A Review of High-Performance Cold Mix Asphalt (HPCMA): Benefits and Challenges for Implementation in Canada

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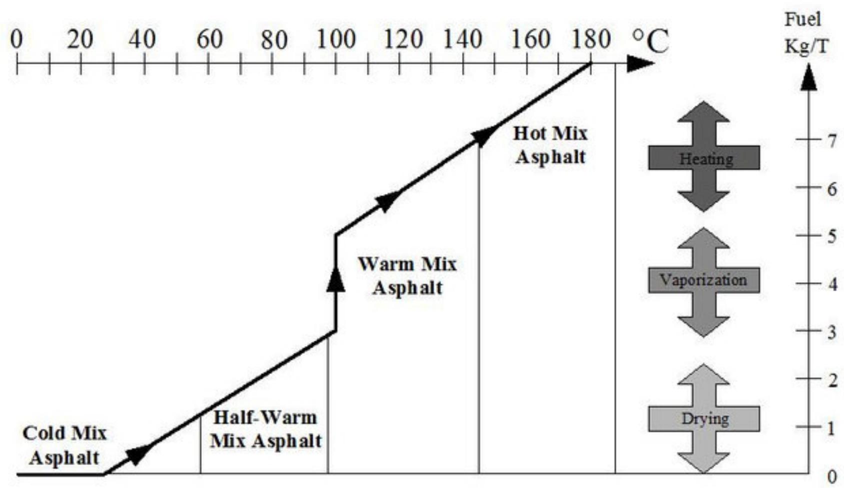
Abstract

Road infrastructure, vital for a nation's socio-economic progress, has traditionally relied on resource and energy-intensive methods. The demand for sustainable solutions, particularly in urban areas, with greater resistance to increasing traffic loads, lower moisture sensitivity, and suitability for cold regions, is evident. Cold Mix Asphalt (CMA), benefiting from recent technological advancements, emerges as a promising solution. This paper examines the development of cold-mix pavement materials in the context of Canada's road networks. This literature review compares CMA to Hot Mix Asphalt (HMA) and Warm Mix Asphalt (WMA) in various aspects. While CMA offers advantages such as suitability for emergency repairs, ease of application, and cost-effectiveness, drawbacks include lower durability compared to HMA and the lack of internationally recognized standard tests, posing challenges in performance assessment, thus, decreasing predictive accuracy. Despite these drawbacks, CMA stands out for its energy-saving and environmentally friendly attributes, as it is mixed at considerably lower temperatures. This paper emphasizes the importance of further research into High-Performance CMA (HPCMA), especially considering ongoing environmental concerns. Recognizing both advantages and challenges, the review underscores the need for comprehensive understanding and continued research to develop resilient HPCMA pavements comparable to conventional HMA.

Introduction

Traditional hot mix asphalts (HMA) in road construction typically manufactured at temperatures between 150°C and 170°C, necessary to reduce bitumen viscosity for proper coating of aggregates, workability, and compaction. Economic and environmental concerns led to the development of warm mix asphalts (WMA), half-warm mix asphalt (HWMA) and cold mix asphalt (CMA); their broader classification is shown in Figure 1 below. WMA reduces production temperatures by about 30°C using additives, while CMAs can be produced at atmospheric temperatures using bitumen foam or emulsions [1]. Half-warm mix asphalt technologies are similarly produced at temperature below 100°C but warmer than ambient temperature [2]. By substituting the traditional asphalt binder found in HMA and WMA with asphalt emulsion, cold mix asphalt enables production and compaction at ambient temperatures, presenting even a viable solution even during winter months [3]. Due to these lower production temperatures, CMA pavements are an environmentally and economically attractive options for sustainable pavements.

Figure 1. Classification of different asphalt mixture technologies from Vaitkus et al. (2009).



High-performance CMA (HPCMA) can be loosely defined as a durable cold-placed asphalt mixture that is designed to withstand harsh environmental conditions and heavy traffic loads. The most conventional use of HPCMA is cold patching products used for pot hole repair; each province having their own standard and regulations outlining the usage of these products (for example, Ontario Provincial Standard Specifications 1153, British Columbia Standard Specification for Highway Construction Section 537, and Alberta Transportation Highway Maintenance Specifications 53.10, etc.). Despite being considered "high-performance", many of these cold patch materials are only used for emergency repairs and are not expected to have a long lifespan before additional repairs are needed [4]. Consequently, "virgin" CMAs as well as cold recycling technology typically used for road maintenance and rehabilitation should be further explored and enhanced due to their economic, environmental, and mechanical advantages.

