A Study on the Effect of Bitumen Emulsion and Cement on the Strength of Gravelly Subgrade Soil

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Abstract:-Soil serves as a foundational material in nearly all construction activities, particularly in road infrastructure, where the strength of the subgrade layer directly influences pavement performance and longevity. In many regions, especially rural or semi-urban areas, naturally available gravelly subgrade soils often lack sufficient strength to withstand increasing traffic loads and environmental stresses. This necessitates soil stabilization to improve load-bearing capacity and long-term durability.

This experimental study investigates the combined effect of Medium Setting (MS) cationic bitumen emulsion and Ordinary Portland Cement (OPC) on enhancing the engineering properties of red lateritic gravel soil. The primary objective is to evaluate improvements in California Bearing Ratio (CBR) and Maximum Dry Density (MDD), key parameters that influence pavement design and cost-efficiency.

Laboratory tests were conducted under four different material combinations to determine the most effective mix in terms of strength gain. A small percentage of cement was used along with 3% bitumen emulsion to assess their combined influence on compaction characteristics and subgrade performance under soaked and unsoaked conditions.

The results indicate that the incorporation of bitumen emulsion and cement significantly improves CBR values and dry density, suggesting a viable and sustainable solution for low-cost rural and secondary road stabilization, especially in regions with weak or variable subgrade conditions.

Keywords: CBR, Bitumen Emulsion, Cement, Gravel Soil, Subgrade Stabilization, Soil Strength, Pavement Performance

1.1 Introduction

Soil is one of the most abundant and essential natural construction materials, forming the backbone of virtually every civil engineering project. In transportation infrastructure, particularly road construction, the strength and reliability of subgrade soils are vital determinants of pavement performance and longevity. As traffic intensity increases and environmental conditions become more unpredictable due to climate change, the demand for durable, cost-effective, and sustainable road foundations is greater than ever.

In many developing regions, especially rural and semi-urban areas, naturally occurring subgrade soils such as red lateritic gravel often lack the strength and stability required to support modern traffic loads. This deficiency can lead to premature pavement failures, higher maintenance costs, and overall economic inefficiencies. Therefore, soil stabilization techniques are increasingly used to improve subgrade quality by modifying its engineering properties using mechanical or chemical methods.

Among chemical stabilizers, materials like Portland cement, lime, fly ash, and bitumen emulsion have been extensively used. While cement and lime stabilization are widely adopted, the use of bitumen emulsion remains relatively underutilized, particularly in the context of gravelly or coarse-grained soils. Bitumen emulsion offers several advantages: it is easy to handle, works at ambient temperatures, provides water resistance, and is compatible with a wide range of aggregates.

This experimental study explores the combined effect of Medium Setting (MS) cationic bitumen emulsion and Ordinary Portland Cement (OPC) on the geotechnical behavior of locally available gravel soil. The primary focus is to evaluate improvements in the California Bearing Ratio (CBR) and Maximum Dry Density (MDD) two key indicators used in pavement design. The study aims to identify the optimal proportions and mixing techniques that maximize strength without significantly increasing material or construction costs.

In response to the current push for low-cost, sustainable road development especially under PMGSY (Pradhan Mantri Gram Sadak Yojana) and similar rural road schemes bitumen emulsion offers a promising alternative for strengthening marginal subgrade materials. With increasing emphasis on resource-efficient infrastructure, this research seeks to provide a practical solution for improving subgrade performance using locally available materials and simple technology.

The methodology involves subjecting gravel soil to various combinations of bitumen emulsion and cement, followed by laboratory testing to assess strength gains. Four distinct test cases are analyzed under soaked and unsoaked conditions, replicating realistic field scenarios. The results provide insights into how bitumen emulsion interacts with coarse-grained soils and how its performance changes with curing time and additive type.

