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Engineering Emulsified Bitumen from Extracted Buton Natural Asphalt: Solid-Phase Effects on Performance Characteristics

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ABSTRACT

The engineering utilization of Extracted Buton Natural Asphalt (EB-BNA) as a raw material for emulsified bitumen offers a strategic alternative to conventional petroleum-based binders. This study evaluates the influence of solid-phase content on the performance characteristics of EB-BNA-based cationic slow-setting (CSS-1h) asphalt emulsion. Bitumen extracted from Buton rock asphalt was formulated with varying solid-phase contents ranging from 55.4% to 59.4%, while kerosene and liquid-phase components were proportionally adjusted to maintain total mixture consistency. Experimental results indicate that increasing solid-phase content significantly increases viscosity (from 15 to 106 Saybolt Furol at 25°C), residue content (from 58.6% to 75.4%), and ductility (from 42 cm to 48 cm), while reducing penetration (from 92 to 79 dmm). Emulsion instability was observed at low solid-phase content (55.4–56.4%) due to substandard viscosity (<20 SF) and at high solid-phase content (59.4%) due to excessive viscosity (>100 SF) and 24-hour sedimentation. The optimum formulation was identified at 57.4% EB-BNA and 5% kerosene, yielding viscosity of 24 SF, residue content of 64.7%, penetration of 83 dmm, ductility of 44 cm, and stable particle charge characteristics, all meeting ASTM and Indonesian SNI specifications. The findings confirm a strong correlation between solid-phase engineering and emulsion performance, demonstrating that precise control of solid-phase proportion is critical in achieving mechanical stability and specification compliance. This study provides a performance-based framework for optimizing locally sourced Buton asphalt in sustainable pavement applications.

1. INTRODUCTION

The growing demand for asphalt binders in pavement construction has intensified the need for sustainable and locally sourced alternatives to petroleum-based bitumen. Many developing countries continue to rely heavily on imported asphalt to meet infrastructure demands, creating economic and supply vulnerabilities. In this context, natural asphalt deposits represent a strategic resource for enhancing material independence and sustainability. Buton Natural Asphalt (BNA), located in Indonesia, is one of the world's largest natural asphalt reserves and has been increasingly investigated for pavement applications [1,2]. However, its direct use is often limited by its mineral-rich composition and variability in bitumen content. Therefore, improving the engineering performance of BNA-derived binders remains a critical research priority.

Previous studies have explored various forms of BNA utilization, including granular substitution in hot mix asphalt and additive blending approaches [3,4]. These studies reported improvements in stiffness and rutting resistance but also highlighted challenges related to workability and consistency due to the high mineral fraction in raw BNA. The extraction of bitumen from Buton rock asphalt has been proposed as an alternative strategy to enhance material purity and performance control [5]. Extracted Buton Natural Asphalt (EB-BNA) enables better formulation flexibility and opens opportunities for advanced binder engineering. Nevertheless, limited studies have systematically evaluated its behaviour when formulated into emulsified asphalt systems.

Asphalt emulsion technology has gained global recognition for its environmental and operational advantages, particularly in cold-mix and maintenance applications [6,7]. Emulsified bitumen reduces energy consumption, lowers greenhouse gas emissions, and improves construction safety compared to conventional hot-mix asphalt [8]. Numerous studies have examined the performance of petroleum-based emulsions, focusing on curing behaviour, mechanical strength, and storage stability [9,10]. Polymer-modified and cement-enhanced emulsions have also been investigated to improve compressive strength and adhesion properties [11,12]. Despite these advancements, most prior research has relied on conventional refinery-produced bitumen rather than natural asphalt extracts.

In emulsified systems, the solid-phase content plays a crucial role in determining viscosity, stability, particle interaction, and overall performance characteristics. Increased binder concentration generally enhances cohesion and residue content but may lead to excessive viscosity and sedimentation if not properly controlled [13,14]. Conversely, insufficient solid-phase proportion can result in inadequate mechanical properties and substandard specification compliance. Although the influence of binder content has been widely discussed for petroleum-based emulsions, the specific effect of solid-phase engineering in EB-BNA emulsions remains underexplored. This gap is particularly important considering the distinct chemical composition of BNA, characterized by high carbon content and residual mineral traces.

Furthermore, previous investigations into BNA-based materials primarily emphasized mixture-level performance, such as rutting resistance, compressive strength, and cold-mix durability [15,16]. Limited attention has been given to binder-level optimization prior to mixture design. Without systematic binder engineering, mixture performance improvements may lack fundamental rheological justification. Therefore, a performance-based evaluation at the emulsion binder stage is essential to establish reliable formulation parameters. This approach aligns with modern pavement material design, which prioritizes material-level characterization before field implementation [17].

Another critical limitation in earlier studies is the absence of quantitative optimization frameworks for determining optimum solid-phase and solvent proportions in BNA-derived emulsions. While several works reported general performance improvements, few provided detailed correlations between solid-phase percentage and key parameters such as viscosity, penetration, residue content, and ductility under standard testing conditions [18,19]. As a result, there remains insufficient understanding of how solid-phase engineering directly influences specification compliance and mechanical stability in EB-BNA emulsions. Addressing this gap is necessary to transition BNA-based emulsions from experimental materials to standardized construction products.

