

Research on Foamed Bitumen and Cement Technology for Cold Recycling of Degraded Asphalt Concrete Pavements

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Abstract: *Asphalt concrete pavements deteriorate over time and require effective rehabilitation strategies. To reduce the need for removal and disposal of existing pavement materials, cold recycling using foamed bitumen and cement has emerged as a sustainable solution. This study presents the design and optimization of mixed proportions for foamed bitumen and cement in cold recycling applications. Laboratory experiments were conducted to evaluate physico - mechanical properties of the recycled mixture, which was applied to a road section of National Highway 26 in Dak Lak province, Vietnam. The results indicate that the cold - recycled mixture, consisting of foamed bitumen, cement, and reclaimed asphalt concrete materials, meets the technical requirements of pavements construction. This approach provides a promising alternative for reusing asphalt materials, contributing to environmental sustainability and cost efficiency.*

Keywords: *construction road, asphalt concrete, Foamed bitumen technology*

1. Introduction

Asphalt concrete is widely used in used to pave road surface layers. However, over time, under the influence of climatic factors and traffic loads, the quality of asphalt concrete deteriorates significantly, leading to loss of serviceability. Consequently, the deteriorated layer is removed and replaced with new materials. This process not only fails to utilize waste materials but also results in resource wastage, increased disposal costs, and environmental pollution due to the need for storage space and construction equipment mobilization.

In response to this situation, pavement recycling technologies, especially cold recycling, have been studied and developed to promote sustainable construction. Recycling asphalt pavement with reclaimed asphalt materials has been widely applied over the past decades (Santos et al., 2017). Among them, cold recycling is emerging as an effective solution that addresses both environmental and economic challenges, such as reducing CO₂ emissions, conserving natural resources, and lowering construction costs (Graziani et al., 2019; Liu et al., 2022; Modarres et al., 2014).

Cold recycling technology has been successfully implemented in several developed countries such as the United States, Australia, Germany, France, and Canada (Orosa et al., 2020; Liu & Sun, 2023). It can be carried out using three main methods: (i) in-place cold recycling, (ii) central-plant cold recycling, and (iii) full-depth reclamation (FDR) (Villegas et al., 2024). Compared to traditional hot mix asphalt (with production temperatures of 120–160°C), cold recycling consumes less energy as it does not require heating of materials, thereby significantly reducing greenhouse gas emissions. Additionally, reusing reclaimed aggregates reduces dependence on increasingly scarce natural aggregates and lowers construction costs (Orosa et al., 2020; Villegas et al., 2024).

However, this technology still faces certain technical challenges. Specifically, quality control of recycled mixtures during field construction remains difficult. Moreover, a widely accepted laboratory mix design method for cold recycled mixtures has not yet been established. Furthermore, cold recycled mixtures also face limitations when used as surface layers in pavement structures (Graziani et al., 2019). In addition, previous studies in Vietnam have mainly focused on small-scale trials without providing comprehensive laboratory data to support the development of a standardized mix design method. These aspects highlight the limitation of current research.

In in-place cold recycling, the existing pavement layer is milled and recycled directly on-site without heating. The resulting mixture is enhanced by the addition of stabilizing agents such as foamed bitumen and cement. Foamed bitumen improves cohesion and enhances the flexibility of the mixture, while cement plays a role in stabilizing the mixture and adjusting moisture content to achieve optimal compaction during

construction (Kaluder & Androjić, 2013). Practical application on the Knin–Biskupija section of the D1 national road in Croatia demonstrated that this technology produces a mixture with high load-bearing capacity, excellent uniformity, and effective resistance to cold weather conditions (Kaluder & Androjić, 2013).

To ensure construction quality, the cold recycling process must be combined with optimal compact techniques to achieve high density and improve the mechanical properties of the recycled mixture (Santos et al., 2017). In the context of sustainable infrastructure development and greenhouse gas emission reduction goals, cold recycling using foamed bitumen and cement presents a promising approach for modern road construction.

In Vietnam, in-place cold recycling technology has been applied with some initial positive outcomes. The country has issued national standard TCVN 13150 to guide the design, construction, and acceptance of cold recycled pavement layers using foamed bitumen and cement TCVN 13150-1:2020; TCVN 13150-2:2020). Several experimental studies have also confirmed the effectiveness of cold recycling on selected road sections in Vietnam (Nguyen & Lu, 2021; Tuan & Tha, 2016).

