

Article

Not peer-reviewed version

---

# Cold Asphalt Mixtures with Industrial Waste for Rapid Pavement Repairs

---

[Paula Cristina Fernandes-Leal](#), [Hernán Patricio Moyano-Ayala](#)<sup>\*</sup>, Marisa Sofia Fernandes Dinis-Almeida

Posted Date: 5 May 2026

doi: 10.20944/preprints202605.0220.v1

Keywords: cold bituminous mixtures; pothole patching; reclaimed asphalt pavement (RAP); greywacke mining waste



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC, OpenAlex.

Copyright: This open access article is published under a [Creative Commons CC BY 4.0 license](#), which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Article

# Cold Asphalt Mixtures with Industrial Waste for Rapid Pavement Repairs

Paula Cristina Fernandes-Leal, Hernán Patricio Moyano-Ayala \*  
and Marisa Sofia Fernandes Dinis-Almeida

C-MADE, Centre of Materials and Civil Engineering for Sustainability, University of Beira Interior, Calçada Fonte do Lameiro, Edifício II das Engenharia, 6200-001 Covilhã, Portugal

\* Correspondence: hernan.moyano.ayala@ubi.pt

## Abstract

The growing demand for sustainable and economically efficient road maintenance solutions has driven the development of materials that reduce the use of natural aggregates and promote waste valorization. In this context, this study evaluates the use of reclaimed asphalt pavement (RAP) and Panasqueira mine waste, in the form of greywacke aggregates, as partial or total substitutes for granite aggregates in cold asphalt mixtures intended for rapid pothole repair. Reference mixtures and recycled mixtures were produced with controlled proportions of RAP and greywacke, using cationic bituminous emulsion and hydrated lime, as well as an additional mixture composed only of RAP with a fluxing cold binder. Three commercial mixtures, identified as CCM1, CCM2, and CCM3, were also evaluated. Performance was analyzed through Cantabro particle loss, Marshall stability and flow, indirect tensile stiffness modulus, and water sensitivity (ITSR). The results show that greywacke provides a robust granular skeleton, while RAP content and binder type influence stiffness, cohesion, and moisture resistance. Overall, the combination of RAP and greywacke proved to be technically viable and, in several cases, superior to the commercial mixtures studied.

**Keywords:** cold bituminous mixtures; pothole patching; reclaimed asphalt pavement (RAP); greywacke mining waste

---

## 1. Introduction

The progressive deterioration of flexible pavements results from the combined action of repeated traffic loading and environmental factors, whose interaction promotes structural fatigue, binder aging, loss of cohesion, and surface deterioration [1–3]. Among the most critical forms of distress, potholes stand out because they directly compromise road safety, ride quality, pavement structural performance, and vehicle operating costs [4]. In addition to the discomfort and risk associated with evasive maneuvers, potholes favor water infiltration and the progressive disintegration of the material, accelerating the deterioration of underlying layers and increasing the frequency and cost of maintenance interventions [5–8]. In this sense, the timely repair of these localized defects is essential to limit damage propagation, preserve the functional and structural integrity of the pavement, and reduce technical, economic, and social impacts [9]. Therefore, the development of high-performance materials for rapid maintenance has become increasingly relevant within the framework of sustainable road infrastructure management.

In this context, cold asphalt mixtures have been recognized as a technically viable solution for localized repairs, especially in situations requiring rapid application, simplified logistics, and minimal operational infrastructure [10–12]. The absence of heating during production and application results in lower energy consumption, greater flexibility in storage and transport, and the possibility of use under different environmental conditions [13]. However, these operational advantages also introduce additional challenges in formulation, particularly regarding gradation control, aggregate binder interaction, and the development of initial cohesion, since strength

evolution depends strongly on physical processes [14], binder characteristics, and compatibility among constituents [15–17]. For this reason, parameters such as air void content, stability, stiffness, indirect tensile strength, and water sensitivity play a decisive role in the durability and in service performance of these mixtures [18].

At the same time, the incorporation of recycled materials and industrial by products has gained increasing attention as a strategy to improve resource efficiency and reduce the environmental impacts associated with road construction and maintenance [19–23]. Among these alternatives, Reclaimed Asphalt Pavement (RAP) is particularly relevant because it enables the valorization of waste generated during pavement rehabilitation while simultaneously reducing the extraction of natural aggregates and landfill disposal [24,25]. However, the presence of aged binder may modify the stiffness and mechanical response of the mixture, affecting workability, cracking susceptibility, and behavior under repeated loading, which requires a carefully justified mix design [18,26]. In a complementary way, the use of greywacke aggregates from the Panasqueira mine [27,28] represents a promising route for the valorization of mining by products, since their high angularity and predominantly siliceous nature may favor particle interlock and improve the mechanical resistance of the mixture, provided that their suitability is confirmed through appropriate physical-mechanical characterization [29,30].

Based on this framework, the present study develops and experimentally evaluates three cold asphalt mixtures formulated with RAP and greywacke aggregates as total replacements for natural aggregates, aiming at their application in rapid pavement repair. The performance of the proposed mixtures is compared with that of three commercial cold asphalt mixtures through the analysis of volumetric and mechanical properties, including particle loss due to abrasion, Marshall stability, stiffness modulus, and water sensitivity [18]. The results demonstrate that the combination of RAP and greywacke constitutes a technically viable solution with strong potential for immediate road maintenance interventions and may, in several cases, provide competitive or superior performance compared with conventional commercial mixtures.

## 2. Materials and Methods

The experimental program was designed to systematically develop and evaluate cold asphalt mixtures intended for rapid pavement repair, with particular emphasis on pothole patching using Reclaimed Asphalt Pavement (RAP) and greywacke aggregates derived from Panasqueira mine waste. First, all constituent materials, including virgin aggregates, RAP, greywacke aggregates in accordance with EN 933 -1 [31], binders, and additives, were characterized through relevant physical and mechanical tests to assess their suitability for cold mix production. Based on these results, three experimental mixtures were designed with different proportions of aggregates, binder, and additives. The mixtures were then produced under controlled laboratory conditions, compacted, and cured according to the requirements of each formulation, with binder contents adjusted on the basis of workability and mechanical performance criteria. Laboratory testing included Cantabro particle loss, Marshall stability and flow, indirect tensile stiffness modulus, and water sensitivity, together with volumetric characterization through bulk density and air void content. All testing procedures were conducted in accordance with applicable technical standards to ensure the reliability, repeatability, and comparability of the results. This methodological approach enabled the assessment of mechanical performance, handling properties, and durability related indicators, supporting the identification of technically viable and environmentally sustainable mixtures for emergency road maintenance applications.

### 2.1. Materials

This study considered the development of three cold asphalt mixtures for rapid pavement repair, particularly for pothole patching. One mixture was produced by incorporating greywacke aggregates from the Panasqueira mine and RAP (ACM1), a second mixture was produced with 100% greywacke aggregates from the Panasqueira mine (ACM2), and a third mixture was produced using

100% RAP (ACM3). The aggregates were subsequently mixed with a cationic bituminous emulsion and hydraulic lime. The three commercial mixtures tested present distinct formulations, consisting of natural aggregates and waste materials, which influence their volumetric and mechanical behavior and make it possible to establish a comparative basis for evaluating the performance of the formulated solutions against market available alternatives.

### 2.1.1. Binder

Two binders were used in the experimental program. For the formulations containing greywacke aggregates, a C67BF3 cationic bituminous emulsion supplied by Lusafal was adopted as the binder, as presented in Table 1. In contrast, the formulation composed of 100% RAP was produced using IterBflux Cold, supplied by Iterchimica. IterBflux Cold is a high-performance binder for cold mixtures, with the dual function of binder and fluxing agent, consisting of a blend of hydrocarbons, vegetable esters, and distillation derivatives, and having a density of 1.00 g/cm<sup>3</sup> at 25 °C. The recommended dosage of IterBflux Cold is 3.0 to 4.5% by mass of aggregates or RAP.