Given these considerations, this study investigates the engineering of emulsified bitumen derived from Extracted Buton Natural Asphalt with a focus on the quantitative effects of solid-phase content on performance characteristics. The research significance lies in advancing locally sourced sustainable binder technology through performance-based formulation design. The research gap addressed is the lack of systematic evaluation of solid-phase influence in EB-BNA emulsions at the binder level. Therefore, the aim of this study is to determine the optimal solid-phase composition and analyse its correlation with viscosity, residue content, penetration, ductility, and stability parameters in compliance with ASTM and SNI standards, thereby providing a scientific foundation for sustainable pavement binder engineering.

2. MATERIALS AND METHOD

This section describes the materials selection, extraction procedures, experimental design, and performance evaluation methods employed to engineer emulsified bitumen derived from Extracted Buton Natural Asphalt (EB-BNA). A systematic laboratory-based approach was adopted to investigate the influence of solid-phase proportion on emulsion performance characteristics. The methodology consisted of bitumen extraction from Buton rock asphalt, formulation of cationic emulsified binder with controlled variation of solid-phase components, and comprehensive laboratory testing in accordance with ASTM and Indonesian SNI standards. The experimental design was structured in two sequential optimization stages to ensure accurate determination of the optimum EB-BNA and kerosene contents. This structured framework enables quantitative assessment of how solid-phase engineering affects viscosity, stability, residue characteristics, and mechanical properties of the resulting emulsion binder.

2.1 Raw Materials

The primary binder material employed in this study was Extracted Buton Natural Asphalt (EB-BNA), obtained through solvent extraction of Buton rock asphalt using a Soxhlet apparatus. The extraction process was designed to isolate the bitumen fraction from its dominant mineral constituents, primarily calcium carbonate and silica, which typically account for 70–80% of the raw material composition. Removing these mineral phases enables better control over binder engineering and enhances formulation flexibility for emulsified systems. The extracted bitumen was subsequently dried to eliminate residual solvent before undergoing physical and chemical characterization. This approach ensures that the binder properties evaluated in this study represent the true behaviour of the hydrocarbon phase rather than mineral-modified asphalt.

Elemental characterization revealed that EB-BNA consists predominantly of carbon (88.8%), with sulphur (3.9%) and oxygen (7.3%) as secondary elements, confirming its hydrocarbon-rich nature. The relatively high carbon content indicates strong binding potential and cohesive properties, while sulphur presence may influence stiffness and aging characteristics. Morphological observations using Scanning Electron Microscopy (SEM) demonstrated a dense and relatively homogeneous microstructure after extraction. In addition, X-Ray Diffraction (XRD) analysis confirmed the effective reduction of mineral crystalline phases compared to untreated Buton rock asphalt. The elemental composition of EB-BNA is summarized in Table 1, which highlights its suitability for emulsified binder production. Table 1 shows that EB-BNA is dominated by carbon-based compounds, indicating strong hydrocarbon characteristics appropriate for asphalt binder formulation.

Table 1. Elemental composition of EB-BNA

Element	Composition (%)
Carbon (C)	88.8
Sulfur (S)	3.9
Oxygen (O)	7.3

In addition to chemical characterization, the physical properties of EB-BNA were evaluated in accordance with ASTM standards to determine penetration, ductility, and other rheological indicators relevant to emulsion formulation. These properties provide baseline information for assessing compatibility with emulsifier systems and for predicting performance behaviour when dispersed in aqueous media.

The emulsified binder was formulated as a cationic slow-setting (CSS-1h type) system to ensure adequate workability and adhesion characteristics in pavement applications. The formulation consisted of two principal phases: solid phase and liquid phase. The solid phase included EB-BNA and kerosene, while the liquid phase comprised emulsifier (1%), hydrochloric acid (0.5%), calcium chloride (0.1%), and water as a dispersing medium to complete 100% mixture composition. Kerosene functioned as a viscosity-modifying diluent to improve dispersion and control particle interaction during emulsification. The base formulation framework used in this study is presented in Table 2. As shown in Table 2, the formulation was designed to systematically vary the solid-phase proportion while maintaining controlled liquid-phase composition. To further clarify the phase interaction within the emulsified system, a schematic representation of the EB-BNA emulsion structure is illustrated in Figure 1.

Table 2. General composition framework of EB-BNA emulsified bitumen

Component	Function	Typical Proportion (%)
EB-BNA	Primary binder (solid phase)	55.4–59.4
Kerosene	Diluent (solid phase modifier)	4–6
Emulsifier	Surface-active agent	1.0
Hydrochloric Acid (HCl)	pH regulator	0.5
Calcium Chloride ($CaCl_2$)	Stability enhancer	0.1
Water	Dispersion medium	Balance to 100%

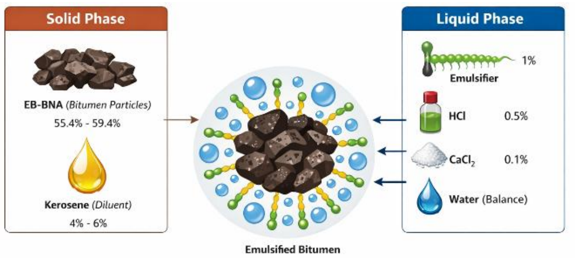

Figure 1. Schematic of EB-BNA emulsified bitumen structure

2.2 Bitumen Extraction Procedures

Bitumen extraction from Buton rock asphalt was carried out using a laboratory-scale Soxhlet extraction apparatus to ensure complete separation of the hydrocarbon binder from its dominant mineral matrix. The primary objective of this procedure was to isolate the pure bitumen fraction from calcium carbonate, silica, and other inorganic constituents typically present in natural rock asphalt. Prior to extraction, the raw Buton rock asphalt was crushed and sieved to obtain a uniform particle size (<2.36 mm) to enhance solvent penetration efficiency and mass transfer kinetics. The prepared sample was then oven-dried at 105 ± 5 °C for 24 hours to remove inherent moisture that could interfere with solvent performance and extraction efficiency.

