low bearing capacity, high sensitivity to moisture and large volume change.

Over the years engineers have developed soil stabilization techniques to improve such problematic soils. Soil stabilization is a process of altering the physical or chemical properties of soil to enhance its strength, stiffness, durability and resistance against water action. Cement and lime are traditional stabilizers that are effective technologically, but the rising market price and carbon emissions during the production of these stabilizers have become a serious concern in sustainable construction practice [1].

At the same time, rapid industrialization, agricultural processing and urban redevelopment are generating massive quantities of waste materials every year. Fly ash from thermal power plants, slag from steel industries, rice husk ash from agricultural burning, plastic waste from municipal sources and debris from demolished structures are commonly available but often remain underutilized. Disposal of these materials causes land occupation, air pollution and groundwater contamination. Therefore, the idea of reusing these wastes in geotechnical engineering has attracted considerable attention over the last decade [2].

The concept is straightforward yet effective. If waste materials can enhance soil properties while reducing environmental impact, they offer the dual benefits of better engineering and sustainable waste management. Many researchers have confirmed that additives made from waste improve plasticity, compaction, shear strength, California Bearing Ratio, and settlement characteristics of weak soils [3][4]. This paper serves as a thorough review study that critically examines how major waste materials perform in soil stabilization and highlights their practical importance in modern geotechnical construction.

2. OBJECTIVES OF THE STUDY

This review paper has been created with the following goals:

1. To examine the importance of stabilizing soil in weak ground conditions.
2. To review commonly used industrial and agricultural waste materials for soil improvement.
3. To evaluate the effects of each waste material on key geotechnical properties.
4. To compare the effectiveness of different stabilizers based on earlier studies.
5. To understand the environmental and economic advantages of sustainable stabilization.
6. To identify the future potential of waste-based stabilizers in civil engineering projects.

3. RESEARCH METHODOLOGY

This paper relies solely on secondary research. Instead of conducting direct experiments, the study gathers and evaluates previously published data from reputable journals, conference proceedings, and review manuscripts related to sustainable soil stabilization. A total of twelve research papers published between 2017 and 2025 were selected for their relevant data on various waste materials in weak soils. These papers included experimental studies and review discussions. The selected literature was studied thoroughly, and the engineering outcomes were compared based on the following criteria:

- Variations in liquid limit and plasticity index,
- Changes in maximum dry density and optimum moisture content,
- Improvements in California Bearing Ratio (CBR),
- Increases in unconfined compressive strength,
- Control of settlement and deformation,
- Environmental sustainability,
- Economic feasibility.

After gathering these observations, a comparative analytical discussion was created. This method presents a broader understanding of current stabilization trends without the need for laboratory facilities

4. LITERATURE REVIEW

A strong review paper relies heavily on how well previous studies are understood and connected. For this study, literature from twelve different sources was reviewed.

Shinde et al. [1] conducted a broad overview of using industrial and agricultural wastes, concluding that fly ash, rice husk ash, and demolition debris are highly effective in improving problematic soils. Almuaythir et al.

[2] focused on expansive clay stabilized with industrial waste ash and noted significant swelling reduction and increased shear strength after curing. Cai et al.

[3] experimentally compared various waste stabilizers, including rice husk ash, steel slag, and iron tailing powder. Their results indicated that slag-based additives offer stronger long-term strength gain. Abarajithan et al.

[4] investigated rice husk ash mixed with natural fibers, finding improvements in dry density and a moderate increase in load-carrying capacity. Prasad et al.

[5] reviewed the use of plastic waste and rice husk ash in expansive soils, observing that plastic fibers significantly contribute to deformation resistance. Koliass et al.

[6] found that fly ash-stabilized soils demonstrate better moisture resistance and improved pavement performance.

Yadu and Tripathi [7] concluded that GGBS can effectively replace some cement in weak subgrade treatment.

Muntohar [8] highlighted how agricultural ash helps reduce shrinkage cracks in soft clay.

Arulrajah et al. [9] demonstrated the utility of recycled demolition aggregates in pavement engineering.

Shahu and Reddy [10] showed that adding steel slag greatly increases CBR in black cotton soils.

Basha et al. [11] found that waste additives are more economical in rural road applications than traditional stabilization methods.

James and Pandian [12] pointed out that sustainable stabilizers are becoming necessary due to stricter environmental regulations. Collectively, these studies show that waste-based stabilization is not just an experimental idea but a viable geotechnical solution.

