Experimental Evaluation of Gravel Sub-Base Stabilization for Sustainable Road Infrastructure

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Abstract

Stabilized gravel is increasingly recognized as a vital component in modern road construction, particularly for sub-base layers where strength, durability, and cost-efficiency are critical. This research presents a detailed laboratory investigation into the mechanical performance of gravel stabilized using a blend of cement, lime, and fly ash. The primary objective was to identify an optimal mix design and assess the structural improvements achieved through stabilization.

The study involved standard laboratory testing procedures, including Modified Proctor Compaction, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS) tests. The optimum mix was determined to consist of 6% cement, 4% lime, and 10% fly ash by dry weight of the gravel. Test results revealed a remarkable improvement in the mechanical behavior of the stabilized gravel. The CBR value reached 110%, substantially exceeding the minimum threshold of 80% typically required for sub-base applications. Similarly, the UCS of the stabilized mixture showed a significant increase compared to that of the untreated gravel, indicating enhanced load-bearing capacity and structural reliability.

Overall, the findings affirm that the incorporation of cement, lime, and fly ash can transform conventional gravel into a high-performance sub-base material suitable for flexible pavement systems. This stabilization approach not only improves mechanical properties but also promotes sustainability through the reuse of industrial by-products. Further field-based studies are recommended to evaluate the long-term performance of the stabilized gravel under varying climatic and traffic conditions.

Keywords: Gravel Stabilization, Sub-base Layer, Cement-Lime-Fly Ash Mix, California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), Sustainable Road Construction, Pavement Engineering, Soil Stabilization, Industrial Waste Utilization, Flexible Pavement Design

1. Introduction

High-quality aggregates are getting harder to find and more expensive in many areas making it difficult to meet traditional flexible pavement specifications. Materials for base course and mixes of asphalt and concrete used in these pavements typically require high-quality aggregates. However, materials that are readily available locally are increasingly not satisfying the requisite standards, and importing materials that do can be prohibitively expensive.

One solution to this problem is to produce flexible pavement using marginal aggregates. Marginal aggregates can any aggregate does not meet the standards can be widely defined.for normal use but can still be successfully used in pavement construction with modifications to the design and construction procedures. By using marginal aggregates, it may be possible to reduce pavement construction costs and overcome the challenges posed by a scaracity of high-quality aggregate sources.

Moreover, it's essential to identify any potential problem areas that could arise from using marginal materials. For example, if the materials have a high percentage of fines or are prone to swelling, they could lead to issues such as

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rutting, cracking, or moisture damage. These issues could ultimately offset any expected cost savings from using marginal materials.

Therefore, the choice to use or reject marginal materials must be based on thorough evaluation that takes into account all relevant factors. By doing so, it's possible to optimize pavement construction costs without compromising performance or quality. Ultimately, it's essential to strike a balance between cost-effectiveness and long-term durability and performance.

The implications of using marginal aggregates in flexible pavements will be defined in technical terms in this study. We'll look at different approaches for bringing marginal aggregate performance up to parity with standard aggregate performance. The primary focus will be on marginal aggregates for flexible pavements.

1.1 Current Research Need

Before adopting marginal materials for construction purposes, a comprehensive assessment of their benefits and limitations is essential. As certain influencing factors may not be quantifiable in purely economic terms, the evaluation must extend beyond simple cost analysis. The suitability of such materials should primarily be determined based on their technical performance, while also incorporating thorough consideration of economic viability and environmental sustainability.

1.2 Goal and Purpose of the Work

This study primarily focused on the gaps mentioned above. The development of stabilised gravel will allow for the use of subpar aggregates in road building, which is the overall goal.