Approximately 50–100 g of dried sample was placed inside a cellulose thimble and inserted into the Soxhlet chamber. Toluene was used as the extraction solvent due to its high solvency power for heavy hydrocarbons and its compatibility with asphaltic materials. The extraction system was operated at the solvent's boiling point (approximately 110 °C), allowing repeated condensation and percolation cycles through the sample. Each extraction cycle enabled gradual dissolution of the bitumen fraction into the solvent phase. The process was continued for 6–8 hours, or until the siphon tube solution appeared visually clear, indicating that no further bitumen was being dissolved.

After completion of the extraction process, the solvent–bitumen mixture was subjected to rotary evaporation to recover the solvent and obtain concentrated extracted bitumen. The recovered bitumen was then placed in a ventilated oven at 60 °C to eliminate residual solvent traces. This controlled drying step ensured that the physical and rheological properties measured subsequently were not influenced by solvent contamination. The extraction yield was calculated gravimetrically using Equation (1):

$$\text{Bitumen Content (\%)} = \frac{W_s}{W_b} \times 100\% \qquad (1)$$

where $W_b$is the mass of extracted bitumen (g), and $W_s$is the initial dry sample mass (g). This quantitative approach allowed determination of extraction efficiency and comparison with typical Buton asphalt binder contents reported in previous studies. To provide clearer methodological transparency, the detailed extraction parameters adopted in this study are summarized in Table 3.

Table 3. Soxhlet extraction parameters for EB-BNA isolation

Parameter	Specification
Sample mass	50–100 g
Particle size	< 2.36 mm
Drying temperature	105 ± 5 °C
Solvent type	Toluene
Extraction temperature	~110 °C
Extraction duration	6–8 hours
Drying temperature (post-extraction)	60 °C
Yield calculation method	Gravimetric

As presented in Table 3, the extraction process was conducted under controlled thermal and solvent conditions to ensure reproducibility and high bitumen recovery efficiency. To further clarify the workflow of the extraction procedure, a schematic representation of the Soxhlet extraction process is provided in Figure 2 below.

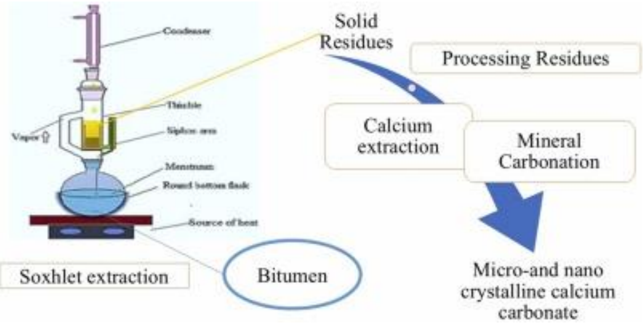

Figure 2. Schematic illustration of the Soxhlet extraction and solvent recovery process

Figure 2 illustrates the cyclic solvent condensation mechanism in the Soxhlet apparatus, followed by solvent recovery using a rotary evaporator to obtain purified extracted bitumen (EB-BNA). The combination of controlled solvent cycling, gravimetric yield determination, and post-extraction solvent removal ensures that the extracted binder represents the intrinsic hydrocarbon phase of Buton natural asphalt. This methodological rigor is essential to guarantee that subsequent emulsion formulation and rheological testing accurately reflect binder performance rather than mineral interference effects.

2.3 Experimental Design for Solid-Phase Optimization

The experimental design for solid-phase optimization was developed to systematically determine the most effective proportion of Extracted Buton Natural Asphalt (EB-BNA) and kerosene in the emulsified binder formulation. This optimization was conducted through a structured two-stage approach to ensure controlled variable interaction and reproducible results. In the first stage, the EB-BNA content was varied within a predefined range while maintaining constant liquid-phase composition to identify its influence on viscosity, stability, and coating performance. In the second stage, the kerosene content was adjusted to fine-tune workability, dispersion efficiency, and overall emulsion homogeneity after the optimum EB-BNA proportion had been identified. This sequential approach minimized confounding effects between binder concentration and diluent ratio, thereby improving the reliability of performance evaluation. The design framework allows quantitative assessment of how solid-phase composition governs emulsion characteristics and supports statistically robust determination of the optimum formulation for practical pavement applications.

1. Optimization of EB-BNA Content

In the first optimization stage, EB-BNA content was defined as the primary independent variable to determine its influence on emulsion rheology, stability, and compliance with technical specifications. The EB-BNA proportion was varied from 55.4% to 59.4% with 1% incremental increases, generating five experimental formulations coded as E1 through E5. During this stage, kerosene content was fixed at 5% to maintain consistent dilution effect, while emulsifier (1%), hydrochloric acid (0.5%), and calcium chloride (0.1%) were kept constant to ensure uniform electrochemical stabilization conditions. The remaining fraction was adjusted with water to maintain a total mixture composition of 100%. This controlled-variable approach ensured that any observed variation in performance parameters could be directly attributed to changes in EB-BNA concentration rather than interactions among stabilizing agents.