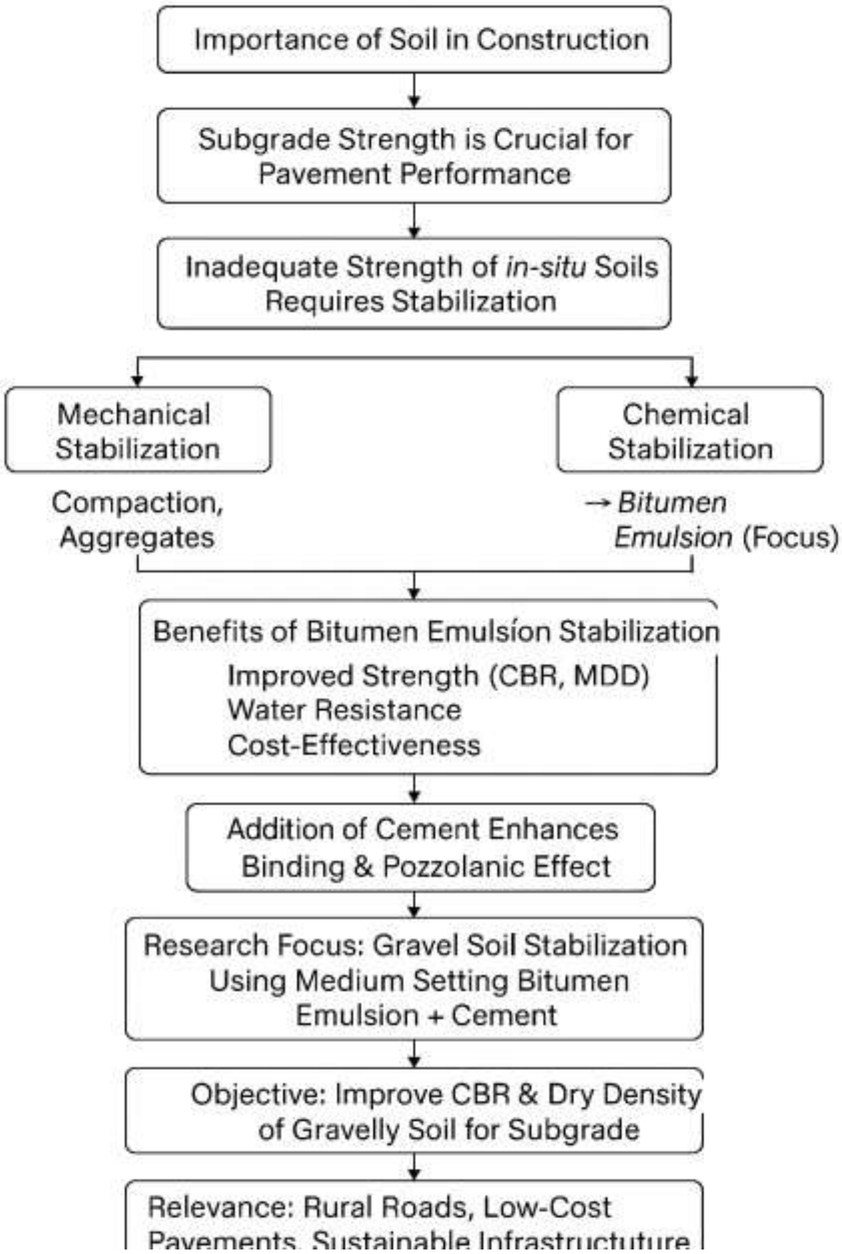


Figure 1.1:-Conceptual Framework of the Study

1.3 Objective

The primary objective of this experimental study is to evaluate the effectiveness of bitumen emulsion combined with a minor quantity of cement in improving the engineering properties particularly the strength characteristics of gravelly subgrade soil. The study specifically aims to:

- Enhance the California Bearing Ratio (CBR) value of gravelly soil to improve its load-bearing capacity.
- Identify the optimal proportion of bitumen emulsion and cement required to achieve maximum strength improvement.
- Promote the use of sustainable and cost-effective stabilization techniques in pavement subgrade design.
- Provide a reliable solution to enhance subgrade performance under the increasing demand for durable transportation infrastructure.

1.4 Scope of Work

To achieve the above objectives, a series of laboratory tests are conducted to evaluate the geotechnical behavior of gravelly soil treated with bitumen emulsion and cement. The scope of this experimental program includes:

- **Deter mination of Specific Gravity: -** To understand the density and heaviness of soil particles.

