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Application of Cost-Effectiveness and Durability of Cement Treated Base in Road Construction

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ABSTRACT

Cement Treated Base (CTB) is a type of stabilized base layer widely used in modern road construction to improve pavement strength and durability. It involves mixing a predetermined amount of cement with aggregate and water, resulting in a bound layer with enhanced load-bearing capacity and resistance to environmental conditions. The expense of producing the base layer of road and material used in pavements, including as drilling, blasting, crushing, and transporting, makes it an expensive choice. However, when subjected to high traffic and/or strong weather, this material does not hold up. The purpose of the research is, to increase the load bearing capacity of the road using CTB at feasible cost. The methods used are the Unconfined compressive strength, Modified proctor test for the cement-treated base. Results showed the optimal strength at the 3.5 % cement ratio, indicating its suitability for high-load-bearing applications. While 4% cement ratio demonstrated the least amount of rutting, making it ideal for high-traffic roads and areas prone to heavy loads. Cracking behaviors was influenced by both the cement content and curing conditions. The CTB methods saved the most money on construction costs of road, focusing on its benefits and inconveniences. In light of the writing survey and contextual investigations, the paper reveals that CTB can bea practical and robust solution for roads, development, especially in regions with frail subgrades dhigh traffic volumes.

1. Introduction

The development of roads remains one of the most imperative and capital-intensive projects that governments and even the private agencies are engaged in during infrastructure development. Roads will not only be used as means of transportation and trades but they are central to socio-economic development of a region [1]. Nevertheless, its ability to meet a load-bearing long-lasting road and face heavy traffic loads and changing weather conditions

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continues to revolve around challenges, particularly in regions with poor sub-grades, high moistures or where the roads are to be established within a short time frame either due to logistics or emergency situations [2].

A layered system is provided by traditional flexible pavement structures which are normally constructed of granular sub-base, water-bound macadam (WMM), dense bituminous macadam (DBM), and semi-dense bituminous concrete (SDBC). Although they are extensively used, the traditional designs may need large quantities of high-quality aggregate materials and bituminous binders [3]. Energy intensive activities in the extraction of these materials include drilling, blasting, crushing, screening and transportation which raises the cost of preparation besides raising the question of environmental sensitivity. Moreover, the traditional pavements tend to be susceptible to rutting, cracks and water penetrations, especially where they are constructed on poorly consolidated soils. The results of such limitations are short maintenance and rehabilitation cycles, which even increase lifecycle costs [4].

It is against this background that a possible alternative, the so-called Cement Treated Base (CTB), has come up as a good prospect. CTB is a combination of granular aggregates, cement and water which after it has been compacted and reached perfect cure, creates a bound layer that has a significant structural strength with better durability [5]. Incorporating cement into stabilization of base or sub-base layers is not a completely unknown tool, but the complications of the old technology through material science, better knowledge on how soil behaves and innovations in the development of construction processes resurrected the idea of CTB as one of the possible pavement options full of sustainability [6].

The main motivation behind CTB is that it has the capacity of strengthening the load-distribution capability of pavements. Through introduction of a stiff or semi-stiff layer in the pavement structure, CTB minimizes stress ratings to the sub grade beneath the pavement thus enhancing the overall performance of the pavement. It provides an option of reducing the thickness of upper bituminous layers which saves materials and therefore cost [7]. Moreover, the fact that CTB performs well in moisture filled surroundings and is resistant to erosion is the reason that renders CTB the most appropriate in poor drainage areas or even in the regions where water-logging is prevalent. It also provides quick setting and shorter construction schedules that are important in time critical projects [8, 9].

Although CTB does have advantages (a subject to reflective cracking caused by shrinkage or stress due to temperature extremes), these shortcomings can easily be addressed with adequate curing, a controlled mix formula, and crack-relief interlayers, respectively [10, 11]. Among the issues that keep returning in CTB is the fact that CTB forms minute cracks almost immediately after being cured [12, 13]. Failure to perform this task may later lead to spreading of these micro-cracks in the asphalt surface, and as a result may impede the quality of the ride. Nevertheless, this problem has been addressed through the development of the construction technology and introducing usage of stress-absorbing membranes, which proved to be effective [14].