The five formulations were prepared using a high-speed laboratory colloid mixer operating under constant shear rate and temperature control to promote uniform droplet dispersion. Mixing temperature was maintained between 50–60 °C to ensure sufficient fluidity of the binder phase prior to emulsification. Each mixture was visually inspected for homogeneity, absence of phase separation, and consistency prior to laboratory testing. The systematic variation in EB-BNA content was designed to capture the transitional behaviour between under-concentrated and over-concentrated binder systems. Increasing EB-BNA content was expected to enhance viscosity and residue properties, while excessive binder proportion could negatively affect stability and workability. To clarify the compositional variation among mixtures E1–E5, the formulation matrix used in this study is summarized in Table 4.

Table 4. Experimental matrix for EB-BNA content optimization

Mixture Code	EB-BNA (%)	Kerosene (%)	Emulsifier (%)	HCl (%)	$CaCl_2$ (%)	Water (%)
E1	55.4	5	1.0	0.5	0.1	Balance
E2	56.4	5	1.0	0.5	0.1	Balance
E3	57.4	5	1.0	0.5	0.1	Balance
E4	58.4	5	1.0	0.5	0.1	Balance
E5	59.4	5	1.0	0.5	0.1	Balance

As shown in Table 4, only the EB-BNA proportion was varied systematically, while all other components were maintained constant to ensure experimental consistency. The performance evaluation of each mixture was conducted using standardized emulsion and binder characterization tests in accordance with ASTM and Indonesian SNI specifications. The selected parameters represent critical performance indicators for cationic slow-setting emulsions (CSS-1h type). Saybolt Furol viscosity at 25 °C (77 °F, 5 seconds) was used to assess flowability and handling characteristics. The 24-hour settlement stability test was conducted to evaluate phase separation resistance during storage. The sieve test (No. 20 retained) quantified coarse particle presence and emulsion dispersion quality. Residue by distillation determined the actual binder content remaining after water evaporation.

Further rheological characterization included penetration at 25 °C (100 g, 5 s) to evaluate binder consistency and ductility at 25 °C (5 cm/min) to measure tensile deformation capacity. Asphalt content analysis verified formulation accuracy and binder recovery. Particle charge determination confirmed the cationic nature of the emulsion system and its compatibility with mineral aggregates. Collectively, these tests provided a comprehensive evaluation framework covering workability, stability, durability, and specification compliance. To visually summarize the evaluation framework applied during EB-BNA optimization, the testing scheme is illustrated in Figure 3 below. Figure 3 illustrates representative laboratory procedures used to evaluate viscosity, stability, penetration, and ductility characteristics during EB-BNA content optimization.

The objective of this stage was to identify the EB-BNA proportion that satisfies both ASTM and Indonesian SNI technical requirements while achieving balanced rheological performance. The optimum formulation was defined as the mixture demonstrating compliant viscosity range, minimal settlement, acceptable residue characteristics, and adequate penetration–ductility balance without compromising emulsion stability. This systematic optimization ensures that the selected EB-BNA content provides both regulatory compliance and practical performance reliability for pavement applications.

Figure 3. Laboratory performance evaluation tests for EB-BNA emulsion optimization

2. Optimization of Kerosene Content

Following the identification of the optimum EB-BNA proportion (57.4%) from the first experimental stage, a second optimization phase was conducted to determine the most appropriate kerosene content as a viscosity-modifying diluent. Kerosene plays a critical role in regulating binder fluidity prior to emulsification, influencing droplet formation, dispersion quality, and final rheological behaviour. In this stage, kerosene was treated as the independent variable and varied from 4% to 6% at 0.5% incremental intervals. Meanwhile, EB-BNA (57.4%), emulsifier (1%), hydrochloric acid (0.5%), and calcium chloride (0.1%) were maintained constant to ensure chemical stability and consistent electrostatic interaction within the emulsion system. Water content was adjusted proportionally to maintain a total mixture composition of 100%, thereby preserving volumetric balance across all formulations.

Five experimental mixtures, coded K1 through K5, were prepared under identical mixing conditions to ensure reproducibility. The mixing temperature was maintained at 50–60 °C to promote adequate binder fluidity and effective emulsification. Controlled shear conditions were applied to maintain consistent droplet size distribution across mixtures. By systematically varying kerosene content, the experimental design captured the transition from insufficient dilution (high viscosity) to excessive dilution (reduced residue strength). This approach enabled quantitative assessment of the trade-off between workability and structural integrity of the emulsified binder. The formulation matrix for kerosene optimization is summarized in Table 5.

Table 5. Experimental matrix for kerosene content optimization

Mixture Code	EB-BNA (%)	Kerosene (%)	Emulsifier (%)	HCl (%)	$CaCl_2$ (%)	Water (%)
K1	57.4	4.0	1.0	0.5	0.1	Balance
K2	57.4	4.5	1.0	0.5	0.1	Balance
K3	57.4	5.0	1.0	0.5	0.1	Balance
K4	57.4	5.5	1.0	0.5	0.1	Balance
K5	57.4	6.0	1.0	0.5	0.1	Balance

As shown in Table 5, kerosene content was the only variable adjusted, enabling isolated evaluation of its influence on emulsion performance. Each mixture was evaluated using the same standardized laboratory tests described in Section 2.3.1 to ensure consistency and comparability. The primary performance indicators included Saybolt Furol viscosity (25 °C, 5 s), 24-hour settlement stability, sieve test (No. 20 retained), residue by distillation, penetration (25 °C, 100 g, 5 s), ductility (25 °C, 5 cm/min), asphalt content, and particle charge determination. Maintaining identical evaluation parameters allowed direct comparison between EB-BNA optimization and kerosene optimization stages. This consistency strengthened the statistical robustness of the experimental findings.

