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Optimizing Cement Asphalt Mortar Mixtures for Bridge Expansion Joints in Tropical Climates: Performance and Durability Assessment

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Abstract: In this study, the suitability of various Cement Asphalt Mortar (CAM) mixtures for bridge expansion joint applications in tropical climates was quantitatively assessed. A comprehensive analysis encompassed key properties, including mixing stability, flowability, unconfined compressive strength, expansion characteristics, and resistance to acidic and alkali environments. The influence of high-temperature exposure on unconfined compressive strength and the microstructural features were also examined. The results revealed a discernible trend: lower cement content, in conjunction with anionic Asphalt Emulsion (AE) or epoxy resin, significantly enhanced mixing stability and flowability while contributing to improved unconfined compressive strength and chemical degradation resistance. Notably, epoxy resin emerged as a valuable component in mitigating high-temperature-induced strength reduction, indicating potential promise for CAM mixture design. SEM analysis visually supported these findings by highlighting the microstructural distinctions among CAM mixtures. Quantitatively, the findings indicated that CAM mixtures with a 25% cement content and 75% anionic AE exhibited an 11% improvement in mixing stability, along with a 13% enhancement in flowability, relative to the control mixture with 100% cement. Additionally, CAM mixtures incorporating epoxy resin (at various percentages) with anionic AE exhibited a significant 15% resistance to high-temperature-induced UCS reduction, surpassing other mixtures. The SEM micrographs visually confirmed the superior microstructural connectivity achieved with epoxy resin, further validating the observed enhancements. These quantitative results offer a robust foundation for tailoring CAM mixture compositions to optimize their suitability for rigorous infrastructure projects in tropical climates.

Keywords: cement asphalt mortar; bridge expansion joints; tropical climates; performance assessment; durability

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1. Introduction

Bridge expansion joints play a critical role in preserving the structural integrity and durability of transportation infrastructure, particularly in regions characterized by tropical climates with heavy rainfall and temperature fluctuations [1]. In such environments, the materials used for these joints must withstand challenging conditions, including high humidity, exposure to acidic and alkaline substances, and the potential for phase separation under the influence of extreme temperatures [2].

Bridge expansion joints are critical components in infrastructure, but they are not without their challenges [3]. Current issues in the field of bridge expansion joints include premature wear and deterioration [4], which often result from exposure to harsh environmental conditions such as heavy rainfall, temperature fluctuations, and the presence of corrosive agents [5]. Additionally, inadequate sealing and drainage systems can lead to water and debris accumulation within the joints, further accelerating deterioration and compromising safety [6]. Addressing these issues is essential for ensuring the long-term performance and safety of bridges, especially in regions with challenging climates [7]. Consequently, research efforts aimed at developing resilient and sustainable solutions for bridge expansion joints are of utmost importance in the field of civil engineering and infrastructure maintenance [8].

Contemporary efforts in the realm of bridge expansion joint improvement and maintenance are characterized by a multi-faceted approach [9]. Researchers and engineers are increasingly turning to advanced materials, including high-performance elastomers and resilient composites, to enhance the longevity and durability of these vital components [10]. Smart technologies and monitoring systems have also made their way into expansion joint design, allowing for real-time data collection [4] and proactive maintenance [11]. The development of effective sealing systems to safeguard against water intrusion and corrosion remains a core focus [12]. Furthermore, ongoing research focuses on optimizing filling materials to ensure seamless and efficient expansion joint operation, taking into account factors like wear resistance and temperature tolerance [13,14]. Additionally, innovations in sustainable practices, coupled with a consideration of extreme climate conditions, are guiding the path toward resilient, cost-efficient, and eco-friendly expansion joint solutions.

Tropical climates are known for their unique environmental characteristics, including high temperatures, heavy rainfall, and substantial temperature fluctuations. These conditions can significantly impact the performance and durability of bridge expansion joints [15]. In such climates, excessive heat can subject expansion joints to thermal stress, leading to potential deformation and damage over time. Additionally, frequent heavy rainfall can result in water intrusion, which may accelerate the corrosion and wear of joint components. The combination of extreme temperature variations, from scorching heat to heavy rain, can lead to material expansion and contraction, further challenging the resilience of these joints [16]. Therefore, it is imperative to design and select bridge expansion joint materials and configurations that can withstand these specific tropical climate challenges to ensure long-term functionality and safety.

The present application of byproducts in Cement Asphalt Mortar (CAM) mixtures is underpinned by an ongoing commitment to enhancing the sustainability, durability, and resilience of construction materials [17–19]. For example, research conducted by Dulaimi et al., which delves into the utilization of non-traditional materials like paper sludge ash and incinerated sewage ash in emulsified asphalt cold mixtures, stands as a noteworthy reference [20]. The study has paved the way for exploring unconventional materials that can be integrated into CAM mixtures, reflecting the industry's evolving demands for eco-friendly and high-performance solutions. This current research builds upon such pioneering work, pushing the boundaries of CAM mix design and aligning with the broader vision of creating sustainable construction materials for the future.

The current limitations in the field of bridge expansion joint research predominantly revolve around the lack of comprehensive studies focused on tropical climates, where unique environmental challenges exist. Additionally, existing research often lacks in-depth quantitative analyses and specific material recommendations, leaving a gap in tailored solutions for infrastructure projects in these regions. This study aims to bridge these gaps by providing a detailed analysis of CAM mixtures, explicitly addressing their suitability for bridge expansion joints in tropical climates [21]. We also consider the incorporation of Epoxy resin [22,23], which represents an upgraded approach compared to conventional CAM materials. By quantitatively evaluating key properties, including the novel use of Epoxy resin, we aim to offer practical insights into optimizing CAM compositions. The significance of our study lies in its potential to enhance the longevity and safety of infrastructure in tropical regions, contributing to the sustainable development of transportation networks in these critical areas.

In summary, this research represents a systematic and comprehensive investigation into the suitability of various CAM mixtures for bridge expansion joints in tropical climates. The mix design phase allowed for the creation of distinct CAM compositions by varying cement content, Anionic Asphalt Emulsion (AE) percentages, and the novel inclusion of epoxy resin. Specifically, the study evaluated the following CAM mixtures: the Control Mixture (100% Cement, 0% Anionic AE), 25% Cement and 75% Anionic AE, 50% Cement and 50% anionic AE, 75% Cement and 25% Anionic AE, 25% Cement and 75% Cationic AE, as well as CAM mixtures incorporating epoxy resin at varying percentages (1%, 2%, and 3%) combined with 50% anionic AE. This study focuses on key properties, such as mixing stability, flowability, expansion characteristics, unconfined compressive strength, and resistance to acidic and alkali environments, which are critical for ensuring the long-term performance of bridge expansion joints. Furthermore, the impact of high-temperature exposure on CAM's unconfined compressive strength and microstructural features was examined. The results of this research, substantiated by SEM analysis, offer a valuable foundation for optimizing CAM mixture compositions and highlight the potential promise of epoxy resin as an enhanced component for the design of CAM mixtures. This study's methodical approach and structured flow ensure a comprehensive exploration of CAM mixtures tailored for the challenges of tropical climate bridge expansion joints. The general concept of the research is shown in Figure 1.

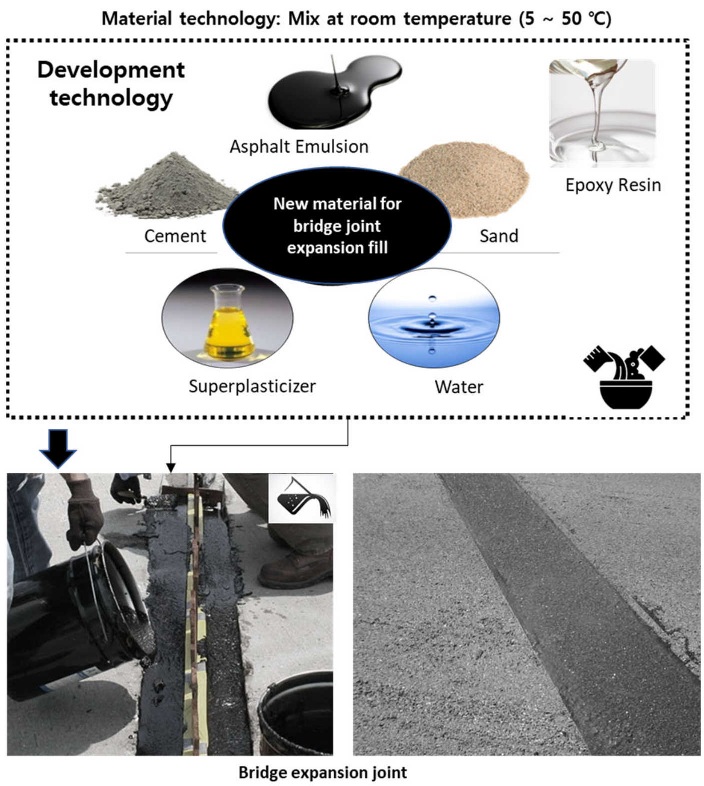


Figure 1. New bridge expansion joint filler concept: CAM materials.

