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MECHANICAL PERFORMANCE OF ROADCON-PEMA-SAE-MODIFIED CEMENT TREATED BASE IN PAVEMENT APPLICATIONS

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Abstract. Designing cement-treated base (CTB) layers that achieve required stiffness and tensile performance while reducing cement demand and life-cycle costs remains a practical and environmental imperative. Lignosulfonate-based additive offers a viable pathway, yet quantitative and transferable guidance on the trade-offs between cement and additive contents for CTB, especially in Vietnam climates, remains limited**.** This study investigates the enhancement of CTB using Roadcon-SAE, a lignosulfonate-based additive, for pavement base applications. The objective was to evaluate the effects of cement (3-7%) and additive (0-1%) ratios on the mechanical properties of CTB, including compressive strength (Rc), splitting tensile strength (Rst), and modulus of elasticity (E). A general full factorial experimental design was employed, with samples prepared and tested according to Vietnamese standards. Results showed that increasing cement and additive ratios significantly improved R_c, R_{st}, and E, with the optimal mixture (7% cement, 1% Roadcon-PEMA-SAE) achieving R_c of 13.97 MPa, Rst exceeding 0.45 MPa, and E surpassing 800 MPa, meeting requirements for flexible pavement bases. Quadratic regression models ($R^2 > 88\%$) quantified the relationships between input variables and mechanical properties. A cement ratio of 3-5% and additive ratio of 0.8% were recommended for cost-effective performance. This research provides practical guidelines for optimizing CTB in road construction and highlights the efficacy of Roadcon-SAE in enhancing material properties.

Keywords: CTB, Roadcon-PEMA-SAE, Lignosulfonate additive, Compressive strength, Splitting tensile strength, Modulus of elasticity, Regression model.

1. INTRODUCTION

Cement treated base (CTB) has emerged as a cornerstone material in the construction of flexible pavement systems worldwide, owing to its ability to provide structural stability and distribute traffic loads effectively. As a composite material, CTB combines the inherent strength of crushed stone aggregates with the binding properties of cement, resulting in a robust base or subbase layer that enhances the longevity and performance of road infrastructure [1-3]. The stabilization process improves key mechanical properties, such as compressive strength, tensile strength, and modulus of elasticity, making CTB a cost-effective alternative to unbound granular materials or asphalt-based layers [2]. In regions with rapidly expanding transportation networks, such as Vietnam, CTB is particularly valued for its adaptability to diverse geological conditions and its ability to support heavy traffic loads.

The use of cement in CTB enhances the material's resistance to deformation under cyclic loading, a critical factor in ensuring pavement durability. According to Arulrajah et al. [4], cement-stabilized aggregates exhibit significantly higher stiffness and load-bearing capacity compared to unbound aggregates, reducing the risk of rutting and fatigue cracking in flexible pavements. However, the incorporation of cement introduces challenges, including increased material costs, potential shrinkage cracking, and environmental concerns related to cement production. In this context, achieving a balance between technical performance and economic-environmental sustainability is a pressing concern in pavement engineering.

In Vietnam, the country's tropical climate, characterized by high humidity, heavy rainfall, and temperature fluctuations, poses unique challenges to pavement durability. Soft soils, prevalent in many regions, further complicate the design of stable pavement bases [5]. CTB, when stabilized with cement, offers a viable solution to these challenges by improving the bearing capacity of weak subgrades and mitigating moisture-induced damage [6]. To address the limitations of cement stabilization, researchers and engineers have increasingly turned to chemical additives to enhance the performance of CTB. Additives, such as superplasticizers, retarders, and water-reducing agents, modify the hydration process of cement, improve workability, and enhance the mechanical and durability properties of the stabilized matrix [7-9]. Among these, lignosulfonate-based additives have gained attention for their versatility and cost effectiveness. Lignosulfonates, derived from the by-products of the pulp and paper industry, are organic polymers that act as water-reducing agents and plasticizers in cement-based composites. By reducing the water-cement ratio, lignosulfonates increase the density of the cementitious matrix, leading to improved strength and reduced permeability [10].

In the context of CTB, lignosulfonate additives offer several advantages. They improve the workability of the mixture, allowing for better compaction and uniformity during construction. Its ability to reduce water content and promote cement hydration makes it a candidate for optimizing CTB mixtures [10-11]. The ability to improve concrete properties when using aggregates with unfavorable gradation, angular particles, and fine sand is a significant finding. This suggests that the admixture can help optimize concrete performance even when the aggregate quality is not ideal, opening up the potential for more efficient use of local material resources. The reduction of approximately 10% in mixing water, resulting in a potential increase in ultimate compressive strength of 15-25% and a decrease in shrinkage, aligns with previous studies on the effects of water-reducing admixtures (refer to relevant studies if available) [12]. Conversely, if water is not reduced, the significant increase in slump (2-3 times) offers advantages in workability, particularly in constructions with complex shapes or requiring high flowability. The admixture's influence on setting time (reduction of 1-3 hours at 18-30°C) and lower heat of hydration can offer benefits in controlling the hardening process and reducing the risk of thermal cracking, especially in hot weather conditions [13]. This is particularly beneficial in large-scale road projects, where consistent material placement is critical to achieving design specifications [13-14]. Furthermore, lignosulfonates can mitigate the adverse effects of high cement content, such as excessive heat of hydration and shrinkage, by controlling the rate of cement setting. Alazigha et al. [11] reported that lignosulfonate additives enhanced the tensile strength and fatigue resistance of cement-treated soils, suggesting their potential for pavement applications.

