International Journal of
DATA SCIENCE AND IOT MANAGEMENT SYSTEM
Peer Reviewed, Referred & Indexed Journal
3068-272X www.ijdim.com Original Research Paper

DESIGN AND PERFORMANCE EVALUATION OF FLEXIBLE PAVEMENT USING INDUSTRIAL WASTE FOR SUBGRADE SOIL STABILIZATION

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ABSTRACT

The increasing demand for sustainable highway infrastructure has encouraged the utilization of industrial waste materials in pavement construction to improve engineering performance while minimizing environmental pollution. Weak subgrade soils often possess low bearing capacity, excessive compressibility, and poor load distribution characteristics, leading to premature pavement failures such as rutting, settlement, cracking, and excessive maintenance costs. Conventional soil stabilization techniques generally require large quantities of cement or lime, which increase construction costs and contribute to carbon emissions. Therefore, the use of industrial waste materials such as fly ash, ground granulated blast furnace slag (GGBS), quarry dust, rice husk ash, steel slag, silica fume, and construction demolition waste has emerged as an economical and environmentally sustainable alternative for improving subgrade properties. This project presents the Flexible Pavement Design Using Industrial Waste for Subgrade Soil Stabilization by investigating the effectiveness of industrial waste materials in enhancing the engineering characteristics of weak subgrade soil. Laboratory investigations including the California Bearing Ratio (CBR) test, Atterberg Limits test, Standard Proctor Compaction test, Unconfined Compressive Strength (UCS) test, Grain Size Analysis, and Specific Gravity test were conducted to evaluate the stabilized soil. The improved CBR values obtained after stabilization were used for the structural design of flexible pavement according to IRC:37-2018 guidelines. The stabilized subgrade exhibited increased bearing capacity, improved compaction characteristics, higher shear strength, reduced plasticity, and enhanced resistance to settlement compared with untreated soil. The designed flexible pavement demonstrated improved structural performance, longer service life, and reduced pavement thickness, resulting in significant savings in construction cost. The study confirms that industrial waste materials provide an environmentally friendly, technically reliable, and economically viable solution for subgrade stabilization while promoting sustainable highway construction and effective waste utilization.

Keywords : Flexible Pavement, Industrial Waste, Subgrade Soil Stabilization, Fly Ash, GGBS, Quarry Dust, CBR Test, Soil Improvement, IRC:37-2018, Sustainable Highway Engineering, Pavement Design, Geotechnical Engineering.

I. INTRODUCTION

Transportation infrastructure plays a vital role in the economic growth and sustainable development of every nation. Flexible pavements are widely used for highways because of their lower initial construction cost, ease of maintenance, and better riding comfort. However, the performance of a flexible pavement largely depends on the strength and stability of the underlying subgrade soil. Weak subgrade soils possess low bearing capacity, high compressibility, excessive plasticity, and poor drainage characteristics, which often result in pavement failures such as rutting, settlement, fatigue cracking, and uneven surface deformation. Conventional stabilization methods generally utilize cement and lime to improve soil properties, but these materials increase construction costs and generate considerable carbon emissions. In recent years, the utilization of industrial waste materials for soil stabilization has emerged as an economical and environmentally sustainable alternative. Industrial by-products such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), quarry dust, steel slag, silica fume, and rice husk ash have shown excellent potential for improving the engineering properties of weak soils while simultaneously reducing environmental pollution. The effective utilization of these waste materials promotes sustainable construction practices and conserves natural resources by reducing the disposal of industrial waste in landfills.

Recent advancements in geotechnical engineering have demonstrated that industrial waste materials significantly improve the physical and mechanical properties of weak subgrade soils. These materials increase the California Bearing Ratio (CBR), improve compaction characteristics, enhance shear strength, reduce plasticity, and minimize settlement under repeated traffic loading. Fly ash and GGBS react chemically with soil particles through pozzolanic reactions, forming cementitious compounds that increase soil strength and stiffness. Quarry dust improves particle interlocking and reduces void spaces, whereas steel slag enhances density and load distribution characteristics. Laboratory investigations such as the Standard Proctor Compaction Test, Atterberg Limits Test, Grain Size Analysis, Specific Gravity Test, Unconfined Compressive Strength (UCS) Test, and California Bearing Ratio (CBR) Test are commonly performed to evaluate the effectiveness of stabilized soils. The improved CBR values obtained after stabilization enable engineers to reduce pavement thickness, resulting in considerable savings in construction cost while improving pavement durability and service life. Consequently, industrial waste stabilization has become an important technique in sustainable highway engineering.