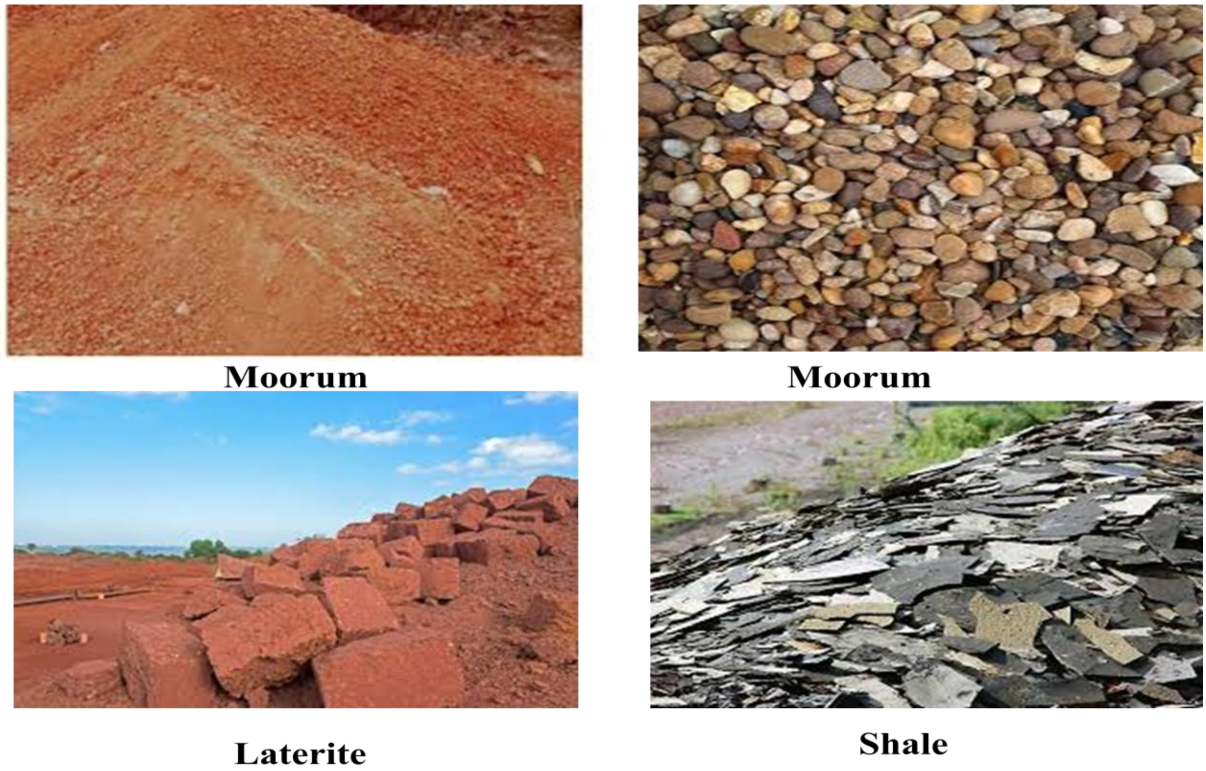


Figure 1.1 :-Various Types of Marginal Aggregates Available in India

Out of different marginal aggregates found in India, the marginal aggregates used in this study is Moorum which is a fragmented weathered rock naturally occurring with varying proportions of silt and clay. It is considered as a low grade marginal material for road construction. It is widely available in different parts of our country with significant variation in its qualities from one location to another in terms of its crushing and impact value, grain size, clay and deleterious content. It has generally low bearing capacity and high water absorption value in comparison to conventional aggregates. It finds application in the construction of base/sub base course in rural roads of India with suitable stabilization methods. Moorum is a locally available marginal aggregates widely present in different parts of our country. It has less productive use as compared to other marginal aggregates. So the purpose of this research is to utilize moorum by focusing on the following features.

- To ensure optimal moorum usage in pavement construction for base/sub base course and achieve satisfactory field performance in terms of strength and shear value.
- To examine the feasibility of incorporating cement and bitumen emulsion as moorum additives.

