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Enhancing waste asphalt durability through cold recycling and additive integration

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Abstract
The longevity of waste asphalt can be considerably improved through cold recycling techniques combined with various additives. This research investigates the cold regeneration of aged asphalt concrete using Reclaimed Asphalt Pavement (RAP), Portland cement, cationic bitumen emulsion, and additional aggregates. The primary goal is to evaluate the performance enhancements in terms of average density, compressive strength, water resistance, and swelling across different mix compositions. Three distinct mixtures were formulated and assessed. Mix No. 1, composed solely of RAP, showed the lowest average density and highest swelling, indicating poor performance due to the lack of binding agents. Mix No. 2, which incorporated RAP, Portland cement, and water, exhibited the highest density and compressive strength, highlighting the crucial role of Portland cement in improving structural integrity. Mix No. 3, a more complex mixture including RAP, aggregates, Portland cement, water, and bitumen emulsion, displayed balanced properties with enhanced moisture resistance and reduced swelling. The experimental findings emphasize the effectiveness of adding Portland cement and bitumen emulsion to improve the mechanical and durability characteristics of recycled asphalt mixtures. Specifically, Mix No. 2 and Mix No. 3 demonstrated significant performance improvements, making them suitable for road maintenance applications. This study advocates for the widespread use of cold recycling methods with additive integration to achieve sustainable and cost-effective pavement restoration solutions.

Keywords Cold recycling, Portland cement, Cationic bitumen emulsion, Compressive strength, Water saturation

Introduction

The most common technique to restore or increase pavement strength is to place reinforcement layers on the old pavement. However, this method often proves ineffective, as cracks appear in the new layers within one to two years. Alternatively, the re-laying method, which involves removing cracked layers by milling and laying new ones in their place, provides a service life that aligns with the design life and is more cost-effective due to partial cost recovery from the sale of recycled asphalt (RAP) [1–5].

Cold Recycling (CR) presents numerous advantages. It is environmentally friendly, fully utilizing old pavement material and minimizing the need for new materials and transportation, thereby reducing road damage and overall energy costs. The process ensures high-quality repaired layers through precise, high-quality mixing of materials. It maintains structural integrity with thick, uniform layers and minimal subgrade damage, as recyclers typically complete the process in one pass without contacting the underlying layers. Additionally, CR significantly reduces construction time and costs due to the high productivity of recyclers and enhances safety by allowing partial road use during operations. Furthermore, it can be performed

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at lower temperatures, extending the construction season. These combined benefits make CR a cost-effective and efficient method for road pavement restoration. While the benefits of Cold Asphalt Recycling are notable, it is essential to recognize its potential drawbacks. A primary concern is the variability in the quality of reclaimed asphalt pavement (RAP), which can impact the performance and durability of the recycled pavement. Additionally, the initial investment required for specialized equipment and training for cold recycling processes can be considerable. These aspects, coupled with the necessity for a comprehensive assessment of existing pavement conditions, underscore the need for a balanced approach when considering cold recycling for road pavement projects [6–8].

Cold asphalt recycling, encompassing Cold In-Place Recycling (CIR) and Cold Central Plant Recycling (CCPR), is noted for its sustainable approach, cost efficiency, and effective reuse of existing pavement materials. Cold In-Place Recycling (CIR) involves recycling the existing asphalt pavement directly at the job site. This is achieved by milling the top layers of the pavement and mixing them with recycling agents such as emulsified asphalt, foamed asphalt, or chemical additives. The resulting mixture is then laid back down and compacted to form a new base layer. Conversely, Cold Central Plant Recycling (CCPR) entails transporting the milled asphalt material to a central processing plant, where it is mixed with recycling agents before being transported back to the site for paving. The primary distinction between these methods lies in the location of the recycling process: CIR is performed on-site, whereas CCPR takes place at a central plant. This allows for more controlled processing in CCPR but requires additional transportation. Both methods promote sustainability by reducing the need for new materials and minimizing waste [8]. Recent research highlights numerous advancements and elements of this method. For example, Zhao et al. (2022) reported that cold recycling significantly lowers greenhouse gas emissions and energy consumption compared to traditional hot mix asphalt (HMA) methods, emphasizing its potential for sustainable road construction [9].

Table 1 Aggregate composition of the RAP granulate

Test	Selected Gradation For RAP Aggregate	Specification Limits (STO NOSTROY 2.25.35–2011) [16]
Sieve analysis		
Sieve no		
40	100	90–100
20	78.24	75–100
15	68.41	64–100
10	55.81	52–88
5	44.50	40–60
2.5	33.01	28–60
1.25	26.37	16–60
0.63	18.75	10–60
0.315	13.34	8–37
0.14	7.44	5–20
0.071	3.91	2–8

Recent studies have focused on improving the performance and durability of cold recycled asphalt mixtures (CRAM). Bocci et al. (2023) explored the addition of synthetic fibers to CRAM to boost fatigue resistance and overall mechanical properties, demonstrating that fiber inclusion substantially increases the longevity and durability of recycled pavements, making them better suited for heavy traffic conditions [10]. Similarly, Li et al. (2023) studied the performance of CRAM incorporating electric arc furnace slag (EAFS) and observed enhancements in mechanical properties and microwave heating efficiency [11].