**Table 1.** Characteristics of the C67BF3 Emulsion.

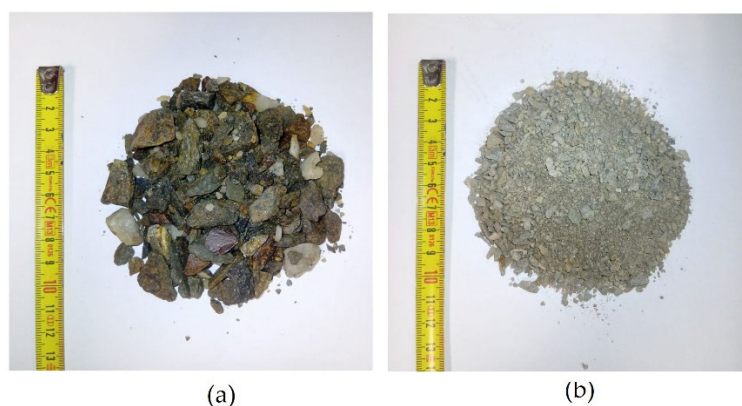
Properties	Standard	Result
Breaking index	EN 13075-1 [32]	115
Binder content, %	EN 1431 [33]	65
Distillate oil content, %	EN 1431 [33]	5
Flow time, 4 mm at 40 °C, s	EN 12846 [34]	8
Sieve residue on 0.500 mm sieve, %	EN 1429 [35]	0
Sedimentation (7 days), %	EN 12847 [36]	1

### 2.1.2. Reclaimed Asphalt Pavement

The RAP used in this study was recovered from the surface course of the A23 motorway in Castelo Branco, Portugal, and incorporated as the main recycled component in the cold mixtures. In addition to its contribution as an aggregate, the recovered material was analyzed in order to quantify the condition of the aged binder present in the RAP. This characterization was carried out by CEPESA Betumes at its Madrid laboratory, including the determination of aged binder content according to EN 12697-1 [37], penetration according to EN 1426 [38], and softening point according to EN 1427 [39]. The extracted binder showed a content of 5.6%, a penetration value of  $11 \times 10^{-1}$  mm, and a softening point of 77.8 °C, indicating a highly aged and stiff binder with reduced elasticity, consistent with prolonged field exposure. The gradation curve of the RAP after processing, including sieving and crushing to remove oversized particles and impurities, is presented in Table 1.

### 2.1.3. Greywacke Aggregates

The greywacke aggregates recovered as mining waste from the Panasqueira operation, in the stone dust 0/4 and crushed aggregate 2/12.5 fractions, are shown in Figure 1.



**Figure 1.** Greywacke aggregates from the Panasqueira Mine: (a) stone Dust, (b) gravel 2/12,5.

The greywacke aggregates from the Panasqueira mine showed very high resistance to fragmentation, with a Los Angeles coefficient (LA) value of 8.8%, determined in accordance with EN 1097-2 [40], indicating a hard material with high resistance to impact, abrasion, and traffic induced wear, which favors the development of a mechanically robust cold mixture.

Hydraulic lime was incorporated as a mineral additive to adjust the gradation and improve mixture cohesion. The gradation results are presented in Table 2 as cumulative percentages passing each sieve, determined according to EN 933-1 [31].

**Table 2.** Gradation of greywacke aggregates, and RAP.

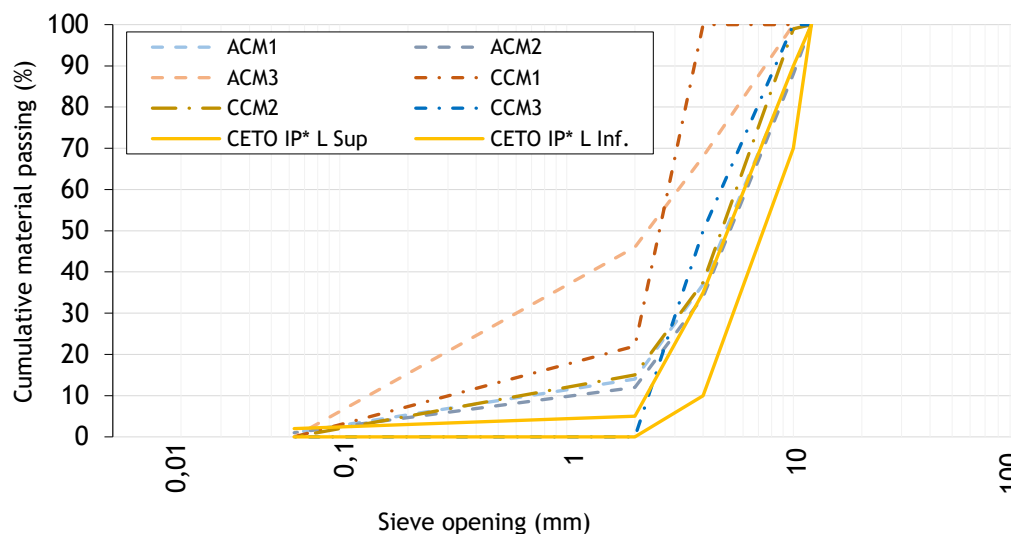
Sieve size [mm]	Cumulative Passing [%]			
	Greywacke aggregates		RAP	Hydraulic lime
	Stone Dust	Gravel 2/12,5		
12,5	100	74	100	100
10	100	62	100	100
4	93	22	68	100
2	61	6	46	100
0,063	0	0	0	100

The mixture compositions, expressed as percentages by mass, are summarized in Table 3 and were established in accordance with the specified limits for routine maintenance works with thicknesses below 4 cm specified by the Portuguese Road Administration [41].

**Table 3.** Asphalt mixture compositions [%].

Aggregate	ACM1	ACM2	ACM3
Greywacke stone dust	5	10	-
Greywacke Gravel 4/12,5	80	89	-
Hydraulic lime	1	1	-
RAP	14	-	100

The gradation curves of the different mixtures (ACM1, ACM2, and ACM3), as well as the gradation limits defined in the Portuguese specifications, are presented in Figure 2.

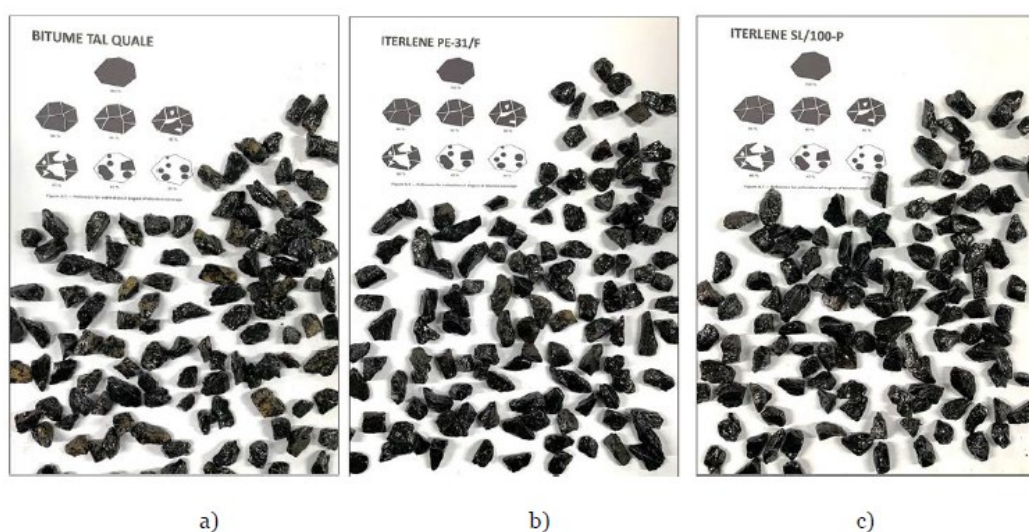


**Figure 2.** Gradation curves of the formulated mixtures (ACM1, ACM2, and ACM3) and commercial mixtures (CCM1, CCM2, and CCM3).

#### 2.1.4. Adhesion Promoting Additive

In this study, two adhesion promoting additives, Iterlene PE 31/F and Iterlene SL/100 PLUS, supplied by Iterchimica, were used to enhance the bond between the cationic bituminous emulsion and the greywacke aggregates. The use of this additive proved particularly relevant due to the mineralogical characteristics of the Panasqueira aggregates, which require greater affinity with the binder to ensure adequate coating and durability.

As illustrated in Figure 3, the adhesion tests carried out on the greywacke aggregates showed a significant improvement with the incorporation of the additive. Without the use of the additive, the coating was approximately 70%; with 0.3% Iterlene PE 31/F, the coating increased to 85%; and with 0.1% Iterlene SL/100 PLUS, complete coating of 100% was achieved.



**Figure 3.** Binder-aggregate adhesion tests on greywacke with different additives: (a) without additive ( $\approx 70\%$  coating); (b) with 0.3% Interlene PE-31/F ( $\approx 85\%$  coating); (c) with 0.1% Interlene SL/100-P (100% coating).

#### 2.2. Methods

This section describes the experimental procedure adopted to determine the optimum binder content of the cold mixtures produced with industrial residues, namely greywacke aggregates from Panasqueira mining operations and Reclaimed Asphalt Pavement (RAP), as well as the characterization tests performed on these mixtures and on three commercial mixtures frequently used by the Municipal Works Department of the Covilhã City Council for rapid pavement repair in localized areas, particularly pothole patching. To ensure confidentiality, the commercial mixtures were randomly identified as CCM1, CCM2, and CCM3.

The optimum binder content for the laboratory formulated mixtures was determined by means of the Cantabro test. The experimental program also included the Marshall test, the determination of the indirect tensile stiffness modulus, and the evaluation of water sensitivity for both the formulated mixtures and the three commercial mixtures. For all tests, Marshall specimens were prepared for each mixture using 50 blows per face, followed by accelerated curing under the following conditions: 2 hours in the mold, 1 day in air at room temperature, and 3 days in an oven at 60 °C.