2. Literature Review

Kumar et al. (2020) examined the use of bitumen emulsion for stabilizing gravel sub-base layers in low-volume roads. The study aimed to assess improvements in load-bearing capacity and moisture resistance. The test results indicated a significant increase in California Bearing Ratio (CBR) values and enhanced resistance to water penetration compared to untreated gravel. The authors emphasized the suitability of bitumen-stabilized gravel in regions with variable and heavy rainfall, due to its superior waterproofing characteristics and durability under moist conditions.

Zhou and Li (2020) focused on the utilization of industrial by-products, specifically fly ash and ground granulated blast furnace slag (GGBS), as alternative stabilizing agents for gravel sub-bases. Their research demonstrated that partial replacement of gravel with these materials led to improved compressive strength and long-term environmental performance. The study concluded that using such industrial waste materials reduces dependence on traditional cement-based stabilizers and significantly lowers the carbon footprint of pavement construction.

Singh and Choudhary (2021) conducted a study on gravel stabilization using cement and lime for rural road sub-base construction. Their investigation revealed that the use of cement led to a 40–50% improvement in unconfined compressive strength (UCS), along with enhanced durability under cyclic wetting and drying. However, the researchers highlighted the environmental drawbacks of cement production and advocated for the adoption of more sustainable alternatives.

Ahmed et al. (2021) explored the use of enzyme-based stabilizers for improving gravel sub-base layers. The study reported considerable enhancement in load-bearing capacity and particle bonding while maintaining a minimal environmental footprint. The enzyme treatment was especially effective in semi-arid regions by reducing dust emission and enhancing the mechanical interlocking of gravel particles.

Rahman et al. (2023) investigated the performance of geopolymer binders derived from fly ash and alkaline activators in stabilizing gravel. The research indicated that geopolymer-stabilized gravel exhibited superior mechanical strength, improved durability, and low leachate emissions, making it a promising sustainable alternative to Portland cement-based stabilization.

Patil and Verma (2023) evaluated the effectiveness of recycled plastic waste as a stabilizing additive in gravel sub-base construction. The study demonstrated that the addition of shredded plastic improved cohesion and resistance to deformation under repeated loading. Their findings support the dual benefit of waste management and improved road performance, particularly in heavily trafficked or environmentally sensitive areas.

Mohan et al. (2024) conducted full-scale field trials to assess the impact of nano-silica additives in gravel stabilization. The results showed that the treated sub-base exhibited enhanced fatigue resistance, stiffness, and reduced rutting. The study highlighted the potential of nano-materials to significantly extend the service life of sub-base layers under varying climatic and load conditions.

Sarkar and Das (2024) examined a hybrid stabilization approach using bitumen emulsion combined with cementitious additives. Their findings revealed that this combination resulted in excellent stiffness, water resistance, and long-term structural performance. The hybrid method was found to be particularly suitable for rural roads with high traffic loads and poor drainage conditions.

2.1 Critical Reviews

- The reviewed studies indicate that the strength of marginal aggregates can be significantly improved through the incorporation of various stabilizing additives, making them suitable for use in road sub-base or base course layers.
- However, limited research has focused on the combined application of bitumen emulsion with calcium-based additives such as cement or lime to enhance the performance of marginal aggregates.
- This highlights a potential research opportunity to explore the effectiveness of using both emulsion and cement for stabilizing locally available marginal materials like Moorum.