The particular importance of CTB to the present context is that it is fully in line with general sustainability objectives. Finally, through the minimized use of bitumen, which is a material of petroleum origin, CTB will help minimize the release of carbon dioxide emissions and preserve natural resources [15, 16]. It also facilitates the consumption of marginal uses of materials and recycled aggregates that would otherwise be discarded during the traditional construction.

These make CTB a future-oriented product that may enable the environmentally flexible without threatening stability and costs [17].

An overview of recent studies confirms the belief that CTB has significant mechanical and economic advantages in case it is designed and used adequately. The previous review has established that there was an increment in pavement functionality compared to the values in the non-treated pavements especially due to increased compressive strength, resistivity towards rutting areas and the long-life [18-22]. Besides, practical experiments in the field have demonstrated that roads made with CTB are more resistant to moisture destruction and have less repairs intervention during its service life. The literature along with a lot of depth on the significance of optimization of mix design especially in terms of aggregate gradation, cement content, and methods of cure to be applied, so as to achieve similar strength development and long-term durability also exists [23]. Previous research estimated the optimum cement content in CTB mixes, finding 4% cement as optimum for compressive strength, supporting with 2018 highway specifications [24]. Recent research determined that sustainable pavement designs integrating with CTB and recycled concrete aggregates has shown the environmental and economic benefits [25].

This gap in applied research, where laboratory-scale findings are brought into purposeful application in the field of construction, is still present in spite of these encouraging results. Most past researchers have developed theoretical design models or field-isolated testing, and in most cases, little attention is paid to the practical issues facing the engineers in the field [21,26]. In this research paper, we will try to fill this gap by combining such rigor as hard laboratory tests with soft cost-benefit analysis and construction methodology allowing having a more comprehensive picture of the applicability of CTB to actual road construction schemes.

The aim of the current paper is to investigate the applicability of CTB in actual road construction practices, in particular, in relation to economic viability and mechanical efficiency. The study more specifically tests the compressive strength and structural properties of cement-treated materials on different levels of cement contents. The research will source attainment of a scientifically supported mix structure by implementing normal geotechnical testing requirements like the Unconfined Compressive Strength (UCS), Modified Proctor Compaction Test and sieve analysis to create an ideal structure at the least expense. This study has created a basis of comprehending the material, economic, and practical aspects of CTB to carry the groundwork of better and stronger road systems in future.

2. Methodology

This study designed to evaluate the mechanical performance and cost-effectiveness of Cement Treated Base (CTB) over and against the established road building practices. The lab tests, mix design preparation, material tests, and the procedures of the experiment carried out during the research process are presented in Figure 1. Each activity was conducted methodically in order to know that it can be repeated, precise and also meet the national highway building standards.