Technological advancements have been crucial in refining cold recycling processes. Contemporary milling machines, fitted with accurate dosing systems for additives, ensure a consistent and high-quality recycled mix. Saidi et al. (2022) assessed CIR mixtures and found them to exhibit excellent resistance to rutting and cracking, confirming their viability for road rehabilitation projects [12]. Practical applications of cold recycling have been observed in various regions, with Lee et al. (2023) evaluating CIR in urban environments and reporting significant cost savings and environmental benefits while maintaining high-performance standards [13]. Haider et al. (2022) in Saudi Arabia also determined that CIR is a more sustainable option for different road types under varying traffic loads [14].

In conclusion, cold asphalt recycling offers a promising approach to sustainable pavement rehabilitation. Its environmental and economic advantages, coupled with continuous technological advancements, make it a compelling choice for road maintenance. Ongoing research and innovation are anticipated to further improve its effectiveness and promote its global adoption.

This study aims to advance and perfect the technology for repairing pavements through the cold regeneration method for aged asphalt concrete. The materials employed in this research comprise recycled asphalt concrete obtained from milling old asphalt concrete pavements, mineral binders like Portland cement, and bitumen emulsion—a low-viscosity liquid bitumen that improves the mix's binding properties.

Materials

Reclaimed Asphalt Pavement (RAP) Granulate Fraction 0/40 mm according to GOST R 55,052−2012 [15] was obtained from milling asphalt concrete pavements during repair work in the city of Moscow, the aggregate composition is shown in Table 1.

Alongside the RAP, the study also incorporated granite crushed stone with a fraction size of 5/20 mm, Portland cement (CEM I 42.5 H), and cationic bitumen emulsion. The characteristics of these materials are outlined in Tables 2, 3 and 4.

Mix composition alternatives

The research examined different formulations of organomineral mixtures, utilizing granulated reclaimed asphalt concrete combined with several types of binding agents. The most favorable property metrics were observed in three specific variants, detailed in Table 5.

Methods

Average density of the compacted sample

The method involves determining the average density of samples, accounting for the pores present in them, using hydrostatic weighing. The samples can be either laboratory-made or taken from the structural layers of road pavements. Laboratory scales equipped with a device for hydrostatic weighing are used.

To begin, weigh the samples in air. Then, submerge the samples from mixtures in a vessel with water at a temperature of (20±2)°C for 30 min, ensuring that the water level is at least 20 mm above the sample surface. Afterward, weigh the samples in water, making sure there are no air bubbles on the samples. For samples from stabilized soils, immerse them in paraffin at a temperature of (60±15)°C before weighing in water. After weighing in water, wipe the samples with a soft cloth and weigh them again in air. The average density of the sample is then calculated is calculated by the following formula (Eq. (1)).

$$\rho_m = \frac{g\rho^B}{g_1 - g_2} \tag{1}$$

where g is the mass of the sample in the air (g); ρ^B is the density of water equal to 1 (g/cm^3); g_1 is the mass of the sample immersed in water (g); g_2 is the mass of the sample kept for 30 min in water and re-suspended in the air (g).

Determination of compressive strength

This method involves determining the load required to fracture a sample under specified conditions. Mechanical or hydraulic presses, with loads ranging from 50 to 500 kN, are equipped with force sensors with a maximum error of 2%. Before testing, samples are thermostated at (50±2)°C, (20±2)°C, or (0±2)°C for 1 h for hot mixes and 2 h in air for mixtures with liquid/emulsified bitumen. For the water-saturated state, samples tested are maintained in water at (20±2)°C before testing.