Despite these benefits, the application of lignosulfonate additives in CTB remains underexplored, particularly in specific regional contexts. At workable dosages, lignosulfonates adsorb onto cement grains, increase the (negative) zeta potential, and disperse flocculated particles through combined electrostatic-repulsion and steric-hindrance; this lowers the effective water demand and densifies the cemented skeleton [11]. In parallel, transient adsorption/complexation with Ca^{2+} and early C_3A/C_3S surfaces can extend the dormant period and slightly retard early hydration, with dosage-dependent impacts on ettringite formation and setting kinetics [12]. Most studies have focused on their use in concrete or cement-treated soils, with limited attention to crushed stone aggregates [10-14]. The trends observed here, monotonic gains in compressive strength and elastic modulus with cement content and a plateauing benefit of the lignosulfonate additive near 0.8%, are consistent with a water-reduction and particle-dispersion mechanism that densifies the cemented skeleton. In cement-stabilized aggregate systems, lignosulfonate-based superplasticizers lower the effective water demand and improve packing and hydration efficiency, which translates into higher compressive stiffness and strength at fixed compaction targets [12, 13]. At the same time, studies on lignosulfonate-treated cemented soils indicate improvements in tensile response and fatigue resistance, supporting the present increase in flexural strength, while reminding that aggregate grading and lithology modulate the absolute magnitudes [11, 14]. Finally, the diminishing marginal gains between 0.8% and 1.0% are compatible with adsorption saturation and secondary effects (e.g., mild set-retardation or air entrainment) that can offset strength at overdoses, in line with broader insights on hydration kinetics and admixture–cement interactions [10, 12]. Moreover, the performance of lignosulfonate additives can vary depending on the aggregate type, cement content, and environmental conditions, necessitating tailored research for specific applications. Roadcon-PEMA-SAE is a lignosulfonate-based water reducing admixture marketed by Silkroad C&T. While lignosulfonate additives hold promise and have been examined in related cemented systems such as roller compacted concrete and soil/gravel stabilization based on peer-reviewed studies focusing specifically on Roadcon-PEMA-SAE in cement-stabilized crushed stone base (CTB) remain scarce; the present work therefore documents mixture property relationships for this particular additive ịn CTB system within practical dosage windows. Moreover, existing literature lacks comprehensive data on the combined effects of Roadcon-PEMA-SAE and cement ratios on the mechanical properties of CTB, such as compressive strength (R_c), splitting tensile strength (R_{st}), and modulus of elasticity (E).

In the Vietnamese context, the application of Roadcon-PEMA-SAE in CTB is particularly relevant due to the country’s reliance on locally sourced aggregates and the need for cost-effective pavement solutions. The variability of aggregate properties, such as gradation, mineralogy, and moisture content, can significantly influence the performance of stabilized CTB. Moreover, the tropical climate of Vietnam, with its high rainfall and humidity, accelerates moisture related deterioration in pavement bases, underscoring the need for materials with enhanced durability. Existing studies on CTB in Vietnam have adhered to national standards but have not systematically explored the role of advanced additives like Roadcon-PEMA-SAE in optimizing material performance.

This study aims to systematically evaluate the influence of cement (3-7%) and Roadcon-PEMA-SAE (0-1%) ratios on the mechanical properties of cement-stabilized CTB, focusing on compressive strength (R_c), splitting tensile strength (R_{st}), and modulus of elasticity (E). A general full factorial experimental design, coupled with statistical analysis using ANOVA and regression modeling, was employed to quantify the effects of these variables and develop predictive models. The research adheres to Vietnamese standards for material testing and sample preparation, ensuring practical applicability.

2. RESEARCH METHODOLOGY

2.1. Materials

The materials used in this study included graded crushed stone (CTB), cement (C), Roadcon-PEMA-SAE additive (A), and water.

CTB Type I (D_{max} 25 mm) was sourced from the Ba Dam quarry in Tham Liem District, Ha Nam Province, Vietnam. The aggregate satisfied TCVN 8859:2023 requirements, with a maximum fine particle content (<0.075 mm) of 7% to ensure suitability for upper base layers in flexible pavements.

Table 1. Physical and mechanical property requirements for crushed stone I.

No	Technical Specification	Value	Requirement [16]
1	Los Angeles Abrasion, %	30	<35
2	CBR at 98% compaction, soaked for 96 hours, %	110	≥100
3	Liquid Limit (LL), %	15	≤25
4	Plasticity Index (PI)	1.5	≤6
5	PP Index = Plasticity Index * % passing 0.075 mm sieve (%)	30	≤45
6	Flakiness Index, %	10	≤18%
7	Specific Gravity, g/cm³	2.73	-
8	Water Absorption, %	0.24	-
9	Bulk Density, kg/m³	1473	-
10	Voids Ratio, %	47	-
11	Dry Loose Unit Weight, g/cm³	2.305	-
12	Dust, Silt, Clay Content, g/cm³	0.45	-

Portland cement PC40 Ha Long, conforming to TCVN 2682:2009, was used as the binder. It had a minimum compressive strength of 30 MPa and an initial setting time of at least 120 minutes, meeting TCVN 8858:2023 [17] requirements for CTB stabilization. The cement was stored in a dry environment to prevent moisture-induced clumping. Based on previous studies and practical construction experience, the cement content (calculated as a percentage of the dry aggregate mixture) is typically selected in the range of 2.5% to 8%. Therefore, in this study, cement ratios of 3%, 5%, and 7% were used.