Against this background, the novelty of this research lies in the development and evaluation of cold recycled asphalt mixtures using a combined foamed bitumen–cement stabilization approach under Vietnamese conditions. Laboratory samples were systematically prepared and tested to establish key mechanical and durability indicators, thereby contributing new experimental evidence, refining design recommendations, and supporting the practical application of pavement recycling technology in Vietnam.

This paper focuses on the mixed design of cold recycled asphalt concrete using foamed bitumen and cement. Laboratory samples were prepared and tested to determine key technical indicators, thereby providing appropriate recommendations for the practical application of pavement recycling technology under Vietnamese conditions.

2. Materials and methods

In this study, the selected materials include high-quality Shell 60/70 grade bitumen suitable for foaming processes, and PCB40 cement manufactured by Hoang Thach Cement Plant. The chemical composition of the cement was determined according to TCVN 141:2008 and is presented in Tab 1.

Tab. 1. Chemical Composition of PCB40 Cement (Hoang Thach)

Properties	Content, %
SiO ₂	22.76
Fe ₂ O ₃	3.51
Al ₂ O ₃	6.69
CaO	54.18
MgO	3.73
SO ₃	1.97
K ₂ O	0.97
Na ₂ O	0.05
TiO ₂	0.12
Loss on ignition (LOI)	5.04

In addition, reclaimed asphalt pavement (RAP) materials were collected from the deteriorated surface and base course layers of National Highway 26 (Dak Lak province, Vietnam). Before use, the RAP was crushed, sieved, and homogenized to achieve a maximum particle size of 25 mm, with fines content (<0.075 mm) controlled below 10% as recommended in TCVN 13150-2:2020.

The preliminary mixture proportions were selected as 3.0–3.5% foamed bitumen (by dry aggregate weight), 1.0–1.5% cement (by dry aggregate weight), and 2.5–3.5% added water (by dry aggregate weight). In this context, foamed bitumen content refers to the proportion of hot bitumen that is expanded by injecting water and air, expressed as a percentage of the dry aggregate mass. Meanwhile, water content refers to the additional water incorporated into the mixture to achieve the optimum moisture content required for compaction. Both parameters were adjusted to obtain the best workability and maximum dry density of the recycled mixture.

The cold recycling process of asphalt concrete using foamed bitumen and cement is carried out through a sequence of well-defined steps, ensuring the quality and consistency of the recycled mixture.

Firstly, preparation of raw materials is conducted by collecting damaged asphalt concrete and old base course materials from deteriorated pavement layers. These materials are subsequently crushed and homogenized to create a representative sample corresponding to the intended recycling depth.

Secondly, the production of foamed bitumen is initiated by heating the bitumen to approximately 160 ± 1 °C. To ensure the effectiveness of the foamed bitumen, it is crucial to determine the optimal water content that achieves the desired expansion and stability. The heated bitumen is subsequently injected into a specialized laboratory-scale foaming device (WLB 10S, shown in Fig. 1) to generate foamed bitumen with targeted characteristics. During this process, two key parameters are evaluated: the Expansion Ratio (ER), which quantifies the degree of foaming, and the half-life ($\tau_{1/2}$), which indicates the time required for the foam to collapse to half of its maximum volume. According to the Vietnamese standard TCVN 13150-2:2020, the minimum required values for these parameters are $ER \geq 10.8$ for ambient temperatures between 10 °C and 25 °C, and $ER \geq 8.6$ for temperatures exceeding 25 °C.

The water injection content for foaming was varied from 1.5% to 3.0% by weight of bitumen, with the optimum value selected at 2.5% to achieve $ER \approx 14$ and $\tau_{1/2} \approx 16$ s.