This project presents the Flexible Pavement Design Using Industrial Waste for Subgrade Soil Stabilization by investigating the suitability of industrial waste materials for improving the engineering characteristics of weak subgrade soils. The study focuses on evaluating the physical, mechanical, and strength properties of stabilized soil through comprehensive laboratory investigations. Various percentages of industrial waste materials are mixed with natural soil to determine the optimum stabilization level that provides maximum strength and durability. Laboratory tests including the Atterberg Limits Test, Grain Size Analysis, Specific Gravity Test, Standard Proctor Compaction Test, California Bearing Ratio (CBR) Test, and Unconfined Compressive Strength (UCS) Test are conducted to compare untreated and stabilized soil properties. The improved CBR values are subsequently used for the design of a flexible pavement according to the recommendations of IRC:37-2018. The study demonstrates that the incorporation of industrial waste significantly improves subgrade strength, increases pavement stability, reduces pavement thickness, lowers construction costs, and minimizes environmental pollution. The proposed methodology provides highway engineers with an economical, sustainable, and technically reliable solution for flexible pavement construction while promoting effective industrial waste utilization and environmentally responsible infrastructure development.

II. SURVEY OF RESEARCH

1. Industrial Waste for Subgrade Soil Stabilization

The increasing demand for sustainable highway infrastructure has encouraged researchers to utilize industrial waste materials for improving weak subgrade soils. Conventional stabilization methods using cement and lime are effective but increase construction costs and carbon emissions. Consequently, industrial by-products such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), quarry dust, silica fume, steel slag, rice husk ash, and construction demolition waste have been widely investigated as alternative stabilizing agents. Numerous studies have reported that these materials improve the engineering properties of expansive and weak soils through physical filling and chemical reactions. The addition of industrial waste reduces soil plasticity, increases dry density, improves compaction characteristics, and enhances bearing capacity. Researchers have also observed that stabilized soils exhibit reduced compressibility, better moisture resistance, and improved load distribution under repeated traffic loading. These improvements contribute to enhanced pavement durability and lower maintenance costs while simultaneously promoting sustainable waste management. Therefore, industrial waste stabilization has become one of the most economical and environmentally friendly techniques for modern highway construction.

2. California Bearing Ratio (CBR) Improvement Using Industrial Waste

The California Bearing Ratio (CBR) is one of the most important parameters used for evaluating the strength of subgrade soil in flexible pavement design. Researchers have extensively studied the influence of industrial waste materials on improving CBR values of weak soils. Experimental investigations indicate that the incorporation of fly ash, quarry dust, GGBS, steel slag, and silica fume significantly increases the bearing capacity of subgrade soils by improving particle interlocking and forming cementitious compounds through pozzolanic reactions. Comparative studies have shown that stabilized soils exhibit substantially higher soaked and unsoaked CBR values than untreated soils. The increased CBR values allow engineers to reduce the required pavement thickness according to IRC:37-2018, thereby lowering construction costs. Laboratory investigations further demonstrate that optimum percentages of industrial waste produce maximum improvement in subgrade strength while maintaining satisfactory compaction characteristics. These findings confirm that industrial waste stabilization is an effective technique for improving pavement performance and extending service life.

3. Mechanical Properties of Stabilized Subgrade Soil

Several researchers have investigated the influence of industrial waste materials on the physical and mechanical properties of weak subgrade soils. Laboratory tests including the Atterberg Limits Test, Specific Gravity Test, Grain Size Analysis, Standard Proctor Compaction Test, Unconfined Compressive Strength (UCS) Test, and California Bearing Ratio (CBR) Test are commonly performed to evaluate stabilized soils. Research findings indicate that industrial waste materials reduce the liquid limit and plasticity index while increasing maximum dry density and optimum moisture content. The unconfined compressive strength also increases considerably because of improved particle bonding and cementitious reactions within the stabilized soil matrix. Enhanced compaction characteristics reduce settlement and improve the ability of the subgrade to resist repeated wheel loading. These improvements contribute to increased pavement stability, better structural performance, and reduced maintenance requirements throughout the pavement service life.