- **Grain Size Distribution Analysis: -** To classify the soil and assess the proportion of gravel, sand, silt, and clay in the sample.

- **Atter berg Limits Tests (Liquid Limit & Plastic Limit):-** To identify the consistency limits and plasticity characteristics of the soil.

- **Stand ard Proctor Compaction Test: -** To determine the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) for untreated and treated soils.

- **CBR (California Bearing Ratio) Tests: -** To assess the strength improvement of gravelly soil treated with varying percentages of bitumen emulsion and cement.

This study will help establish the best-performing mix of bitumen emulsion and cement that results in superior CBR values, enabling the design of more durable, economical, and sustainable pavements, especially in regions with poor natural subgrade conditions.

2. Literature Review

2.1 General

Bitumen emulsion is used as chemical stabilizer. Cement is used here as a binder only to improve strength of road. Previously lots of work was done on sand bitumen stabilization and gravel soil bitumen stabilization in different places. This study is being inspired from those researches. Here gravel red coloured soil is used, as it is available in many states of India. Some similar works, done before, is discussed below.

Michael (1993) had proposed about Bench-Scale Evaluation of Asphalt Emulsion Stabilization of Contaminated Soils. In this study, it was discussed about the application of ambient temperature asphalt emulsion stabilization technology and discussed to the environmental fixation of soils contaminated by organic contaminants.

Razouki et al. (2002) propose an experimental study on Granular Stabilized Roads. Bitumen was used as a stabilizing agent may act as a binder or as a water-proofing material. Soil-bitumen systems had found the greatest used in road bases and surfaces.

Cokca et al. (2003) concentrated on the impacts of compaction dampness content on the shear quality of an unsaturated mud. In this study, the impacts of compaction dampness substance and soaking on the unsaturated shear quality parameters of mud were investigated. Experiments werecarried out on specimens compacted at optimum dampness content, on the dry side of optimum and on the wet side. It was found that edge of erosion reductions quickly with increasing dampness substance, the union segment of shear quality attained its top worth at around optimum Moisture substance and afterward diminishes.

Kheradmand et al. (2013) investigated the potentials of Portland cement and bitumen emulsion mixtures for soil stabilization in road base applications. Using mixes of 3 % OPC and 3 % medium setting bitumen emulsion, they performed Unconfined Compressive Strength (UCS) and Modulus of Elasticity tests. Their findings showed that this dual binder system significantly enhanced stiffness and elasticity, reducing curing time and project costs demonstrating an optimum mix of 3 % cement + 3 % emulsion for improved pavement bearing capacity.

Prudhvi Teja (2015) work on silty subgrade soils stabilized with bituminous emulsion revealed that increasing emulsion content up to 8 % yields marked gains in soaked CBR compared to untreated samples. His study underscores that bitumen emulsion improves both compaction characteristics (higher MDD) and strength (higher CBR), making it viable for regions with moisture sensitive soils.

Research Gate Case Review (2023) A recent (2023) case study review synthesized global experiences with bitumen emulsions for subgrade stabilization. It emphasized the dual benefits of waterproofing and adhesion, noted successful field applications in rural roads, and called for performance based specification development to facilitate wider adoption.

IJIREM Investigation (2023) In the latest laboratory investigation, researchers applied 4 % medium setting emulsion to gravel road soils and observed a systematic rise in CBR across multiple curing scenarios. They reported that while dry density changes were modest, the strength gains under both soaked and un-soaked conditions validate emulsion’s role as an effective stabilizer for low volume roads.

From those literature review part it can be observed that different types of work had been done previously on bitumen soil stabilization. But in India the number of work on it is very few. Actually in India there is no any appropriate code for bitumen soil stabilization. As from those papers it is very difficult to get any actual idea about how to mix bitumen emulsion with soil and what will be its actual quantity. This experimental investigation is mainly to make a process for mixing bitumen emulsion with soil.