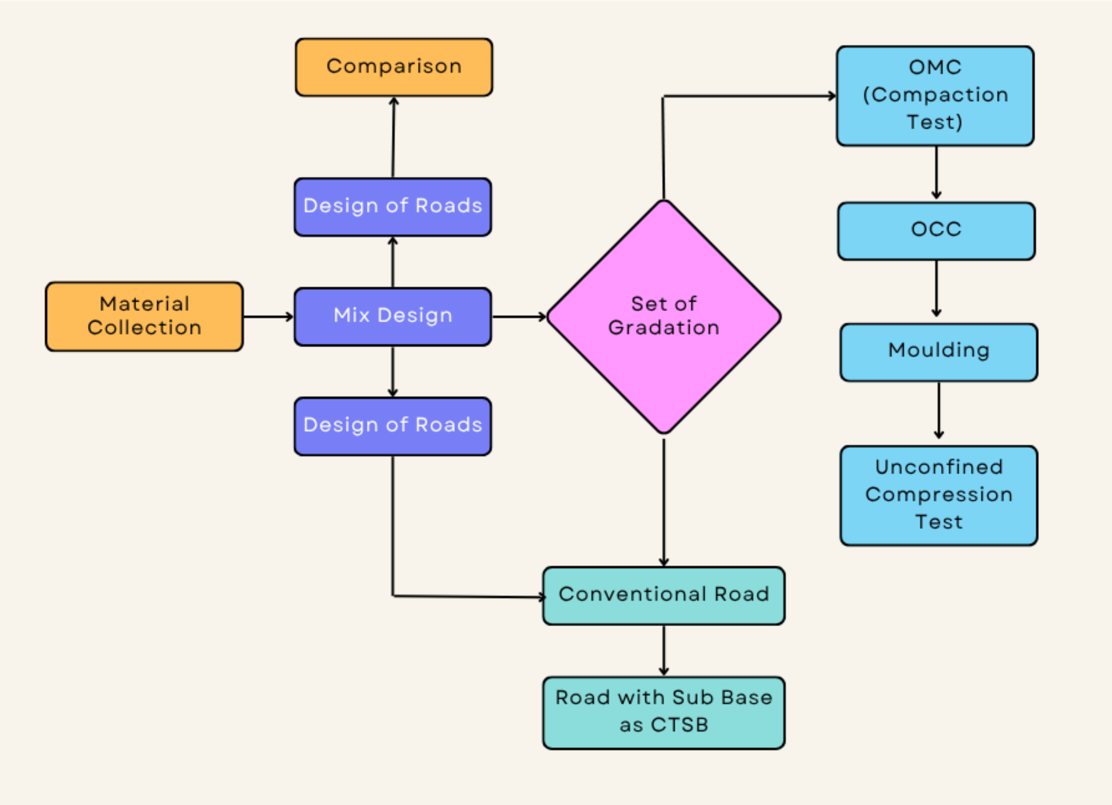

Fig. 1. Flowchart of methodology

2.1 Materials Used

Preparation and selection of the materials used to carry out CTB construction is very vital. This was done using three primary materials namely coarse aggregates, fine aggregates and Ordinary Portland Cement (OPC). Mixing and curing was also done using water.

2.1.1 Aggregates

Aggregates locally sourced were applied, and these were between 6 mm and 40 mm. Sieve analysis was conducted on these aggregates in order to meet the requirements of gradation as required in the standard guidelines (AASHTO T27) [27] on road construction as shown in Table 1. It is very important to apply proper gradation in order to produce good quality of interlocking, compaction and reduces the voids.

Table 1 Sieve analysis result of all material 6 mm down to 40 mm down

Sieve Size(mm)	Passing %	Passing %	Passing %	Passing %	Desired Passing %	Desired Passing %	Desired Passing %	Desired Passing %	Desired Passing %	Specification limits	Mid value
	40mm Down	20mm Down	10mm Down	6mm Down	40mm Down	20mm Down	10mm Down	6mm Down	Total		
53	100	100	100	100	8	21	21	50	100	100	100
37.5	73.27	100	100	100	5.83	21	21	50	97.3	95-100	97.5
19	47.27	92.07	100	100	3.3	19.4	21	50	94.3	45-100	72.5
9.5	25.4	53.13	72.07	99.53	2.03	11.8	15.4	49.77	78.97	35-100	67.5
4.75	12.27	21.47	36.267	55	0.983	4.8	7.6	27.5	40.63	25-100	62.5
0.6	6.4	6.6	13.47	17.8	0.51	1.386	2.28	8.9	13.6	8--65	36.5
0.3	2.4	3.87	6.67	10.13	0.19	0.81	1.4	5.067	7.7	5--40	22.5
0.075	0.6	0.33	1	0.53	0.04	0.07	0.21	0.27	0.57	0--10	5
Pan	0	0	0	0	0	0	0	0	0		
	% of required aggregates				8	2 1	2 1	50		100	

2.1.2 Cement

As a stabilizing agent, the Ordinary Portland Cement (OPC, 43-grade) was employed. In a number of test batches, it ranged between 2.5 and 4.5 percent of the dry weight of aggregate. The cement is essential in enhancing the strength, plasticity and ensuring the provision of long run stability to the base layer.

2.1.3 Water

The mixing and curing took place with potable tap water. We also have to ensure proper water-to cement ratio to ensure that hydration starts and the material has workability.

2.1.4 Preliminary Testing

Raw materials were tested to find their suitability before any mix design or compaction was carried out.

2.2 Sieve Analysis

The analysis of particle size distribution of aggregates was done using sieve analysis. Several levels were used, 6 mm down, 10 mm down, 20 mm down, as well as 40 mm down as shown in Table 2.

Table 2 Showing passing percentage of varies down material

Passing % of 6mm Down	Passing % of 10mm Down	Passing % of 20mm Down	Passing % of 40mm Down
8	21	21	50

2.3 Specific Gravity and Water Absorption

These parameters are useful when explicating the density and absorptive capacity of the aggregates that, in turn, influences moisture content and compaction behavior.