### 2.2.1. Optimum Bitumen Content

The initial emulsion content (IEC) was ascertained according to the Asphalt Institute utilizing empirical Equation 1:

$$P = K \times \alpha \times \sqrt[5]{\Sigma} \quad (1)$$

Where:

P - is the percent residual asphalt content by weight of total mix.

K - is the richness modulus = 3.8

$\alpha = \frac{2,65}{\rho_a}$ ;  $\rho_a$  - is the bulk density of aggregates mixture

$$\Sigma = \frac{1}{100} \times (0,25 \times G + 2,3 \times S + 12 \times s + 135 \times f)$$

G = percentage of aggregate retained on 6,3 mm sieve;

S = percentage of aggregate passing 6,3 mm sieve and 0,315 mm sieve;

s = percentage of aggregate passing 0,315 mm sieve and 0,075 mm sieve;

f = percentage of aggregate passing 0,075 mm sieve

The value of IEC was determined using Equation (2):

$$IEC = \frac{P}{X} \times 100 \quad (2)$$

Where:

X - is the residual bitumen percentage of the emulsion (X), which was 65%.

Thus, the IEC values for ACM1 and ACM2 are 7.5% and 7.4%, respectively.

The optimum emulsion content of the cold asphalt mixtures was determined by means of the Cantabro test, in accordance with EN 12697-17 [42]. Marshall specimens were prepared for each mixture considering three emulsion contents: the initial content, the initial content increased by 0.5%, and the initial content reduced by 0.5%. Each specimen was weighed before testing, and the mass was recorded as P1. The specimens were then individually placed in the Los Angeles drum, without steel balls, and subjected to 300 revolutions at a speed between 30 and 33 rpm. After the test, each specimen was removed and weighed again to obtain P2. Particle loss was calculated for each specimen using Equation (3):

$$PL = \frac{W_1 - W_2}{W_1} \times 100 \quad (3)$$

Where:

PL is the value of particle loss, in percent (%);

W1 is the initial specimen mass, in grams (g);

W2 is the final specimen mass, in grams (g).

### 2.2.2. Marshall Test

All aggregates, RAP, and filler were mixed using the binder contents defined through the Cantabro test, and cylindrical Marshall specimens were subsequently prepared by applying 50 blows per face. After the accelerated curing period, the specimens were conditioned in a water bath at 60 °C for the duration specified in EN 12697-34 [43] and then tested to determine Marshall stability and flow, allowing the evaluation of mixture cohesion and its response to loading. Bulk density was determined according to EN 12697-6 [44], Procedure D (by dimensions), and the main volumetric parameters were calculated to support the interpretation of performance.

### 2.2.3. Stiffness Modulus

The stiffness modulus of the developed cold mixtures was determined in accordance with NP EN 12697-26 [45] (Annex C), using the indirect tensile stiffness modulus (ITSM) procedure on cylindrical specimens prepared with the selected optimum binder contents. For each mixture (ACM1, ACM2, and ACM3), five specimens were tested, with the load applied in two diametrically opposite directions to improve repeatability. The tests were carried out at 20 °C, considering a Poisson's ratio of 0.35, a load rise time of 124 ms, and a maximum horizontal deformation of 5 µm, as specified in the standard. The modulus was obtained from five repeated load applications, preceded by a preloading phase intended to condition the testing system to the type of mixture.

### 2.2.4. Water Sensitivity

Water sensitivity was evaluated by means of the indirect tensile strength ratio (ITSR), in accordance with EN 12697-12 [46]. A total of thirty specimens were produced, ten for each mixture (CCM1, CCM2, and CCM3), all compacted using their respective optimum bitumen contents.

The specimens were divided into two groups: one stored under dry conditions at 20 °C and the other subjected to vacuum saturation and immersion in water at 40 °C for 72 h, followed by conditioning at 15 °C. Dimensional stability was verified, ensuring that no specimen exhibited a volume increase greater than 2%. Indirect tensile strength (ITS) was determined by diametral compression, in accordance with EN 12697-23 [47], using a loading rate of 50 mm/min and according to Equation (4).

$$ITS = \frac{2P}{\pi DH} \quad (4)$$

Where:

ITS is the indirect tensile strength, expressed in megapascals (MPa);

P is the peak load, expressed in kilonewtons (kN);

D is the diameter of the specimen, expressed in millimeters (mm); and

H is the height of the specimen, expressed in millimeters (mm).

The ITSR was calculated by comparing the ITS values under wet and dry conditions, using Equation (5):

$$ITSR = \frac{ITS_w}{ITS_D} \times 100 \quad (5)$$

Where:

ITSR represents the indirect tensile strength ratio (%);

ITS<sub>w</sub> is the average indirect tensile strength of the specimens conditioned under wet conditions (kPa); and

ITS<sub>D</sub> is the average indirect tensile strength of the specimens not conditioned under dry conditions (kPa).

## 3. Results

### 3.1. Cantabro Test

The results indicate that mixtures ACM1 and ACM2 exceeded the maximum particle loss limit of 25% for cold mixtures established in the Portuguese Specifications [41], whereas ACM3 showed excellent performance, with only 1% particle loss.

The commercial mixtures CCM1, CCM2, and CCM3 were also subjected to the Cantabro test, and their results are likewise presented in Figure 4.

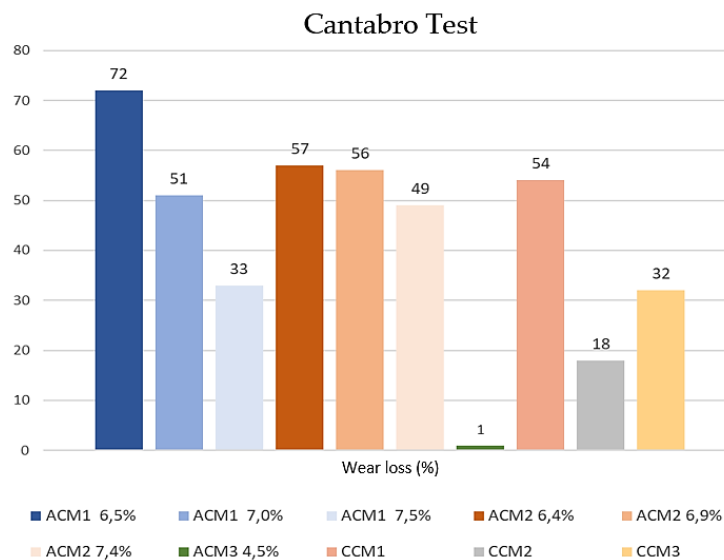


Figure 4. Cantabro Test Results.

Based on this test, the optimum emulsion contents for mixtures ACM1 and ACM2 were defined as 7.5% and 7.4%, respectively. Mixture ACM3 showed excellent performance in the Cantabro test, with a particle loss of only 1%.

The commercial mixtures analyzed exhibited distinct behaviors in the Cantabro test, highlighting significant variability in performance. CCM2 showed the lowest wear loss, indicating greater resistance to raveling. In contrast, CCM1 presented high values, suggesting lower cohesion, whereas CCM3 showed intermediate behavior. These results demonstrate that the commercial solutions available on the market do not provide uniform performance, making prior evaluation essential for rapid repair applications.

### 3.2. Marshall Test

Table 4 presents the Marshall test results, expressed as the average of five specimens, for the mixtures produced in the laboratory (ACM1, ACM2, and ACM3). Regarding the commercial mixtures, results could only be obtained for CCM2, since the specimens prepared from the remaining mixtures disintegrated during testing.

Table 4. Mechanical and volumetric properties of the developed cold mixtures.

Bituminous Mixtures	Bitumen [%]	Bulk Density [kg/m <sup>3</sup> ]	Marshall Stability [kN]	Marshall Flow [mm]	VMA [%]	Porosity [%]
ACM1	7.5	2079	8.1	2.0	40.5	24.8
ACM2	7.4	2103	6.2	1.6	40.7	24.9
ACM3	4.5	2054	3.5	1.2	29.0	19.9
CCM2	3.5	1732	2,9	3,5	23.7	12.9
CCM3		1799			42.6	31.3
Portuguese road requirements	> 4.0	-	7.5–15	2–4	>14	22-30

The experimental results reveal substantial differences in the mechanical and volumetric behavior of the asphalt mixtures studied with respect to the requirements established for road applications. Mixture ACM1 showed overall compliant performance, simultaneously meeting the criteria for Marshall stability, with a value of 8.1 kN, flow, with 2.0 mm, and air void content, with 24.8%, indicating an adequate balance between internal cohesion and deformation capacity. In contrast, ACM2, although meeting the volumetric requirements, exhibited a stability value below the specified minimum of 6.2 kN and a flow value of 1.6 mm, suggesting a stiffer behavior and a potential tendency to crack under repeated traffic loading. ACM3 showed clearly insufficient performance, characterized by low stability, 3.5 kN, and an air void content below the recommended range, 19.9%, which may indicate an excessively dense structure, with an increased risk of bleeding and loss of functional performance.