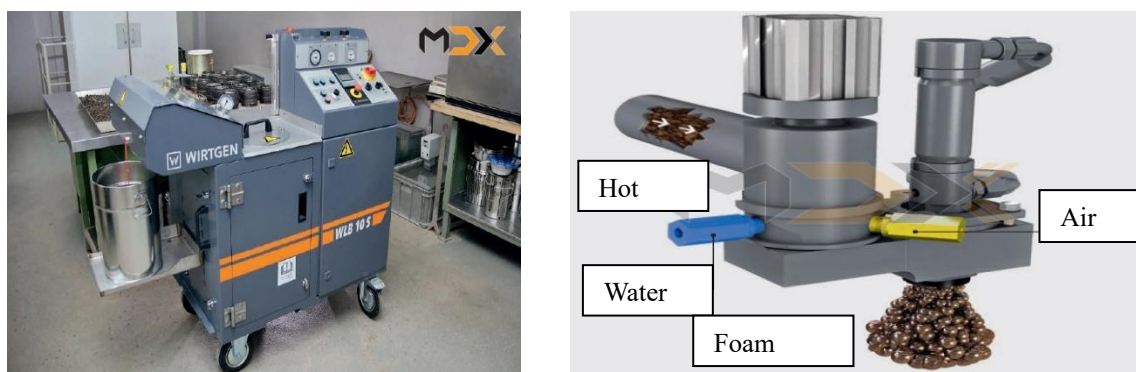


Fig. 1. Laboratory-scale foamed bitumen generator WLB 10S

Next, sampling and preparation of the recycled mixture involves collecting representative material samples directly from the field (Fig. 2). These samples are transported to the laboratory, where they are mixed with predetermined proportions of foamed bitumen, cement (PCB40 from Hoang Thach Cement Plant), and water to form a cold recycled blend (Fig. 3).

The mixing process was conducted in a laboratory mechanical mixer, following the sequence: (i) dry mixing of RAP and cement for 60 s; (ii) spraying of foamed bitumen and mixing for 90 s; (iii) gradual addition of water to reach the targeted optimum moisture content, followed by mixing for an additional 60 s to achieve homogeneity.

Then, particle size distribution and plasticity index tests are performed on the recycled mixture. The gradation analysis is conducted in accordance with TCVN 7572-2:2006, while the plasticity index is determined according to TCVN 4197:1995 to evaluate the workability and cohesion characteristics of the mixture.



Fig. 2. Field sampling from damaged pavement a road section of National Highway 26 in Dak Lak province, Vietnam



Fig. 3. Laboratory mixer for recycled aggregate blend used in foamed bitumen content design

Subsequently, specimen preparation and mechanical testing are conducted to evaluate the performance of the recycled mixture. Cylindrical specimens (100 mm diameter × 63.5 mm height) were compacted using a Marshall compactor with 75 blows per face (TCVN 8860-1:2011). For each testing condition, at least 3 specimens were prepared. The blended material is first molded into standard specimens and cured under controlled laboratory conditions to simulate field compaction and curing. The curing duration was 72 hours.

Mechanical performance is then assessed through indirect tensile strength testing in both dry (R_{tdk}) and wet (R_{tdw}) conditions, following the procedures outlined in TCVN 13150-2:2020. Additionally, the compactability of the material is evaluated in accordance with TCVN 12790:2020 to determine the optimal moisture content and maximum dry unit weight required to achieve the desired density and structural integrity.

Finally, the optimum mix design and elastic modulus of the recycled mixture are identified. The mix composition yielding satisfactory mechanical properties is selected as the optimal formulation, and the resilient modulus is determined in accordance with TCVN 9843:2013 to support structural design calculations.

3. Results and discussion

3.1. Optimal Water Content for Foamed Bitumen Production

Determining the optimal water content is a critical step in the foamed bitumen production process to ensure that the expansion and stability characteristics of the foam meet technical requirements. The experimental results on the influence of water content on the Expansion Ratio (ER) and half-life ($T_{1/2}$) are presented in Table 2. The data indicate that as the water content increases, the spray rate increases correspondingly, the minimum ER rises progressively, while the minimum half-life ($T_{1/2}$) decreases. This relationship reflects a fundamental characteristic of the foaming process: increasing water content enhances the foaming capability but simultaneously reduces the volumetric stability of the foam over time. Similar findings were highlighted by Villegas et al. (2024), who reported that while higher water content increases ER, it can accelerate foam collapse, thus requiring a careful balance to meet field application standards. Graziani et al. (2019) also emphasized that foam expansion and stability are key factors affecting binder–aggregate interaction in cold recycled mixtures, particularly when evaluating mechanical performance under cyclic loading.