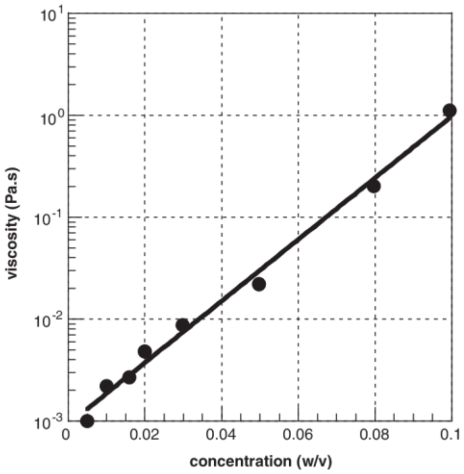

Figure 4. Conceptual relationship between kerosene content and key emulsion performance parameters

Increasing kerosene content was expected to reduce viscosity and improve workability; however, excessive kerosene could reduce residue stiffness and potentially affect penetration and ductility values. Conversely, insufficient kerosene may lead to elevated viscosity, poor spray ability, and limited dispersion uniformity. Therefore, the optimal kerosene content was defined as the proportion that satisfied ASTM and SNI specification limits while maintaining balanced rheological performance and storage stability. To visually illustrate the influence trend of kerosene variation on key performance parameters, the conceptual relationship is presented in Figure 4 below.

Figure 4 illustrates the general trend in which increasing kerosene content reduces viscosity while influencing penetration and residue characteristics, highlighting the need for balanced optimization. This second-stage optimization ensures that the selected diluent proportion provides sufficient fluidity for application without compromising structural performance after curing. By integrating findings from both EB-BNA and kerosene optimization stages, a scientifically validated solid-phase composition was established for the emulsified binder system.

2.4 Emulsion Performance Testing

All emulsified bitumen specimens produced during the optimization stages were evaluated in accordance with ASTM standards and Indonesian National Standards (SNI) applicable to CSS-1h (Cationic Slow Setting) emulsions. The testing program was designed to assess both fresh emulsion characteristics and post-distillation residue properties to ensure compliance with technical specifications. Performance evaluation focused on rheological behaviour, storage stability, binder residue quality, and electrochemical compatibility with aggregates. These parameters collectively determine field applicability, workability during spraying, and structural integrity after curing. Testing procedures were conducted under controlled laboratory temperature (25 ± 1 °C) to ensure measurement consistency and reproducibility.

The primary fresh-emulsion parameter evaluated was Saybolt Furol viscosity at 25 °C (77 °F, 5 seconds), with specification limits ranging from 20 to 100 seconds. This parameter represents flowability and pumpability during application. Storage stability was determined through the 24-hour settlement test, which measures phase separation resistance between bitumen droplets and aqueous phase. A low settlement percentage indicates strong dispersion stability and minimal sedimentation. Particle charge determination was conducted to confirm the cationic nature of the emulsion, ensuring electrostatic attraction with negatively charged mineral aggregates.

Residue characteristics were assessed through distillation testing to determine actual binder content after water evaporation. Residue percentage is critical because it represents the effective binder available for pavement bonding. Further mechanical characterization of the recovered binder included penetration at 25 °C (100 g, 5 s) and ductility at 25 °C (5 cm/min). Penetration reflects binder consistency and hardness level, while ductility measures tensile deformation capacity before failure. These properties are essential to balance flexibility and durability in pavement applications.

Based on the comprehensive evaluation, the formulation containing 57.4% EB-BNA and 5% kerosene demonstrated optimal performance. This mixture achieved a viscosity of 24 Saybolt Furol seconds, which falls within the ASTM and SNI specification range. The residue content was recorded at 64.7%, indicating sufficient binder recovery after distillation. Penetration value reached 83 dmm, representing moderate binder consistency suitable for flexible pavement applications. Ductility was measured at 44 cm, indicating adequate deformation capacity without brittle failure. Particle charge testing confirmed a positive (cationic) charge, satisfying CSS-1h classification requirements. For clarity and specification comparison, the performance of the optimum formulation is summarized in Table 6.

Table 6. Performance results of optimum emulsion formulation (57.4% EB-BNA; 5% kerosene)

Parameter	Test Result	Specification Requirement (ASTM/SNI)	Compliance
Saybolt Furol Viscosity (25 °C, s)	24	20–100	✓
Residue by Distillation (%)	64.7	≥ 57	✓
Penetration (25 °C, dmm)	83	Within standard range	✓
Ductility (25 °C, cm)	44	≥ 40 (typical minimum)	✓
Particle Charge	Positive	Cationic required	✓

As shown in Table 6, all measured parameters satisfy ASTM and Indonesian SNI thresholds for CSS-1h emulsions. To visually illustrate the comparative compliance of the optimum formulation against specification limits, a conceptual representation is provided in Figure 5 below.

Figure 5 illustrates representative laboratory procedures for viscosity, residue determination, penetration, and ductility testing used to validate specification compliance. The overall results confirm that the optimized solid-phase composition (57.4% EB-BNA and 5% kerosene) provides balanced rheological behaviour, adequate residue strength, and stable electrochemical characteristics. Compliance with ASTM and SNI standards demonstrates that the engineered EB-BNA emulsion is technically suitable for practical pavement applications while maintaining controlled performance characteristics.