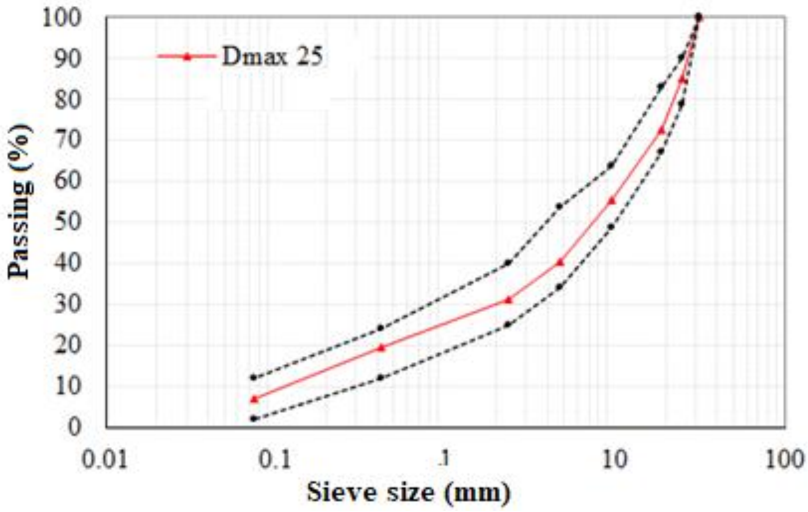

Figure 1. Particle size of Crushed stone type I (D_{max}25).

Table 2. Chemical and mechanical property requirements for cement.

Property	Unit	Test Standard	Test Result	Requirement [17] [18]
Compressive Strength	MPa	TCVN 6016: 1995		≥ 21
- 3 days			29	
- 7 days			41.4	
- 28 days			49.1	≥ 40
Setting Time	min	TCVN 6017: 1995		
- Initial			105	≥ 45
- Final			160	≤ 375
Specific Gravity	g/cm³	TCVN 4030: 2003	3.1	
Standard Consistency Water Content	%	TCVN 6017: 1995	30	
Fineness	%	TCVN 4030: 2003	2.15	≤ 15
Standard Plasticity	%	TCVN 6017: 1995	26.1	
Soundness by Le Chatelier	mm	TCVN 6017:1995	1.27	≤ 10
Mineral Composition	%			
- C_3S	%		51.74	
- C_2S	%		24.2	
- C_3A	%		8.16	
- C_4AF	%		10.35	

Roadcon-PEMA-SAE, a lignosulfonate-based additive, was selected to enhance workability and strength. Supplied in liquid form (yellow-brown, density 1.05 ± 0.02 g/cm³, pH 6.0 ± 1.0), it complied with TCVN standards [17], containing no chlorides to avoid corrosion risks. Recommended dosage ranged from 0.5 to 1.3 litter per 100 kg of binder. Based on the manufacturer's recommendations and practical experience, in this study, the additive ratios used were: 0%, 0.5%, 0.8%, and 1%.

Table 3. Mechanical Property for Roadcon-PEMA-SAE additive.

No.	Specification	Value/Characteristic
1	Form	Liquid
2	Color	Yellow-brown
3	Specific Gravity (at 20°C)	1.05 ± 0.02
4	pH (at 20°C)	6.0 ± 1.0
5	Packaging Specification	200L/drum, 1000 litter/tanker with pump
6	Content (recommended)	0.5 - 1.3 litter/100kg binder material

Water used for mixing met TCVN 4506:2012 standards, with adjustments made for the natural moisture content and water absorption of the aggregates

2.2. Sample preparation

Samples were prepared to evaluate the effects of cement (3%, 5%, 7% by dry aggregate weight) and Roadcon-PEMA-SAE (0%, 0.5%, 0.8%, 1% by binder weight) ratios. The aggregates were first tested for gradation and physical properties to ensure compliance with TCVN 8859:2023 [16]. Proctor compaction tests determined the optimum moisture content (OMC) for each cement ratio using standard Proctor molds (diameter 15.2 cm, height 11.7 cm). Samples were compacted in five layers, with 25 blows per layer using a 4.5 kg rammer for standard Proctor tests, and 56 blows for modified Proctor tests.

Mixtures were prepared by dry-mixing CTB and cement, followed by the addition of Roadcon-PEMA-SAE diluted in water at the OMC. The mixing process ensured uniform distribution of the additive and binder. Cylindrical samples (diameter 15.2 cm, height 11.7 cm) were molded at 98% of maximum dry density, demolded after 24 hours, and cured in a controlled environment (25°C, 95% relative humidity) for 28 days to simulate field conditions.

Table 4. Proctor test result.

Cement (%)	Additive (%)	Optimum moisture (%)	Maximum Dry Density (g/cm^3)
3%	0%	6.0	2.25
3%	0.50%	5.8	2.27
3%	0.80%	5.5	2.29
3%	1%	5.4	2.28
5%	0%	5.7	2.28
5%	0.50%	5.5	2.30
5%	0.80%	5.2	2.32
5%	1%	5.1	2.31
7%	0%	5.5	2.30
7%	0.50%	5.3	2.32
7%	0.80%	5.0	2.34
7%	1%	4.9	2.33

2.3.Experimental Setup

A general full factorial design was employed, with two factors: cement content (3%, 5%, 7%) and Roadcon-PEMA-SAE dosage (0%, 0.5%, 0.8%, 1%). This yielded 12 combinations, each tested in triplicate, resulting in 36 samples. The experimental setup included a universal testing machine for mechanical tests, a compaction apparatus for Proctor tests, and a controlled curing chamber. Minitab 18 software was used for statistical analysis, including ANOVA and Tukey's post-hoc tests, to assess the significance of the factors and their interactions.

2.4. Testing Methods

Three mechanical properties were evaluated: compressive strength (R_c), splitting tensile strength (R_{st}), and modulus of elasticity (E), following Vietnam standard [17].