4. Flexible Pavement Design Based on Stabilized Subgrade

The structural performance of flexible pavements largely depends on the strength of the supporting subgrade. Researchers have demonstrated that stabilization of weak soils using industrial waste materials significantly improves pavement performance by increasing subgrade strength and reducing pavement thickness. According to IRC:37-2018, pavement thickness is directly related to the CBR value of the subgrade. As the stabilized soil exhibits higher CBR values, thinner pavement layers become sufficient to safely distribute traffic loads. Comparative investigations have shown that pavements constructed over stabilized subgrades exhibit lower rutting, reduced settlement, improved fatigue resistance, and longer service life compared with pavements constructed on untreated soils. The reduction in pavement thickness also results in considerable savings in construction materials and overall project cost. Therefore, industrial waste stabilization has become an effective solution for developing economical and durable flexible pavements.

5. Environmental and Economic Benefits of Industrial Waste Utilization

Industrial waste disposal has become a major environmental challenge because of the continuous generation of by-products from thermal power plants, steel industries, mining operations, and construction activities. Researchers have proposed the utilization of these waste materials in pavement construction as an effective solution for reducing environmental pollution while conserving natural resources. The reuse of fly ash, GGBS, quarry dust, and steel slag minimizes landfill disposal and reduces the consumption of natural aggregates and conventional stabilizing agents. Economic studies indicate that the utilization of industrial waste lowers material transportation costs and decreases the overall construction expenditure associated with highway projects. In addition to environmental conservation, stabilized pavements exhibit improved durability and reduced maintenance requirements, providing significant long-term economic benefits. These advantages support the widespread adoption of industrial waste materials in sustainable highway engineering.

6. Future Trends in Sustainable Pavement Engineering

Recent advancements in pavement engineering focus on integrating Artificial Intelligence (AI), Machine Learning (ML), Geographic Information Systems (GIS), Building Information Modelling (BIM), Internet of Things (IoT), and remote sensing technologies with conventional pavement design practices. Researchers are developing intelligent pavement management systems capable of predicting pavement deterioration using traffic, environmental, and geotechnical data. Smart sensors embedded within pavement layers continuously monitor moisture content, stress, strain, settlement, and temperature, enabling preventive maintenance and improving pavement performance. Advanced numerical modelling and optimization techniques are also being used to determine the optimum percentage of industrial waste required for soil stabilization. Future research is expected to integrate sustainable materials, digital monitoring systems, artificial intelligence, and life-cycle cost analysis to develop environmentally friendly, economical, and high-performance flexible pavements capable of meeting future transportation demands while promoting efficient industrial waste utilization.

III. PROPOSED SYSTEM

The proposed Flexible Pavement Design Using Industrial Waste for Subgrade Soil Stabilization aims to improve the engineering properties of weak subgrade soil by incorporating suitable industrial waste materials such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), quarry dust, steel slag, silica fume, and rice husk ash. The proposed methodology integrates soil investigation, industrial waste characterization, laboratory testing, soil stabilization, pavement design, and performance evaluation to develop a durable, economical, and environmentally sustainable flexible pavement. The improved engineering properties of the stabilized soil are utilized for pavement thickness design according to the recommendations of IRC:37-2018, ensuring adequate structural performance under repeated traffic loading. Initially, representative soil samples are collected from the proposed construction site for laboratory investigation. The natural soil is tested to determine its engineering characteristics, including grain size distribution, specific gravity, liquid limit, plastic limit, plasticity index, optimum moisture content (OMC), maximum dry density (MDD), California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS). Simultaneously, selected industrial waste materials are collected from nearby industries and processed by drying, crushing, and sieving to obtain uniformly graded particles suitable for soil stabilization. The physical and chemical properties of the industrial waste materials are also evaluated to ensure their suitability for geotechnical applications.