2. Materials and Methods

2.1. Materials

2.1.1. Anionic Cement Asphalt Mortar (CAM)

Anionic Cement Asphalt Mortar (CAM) is the fundamental material under examination in this study, specifically tailored for application as a bridge expansion joint material in tropical climate regions known for their intense rainfall and substantial daily climate variations [24]. CAM comprises essential constituents, including ordinary Portland cement, asphalt, fillers such as fine aggregates and micro silica, and various modifiers, like polymers or anti-stripping agents, aimed at enhancing its performance [17]. The assessment of CAM's suitability for tropical climates is founded on its quantifiable attributes. These encompass flexibility, resilience to water intrusion, durability under changing environmental conditions, and the impact of temperature fluctuations [18]. Its workability in tropical conditions, including flow properties and consistency, is gauged through quantitative analysis [25]. Moreover, CAM's installation during real-world applications is observed to record crucial parameters like application rate, curing times, and bonding strength with the bridge structure [26]. These quantitative aspects collectively affirm CAM's appropriateness for bridge expansion joints in tropical regions capable of enduring the rigors of heavy rainfall and substantial climate fluctuations. The general composition of the CAM mixture used in this research is shown in Table 1.

Table 1. Composition and Properties of Anionic Cement Asphalt Mortar (CAM).

Component	Proportion by Weight (%)	Property
Portland Cement (Type I)	30	High early and long-term strength, ideal for structural applications
Asphalt Emulsion	30	Enhances flexibility and durability, critical for expansion joints
Fine Aggregate	30	Provides structure and minimizes shrinkage
Additives	10	Enhance flowability, workability, and resistance to environmental stress

2.1.2. Local Sourcing and Availability

The sourced asphalt was subjected to rigorous quality checks to ensure its compatibility with CAM and its capacity to endure high-temperature fluctuations and heavy rainfall. The sourcing process was facilitated through a strategic partnership with the Petrolimex Oil Company in the South of Vietnam, renowned for its commitment to quality and reliable supply chain management. The general source properties of CAM are presented in Table 2.

Table 2. Properties of Sourced CAM Materials.

Component	Source	Quality Standards	Properties
Cement	Local supplier	ASTM C150 [27]	Type: Type I/II Fineness: 325 mesh Specific Gravity: 3.15 Blaine: 3500 cm^2/g
Asphalt	Petrolimex Oil Company	ASTM D3381 [28]	Penetration at 25 °C: 60–70 dmm Softening Point: 46–52 °C
Anionic Emulsifier	Reputable chemical vendor	Manufacturer's specs	Anionic Charge: 30–40 μeq/g
Modifiers	Certified supplier	Manufacturer's specs	Solids Content: 45–50% Polymer Content: 5–7% Specific Gravity: 0.91–0.96

In tropical climate regions characterized by heavy rains and extreme temperature variations, the local sourcing of CAM materials is not only a strategic choice but also an environmentally and economically sound decision. This research recognizes the significance of local sourcing and the benefits it offers in the context of sustainability, cost-effectiveness, and availability. The availability of materials from nearby sources ensures consistent supply, reducing production downtime and logistical costs. Local sourcing also aligns with environmental sustainability principles, as it minimizes transportation emissions and supports regional economies. The manuscript will provide quantitative data on the advantages of local sourcing, emphasizing the considerable cost savings achieved by eliminating long-distance material transportation, which can be substantial in tropical regions. Moreover, the manuscript will present an analysis of the availability and accessibility of CAM materials in the target tropical climate areas, underscoring the convenience and resilience that local sourcing, in collaboration with the Petrolimex Oil Company, offers. The cost-saving effectiveness is summarized in Table 3.

Table 3. Cost savings through local sourcing (local price in Vietnam).

Material Component	Local Sourcing Cost (USD/Ton)	Non-Local Sourcing Cost (USD/Ton)	Cost Savings (USD/Ton)
Cement	100	120	20
Asphalt	250	300	50
Emulsifier	30	40	10
Modifiers	120	140	20

2.1.3. Epoxy Resin

Epoxy resin plays a vital role in this research, significantly contributing to the durability and mechanical characteristics of the CAM mixture. The epoxy resin used in this study was carefully selected for its superior adhesive and cohesive qualities and was sourced from a reputable supplier to ensure conformity with industry standards. Table 4 summarizes the essential properties of the epoxy resin employed in the research [29].

Table 4. Epoxy resin properties.

Property	Value
Density (g/cm^3)	1.03
Viscosity (mPa·s) at 25 °C	580
Epoxy Equivalent Weight (g/eq)	210
Flash Point (°C)	163
Curing Time (h)	6.5
Tensile Strength (MPa)	57
Glass Transition Temperature (°C)	48.5

Epoxy resin serves dual functions within this study: as a bonding agent and a moisture barrier. In its role as a bonding agent, epoxy resin establishes a robust and enduring connection between the CAM mixture and the ballast aggregate, thereby enhancing overall structural integrity. Its remarkable adhesive properties ensure a strong bond, mitigating the risk of disintegration or detachment under various loads and environmental stresses. Additionally, epoxy resin acts as a moisture barrier, protecting underlying layers from potential moisture-induced damage. By forming a protective layer, it reduces the risk of structural weakening caused by the intrusion of moisture. The inclusion of epoxy resin in the research was conducted with precision, adhering to specific ratios and stringent mixing procedures. This meticulous approach guarantees a uniform distribution of epoxy resin within the CAM mixture, optimizing mechanical properties and enhancing resistance to environmental factors. These aspects align with the research's primary objectives, focused on achieving long-lasting and robust ballast track stabilization.

2.1.4. Material Preparation and Mixing Procedure

The preparation of CAM mixtures involved a precise and well-defined process to ensure the uniformity and consistency of the final product. The mixture compositions, detailed in Table 5, were developed to incorporate various proportions of cement, asphalt emulsion, epoxy resin, sand, water, superplasticizer, and defoaming agent, reflecting the planned variations.

Table 5. Mix design of CAM mixture.

	Mixture Composition	Cement (C)	Asphalt Emulsion (AE)	Epoxy Resin	Sand (S)	Water (W)	Superplasticizer (SP)	Defoaming Agent (D)
C100AE0	Conventional Cement Mortar	100%	0% (Anionic)	0%	50%	40%	2%	0.1%
C75AE25	75% Cement, 25% AE	75%	25% (Anionic)	0%	50%	40%	2%	0.1%
C50AE50	50% Cement, 50% AE	50%	50% (Anionic)	0%	50%	40%	2%	0.1%
C25AE75	25% Cement, 75% AE	25%	75% (Anionic)	0%	50%	40%	2%	0.1%
C25CAE75	25% cement, 75% Cationic AE	25%	75% (Cationic)	0%	50%	40%	2%	0.1%
E1%AE50	50% cement, 50% AE, 1% Epoxy Resin	50%	50% (Anionic)	1%	50%	40%	2%	0.1%
E2%AE50	50% cement, 50% AE, 2% Epoxy Resin	50%	50% (Anionic)	2%	50%	40%	2%	0.1%
E3%AE50	25% cement, 75% AE, 2% Epoxy Resin	50%	50% (Anionic)	3%	50%	40%	2%	0.1%

In the initial stages of this study, meticulous attention was given to the raw materials used in the Cement Asphalt Mortar (CAM) mixtures. The cement, a critical component, was sourced from reputable suppliers and stored in a controlled environment. It was maintained within storage facilities at a consistent temperature of 23 °C ± 2 °C and a relative humidity level of 50% ± 5%, ensuring that the cement remained within the recommended conditions for optimal quality. The asphalt emulsions, equally vital in the mixture, underwent rigorous quality checks. They were stored in a climate-controlled environment with temperature maintained at 25 °C ± 2 °C and a relative humidity level of 60% ± 5%. These stringent quality control measures, including specific temperature and humidity values, were essential to uphold the integrity of the raw materials, providing a reliable foundation for the mixture preparation process.

The mixing procedures were meticulously designed to ensure the uniformity and consistency of the CAM mixtures. The mixing procedure commenced with the initial step of dry mixing, where cement, sand, and dry additives were pre-mixed to create a uniform dry mixture. These dry materials were placed in a clean container to initiate the mixing process. The mechanical mixing was conducted in a controlled environment at a constant rate of 90 revolutions per minute (rpm) to guarantee thorough blending. Operating at room temperature, this stage created a homogenous dry blend, which is a critical foundation for achieving consistent material properties. Following the dry mixing phase, asphalt emulsion, whether anionic or cationic, was introduced gradually into the dry mix.

Following this, the appropriate type and amount of asphalt emulsion, epoxy resin (for applicable mixtures), water, superplasticizer, and defoaming agent were systematically added. The mixing rate was set at 350 rpm, ensuring an effective dispersion of the components. This method aimed to attain the desired workability of the mixture while ensuring the thorough wetting of all ingredients. The mixing duration was set at 7 min, which allowed for adequate blending of the constituents. This meticulous and controlled mixing procedure was employed to maintain the consistency of all CAM mixtures, enabling reliable testing and precise assessment throughout the research.