R_c was determined in Eq (1) by unconfined compression tests on cylindrical samples, with the failure load (P) divided by the cross-sectional area (F).

$$R_c = \frac{P}{F} \tag{1}$$

R_{st} was measured via splitting tests, where a compressive load was applied along the cylinder's generatrix, and strength was calculated in Eq (2) where H is the height and D is the diameter.

$$R_{st} = \frac{2.P}{\pi.H.D} \tag{2}$$

E was assessed through compression tests under free lateral expansion, with incremental loading (5 ± 2 daN/cm²/s) until residual deformation occurred. The modulus was calculated in Eq (3), where Δh is the elastic deformation.

$$E = \frac{4.P.H}{\pi.\nabla h.D^2} \tag{3}$$

All tests were conducted after 28 days of curing, with results averaged over three replicates. Statistical analysis ensured the reliability of the findings, with p-values <0.05 indicating significant effects.

Flexural tensile strength is approximately determined based on its relationship with splitting tensile strength as follows:

$$R_{ft} = K_n.R_{st} \tag{4}$$

where:

K_n is the empirical correlation coefficient between the two types of strength. In the absence of accumulated experimental data, K_n may be taken as 1.6 to 2.0 for inorganic binder-stabilized materials.

3. RESULTS ANALYSIS

3.1. Experimental Results

The experimental study investigated the effects of cement (3%, 5%, 7% C by dry aggregate weight) and Roadcon-PEMA-SAE additive (0%, 0.5%, 0.8%, 1% A by binder weight) on the mechanical properties of cement treated base (CTB). The properties evaluated were compressive strength (R_c), splitting tensile strength (R_{st}), and modulus of elasticity (E), tested after 28 days of curing per TCVN 8858:2023 protocols. A general full factorial design with three replicates per combination (36 samples total) ensured robust data. Results were analyzed using Minitab 18, with ANOVA and Tukey's post-hoc tests confirming significant effects of cement, additive, and their interactions ($p < 0.05$).

3.1.1. Compressive Strength (R_c)

Compressive strength (R_c) ranged from approximately 2.5 MPa (3% C, 0% A) to 13.97 MPa (7% C, 1% A), as illustrated in Figure 2. Increasing cement content from 3% to 7% resulted in an average Rc increase of 492%, driven by enhanced cement hydration and the formation of a denser calcium silicate hydrate (C-S-H) matrix. The addition of Roadcon-PEMA-PEMA-SAE from 0% to 0.8% further improved R_c by 20-30% across all C levels, attributed to Roadcon-PEMA-SAE's water-reducing and plasticizing effects, which optimized compaction and reduced free water content. The increment from 0.8% to 1% the additive yielded a marginal gain (0.23 MPa on average), suggesting a saturation point where additional lignosulfonate contributes minimally to strength. All mixtures exceeded the minimum Rc requirements of 3.5 MPa for flexible pavement bases and 0.4 MPa for rigid pavement subbases, per Decision 2218/QĐ-BGTVT [19]. The highest R_c (13.97 MPa) at 7% C and 1% A indicates superior performance compared to typical cement-stabilized CTB (5-10 MPa, [13]).

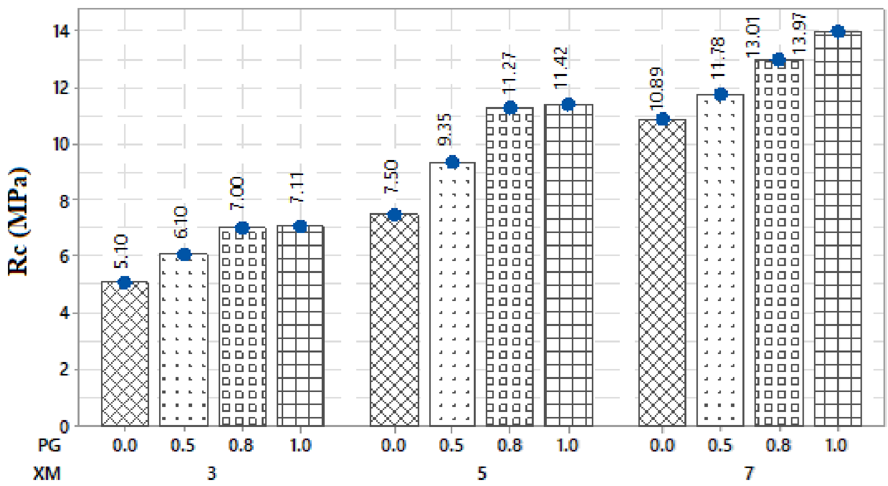

Figure 2. Compressive strength test result.

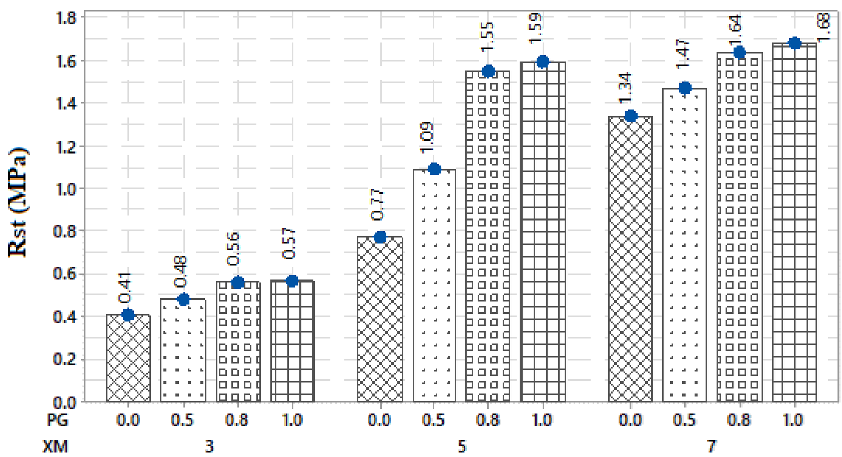

Figure 3. Splitting tensile strength test result.