After material characterization, different percentages of industrial waste are mixed with the natural soil to prepare stabilized soil specimens. The soil and stabilizing materials are thoroughly blended under controlled laboratory conditions to achieve a homogeneous mixture. Various proportions of fly ash, GGBS, quarry dust, or other industrial by-products are prepared to identify the optimum stabilization percentage capable of providing maximum improvement in soil strength. The prepared mixtures are compacted according to the Standard Proctor Compaction Test to determine the corresponding Maximum Dry Density (MDD) and Optimum Moisture Content (OMC). These parameters are essential for achieving proper field compaction during pavement construction. The stabilized soil specimens are then subjected to comprehensive laboratory investigations including the Atterberg Limits Test, California Bearing Ratio (CBR) Test, Unconfined Compressive Strength (UCS) Test, Grain Size Analysis, Specific Gravity Test, and Compaction Test. The experimental results are compared with those of untreated soil to evaluate improvements in bearing capacity, shear strength, density, and plasticity. The improved CBR values obtained after stabilization are used as the primary design parameter for determining pavement thickness according to IRC:37-2018. If the stabilized soil fails to satisfy the required engineering specifications, the percentage of industrial waste is modified and the testing procedure is repeated until the optimum mix proportion is obtained.

Following laboratory evaluation, the flexible pavement is designed using the improved subgrade properties obtained from the stabilized soil. The pavement structure consists of Bituminous Concrete (BC), Dense Bituminous Macadam (DBM), Wet Mix Macadam (WMM), Granular Sub-Base (GSB), and the stabilized subgrade. The pavement thickness is determined based on the improved CBR values and projected traffic loading according to IRC guidelines. The stabilized subgrade distributes wheel loads more effectively, reduces pavement deformation, minimizes settlement, and increases pavement service life while reducing the thickness of pavement layers compared with conventional designs. Finally, the effectiveness of the proposed system is evaluated using important engineering parameters including California Bearing Ratio (CBR), Maximum Dry Density (MDD), Optimum Moisture Content (OMC), Unconfined Compressive Strength (UCS), plasticity index, pavement thickness, and overall pavement performance. Comparative analysis demonstrates that industrial waste stabilization significantly improves the structural behaviour of weak subgrade soils while reducing construction cost and environmental impact. The proposed methodology provides highway engineers with an efficient, economical, and environmentally sustainable solution for designing flexible pavements using recycled industrial waste materials, thereby promoting sustainable infrastructure development and effective waste utilization.

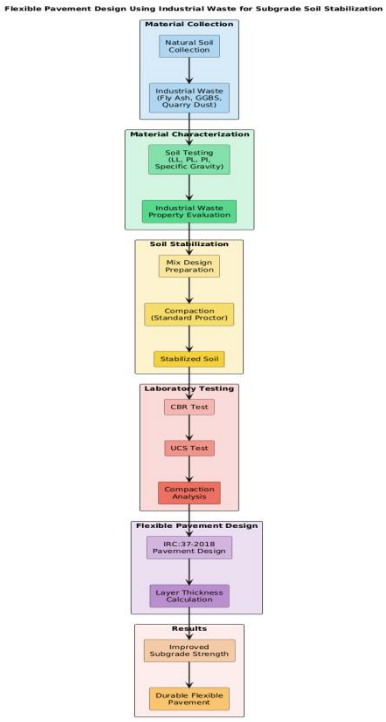

Fig1: Proposed workflow

III. WORKING METHODOLOGY

The proposed Flexible Pavement Design Using Industrial Waste for Subgrade Soil Stabilization follows a systematic methodology to improve the engineering properties of weak subgrade soil using industrial waste materials such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), quarry dust, steel slag, silica fume, and rice husk ash. The methodology integrates soil investigation, material characterization, stabilization, laboratory testing, pavement design, and performance evaluation to develop a durable and economical flexible pavement. The complete procedure follows the recommendations of IRC:37-2018, MoRTH Specifications, and relevant Indian Standard codes to ensure adequate pavement performance throughout the design life.

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Initially, representative subgrade soil samples are collected from the proposed construction site. The collected soil is dried, pulverized, and prepared for laboratory investigation. The engineering properties of the natural soil are determined by conducting Grain Size Analysis, Specific Gravity Test, Atterberg Limits Test, Standard Proctor Compaction Test, California Bearing Ratio (CBR) Test, and Unconfined Compressive Strength (UCS) Test. These tests provide important parameters such as Liquid Limit (LL), Plastic Limit (PL), Plasticity Index (PI), Maximum Dry Density (MDD), Optimum Moisture Content (OMC), bearing capacity, and shear strength of the untreated soil. The obtained values serve as the reference for evaluating the effectiveness of industrial waste stabilization.