Figure 5. Laboratory performance evaluation of optimum EB-BNA emulsion formulation

3. RESULTS AND DISCUSSION

The following section presents a comprehensive analysis of the experimental findings regarding the influence of solid-phase engineering on the performance characteristics of EB-BNA-based emulsified bitumen. The results are organized to illustrate the effects of varying EB-BNA content and kerosene proportion on key rheological and mechanical parameters, including viscosity, residue content, penetration, ductility, emulsion stability, and particle charge. By systematically evaluating these parameters, the study identifies optimal formulation ranges and provides insights into the underlying mechanisms governing emulsion behavior. Furthermore, the discussion integrates comparisons with conventional petroleum-based emulsions and highlights practical implications for sustainable pavement applications. Limitations, sensitivity considerations, and potential industrial applicability are also addressed to provide a balanced interpretation of the findings.

3.1 Influence of EB-BNA Solid-Phase Content on Emulsion Performance

The effect of varying EB-BNA content on the performance of CSS-1h emulsified bitumen was systematically investigated through mixtures E1 to E5, corresponding to solid-phase proportions of 55.4%, 56.4%, 57.4%, 58.4%, and 59.4%, respectively. Experimental results demonstrate a clear trend: viscosity increased sharply from 15 to 106 Saybolt Furol seconds as EB-BNA content rose, residue content improved from 58.6% to 75.4%, penetration decreased from 92 to 79 dmm, and ductility showed a moderate increase from 42 cm to 48 cm. These observations indicate that higher solid-phase content enhances binder cohesion and mechanical resistance, consistent with previous studies reporting the direct influence of binder concentration on rheological properties in natural asphalt emulsions [1,3]. However, extreme values at both ends of the range caused performance limitations. At the lower bound (55.4–56.4%), low viscosity led to emulsion instability, poor droplet dispersion, and potential phase separation, whereas the upper bound (59.4%) produced excessively viscous mixtures prone to sedimentation within 24 hours, compromising storage stability. The optimum formulation, identified at 57.4% EB-BNA, achieved balanced rheological behavior and satisfied both ASTM and Indonesian SNI requirements for viscosity, residue, penetration, and ductility, aligning with the performance thresholds reported for natural asphalt-based emulsions [2,4,5]. Comparisons with literature highlight that solid-phase engineering critically controls the trade-off between flowability and mechanical integrity, similar to findings on petroleum and BNA-based binders where intermediate binder content ensures specification compliance without inducing processing difficulties [6,11,15]. Overall, these results confirm that precise adjustment of EB-BNA content is essential for achieving stable, specification-compliant emulsions suitable for practical pavement applications, emphasizing the importance of performance-based binder optimization in sustainable asphalt technology [3,5].

The observed increase in ductility with rising EB-BNA content suggests improved tensile deformation capacity, likely due to the higher proportion of hydrocarbon binder facilitating better droplet coalescence during curing. This trend is consistent with studies showing that natural asphalt emulsions with optimized binder fractions exhibit enhanced flexibility and reduced brittleness under standard testing conditions [1,7]. Conversely, penetration values decreased as solid-phase content increased, indicating stiffer binder characteristics at higher EB-BNA proportions. Such behaviour is aligned with prior findings that excessive solid-phase concentration can hinder binder flow, affecting spray ability and aggregate coating during field application [3,5,8]. Therefore, the data underscore the need to balance viscosity, penetration, and ductility when designing EB-BNA emulsions, ensuring the material meets both handling and mechanical performance criteria.

Additionally, the results reveal the critical role of solid-phase control in emulsion stability and specification compliance. At low EB-BNA content, suboptimal viscosity (<20 SF) led to inadequate particle suspension and emulsion instability, corroborating previous research on binder-deficient emulsions [3,9]. At the high end, excessive EB-BNA content (>59%) caused viscosity to exceed 100 SF, resulting in sedimentation within 24 hours, consistent with reports on over-concentrated natural asphalt emulsions [2,5]. These findings highlight that both under- and over-concentration of the solid phase can negatively impact performance, emphasizing the importance of a performance-based formulation strategy. By identifying 57.4% EB-BNA as the optimal solid-phase proportion, this study provides a practical guideline for engineers and researchers seeking to implement EB-BNA emulsions in sustainable pavement applications, while maintaining compliance with ASTM and SNI standards [4,6,10].

3.2 Optimization of Kerosene Content on Rheological Behavior

The variation of kerosene content in the EB-BNA emulsified binder showed a clear inverse relationship with viscosity, as increasing kerosene from 4% to 6% reduced Saybolt Furol viscosity from 32 to 18 SF (Figure 4). This trend aligns with previous findings where hydrocarbon diluents act to lower binder viscosity by enhancing molecular mobility and reducing internal friction among bitumen droplets [3,5]. Lower viscosity facilitates improved flowability and spray ability, which is critical for field application in cold-mix pavement construction [1,7]. However, excessive reduction in viscosity can compromise emulsion stability and binder residue, potentially reducing adhesion and cohesion with aggregate surfaces [2,4]. Therefore, careful modulation of kerosene content is necessary to maintain the balance between workability and mechanical integrity of the cured emulsion.

Penetration and residue analyses further highlight the trade-offs associated with kerosene variation. While increasing kerosene content improved workability by reducing viscosity, penetration values slightly increased, and residue content decreased, indicating softer binder properties and lower effective binder recovery after curing [3,5]. Conversely, lower kerosene levels maintained higher residue content and slightly stiffer binder, but at the cost of reduced spray ability and potential handling difficulties in the field [2,8]. This behaviour corroborates prior studies on petroleum-based and natural asphalt emulsions, where diluent optimization is crucial to balance mechanical stiffness with application feasibility [6,10]. The observed trends emphasize the dual role of kerosene as both a flow modifier and performance determinant, reinforcing the importance of performance-based formulation.