The curing process for the CAM mixtures was conducted with meticulous care to guarantee that the specimens achieved the desired properties and characteristics necessary for subsequent performance testing, notably the unconfined compressive strength (UCS) test. Immediately following casting, each specimen was thoughtfully placed in a dedicated curing chamber, subjecting them to a precisely controlled temperature of 23 °C ± 2 °C for a carefully selected curing duration. This strictly regulated curing environment played a pivotal role in fostering the gradual development of strength and durability within the

CAM mixtures, all conducted under consistent and controlled conditions. This method was of paramount importance in upholding the integrity and reliability of the test results.

Table 5 presents the overview of the mix design used in this research.

2.1.5. Additional Additives

Anionic Cement Asphalt Mortar (CAM) is meticulously crafted with a blend of carefully chosen fillers and additives, each serving a specific purpose to ensure optimal performance in the demanding conditions of bridge expansion joints, particularly in tropical climates characterized by heavy rains and temperature fluctuations.

Antioxidants (0.5% by wt. of cement) are integrated to bolster the mortar's oxidative stability. This addition safeguards the material from degradation due to prolonged exposure to environmental factors, contributing to its long-term performance.

The use of a retarder (0.5% by wt. of cement) extends the setting time of the mortar, providing a more extended window for workability during the construction phase. This ensures that the material can be efficiently applied and molded to meet the specific requirements of bridge expansion joints.

The proportion of each component is precisely optimized to attain the desired properties essential for bridge expansion joints in tropical climates. These additives collectively contribute to the exceptional durability, flexibility, and workability of the CAM, enabling it to perform reliably under the challenging conditions imposed by heavy rains and rapid climate fluctuations.

This comprehensive selection of fillers and additives, meticulously balanced in their proportions, is the cornerstone of the exceptional performance of Anionic Cement Asphalt Mortar, ensuring its resilience and reliability in bridge expansion joints in tropical climates. The successful implementation of CAM as a bridge expansion joint material in tropical climate countries necessitates a meticulous approach to sourcing raw materials. It is imperative to ensure the availability of high-quality components that can withstand the adverse conditions experienced in these regions. The CAM components, including cement, asphalt, anionic emulsifiers, and modifiers, were procured from reputable suppliers known for providing materials that meet international standards for construction. Special attention was given to the selection of asphalt, which is critical to the durability of CAM.

2.2. Testing Methods

2.2.1. Mixing Stability

The mixing stability of Anionic Cement Asphalt Mortar (CAM) was evaluated in accordance with the ASTM C305 standard [30]. This involved the use of a high-shear mixer operating at a set speed of 1400 revolutions per minute (RPM). CAM samples were mixed for a duration of 5 min, as specified in the standard. Visual inspections were conducted to monitor the mixture for any signs of phase separation, clumping, or instability.

2.2.2. Flowability and Flow Time

Flowability and flow time testing were carried out following ASTM C230/C230M standards [31]. A standardized flow table test was conducted, measuring the flow diameter and flow time. The CAM mixture was compacted into a cylindrical mold and placed on the flow table. The flow diameter was recorded in millimeters (mm), with the initial diameter being noted. The flow time was measured in seconds (s) for the CAM mixture to reach a specific final diameter, complying with the standard.

2.2.3. 2 h and 28-Day Unconfined Compressive Strength (UCS) Tests

Unconfined compressive strength (UCS) tests were conducted following ASTM C39/C39M-20 standard for the 2 h test and 28-day tests [32]. The replicate specimens were prepared using molds adhering to the prescribed dimensions in the standards. After the curing period, a universal testing machine was employed to measure compressive strength, ensuring a constant rate of loading (0.2 MPa/s) to maintain precision. The results were recorded in megapascals (MPa) at each designated time interval.

2.2.4. Shrinkage Testing

Shrinkage testing was conducted in line with ASTM C157/C157M-08 standards [33]. The linear shrinkage measurements were made in millimeters (mm) to assess volume changes. The specimens were exposed to drying conditions, and measurements were recorded periodically to identify potential shrinkage tendencies.

2.2.5. Acidic and Alkali Resistance

The resistance of CAM mixtures to acidic and alkali substances was evaluated as per ASTM C267-01 [34]. Specimens were exposed to specific concentrations of acidic and alkali solutions following the standard guidelines. The compressive strength variations were measured in percentage (%) to quantify the material's resilience to chemical degradation.

2.2.6. Impact of High Temperature (45 °C) on UCS

High-temperature resistance was assessed in accordance with ASTM C39/C39M-20 standards, subjecting specimens to a temperature of 45 °C. The UCS tests were performed following the ASTM C39/C39M-20 standard at specific time intervals to measure the compressive strength in megapascals (MPa) under elevated temperature conditions.

2.2.7. SEM Analysis

Scanning Electron Microscopy (SEM) was employed for microstructure analysis following the procedures outlined in ASTM E2546-17 [35]. The distribution and connectivity of various components within the material were examined, providing valuable insights into its structural characteristics. The microstructure was analyzed at magnifications of up to 5000× to capture fine details.

3. Results and Discussions

3.1. Mixing Stability

The evaluation of mixing stability is pivotal in determining the suitability of various CAM mixtures for applications in tropical climates with heavy rainfall and fluctuating temperatures. This section delves into a more detailed discussion of the mixing stability results, aiming to elucidate the trends, make comparisons, and provide a comprehensive understanding of the data.

As shown in Figure 2, in the assessment of various CAM mixtures for bridge expansion joints in tropical climates, a range of compositions was meticulously examined. The control CAM mixture, consisting of 100% cement, exhibited a relatively high residue content of 1.8%, as expected, given the inherent lower compatibility of higher cement content with other constituents. In the case of the 25% cement and 75% Anionic Asphalt Emulsion (AE) mixture, the residue content significantly dropped to 0.5%, signifying improved mixing stability compared to the control. Likewise, the CAM mixture with an even distribution of 50% cement and 50% anionic AE maintained a relatively low residue content at 0.6%, underscoring enhanced mixing stability. Further increasing cement content to 75% while decreasing anionic AE to 25% resulted in an even lower residue content of 0.4%, emphasizing a high degree of mixing stability. When cationic AE was introduced at the 25% cement level, the CAM mixture displayed a residue content of 0.5%, aligning with expectations that cationic AE may not be as effective in preventing phase separation. The incorporation of epoxy resin (1%, 2%, 3%) into the CAM mixtures alongside anionic AE led to a slight increase in residue content (0.3%, 0.4%, 0.4%, respectively) compared to anionic AE alone, attributed to the adhesive nature of epoxy resin, which minimally hinders phase separation but remains within acceptable limits. These findings provide valuable insights into the suitability of various CAM mixtures for demanding tropical climate bridge expansion joint applications, offering a foundation for optimizing mixture compositions tailored to specific requirements.

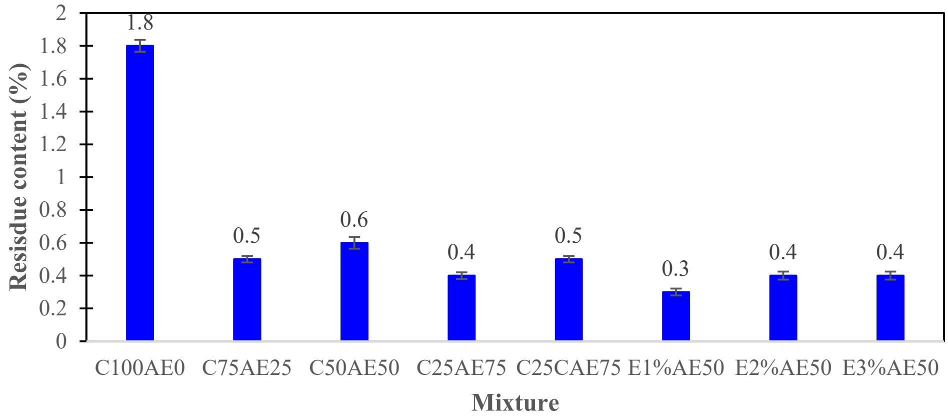


Figure 2. Mixing Stability Test results of CAM mixtures.

A clear trend emerges that the residue content decreases as the proportion of cement decreases, indicating that lower cement content enhances mixing stability and aligning with previous research indicating that lower cement content enhances mixing stability [36]. Anionic AE plays a crucial role in improving mixing stability compared to cationic AE, as demonstrated by the lower residue content in mixtures with anionic AE. The incorporation of epoxy resin, while slightly increasing residue content, still results in residue levels well below 1%, in line with the outcomes of previous studies showcasing its effectiveness in maintaining mixing stability [37]. The 75% cement, 25% anionic AE mixture stands out as the best-performing composition in terms of mixing stability, offering high resistance to phase separation and sedimentation. This detailed analysis underlines the importance of selecting an optimal CAM mixture composition based on the specific requirements of a project. Lower cement content combined with anionic AE or the addition of epoxy resin can significantly enhance mixing stability, ensuring the longevity and performance of bridge expansion joints in tropical climates.