After evaluating the natural soil, selected industrial waste materials including fly ash, GGBS, quarry dust, steel slag, or silica fume are collected from nearby industries and processed to remove impurities. The waste materials are dried, sieved, and stored under controlled conditions before mixing with soil. Different percentages of industrial waste are blended with the natural soil to prepare stabilized specimens. The soil–waste mixtures are thoroughly mixed to ensure uniform distribution of stabilizing materials throughout the soil matrix. The prepared mixtures are compacted according to the Standard Proctor Test to determine the corresponding Maximum Dry Density (MDD) and Optimum Moisture Content (OMC). Proper compaction improves particle interlocking and enhances the strength characteristics of the stabilized subgrade.

The stabilized specimens are then subjected to laboratory investigations to evaluate improvements in engineering properties. Important tests include the California Bearing Ratio (CBR) Test, Unconfined Compressive Strength (UCS) Test, Atterberg Limits Test, and Compaction Test. The CBR Test is performed to determine the load-bearing capacity of the stabilized soil, whereas the UCS Test evaluates the compressive strength after stabilization. The Atterberg Limits Test determines the reduction in soil plasticity, while the compaction test evaluates density improvement. The obtained results are compared with untreated soil to identify the optimum percentage of industrial waste providing maximum improvement in subgrade performance.

Following laboratory testing, the improved CBR values obtained after stabilization are used for designing the flexible pavement according to IRC:37-2018. The pavement structure consists of Bituminous Concrete (BC), Dense Bituminous Macadam (DBM), Wet Mix Macadam (WMM), Granular Sub-Base (GSB), and the stabilized subgrade. Pavement layer thicknesses are determined based on the design traffic and improved bearing capacity of the stabilized soil. Since the stabilized subgrade possesses higher strength, the required pavement thickness is reduced, resulting in savings in construction materials and overall project cost. Comparative evaluation is performed between pavements designed on untreated and stabilized soils to determine improvements in structural performance.

Finally, the stabilized pavement system is evaluated using important engineering parameters including California Bearing Ratio (CBR), Maximum Dry Density (MDD), Optimum Moisture Content (OMC), Unconfined Compressive Strength (UCS), plasticity index, pavement thickness, load-bearing capacity, and overall pavement performance. The experimental results demonstrate significant improvement in soil strength, reduced settlement, increased pavement durability, enhanced load distribution, and longer pavement service life. The proposed methodology confirms that industrial waste stabilization provides an environmentally sustainable, technically reliable, and economically efficient solution for flexible pavement construction while promoting effective utilization of industrial by-products.

Engineering Formulae

Equation (1): California Bearing Ratio (CBR)

$$CBR = \frac{P}{P_s} \times 100$$

Equation (2): Maximum Dry Density (MDD)

$$MDD = \frac{\rho}{1+w}$$

sEquation (3): Moisture Content

$$w = \frac{W_w}{W_d} \times 100$$

These equations are commonly used in subgrade soil stabilization, geotechnical engineering, and flexible pavement design according to IRC:37-2018, IS 2720, and MoRTH specifications.

V. IMPLEMENTATION

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The implementation of the proposed Flexible Pavement Design Using Industrial Waste for Subgrade Soil Stabilization was carried out to evaluate the effectiveness of industrial waste materials in improving weak subgrade soil and reducing the overall pavement thickness. The implementation involved soil collection, industrial waste preparation, laboratory testing, soil stabilization, flexible pavement design, and performance evaluation. The complete experimental work was conducted according to the recommendations of IRC:37-2018, MoRTH Specifications, and IS 2720 standards to ensure reliable and accurate results.

Initially, representative subgrade soil samples were collected from the proposed road construction site. The collected soil was air-dried, pulverized, and sieved to remove oversized particles before laboratory testing. Industrial waste materials such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), quarry dust, steel slag, and silica fume were collected from nearby industries and processed by drying and sieving to obtain uniformly graded materials. The engineering properties of the natural soil were determined by conducting Grain Size Analysis, Specific Gravity Test, Atterberg Limits Test, Standard Proctor Compaction Test, California Bearing Ratio (CBR) Test, and Unconfined Compressive Strength (UCS) Test. These preliminary investigations provided the baseline engineering characteristics of the untreated soil for comparison with stabilized soil.