3. Experimental Programme

3.1 Specific Gravity of Soil

Specific gravity is defined as the ratio between the mass of a substance and the mass of an equal volume of water. For soils, it represents how many times soil solids are heavier compared to an equal volume of water. This property is denoted by ‘G’. Specific gravities vary for different soil types. During experiments, it is important to account for temperature correction and to use gas-free distilled water.
Specific gravity is a crucial physical property used to calculate other soil engineering properties such as void ratio, density, porosity, and saturation condition.
To measure specific gravity, a volumetric flask is used. The procedure involves determining the volume of the soil, measuring its weight, and then dividing it by the weight of an equal volume of water. This measurement provides essential data for understanding and predicting the behavior of soils in engineering applications.

G is Specific Gravity

$$G = (M2-M1)/((M4-M1)-(M3-M2))$$

Here,
M1=Weight of bottle
M2=Weight of bottle and Dry soil
M3=Weight of bottle, Dry soil and Water
M4= Weight of bottle and water

Table 3.1:- Standard Specific Gravity

Type of Soil	Specific Gravity
Sand	2.63-2.67
Silt	2.65-2.7
Clay and Silty Soil	2.67-2.9
Organic Soil	1+ to 2.6

3.2 Particle Size Distribution

Soil particles vary widely in size and shape, ranging from a few microns to several centimeters. The size and shape of these particles significantly influence the soil's physical properties, such as strength, permeability, and density.
Particle size distribution is determined using two primary methods: sieve analysis for coarse-grained soils and sedimentation analysis for fine-grained soils. The results from these methods are plotted on a semi-logarithmic graph, where the ordinate represents the percentage finer and the abscissa represents the particle diameter or sieve sizes on a logarithmic scale.
For this study, sieve analysis was conducted on coarse-grained soil samples. This analysis helps to determine the distribution of particle sizes in the gravel soil, which is essential for understanding its suitability for bitumen emulsion stabilization and overall performance in road construction.
Soils are categorized as well-graded or poorly graded based on the distribution of particle sizes. Well-graded soils contain a variety of particle sizes and shapes, ensuring a good distribution across the spectrum. Conversely, poorly graded soils exhibit an excess of certain particle sizes and a deficiency in others, leading to a less uniform distribution.

To analyze particle size distribution, sieve analysis results are plotted on a semi-logarithmic graph. In this graph, the particle diameter or sieve size (in millimeters) is plotted on the X-axis using a logarithmic scale, while the percentage finer is plotted on the Y-axis. This graph provides a clear depiction of the particle size distribution.

From the resulting curve, key parameters such as D10 and D60 are determined. D10 is the diameter at which 10% of the soil particles are finer, while D60 is the diameter at which 60% of the particles are finer. The uniformity coefficient (Cu) is calculated as the ratio of D60 to D10. The uniformity coefficient provides a measure of the soil's particle size range and helps in assessing the soil's grading quality.

3.3 Liquid Limit and Plastic Limit Test

The liquid limit (WL) of a soil is the moisture content at which the soil transitions from a liquid to a plastic state. At this limit, the soil has shear strength of 17.6 g/cm² and flows to standard dimensions for a groove when jarred 25 times using the Casagrande apparatus. The liquid limit is determined as the water content at which 25 drops of the cup cause the groove to close.
The plastic limit (PL) is the moisture content at which the soil transitions from a plastic to a semi-solid state. It is defined as the water content at which the soil begins to crumble when rolled into a 3 mm diameter thread.

Plasticity Index (IP) = Liquid Limit (WL) - Plastic Limit (WP) In summary, the liquid limit (WL) marks the transition from a liquid to a plastic state with minimal shear strength, while the plastic limit (PL) marks the transition from plastic to semi-solid state.

3.4 Compaction Test (Modified Proctor Test)

The Proctor Test is used to determine the relationship between moisture content and dry density of soils. This test involves compacting soil in a standard mold using a rammer dropped from a specified height. The objective is to find the optimum moisture content (OMC) at which the soil achieves its maximum dry density (Yd). The Proctor Test was first developed by R.R. Proctor in 1933, who demonstrated that the dry density of soil under compaction depends on the amount of water the soil contains. The standard Proctor compaction test, named in his honor, has been updated to include variations such as the Modified Proctor Test.