Cold Recycling Technologies

A subset of CMAs, cold recycling technologies refer to a range of cost-effective and sustainable techniques used to rehabilitate asphalt pavements, utilizing reclaimed asphalt pavement (RAP) as the primary aggregate source and asphalt emulsion or foamed bitumen as main binders [5] [6]. However, these alternatives often face challenges in quality and durability [7]. Mechanical properties of cold recycled mixtures vary widely due to the variability in materials and production techniques, leading to three main mixture families: bitumen stabilized materials, cement-bitumen treated materials (CBTM), and "true" cold-mix asphalts. These mixture families can be produced as cold recycling mixture (CRM), cold-in-place recycling (CIR) mixtures, and cold in-place recycling with expanded asphalt mix (CIREAM). Cold-in-place (CIR) recycling, as demonstrated in Figure 2, is a common method for rehabilitating road pavements without heat application [8]. In Ontario, both CIR and CIREAM technologies were introduced in 2003 [9]. CIREAM, as shown in Figure 3, uses foamed asphalt technology and serves as an alternative to CIR's emulsion technology [10]. The first demonstration of CIREAM alongside CIR showed equivalent performance [10]. Cold recycled mixtures are increasingly used in road pavement construction of lower volume roads due to their ability to produce reliable materials at ambient temperature, replacing the bituminous phase with an asphalt emulsion [11]. It should be noted that due to the binders used in these materials, they exhibit an evolving behavior, transitioning from a fresh to a hardened state over time, influenced by factors such as layer thickness, drainage conditions, and temperature [12].

Figure 2. Cold In-Place Recycling (CIR) in the field (Left) [13], and CIR field placement process diagram (Right) [9].

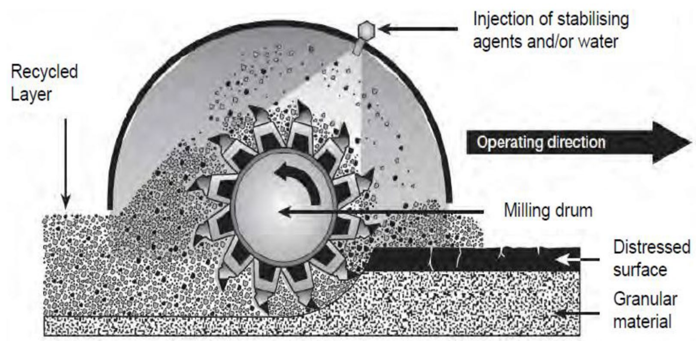
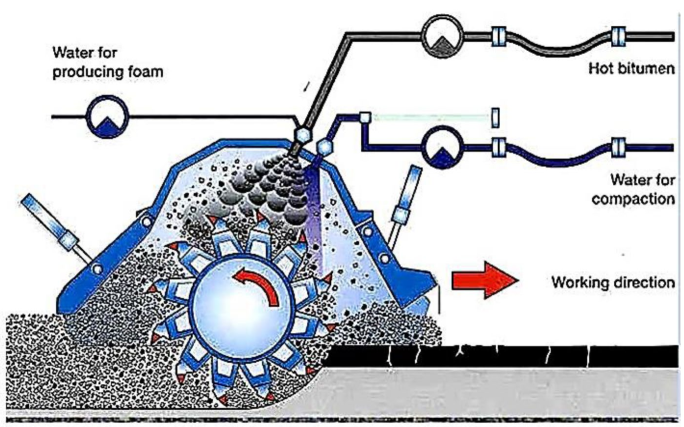


Figure 3. CIREAM technology demonstrating the use of expanded asphalt binders with reclaimed asphalt in the mixing chamber [13].



The curing process, influenced by environmental conditions such as temperature and humidity, is crucial for water evaporation and reaction with hydraulic binders, affecting the development of cold mixture properties [14]. Thus, water plays a crucial role in ensuring homogeneous distribution of bitumen within the mixture during mixing [6] and reducing internal friction during compaction and aiding cement hydration, with higher water content allowing for higher density with less compaction effort. During curing, water is utilized by cement for hydration and expelled through evaporation, but some water remains in the solid structure of the mixture, making it challenging to achieve total water loss [11]. Curing conditions significantly affect CBTM mechanical properties, with water evaporation during curing accelerating emulsion breaking and improving mechanical properties. However, establishing a standardized laboratory procedure to represent field curing is challenging due to environmental variability. Studies show that changing curing temperatures in the laboratory can achieve similar stiffness levels but require different curing times. Double-step curing simulations, where mixtures are first cured during the cold season and then long-term cured, highlight the complexity of curing effects on CBTM properties [1]. Further studies suggest that factors such as RAP source, cement content, and gradation significantly influence compaction ability, mechanical properties, and cracking resistance of CMA mixtures [6] [15] [16]. Furthermore, investigations into the curing properties of cold-in-place recycled asphalt pavements have identified laboratory test methods to evaluate the evolution of properties over time [17].

Past CMA Field Mixtures and Performance

A trial section of CIREAM was constructed alongside a conventional CIR mix on Highway 7 in Ontario, allowing for a comparison of the two technologies [8]. After 20 years of monitoring, CIREAM with a 50 mm HMA overlay performed comparably to conventional CIR with a 50 mm HMA overlay, demonstrating equivalent or better performance at a reduced cost. Pavement distresses after 18 years are minor, with no significant issues [8]. In another trial, the project on Highway 7 spans 15.4 km from Innisville to Perth, Ontario, with varying pavement conditions. The western portion exhibits severe cracking and rutting, while the eastern part is in better condition. After evaluating different rehabilitation options, CIR with a 50 mm HMA overlay emerged as the most cost-effective and efficient solution, addressing reflection cracking and minimizing new material usage. CIR involves recycling existing pavement, making it an environmentally friendly choice [18]. Another field trial evaluating the low volatile organic compounds (VOC) and conventional HPCM involved patching five potholes in January 2013, subjected to slow-moving construction vehicle traffic over four months, with both materials demonstrating good workability and similar performance, maintaining integrity and effectiveness despite heavy traffic and freeze-thaw cycles, highlighting the importance of field evaluations in ensuring the reliability and effectiveness of cold patch materials in real-world conditions [19].

