Green Pavement Innovation Using Stabilized Red Mud and Industrial By- Products for Sustainable Infrastructure in Tamil Nadu

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***Abstract*—The increasing generation of red mud, a by-product of the aluminum industry, poses significant environmental challenges. This study explores its effective utilization in pavement applications by stabilizing it with lime and Ground Granulated Blast Furnace Slag (GGBS). Experimental investigations were carried out using California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and pH tests to evaluate the performance of stabilized red mud. Different mix proportions were prepared, and the results showed substantial improvement in strength properties. The maximum CBR value of 24.56 % was obtained at 2.5 mm penetration for the mix containing 75 % red mud, 15 % lime, and 10 % GGBS. Additionally, an optimum lime content (OLC) of 12.5% yielded a peak CBR value of approximately 26 %. The UCS test results indicated progressive strength gain with curing time. At 7 days, UCS values ranged from 1.26 MPa to 1.41 MPa, while at 14 days, they increased from 1.44 MPa to 1.53 MPa, with the maximum strength observed for Sample 4. The pH values of the stabilized mixes were found to be in the range of 12 to 13, satisfying the IRC recommended range (10–13) for subbase materials. The results confirm that the addition of lime and GGBS significantly enhances the engineering properties of red mud, making it a viable and sustainable alternative material for pavement subgrade and subbase applications. This approach not only improves soil performance but also promotes environmentally responsible waste utilization.**

***Key Words*— Red Mud, Soil Stabilization, Pavement Engineering, California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), Lime Stabilization, Ground Granulated Blast Furnace Slag (GGBS), Subgrade Improvement, Eco-Friendly Materials, Pavement Subbase.**

I. INTRODUCTION

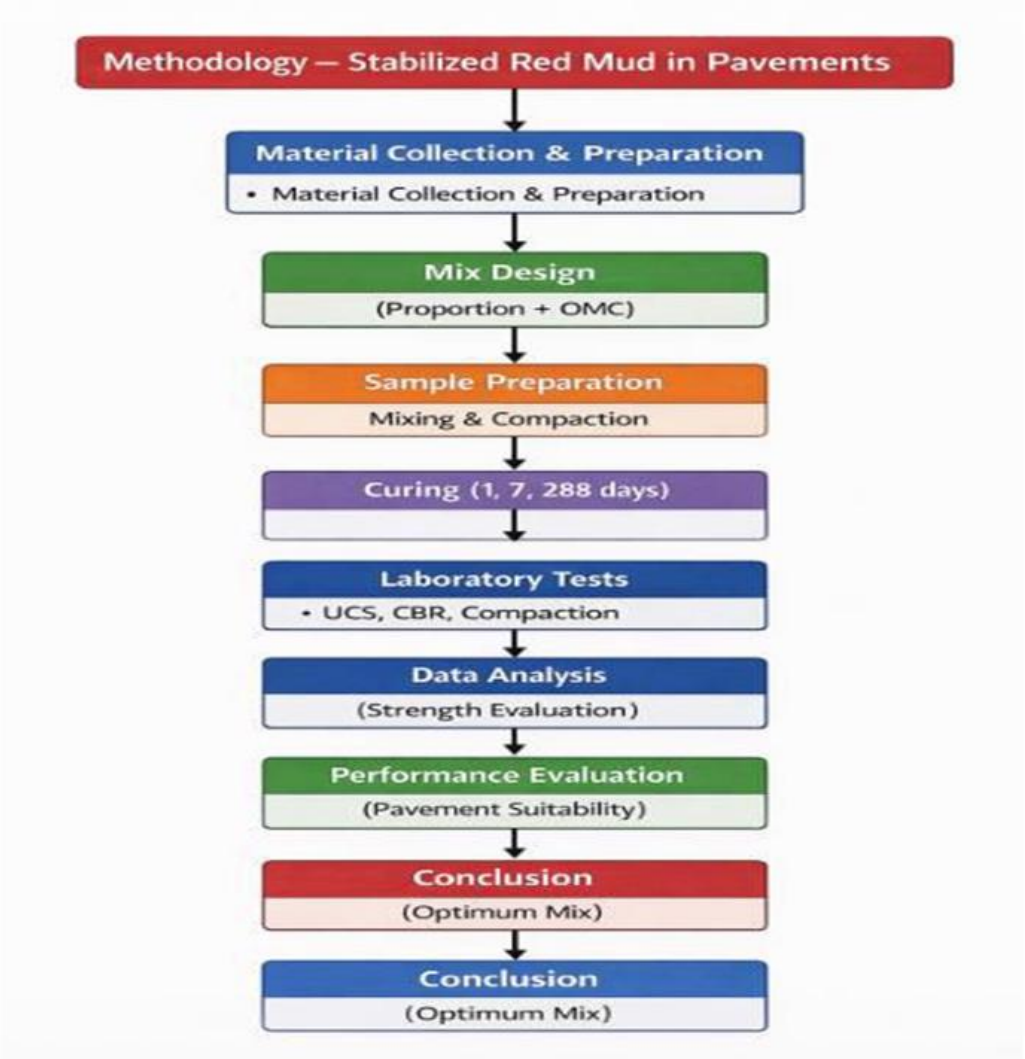
Laboratory tests investigated red mud as a stabilizer for subgrade soils. Results showed notable improvements in strength and load-bearing capacity.[1] Red mud was combined with lime and cement to enhance pavement layers. The treatment led to higher compressive strength and better durability.2] The study evaluated red mud as a partial substitute in sub-base layers. Findings revealed improved compaction and reduced need for natural aggregates.[3] Red mud's geotechnical properties were assessed in embankment applications. Both lab and field experiments demonstrated increased stability and shear strength.[4] A review summarized the sustainable use of red mud in pavements. Evidence pointed to strength enhancement and environmental benefits.[5] Mechanical behaviour and environmental impact of red mud-modified pavement materials were analyzed. Strength was boosted while leaching remained minimal.[6] The use of red mud in bituminous and granular layers was tested. Layer stiffness and overall performance showed substantial improvement.[7] Expansive soils were stabilized with red mud to improve engineering properties. Plasticity decreased and strength increased significantly.[8] Red mud was blended with fly ash for pavement applications. The mixture enhanced durability and promoted the reuse of industrial waste.[9] Red mud-treated soils were examined for flexible pavement foundations.