In the Modified Proctor Test, the procedures are similar to the standard test but with some key differences. Notably, the compaction effort is greater: the rammer weighs 4.5 kg and is dropped from a height of 18 inches. This increased compactive effort results in a higher degree of soil compaction.

The test involves compacting soil into a cylindrical mold in several layers, each receiving a specific number of blows from the rammer. For the Modified Proctor Test, the soil is compacted into the mold in five equal layers, with each layer receiving 25 blows from the rammer. The soil is compacted at various moisture contents, and the dry densities are calculated for each case.

The procedure for both the Standard and Modified Proctor Tests includes:

1. **Preparation of Soil Samples:**
   - ➢ Soil is mixed with water to achieve different moisture contents.
   - ➢ The mixture is allowed to equilibrate.
2. **Compaction Process:**
   - ➢ Soil is placed into the mold in layers.
   - ➢ Each layer is compacted with a specified number of blows from the rammer.
3. **Measurement and Calculation:**
   - ➢ The volume of the compacted soil is determined.
   - ➢ The wet and dry densities are calculated.
   - ➢ The optimum moisture content (OMC) is identified as the moisture content at which the maximum dry density (Yd) is achieved.

The hammer and the mold used for the Modified Proctor Test are designed to ensure consistent and reliable results, providing valuable information for soil compaction and construction quality control.

Figure 3.1:- Modified Proctor Test Apparatus

The graphical relationship of the dry density to moisture content is then plotted considering the values found to establish the compaction curve. The determined curve comes in parabolic shape and dry density value is increasing up to a maximum limit and after that again the value decreased. The maximum dry density is finally obtained from the peak point of the compaction curve and its corresponding moisture content, which is known as the optimal moisture content (OMC). Used formulas are listed below.

Normal wet density = (Weight of wet soil in mould gms) / (Volume of mould cc)
Moisture content (%) = ((Weight of water gms) / (Weight of dry soil gms)) 100 %

Dry Density γ_d (gm/cc) = $\frac{\text{Wet Density}}{1+\frac{\text{Moisture Content}}{100}}$

3.5 Bitumen Emulsion

Emulsified Bitumen usually consists of bitumen droplets suspended in water. Most emulsions are used for surface treatments. Because of low viscosity of the Emulsion as compared to hot applied Bitumen, The Emulsion has a good penetration and spreading capacity. The type of emulsifying agent used in the bituminous emulsion determines whether the emulsion will be anionic or cationic. In case of cationic emulsions there are bituminous droplets which carry a positive charge and Anionic emulsions have negatively charged bituminous droplets.

Based on their setting rate or setting time, which indicates how quickly the water separates from the emulsion or settle down, both anionic and cationic emulsions are further classified into three different types. Those are rapid setting (RS), medium setting (MS), and slow setting (SS). Among them rapid setting emulsion is very risky to work with as there is very little time remains before setting. The setting time of MS emulsion is nearly 6 hours. So, work with medium setting emulsion is very easy and there is sufficient time to place the material in proper place before setting. The setting rate is basically controlled by the type and amount of the emulsifying agent. The principal difference between anionic and cationic emulsions is that the cationic emulsion gives up water faster than the anionic emulsion.

Over a time of time, which may of years, the asphalt stage will in the long run separate from the water. Asphalt is insoluble in water, and breakdown of the emulsion includes the combination of droplets. The asphalt droplets in the emulsion have a little charge. The wellspring of the charge isthe emulsifier, and ion is able segments in the asphalt itself. However when two droplets do attain enough vitality to defeat this hindrance and approach nearly then they hold fast to one another. Over a time of time, the water layer between droplets in floccules will thin and the droplets will combine. Components which constrain the droplets together, for example, settlement under gravity, dissipation of the water, shear or solidifying will quicken the flocculation and mixture process. In this case mixing with soil slow setting bitumen emulsion is not so much effective andrapid setting is not easy to work with soil. So here I use medium setting emulsion as main stabilizing agent.