2.4 Mix Design Preparation

The other approach was to mix various designs of the mix by increasing or decreasing the amount of cement. The dry method of mixing was well done in that; cement was combined with the aggregates then gradually water was added until even consistency is attained. The designs of mixes were: 2.5% cement mix, 3.0% cement blend, 3.5% cement mix, 4.0% cement mix, and 4.5% cement mix. The cement content was chosen to range over the broadest possible range stretching between the least possible stabilization and overstabilization, so as to establish the best compromise between cost and strength.

In order to obtain the best density and moisture content for the Cement Treated Base (CTB) mix, the Modified Proctor Test was conducted for each cement percentage. This test was used to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). The procedure involved densifying the prepared mixture in five layers within a standard cylindrical mold, with each layer compacted by applying 56 blows using a Modified Proctor Rammer. The samples were then weighed in both wet and dry conditions to calculate the moisture content and dry density accurately.

Each cement variant was cast in three cylindrical molds according to the Optimum Moisture Content (OMC) values obtained from the Modified Proctor Test. Each specimen was prepared in the form of a cylinder measuring 150 mm in diameter and 150 mm in height. The mix was compacted in five equal layers to achieve the desired density under standard compaction effort, with careful attention to prevent the formation of air gaps and to ensure uniform distribution. After 24 hours, the molded specimens were demolded and subjected to moist curing for up to 28 days. During the curing period, the samples were kept covered with wet jute bags and plastic sheets to maintain adequate moisture. They were stored in a controlled environment at approximately 27°C, simulating field curing conditions. Regular moisturizing was carried out to prevent drying and cracking, as proper curing promotes continuous cement hydration, thereby enhancing the long-term strength of the CTB specimens.

2.5 Compressive strength test

Compressive strength testing was carried out on all specimens after the completion of the curing period using a standard Universal Testing Machine (UTM). The loading rate was kept constant throughout the test, and the peak load was recorded at the point of specimen failure. The results clearly indicated a consistent increase in strength with higher cement content. However, the optimal performance was observed within the range of 3.5% to 4.5% cement, beyond which the increase in strength showed diminishing returns, indicating that excessive cement content did not significantly enhance the compressive strength of the CTB mix.

2.6 Visual Observation of Cracking & Texture

Each sample was visually examined for surface cracks, texture uniformity, and any signs of disintegration or brittleness. This inspection helped assess the overall quality and integrity of the specimens, ensuring that the mixes not only achieved sufficient strength but also maintained structural consistency and durability.

It was observed that higher cement ratios (above 4%) increased stiffness but led to fine surface cracking due to shrinkage. Meanwhile, 3.5% cement offered good balance—sufficient strength with minimal cracking.

A comparative cost analysis was performed to evaluate the financial feasibility of using CTB over conventional methods. Bills of Quantities (BOQ) were prepared for both cases using the same geometric dimensions (1 km × 28 ft).

- Conventional Road: Included SDBC (Semi Dense Bituminous Concrete), DBM (Dense Bituminous Macadam), WMM (Wet Mix Macadam), and GSB (Granular Sub-Base) layers with their respective rates and thicknesses.
- CTB Road: Included SDBC (Semi Dense Bituminous Concrete), CTB (Cement Treated Base), CTSB (Cement Treated Sub-Base), and granular base materials with adjusted thickness and reduced bitumen usage.

3 Results and Discussion

3.1 Modified Proctor Test Results

Modified proctor test can be performed to obtain the optimum water content which can be seen through the relationship between dry density (MPA) and water content (%) as shown in Tables (03-06). it can be seen that the dry density of the aggregate mixture has increased to a certain extent along with the addition of water to the aggregate mixture. This is because the added water in the compaction causes the aggregate mixture to be tightly packed with each other.

When the water content of the aggregate mixture is low, it causes the aggregate to become stiff and difficult to compact so that the value of the dry density of the aggregate mixture becomes low. If the addition of water to the aggregate mixture is too much, the density value will decrease because the aggregate mixture is saturated with water and the pores of the aggregate mixture are filled with water.