5. FLY ASH AS AN INDUSTRIAL SOIL STABILIZER

Among various industrial waste materials for geotechnical use, fly ash has gained the most attention due to its high pozzolanic content and easy availability. Fly ash is produced as a residue from coal combustion in thermal power plants and mainly contains silica, alumina, and small amounts of calcium compounds.

These components react with the natural minerals in clayey soils and form cement-like gels under moist conditions. This reaction creates stronger bonds between soil particles, reducing plasticity and improving compressive strength. Researchers have consistently found that adding fly ash lowers the liquid limit and plasticity index of expansive soils, making them less sensitive to seasonal moisture changes [1][6].

Another significant geotechnical benefit is the increase in California Bearing Ratio. Since CBR reflects subgrade load-carrying capacity, this makes fly ash suitable for road pavement construction and embankment foundation work. Many studies report that 10% to 20% fly ash content yields the best engineering improvement.

Economically, fly ash is very advantageous because thermal power plants produce it in large quantities, and disposal poses a challenge. Using it for soil stabilization transforms a waste management problem into a valuable engineering resource.

6. RICE HUSK ASH AS AN AGRICULTURAL WASTE STABILIZER

Rice husk ash comes from the controlled burning of rice husks generated in rice mills. In India and many Asian nations, rice production is high, leading to plenty of this ash.

Chemically, rice husk ash contains a significant amount of reactive amorphous silica, which contributes to moderate pozzolanic action. Unlike fly ash, rice husk ash works through both filling voids and chemical interaction. The fine particles fill gaps between soil grains, leading to denser compaction. Simultaneously, the silica in the ash reacts with moisture to improve internal bonding. This results in reduced swelling pressure and lower moisture susceptibility [4][8].

One major advantage of rice husk ash is its low cost. Being an agricultural by-product, it is often available at little to no cost in rural areas. Researchers have shown that soils treated with rice husk ash exhibit better dry density, moderate enhancements in shear strength, and fewer shrinkage cracks.

Although the strength gain from rice husk ash may not match that of GGBS or fly ash, its sustainability value is significant because it turns agricultural waste into a beneficial construction additive. Thus, rice husk ash is a practical option where both cost-efficiency and moderate stabilization are needed.

7. WASTE PLASTIC FIBERS FOR SOIL REINFORCEMENT

Plastic waste poses a serious environmental issue due to its non-biodegradable nature. Municipal solid waste now contains a large volume of plastic bottles, packaging materials, carry bags, and synthetic fibers. Rather than sending this waste to landfills, many researchers propose using it as shredded strips or fibers mixed into soil.

Plastic fibers do not act as chemical stabilizers; their function is primarily mechanical reinforcement. When randomly distributed in soil, these fibers act like small tensile elements that prevent particle separation during loading. Consequently, the soil gains more ductility and is less likely to fail suddenly [5].

Many studies observe that soil reinforced with plastic fibers experiences reduced settlement and improved resistance to cyclic loading. This is especially beneficial in pavement subgrades, where repeated wheel loads could otherwise cause rutting or deformation.

Another advantage is that waste plastic requires minimal processing. Even discarded bottles and packaging strips can be cut into small fibers and used after cleaning. Thus, this method offers a simple but impactful way to enhance weak soils while also addressing plastic pollution.

8. GROUND GRANULATED BLAST FURNACE SLAG (GGBS)

GGBS is a by-product from the iron and steel manufacturing industries. It forms when molten slag is quickly cooled and ground into a fine powder. This powder contains calcium silicates and aluminates with latent hydraulic properties, meaning they function like cement when moisture is present.

Of all the waste materials reviewed in this paper, GGBS has shown one of the highest long-term strength gains. Its hydration continues over a curing period, gradually forming strong cement-like bonds within the soil matrix. Cai et al. [3] and Yadu and Tripathi [7] both noted that GGBS-treated soil demonstrated a significant increase in unconfined compressive strength and better durability under wet conditions. GGBS also decreases the plasticity of soft clays and improves stiffness, making it useful in foundation beds, embankments, and pavement layers.

As it can partially replace cement, using it directly reduces the carbon footprint of stabilization efforts. For this reason, many engineers view GGBS not just as a waste material but as a valuable sustainable binder for long-term soil improvement projects.

9. STEEL SLAG AND OTHER INDUSTRIAL SLAGS

Steel slag is a heavy by-product produced during steel refining. It mainly contains calcium oxide, iron oxide, and silicate compounds. Its rough texture and mineral content help improve granular friction and chemical bonding.