Regarding the commercial mixtures, CCM2 presented a binder content lower than the reference value of 3.5%, which was reflected in a low Marshall stability of 2.9 kN, although its flow value remained within the admissible range, 3.5 mm, indicating limited resistance to permanent deformation and reduced cohesion. CCM3, although with incomplete mechanical data, showed a high air void content, 31.3%, suggesting an open granular structure, susceptible to high permeability and consequent reduction in service durability. Overall, the results confirm the strong dependence of mechanical performance on binder content, with mixtures containing higher bitumen contents tending to exhibit greater stability and cohesion. In addition, significant deviations in volumetric parameters, particularly air void content, were shown to have a decisive influence on the functional behavior of the mixtures, compromising both resistance to permanent deformation and durability under water and traffic action.

Since no minimum requirements are defined for cold open graded mixtures, the Marshall test results were compared with those established for AC14 Surf (Asphalt concrete 14 surface) mixtures. In the case of air void content, the reference limits adopted correspond to the hot mix porous asphalt PA12.5.

### 3.3. Stiffness Modulus

Table 5 presents the average stiffness modulus of five specimens obtained for the three formulated cold asphalt mixtures and for the commercial mixture CCM2. Among the evaluated formulations, ACM3 exhibited the lowest stiffness modulus, at 210 MPa, indicating a more flexible behavior. In contrast, mixtures ACM1 and ACM2 showed higher stiffness values, 1030 MPa and 642 MPa, respectively, reflecting a stiffer response. CCM2 was the only commercial mixture for which results could be obtained, since the specimens of the remaining commercial mixtures disintegrated during testing, yielding a stiffness modulus of 592 MPa. Overall, these results confirm that increasing stiffness reduces mixture flexibility. However, the lower modulus observed for ACM3 may be advantageous in pothole repair applications, since greater flexibility can reduce cracking susceptibility and the subsequent risk of raveling in service.

**Table 5.** Stiffness modulus (average of 5 specimens).

Asphalt Mixtures	Stiffness Modulus [MPa]
ACM1	1030
ACM2	642
ACM3	210
CCM2	592

### 3.4. Water Sensitivity

The water sensitivity results are presented in Figure 5, which shows the indirect tensile strength (ITS) measured under dry conditions and after immersion, as well as the corresponding indirect tensile strength ratio (ITSR), calculated from Equation (4). Overall, the conditioning protocol

produced distinct responses depending on mixture composition. ACM1 showed an increase in ITS after immersion, rising from 330 kPa under dry conditions to 410 kPa under immersed conditions, resulting in an ITSR of 124%. ACM2 decreased from 310 kPa to 280 kPa, with an ITSR of 90%, while ACM3 decreased from 70 kPa to 50 kPa, yielding an ITSR of 71%. CCM2 remained unchanged at 90 kPa, resulting in an ITSR of 100%. Although Estradas de Portugal (2014) does not establish specific ITSR limits for cold asphalt mixtures, minimum values of 75% for MBA-BBA and 65% for MBR-BBR are defined for surface courses, and the developed mixtures meet these reference requirements.

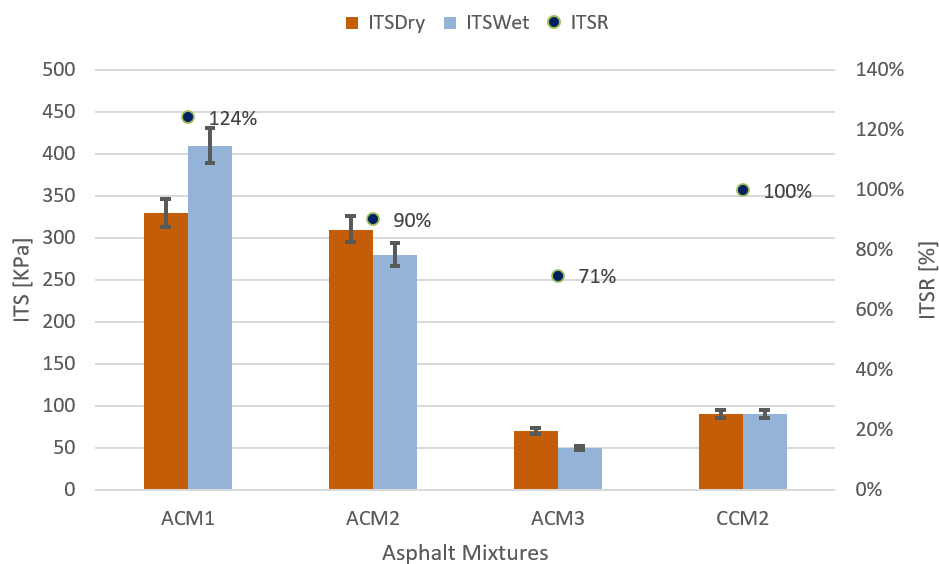


Figure 5. Water sensitivity test: ITS (kPa) and ITSR (%) (average of 4 specimens).

#### 4. Discussion

The results show that cold asphalt mixtures with RAP and Panasqueira mine waste are strongly influenced by recycled material content, binder type, additive selection, and aggregate structure. ACM1 presented the best overall balance, meeting the reference limits for stability, flow, and air voids, while also showing high stiffness and excellent water resistance. ACM2 performed adequately but requires adjustment due to its lower stability and reduced deformation capacity, whereas ACM3 showed very low particle loss and greater flexibility, although with limited structural performance. Overall, the use of RAP and greywacke aggregates represents a technically viable alternative for localized pavement repair, supporting previous studies that highlight the performance and sustainability benefits of incorporating reclaimed materials and industrial by products in pavement construction [4,8,48–52].

In terms of aggregate quality, greywacke was not a limiting factor. The material exhibited excellent resistance to fragmentation, with a Los Angeles value of 8.8%, comfortably satisfying national road requirements [41], thus confirming its suitability as a durable granular skeleton for cold repair mixtures. This high particle resistance is particularly relevant in localized patches, where braking actions, wheel loads, and vehicle maneuvers may intensify abrasion and accelerate raveling if the aggregate skeleton is weak [53–55]. Therefore, the mechanical quality of the Panasqueira greywacke supports its use as a sustainable aggregate source, while also contributing to circular economy objectives through the valorization of mining waste [18,27].

Binder and additive selection had a direct influence on the mechanical response and durability potential of the studied mixtures. In ACM1 and ACM2, the use of C67BF3 cationic emulsion required careful control of coating, adhesion, and early cohesion, since emulsion based cold mixtures develop strength through binder aggregate bonding, demulsification, and water loss. This agrees with Pi et al. [56], who reported that the strength of emulsified asphalt cold mixtures depends on aggregate

gradation, emulsion content, moisture evolution, and additive selection. Similarly, Al-Mohammedawi and Mollenhauer [57] showed that the chemical nature of fillers affects the rheological behavior of bitumen emulsion mastics, supporting the role of hydraulic lime in improving cohesion and stabilizing the fine fraction. In this study, Iterlene was essential to improve the affinity between the cationic emulsion and the greywacke aggregates, achieving complete coating, which is critical for moisture resistance and early integrity. By contrast, ACM3, composed entirely of RAP and produced with IterBflux Cold, exhibited very low Cantabro particle loss, at 1%, indicating strong internal cohesion and reduced susceptibility to raveling. This behavior is consistent with Hafezzadeh et al. [4], who found that flux oil and RAP content significantly influence the workability, compactability, stability, and strength of cold patching materials, and with Geng et al. [58], who demonstrated that cold patch binder systems can improve practical performance in pothole repair mixtures.

For the Marshall test, ACM1 showed the most suitable response, reaching the required stability, flow, and air void limits, which indicates adequate cohesion and deformation capacity for rapid repair interventions. Compared with ACM1, ACM2 presented lower stability and reduced flow, suggesting a stiffer and less deformable structure, while ACM3 showed the lowest Marshall stability despite its excellent Cantabro performance. This indicates that high resistance to particle loss does not necessarily imply sufficient load bearing capacity. This is consistent with Zhang et al. [59], who reported that cold patch asphalt mixtures modified with SEBS achieved higher Marshall stability and better residual stability than unmodified mixtures, confirming the importance of binder modification in mechanical performance. Compared with Zhou et al. [60], who observed that Marshall stability in cold mixed modified asphalt increased with curing time and was affected by diluent content, the lower stability of ACM3 may be related to the specific behavior of the fluxing binder and the need for further curing optimization. In addition, Liu et al. [61] showed that cold mix epoxy asphalt systems require careful formulation of binder components to achieve early strength and adequate workability, which supports the superior mechanical balance observed in ACM1 compared with the other laboratory and commercial mixtures.