3. Methodology

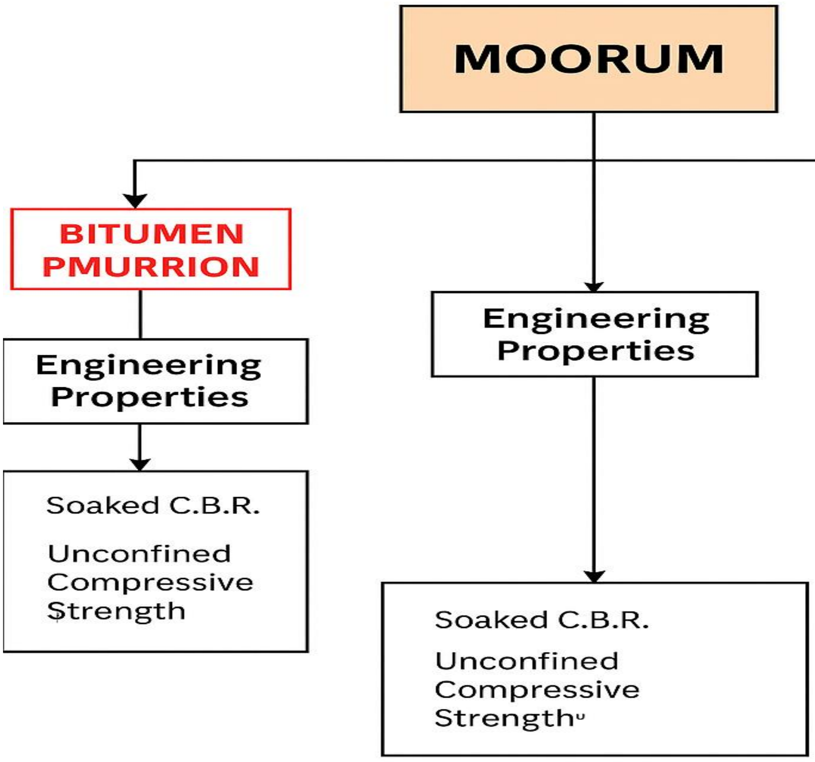


Figure 2.1:- Methodology Flow Chart

3.1 Tests on Moorum

2.1.1 Basic Physical Properties

The basic physical properties of the moorum (Gravel) used in this experiment have been identified and are listed in Table 2.2

Table 2.1: Basic Properties of Moorum

S.No.	Property	Result of Test
1	Specific Gravity	2.7
2	Liquid Limit, %	30.1
3	Plastic Limit, %	21.1
4	Plasticity Index, %	8.9

5	Optimum Moisture Content, %	10.1
6	M.D.D. gm/cm^3	2.01

2.2.2 Grain Size Distribution

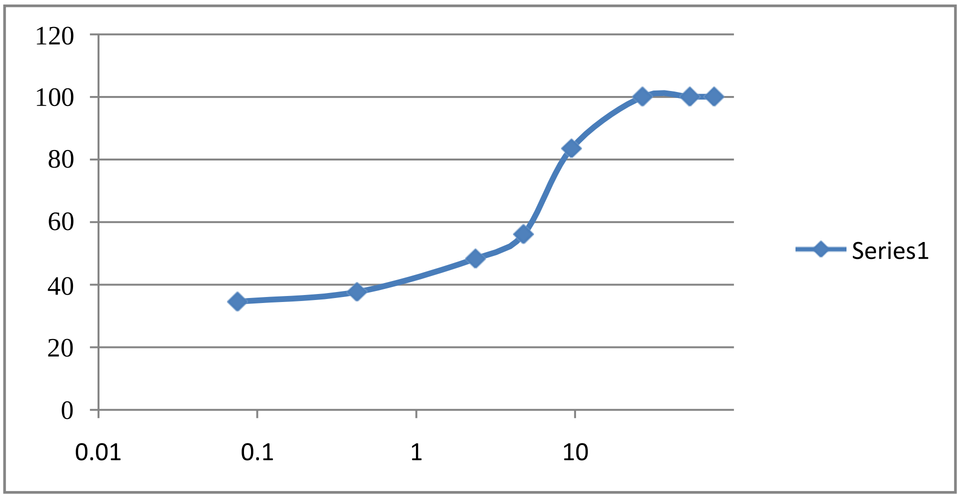


Figure 2.2: Grain Size Distribution Graph

The grading was done in accordance with section 404 of the Indian Road Congress-published "Specifications for Rural Roads" Ministry of Rural Development (First version 2010).