Table 2 Aggregate 5/20 composition

Test	Selected Gradation For Crushed Stone 5/20	Specification Limits (GOST 8267-93 / GOST 8269.0–97)
Sieve analysis		
Sieve no		
25	100	100
20	95.45	80–100
15	80.16	70–95
12.5	58.19	40–75
10	44.75	35–55
5	4.05	3–10
2.5	1.56	1–5
1.25	1.56	1–5
0.63	1.56	1–5
0.315	1.56	1–5
0.1	1.56	1–5
0.071	1.56	1–5

Table 3 Characteristics of Portland Cement

Property Name	GOST 31,108 – 2003 Requirement [17]	Indicator Value
Fineness (residue on 0.08 mm sieve)	up to 10%	5.3
Residue on 0.05 mm sieve	not standardized	4.6
Compressive strength at 2 days, MPa	not less than 9	10.2
Compressive strength at 2 days, MPa	not less than 10	11.2
Compressive strength at 28 days, MPa	not less than 42.5	59.6
Compressive strength at 28 days, MPa	not less than 62.5	59.6
Initial setting time	not earlier than 60 min	2:15
Uniformity of volume change, mm	not more than 10	7.0

Table 4 Properties of Cationic Bitumen Emulsion of the 3rd class (EBK-3) according to GOST R 52,128 – 2003 [18]

Property	GOST *R* 52,128 – 2003 Requirement [18]	Indicator Value
Binder content with emulsifier, % by mass	from 55 to 60	57.40
Residue on sieve No. 014, % by mass	not more than 0.25	0.20
Conditional viscosity at 20 °C, s	from 15 to 25	17
Adhesion with mineral materials, points	not less than 4	5
Stability during storage, %	not more than 0.3 after 7 days	0.25
Properties of residue after water evaporation from emulsion:		
Penetration depth of the needle, 0.1 mm at 25 °C / 0 °C	not less than 90 / not less than 4	98/30
Softening point, °C	not lower than 43	45
Ductility, cm at 25 °C / 0 °C	not less than 65 / not less than 4	90/5.0

The compressive strength limit is determined using presses with a platen speed of (3.0±0.3) mm/min. The sample is centered on the press platen, and the upper platen is lowered to 1.5–2 mm above the sample before

Table 5 Compositions of asphalt mixtures

Materials	Mix No. 1	Mix No. 2	Mix No. 3
RAP 0/40	100%	95.1%	83.3%
Aggregate 5/20	-	-	9.5%
Portland cement (CEM I 42.5 H)	-	2.9%	2.4%
Water	-	2%	1.9%
Bitumen Emulsion (EBK-3)	-	-	2.9%
Total	100%	100%	100%

loading begins. A hinge device with a ball and metal plates ensures even load distribution if the sample bases are non-parallel. The maximum force sensor reading is recorded as the breaking load.

The compressive strength limit, in MPa, is calculated using the formula (Eq. (2)):

$$R_c = \frac{P}{F} 10^{-2} \tag{2}$$

where:

P is the breaking load, in N; F is the initial cross-sectional area of the sample, in cm^2; 10^{-2} is the conversion factor to MPa.

Determination of water resistance coefficient

The method involves assessing the degree of compressive strength reduction of samples after exposure to water under vacuum conditions and determining the ratio of compressive strength after long-term water saturation. For the initial water resistance test, samples are saturated in a vacuum setup (*Kp*) is calculated to the second decimal place using the formula (Eq. (3)):

$$Kp = \frac{R_c^B}{R_C^{20}} \tag{3}$$

where R_c^B is the compressive strength of samples conditioned by vacuum saturation with water at a temperature of (20±2) ∘C for 1- hour (MPa); and R_C^{20} is the compressive strength at (20±2) °C of samples before water saturation, in MPa.

For the determination of water resistance after long-term water saturation, samples are saturated in a vacuum setup and then transferred to another vessel with water, maintained at a temperature of (20±5) °C for 15 days. After this period, the samples are removed and wiped, and their compressive strength is determined. water resistance coefficient (*Kv*) after long-term water saturation is calculated using the formula (Eq. (4)):

$$Kp = \frac{R_c^{Bl}}{R_C^{20}} \tag{4}$$

where R_c^{Bl} is the compressive strength at (20±2)°C of samples after 15 days of water saturation, in MPa; and R_C^{20} is the compressive strength at (20±2)°C of samples before water saturation, in MPa.

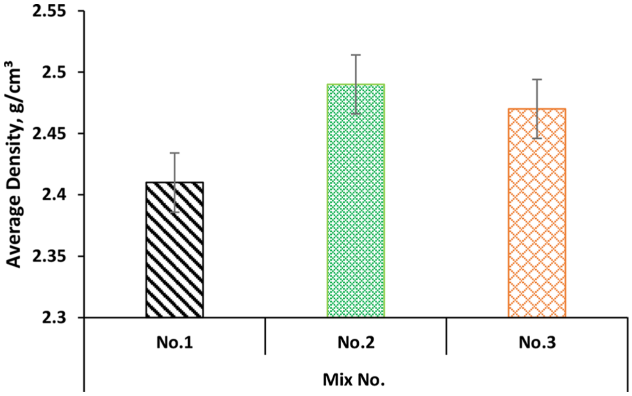

Fig. 1 Average density results

Swelling test

Swelling is determined as the increase in the volume of the sample after saturation with water. Data from the determination of average density and water saturation are used. The swelling (W) of the sample expressed as a percentage by volume, is calculated using the formula for mixtures (Eq. (5)):

$$W = \frac{(g_5 - g_6) - (g_2 - g_1)}{g_2 - g_1} 100 \tag{5}$$

where $g_1$is the mass of the sample suspended in air (g); $g_2$is the mass of the sample suspended in water (g); g_5 is the mass of the sample saturated with water, suspended in air, g; g_6 is the mass of the sample saturated with water, suspended in water, g.