Table 3 Value of dry density of soil and MC when cement content is 3%

Parameters	Sample-1	Sample-2	Sample-3
Weight of mold (g)	6832	6832	6832
Weight of mold +soil (g)	11172	11713	11499
Weight of soil (g)	4340	4906	4667
Volume of mold (cm^3)	943	943	943
Wet density of soil	4.60	5.69	4.21
Dry density of soil (g/cm^3)	0.641	0.73	0.433
Weight of wet soil (g)	131	130	134
Weight of dry soil (g)	123	122	119
Weight of water (g)	8	8	15
Moisture Content %	6.19	6.54	11.185

Table 4 Value of dry density of soil and MC when cement content is 3.5%

Parameters	Sample-1	Sample-2	Sample-3
Weight of mold (g)	6832	6832	6832
Weight of mold +soil (g)	11317	11923	11900
Weight of soil (g)	4485	5091	5068
Volume of mold (cm^3)	943	943	943
Wet density of soil	4.71	5.66	5.32
Dry density of soil (g/cm^3)	0.78	0.37	0.73
Weight of wet soil (g)	112	101	112
Weight dry soil (g)	106	95	105
Weight of water (g)	6	6	7
Moisture content %	5.37	5.59	6.25

Table 5 Value of dry density of soil and MC when cement content is 4%

Parameters	Sample-1	Sample-2	Sample-3
Weight of mold (g)	6832	6832	6832
Weight of mold + soil (g)	10445	11833	11601
Weight of soil (g)	3613	4998	4769
Volume of mold(cm^3)	943	943	943
wet density of soil	3.83	5.305	5.051
dry density of soil (g/cm^3)	0.76	0.89	0.323
Weight of wet soil(g)	95	92	96
Weight of dry soil(g)	91	87	82
Weight of water(g)	4	5	14
Moisture Content %	4.216	5.439	14.3

Table 6 Value of dry density of soil and MC when cement content is 4.5%

Parameters	Sample-1	Sample-2	Sample-3
Weight of mold (g)	6832	6832	6832
Weight of mold +soil (g)	11138	11958	11743
Weight of soil (g)	4306	5126	4911
Volume of mold (cm^3)	943	943	943
Wet density of soil	4.56	5.44	5.26
Dry density of soil (g/cm^3)	0.72	0.785	0.53
Weight of wet soil (g)	123	135	128
Weight of dry soil(g)	117	127	117
Weight of water(g)	6	8	11
Moisture Content %	4.87	5.92	8.5

3.2 Compaction Test Results

The results of the compaction test, as presented in both the data table (Table 07) and the accompanying bar chart (Figure 2), indicate a clear and consistent increase in strength with rising cement content. Across all four moulds tested, the strength values gradually rise from an average of 0.327 N/mm² at 2.5% cement content to a significantly higher value of 4.675 N/mm² at 4.5% cement content. This trend reflects the beneficial effect of cement as a binding agent, enhancing the density and cohesion of the compacted material. The rate of strength gain is especially notable between the 3.5% and 4.0% cement content, where the average strength jumps from 1.375 to 3.085 N/mm², indicating a threshold where cement content begins to have a more pronounced structural impact. The graph visually supports this progression, making it easier to observe the exponential nature of the strength development. These findings confirm that increasing cement content positively influences compaction strength, although practical considerations such as cost and diminishing returns at higher concentrations should also be evaluated when determining optimal mix design for field applications.

Table 7 Compaction test result of different mold containing different cement content

	CEMENT CONTENT				
MOLD#	2.5%	3%	3.5%	4%	4.5%
	STRENGTH N/mm^2	STRENGTH N/mm^2	STRENGTH N/mm^2	STRENGTH N/mm^2	STRENGTH N/mm^2
1	0.28	0.88	1.28	2.82	3.75
2	0.39	0.81	1.39	2.92	4.26
3	0.35	0.96	1.8	3.116	5.06
4	0.37	0.98	1.53	3.24	5.54
AVG	0.327	0.925	1.375	3.085	4.675