CBR and load-bearing performance improved notably.[10] Red mud was studied through experimental and analytical methods for pavement construction. Mechanical properties and durability were significantly enhanced.[11] The study tested red mud-treated subgrade soils using CBR and UCS. Treated soils exhibited higher strength and stiffness.[12] Red mud's influence under repeated loading was evaluated. The material reduced deformation and increased long-term durability.[13]

Red mud with GGBS and lime was tested for base courses. Results showed improved strength and resistance to environmental effects.[14] Pavement performance and leachability of red mud were assessed. Strength was adequate, and the release of harmful elements was controlled.[15] Weak subgrades were stabilized using red mud. Treated soils demonstrated higher stiffness and reduced deformation.[16] The feasibility of red mud in rural road sub-base layers was investigated. Adequate compaction and strength made it a cost-effective option.[17] Red mud-blended soils were tested for compaction and strength characteristics. Maximum dry density and load capacity improved noticeably.[18]

Laboratory and field assessments were conducted on red mud in pavements. Both approaches confirmed enhanced strength and durability.[19] Red mud combined with industrial by- products was used to improve subgrade soils. Enhanced stability and reduced deformation were observed.[20] Demonstrates that increasing red mud content in alkali-activated slag cement improves strength while influencing efflorescence behavior in pavement materials.[21] Evaluates the suitability of fly ash and red mud-based geopolymer materials for rigid pavement through strength and performance analysis.[22] Investigates the mechanical properties and microstructure of soils stabilized with red mud-based cementitious materials for enhanced engineering performance.[23]

Methodology:



The methodology for an experimental study on stabilized red mud in pavement applications involves collecting red mud and stabilizing materials such as cement, lime, or fly ash, followed by testing their basic properties like grain size, Atterberg limits, and pH. Different mix proportions are prepared and compacted at optimum moisture content to form test specimens. These samples are cured for specified periods (7, 14, and 28 days) and then tested for strength using Unconfined

Compressive Strength (UCS) and California Bearing Ratio (CBR), along with compaction characteristics. Durability and permeabilitytests may also Be conducted. Microstructural analysis (SEM/XRD) and environmental tests (leachability) are performed to evaluate bonding and safety. Finally, results are analyzed to identify the optimum mix suitable for pavement subgrade or sub-base applications.

1.1 Materials used:

Red mud

Red mud is an industrial waste from alumina production, having high alkalinity and fine particles. It alone has low strength,but improves soil properties when used as a filler. Its properties are determined using IS 2720 Part 3 and IS 2720 Part 4, while compaction behavior is studied using IS 2720 Part 7.

Limestone

Lime (from limestone) acts as a stabilizer by reacting with silica and alumina to form cementitious compounds, reducing plasticity and increasing strength; this is evaluated using IS 2720 Part 5 and IS 2720 Part 10.