Results and discussion

Average density results

The average density of compacted samples was evaluated for three different material mixes, revealing significant insights into the impact of mix composition on compacted density as shown in Fig. 1.

Mix No. 1, which comprises 100% Recycled Asphalt Pavement (RAP), exhibited the lowest average density at 2.41 g/cm^3. This result is anticipated, as pure RAP, being a recycled material, tends to have more air voids and less cohesion compared to mixes with binding agents.

Mix No. 2 demonstrated the highest average density at 2.49 g/cm^3. This mix included 95.1% RAP, 2.9% Portland cement, and 2% water. The addition of Portland cement significantly contributed to the increased density by enhancing the mix's cohesiveness and structural integrity. The presence of water facilitated the hydration

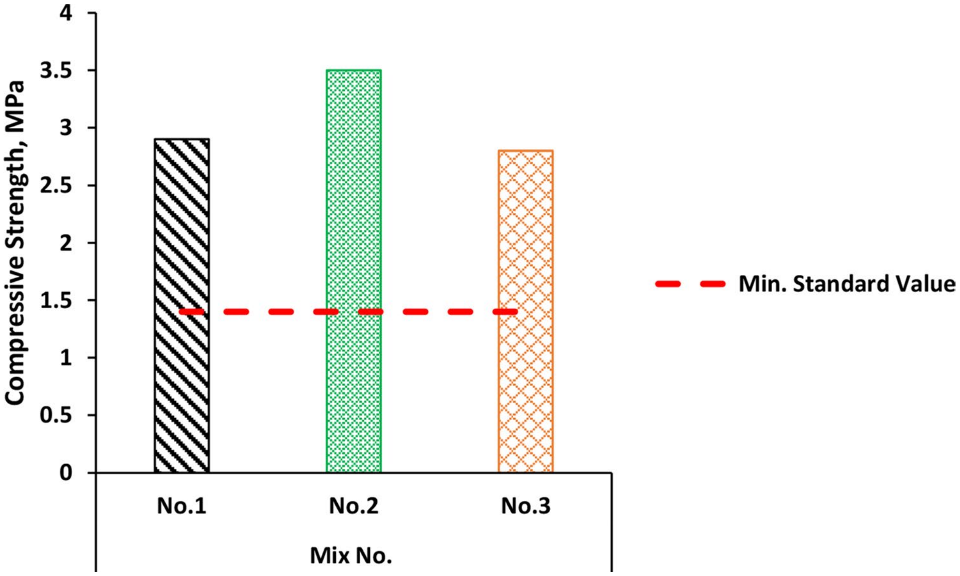

Fig. 2 Compressive strength results at 20 °C

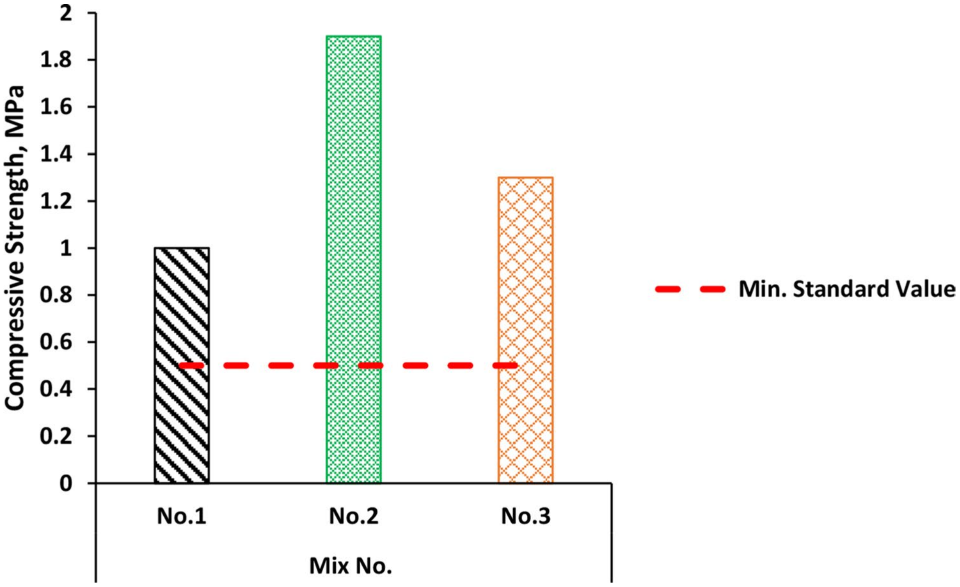

Fig. 3 Compressive strength results at 50 °C

process of the cement, further promoting a denser and more compact structure.