Shahu and Reddy [10] found that adding steel slag to black cotton soil significantly improved the California Bearing Ratio and reduced excessive settlement. Because of its angular shape, steel slag provides stronger particle interlocking than fine powdered ash.

However, one drawback is that steel slag is heavier, which can make transportation more expensive than fly ash. This makes it more practical to use in areas close to steel plants. Despite this limitation, steel slag is a valuable stabilizer where high strength is required.

10. CONSTRUCTION AND DEMOLITION WASTE IN GEOTECHNICAL APPLICATIONS

Construction and demolition waste includes broken concrete, crushed bricks, mortar fragments, old plaster, ceramic pieces, and debris from dismantled structures.

Traditionally, this waste has been dumped in open areas, leading to environmental and land management issues. Recent studies show that after crushing and grading, these materials can be mixed with weak soil to improve density and compaction behavior. Since demolition debris serves as coarse granular filler, it increases frictional resistance and reduces compressibility [9].

While the chemical stabilization effect is not very strong, construction waste is quite useful for low-cost embankment fills, road shoulders, and temporary access roads. It also helps lessen the demand for natural aggregates, which are becoming more expensive and hard to obtain.

Thus, recycled construction waste fits well within the idea of circular construction engineering.

11. COMPARATIVE TECHNICAL INTERPRETATION

When comparing the findings of all twelve reviewed studies, a clear technical pattern appears.

- Fly ash and GGBS create the strongest chemical stabilization.
- Steel slag offers high frictional resistance and good CBR.
- Rice husk ash provides moderate strength at a low cost.
- Plastic fibers mainly enhance tensile resistance and control deformation.
- Demolition waste boosts compaction but offers lower chemical bonding.

This means each material has a specific role. For highly expansive clay needing chemical modification, fly ash and GGBS are better choices. For low-cost rural roads, rice husk ash and demolition waste are practical options.

For pavements sensitive to deformation, plastic fibers can be very beneficial. Therefore, engineers must choose the stabilizer based not only on availability but also on the specific engineering issue at hand.

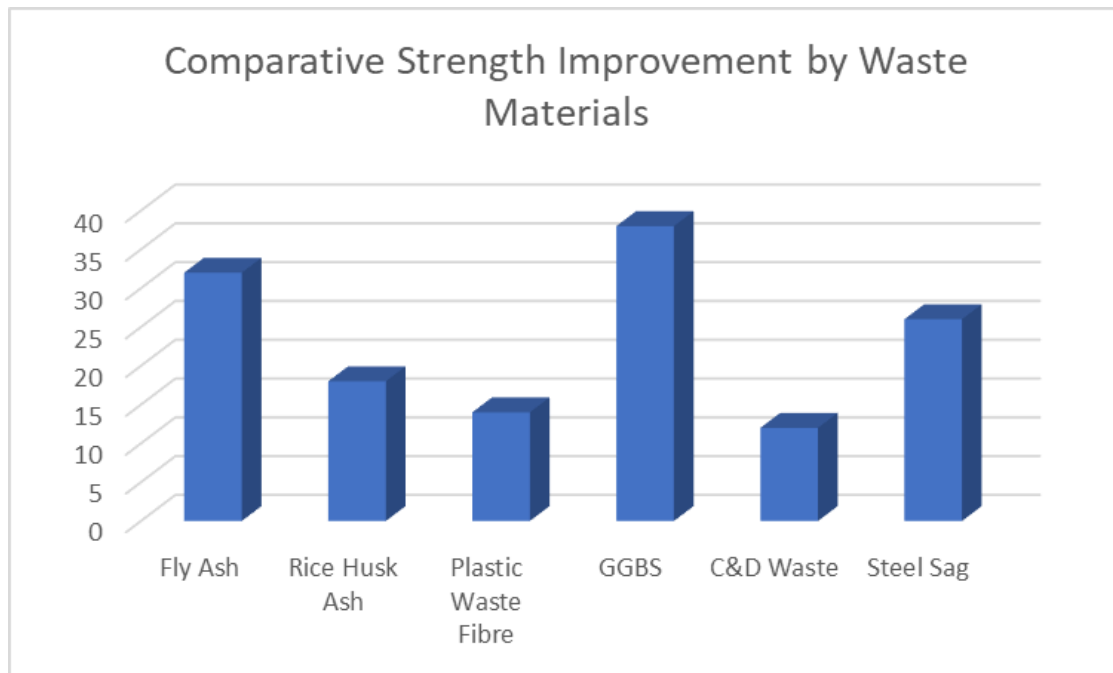


Figure 1: Comparative Increase in Soil Strength due to Different Waste Stabilizers

Source: Data synthesized by the authors based on an analytical review of the existing literature [1]-[12]

12. RESULTS AND DISCUSSION

The comparative review of all selected studies shows that sustainable waste materials significantly improve the engineering properties of weak soils. While the level of improvement varies from one additive to another, all reviewed materials positively impacted one or more key geotechnical parameters.