For the stiffness modulus, the formulated mixtures showed a clear dependence on mixture composition, binder type, and aggregate structure. ACM1 exhibited the highest stiffness modulus, with 1030 MPa, followed by ACM2 with 642 MPa, reflecting a stiffer response and greater structural support capacity associated with the rigid granular skeleton provided by the Panasqueira greywacke aggregates, together with the contribution of the cationic emulsion and hydraulic lime to binder aggregate interaction and early cohesion. This behavior agrees with W. Zhang et al. [6], who reported that the stiffness of emulsion stabilized cold recycled mixtures is strongly affected by filler type, internal suction, and the mechanical interaction between constituents, and with Bao et al. [10], who observed that stiffness development in cold recycled mixtures is closely related to curing and water loss. In contrast, ACM3 presented a substantially lower modulus, 210 MPa, indicating a more flexible response, which may be attributed to the exclusive use of RAP combined with a fluxing cold binder, allowing greater deformability despite the presence of aged binder. Similar trends were noted by Bi et al. [62], who emphasized that the performance of cold patching asphalt mixtures depends strongly on binder formulation, adhesion development, and cohesion. The commercial mixture CCM2 exhibited an intermediate stiffness modulus of 592 MPa, below ACM1 and ACM2 but above ACM3, suggesting that ACM2 can reproduce a stiffness response comparable to a market available solution.

Water sensitivity, evaluated through ITS and ITSR, showed that the formulated mixtures maintained acceptable moisture resistance despite their different compositions. ACM1 presented the best response, with an ITSR of 124%, indicating that immersion did not weaken the mixture and may have favored additional cohesion development during conditioning. ACM2 also showed good moisture resistance, with an ITSR of 90%, while ACM3 reached 71%, remaining above the reference value commonly adopted for mixtures containing reclaimed materials. Compared with Jin et al. [63], who reported that moisture conditioning can reduce stiffness and accelerate damage in cold recycled asphalt mixtures, the results obtained for ACM1 and ACM2 indicate a more stable response under

water action, probably due to the combined effect of hydraulic lime, cationic emulsion, and improved binder aggregate adhesion. This is also consistent with Eleyedath et al. [64], who highlighted that lime or cement additives can improve the moisture resistance of cold recycled mixtures. Therefore, the ITSR results confirm that adequate binder selection, active filler incorporation, and aggregate coating are essential to preserve durability in cold mixtures for emergency maintenance applications.

Overall, the laboratory formulations demonstrated different but complementary performance profiles. ACM1 showed the most complete performance profile, combining adequate Marshall behavior, high stiffness, and excellent moisture resistance. ACM2 showed a comparable structural response to CCM2 but requires improvement in stability and deformation capacity. ACM3 presented the highest resistance to particle loss and the greatest flexibility, although its limited Marshall response indicates the need for further optimization before structural application. These findings confirm that cold repair mixtures with high recycled content can achieve technically promising performance, provided that gradation, binder compatibility, aggregate coating, and curing conditions are carefully controlled.

## 5. Conclusions and Recommendations

This study developed and experimentally evaluated cold asphalt mixtures for rapid pavement repair, with a focus on pothole patching and the valorization of recycled materials and industrial by products, particularly reclaimed asphalt pavement and greywacke waste from the Panasqueira mine. The inclusion of three commercial mixtures provided a comparative benchmark to assess the technical performance of the laboratory formulations.

The testing program, including Cantabro particle loss, Marshall stability and flow, stiffness modulus, and water sensitivity, confirmed that cold repair mixtures can be technically viable when gradation, aggregate morphology, binder content, and binder aggregate compatibility are properly adjusted. Under these conditions, the mixtures can achieve workability, mechanical strength, and durability potential suitable for emergency maintenance interventions [15,65].

From a materials standpoint, the greywacke aggregates showed very high resistance to fragmentation, with a Los Angeles value of 8.8%, meeting the Portuguese Road Administration requirement [41]. This confirms their suitability as a durable granular skeleton for cold mixtures. The stiffness modulus results revealed clear differences among the formulations: ACM1 reached the highest modulus, with 1030 MPa, followed by ACM2 with 642 MPa, while ACM3 showed a much lower modulus of 210 MPa. Therefore, ACM1 and ACM2 provided greater structural support capacity, whereas ACM3 showed higher flexibility, which may be advantageous in pothole repair by reducing cracking susceptibility and subsequent raveling under localized stresses.

The commercial mixtures showed significant variability in performance. Two of them could not be subjected to the planned tests because of their high susceptibility to raveling, revealing insufficient cohesion to maintain specimen integrity during preparation and testing. This behavior limits their applicability in rapid repair interventions. In contrast, CCM2 exhibited a stiffness modulus of 592 MPa, placing it below ACM1 and ACM2, but above ACM3, which indicates an intermediate and relatively flexible response compatible with emergency repair applications.

Regarding moisture performance, the mixtures with valid ITSR results achieved acceptable strength retention when compared with reference limits commonly used for surface course mixtures. ACM1 and ACM2 presented ITSR values of 124% and 90%, respectively, while ACM3 reached 71%, remaining above the 65% reference level often adopted for mixtures containing reclaimed material. In comparative terms, CCM2 presented an ITSR of 100%, demonstrating good resistance to water action and positioning itself in line with current market solutions.

The results highlight the importance of selecting and ensuring compatibility of the binder system, since in emulsion-based mixtures, performance strongly depends on adhesion and the initial development of cohesion [66]. In this context, Iterlene was decisive in the greywacke mixtures by ensuring complete aggregate coating, while the IterBflux Cold system, used in the mixture composed exclusively of RAP, showed a consistent cohesion response and excellent resistance to particle loss.

Cantabro particle loss revealed both the main limitation and the main strength among the studied designs. ACM1 and ACM2 exceeded the maximum limit of 25% suggested by the Portuguese Road Administration specifications for cold mixtures, indicating susceptibility to raveling. In contrast, ACM3 showed remarkable performance, with only 1% loss, making it particularly promising for rapid patching where initial integrity is critical. CCM2 recorded a Cantabro loss of 18%, indicating a more conservative behavior compared with the laboratory formulations and reflecting the typical tradeoff between durability and ease of application.

Overall, ACM1 was identified as the most balanced formulation for rapid pothole repair, combining adequate Marshall performance, high stiffness, and excellent moisture resistance. ACM3 showed the best resistance to particle loss and the highest flexibility, but its limited structural response indicates the need for further optimization. Therefore, the use of RAP and Panasqueira greywacke waste is technically promising, provided that binder compatibility, aggregate coating, and curing conditions are carefully controlled [67].

As recommendations for future work, the variability of RAP sources and milling processes should be evaluated, since the origin and heterogeneity of the reclaimed material may significantly influence mixture behavior. The storage stability of the mixtures should also be analyzed under controlled and field conditions to define shelf life and conservation procedures suitable for emergency use. Finally, full scale field trials under different climates, traffic levels, and pavement conditions are necessary to validate the laboratory trends, with particular attention to in situ compactability, adhesion to the existing pavement, moisture resistance, raveling evolution, and long-term performance.

**Author Contributions:** Conceptualization P.C.F.L., H.P.M.A., and M.S.F.D.A.; methodology, P.C.F.L., H.P.M.A., and M.S.F.D.A.; validation, M.S.F.D.A.; formal analysis, P.C.F.L., H.P.M.A., and M.S.F.D.A.; investigation, P.C.F.L., H.P.M.A., and M.S.F.D.A.; writing—original draft preparation, P.C.F.L., H.P.M.A., and M.S.F.D.A.; writing—review and editing, P.C.F.L., H.P.M.A., and M.S.F.D.A.; supervision, M.S.F.D.A. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work is supported with Portuguese national funds by FCT—Foundation for Science and Technology, I.P. in the C-MADE. This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data are available upon request.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. J. Li, M. Li, and H. Wu, "Key Performance Analysis of Emulsified Asphalt Cold Recycling Mixtures of the Middle Layer of Pavement Structure," *Materials* 2023, Vol. 16, Page 1613, vol. 16, no. 4, p. 1613, Feb. 2023, doi: 10.3390/MA16041613.
2. Y. Qiao, A. R. Dawson, T. Parry, G. Flintsch, and W. Wang, "Flexible Pavements and Climate Change: A Comprehensive Review and Implications," *Sustainability* 2020, Vol. 12, Page 1057, vol. 12, no. 3, p. 1057, Feb. 2020, doi: 10.3390/SU12031057.
3. E. Mączka and P. Mackiewicz, "Asphalt Mixtures and Flexible Pavement Construction Degradation Considering Different Environmental Factors," *Applied Sciences* 2022, Vol. 12, Page 12068, vol. 12, no. 23, p. 12068, Nov. 2022, doi: 10.3390/APP122312068.
4. R. Hafezzadeh, F. Autelitano, and F. Giuliani, "Asphalt-based cold patches for repairing road potholes – An overview," *Constr. Build. Mater.*, vol. 306, p. 124870, Nov. 2021, doi: 10.1016/J.CONBUILDMAT.2021.124870.