Ground granulated blast furnace slag(GGBS)

GGBS is an industrial by-product with cementitious properties that, when activated by lime or red mud, enhances strength and durability through formation of C-S-H gel. Its performance is also assessed using IS 2720 Part 7, IS 2720 Part 10, and IS 2720 Part 16, making the combination suitable for pavement and subgrade applications.

Preparation of Materials:

The materials used in this study include red mud, ground granulated blast furnace slag (GGBS), and limestone, which are prepared prior to testing to ensure uniformity and consistency. The red mud collected is first air-dried to remove moisture and then pulverized to break down lumps. It is subsequently sieved through a 4.75 mm sieve to obtain a uniform gradation suitable for laboratory testing. GGBS and limestone are also dried if necessary and sieved to remove any impurities or oversized particles. The required quantities of red mud, GGBS, and limestone are then proportioned according to the selected mix ratios (such as varying percentages of GGBS and limestone replacing red mud). The dry materials are thoroughly mixed to achieve a homogeneous blend. After dry mixing, water is added gradually based on the Optimum Moisture Content (OMC) determined from compaction tests, and the mixture is mixed uniformly until a consistent and workable mass is obtained. The prepared mix is then used immediately for specimen preparation for tests such as pH, UCS, and CBR, ensuring proper compaction and curing conditions as per relevant standards.

1.2 Test Procedure:

pH Test Procedure

The pH test for red mud stabilized with GGBS and limestone is carried out to determine the alkalinity of the mix. A representative soil sample is air-dried and sieved through a 425 μm sieve. About 20 g of the sample is taken and mixed with distilled water in a ratio of 1:2.5 (soil: water). The mixture is stirred thoroughly and allowed to stand for about 30 minutes with intermittent stirring to ensure proper interaction. A calibrated digital pH meter is then inserted into the suspension, and the pH value is recorded once the reading stabilizes. The test is conducted at room temperature, ensuring proper calibration of the pH meter using standard buffer solutions before measurement.

Unconfined Compressive Strength (UCS) Test Procedure

The UCS test is conducted to evaluate the compressive strength of red mud stabilized with GGBS and limestone. The materials are mixed in required proportions at optimum moisture content and compacted into cylindrical molds (typically 38 mm diameter and 76 mm height). The specimens are carefully extruded and cured for specified durations such as 7, 14, or 28 days under controlled conditions. After curing, the specimen is placed in the compression testing machine, and axial load is applied at a constant strain rate (usually 1.25 mm/min) until failure occurs. The maximum load at failure is recorded, and the UCS value is calculated by dividing the peak load by the cross-sectional area of the specimen.

California Bearing Ratio (CBR) Test Procedure

The CBR test is performed to assess the load-bearing capacity of red mud stabilized with GGBS and limestone for pavement applications. The prepared mix is compacted into a CBR mold at optimum moisture content using standard Proctor compaction. The compacted specimen is then soaked in water for 4 days (for soaked CBR) to simulate worst field conditions. After soaking, the mold is placed under the CBR testing machine, and a plunger of 50 mm diameter is penetrated into the specimen at a rate of 1.25 mm/min. The load corresponding to penetrations of 2.5 mm and 5 mm is recorded. The CBR value is calculated as the ratio of the measured load to the standard load, expressed as a percentage, and the higher value is reported as the CBR of the material.

II. RESULTS

The experimental investigation on stabilized red mud using lime and Ground Granulated Blast Furnace Slag (GGBS) demonstrated a significant improvement in engineering properties required for pavement applications. The California Bearing Ratio (CBR) values increased considerably with the addition of lime and GGBS, with a maximum CBR value of 24.56% obtained at 2.5 mm penetration for the mix containing 75% red mud, 15% lime, and 10% GGBS. Additionally, the optimum lime content of 12.5% yielded a peak CBR value of approximately 26%, indicating a substantial enhancement in load-bearing capacity and confirming the material's suitability for subgrade and subbase layers. The Unconfined Compressive Strength (UCS) values also showed consistent improvement with curing time, reflecting strength gain due to pozzolanic reactions. At 7 days of curing, UCS values ranged from 1.26 MPa to 1.41 MPa, with the maximum recorded for Sample 4, while at 14 days, values increased from 1.44 MPa to 1.53 MPa, again with Sample 4 showing the highest strength. This increase in strength highlights improved bonding and durability of the stabilized mix. Furthermore, the pH values of the stabilized red mud ranged between 12 and 13, which falls within the permissible limits specified by IRC guidelines (pH 10–13), confirming the chemical suitability of the material for pavement applications. Overall, the addition of lime and GGBS significantly enhanced both CBR and UCS values, with strength increasing over the curing period due to pozzolanic reactions, and the optimum mix proportion identified as 75% red mud, 15% lime, and 10% GGBS.

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