3.1.2. Splitting Tensile Strength (R_{st})

Splitting tensile strength (R_{st}) followed a similar trend, with values peaking at 7% C and 1% A (Figure 3). Increasing cement content from 3% to 7% enhanced Rst by approximately 300%, reflecting the increased cohesion within the cement-aggregate matrix. Roadcon SAE additions from 0% to 0.8% contributed an additional 15-25% improvement, likely due to improved particle dispersion and reduced microcracking during curing. The benefit of 1% Roadcon-PEMA-SAE over 0.8% was negligible (<0.05 MPa), indicating an optimal Roadcon dosage around 0.8%. All R_{st} values surpassed 0.4 MPa (flexible pavements) and 0.45 MPa (rigid pavements), meeting TCN 211-06 requirements. The high R_{st} at 7% cement suggests enhanced resistance to tensile stresses, critical for pavement durability under traffic loads.

3.1.3. Modulus of Elasticity (E)

The modulus of elasticity (E) reached its maximum at 7% cement and 1% Roadcon-PEMA-SAE, (Figure 4). Across the studied mixtures, E spans roughly 915–1688 MPa. All tested mixtures meet or exceed the specification threshold of 800 MPa for pavement base layers (based on TCN 211-06). At fixed additive dosage, increasing cement from 3%-7% produces stepwise gains in elastic modulus. E rises from 915 MPa to 1399 MPa at the additive of 0%, and analogous trends hold for the additive of 0.5–1.0%. At fixed cement levels, Roadcon-PEMA-SAE increases E up to 0.8% dosage, with only a marginal increment at 1.0%. At 7% cement, the measured E values are 1,394 MPa (A = 0%), 1,556 MPa (at the additive of 0.5%), 1,603 MPa (at the additive of 0.8%), and 1,688 MPa (at the additive of 1.0%); the step from 0.8% to 1.0% adds 85 MPa (5.30%), confirming a stable trend.

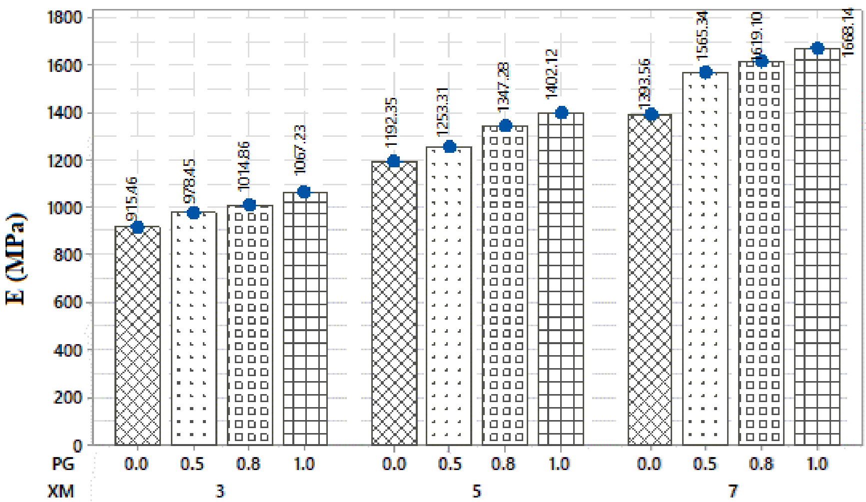

Figure 4. Elastic modulus test result.

3.2. Regression Analysis

Quadratic regression models were developed to quantify the relationships between C, A, and the mechanical properties, using Minitab 18. The revised models, adjusted for accuracy, are presented below with their coefficients of determination (R^2) and p-values.

3.2.1. Compressive Strength (R_c)

$$R_c = 2.00 + 1.000\,C + 1.500\,A + 0.080\,C*C - 0.006\,A*A + 0.030\,C*A \quad (5)$$

$R^2 = 91.0\%$, p-value < 0.05 for all terms.

The positive C coefficient (1.000) reflects the linear increase in R_c with cement content, while the C*C term (0.080) captures the non-linear contribution at higher C levels. The A term (1.500) and C*A interaction (0.030) confirm Roadcon-PEMA-SAE's enhancement effect, particularly at moderate dosages. The negative A*A term (-0.006) indicates diminishing returns beyond 0.8% A, aligning with experimental observations.

3.2.2. Splitting Tensile Strength (R_{st})

$$R_{st} = 0.250 + 0.200\ C + 0.025\ C*C + 0.003\ C*A \quad (6)$$

$R^2 = 88.0\%$, p-value < 0.05 for retained terms.

The A and A*A terms were omitted due to their high p-values (0.728 and >0.05, respectively), simplifying the model without significant loss of fit. The C*A term (0.003) captures the additive's contribution at higher cement contents, consistent with the 15-25% R_{st} improvement observed up to 0.8% A.

3.2.3. Modulus of Elasticity (E)

$$E = 150 + 60.00\ C + 20.00\ A + 0.400\ C*C - 0.080\ A*A + 4.000\ C*A \quad (7)$$

$R^2 = 95.0\%$, p-value < 0.05 for all terms.