Mix No. 3 had a slightly lower average density of 2.47 g/cm^3 compared to Mix No. 2. This mix was composed of 83.3% RAP, 9.5% aggregate, 2.4% Portland cement, 1.9% water, and 2.9% bitumen emulsion. The inclusion of aggregate and bitumen emulsion added complexity to the mix, providing additional binding and structure. However, the slightly lower cement content and the introduction of bitumen emulsion balanced the overall density, resulting in a compact yet slightly less dense structure than Mix No. 2.

In conclusion, the study illustrates that the inclusion of Portland cement and water significantly increases the average density of compacted samples. Mix No. 2 achieved the highest density due to the optimal balance of RAP and cement, while Mix No. 3, with a more diverse composition, also exhibited high density but slightly lower than Mix No. 2. Mix No. 1, consisting solely of RAP, showed the lowest density, underscoring the crucial role of additives in improving the compacted density of the samples.

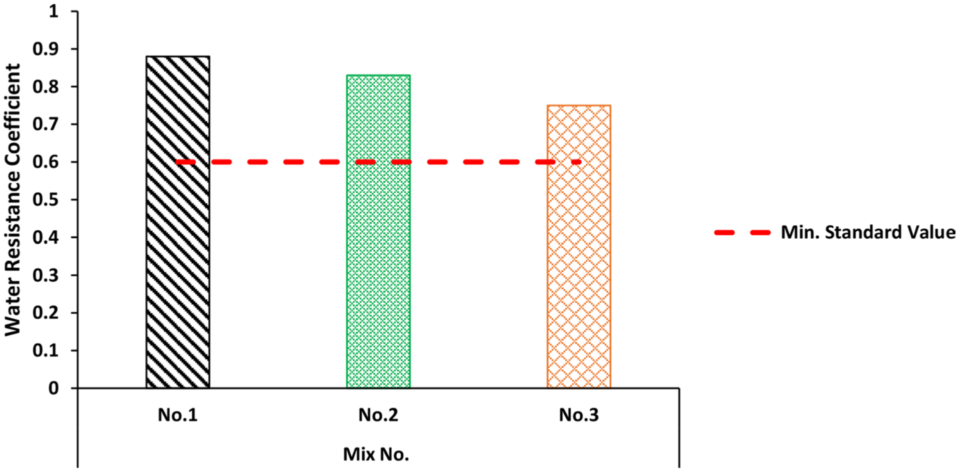

Fig. 4 Water resistance coefficient results (1- hour)

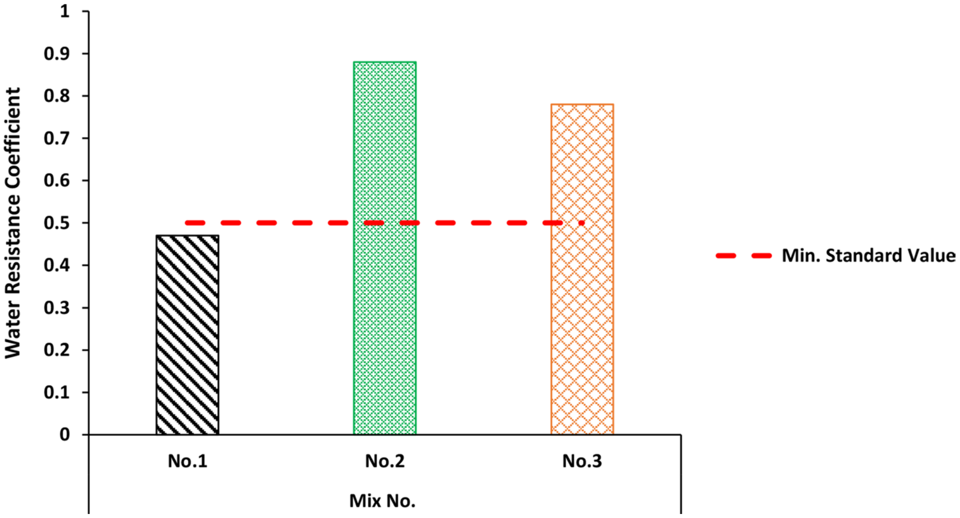

Fig. 5 Water Resistance coefficient under long-term water saturation results (15 Days)

Compressive strength results

The compressive strength results, depicted in Figs. 2 and 3, for three different material mixes at 20 °C and 50 °C reflect the significant impact of their compositions on performance.