Table 2.2:- Gradation followed for Moorum

IS Sieve	Percentage of the Total Weight Passing Inside the Range
53.00 Mm	100
37.00 Mm	100
19.00 Mm	100
9.50 Mm	-
4.75 Mm	-
600 Micron	8-65
300 Micron	5-40
75 Micron	0-10

2.2.3 California Bearing Ratio (C.B.R.) Test

CBR quantifies the resistance of a material to penetration by a standard plunger under controlled moisture and thickness conditions. This is an example of very common test to evaluate the sub-level quality prior to the construction of roads. The test has been thoroughly investigated for the necessity for adaptive asphalt thickness in the field. Testing is carried out in accordance with IS: 2720 (Part 16) in a comprehensive manner. The test is inserting a circular, barrel-shaped plunger 50 mm wide into an asphalt component material at a rate of 1.25 mm/moment. The heaps for 0.5, 1, 1.5, 2, 2.5, 5, 5.5, and 6 mm. Every 0.5mm of expanding results in up to 12 to 13 mm of measurement. For different examples, weight conveyed in Kg with constrasting focal points is plotted in the Y hub and plan diagram while infiltration in mm is plotted in the X pivot. The CBR value at 2.5 mm infiltration is generally accepted as being greater. CBR is defined as the test burden ratio, stated as a rate for a specific plunger entrance. This is reflected in the rate. Ocasionally, typical heap of several varieties is discussed.

Mould size: standard volume 2250 cc
Normal available tested soil is used for testing in this case
Used proctor test result of previous case
Maximum Dry Density value: 2.02 gm./cc
Optimum Moisture Content: 10.12%
The CBR test lasts four days in a soggy environment.
CBR values were calculated at 2.5 mm and 5 mm penetration.
4 Days Moorum soaked CBR value of is discovered to be 14.620%

Figure 2.3: C.B.R. Testing Apparatus

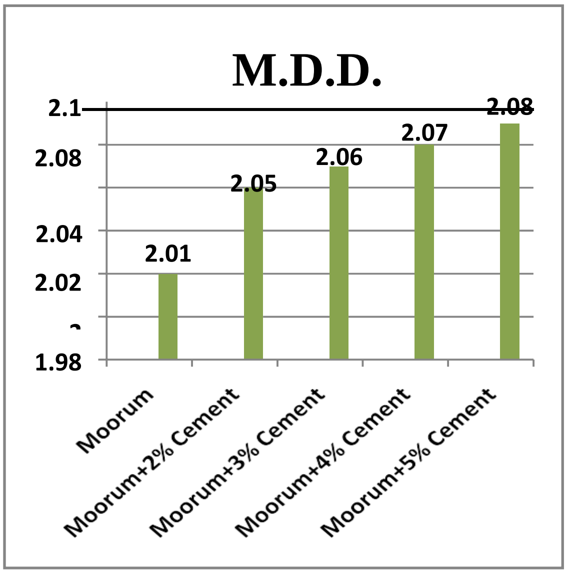
Figure 2.4:- UCS Testing Apparatus

2.2.4 U.C.S. Test

Uni-axial load is applied during the unconfined compression test for the remoulded Moorum sample until the specimen fails. This test offers a reliable evaluation of the cohesive soils' shear strength. The gravel soils test is carried out in accordance with IS 4332, part (v). Using the UCS mould, a sample measuring 100 mm diameter and 200 mm high sample is prepared and tested using the UCS testing machine. Soil and water requirements for sample preparations are determined using O.M.C. and M.D.D. data from modified Proctor test. Moorum has UCS value of 0.730 kg/cm^2