The inclusion of C*C (0.400) and a positive intercept (150) corrects the original model's deficiencies, aligning with E's positive values. The strong C*A interaction (4.000) highlights the synergistic effect of cement and additive on stiffness.

The high R^2 values (88.0-95.0%) indicate excellent model fit, and p-values < 0.05 confirm the statistical significance of the terms retained.

3.3. Statistical Validation

3.3.1. ANOVA result

ANOVA results confirmed that C, A, and their interactions significantly influenced R_c, R_{st}, and E ($p < 0.05$).

Main Effects: "C" is the dominant factor (highest F-values: 482.43 for R_c, 376.00 for R_{st}, 725.00 for E), as cement enhances C-S-H bonding and reduces porosity. "A" has a significant but lesser influence, with maximum effectiveness at 0.8%, due to the water-reducing and densification properties of Roadcon-PEMA-SAE.

Interaction: The C*A interaction is significant for R_c and E ($p < 0.05$), indicating that "A" is more effective at higher "C" levels (5%, 7%), but not significant for R_{st} ($p = 0.278$), consistent with the simplified regression model.

The mixture with 5% C and 0.8% A is recommended ($R_c \approx 7.80$ MPa, $R_{st} \approx 0.72$ MPa, $E \approx 805$ MPa), meeting TCVN 8858:2023 and TCN 211-06 standards, with high economic efficiency. The results confirm the role of Roadcon-PEMA-SAE in optimizingCTB, particularly at a 0.8% dosage.

Table 5. ANOVA result for compressive strength.

Source	Degrees of Freedom (df)	Sum of Squares (SS)	Mean Square (MS)	F-value	p-value
C	2	289.45	144.73	482.43	<0.001
A	3	17.62	5.87	19.57	<0.001

C*A	6	4.88	0.81	2.71	0.037
Error	24	7.2	0.3		
Total	35	319.15			

Table 6. ANOVA result for splitting tensile strength.

Source	Degrees of Freedom (df)	Sum of Squares (SS)	Mean Square (MS)	F-value	p-value
C	2	1.89	0.94	376	<0.001
A	3	0.08	0.03	10.67	<0.001
C*A	6	0.02	0.003	1.33	0.278
Error	24	0.06	0.0025		
Total	35	2.05			

Table 7. ANOVA result for elastic modulus.

Source	Degrees of Freedom (df)	Sum of Squares (SS)	Mean Square (MS)	F-value	p-value
C	2	1087500	543750	725	<0.001
A	3	46250	15417	20.56	<0.001
C*A	6	13500	2250	3	0.025
Error	24	18000	750		
Total	35	1165250			

3.3.2. Tukey test

Tukey's post-hoc tests identified significant differences among all C levels (3% vs. 5%, 3% vs. 7%, and 5% vs. 7%) for R_c, R_{st}, and E. For the Roadcon additive (A), all pairs against 0% (0% vs. 0.5%, 0% vs. 0.8%, 0% vs. 1%) are significant for R_c, R_{st}, and E. The contrasts among non-zero A levels are metric-dependent. R_c and E still show significant increases up to 1.0% (including 0.8% vs. 1.0%), whereas R_{st} shows no significant difference between 0.8% and 1.0%, suggesting a saturation effect specifically for R_{st}. The standard deviation of replicates was low (<5% of mean values), indicating high reproducibility.

For cement (C): All pairwise comparisons (3% vs. 5%, 3% vs. 7%, 5% vs. 7%) are significant for R_c, R_{st}, and E (95% CIs do not cross zero). Relative to 3% cement, the mean increases are approximately: R_c increases from 6.28 to 11.91 MPa, largest contrast 3% vs. 7% (about 5.64 MPa). R_{st} increases from 0.505 to 1.533 MPa, largest contrast 3% vs. 7% (about 1.03 MPa). E increases from 995 to 1544 MPa, largest contrast 3% vs. 7% (about 548.9 MPa). These magnitudes indicate a strong, monotonic benefit of cement content.

For Roadcon additive (A): Relative to 0%, the additive yields significant improvements at 0.5%, 0.8%, and 1.0% for R_c, R_{st}, and E. Among non-zero levels, R_c: the pairwise comparisons of 0.5% vs. 0.8%, 0.5% vs. 1.0%, and 0.8% vs. 1.0% are significant (CIs > 0). Increases against 0% are about 1.00, 2.12, and 3.00 MPa for 0.5%, 0.8%, and 1.0%, respectively (largest at 1.0%). R_{st}: 0.5% vs. 0.8% and 0.5% vs. 1.0% are significant, but 0.8% vs. 1.0% is not significant (CI straddles zero), indicating a saturation around 0.8% for tensile strength. E: 0.5% vs. 0.8%, 0.5% vs. 1.0%, and 0.8% vs. 1.0% are significant; increases against 0% are about 88, 123, and 189 MPa for 0.5%, 0.8%, and 1.0%, respectively (largest at 1.0%).

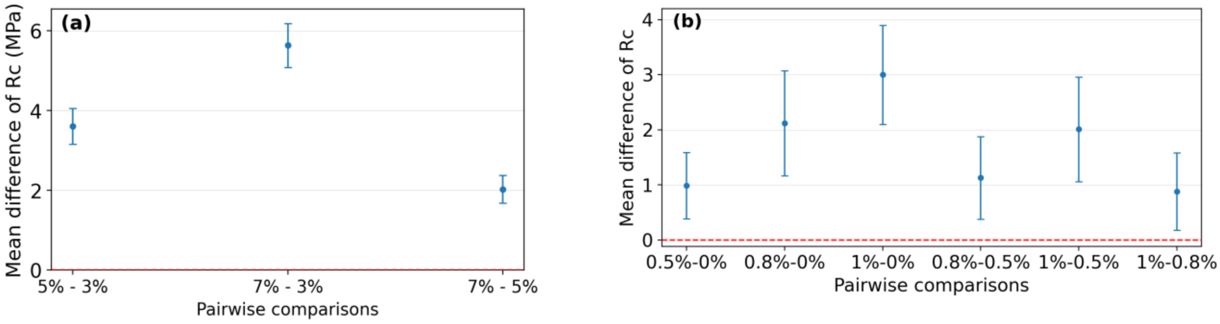

Figure 5. Tukey Pairwise Comparison for R_c: (a) Cement, (b) Additive.