5. S. Kocak and S. W. Haider, "Performance and cost evaluations of 100% recycled hot asphalt mixtures for pothole patching applications in flexible pavements," *Constr. Build. Mater.*, vol. 392, p. 131921, Aug. 2023, doi: 10.1016/J.CONBUILDMAT.2023.131921.
6. W. Zhang, S. Zuo, K. Zhang, Z. Liu, Y. Sun, and B. Ding, "Second Distress Mechanism of Repaired Potholes and Performance Evaluation of Repair Techniques from Multiple Perspectives," *Coatings 2025, Vol. 15, Page 1188*, vol. 15, no. 10, p. 1188, Oct. 2025, doi: 10.3390/COATINGS15101188.
7. Y. S. Jweihan, M. J. Al-Kheetan, and M. Rabi, "Empirical Model for the Retained Stability Index of Asphalt Mixtures Using Hybrid Machine Learning Approach," *Applied System Innovation 2023, Vol. 6, Page 93*, vol. 6, no. 5, p. 93, Oct. 2023, doi: 10.3390/ASI6050093.
8. S. Bruno et al., "Maintenance and Safety of the Road Infrastructure by a New Robotised System for Pothole Repair," *Lecture Notes in Mobility*, vol. Part F903, pp. 463–469, 2026, doi: 10.1007/978-3-031-88974-5\_68/FIGURES/3.
9. M. M. fawzy, A. shawky el shrakawy, A. atef Hassan, and Y. ali khalifa, "Enhancing sustainability for pavement maintenance decision-making through image processing-based distress detection," *Innovative Infrastructure Solutions 2024 9:3*, vol. 9, no. 3, pp. 58–, Feb. 2024, doi: 10.1007/S41062-024-01370-3.
10. L. Bao, R. Guo, and F. Yan, "Effect of Biodiesel on Performance of Cold Patch Asphalt Mixtures," *Materials 2024, Vol. 17, Page 5566*, vol. 17, no. 22, p. 5566, Nov. 2024, doi: 10.3390/MA17225566.
11. Y. Bi, R. Li, S. Han, J. Pei, and J. Zhang, "Development and Performance Evaluation of Cold-Patching Materials Using Waterborne Epoxy-Emulsified Asphalt Mixtures," *Materials 2020, Vol. 13, Page 1224*, vol. 13, no. 5, p. 1224, Mar. 2020, doi: 10.3390/MA13051224.
12. R. Hafezzadeh, F. Autelitano, and F. Giuliani, "Performance-related methods for the characterization of cold mix patching materials used in asphalt pavements maintenance," *Case Studies in Construction Materials*, vol. 19, p. e02600, Dec. 2023, doi: 10.1016/J.CSCM.2023.E02600.
13. Z. Suo, S. Xu, T. Hu, Y. Zhang, Y. Wang, and S. Yang, "Study on Performance of Reactive Diluted Cold Patch Asphalt Fluid," *Lecture Notes in Civil Engineering*, vol. 535, pp. 115–130, 2025, doi: 10.1007/978-981-97-6238-5\_10/TABLES/3.
14. H. Nanda and A. K. Siddagangaiah, "Effect of RAP fractionation and dosage on design and mechanical behaviour of cold asphalt mixes," *Constr. Build. Mater.*, vol. 422, p. 135773, Apr. 2024, doi: 10.1016/J.CONBUILDMAT.2024.135773.
15. K. A. Boateng, Y. A. Tuffour, D. Obeng-Atuah, and S. Agyeman, "Quality of cold-mix asphalt in bituminous pavement maintenance in Ghana: Preliminary indications," *Case Studies in Construction Materials*, vol. 15, p. e00769, Dec. 2021, doi: 10.1016/J.CSCM.2021.E00769.
16. A. Dulaimi et al., "A Sustainable Cold Mix Asphalt Mixture Comprising Paper Sludge Ash and Cement Kiln Dust," *Sustainability 2022, Vol. 14, Page 10253*, vol. 14, no. 16, p. 10253, Aug. 2022, doi: 10.3390/SU141610253.
17. Y. Li, Y. Lyv, L. Fan, and Y. Zhang, "Effects of Cement and Emulsified Asphalt on Properties of Mastics and 100% Cold Recycled Asphalt Mixtures," *Materials 2019, Vol. 12, Page 754*, vol. 12, no. 5, p. 754, Mar. 2019, doi: 10.3390/MA12050754.
18. H. P. Moyano-Ayala and M. S. F. Dinis-Almeida, "Mechanical Performance of Sustainable Asphalt Mixtures Incorporating RAP and Panasqueira Mine Waste," *Construction Materials 2025, Vol. 5, Page 52*, vol. 5, no. 3, p. 52, Aug. 2025, doi: 10.3390/CONSTRMATER5030052.
19. A. Tamimi et al., "Waste By-Products in Asphalt Concrete Pavement Construction: A Review," *Materials 2025, Vol. 18, Page 4092*, vol. 18, no. 17, p. 4092, Sep. 2025, doi: 10.3390/MA18174092.
20. K. Mantalovas, F. Graziano, R. Teresi, M. C. Mangano, G. Sarà, and C. Celauro, "Life Cycle Assessment of Asphalt Mixtures Incorporating Secondary Raw Materials Under a Circular Economy Perspective," *Sustainability 2025, Vol. 17, Page 10869*, vol. 17, no. 23, p. 10869, Dec. 2025, doi: 10.3390/SU172310869.
21. J. Choudhary, B. Kumar, and A. Gupta, "Utilization of solid waste materials as alternative fillers in asphalt mixes: A review," *Constr. Build. Mater.*, vol. 234, p. 117271, Feb. 2020, doi: 10.1016/J.CONBUILDMAT.2019.117271.

22. A. C. Raposeiras, D. Movilla-Quesada, O. Muñoz-Cáceres, V. C. Andrés-Valeri, and M. Lagos-Varas, "Production of asphalt mixes with copper industry wastes: Use of copper slag as raw material replacement," *J. Environ. Manage.*, vol. 293, p. 112867, Sep. 2021, doi: 10.1016/J.JENVMAN.2021.112867.
23. K. Zhang, W. Zhang, W. Xie, Y. Luo, and G. Wei, "Investigation of mechanical properties, chemical composition and microstructure for composite cementitious materials containing waste powder recycled from asphalt mixing plants," *Journal of Building Engineering*, vol. 96, p. 110362, Nov. 2024, doi: 10.1016/J.JOBE.2024.110362.
24. M. Sukhija and E. Coleri, "A systematic review on the role of reclaimed asphalt pavement materials: Insights into performance and sustainability," *Cleaner Materials*, vol. 16, p. 100316, Jun. 2025, doi: 10.1016/J.CLEMA.2025.100316.
25. Y. Song et al., "High-quality utilization of reclaimed asphalt pavement (RAP) in asphalt mixture with the enhancement of steel slag and epoxy asphalt," *Constr. Build. Mater.*, vol. 445, p. 137963, Sep. 2024, doi: 10.1016/J.CONBUILDMAT.2024.137963.
26. A. Elnihum, Q. Lu, M. Alharthai, M. Alamri, C. Chen, and A. Elmagarhe, "Evaluation of an Asphalt Mixture Containing a High Content of Reclaimed Asphalt Pavement (RAP) Materials with Epoxy Asphalt," *Sustainability 2024, Vol. 16, Page 4988*, vol. 16, no. 12, p. 4988, Jun. 2024, doi: 10.3390/SU16124988.
27. C. Marignac, M. Cuney, M. Cathelineau, A. Lecomte, E. Carocci, and F. Pinto, "The Panasqueira Rare Metal Granite Suites and Their Involvement in the Genesis of the World-Class Panasqueira W-Sn-Cu Vein Deposit: A Petrographic, Mineralogical, and Geochemical Study," *Minerals 2020, Vol. 10, Page 562*, vol. 10, no. 6, p. 562, Jun. 2020, doi: 10.3390/MIN10060562.
28. M. Mateus, F. Noronha, and F. Pinto, "The Panasqueira Mine (Portugal): a landmark in W (-Sn-Cu) mining and geological research." Accessed: Apr. 24, 2026. [Online]. Available: [https://www.researchgate.net/publication/391768972\\_The\\_Panasqueira\\_Mine\\_Portugal\\_a\\_landmark\\_in\\_W\\_-Sn-Cu\\_mining\\_and\\_geological\\_research](https://www.researchgate.net/publication/391768972_The_Panasqueira_Mine_Portugal_a_landmark_in_W_-Sn-Cu_mining_and_geological_research)
29. L. S. V. E. Monteiro, B. S. Bandarra, M. J. Quina, and P. A. L. F. Coelho, "A multidisciplinary evaluation of mixtures of municipal solid waste incineration bottom ash and mine tailings for sustainable geotechnical solutions," *Constr. Build. Mater.*, vol. 455, p. 139139, Dec. 2024, doi: 10.1016/J.CONBUILDMAT.2024.139139.
30. A. Solouki, G. Viscomi, R. Lamperti, and P. Tataranni, "Quarry Waste as Precursors in Geopolymers for Civil Engineering Applications: A Decade in Review," *Materials 2020, Vol. 13, Page 3146*, vol. 13, no. 14, p. 3146, Jul. 2020, doi: 10.3390/MA13143146.
31. CEN—European Committee for Standardization, "EN 933-1:2012; Tests for Geometrical Properties of Aggregates-Part 1: Determination of Particle Size Distribution-Sieving Method.," *Brussels, Belgium*, 2018, Accessed: Apr. 24, 2026. [Online]. Available: [https://standards.iteh.ai/catalog/standards/cen/100b983f-85a4-4a80-934c-e93c584dbdb4/en-933-1-2012?srsId=AfmBOopNdLqu051OZ95mNmBGqhoEZavu2fYBmNJuf\\_fkxjaatCjKInrd](https://standards.iteh.ai/catalog/standards/cen/100b983f-85a4-4a80-934c-e93c584dbdb4/en-933-1-2012?srsId=AfmBOopNdLqu051OZ95mNmBGqhoEZavu2fYBmNJuf_fkxjaatCjKInrd)
32. CEN—European Committee for Standardization, "EN 13075-1:2016; Bitumen and Bituminous Binders—Determination of Breaking Behaviour—Part 1: Determination of Breaking Value of Cationic Bituminous Emulsions, Mineral Filler Method," *Brussels, Belgium*. Accessed: Apr. 24, 2026. [Online]. Available: [https://standards.iteh.ai/catalog/standards/cen/5ed21851-dd43-4a81-827c-385904644f19/en-13075-1-2016?srsId=AfmBOoqUsvuVk\\_4KeienPW9EYDCTWcCcGjE-McvPoOfjd3rDhP8qh46v](https://standards.iteh.ai/catalog/standards/cen/5ed21851-dd43-4a81-827c-385904644f19/en-13075-1-2016?srsId=AfmBOoqUsvuVk_4KeienPW9EYDCTWcCcGjE-McvPoOfjd3rDhP8qh46v)
33. CEN—European Committee for Standardization, "EN 1431:2018; Bitumen and Bituminous Binders—Determination of Residual Binder and Oil Distillate from Bitumen Emulsions by Distillation.," *Brussels, Belgium*. Accessed: Apr. 24, 2026. [Online]. Available: [https://standards.iteh.ai/catalog/standards/cen/8e818c03-dd9a-4ce6-80d5-d8d41d85a81e/en-1431-2018?srsId=AfmBOoqfMB9UUfZ3cBt6\\_Pa\\_hNGJWNbbIv-g1D8wT1SipdgiQIANavZI](https://standards.iteh.ai/catalog/standards/cen/8e818c03-dd9a-4ce6-80d5-d8d41d85a81e/en-1431-2018?srsId=AfmBOoqfMB9UUfZ3cBt6_Pa_hNGJWNbbIv-g1D8wT1SipdgiQIANavZI)
34. CEN—European Committee for Standardization, "EN 12846-1:2022; Bitumen and Bituminous Binders—Determination of Efflux Time by the Efflux Viscometer—Part 1: Bituminous Emulsions," *Brussels, Belgium*. Accessed: Apr. 24, 2026. [Online]. Available: <https://standards.iteh.ai/catalog/standards/cen/beb6fbcc-ed98-4499-8bef-ac4f625f094d/en-12846-1-2022?srsId=AfmBOopQRFeCwHygMbTo5vPigJN6CpVWQU1ZdwUq-pueaqrN6bkoQboE>