The most common enhancement was a reduction in the plasticity index. Highly plastic soils typically exhibit severe swelling and shrinkage, especially during seasonal moisture changes. Adding fly ash, GGBS, and rice husk ash markedly reduced this behavior by changing the interactions between clay minerals and decreasing water affinity [1][2].

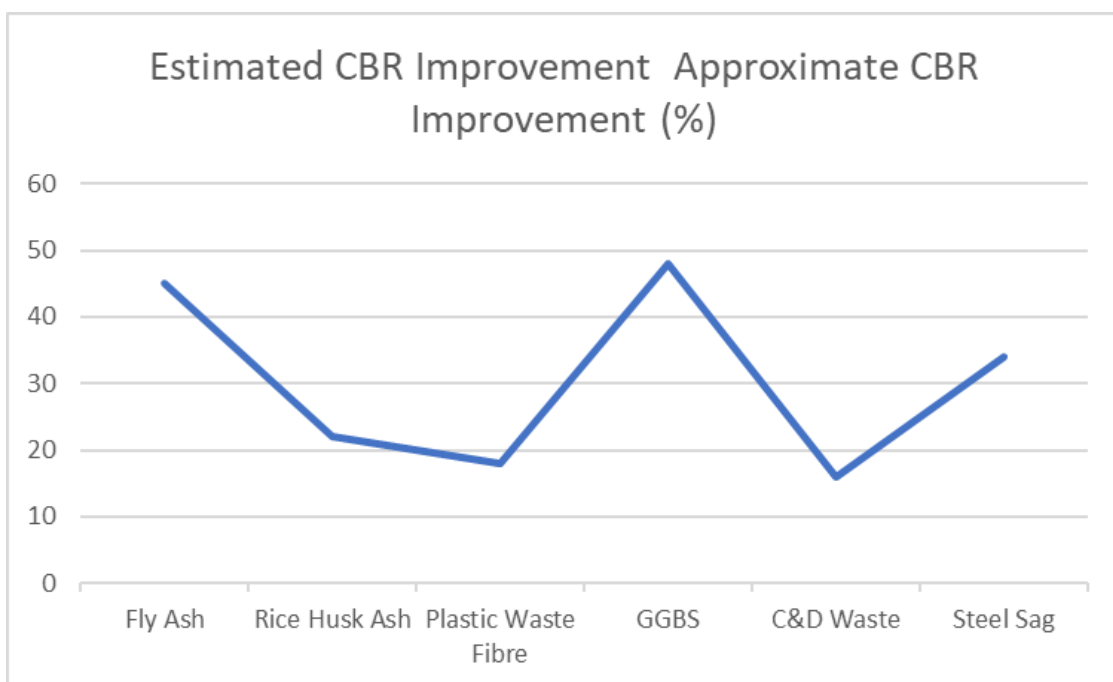


Figure 3: California Bearing Ratio Enhancement Observed with Different Stabilizers

Source: Compiled by Authors from reviewed literature [1]-[12]

Another important observation was the increase in dry density and compaction efficiency. Fine powdered additives like fly ash and rice husk ash filled the micro voids between soil particles, resulting in denser packing. In contrast, demolition waste and steel slag mainly enhanced compaction through coarse granular interlocking [3][9].

In terms of strength improvement, GGBS and fly ash performed best due to their strong pozzolanic and hydraulic bonding. Steel slag also showed a marked increase in CBR values thanks to its rough, angular nature. Plastic waste fibers, while not chemically reactive, effectively reduced deformation and settlement by resisting tensile separation [5]. Overall, this discussion confirms that every waste material has its value from a geotechnical perspective. Each material contributes uniquely and can be selected based on project needs.

13. ENVIRONMENTAL AND ECONOMIC SIGNIFICANCE

One of the main reasons for using waste materials in soil stabilization is their environmental benefits. Modern construction creates a large carbon footprint because of heavy reliance on cement, lime, and natural aggregates. At the same time, industries and cities produce millions of tons of ash, slag, plastics, and demolition debris that often go unused. By redirecting these waste products into geotechnical applications, two benefits can be achieved:

1. Reducing environmental pollution from waste disposal.
2. Decreasing the use of traditional construction materials.

For example, using fly ash and slag reduces space occupied around industries. Rice husk ash helps avoid uncontrolled agricultural burning. Stabilizing with plastic fibers cuts down on municipal plastic waste. Reusing demolition waste decreases demand for landfills.