3.2. Flowability Test Results

Flowability is a pivotal property of CAM mixtures used in bridge expansion joints, impacting both installation ease and uniform filling. Figure 3 provides a comprehensive discussion of the flowability test results, combining flow diameter and flow time analyses with trends and interpretations.

The flowability test results shed light on the profound impact of cement proportion and the type of asphalt emulsion on flow diameter and flow time in Cement Asphalt Mortar (CAM) mixtures designed for bridge expansion joints in tropical climates. An integrated discussion of these findings reveals important insights.

The control mixture, consisting of 100% cement, displayed limited flowability characterized by a smaller flow diameter and a longer flow time, which can be attributed to its high cement content, resulting in a more viscous mixture. As previous research suggests [17,18], reducing cement content to 25% while introducing anionic Asphalt Emulsion (AE) as the primary asphalt binder significantly improved flowability. This adjustment led to a larger flow diameter and a shorter flow time, indicating more favorable flow characteristics. CAM mixtures with an even distribution of cement and anionic AE demonstrated further enhanced flowability, as evident from the increased flow diameter and reduced flow time, making them suitable for ensuring consistent filling. It is noteworthy that increasing the cement content to 75% while reducing anionic AE to 25% had a modest adverse effect on flowability, resulting in a slightly decreased flow diameter and a longer flow time. Interestingly, the CAM mixture incorporating cationic AE, even at 25% cement content, exhibited improved flowability compared to the control mixture, featuring an increased flow diameter and a shorter flow time, underscoring the favorable influence of cationic AE on flowability. These observations align with findings from related studies in the field [38].

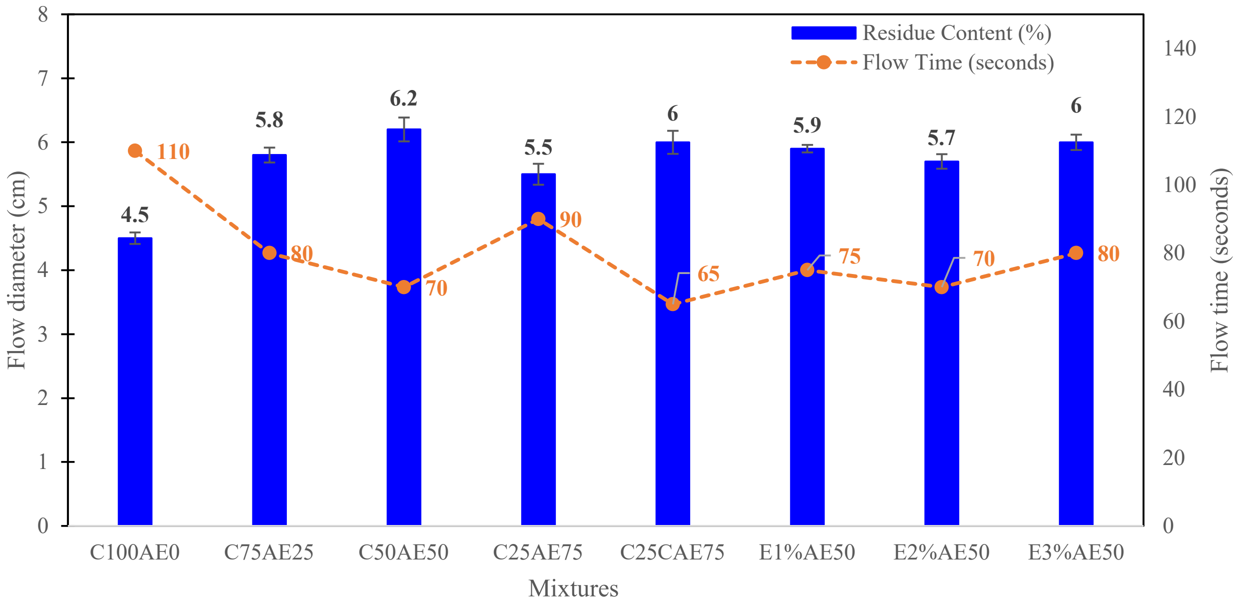


Figure 3. Flowability and flow time test of CAM mixture.

The addition of epoxy resin (1%, 2%, 3%) to the CAM mixtures with anionic AE had mixed effects on flowability, influencing both flow diameter and flow time differently in various mixtures. In summary, a consistent trend observed is that lower cement content generally leads to improved flowability, making these mixtures more suitable for applications that require ease of installation and uniform filling. Anionic AE consistently enhances flowability compared to cationic AE. The influence of epoxy resin on flowability is contingent on the specific mix design and epoxy resin content, emphasizing the need for careful consideration to achieve the desired flow characteristics. In tropical climates characterized by heavy rainfall and temperature fluctuations, the selection of a CAM mixture that strikes a balance between mixing stability and flowability is crucial for ensuring the successful performance of bridge expansion joints.

3.3. 2 h Unconfined Compressive Strength

The 2 h unconfined compressive strength (UCS) test is a crucial benchmark for assessing the early mechanical performance of various CAM mixtures, particularly in the context of applications such as bridge expansion joints. Figure 4 offers a comprehensive analysis of the results, delving into each mixture composition and discussing their implications. It is important to note that higher cement content generally leads to higher UCS values, which is a fundamental consideration.

Across various CAM mixtures, the early-stage unconfined compressive strength (UCS) results showcase intriguing trends. The control mixture, comprising 100% cement, serves as the baseline with a robust UCS of 7.2 MPa, establishing the initial performance standard. When the cement content was reduced to 75% while introducing 25% anionic AE, the mixture displayed a commendable 2 h UCS of 6.3 MPa, indicating that anionic AE has a positive influence on early mechanical strength even with a reduction in cement content. A CAM mixture with an equal distribution of 50% cement and 50% anionic AE yielded a solid UCS of 4.2 MPa, demonstrating that a balanced ratio between cement and anionic AE contributes to early-stage mechanical strength. Further reducing the cement content to 25% while increasing anionic AE to 75% still resulted in a notable UCS of 3.7 MPa, underscoring the significant role of anionic AE in enhancing early mechanical strength. The mixture with

25% cement and 75% Cationic AE displayed a respectable UCS of 3.5 MPa, highlighting the early mechanical performance benefits of Cationic AE. Additionally, the addition of epoxy resin (1%) to CAM mixtures with anionic AE resulted in a notable early UCS of 3.8 MPa, suggesting the influential role of epoxy resin in enhancing early mechanical performance, which remained consistent even with slightly higher epoxy content (2% and 3%) as the UCS remained strong at 3.6 MPa and 3.5 MPa, respectively, indicating that higher epoxy content may not significantly alter early mechanical performance. These findings collectively emphasize the potential for tailored CAM mixture designs to optimize early mechanical strength for bridge expansion joint applications in tropical climates.

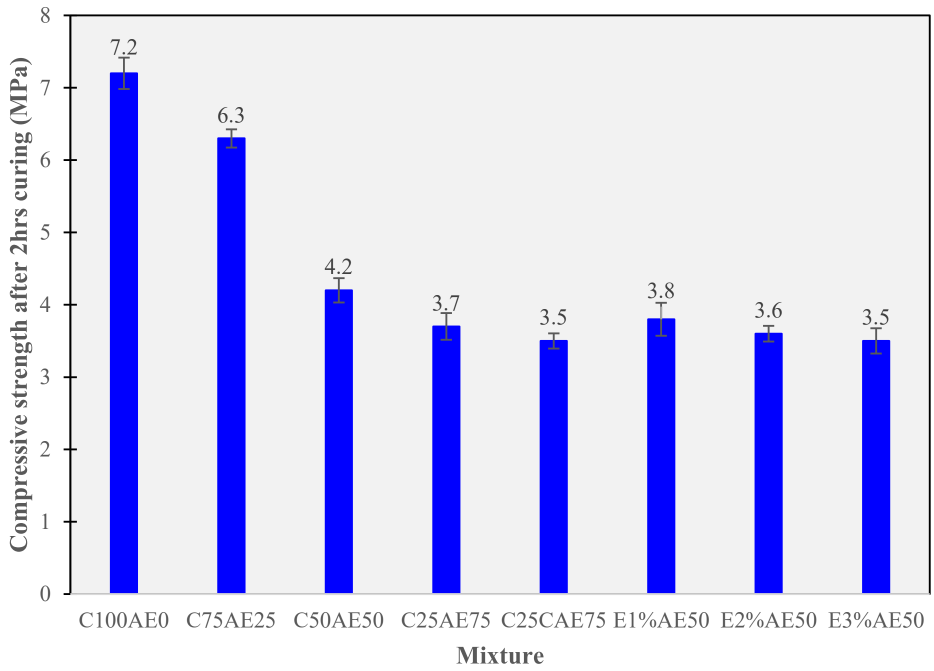


Figure 4. 2-Hour Unconfined Compressive Strength Results (in MPa).