Today the main utilization of bitumen is in the pavement industry for construction and maintenance. Bitumen emulsions are a scattering of bitumen in a watery continuous stage, settled by the expansion of an emulsifier. They are ready as emulsions at high temperatures, however connected as robust scatterings at encompassing temperatures. In pavement engineering bitumen items are commonly added with aggregate. The solid adhesion that happens between the bitumenand mineral aggregate empowers the bitumen to go about as a binder, with the mineral aggregateproviding mechanical quality for the way.

3.6 California Bearing Ratio Test

The California Bearing Ratio (CBR) is a measure of the strength of soil, reflecting the resistance of the soil to penetration by a standard loading device. It is defined as the ratio of the force per unit area required to penetrate a soil mass with a standard load at a rate of 1.25 mm/min, compared to the force required for the same penetration of a standard material, typically limestone.

The CBR value is expressed as a percentage, with a standard material (limestone) used as the reference. The standard loads for various penetrations for this reference material are as follows:

- **At 2.5 mm penetration**: The standard load for limestone corresponds to a CBR value of 100%.
- **At 5 mm penetration**: The standard load for limestone corresponds to a CBR value of 100%.
- **At 7.5 mm penetration**: The standard load for limestone corresponds to a CBR value of 100%.
- **At 10 mm penetration**: The standard load for limestone corresponds to a CBR value of 100%.

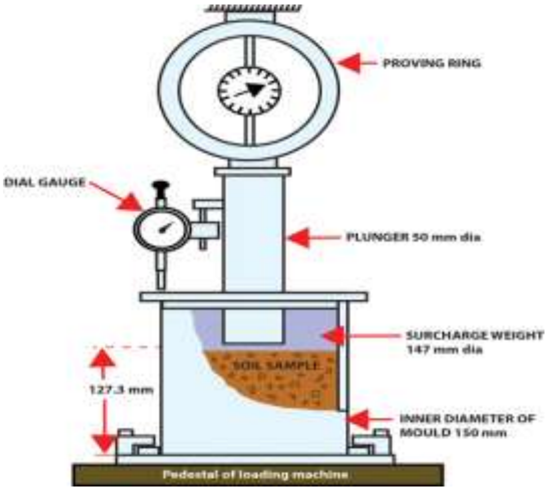


Fig. 3.2:- California Bearing Ratio Testing Machine

CBR value is calculated by this formula:
C.B.R. = (Test load /Standard load) 100 %

Standard load is for particular depth of penetration of plunger is given bellow.

Table 3.2:- Standard Load in Different Penetration

Penetration of Plunger (mm)	**Standard Load (Kg)**
2.5	1370
5	2055
7.5	2630
10	3180

4. Results and Discussion

4.1 Specific Gravity Test

Specific gravity of soil is very important property to understand the soil condition. As previously discussed here M1 is empty bottle weight, M2 is mass of bottle and dry soil, M3 is weight of bottle, dry soil and water and M4 is weight of bottle with water.

Table 4.1:- Specific Gravity Test Result

Sample No.	**M1 (gm)**	**M2 (gm)**	**M3 (gm)**	**M4 (gm)**	**Specific Gravity**
1	114.66	164.66	383.55	351.85	2.73
2	113.75	163.75	384.40	352.85	2.71
3	115.33	165.34	385.67	353.92	2.7

Here soil material is tested three times. And the average specific gravity value comes 2.726. But here no temperature correction is done. This test have been done in room temperature nearly 25*C

4.2 Liquid Limit and Plastic Limit Test

The gravel soil used in this study was course grained soil obtained from local road routes in Raipur NIT campus. The soil was tested for specific gravity, liquid limit, plastic limit and grain size distribution as to be well known about physical properties of this particular soil material. From these experimental results a proper idea about the type of soil has been found.

Liquid Limit (WL): 28.91%

Plastic Limit (WP): 21.67%

Plasticity Index (IP): 7.24%

4.3 Grain Size Distribution (Sieve Analysis)

Index properties are essential physical and engineering characteristics used to identify and classify soil. These properties are intrinsic to the soil grains themselves and remain consistent regardless of the soil's state in nature.

To determine the grain size distribution, a sample of 2000 grams of soil was dried in an oven for 12 hours. The sieve analysis is the most commonly used test for this purpose. In this analysis, soil is passed through a series of sieves with progressively smaller mesh sizes.