Economically, the studies show that waste-based stabilizers are much cheaper than cement-lime stabilization, especially for rural roads, embankments, and temporary structures [11].

Transportation costs are the only variable issue, but when waste sources are locally available, the total project cost can be notably reduced. Thus, sustainable stabilization is not just a technical option but also a smart financial choice in engineering practice.

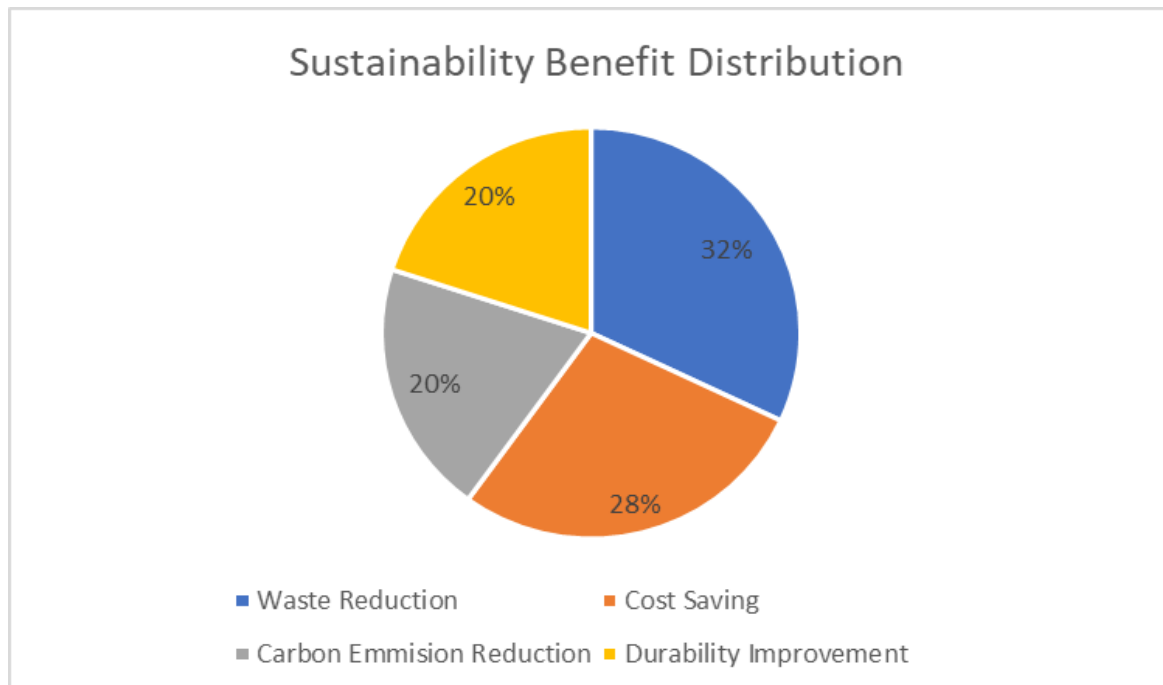


Figure 2: Overall Sustainability Benefits of Waste-Based Soil Stabilization

Source: Compiled by Authors from reviewed literature [1]-[12]

14. MAJOR ADVANTAGES OF WASTE-BASED SOIL STABILIZATION

This review highlights several practical advantages:

14.1 Low Material Cost

Most waste materials are either free or available at very low prices.

14.2 Sustainable Waste Management

Large amounts of industrial and municipal waste can be reused productively.

14.3 Improved Soil Strength

Bearing capacity, CBR, and compressive strength improve significantly.

14.4 Reduction in Settlement

Stabilized soils show less compressibility and better dimensional stability.

14.5 Eco-Friendly Construction

Using waste lowers carbon emissions tied to conventional stabilizers.

14.6 Resource Conservation

Natural aggregates and expensive binders are partially preserved.

These advantages clarify why sustainable stabilization is becoming an essential area of current geotechnical research.

15. LIMITATIONS OF THE PRESENT REVIEW

Although this paper provides a detailed understanding, it is important to note some limitations.

Firstly, the study is entirely based on secondary literature, with no direct laboratory experiments conducted by the authors.