35. CEN—European Committee for Standardization, “EN 1429:2013; Bitumen and Bituminous Binders—Determination of Residue on Sieving of Bituminous Emulsions, and Determination of Storage Stability by Sieving,,” Brussels, Belgium. Accessed: Apr. 24, 2026. [Online]. Available: <https://standards.iteh.ai/catalog/standards/cen/c4a9f5dd-3755-4e91-b1b1-ead18c0fdc12/en-1429-2013?srsId=AfmBOooawoPJ4ZAt1YU09OQoEKcIR6B2iXkRlqoBl65SJ1pmPIpAyRZt>
36. CEN—European Committee for Standardization, “EN 12847:2022; Bitumen and Bituminous Binders—Determination of Settling Tendency of Bituminous Emulsions,,” Brussels, Belgium. Accessed: Apr. 24, 2026. [Online]. Available: <https://standards.iteh.ai/catalog/standards/cen/61c6a04e-e29b-46b4-9041-4a572a856081/en-12847-2022?srsId=AfmBOopVBbcapaPJJQE8hQ58ELLTiA58R2WUYkGFNtzq6Mj6ge0hHRA>
37. CEN—European Committee for Standardization, “EN 12697-1:2020; Bituminous Mixtures—Test Methods—Part 1: Soluble Binder Content,,” Brussels, Belgium. Accessed: Apr. 24, 2026. [Online]. Available: <https://standards.iteh.ai/catalog/standards/cen/11612a5a-5f05-41cb-869f-a6b8abd60c3f/en-12697-1-2020?srsId=AfmBOoqeLAS0NmnaSQfeYotd4zGnXhGGfiGv2PhKQD8utQvug1ZWIt5N>
38. CEN—European Committee for Standardization, “EN 1426:2024; Bitumens and Bituminous Binders—Determination of Needle Penetration,,” Brussels, Belgium. Accessed: Apr. 24, 2026. [Online]. Available: <https://standards.iteh.ai/catalog/standards/cen/69de2641-b52b-4730-bafa-c50c63f81b12/en-1426-2024?srsId=AfmBOorIPsxfj4CTGyJyjG9YId-6LXL4gX80jLcNkreRzLrAIZa2eDOA>
39. CEN—European Committee for Standardization, “EN 1427:2015; Bitumen and Bituminous Binders—Determination of the Softening Point—Ring and Ball Method,,” Brussels, Belgium. Accessed: Apr. 24, 2026. [Online]. Available: <https://standards.iteh.ai/catalog/standards/cen/0edd2612-e3e1-43b4-b533-8debe5c55040/en-1427-2015?srsId=AfmBOoNldAj4HtLPQIwASicTbfwZ5a2K-UeGlfeUogwfr5B9N-hNfje>
40. CEN—European Committee for Standardization, “EN 1097-2:2020; Tests for Mechanical and Physical Properties of Aggregates—Part 2: Methods for the Determination of Resistance to Fragmentation,,” Brussels, Belgium. Accessed: Apr. 24, 2026. [Online]. Available: [https://standards.iteh.ai/catalog/standards/cen/2b59008c-ab4d-428f-9e85-780705498a57/en-1097-2-2020?srsId=AfmBOopTNXmzrtcbBiq346HutK\\_7oSQRoPnD\\_aBuTtBs6LTr7GJT-qHB](https://standards.iteh.ai/catalog/standards/cen/2b59008c-ab4d-428f-9e85-780705498a57/en-1097-2-2020?srsId=AfmBOopTNXmzrtcbBiq346HutK_7oSQRoPnD_aBuTtBs6LTr7GJT-qHB)
41. S. A. Estradas de Portugal, “Caderno de Encargos Tipo Obra (CETO), 14.03-Pavimentação Características dos Mate-riais.” Accessed: Apr. 24, 2026. [Online]. Available: [https://servicos.infraestruturasdeportugal.pt/sites/default/files/pdfs/infraestruturas/14\\_03\\_set\\_2014.pdf](https://servicos.infraestruturasdeportugal.pt/sites/default/files/pdfs/infraestruturas/14_03_set_2014.pdf)
42. CEN—European Committee for Standardization, “EN 12697-17:2017; Bituminous Mixtures—Test Methods—Part 17: Particle Loss of Porous Asphalt Specimens,,” Brussels, Belgium. Accessed: Apr. 25, 2026. [Online]. Available: <https://standards.iteh.ai/catalog/standards/cen/6be521b4-d355-458b-83bb-11c90a00df2e/en-12697-17-2017?srsId=AfmBOorshvnMQICvV4p4EIVLZ4wHE2JGCEOUVjFzdNmEOFaxH4uoeGCF>
43. CEN—European Committee for Standardization, “EN 12697-34:2020; Bituminous Mixtures—Test Methods—Part 34: Marshall Test,,” Brussels, Belgium. Accessed: Apr. 24, 2026. [Online]. Available: <https://standards.iteh.ai/catalog/standards/cen/3932b867-10ea-4628-9113-dde2768f04b6/en-12697-34-2020?srsId=AfmBOoqqvGygZ4HxQVJzvAf6uU-wIzL6xG36GpM300SNbsEq648Xod8F>
44. CEN—European Committee for Standardization, “EN 12697-6:2020; Bituminous Mixtures—Test Methods—Part 6: Determination of Bulk Density of Bituminous Specimens,,” Brussels, Belgium. Accessed: Apr. 24, 2026. [Online]. Available: [https://standards.iteh.ai/catalog/standards/cen/c02553f4-7a24-43c8-bbcd-6cdb7b516662/en-12697-6-2020?srsId=AfmBOoq5C-bGj51rwLoXP\\_p34Uwohly4r6nxFi7ouYhX3CXutoybA8P0](https://standards.iteh.ai/catalog/standards/cen/c02553f4-7a24-43c8-bbcd-6cdb7b516662/en-12697-6-2020?srsId=AfmBOoq5C-bGj51rwLoXP_p34Uwohly4r6nxFi7ouYhX3CXutoybA8P0)
45. CEN—European Committee for Standardization, “EN 12697-26:2018+A1:2022; Bituminous Mixtures—Test Methods—Part 26: Stiffness,,” Brussels, Belgium. Accessed: Apr. 24, 2026. [Online]. Available: <https://standards.iteh.ai/catalog/standards/cen/4f6c3726-f142-4a05-be4d-ae9f0bbb5fb4/en-12697-26-2018a1-2022?srsId=AfmBOoqUMxJBI5wT4TG91EDk3tRt7CtBD1oWWXgWC5NbCBCRZ77KGo8>
46. CEN—European Committee for Standardization, “EN 12697-12:2018; Bituminous Mixtures—Test Methods—Part 12: Determination of the Water Sensitivity of Bituminous Specimens,,” Brussels, Belgium.