Tab. 2. Relationship between water content, ER, and $T_{1/2}$

Water content, %	Flow rate, l/h	Minimum Expansion Ratio, ER (times)	Minimum Half-life, $T_{1/2}$ (s)
1	108	403	1500
2	306	703	1205
3	504	1008	903
4	702	1405	503
5	900	1707	300

To determine the optimal water content, the relationships between ER and $T_{1/2}$ as functions of water content are shown in Figure 4. Based on both the experimental results and the standard, a water content of 3% is identified as optimal, as it achieves an ER of 10.8, in accordance with the technical requirements

specified in TCVN 13150-2:2020 for ambient temperatures ranging from 10°C to 25°C, while maintaining a sufficiently long half-life to ensure foam stability during field application.

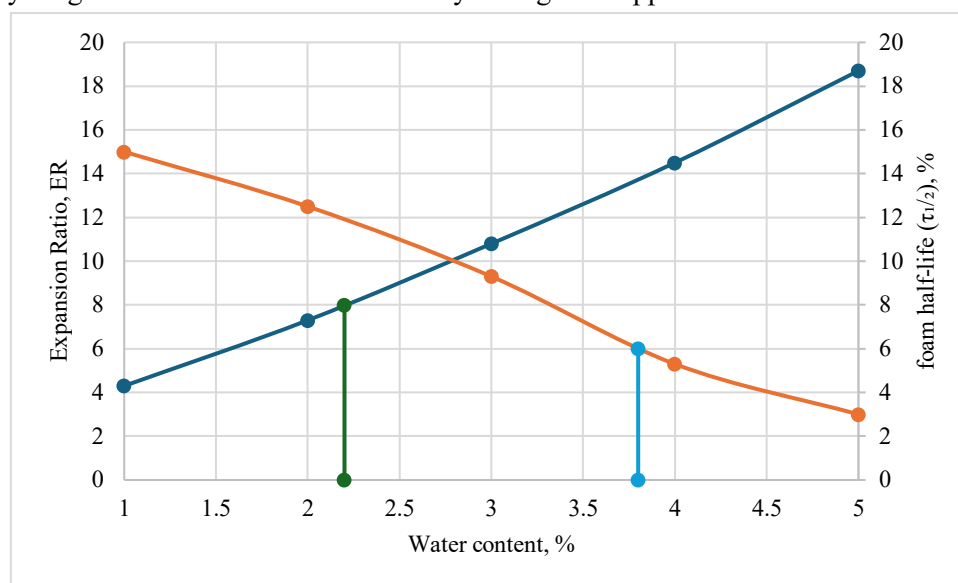


Fig. 4. Determination of optimal water content

3.2. Optimal Mix Design

To determine the optimal gradation for the cold-recycled asphalt concrete mixture, RAP samples collected in the field were first subjected to particle-size analysis (Fig. 5). Based on the resulting grading curve, five laboratory mixes were prepared with foamed bitumen contents of 1.7 %, 1.9 %, 2.1 %, 2.3 %, and 2.5 % by mass, while the cement content was fixed at 1 %, the water content at 3 %, and the bitumen temperature at 160 °C. The dry components (RAP and cement) were mixed until uniform, then foamed bitumen and the prescribed water were introduced in a specialized mixer until homogeneity was achieved. Li et al. (2021) demonstrated that particle size distribution and aggregate degradation significantly influence compaction behavior and dry density, which aligns with our OMC and maximum dry density findings.