2.3 Changes in the Properties of Moorum as a Result of the Addition of Cement.

2.3.1 Change in O.M.C. and M.D.D.



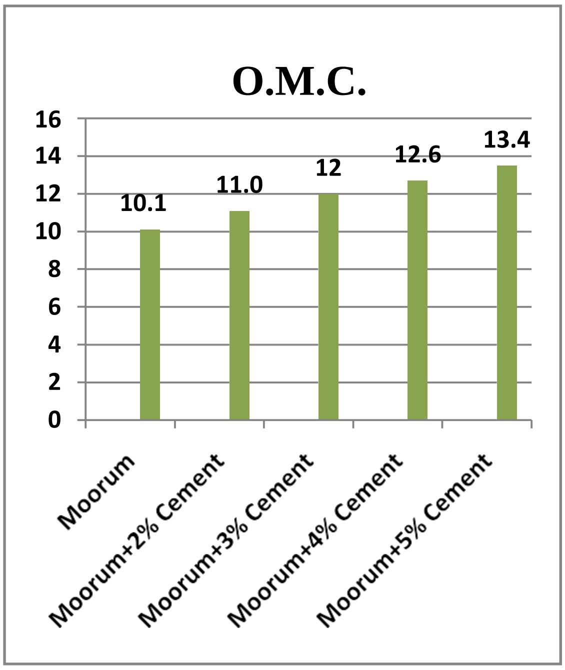


Figure 2.5: Graph of Modified Proctor Test

OPC enhances the stabilizing effect leading to higher dry density in mixtures with added cement, as compared to Moorum alone The proable mechanism involves pore filling and initiation of hydration reactions. Increased surface area from pore filling results in increased moisture, and hydration itself triggers water consumption. The OMC of the mix would be increased as a result.

2.3.2 Change in C.B.R.

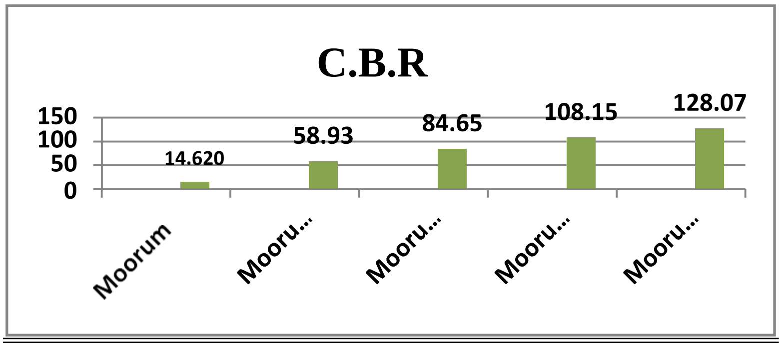


Figure 2.6: Comparasion Graph of C.B.R. Test

2.4.4 After the Addition of 5.0% Cement and Varying Amounts of Emulsion, Moorum's Properties Changed.

2.4.4.1 Change in C.B.R.

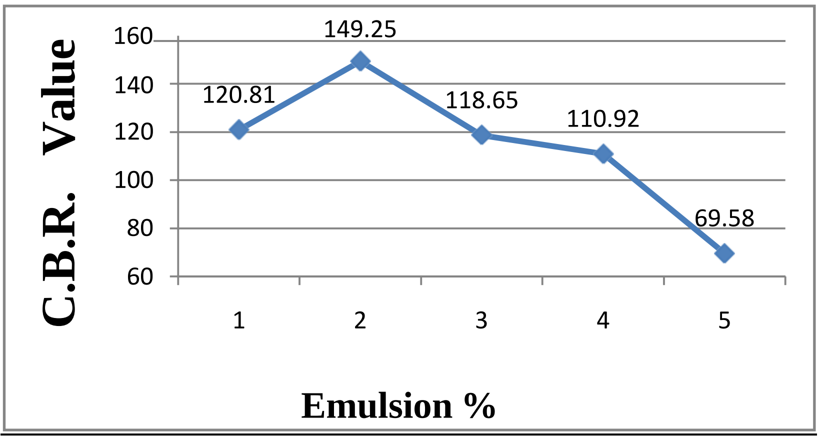


Figure 2.7: Comparasion Graph of C.B.R. Test

C.B.R. value increases as emulsion percentage goes up from 1 to 2, and then gradually decreases as emulsion percentag e goes up.The C.B.R. value is slightly higher at 2% than it is at 5% cement in regular Moorum.