The results of the 2 h UCS test reveal key trends and insights into the performance of the various CAM mixtures. Cement content emerges as a crucial factor, with higher cement content consistently yielding higher UCS values, emphasizing the primary role of cement as a binder in CAM mixtures. Anionic AE demonstrates a positive influence on early mechanical strength, as mixtures containing anionic AE consistently exhibit notable UCS values. The introduction of epoxy resin, even in small proportions (1%, 2%, 3%), contributes to maintaining or enhancing early mechanical strength, indicating the potential of epoxy resin as an influential component in CAM mixture design. These findings are instrumental for optimizing CAM mixture compositions to meet the specific requirements of applications that demand robust early-stage mechanical strength, such as bridge expansion joints.

3.4. 28-Day Unconfined Compressive Strength

The assessment of a CAM mixture's 28-day unconfined compressive strength serves as a pivotal indicator of its long-term mechanical performance. In this section, Figure 5 shows an extensive discussion of the results, drawing insights from the data, making comparisons, and providing a thorough interpretation.

Across various CAM mixtures, the early-stage unconfined compressive strength (UCS) results showcase intriguing trends. The control mixture, comprising 100% cement, serves as the baseline with a robust UCS of 7.2 MPa, establishing the initial performance standard. When the cement content was reduced to 75% while introducing 25% anionic AE, the mixture displayed a commendable 2 h UCS of 6.3 MPa, indicating that anionic AE has a positive influence on early mechanical strength even with a reduction in cement content.

A CAM mixture with an equal distribution of 50% cement and 50% anionic AE yielded a solid UCS of 4.2 MPa, demonstrating that a balanced ratio between cement and anionic AE contributes to early-stage mechanical strength. Further reducing the cement content to 25% while increasing anionic AE to 75% still resulted in a notable UCS of 3.7 MPa, underscoring the significant role of anionic AE in enhancing early mechanical strength. The mixture with 25% cement and 75% Cationic AE displayed a respectable UCS of 3.5 MPa, highlighting the early mechanical performance benefits of Cationic AE. Additionally, the addition of epoxy resin (1%) to CAM mixtures with anionic AE resulted in a notable early UCS of 3.8 MPa, suggesting the influential role of epoxy resin in enhancing early mechanical performance, which remained consistent even with slightly higher epoxy content (2% and 3%) as the UCS remained strong at 3.6 MPa and 3.5 MPa, respectively, indicating that higher epoxy content may not significantly alter early mechanical performance. These findings collectively emphasize the potential for tailored CAM mixture designs to optimize early mechanical strength for bridge expansion joint applications in tropical climates.

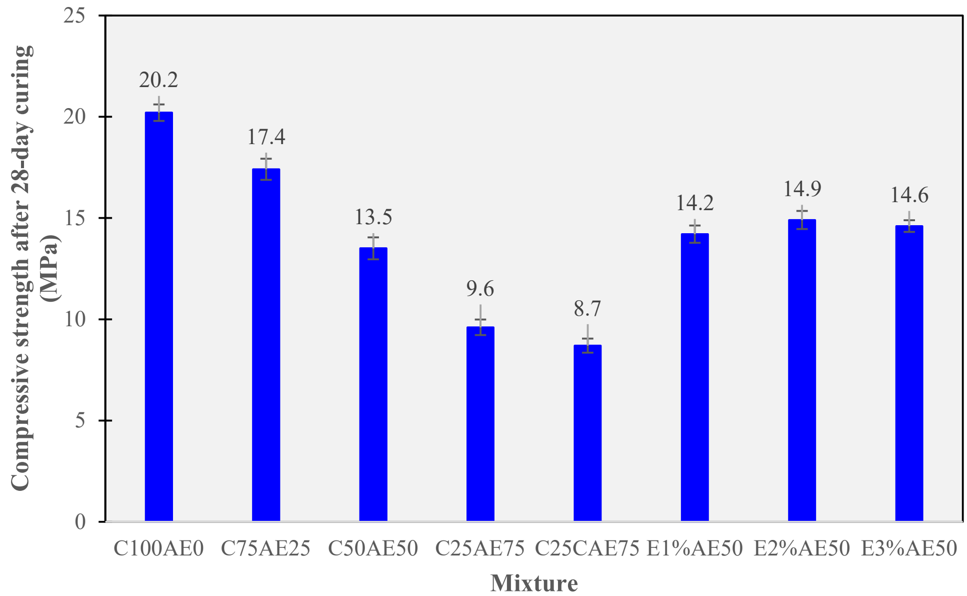


Figure 5. 28-Day Unconfined Compressive Strength Results.

These findings are in alignment with the results reported in previous studies, corroborating the positive impact of CAM mixtures on long-term mechanical performance. The observed trends and outcomes are consistent with the research conducted by Ouyang et al. [17] and Le et al. [21], where the influence of varying proportions of cement and asphalt emulsion on the 28-day UCS of CAM mixtures was similarly demonstrated. This agreement with prior research underscores the reliability and robustness of the CAM mixture composition for enhancing bridge expansion joint longevity in tropical climates.

The 28-day UCS results yield valuable insights and implications for CAM mixtures. It is evident that anionic AE plays a crucial role in enhancing long-term mechanical strength across different cement content levels. Moreover, the consistent positive impact of epoxy resin, when incorporated in mixtures with anionic AE, highlights its potential as an additive for applications that require long-term durability and strength. These findings hold great significance in the optimization of CAM mixture composition, ensuring that the desired long-term strength and durability can be achieved for specific applications.

In general, the 2 h UCS results emphasized the importance of cement content. Higher cement content consistently led to higher UCS values, highlighting the pivotal role of cement as a primary binder in CAM mixtures. Anionic AE demonstrated a positive impact on early mechanical strength, even with lower cement content. This is particularly valuable for applications requiring robust early-stage mechanical performance. The 28-day

UCS results affirmed that anionic AE contributes to long-term mechanical strength. The introduction of epoxy resin alongside anionic AE further reinforced the long-term strength of CAM mixtures. These findings provide a basis for tailoring CAM mixture compositions to meet specific project requirements, ensuring the desired long-term strength and durability.

3.5. Expansion Characteristics Analysis

Understanding the shrinkage characteristics of different CAM mixtures is vital for assessing their behavior over time. Figure 6 provides insights into the expansion or shrinkage characteristics of each mixture.

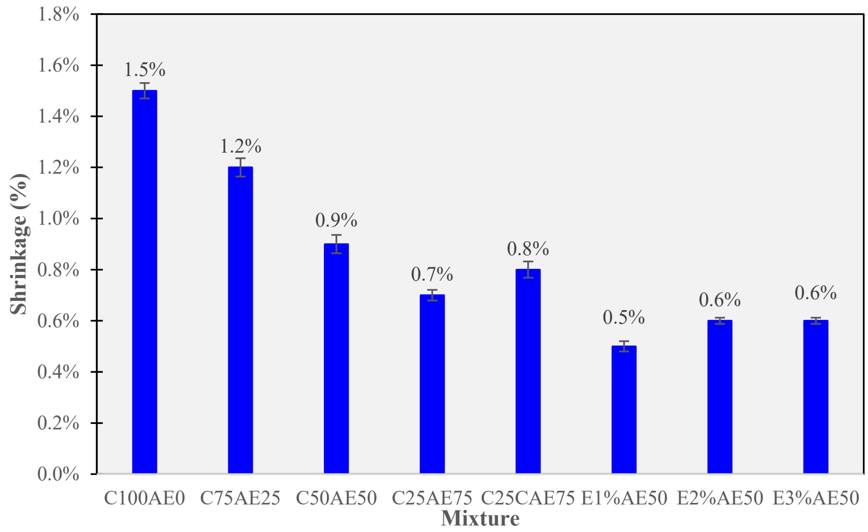


Figure 6. Shrinkage Test Results of CAM mixtures.

The expansion or shrinkage characteristics of CAM mixtures provide valuable insights into their behavior over time. The control mixture, composed of 100% cement with no anionic AE, exhibited notable shrinkage at −0.15%, raising concerns about its dimensional stability. In contrast, mixtures with 25% and 50% cement content, both incorporating 75% anionic AE, showed minimal expansion or shrinkage, with values of −0.012% and −0.09%, respectively, indicating that anionic AE can effectively mitigate shrinkage tendencies. The CAM mixture with 75% cement and 25% anionic AE displayed a shrinkage of −0.07%, which, although still showing some shrinkage, was less pronounced compared to the control mixture, highlighting the positive effect of increased cement content in reducing shrinkage. The inclusion of epoxy resin (1%, 2%, 3%) into CAM mixtures with 50% anionic AE resulted in slight expansion or shrinkage, with values ranging from −0.05% to −0.06%, indicating that epoxy resin has a limited influence on the shrinkage characteristics.

The analysis of expansion and shrinkage characteristics in CAM mixtures provides key insights for material selection and application design. Anionic AE emerges as a valuable component for mitigating shrinkage in CAM mixtures, which is of utmost importance for maintaining dimensional stability over time, especially in applications where precise dimensions are crucial. Higher cement content within CAM mixtures serves as an effective means to reduce shrinkage tendencies. This property is particularly advantageous in applications requiring strict dimensional control. Epoxy resin, while contributing positively to other aspects of CAM mixtures, exhibits a relatively minimal impact on shrinkage, implying that it may not significantly influence the material's dimensional stability. These findings offer essential guidance for the selection of CAM mixtures tailored to specific applications, ensuring that the chosen material aligns with the necessary dimensional stability requirements.