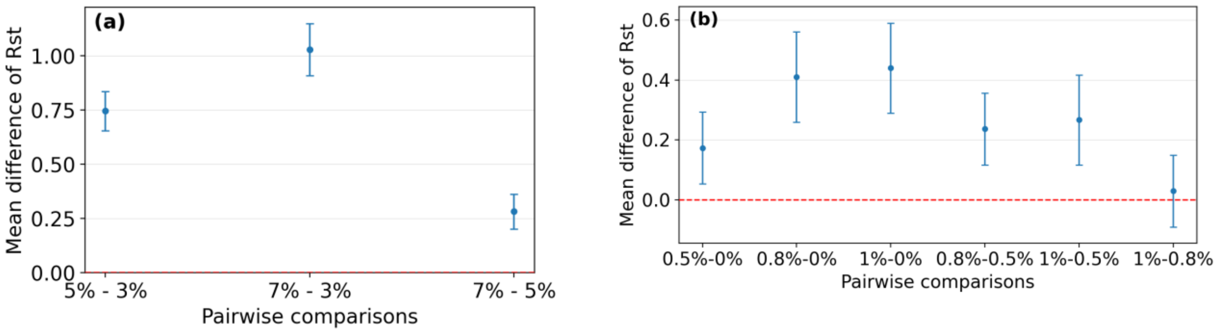

Figure 6. Tukey Pairwise Comparison for R_{st}: (a) Cement, (b) Additive.

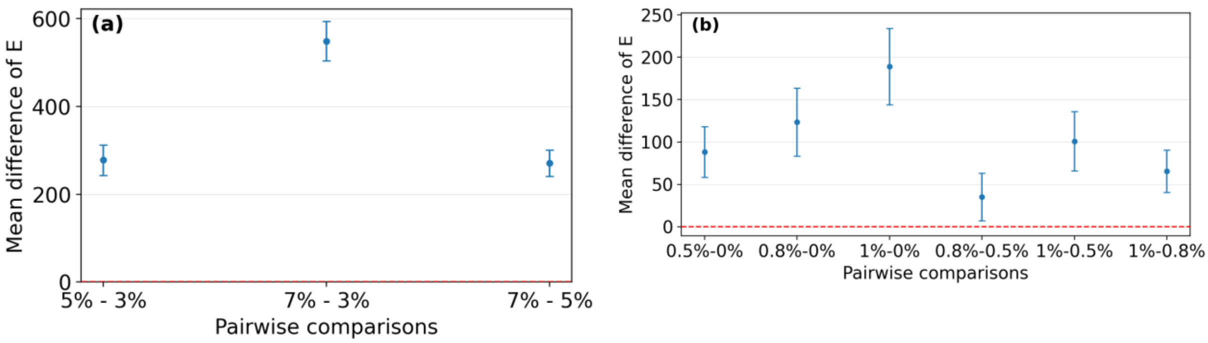

Figure 7. Tukey Pairwise Comparison for E: (a) Cement, (b) Additive.

3.4. Discussion

Vietnam's ambitious infrastructure development plans, including the expansion of the North-South Expressway and urban road networks, demand high-performance pavement materials that are both durable and cost-effective. Besides, the country's tropical climate and diverse geological conditions require pavement materials that can withstand moisture ingress, temperature fluctuations, and heavy traffic loads. The use of cement-stabilized CTB is a cornerstone of these projects, but rising material costs and environmental concerns necessitate innovative solutions to reduce cement content without compromising performance. Additives like Roadcon-PEMA-SAE offer a pathway to achieve this goal by enhancing the efficiency of cement hydration and reducing water demand, thereby lowering the overall cost and carbon footprint of pavement construction.

The results demonstrate that increasing cement and Roadcon-PEMA-SAE dosages significantly enhances the mechanical properties of CTB, with optimal performance at 7% C and 1% A. The 49% Rc increase with C reflects the formation of a robust C-S-H matrix, driven by calcium ion exchange and hydration reactions. The mechanism of lignosulfonate additives involves electrostatic repulsion and steric hindrance, which disperse cement particles and enhance the fluidity of the mixture. Zhang et al. [12] demonstrated that lignosulfonate-based superplasticizers can reduce water demand by up to 15%, resulting in a 20-30% increase in compressive strength in cement-stabilized aggregates. Additionally, lignosulfonates promote the formation of calcium silicate hydrates (C-S-H), the primary strength-contributing phase in cement hydration, by facilitating ion exchange and reducing the thickness of the diffusion layer around cement particles. This chemical interaction not only enhances early-age strength but also contributes to long-term durability by minimizing microcrack formation. Roadcon-PEMA-SAE's lignosulfonate compounds reduce water demand, enhancing hydration efficiency and forming fibrous linkages within the matrix, contributing to the 20-30% strength gains up to 0.8% A. The saturation effect beyond 0.8% A suggests adsorption limitations, where excess lignosulfonate forms non-contributory complexes, consistent with Alazigha et al. [11].