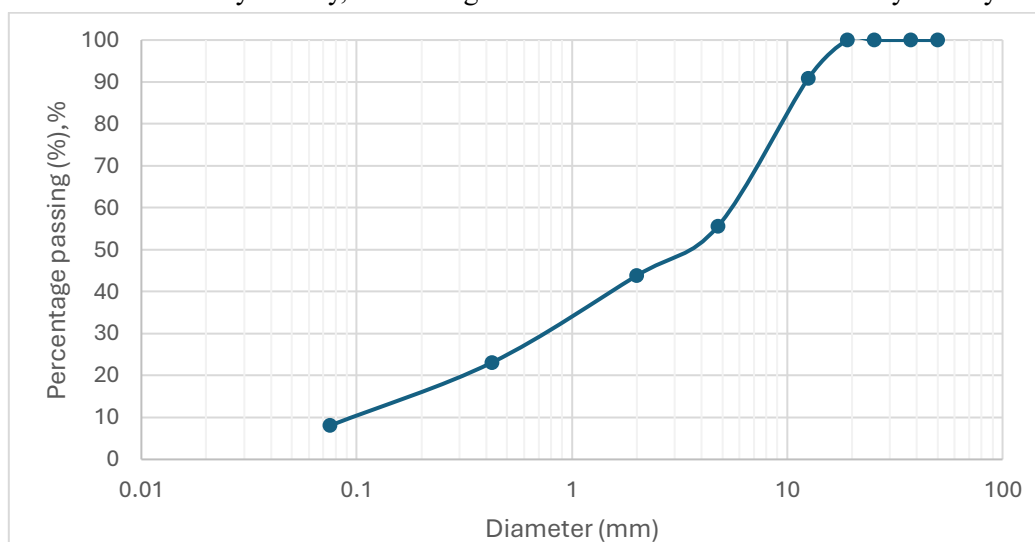


Fig. 5. Particle size distribution of the asphalt concrete in a road section of National Highway 26 in Dak Lak province, Vietnam

Each blend was molded into standard specimens and cured at 40 °C for 72 hours. Thereafter, indirect tensile strength tests were conducted in both dry (R_{tck}) and wet (R_{tcu}) conditions in accordance with TCVN 13150-2:2020, and the Tensile Strength Ratio (TSR) was calculated. The results are summarized in Tab 3. For comparison, Kaluđer and Androjić (2013) reported an indirect tensile strength of 553 kPa (dry) and 429 kPa (wet) (TSR = 0.78) using a mixture with 1.5% cement, 2.5% paving bitumen (70/100), and 2.8% water content. In contrast, the present study maintained a fixed water content of 3.0% for all mixes, and under these conditions, the mixtures demonstrated improved performance.

Similar improvements in TSR have also been observed in recent studies. Kumar and Meena (2023) reported that incorporating suitable filler additives and optimized RAP proportions can enhance tensile strength and moisture resistance, with TSR values exceeding 0.80 across multiple mixes. Likewise, Zhao et al. (2025) demonstrated that interface modification in foamed bitumen recycled mixtures significantly improved wet strength and TSR, highlighting the role of binder–aggregate bonding in moisture susceptibility. Furthermore, Nguyen & Lu (2021) and Modarres et al. (2014) also noted that optimized mixture composition and proper curing are critical for achieving high indirect tensile strength in cold-recycled asphalt mixtures.

Tab. 3. Engineering properties of cold-recycled asphalt concrete mixtures

Foamed bitumen content, %	Cement content, %	Bulk density, kg/m ³	Indirect tensile strength in dry condition, $R_{tck} \pm SD$, Mpa	Indirect tensile strength in web condition, $R_{tcu} \pm SD$, Mpa	TSR $\pm SD$
1.7	1	2191	0.290 ± 0.040	0.203 ± 0.051	0.701 ± 0.201
1.9	1	2252	0.323 ± 0.040	0.273 ± 0.035	0.845 ± 0.151
2.1	1	2268	0.390 ± 0.010	0.343 ± 0.025	0.879 ± 0.068
2.3	1	2193	0.320 ± 0.010	0.270 ± 0.010	0.844 ± 0.041
2.5	1	2151	0.283 ± 0.025	0.207 ± 0.015	0.729 ± 0.084

3.3. Technical Properties of the Recycled Mixture

To comprehensively evaluate the mechanical properties of the cold recycled mixture using foamed bitumen, the optimum bitumen content was first determined to be 2.1%. Based on this value, the mixture was subjected to standard Proctor compaction tests to determine the optimum moisture content and maximum dry density. The results (Fig. 6) indicated that the optimum moisture content was 4.5%, corresponding to a maximum dry density of 2,179 kg/m³. It should be noted that this OMC value refers to the compaction characteristics of the mixture and is distinct from the fixed water content of 3.0% that was used during the preparation of specimens for indirect tensile strength testing (Tab 3). The obtained maximum dry density is comparable to the value of 2,173 kg/m³ reported by Kaluđer and Androjić (2013), indicating consistency in compaction characteristics between studies. Liu & Sun (2023) emphasized that compaction methods strongly affect void distribution and mechanical properties in cold recycling asphalt mixtures, supporting our findings.