- Accessed: Apr. 24, 2026. [Online]. Available: [https://standards.iteh.ai/catalog/standards/cen/826f6b09-ffd9-4234-955e-690c9ba4eb40/en-12697-12-2018?srsltid=AfmBOooW9\\_bZppe\\_C7yu31XZuSFaE-J7K3avjbcCNQus\\_vSLeY7PP9AE](https://standards.iteh.ai/catalog/standards/cen/826f6b09-ffd9-4234-955e-690c9ba4eb40/en-12697-12-2018?srsltid=AfmBOooW9_bZppe_C7yu31XZuSFaE-J7K3avjbcCNQus_vSLeY7PP9AE)
47. CEN—European Committee for Standardization, “EN 12697-23:2017; Bituminous Mixtures—Test Methods—Part 23: Determination of the Indirect Tensile Strength of Bituminous Specimens,” Brussels, Belgium. Accessed: Apr. 24, 2026. [Online]. Available: <https://standards.iteh.ai/catalog/standards/cen/4920c3b0-a083-4d95-acb7-1c9a3fc1e0c5/en-12697-23-2017?srsltid=AfmBOopOyEgEziL4y6IRB8cPuduxi8kNCgtCeuh18UzQ-5t-SPDvmesM>
  48. J. Yan, H. Liao, X. Yang, X. Du, D. Shi, and H. Lin, “Laboratory Evaluation of Cold Patching Asphalt Mixture with Refined–Processed Recycled Asphalt Pavement,” *Processes* 2025, Vol. 13, Page 869, vol. 13, no. 3, p. 869, Mar. 2025, doi: 10.3390/PR13030869.
  49. J. Neves, A. C. Freire, V. Antunes, C. Carpani, E. Bocci, and M. Bocci, “Characterization of Cold Recycled Asphalt Mixtures including Reinforcing Fibers,” *Sustainability* 2023, Vol. 15, Page 16209, vol. 15, no. 23, p. 16209, Nov. 2023, doi: 10.3390/SU152316209.
  50. T. Wang et al., “Road performance of cold repaired asphalt mixture with new green maintenance materials,” *Case Studies in Construction Materials*, vol. 21, p. e03959, Dec. 2024, doi: 10.1016/J.CSCM.2024.E03959.
  51. X. Xu, K. Gong, A. Sreeram, and Z. Tan, “A novel self-curing active cold patch asphalt mixture: Performance evaluation and mechanism analysis,” *Case Studies in Construction Materials*, vol. 22, p. e04629, Jul. 2025, doi: 10.1016/J.CSCM.2025.E04629.
  52. M. Gajewski, D. Busel, W. Bańkowski, R. Horodecka, and A. Butko, “Optimization of the Composition of Mineral–Asphalt Mixture for Pothole Repairs Based on Reclaimed Asphalt Using Innovative Chemical Activators,” *Materials* 2025, Vol. 18, Page 2848, vol. 18, no. 12, p. 2848, Jun. 2025, doi: 10.3390/MA18122848.
  53. Z. Sun, Y. Ma, S. Liu, Y. Li, X. Qiu, and Z. Luo, “Evaluation of engineering properties of Fiber-reinforced Usual-temperature Synthetic Pitch (USP) modified cold mix patching asphalt,” *Case Studies in Construction Materials*, vol. 16, p. e00997, Jun. 2022, doi: 10.1016/J.CSCM.2022.E00997.
  54. T. Wang et al., “Advanced cold patching materials (CPMs) for asphalt pavement pothole rehabilitation: State of the art,” *J. Clean. Prod.*, vol. 366, p. 133001, Sep. 2022, doi: 10.1016/J.JCLEPRO.2022.133001.
  55. W. Xie, L. Li, and R. Yang, “Multiscale Evaluation System for Cold Patch Asphalt Mixtures: Integrating Macro-Performance Tests and Meso-Structural CT Analysis,” *Applied Sciences* 2025, Vol. 15, Page 7121, vol. 15, no. 13, p. 7121, Jun. 2025, doi: 10.3390/APP15137121.
  56. Y. Pi, Y. Li, Y. Pi, Z. Huang, and Z. Li, “Strength and Micro-Mechanism Analysis of Cement-Emulsified Asphalt Cold Recycled Mixture,” *Materials* 2020, Vol. 13, Page 128, vol. 13, no. 1, p. 128, Dec. 2019, doi: 10.3390/MA13010128.
  57. A. Al-Mohammedawi and K. Mollenhauer, “A Study on the Influence of the Chemical Nature of Fillers on Rheological and Fatigue Behavior of Bitumen Emulsion Mastic,” *Materials* 2020, Vol. 13, Page 4627, vol. 13, no. 20, p. 4627, Oct. 2020, doi: 10.3390/MA13204627.
  58. L. Geng, Q. Xu, X. Yu, C. Jiang, Z. Zhang, and C. Li, “Laboratory performance evaluation of a cold patching asphalt material containing cooking waste oil,” *Constr. Build. Mater.*, vol. 246, p. 117637, Jun. 2020, doi: 10.1016/J.CONBUILDMAT.2019.117637.
  59. Y. Zhang et al., “Investigation of the Water Damage Resistance and Storability of a SEBS-Modified Cold-Patching Asphalt Mixture,” *Polymers* 2022, Vol. 14, Page 5191, vol. 14, no. 23, p. 5191, Nov. 2022, doi: 10.3390/POLYM14235191.
  60. C. Zhou, M. Peng, X. Yang, Y. Qi, and B. Xu, “Study of the Cold Curing Characteristics of Isocyanate-Modified Asphalt,” *Materials* 2024, Vol. 17, Page 1048, vol. 17, no. 5, p. 1048, Feb. 2024, doi: 10.3390/MA17051048.
  61. Y. Liu, Z. Qian, Y. Wang, and Y. Xue, “Development and Laboratory Evaluation of a Cold Mix High-Early-Strength Epoxy Asphalt Concrete for Steel Bridge Deck Pavements,” *Materials* 2021, Vol. 14, Page 4555, vol. 14, no. 16, p. 4555, Aug. 2021, doi: 10.3390/MA14164555.

62. C. Bi, X. Wang, J. Fu, H. Zhao, M. Zheng, and J. Xu, "Study on the Filler Composition Optimization and Performance Evaluation of Cold-Patch Asphalt Mixture," *Materials* 2025, Vol. 18, Page 3894, vol. 18, no. 16, p. 3894, Aug. 2025, doi: 10.3390/MA18163894.
63. D. Jin et al., "Cold In-Place Recycling Asphalt Mixtures: Laboratory Performance and Preliminary M-E Design Analysis," *Materials* 2021, Vol. 14, Page 2036, vol. 14, no. 8, p. 2036, Apr. 2021, doi: 10.3390/MA14082036.
64. A. Eleyedath, A. Ali, and Y. Mehta, "Cold Central Plant Recycling Mixtures for High-Volume Pavements: Material Design, Performance, and Design Implications," *Materials* 2025, Vol. 18, Page 3345, vol. 18, no. 14, p. 3345, Jul. 2025, doi: 10.3390/MA18143345.
65. R. Hafezzadeh, F. Autelitano, and F. Giuliani, "Laboratory investigation of the mechanical and functional properties of cold mix patching materials," *Alexandria Engineering Journal*, vol. 108, pp. 332–343, Dec. 2024, doi: 10.1016/J.AEJ.2024.07.074.
66. H. Y. Huang, X. Han, S. Han, X. Ma, J. Guo, and Y. Huang, "Research Progress on Adhesion Mechanism and Testing Methods of Emulsified Asphalt–Aggregate Interface," *Buildings* 2025, Vol. 15, Page 2611, vol. 15, no. 15, p. 2611, Jul. 2025, doi: 10.3390/BUILDINGS15152611.
67. K. Zhang, J. Xiong, C. Ruiz, and J. Zhang, "Design and performance assessment of sustainable road pothole patching materials using waste cooking oil, plastic, and reclaimed asphalt pavement," *Constr. Build. Mater.*, vol. 429, p. 136426, May 2024, doi: 10.1016/J.CONBUILDMAT.2024.136426.

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.