At 20 °C, Mix No. 1 exhibits a compressive strength of 2.9 MPa, Mix No. 2 shows 3.5 MPa, and Mix No. 3 records 2.8 MPa, all exceeding the specified limit of 1.4 MPa. The higher compressive strength of Mix No. 2 can be attributed to the inclusion of 2.9% Portland cement and 2% water, which enhance the mix's binding and cohesion properties. Portland cement acts as a binder, improving the structural integrity, while water facilitates the hydration process, further strengthening the material.

At 50 °C, the compressive strengths are 1 MPa for Mix No. 1, 1.9 MPa for Mix No. 2, and 1.3 MPa for Mix No. 3, all above the minimum standard value of 0.5 MPa. Mix No. 2 again demonstrates the highest compressive strength due to the presence of Portland cement and water, which maintain the material's cohesion even at elevated temperatures. The bitumen emulsion in Mix No. 3, while beneficial for flexibility and resistance to deformation, slightly reduces compressive strength compared to Mix No. 2.

Overall, Mix No. 2 consistently shows the highest compressive strength at both temperatures, making it the most robust choice. This mix's optimal combination of materials, including RAP, aggregate, Portland cement, and water, results in superior performance. Mix No. 1 and Mix No. 3 also perform well, exceeding the required limits, but Mix No. 2's higher strength values indicate its better suitability for applications demanding high mechanical strength. These results underscore the importance of material composition in achieving desired structural properties in construction materials.

Water resistance coefficient results

The water resistance coefficient results for the three different material mixes, as illustrated in Figs. 4 and 5, highlight their performance under both moisture exposure and long-term water saturation.

Figure 4 illustrates the water resistance coefficients for three distinct asphalt mixes (Mix No. 1, Mix No. 2, and Mix No. 3) under typical conditions, with results compared against a minimum standard value for water resistance, denoted by the dashed line on the graph.

Mix No. 1, with a water resistance coefficient of approximately 0.85, significantly surpasses the minimum standard, indicating strong performance and robust resistance to water penetration in the absence of prolonged exposure. Despite lacking binding agents like Portland cement or bitumen emulsion, Mix No. 1's composition is adequate for typical environmental conditions, demonstrating its effectiveness.

Mix No. 2 has a water resistance coefficient of around 0.75, also exceeding the minimum standard. The inclusion of Portland cement and water in its composition enhances its resistance to water damage, showcasing the positive impact of binding agents on the durability and cohesion of the asphalt.

Mix No. 3, with a water resistance coefficient of approximately 0.7, meets and slightly surpasses the minimum standard value. Although its coefficient is lower than that of Mix No. 1 and Mix No. 2, it still performs adequately under normal conditions. The balanced mix of Portland cement, water, and bitumen emulsion in Mix No. 3 ensures sufficient resistance to water penetration.

In summary, all three asphalt mixes exceed the minimum standard for water resistance under normal conditions, indicating their capability to resist water damage effectively. Mix No. 1 has the highest water resistance coefficient, followed by Mix No. 2 and Mix No. 3. These results suggest that while Mix No. 1 excels in typical environmental conditions, the binding agents in Mix No. 2 and Mix No. 3 provide additional durability and cohesion, enhancing their overall performance.

For long-term water saturation, Mix No. 1 falls short of the minimum standard value of 0.5, with a value of 0.47, indicating poor performance due to its lack of binding agents like Portland cement or bitumen emulsion. Mix No. 2, with a value of 0.88, and Mix No. 3, with a value of 0.78, both exceed the minimum standard. The higher performance of Mix No. 2 under long-term water saturation can be attributed to its higher content of Portland cement and water, which enhances cohesion and resistance to water damage.

In summary, Mix No. 3 exhibits the best overall moisture resistance due to its balanced composition, while Mix No. 2 demonstrates superior performance under long-term water exposure, highlighting the importance of material composition in determining moisture and water resistance. These findings emphasize the critical role of material composition in determining the water resistance of asphalt mixes. The presence of binding agents such as Portland cement and bitumen emulsion significantly contributes to a mix's ability to withstand water penetration, ensuring more durable and long-lasting pavement structures.