For the analysis, eleven sieves were utilized. The results from the sieve analysis are then plotted on a semi-logarithmic graph. In this graph:

- The X-axis represents the particle diameter or sieve size on a logarithmic scale.
- The Y-axis represents the percentage finer, indicating the cumulative percentage of soil particles that are smaller than the corresponding sieve size.

This graphical representation provides a clear picture of the soil's grain size distribution, which is critical for understanding the soil's behavior and suitability for various engineering applications.

Table 4.2:- Sieve Analysis Result

Sieve No.#	**Sieve Size**	**Mass of Soil Retained in Each Sieve (gm)**	**Percent Retained (%)**	**Cumulative Retained (%)**	**Percent Finer (%)**
1/2 Inch	12.5 mm	0	-----	0	100
3/8 Inch	9.5 mm	99.1	4.95	4.95	95.05
1/4 Inch	6.3 mm	318.8	15.94	20.84	79.16
#4	4.75 mm	397.5	19.88	40.77	59.33
#8	2.36 mm	510.2	25.51	66.28	33.72
#16	1.18 mm	255.1	12.71	79.03	20.97
#30	600 micron	166.2	8.31	87.34	12.66
#50	300 micron	132.1	6.61	93.95	6.05
#80	150 micron	48.7	2.44	96.39	3.61
Pan	-----	72.3	3.6	100	0

4.6 Discussion

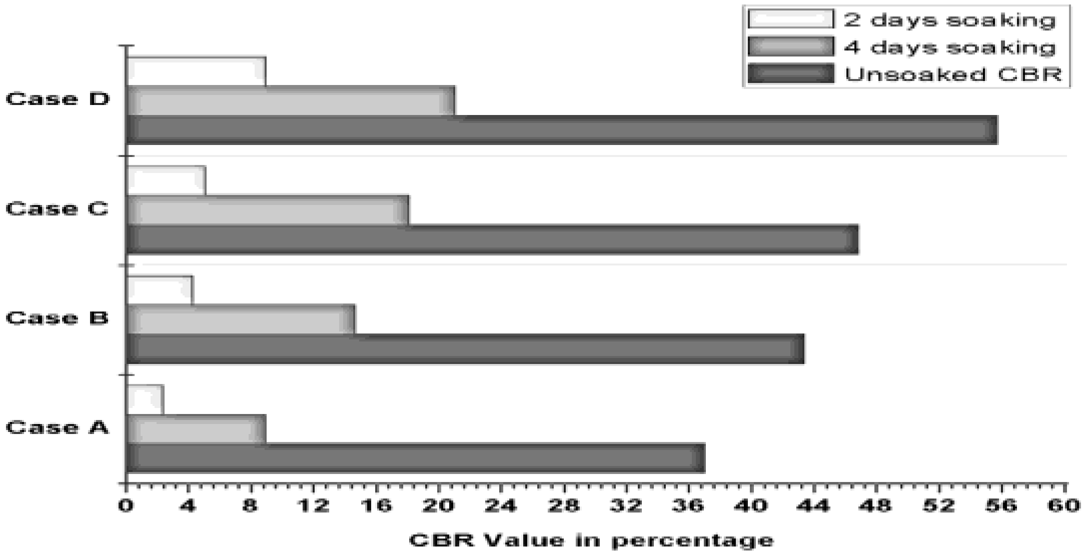
A subgrade is a layer of compacted soil situated directly beneath the pavement crust, typically constructed from locally available soil. This layer, generally assumed to be 300 mm thick, provides a foundational support for the pavement. Enhancing the strength of the subgrade is crucial, as it directly impacts the overall performance and durability of the pavement. This can be achieved either by replacing the existing soil with higher-quality material or by stabilizing the existing soil.

The California Bearing Ratio (CBR) test is a widely used method for evaluating the stability and load-bearing capacity of subgrade soil. The CBR test measures the soil's resistance to penetration under standard load conditions, providing an indication of its strength and suitability for supporting pavement structures.