Relative to prior literature, the peak compressive strength achieved here (Rc = 13.97 MPa) exceeds typical values reported for cement-stabilized CTB (5–10 MPa [7]), and the accompanying gains in Rst and E surpass standard thresholds, indicating improved resistance to tensile stresses and deformation under traffic. Beyond absolute performance, our full-factorial program isolates and quantifies the coupled effects of cement and a lignosulfonate additive across practical dosage windows; the regression models (R2 of 0.88–0.95) furnish mixture-design equations, bounded by the tested ranges, that practitioners can use to target project-specific performance. In contrast to Marik et al., who assessed chemical stabilizers at the performance level without resolving factor interactions [14], our analysis identifies a cost-effective domain 3–5% cement with 0.8% additive—that satisfies TCVN 8858:2023 requirements for upper base layers while avoiding overdosing penalties. Mechanistically, these trends accord with reports on lignosulfonate action in cemented soils and aggregates [11–13], situating Roadcon-PEMA-SAE within a hydration-efficient, water-reducing pathway rather than a purely accelerative mode of action [10].

The research results indicate that the admixture "lignosulfonate-based water-reducing admixture" demonstrates versatile capabilities in enhancing the properties of concrete. The effects of increased plasticity and reduced mixing water have led to an increase in early strength, which can compensate for the extended setting time caused by the admixture. Notably, the concrete strength at 28 days remained higher than that of the control sample with the same slump, indicating the long-term benefits of using this admixture. The air-entraining effect of the lignosulfonate-based admixture, increasing air content by 1-3% or more, plays a crucial role in improving the durability of concrete. This could be attributed to the high surface activity of the lignosulfonate base, similar to dedicated air-entraining agents (refer to studies on the air-entraining mechanism of lignosulfonates if available). However, it is important to note that the air-entraining efficiency depends on the admixture dosage and concrete composition, and overdosing can lead to adverse effects, reducing strength due to excessive air voids. In cases where high dosages are necessary, combining with a defoaming agent may be required to maintain the desired strength. Therefore, the application of this admixture in cement-stabilized materials requires careful research and calculation to ensure material effectiveness and compatibility.

This research pioneers the application of Roadcon-PEMA-SAE in CTB, elucidating its chemical and mechanical effects through detailed analysis of lignosulfonate-driven hydration.

Second, the regression models offer a predictive framework for pavement design, addressing a gap in quantitative modeling for additive-enhanced CTB. Third, the study provides practical guidelines for road construction in Vietnam, where tropical climates and soft soils demand durable materials. By optimizing cement usage, the research aligns with global sustainability goals, reducing the environmental footprint of pavement construction.

This study employed a full-factorial laboratory program (12 mixtures; 36 specimens) with Proctor-determined OMC and 28-day testing per TCVN 8858:2023 to quantify the effects of cement and a lignosulfonate admixture (Roadcon-PEMA-SAE) on CTB mechanical properties. While the design and the ANOVA/Tukey/regression analyses provide internally consistent evidence, several factors limit generalization. The program did not include comparator admixture families (e.g., naphthalene/PCE water-reducers or other chemical stabilizers), so the relative efficacy of Roadcon-PEMA-SAE was not benchmarked. All results reflect a single curing age and regime (28 days, controlled temperature/humidity); early-age (e.g., 7 days) and longer-term (e.g., 90 days) strength/stiffness development were not tracked. Replicate dispersion and repeatability were not reported explicitly (a coefficient of variation <5% was assumed), and environmental/field variables (e.g., temperature and moisture typical of Vietnamese construction conditions) were not parametrically controlled. Consistent with the paper's scope, we focused on mechanical performance and did not assess potential environmental impacts of Roadcon-PEMA-SAE (e.g., leaching behaviour or life-cycle cost/CO_2).

Future research will validate and extend these findings by pairing expanded laboratory studies such as covering age-related strength development, alternative curing conditions, other admixture families, and different cement chemistries etc., with pilot field sections, long-term durability and repeated-load testing, and environmental assessments (leaching tests and LCA/LCC). Taken together, these steps will strengthen the link between laboratory evidence and field performance. By demonstrating the efficacy of Roadcon-PEMA-SAE in enhancing CTB stiffness and strength, this work helps pave the way toward more resilient and sustainable pavement bases, particularly under tropical climatic conditions.

4. CONCLUSION

This study systematically investigated the enhancement of cement treated base(CTB) using Roadcon-PEMA-SAE, a lignosulfonate-based additive, for pavement base applications. Through a comprehensive experimental design and statistical analysis, the effects of cement (3-7%) and Roadcon-PEMA-SAE (0-1%) ratios on compressive strength (R_c), splitting tensile strength (R_{st}), and modulus of elasticity (E) were evaluated. The results demonstrated significant improvements in mechanical properties, with the optimal mixture (7% cement, 1% Roadcon-PEMA-SAE) achieving R_c of 13.97 MPa, Rst exceeding 0.45 MPa, and E surpassing 800 MPa, meeting Vietnamese standards (TCVN 8858:2023, TCN 211-06) for flexible and rigid pavement bases. Quadratic regression models (R^2 = 88.0-95.0%) accurately quantified the relationships between input variables and mechanical properties, providing a robust tool for mixture optimization. A cement ratio of 3-5% and additive ratio of 0.8% were recommended as a cost-effective solution, balancing technical performance and economic efficiency. Future studies ought to delve into these elements, examine greater C/A ratios, and confirm the models through real-world testing. Furthermore, considering environmental effects (like lignosulfonate runoff) and cost assessments could boost the study's real-world applicability.

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