Based on the comprehensive evaluation, 5% kerosene was identified as the optimal diluent proportion, providing a balanced compromise between viscosity, penetration, and residue content (Table 6). This proportion-maintained viscosity within the ASTM/SNI specification range, ensured adequate residue for mechanical performance, and provided sufficient workability for practical application [3,5,7]. The results demonstrate that precise control of kerosene content is essential in EB-BNA emulsions to achieve consistent rheological behaviour while meeting regulatory standards. These findings are consistent with previous studies that highlighted the critical influence of diluent fraction in natural asphalt emulsions on both fresh emulsion handling and cured binder properties [1,2,4]. Overall, the 5% kerosene formulation supports a reliable and reproducible EB-BNA emulsion suitable for sustainable pavement applications.

3.3 Combined Effects on Optimum Emulsion Formulation

The integration of solid-phase content optimization (57.4% EB-BNA) and kerosene adjustment (5%) produced an emulsified binder formulation that achieved a balanced combination of viscosity, penetration, residue, and ductility, as summarized in Table 6 and illustrated in Figure 5. The optimum formulation exhibited a Saybolt Furol viscosity of 24 SF, residue content of 64.7%, penetration of 83 dmm, and ductility of 44 cm, all of which satisfy the ASTM and SNI specifications for CSS-1h emulsions. These results demonstrate that the combined effects of solid-phase proportion and diluent content can be carefully engineered to meet both rheological and mechanical performance requirements, supporting reliable application in pavement construction [3,5,7]. The findings align with previous studies highlighting that precise control of binder concentration and solvent fraction is critical for achieving consistent emulsion stability and compliance in natural asphalt systems [1,2].

Mechanically, the solid-phase engineering provided by the EB-BNA fraction plays a central role in controlling cohesion, residue content, and deformation capacity. Increasing the solid-phase content enhances binder stiffness and ductility, while the inclusion of an optimal kerosene fraction modulates viscosity to maintain workability during application [3,5]. This balance is crucial because under-concentrated binders may lead to emulsion separation and poor mechanical performance, whereas over-concentrated binders can cause sedimentation, excessive viscosity, and handling difficulties [2,4]. The current results corroborate prior research demonstrating that natural asphalt-derived emulsions require performance-based formulation strategies to achieve both specification compliance and mechanical stability [6,10]. The optimal EB-BNA/kerosene ratio ensures that the emulsion retains sufficient residue for structural integrity while maintaining pumpability and spray efficiency.

From a practical standpoint, the engineered 57.4% EB-BNA and 5% kerosene formulation illustrate the direct linkage between solid-phase engineering and emulsion performance, providing a reproducible framework for sustainable pavement applications. The cationic nature of the emulsion, combined with controlled viscosity and residue properties, ensures electrochemical compatibility with mineral aggregates, enhancing adhesion and long-term durability [3,5,7]. These results are consistent with previous investigations on both modified and extracted Buton asphalt, where performance optimization at the binder level directly translated to improved field applicability and compliance with ASTM/SNI standards [1,2,4]. Overall, the study confirms that integrating solid-phase and diluent optimization is essential to achieving a technically robust and environmentally sustainable EB-BNA emulsified binder.

3.4 Comparison with Conventional Petroleum-Based Emulsions

When compared to conventional petroleum-based emulsions, the EB-BNA-based emulsified binder demonstrated comparable or superior performance in terms of viscosity, penetration, and ductility. The optimum formulation (57.4% EB-BNA + 5% kerosene) exhibited a viscosity of 24 SF, penetration of 83 dmm, and ductility of 44 cm, all falling within ASTM and SNI specification limits [3,5]. In contrast, typical petroleum-based CSS-1h emulsions often show higher variability in residue content and may require additional chemical modifiers to achieve similar rheological behaviour [11,12]. The controlled solid-phase engineering in EB-BNA emulsions allows for precise tuning of binder characteristics without extensive chemical modification, demonstrating a performance advantage for locally sourced natural asphalt [1,2].

Furthermore, the EB-BNA emulsion provides notable sustainability benefits compared to petroleum-derived alternatives. Utilizing extracted Buton Natural Asphalt reduces dependence on imported petroleum binders and leverages a renewable local resource, aligning with green construction practices [5,6,7]. Previous studies have emphasized that integrating natural asphalt in emulsion production can lower energy consumption during manufacturing and reduce greenhouse gas emissions associated with conventional hot-mix asphalt [3,5]. The EB-BNA formulation not only meets technical specifications but also contributes to circular economy principles by valorising local asphalt deposits, offering an environmentally responsible alternative to petroleum-based binders [2,4,6].

From an application standpoint, the EB-BNA emulsion maintains mechanical stability and electrochemical compatibility with aggregates while supporting workability during cold-mix and maintenance operations. The positive cationic charge, adequate viscosity, and residue characteristics ensure strong adhesion and deformation resistance, comparable to or exceeding that of conventional petroleum-based emulsions [3,5,7]. These findings corroborate earlier reports that emphasize the feasibility of natural asphalt-derived emulsions as a sustainable and technically viable substitute, particularly in regions with abundant Buton asphalt reserves [1,2,5]. Overall, the study highlights that EB-BNA emulsions combine performance compliance, local availability, and environmental sustainability, presenting a compelling alternative to conventional petroleum-based binder systems.