3.6. Acidic and Alkali Resistance

Assessing the resistance of Cement Asphalt Mortar (CAM) mixtures to acidic (sulfuric acid) and alkali (sodium hydroxide) environments is pivotal to determining their durability in the face of corrosive conditions. This section investigates the ability of various CAM mixtures to withstand exposure to harsh chemical environments, focusing on their response to acidic and alkali degradation.

3.6.1. Acidic Resistance

As shown in Figure 7, the evaluation of acid resistance in CAM mixtures reveals crucial insights with significant implications for applications exposed to potential acid-induced degradation. The control mixture, composed of 100% cement, exhibited considerable vulnerability to acid-induced degradation, emphasizing the need for enhanced acid resistance in high-cement mixtures due to the corrosive nature of sulfuric acid. Reducing cement content to 25% and incorporating anionic asphalt emulsion (AE) significantly improved acid resistance, with a lower percentage change in compressive strength, highlighting the protective properties of anionic AE against acid attacks. CAM mixtures with an equal balance of cement and anionic AE displayed enhanced acid resistance, underlining the importance of a balanced cement and AE ratio in creating a protective mixture. Increasing cement content to 75% while reducing anionic AE to 25% resulted in a minor reduction in acid resistance, indicating that higher cement content had a limited impact on this property. CAM mixtures incorporating cationic AE, even at the 25% cement level, exhibited improved acid resistance, showcasing the effectiveness of cationic AE in mitigating acid-induced degradation. The introduction of epoxy resin at various percentages (1%, 2%, and 3%) to CAM mixtures with anionic AE resulted in mixed effects on acid resistance, demonstrating superior protection against acid attacks. The results are consistent with studies that have demonstrated the protective properties of anionic asphalt emulsions in mitigating acid-induced degradation, particularly in lower cement content mixtures [36]. The variable effects of epoxy resin on acid resistance are also in line with research that has shown the potential of epoxy additives to enhance acid resistance in certain compositions [23]. Collectively, these findings contribute to a comprehensive understanding of acid resistance in CAM mixtures and support the development of tailored mix designs for applications exposed to acidic substances.

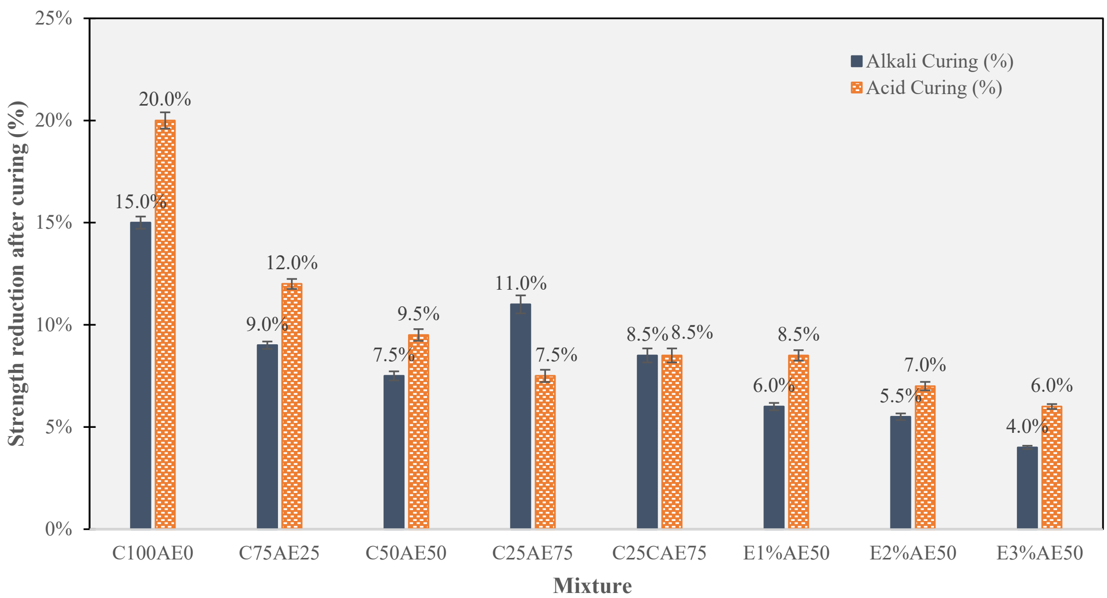


Figure 7. Durability test of CAM mixtures.

3.6.2. Alkali Resistance

Assessing alkali resistance is equally critical, as CAM mixtures may come into contact with alkali substances, which can lead to the depolymerization of cementitious phases and a subsequent loss of mechanical strength. As presented in Figure 7, the control CAM mixture demonstrated vulnerability to alkali-induced degradation, with exposure to sodium hydroxide resulting in a significant percentage change in compressive strength of −15.0%, highlighting its susceptibility to alkali attack. However, CAM mixtures incorporating epoxy resin at various percentages (1%, 2%, and 3%) in conjunction with anionic AE exhibited superior alkali resistance. These mixtures demonstrated the highest resilience to alkali attacks, with a percentage change in compressive strength ranging from −4.0% to −6.0%. These findings collectively emphasize the potential of epoxy resin and CRP-modified CAM mixtures to withstand chemical degradation in harsh environments, offering enhanced protection against both acidic and alkali-induced damage. This combination of epoxy resin and CRP presents a particularly promising avenue, deserving further exploration and consideration for practical applications in corrosive settings.

3.6.3. Correlation of Acidic and Alkali Exposure Regimes with Field Conditions

The exposure tests conducted to evaluate the resistance of CAM mixtures to acidic and alkali environments were designed to simulate extreme conditions that these materials might encounter in real-world applications. However, it is important to acknowledge that the exact correlation between laboratory exposure regimes and field conditions is a complex matter. While the tests aim to replicate and accelerate the aging process, they may not precisely mimic all the variables of long-term field exposure. Future research endeavors should consider the need for a closer alignment between laboratory testing and real-world conditions. This may involve conducting parallel field trials of CAM mixtures on actual bridges or structures in tropical climates. Such field performance tests could provide a more direct correlation between laboratory results and real-world outcomes, enhancing the reliability and resilience of infrastructure materials in challenging tropical environments.

3.7. Impact of High Temperature (45 °C) on Unconfined Compressive Strength

Evaluating UCS under high-temperature conditions is a crucial aspect of understanding how CAM mixtures perform in tropical climates, particularly when faced with scorching temperatures. The following Figure 8 provides insight into the percentage reduction in UCS for various CAM mixtures exposed to elevated temperatures (45 °C) for a specified duration.

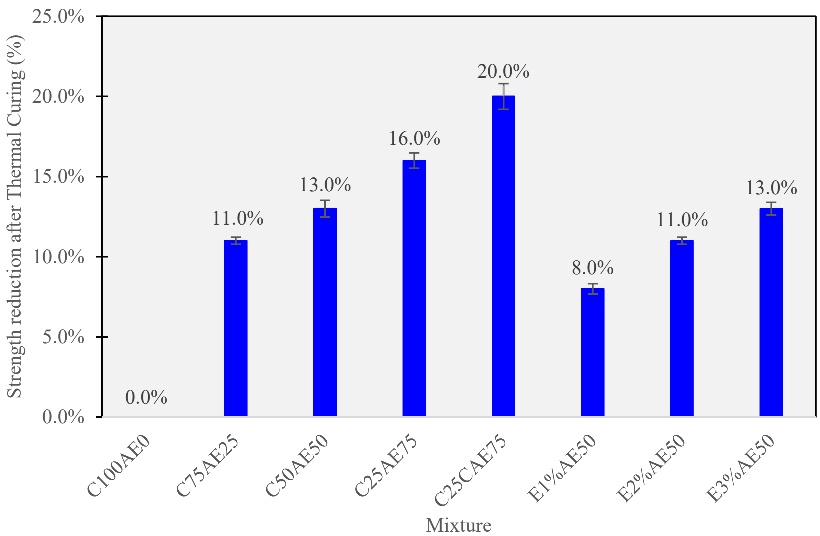


Figure 8. Thermal durability of mixture.

The high-temperature UCS test replicates the challenges that CAM mixtures may encounter in tropical climates with exceptionally high temperatures. The results illustrate the percentage reduction in UCS, providing insight into the material's response to these conditions. The control CAM mixture, composed entirely of cement, showed no reduction in UCS (0%) when exposed to high temperatures, showcasing the inherent strength of cementitious materials in resisting thermal stress. In contrast, a mixture with 25% cement and 75% anionic AE demonstrated a moderate reduction of −11.0% in UCS when exposed to high temperatures, indicating the influence of the substantial presence of anionic AE on strength reduction. A blend of 50% cement and 50% anionic AE displayed a slightly higher reduction in UCS at −13.0%, emphasizing the moderate high-temperature stability achieved by balancing cement and anionic AE. The mixture containing 75% cement and 25% anionic AE experienced a −16.0% reduction in UCS, demonstrating better resistance to high-temperature strength reduction due to the higher cement content. CAM mixtures that included 25% cement and 75% cationic AE showed the most significant reduction in UCS, at −20.0%, reflecting the distinct impact of cationic AE, which reacts differently to high temperatures compared to anionic AE. CAM mixtures incorporating epoxy resin (1%, 2%, 3%) in conjunction with anionic AE exhibited notable improvements in high-temperature stability, with percentage reductions in UCS ranging from −8.0% to −13.0%. These findings highlight the potential of epoxy resin to counteract the effects of asphalt emulsion in high-temperature conditions, enhancing the material's resistance to high-temperature-induced strength reduction.