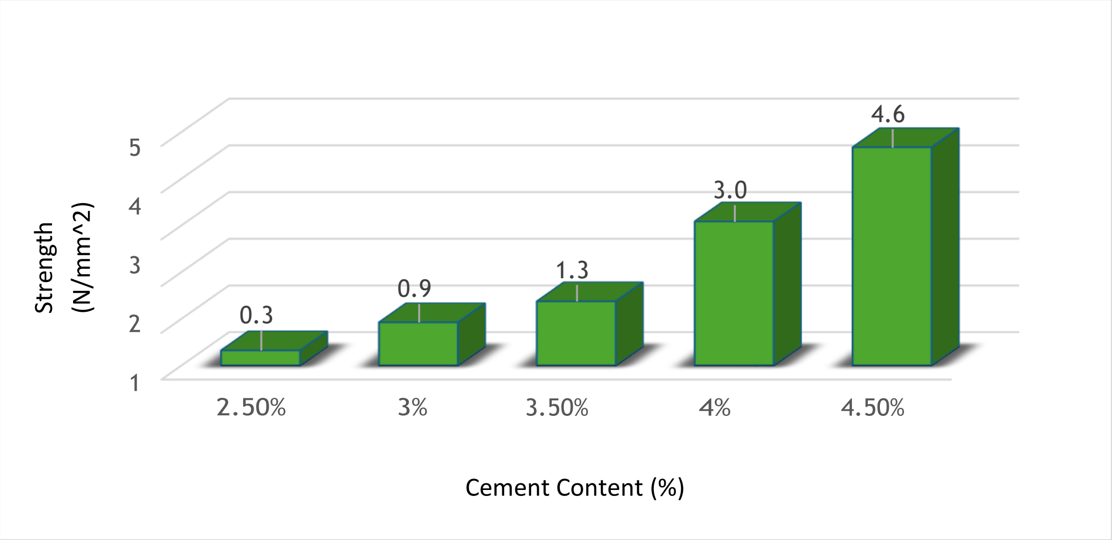

Fig. 2. Compaction Test Result

3.3 Cost estimation of Conventional Road and CTB Road

In comparing the results from the two tables—Table 08 (BOQ of Conventional Road) and Table 09 (BOQ of CTB Road)—several key differences and cost implications emerge. Both tables provide a breakdown of the material quantities and associated costs for road construction, but they represent two different road types: conventional and Cement Treated Base (CTB) roads. In the calculation of BOQ of material for conventional as well CTB road the length are taken as 1 km and the width are 28 ft. Overall, the CTB road has a lower total construction cost primarily due to the different base materials and treatment methods used. A previous study determined that the procedure of CTB not only saves material required for the construction of flexible pavement but also decreases construction costs and prolongs the life of the flexible pavement [28]. The CTB road relies on cement stabilization, which may offer cost advantages in material handling and reduced maintenance over time compared to the conventional road's bituminous layers and aggregate base. The differences in material quantities and treatment methods between the two road types are key factors in determining the cost efficiency of each approach.

Table 8 BOQ of conventional road

Layer	Thickness(inch)	Quantity(cft)	Quantity(ton)	Layers	Rate perton	Rate percft	Cost
SDBC	1.2	9184	295	Bituminous Layer	11,500		3395950
DBM	2	15307	492		11,500		5659150
WMM	5	38267		Aggregate layer		115	4400667
GSB	10	76533				115	8801333
					Total Cost		22257100 Rs.

Table 9 BOQ of CTB road

Layer	Thickness (inch)	Quantity Of Bituminous Layer(ton)	Quantity OfAggregates (CFt)	Quantit y Of Cement (CFt)	Rate of bituminous layer in Ton	Rate of cement per CFt	Rate of Aggregates per CFt	Cost
SDBC	1	295.3	9184		11500			3395950
	2							
AG	4		30613				115	3520533
CTB	2.4		18368	642.88		650.4	115	2456517
CTSB	10		76533	2678.7		650.4	115	10235491
							TOTAL COST	19608492 Rs.

4. Discussion

Material properties of aggregates that would be used in CTB mix were evaluated in the first research step. Sieving and analysis of aggregates of various gradation- starting with coarse and then to fine was done to compare its quality with standard specifications. This fine aggregate was then added to different ratios of cement and water and allowed to cure after which the mechanical tests were done. Among the notable findings in this phase was the fact that the compressive strength worked proportionally with the amount of cement added to it until a certain level that increment of adds gave diminished returns. e.g. By increasing cement content to 4%, further strength gain stopped, although clear improvements were seen between 2.5% and 3.5% cement content, showing a maximum performance limit.