The results of the CBR test are typically presented in a bar chart. This chart allows for a clear comparison of CBR values under different conditions, showing whether improvements in CBR have been achieved. The bar chart helps to identify the optimal conditions for maximizing the CBR value, which is essential for ensuring the stability and performance of the subgrade. The following bar chart provides a detailed view of the CBR values and highlights the effectiveness of various soil stabilization techniques or treatments applied.

Fig 4.18:- CBR Value Comparison Bar Chart

4.7 Summary



This study demonstrates that the application of Medium Setting (MS) bitumen emulsion can significantly enhance the California Bearing Ratio (CBR) of subgrade soil when proper mixing and curing are implemented. Optimal results are achieved when the soil-emulsion mixture is allowed to cure for approximately five and a half hours post-mixing.

The experimental results reveal a steady increase in CBR values from Case A to Case D under various conditions. Notably, the CBR value improved by up to 50% compared to the CBR of untreated soil. This substantial improvement in soil strength underscores the effectiveness of MS bitumen emulsion as a stabilizing agent.

The enhanced stabilization quality and cost-effectiveness of this method make it particularly suitable for use in gravel roads and highway shoulders. The results suggest that MS bitumen emulsion can provide a reliable and economically viable solution for improving the load-bearing capacity and durability of subgrade soils in road construction.

5.1 Conclusion

Based on the experimental investigation carried out on the stabilization of gravelly subgrade soil using bitumen emulsion and a small proportion of cement, the following conclusions can be drawn:

- **Improved Engineering Properties:** The addition of bitumen emulsion significantly enhances the geotechnical properties of gravel soil, particularly its California Bearing Ratio (CBR) and dry density, which are critical for pavement strength and stability.
- **Optimal Stabilizer Dosage:** The study indicates that a bitumen emulsion dosage of 2–3% by weight of dry soil, combined with a minor percentage of Ordinary Portland Cement (OPC), provides substantial improvement in strength. This optimal mix ensures cost-efficiency without compromising structural performance.
- **Uniform Mixing is Critical:** Proper mixing procedures and uniform distribution of the bitumen emulsion and cement are essential for achieving consistent and reproducible strength characteristics throughout the treated soil mass.
- **Reduction in Maintenance Needs:** Stabilization with bitumen emulsion results in more durable and resilient subgrades, reducing deformation and moisture susceptibility. This, in turn, leads to lower maintenance frequency and life-cycle costs, making it a viable solution for rural and low-volume roads.
- **Sustainable Solution for Weak Soils:** The study supports the use of bitumen emulsion as a sustainable alternative to traditional stabilizers, especially in regions where natural subgrade materials are weak or variable in quality.

5.2 Future Scope of Works

The experimental study on the use of bitumen emulsion for gravel road stabilization has revealed significant potential for improving road infrastructure. Several areas for future research can build on these findings:

- **Long-Term Performance Evaluation:** Conduct studies to assess the long-term performance of bitumen emulsion-treated gravel roads under varying traffic loads and environmental conditions. This will help determine the durability and effectiveness of the treatment over extended periods.
- **Comparative Analysis of Emulsions:** Explore and compare different types of bitumen emulsions to evaluate their respective impacts on gravel road performance. Understanding how various formulations affect road stability and longevity can guide more effective choices for different applications.
- **Skid Resistance Investigation:** Examine the effect of bitumen emulsion on the skid resistance of gravel roads. This research is crucial for ensuring the safety of road users by assessing how the treatment influences traction and handling under various weather conditions.
- **Economic and Environmental Analysis:** Analyze the economic and environmental benefits of using bitumen emulsion in gravel road construction and maintenance. This includes evaluating cost-effectiveness, resource utilization, and potential environmental impacts to support more sustainable practices.
- **Guidelines and Specifications Development:** Develop comprehensive guidelines and specifications for the design, construction, and maintenance of bitumen emulsion-treated gravel roads. Standardizing these practices can ensure consistency and reliability in road infrastructure projects.

In summary, the promising results from the experimental study underscore the need for further research to optimize the use of bitumen emulsion in gravel road stabilization. Advancing this research can lead to more sustainable, durable, and cost-effective road infrastructure solutions.

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