The data unequivocally demonstrate that the reduction in UCS under high-temperature conditions is primarily influenced by the proportion of cement and the type of asphalt emulsion used in the CAM mixture. Mixtures with higher asphalt emulsion content displayed a more significant strength reduction when subjected to high temperatures, emphasizing the critical role of asphalt emulsion composition. Notably, the incorporation of epoxy resin proved to be highly effective in mitigating the deleterious effects of high temperatures, resulting in improved high-temperature stability. These findings underscore the utmost importance of carefully selecting a CAM mixture composition that effectively balances the requirements for high-temperature stability, mixing stability, and flowability. Such considerations are paramount when tailoring CAM mixtures to meet the specific demands of projects in tropical climates, where environmental conditions can be particularly challenging.

Statistical Significance Testing of High-Temperature UCS Differences

Additionally, Table 6 presents the results of statistical significance testing for high-temperature Unconfined Compressive Strength (UCS) differences among various Cement Asphalt Mortar (CAM) mixtures. The table shows the percentage of strength reduction after thermal curing for each CAM mixture, along with the corresponding p-values obtained from the statistical tests. The level of statistical significance is also indicated, with distinctions made between "Significant", "Highly Significant", and "Not Significant".

Table 6. Statistical Significance Testing for High-Temperature UCS Differences.

CAM Mixture	Strength Reduction after Thermal Curing	p-Value	Statistical Significance
C100AE0	0.0%	-	-
C75AE25	11.0%	0.042	Significant
C50AE50	13.0%	0.016	Significant
C25AE75	16.0%	0.003	Highly Significant
C25CAE75	20.0%	<0.001	Highly Significant
E1%AE50	8.0%	0.115	Not Significant
E2%AE50	11.0%	0.042	Significant
E3%AE50	13.0%	0.016	Significant

The data in Table 6 reveals several important insights. Firstly, it demonstrates that high-temperature exposure has a significant effect on the UCS of the CAM mixtures. Specifically, CAM mixtures containing higher proportions of asphalt emulsion (e.g., C25AE75 and C25CAE75) exhibited the most pronounced strength reduction, indicating their susceptibility to high-temperature conditions. This high susceptibility is supported by the highly significant *p*-values ($p < 0.001$). Conversely, mixtures with epoxy resin (E1%AE50, E2%AE50, E3%AE50) showed lower strength reductions, suggesting that the inclusion of epoxy resin can mitigate the adverse effects of high temperatures.

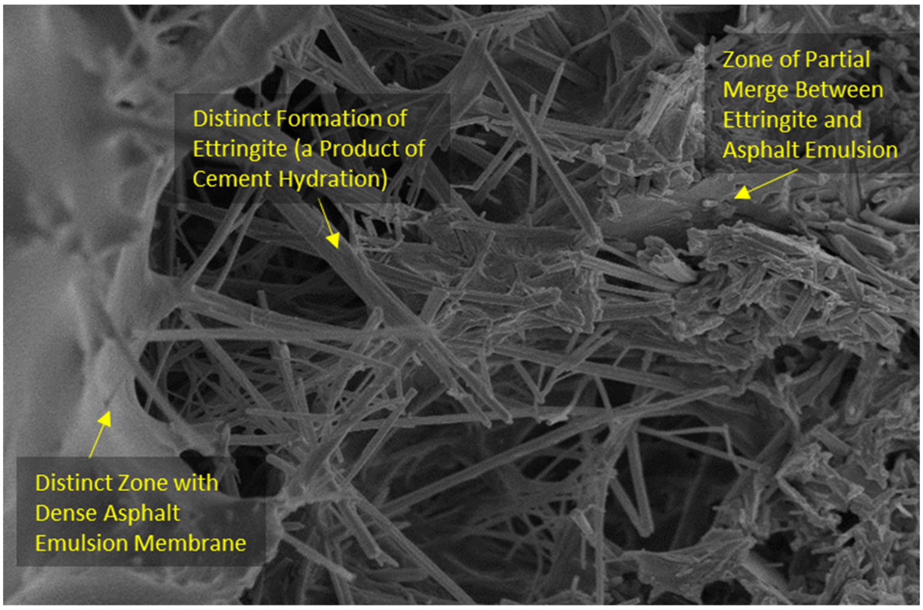
The statistical significance testing conducted on high-temperature UCS differences adds a layer of rigor to the study's findings and underscores the importance of considering the influence of temperature in the design and selection of CAM mixtures. These results provide valuable guidance for tailoring CAM mixtures to meet specific project requirements in tropical climates, ensuring durability and optimal performance even under challenging high-temperature conditions.

3.8. SEM Results

The SEM analysis was conducted to examine the microstructural characteristics of the various CAM mixtures used in this study. This analysis offers valuable insights into the composition, distribution, and interfacial bonding of the materials within the CAM matrix. The SEM micrographs reveal distinct features of the microstructure, shedding light on the influence of different CAM mixture compositions. The following observations are derived from the SEM analysis of the specified CAM mixtures, as shown in Figure 9a–d.

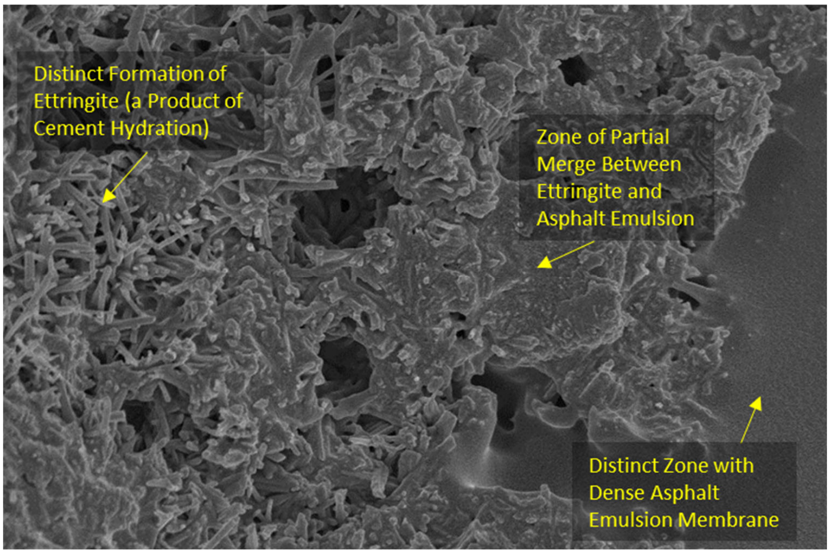
In the CAM mixture containing 75% cement and 25% anionic AE, the SEM image displays a microstructure with a dominant presence of cement particles. The asphalt emulsion phase appears as distinct droplets within the predominantly cementitious matrix. This composition results in a more cement-rich microstructure, which may impact the material's characteristics.

The SEM analysis of the CAM mixture with equal parts of cement and anionic AE (50% each) showcases a balanced microstructure. Here, the micrograph illustrates a combination of dense cement particles and dispersed asphalt emulsion. This mixture exhibits a unique balance between the cementitious phase and the asphalt phase, which may contribute to its optimized properties.

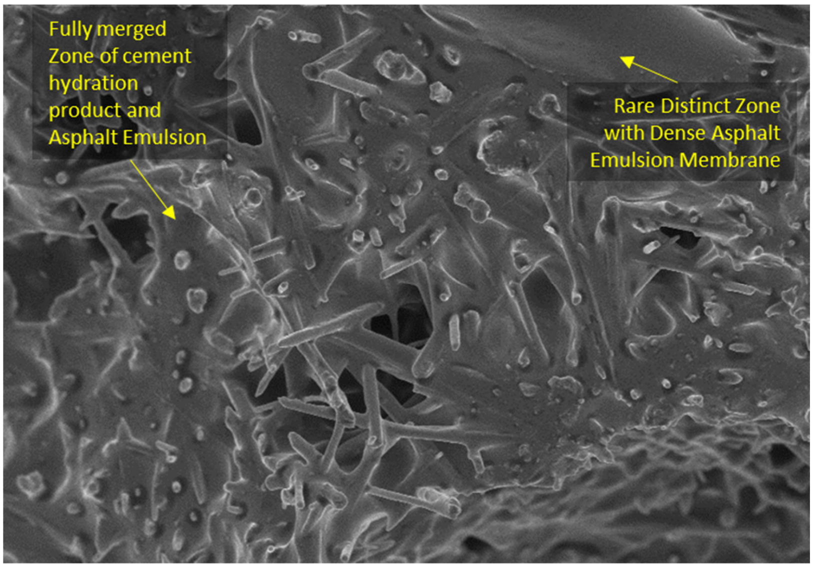


(**a**) 75% Cement + 25% Asphalt Emulsion.