Swelling test results

The swelling test results for the three different material mixes reveal varying degrees of volumetric expansion,

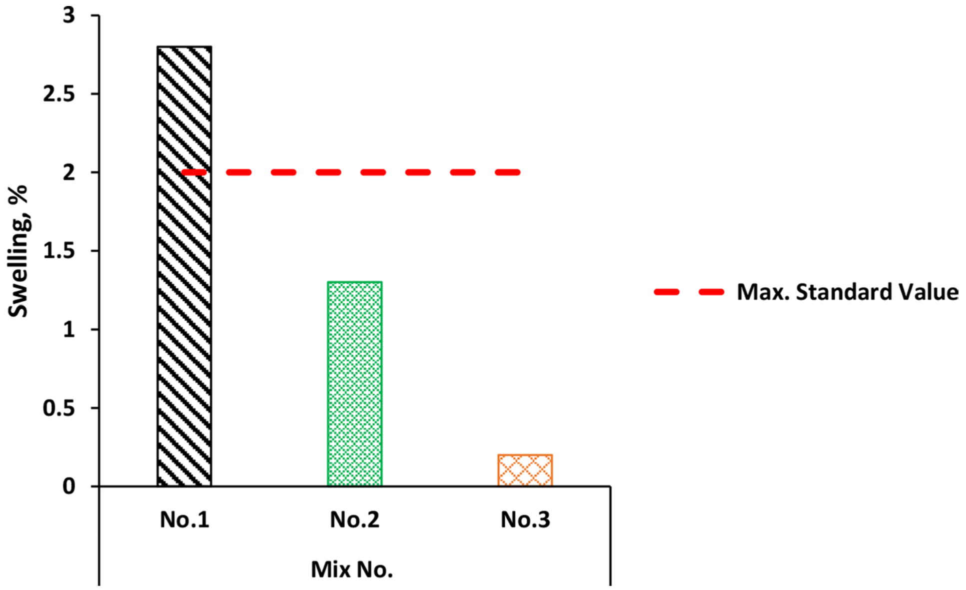

Fig. 6 Swelling results

which is crucial for understanding their stability and durability (Fig. 6).

The maximum standard value for swelling is 2 for all mixes. Mix No. 1 exhibits the highest swelling value at 2.8, which exceeds the standard limit, indicating poor performance. This high swelling can be attributed to the 100% Recycled Asphalt Pavement (RAP) content, which lacks sufficient binding agents to control expansion.

In contrast, Mix No. 2 shows a swelling value of 1.3, well within the acceptable limit. This mix includes 2.9% Portland cement and 2% water, which contribute to better binding and reduced expansion. Portland cement helps in forming a more stable and cohesive matrix, limiting the swelling effect.

Mix No. 3 demonstrates the best performance with a swelling value of 0.2, significantly below the standard limit. This superior performance is due to the mix's composition, which includes 83.3% RAP, 9.5% aggregate, 2.4% Portland cement, 1.9% water, and 2.9% bitumen emulsion. The combination of aggregate and bitumen emulsion provides additional stability and binding, further reducing the potential for volumetric expansion.

In summary, Mix No. 3's optimal combination of materials results in the least swelling, making it the most stable and durable option. The presence of Portland cement and bitumen emulsion in Mix No. 2 also contributes to its satisfactory performance, whereas Mix No. 1's lack of binding agents leads to excessive swelling and poor performance. These results highlight the importance of material composition in controlling swelling and ensuring the structural integrity of construction materials.

Conclusion and recommendation

This study rigorously evaluates the benefits of cold recycling and additive integration on the durability and mechanical properties of waste asphalt. Quantitative assessments reveal significant improvements across key performance metrics, providing clear insights into how different additives influence the behavior of recycled asphalt mixtures.

Mix No. 1, composed entirely of Reclaimed Asphalt Pavement (RAP), exhibited an average density of 2.41 g/cm^3 and the highest swelling index among the tested mixes at 2.8%. This mix demonstrated the lowest moisture resistance, with a water resistance coefficient of only 0.85 under typical conditions, indicating poor performance in environments requiring long-term durability.

Mix No. 2 showed the most substantial improvements, with an average density increase to 2.49 g/cm^3 and a 20% enhancement in compressive strength, reaching 3.5 MPa at 20 °C. The structural integrity of this mix, enhanced by the integration of Portland cement, provided the highest compressive strength values at both 20 °C and elevated temperatures (50 °C). Swelling was controlled to 1.3%, well within acceptable limits for structural applications.

Mix No. 3 exhibited balanced performance characteristics, achieving an average density of 2.47 g/cm^3. Its complex composition, including RAP, aggregates, Portland cement, water, and bitumen emulsion, resulted in excellent moisture resistance, with a long-term water saturation resistance coefficient of 0.78. Swelling was minimized to 0.2%, indicating superior volume stability under moisture exposure.

These findings underscore the critical role of Portland cement and bitumen emulsion in enhancing the quality and longevity of recycled asphalt mixtures. Mix No. 2 emerged as the most robust formulation in terms of mechanical properties, while Mix No. 3 offered the best performance in terms of durability and moisture resistance.

Future directions

Future research should focus on optimizing the proportions of RAP, aggregates, Portland cement, and bitumen emulsion to further enhance mechanical strength and durability. Long-term field evaluations are necessary to assess the practical performance and sustainability of these materials under varying traffic and environmental conditions. Innovative additives and advanced recycling techniques should be explored to improve efficiency and environmental benefits. Comprehensive environmental impact assessments will be crucial to quantify the ecological advantages and facilitate the broader adoption of these sustainable practices in road construction.