Therefore, the observations depend on previously reported data. Secondly, soil behavior can change significantly based on mineral composition, moisture conditions, and additive percentages.

Thus, the exact numerical improvements can vary from place to place. Thirdly, transportation costs and handling issues for some waste materials were not experimentally verified in this study.

Acknowledging limitations is important academically because it adds realism and research orientation to the paper.

16. FUTURE SCOPE OF STUDY

The topic of sustainable soil stabilization has broad future potential. Some areas for further research include:

- Combining two or more waste materials.
- Using nano-materials to assist in waste stabilization.
- Examining long-term durability under cyclic wetting and drying.
- Monitoring the field performance of stabilized rural roads.
- Implementing AI and optimization models for selecting additive percentages.

Future geotechnical engineering will likely rely more on recycled and environmentally responsible construction materials.

17. CONCLUSION

This review paper aimed to explore the sustainable use of waste materials in soil stabilization and understand their engineering and environmental significance. Based on a comparative review of twelve credible research studies, it concludes that industrial and agricultural waste products can effectively improve the geotechnical properties of weak soils.

Fly ash and GGBS were found to be the most effective for chemical strength, while steel slag significantly boosted CBR values. Rice husk ash emerged as a highly cost-effective agricultural stabilizer, and plastic waste fibers proved useful for controlling deformation.

Construction and demolition waste also showed practical benefits for low-cost compaction work. Therefore, the study affirms that waste-based soil stabilization is not simply a way to dispose of materials but also a technically sound and sustainable geotechnical solution.

Adopting these methods can reduce construction costs, lower environmental impacts, and promote circular engineering practices in future infrastructure projects.

ACKNOWLEDGEMENT

The authors sincerely thank **Mr. Atulya Kumar and Dr. Rakesh Kumar Pandey**, Project Guide, Department of Civil Engineering, Amity University Chhattisgarh, for his valuable guidance, technical suggestions, and continuous support during the preparation of this review paper. They also appreciate the Department of Civil Engineering for granting access to journals and technical resources needed for this research.

REFERENCES

- [1] B. Shinde, A. Sangale, M. Pranita, J. Sangale and C. Roham, "Utilization of waste materials for soil stabilization: A comprehensive review," *Procedia Earth and Environmental Science*, 2024.
- [2] S. Almuaythir, M. S. I. Zaini, M. Hasan and M. I. Hoque, "Sustainable soil stabilization using industrial waste ash: Enhancing expansive clay properties," *Heliyon*, vol.10, no.20, 2024.
- [3] D. Cai, M. Ouyang, X. Bao, Q. Zhang, Z. Bi, H. Yan and Y. Shi, "Performance evaluation of stabilized soils with selected common waste materials," *Materials*, vol.18, no.2, 2025.
- [4] G. Abarajithan, P. R. Kumar, R. Srikanth and P. Barathidason, "Feasibility of soil stabilization using rice husk ash and coir fibre," *IJERT*, vol.6, no.4, 2017.
- [5] S. S. G. Prasad, C. Madhu, C. Srikanth, E. Princy, G. V. S. S. Prasad and K. Chinnababu, "A review on stabilization of expansive soil using cement, rice husk ash and waste plastic," *Journal of Geotechnical Studies*, 2023.
- [6] S. Koliass, V. Kasselouri-Rigopoulou and A. Karahalios, "Stabilisation of clayey soils with high calcium fly ash and cement," *Cement and Concrete Composites*, 2005.
- [7] L. Yadu and R. K. Tripathi, "Stabilization of soft soil with granulated blast furnace slag and fly ash," *International Journal of Civil Engineering Research*, 2013.
- [8] A. S. Muntohar, "Utilization of uncontrolled burnt rice husk ash in soil improvement," *Construction and Building Materials*, 2002.
- [9] A. Arulrajah, J. Piratheepan, M. M. Disfani and M. W. Bo, "Geotechnical and geoenvironmental properties of recycled construction materials," *Journal of Materials in Civil Engineering*, 2013.
- [10] J. T. Shahu and Y. V. Reddy, "Application of steel slag in expansive soil stabilization," *Ground Improvement Journal*, 2011.
- [11] A. K. Basha, R. Hashim, H. B. Mahmud and A. S. Muntohar, "Stabilization of residual soil with rice husk ash and cement," *Construction and Building Materials*, 2005.
- [12] J. James and P. K. Pandian, "Industrial wastes as auxiliary additives to cement/lime stabilization of soils," *Advances in Civil Engineering*, 2016.