After completing the characterization of natural soil and industrial waste materials, different proportions of industrial waste were mixed with the soil to prepare stabilized specimens. The mixtures were thoroughly blended to obtain a homogeneous distribution of stabilizing materials throughout the soil mass. Each stabilized specimen was compacted according to the Standard Proctor Compaction Test to determine the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC). Proper compaction improved particle interlocking, reduced air voids, and enhanced the overall strength of the stabilized subgrade. Various percentages of industrial waste were investigated to determine the optimum stabilization level capable of producing maximum improvement in engineering performance.

The prepared stabilized soil specimens were then subjected to comprehensive laboratory investigations. The California Bearing Ratio (CBR) Test was performed to evaluate the load-bearing capacity of the stabilized soil, while the Unconfined Compressive Strength (UCS) Test determined its compressive strength. Additional laboratory investigations such as the Atterberg Limits Test, Specific Gravity Test, and Compaction Test were also conducted to evaluate changes in plasticity, density, and moisture characteristics. The obtained results were compared with those of untreated soil to assess the effectiveness of industrial waste stabilization. Significant improvements in CBR values, compressive strength, and compaction characteristics were observed after stabilization.

Following laboratory evaluation, the improved CBR values obtained from the stabilized soil were used for designing the flexible pavement according to IRC:37-2018 guidelines. The pavement structure consisted of Bituminous Concrete (BC), Dense Bituminous Macadam (DBM), Wet Mix Macadam (WMM), Granular Sub-Base (GSB), and the stabilized subgrade. Pavement layer thicknesses were determined based on the design traffic, subgrade strength, and improved bearing capacity. Since the stabilized soil exhibited considerably higher CBR values, the required pavement thickness was reduced compared with pavements designed on untreated soil. This resulted in savings in construction materials and overall project cost while maintaining structural safety and pavement performance.

Finally, the stabilized pavement system was evaluated using important engineering parameters including California Bearing Ratio (CBR), Maximum Dry Density (MDD), Optimum Moisture Content (OMC), Unconfined Compressive Strength (UCS), plasticity index, pavement thickness, settlement characteristics, and overall structural performance. Comparative analysis confirmed that industrial waste stabilization significantly enhanced subgrade strength, improved load distribution, reduced pavement deformation, and increased pavement durability. The implementation demonstrated that the utilization of industrial waste materials provides an economical, technically reliable, and environmentally sustainable solution for flexible pavement construction while promoting effective recycling of industrial by-products and reducing environmental pollution.

VI. RESULTS EXPLANATIONS

Figure 2. Collection of Soil and Industrial Waste Materials

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Figure 2 illustrates the collection of natural subgrade soil and industrial waste materials used for stabilization. Representative soil samples were collected from the proposed pavement site, while industrial waste materials such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), quarry dust, and steel slag were obtained from nearby industries. The collected materials were dried, sieved, and prepared for laboratory investigations. Proper material preparation ensured uniform particle size and improved mixing efficiency during stabilization. The utilization of industrial waste significantly reduced dependence on conventional stabilizing materials such as cement and lime. Recycling industrial by-products also minimized landfill disposal and promoted sustainable construction practices. The prepared materials exhibited suitable physical characteristics for improving the engineering properties of weak subgrade soils. This stage forms the foundation for the stabilization process and contributes to the development of economical and environmentally friendly flexible pavements.

Figure 3. Preparation of Stabilized Soil Mixture

Figure 3 presents the preparation of the stabilized soil by mixing natural subgrade soil with industrial waste materials in predetermined proportions. The soil and stabilizing materials were thoroughly blended under controlled laboratory conditions to obtain a homogeneous mixture. Various percentages of fly ash, GGBS, quarry dust, and steel slag were investigated to determine the optimum stabilization level. Proper mixing ensured uniform distribution of the stabilizing agents throughout the soil matrix, thereby improving particle bonding and compaction characteristics. The stabilized mixture exhibited improved workability and greater resistance to deformation than untreated soil. The addition of industrial waste enhanced the pozzolanic reaction and increased soil strength by forming cementitious compounds. The prepared stabilized soil was subsequently compacted and used for laboratory investigations including CBR and UCS testing. The mixing process demonstrated the practical feasibility of utilizing industrial waste in highway engineering applications.