2.4.4.2 Change in U.C.S.

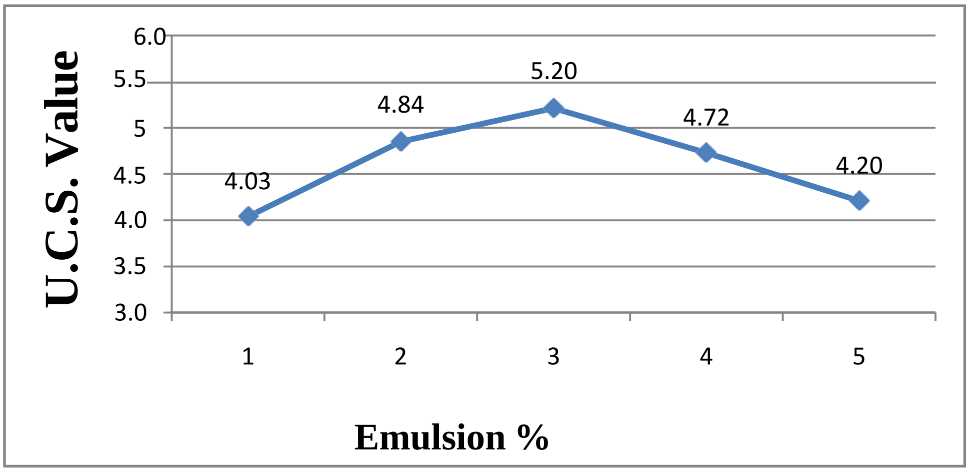


Figure 4.8: Comparasion Graph of U.C.S. Test

The U.C.S. value grows from 1.0 to 3.0, and then steadily falls as the emulsion proportion increases. The UCS value of 3.0 % is slightly more than the UCS value of standard Moorum with 5.0 % cement.

2.6 Overview of Research

According to aforementioned study, adding cement and SS-2 emulsion as stabilisers significantly increases the worth of soaking C.B.R. and Moorum in U.C.S. Therefore, Moorum with 3.0% cement and 2% emulsion is chosen as the ideal combination to utilise as the sub-base course for rural roads while keeping in mind the criteria. A durability test is then carried out to see how long the stabilised mixture will last.

2.7 Ductility Test

Durability tests are performed in accordance with IRC: SP: 89-2010. For the best combination, two identical sets of

UCS specimens are created. To prevent any form of moisture loss throughout the curing time, one is stored in an oven at 27.0+2.0 degree centigrade for 14.0 days for normal curing with paraffin. A 2^{nd} sample was stored in an oven at the same temp. for 7.0 days, following which it was placed in water for another 7.0 days. Following 14.0 days, the U.C.S of both of the samples was determined.

As a result, following is the outcome:-

UCS of specimen kept for 14.0 days in oven = 26.399 kg/cm^2

UCS of specimen kept for 7.0 days in oven and 7.0 days in water = 21.299 kg/cm^2

Sumerged set strength is found to be 80.69% of the strength of sets cured at constant moisture, indicating resistance to water weakening. A durability assessment shows the stabilizer percentage to be appropriate, with a value 80.1% for the test specimen.

3. Conclusions and Future Scope

3.1 Conclusion

The subgrade is a foundational layer of compacted soil, typically around 300 mm in thickness, located directly beneath the asphalt pavement. It plays a critical role in distributing loads and providing structural support to the overlying pavement layers. Generally composed of locally available soil, the subgrade forms the base upon which all other pavement components rest, making its strength and durability paramount for the long-term performance of a roadway.