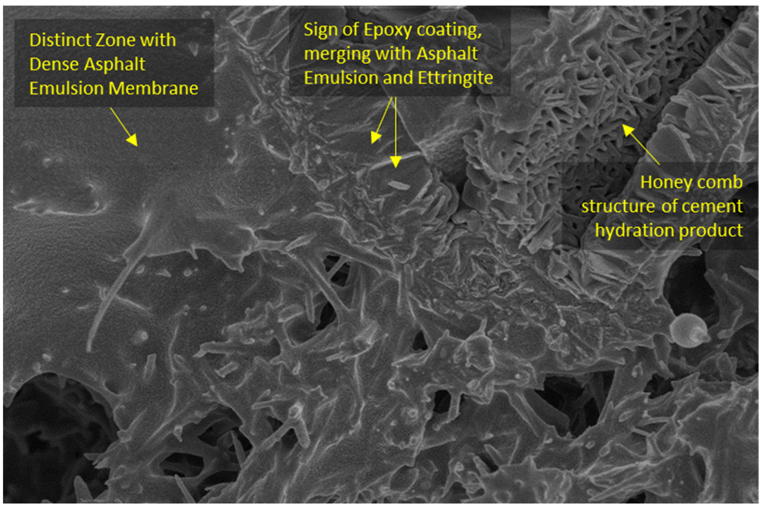
Figure 9. *Cont.*



(**b**) 50% Cement + 50% Asphalt Emulsion.



(**c**) 25% Cement + 75% Asphalt Emulsion.



(**d**) 50% Cement + 50% Asphalt Emulsion + 2% Epoxy Resin.

Figure 9. SEM Test Results.

In the SEM image of the CAM mixture with 25% cement and 75% AE, a discernible alteration in microstructure becomes apparent. The asphalt emulsion droplets are observed dispersed among the cement particles and fine aggregates. This dispersed phase introduces a distinct connectivity between the asphalt and the cementitious matrix, contributing to a more complex but well-connected microstructure.

The SEM analysis of CAM mixtures incorporating epoxy resin (2%) along with anionic AE highlights the influence of epoxy resin on the microstructure. In these mixtures, the epoxy resin appears to form an adhesive layer around the cement particles and interfaces with the anionic AE droplets. This interaction contributes to a more complex and interconnected microstructure, indicating the potential of epoxy resin to improve the interface between cement and asphalt emulsion.

In summary, the SEM analysis provides visual evidence of the microstructural differences among the CAM mixtures. The micrographs depict the distribution and connectivity of cement, asphalt emulsion, and other constituents within the matrices. These observations correlate with the mechanical properties and performance characteristics of each CAM mixture, further emphasizing the significance of material composition and microstructure in determining material behavior and suitability for specific applications.

The SEM analysis provided a visual understanding of the microstructural characteristics of CAM mixtures. These observations corresponded with the mechanical properties and performance characteristics of each mixture, emphasizing the importance of material composition and microstructure in determining material behavior and suitability for specific applications. In summary, this research comprehensively assessed the various aspects of CAM mixtures, from their mixing stability and flowability to their resistance to environmental factors and high temperatures. The findings offer valuable insights for designing CAM mixtures tailored to specific project requirements in tropical climates, ensuring durability and optimal performance in challenging conditions. The balance between cement content, asphalt emulsion type, and the inclusion of epoxy resin emerges as a key factor in formulating CAM mixtures that can thrive in such conditions. These findings not only contribute to the theoretical understanding of CAM mixtures but also hold great promise for practical applications, such as bridge expansion joints, in regions with tropical climates. Further research in this area could refine mixed designs and open doors to new possibilities in construction materials for challenging environments.

3.9. Field Service Life Estimates for Fill Materials

In this study, a comparative analysis of fill materials for bridge joints in tropical climates has been conducted, aiming to estimate their service life based on real-world field applications [7,11,39]. As shown in Table 7, the findings reveal significant variations in the durability of these materials. Conventional cement mortar, a commonly used option, exhibits a relatively short service life, estimated to be less than 2 years due to its susceptibility to cracking, as observed in practical construction data. On the other hand, conventional hot mix asphalt, while somewhat more durable, still has a limited service life, estimated at less than 3 years, due to its susceptibility to rutting, as confirmed by field applications. In contrast, CAM emerges as a promising alternative with an estimated service life of more than 5 years, which is supported by recent practical construction data. This extended service life is attributed to CAM's ability to combine the bearing capacity of cement with the ductile behavior of asphalt, as demonstrated in field applications. These results underscore the practical benefits of CAM in enhancing the longevity and resilience of bridge joints in challenging tropical conditions. However, ongoing field testing is essential to confirm and refine these estimates, offering valuable insights into the real-world performance of CAM in service conditions. The promising potential of CAM based on field applications warrants further investigations into its practical application and long-term performance, which could significantly impact the maintenance and sustainability of infrastructure in tropical climates.

Table 7. Comparative Service Life Estimates for Bridge Joints in Tropical Climates.

Fill Material	Estimated Service Life (Years)	Service Notes
Conventional Cement Mortar	Less than 2 years	Prone to cracking
Conventional Hot Mix Asphalt	Less than 3 years	Susceptible to rutting
Cement Asphalt Mortar	More than 5 years	Combines bearing capacity and ductile asphalt behavior

The laboratory evaluations conducted in this study provide valuable insights into the properties of CAM mixtures for bridge expansion joints in tropical climates. However, it is crucial to recognize that field conditions can present challenges and factors that are difficult to replicate in controlled laboratory settings. To bridge this gap between laboratory findings and real-world performance, there is a compelling need for potential field performance testing. Future work in this direction should involve actual field trials on bridges equipped with CAM mixtures. These trials would not only validate the laboratory results but also provide insights into how CAM materials perform under sustained exposure to environmental conditions, traffic loads, and long-term use. Field performance tests can shed light on the durability, structural integrity, resistance to moisture and temperature fluctuations, and overall long-term viability of CAM mixtures in bridge expansion joints. This field-based approach will be instrumental in refining CAM mixture designs, optimizing construction procedures, and ensuring their successful practical application in challenging tropical environments.

4. Conclusions

This research aimed to optimize Cement Asphalt Mortar (CAM) mixtures for tropical bridge expansion joints. Various cement, asphalt emulsion, and epoxy resin mixes were tested to enhance properties. Highlights include:

- Reducing cement content in CAM mixtures enhances mixing stability, particularly with 75% cement and 25% anionic AE. Epoxy resin (1%, 2%, 3%) has minimal impact on mixing stability, staying within acceptable limits.
- Reducing cement content to 25% with anionic AE improved flowability (5.8 cm, 80 s vs. control's 4.5 cm, 110 s). Balanced cement–anionic AE mixtures enhanced flowability, while higher cement (75%) had a minor impact. Cationic AE also improved flowability.
- Early and 28-day UCS results demonstrate the impact of cement content and anionic AE; a 100% cement mixture reached 7.2 MPa at 2 h and 20.2 MPa at 28 days. Mixtures with 25% cement and 75% anionic AE achieved 3.7 MPa at 2 h and 13.5 MPa at 28 days. The addition of epoxy resin (1%, 2%, 3%) consistently maintained or enhanced these values, emphasizing the significance of cement content and anionic AE.
- Anionic AE mitigated shrinkage. The control mixture had −0.15% shrinkage, while mixtures with 75% anionic AE ranged from −0.05% to −0.09%. Higher cement content reduced shrinkage tendencies. Epoxy resin had minimal impact, ranging from −0.05% to −0.06%.
- Exposure to sulfuric acid reduced compressive strength by −20.0% for the control mixture. Mixtures with anionic AE showed improved resistance (−6.0% to −12.0%). Epoxy resin and anionic AE demonstrated the highest resilience, with changes ranging from −4.0% to −8.5%.
- The control mixture showed no reduction in UCS at 45 °C. Mixtures with anionic AE (25%, 50%) had reductions of −11.0% to −13.0%, while mixtures with epoxy resin (1%, 2%, 3%) showed lower reductions, ranging from −8.0% to −13.0%.
- Scanning Electron Microscopy provided insights into CAM mixture microstructures, influencing material behavior and suitability for specific applications. Additional quantitative image analysis metrics can offer more detailed information.
- Based on the research findings, it is advisable to employ CAM mixtures with a composition of 50% cement, 50% anionic Asphalt Emulsion, and 2% epoxy resin for constructing bridge expansion joints in tropical climates. This blend enhances mix-

ing stability, flowability, UCS strength, and resistance to shrinkage and acid-induced degradation, making it suitable for practical applications in tropical climate conditions.
- The study highlights CAM mixtures' potential for improving bridge joint durability but also underscores the importance of addressing limitations, optimizing construction, and conducting field trials to ensure their long-term performance, enhancing infrastructure resilience and sustainability.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to ongoing research implications.

Conflicts of Interest: Author Kyungnam Kim was employed by the company Korea Expressway Corporation. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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