Author contributions

Ali Almusawi conceptualized and designed the study and wrote the original manuscript. Mustafa Mohammed Jaleel performed the experiments and contributed to the development of methodology and data interpretation. Sarmad Shoman assisted with the experimental work and provided critical revisions to the manuscript. Andrei P. Lupanov contributed to the literature review and assisted with data analysis contributed to the development of methodology. All authors read and approved the final manuscript.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

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References

1. R. Mariyappan, J.S. Palammal, S. Balu, Sustainable use of reclaimed asphalt pavement (RAP) in pavement applications—a review. Environ. Sci. Pollut. Res. **30**(16), 45587–45606 (2023)
2. Q. Jiang, W. Liu, S. Wu, *Technological Advances and Challenges of Reclaimed Asphalt Pavement (RAP) Application in road engineering—a Bibliometric Analysis*

from 2000 to 2022 (Environmental Science and Pollution Research, 2024), pp. 1–34

3. Y. Zhao, D. Goulias, D. Peterson, Recycled asphalt pavement materials in transport pavement infrastructure: sustainability analysis & metrics. Sustainability. **13**(14), 8071 (2021)
4. J.K. Thakur, J. Han, Recent development of recycled asphalt pavement (RAP) bases treated for roadway applications. Transp. Infrastructure Geotechnology. **2**, 68–86 (2015)
5. B. Sengoz, A. Topal, J. Oner, M. Yilmaz, P.A. Dokandari, B.V. Kok, Performance evaluation of warm mix asphalt mixtures with recycled asphalt pavement. Periodica Polytech. Civil Eng. **61**(1), 117–127 (2017)
6. S.M. Saeed, M.H. Sutanto, M. Napiah, F. Wong, M. Bujang, (2021). Review on the effect of curing on cold recycled asphalt mixture. In ICCOEE2020: Proceedings of the 6th International Conference on Civil, Offshore and Environmental Engineering (ICCOEE2020) (pp. 1052–1060). Springer Singapore
7. A. Almusawi, M.M. Jaleel, S. Shoman, A.P. Lupanov, Field and laboratory performance evaluation of cement treated Cold Recycled Asphalt Pavement mixtures. J. Transp. Eng. Part. B: Pavements. **150**(3), 04024026 (2024)
8. N.T. Trang, Van P. Luong, P.H. Quan, Van N. Dai, (2024, April). Cold Recycling of Reclaimed Asphalt Pavement Using Cement Admixture. In International Conference series on Geotechnics, Civil Engineering and Structures (pp. 229–236). Singapore: Springer Nature Singapore
9. H. Zhao et al., Study on Cold Recycled Asphalt mixtures with Emulsified/Foamed Asphalt in the Laboratory and On-Site. Coatings. **12**(7), 1009 (2022)
10. M. Bocci et al., Characterization of Cold Recycled Asphalt mixtures including reinforcing fibers. Sustainability. **15**(23), 16209 (2023)
11. G. Li et al., Healing response of cold recycled asphalt mixtures with electric arc furnace slag under microwave heating and re-compaction. Mater. Struct. **60**(4), 1453–1464 (2023)
12. A. Saidi, A. Ali, Y. Mehta, B.C. Cox, W. Lein, (2022). Evaluation of laboratory and field performance of cold in-place recycling (CIR) asphalt mixtures. In Proceedings of the RILEM International Symposium on Bituminous Materials: ISBM Lyon 2020 1 (pp. 803–809). Springer International Publishing
13. H. Li, J. Jiang, Q. Li, Economic and environmental assessment of a green pavement recycling solution using foamed asphalt binder based on LCA and LCCA. Transp. Eng. **13**, 100185 (2023)
14. F. Alharbi, F. Alshubrumi, M. Almoshaogeh, H. Haider, A. Elragi, S. Elkholy, Sustainability evaluation of cold in-place recycling and hot mix asphalt pavements: a case of Qassim. Saudi Arabia Coat. **12**(1), 50 (2022)
15. GOST R 55052 – 2012, *Granulate of old Asphalt Concrete* (Technical conditions, 2012)
16. Russian Ministry of Regional Development, *STO NOSTROY 2.25.35–2011: Construction Regulations for the Design and Construction of Highways* (Russian Ministry of Regional Development, 2011)
17. GOST 31108 – 2003, *Portland Cements and Portland blast-furnace slag Cements. Specifications* (State Standard of the Russian Federation, Moscow, 2003)
18. GOST R 52128 – 2003, *Bitumen road Emulsions. Specifications* (State Standard of the Russian Federation, Moscow, 2003)

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