Moreover, the Modified Proctor Test was used to assess the moisture-density correlation of the CTB mix. The test played an essential role in identifying the suitable moisture content level, after which the treated base attains its maximum dry density a factor which directly determines structural strength and durability. The findings demonstrated the significance of the accurateness of the ratios of water, cement, and the aggregates in the realization of uniform compaction and the strength outcomes. It is interesting to note that mixtures with low moisture percentage were stiff and highly unworkable whereas mixtures with too much moisture developed lesser density because the aggregate pores became saturated. These factors were played off each other in order to make a high quality yet durable base layer.

This study was also equipped with a detailed cost comparison of the traditional road construction and District-CTB-based construction besides the performance testing. Both methods were computed in a Bill of quantities (BOQ), with one standard road section of 1 km length and 28 ft width. It was found that CTB roads experienced overall costs that were much lower mainly because of the decrease in the thickness and volume of high cost bituminous materials and the replacement of conventional granular materials with cement treated aggregates. Although CTB needs investment early in cement, and its material preparation may be a bit expensive, this is compensated by the project through savings in transportation, construction period and down the line maintenance. Technically, CTB is a more financially viable alternative that is supported by the life-cycle cost analysis. Finally, the whole idea of the present study is to arrive with a more definite picture of optimization of cement-treated base layers with regard to performance and cost. With the research involved in determining the various levels of cement content and comparing the mechanical behavior of the tips obtained to laying of a conventional road, cost implications of such work the research offers information that can be valuable in coming up with future designs and the development of efficient infrastructure development.

The results of the presented study are of specific concern to both policy-makers, engineers, and contractors based in low-quality soil areas or those with limited finances or short schedules. This study will assist in promoting the introduction of CTB into the sustainable road building initiatives by proving that it could address both the structural and economic needs within a construction project. It also leads to the research of other hybrid stabilization methods including the use of industrial by-products like fly ash or slag that would potentially also strengthen the environmental and mechanical characteristics of CTB.

Conclusively, the role of CTB should be seen beyond a different approach to building road infrastructures, as a strategic move that can revolutionize the way we learn to administer road infrastructures in the light of emerging challenges [28]. It is a very good solution to be widely spread as it is quite cost-effective, long-lasting, flexible, and compliant with attainment of sustainable development goals under the condition when it has to be supported by valid engineering decisions and localized performance statistics.

5. Conclusions

The study experimental tests revealed that increasing the cement content generally enhances the compressive and flexural strength of CTSB. The optimal strength was observed at the 3.5 % cement ratio, indicating its suitability for high-load-bearing applications. However, the 3% cement ratio provided a good balance between strength and cost, making it a viable option for many road construction projects. Also, results indicated that higher cement ratios significantly reduce the susceptibility of CTB to rutting. The 4% cement ratio demonstrated the least amount of rutting, making it ideal for high-traffic roads and areas prone to heavy loads. While higher cement ratios (3% and 3.5%) increased the tensile strength of the CTB, they also made the material more brittle and prone to cracking under thermal and shrinkage stresses. The 2.5% cement ratio offered a balance between sufficient tensile strength and reduced brittleness, resulting in fewer and less severe cracks compared to the higher ratios. Roads constructed with 3.5% cement content in the base course exhibited superior long-term performance, with minimal signs of deterioration over time. However, the 3% cement ratio also provided substantial durability benefits with slightly reduced environmental and economic impacts. Sieve analysis aids in optimizing CTB gradation, ensuring better compaction and structural integrity. Its versatility allows customization to project needs, making it suitable for various soil conditions and traffic loads. Future studies on CTB should focus on integrating sustainable materials such as industrial by-products and recycled aggregates, and estimating long-term durability under different traffic and environmental settings. Advanced testing approaches, performance modeling, and region-specific design procedures are also suggested to increase strength, sustainability, and field application.

Some main findings of the study are:

- The increased stiffness and strength provided by higher cement content improve the load bearing capacity of the base course, thereby minimizing deformation under repetitive traffic loads.
- Cracking behaviors was influenced by both the cement content and curing conditions.
- Despite initial costs, CTB proves cost-effective over the road's life cycle due to reduced maintenance needs.
- CTB offers environmental benefits by minimizing resource consumption and waste generation.

Author Contributions

All authors contributed equally to the conception, design, analysis, and writing of this work. All authors have read and approved the final manuscript.

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Conflicts of Interest

There are no known competing financial interests or personal relationships that could have influenced the work reported in this article.

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