In many cases, the native subgrade soil may lack adequate strength or stability. Therefore, enhancing its quality becomes essential, particularly for roads expected to experience even moderate traffic volumes. This enhancement can be achieved either by replacing the poor-quality soil with better material or by modifying the existing soil through stabilization techniques.

Recent studies and experimental investigations have demonstrated that Moorum, a naturally occurring reddish gravelly soil, can be significantly improved through stabilization using cement and bitumen emulsion. These additives chemically and physically enhance the soil structure, leading to a noticeable increase in its load-bearing capacity, shear strength, and durability. The improved mix becomes more resistant to moisture infiltration, deformation under load, and disintegration, making it suitable for use in sub-base layers of low to medium traffic roads.

The California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) values of stabilized Moorum show marked improvement when cement and bitumen emulsion are added in optimal proportions. This directly translates into an increased capacity to bear Equivalent Standard Axle Loads (ESALs), which are used to estimate the cumulative traffic load a pavement can sustain over its lifespan. As a result, roads constructed with such improved subgrades demonstrate extended service life, reduced maintenance frequency, and enhanced performance even under adverse weather conditions.

Moreover, the use of locally sourced Moorum combined with stabilizers proves to be a cost-effective and sustainable solution, especially in rural and semi-urban areas where access to conventional road-building materials such as crushed stone or high-quality aggregates may be limited or expensive. This method not only provides economic advantages but also promotes the efficient utilization of local resources.

In conclusion, stabilizing subgrade soil with cement and bitumen emulsion is a practical and efficient method to improve weak soils like Moorum, making them suitable for sub-base applications in low-volume roads. This technique ensures better load distribution, increases the structural integrity of the pavement system, and helps in enhancing the resilience of roads, particularly in regions with limited access to high-grade construction materials. It is a viable alternative for road infrastructure development in areas with constrained budgets and challenging geotechnical conditions.

3.2 Future Scope of Works

The laboratory investigation of stabilized gravel materials, particularly for their application in road sub-base layers, opens up several promising avenues for extended research and practical implementation. While the current study provides a strong foundation, further exploration is necessary to enhance the understanding and effectiveness of gravel stabilization techniques.

- **Exploration of Alternative Stabilizing Agents:** There is considerable potential in conducting further experimental studies focusing on the effects of different stabilizing additives—such as lime, fly ash, geopolymers, industrial by-products, and nano-materials—on the physical, chemical, and mechanical properties of gravel. Comparing their performance with cement and bitumen emulsion could help identify more cost-effective and environmentally friendly alternatives for diverse soil types.
- **Evaluation of Long-Term Durability and Performance:** Future research should also aim to assess the long-term behavior of stabilized gravel mixtures when subjected to repeated loading, wet-dry cycles, freeze-thaw conditions, and chemical exposure. These investigations are essential for predicting how well stabilized materials will perform over the lifespan of the pavement, especially under dynamic traffic loads and varying climatic conditions.
- **Field Implementation and Validation Studies:** Although laboratory tests provide valuable insights, it is critical to validate the results through field trials and pilot-scale road construction projects. Field studies would enable researchers and engineers to evaluate the real-world performance, constructability, workability, and maintenance requirements of stabilized gravel sub-base layers under actual traffic and environmental conditions.
- **Life-Cycle Cost Analysis and Environmental Assessment:** A comprehensive analysis of the economic viability of different stabilization techniques should also be carried out. This includes evaluating the initial cost, maintenance frequency, service life, and recyclability of the stabilized material. Additionally, the environmental impact, such as carbon emissions associated with the production and transportation of stabilizers, should be considered for sustainable road construction.
- **Optimization through Advanced Modeling Techniques:** The use of numerical modeling and simulation tools, such as finite element analysis (FEA) and machine learning models, can help in predicting the performance of various stabilized mixtures. These tools could assist in optimizing material proportions and predicting pavement behavior under specific design conditions.

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