Figure 4. California Bearing Ratio (CBR) Test

Figure 4 illustrates the California Bearing Ratio (CBR) test conducted on stabilized soil specimens. The CBR test was performed to evaluate the load-bearing capacity of the subgrade before and after stabilization. The stabilized soil exhibited considerably higher CBR values than untreated soil due to improved particle interlocking and cementitious bonding. Increased CBR values indicate greater resistance to penetration under wheel loading and enhanced structural support for flexible pavements. The improved bearing capacity enabled a reduction in pavement thickness according to IRC:37-2018 design guidelines. The laboratory results confirmed that industrial waste materials significantly improve subgrade strength while maintaining satisfactory compaction characteristics. The enhanced CBR performance contributes to better pavement durability, reduced settlement, and lower maintenance requirements throughout the service life of the highway. These findings validate the effectiveness of industrial waste stabilization for sustainable pavement construction.

Figure 5. Standard Proctor Compaction Test

Figure 5 shows the Standard Proctor Compaction Test performed to determine the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of the stabilized soil. Proper compaction is essential for achieving maximum soil strength and minimizing future settlement. The stabilized soil exhibited improved compaction characteristics compared with untreated soil because the industrial waste materials reduced void spaces and enhanced particle interlocking. The increased dry density and optimum moisture relationship resulted in improved bearing capacity and structural stability of the pavement foundation. Better compaction also reduced permeability and moisture-induced deterioration, thereby increasing pavement durability. The experimental observations confirmed that stabilized soil could achieve higher density with proper moisture control, making it suitable for supporting heavy traffic loads. These improvements contribute directly to enhanced pavement performance and longer service life.

Figure 6. Flexible Pavement over Stabilized Subgrade

Figure 6 presents the completed flexible pavement constructed over the stabilized subgrade. The pavement consists of Bituminous Concrete (BC), Dense Bituminous Macadam (DBM), Wet Mix Macadam (WMM), Granular Sub-Base (GSB), and the stabilized soil foundation. The improved subgrade provided greater structural support, enabling a reduction in pavement layer thickness while maintaining the required load-bearing capacity. The stabilized foundation distributed wheel loads more efficiently, reducing settlement, rutting, and pavement deformation under repeated traffic loading. The use of industrial waste materials improved pavement durability and minimized maintenance requirements throughout the design life. In addition to technical benefits, the project promoted sustainable construction by utilizing recycled industrial by-products, reducing landfill waste, and conserving natural resources. The completed pavement demonstrates that industrial waste stabilization is an economical, environmentally friendly, and technically reliable solution for modern flexible pavement construction.

VII. CONCLUSION

The present study successfully investigated the Flexible Pavement Design Using Industrial Waste for Subgrade Soil Stabilization by utilizing industrial by-products such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), quarry dust, steel slag, and silica fume to improve the engineering characteristics of weak subgrade soil. Laboratory investigations including the California Bearing Ratio (CBR) Test, Standard Proctor Compaction Test, Atterberg Limits Test, Specific Gravity Test, Grain Size Analysis, and Unconfined Compressive Strength (UCS) Test were carried out to evaluate the effectiveness of stabilization. The experimental results demonstrated that the incorporation of industrial waste materials significantly enhanced the load-bearing capacity, compaction characteristics, and strength properties of the subgrade while reducing soil plasticity and settlement. These improvements contributed to the development of a stronger pavement foundation capable of supporting heavy traffic loads more efficiently.

The stabilized soil exhibited a considerable increase in CBR values and Unconfined Compressive Strength, indicating enhanced resistance to deformation and improved structural stability. The increase in Maximum Dry Density (MDD) and reduction in Plasticity Index (PI) confirmed better compaction and lower susceptibility to moisture-induced damage. Based on the improved CBR values, the flexible pavement was designed according to IRC:37-2018, resulting in a reduction in pavement layer thickness compared with the pavement designed over untreated soil. This reduction

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minimized the consumption of construction materials and lowered the overall construction cost while maintaining the required structural performance and serviceability.

The utilization of industrial waste materials also provided significant environmental benefits by promoting the recycling of industrial by-products that would otherwise be disposed of in landfills. The replacement of conventional stabilizing materials such as cement and lime reduced carbon emissions and supported sustainable construction practices. The reuse of fly ash, GGBS, quarry dust, and steel slag contributed to resource conservation while minimizing environmental pollution associated with industrial waste disposal. The study demonstrated that industrial waste stabilization is both an environmentally responsible and economically viable solution for modern highway construction.

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