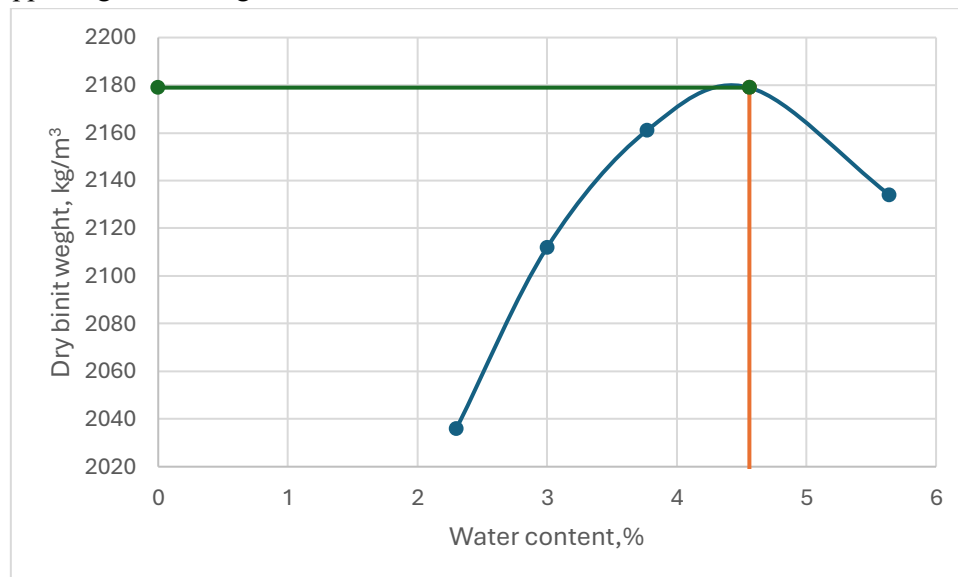


Fig. 6. Relationship between dry unit weight and water content

Subsequently, to determine the elastic modulus of the mixture, test specimens were molded and cured in an oven at 40 °C for 72 hours, followed by testing at a temperature of 25 °C. The results showed that the average elastic modulus of the mixture was 301.30 MPa, which exceeds the minimum requirement of 235 MPa specified in TCVN 8863:2011. This demonstrates the good load-bearing capacity and elasticity of the mixture, making it suitable for use as a subbase or base layer in pavement structures.

For instance, Buczyński and Iwański (2023) investigated the stiffness modulus of cold recycled mixtures with foamed bitumen (FB-RCM) incorporating various recycled materials. Their findings indicated that the stiffness modulus varied depending on the type and proportion of recycled material used. Specifically, mixtures with 40% recycled concrete (RC) content achieved a maximum stiffness modulus of 10,094 MPa, while those with 40% reclaimed asphalt pavement (RAP) content reached 9,914 MPa. These values are significantly higher than the elastic modulus of 301.30 MPa obtained in the current study. However, it's important to note that the testing methods and conditions may differ between studies, which can influence the results. For example, Buczyński and Iwański (2023) used the indirect tension test to determine the stiffness modulus, whereas the current study's methodology may vary. Therefore, while the modulus values differ, direct comparisons should consider the specific testing protocols employed. Lv et al. (2023) also highlighted the effect of cyclic loading and binder rheology on modulus evolution, reinforcing the importance of material selection and mixture design.

4. Conclusion

This study has confirmed the feasibility and effectiveness of applying foamed bitumen and cement in cold recycling of degraded asphalt concrete pavements. The optimal foamed bitumen content was determined as 2.1%, with an optimum moisture content of 4.5% and a maximum dry density of 2,179 kg/m³. The cold recycled mixture achieved an elastic modulus of 301.30 MPa, which exceeds the minimum technical requirement specified in TCVN 8863:2011.

These results demonstrate that the recycled mixture possesses good load-bearing capacity and elasticity, making it suitable for use as a reinforced subbase or upper base layer in pavement structures. The combination of optimized material composition and appropriate curing conditions contributes significantly to the mechanical performance of the mixture, supporting the applicability of cold recycling technology under local conditions.

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