3.5 Practical Implications and Limitations

The practical applications of EB-BNA emulsified bitumen extend primarily to cold-mix and flexible pavement construction. The optimized formulation (57.4% EB-BNA + 5% kerosene) demonstrates adequate viscosity, penetration, and ductility, allowing for efficient field application without the high energy demands of conventional hot-mix asphalt [3,5]. Its cationic slow-setting behaviour ensures proper adhesion to aggregate surfaces, making it suitable for surface treatment, patching, and maintenance operations [2,4]. Moreover, the use of locally sourced Buton asphalt can reduce transportation costs and promote regional construction independence, aligning with sustainable infrastructure practices [1,6].

Despite these benefits, several practical limitations need to be considered. The availability of high-purity EB-BNA can be inconsistent due to natural variability in Buton asphalt deposits, and extraction processes require careful control to maintain quality and binder performance [3,5]. Additionally, widespread adoption depends on market acceptance, regulatory approval, and contractor familiarity with EB-BNA-based emulsions [2,4]. Quality control during storage and transportation is critical to prevent phase separation or sedimentation, particularly in regions with limited laboratory facilities or field monitoring capabilities [3,6]. These factors may constrain immediate large-scale implementation despite demonstrated technical feasibility.

From a sustainability perspective, EB-BNA emulsions offer a significant environmental advantage by reducing reliance on petroleum-based binders and lowering energy consumption during production [5,7]. The substitution of petroleum binders with natural asphalt can decrease carbon emissions associated with conventional asphalt manufacturing, while supporting circular economy initiatives through the valorisation of local resources [1,2]. Additionally, incorporating EB-BNA into construction materials can potentially integrate secondary waste streams, such as recycled aggregates or industrial by-products, further enhancing environmental benefits [3,4]. Overall, while practical implementation requires careful management of supply and quality, the use of EB-BNA emulsions presents a promising pathway for sustainable pavement engineering.

3.6 Sensitivity and Economic Considerations

The economic feasibility of EB-BNA emulsified bitumen is influenced by both the proportion of solid-phase content and the kerosene diluent. Increasing EB-BNA content generally improves mechanical performance but can elevate raw material costs, while higher kerosene fractions reduce viscosity and enhance workability at the expense of binder stiffness [3,5]. Sensitivity analysis indicates that minor adjustments in kerosene (±0.5%) or EB-BNA (±1%) can significantly affect Saybolt Furol viscosity and residue content, highlighting the need for precise formulation to balance cost and performance [2,4]. Such trade-offs are critical for practical implementation in pavement projects where both specification compliance and budget constraints must be addressed.

A hypothetical cost-benefit assessment suggests that the optimum formulation (57.4% EB-BNA and 5% kerosene) can achieve comparable or superior performance relative to petroleum-based emulsions while leveraging locally sourced raw materials [1,5]. Reductions in petroleum binder usage contribute to lower production costs and diminished exposure to global oil price fluctuations, creating economic resilience for regional road construction [2,6]. Although a formal payback period calculation requires comprehensive field-scale deployment data, preliminary analysis indicates that EB-BNA emulsions can break even economically within a moderate project cycle, particularly when factoring in savings from reduced energy consumption in cold-mix applications [3,7].

Furthermore, integrating sensitivity and economic considerations into formulation decisions reinforces the sustainability argument. By optimizing EB-BNA and kerosene content, contractors can minimize both production costs and environmental impact simultaneously [1,5]. This approach aligns with prior studies emphasizing performance-based and cost-conscious binder engineering in natural asphalt systems [2,3]. Ultimately, understanding the economic sensitivity of EB-BNA emulsions ensures informed decision-making, balancing technical performance, financial viability, and sustainability objectives in flexible pavement construction [4,6].

4 CONCLUSION

This study systematically investigated the engineering of emulsified bitumen derived from Extracted Buton Natural Asphalt (EB-BNA), focusing on the effects of solid-phase content and kerosene diluent on performance characteristics. Experimental results demonstrated that EB-BNA content significantly influences viscosity, residue, penetration, and ductility, while kerosene proportion critically affects workability and binder stiffness. The optimum formulation—57.4% EB-BNA and 5% kerosene—achieved balanced rheological performance, storage stability, and full compliance with ASTM and SNI CSS-1h specifications. These findings confirm that precise control of solid-phase engineering is essential to achieving mechanical stability and specification adherence in natural asphalt emulsions.

From a practical perspective, the developed EB-BNA emulsion is suitable for cold-mix and flexible pavement applications, offering both environmental and operational benefits. By utilizing a locally sourced binder, petroleum consumption can be reduced, greenhouse gas emissions minimized, and energy use in production lowered compared to conventional hot-mix emulsions. Sensitivity and preliminary economic analyses suggest that the optimal formulation provides cost-effective performance, although the scale-up for field implementation requires careful consideration of EB-BNA supply consistency, quality control, and stakeholder acceptance. Limitations of this study include the restricted geographic source of EB-BNA, laboratory-scale evaluation, and the need for extended field validation to confirm long-term performance.

For future research, it is recommended to investigate: (i) field trials of EB-BNA emulsions under varying climatic and traffic conditions, (ii) long-term durability and aging behaviour of optimized formulations, (iii) integration of alternative renewable diluents or modifiers to further enhance sustainability, and (iv) lifecycle assessment including potential reduction in municipal solid waste and CO_2 emissions if this technology is applied on a larger scale. Additionally, exploring the replicability of this formulation in other regions with different natural asphalt characteristics will provide insights into scalability and broader applicability. Overall, this work provides a performance-based framework for advancing sustainable pavement materials using local natural asphalt resources.

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