In a project conducted in the summer of 1999, collaboration between the Saskatchewan Department of Highways and Transportation (SDHT) and SaskPower International aimed to improve sections of Highway 155-03 through cold in-place recycling and lime fly ash stabilization [20]. Testing revealed significant improvements in the unconfined compressive strength and stiffness of the subgrade with lime fly ash modification, demonstrating successful performance after two years of service [20]. Another research discusses the effectiveness of cold in-place recycling (CIR) as an alternative to traditional pavement rehabilitation, especially in light of environmental and economic constraints. It highlights the success of CIR in various state agencies since the 1980s and the interest of the Ontario Ministry of Transportation in adopting it for Ontario's highways. The paper specifically focuses on a CIR project conducted on Highway 15 near Ottawa in 1990, detailing the design, construction, mix test results, and pavement performance. It concludes with recommendations for future CIR projects in Ontario [16].

The trial of Cold In-place Recycling (CIR) with expanded asphalt on Highway 7 marked the Ministry of Transportation Ontario's (MTO) first use of this technology. In-house sampling and testing allowed for comparative analysis between CIR and CIR with expanded asphalt. Resilient modulus testing after eight months showed comparable strength. Falling Weight Deflectometer (FWD) testing demonstrated increased pavement structure strength for both, with CIR with expanded asphalt slightly better. One year later, FWD testing indicated further strength gains for both materials. Evaluations of roughness and rutting revealed good ride characteristics and minimal rutting for both, with CIR exhibiting slightly smoother ride characteristics. Field reviews confirmed overall good performance with no significant distress observed. The trial showed promising results, with both materials performing comparably in strength, ride quality, and distress resistance. Continued monitoring through annual FWD testing will provide insights into long-term performance [18].

Aim and objectives

Overall, research in the field of cold asphalt mixes and recycled materials highlights the importance of understanding material properties and behavior for effective pavement design and rehabilitation. By analyzing engineering properties, rheological behavior, and structural composition using various testing methods [20], researchers aim to develop reliable quality control procedures and optimize the performance of cold recycled pavement materials [6] [17]. These efforts contribute to the advancement of sustainable and cost-effective solutions in pavement engineering, addressing the challenges posed by aging infrastructure and increasing demands on transportation networks. The increasing interest in cold recycling, exemplified by CMA, underscores its potential for sustainability and reuse of reclaimed asphalt, addressing the escalating costs associated with road maintenance and rehabilitation projects [9]. However, the performance of CMA is usually weaker than HMA, especially in terms of rutting and moisture-damage resistance. Moisture damage can also be accelerated after rutting or other significant pavement defects such as a later-stage distress [12]. Also, challenges persist, particularly regarding the mechanical behavior influenced by water content, necessitating clear procedures for water absorption determination [11].

The primary aim of this article is to conduct a thorough review of research on various types of cold mix asphalt in Canada. As such, the main focus of this review will be recent laboratory studies and field studies of CMAs and CRMs in a Canadian context. Given that CMA represents an energy-saving and environmentally friendly approach crucial for the future of the pavement industry, there is an urgent need for comprehensive information on this subject.

CMA Components and Mix Design

Asphalt Emulsions and Supplementary Binders

In literature, the terms “workability” and “compactability” are often used interchangeably to describe how easily a material can be laid and compacted with a certain amount of applied energy. With HMA, workability is primarily controlled by production temperature, although aggregate gradation also plays a role. The Bailey method is often used to develop aggregate blends, categorizing them into different particles to evaluate their packing ability, which influences mechanical properties such as rutting resistance in HMA. In CMAs, water is commonly added to improve workability and compactability of the mixture [5]. This leads to one of the major differences between HMA and CMA which is the additional curing time that comes with the use of asphalt emulsions or secondary binders like ordinary Portland Cement (OPC) [6].

Asphalt emulsions, such as Cationic Slow Setting (CSS) and High Float Medium Setting (HFMS), are commonly used for recycling [21]. CSS asphalt emulsions are commonly used in cold recycling projects for their stability and ability to create a compact mixture, but their delayed breaking inhibits the establishment of a binding structure initially. The affinity between asphalt emulsion and aggregate surface plays a crucial role in mix durability, yet undisclosed components from industrial producers pose challenges in determining exact properties during cold mixture design [14]. One study involved the use of two CSS asphalt emulsions, namely CSS-1h and CSS-1hp, both with a hard asphalt base, where CSS-1hp was polymer-modified. These emulsions were directly sourced from the manufacturer to ensure consistency [21]. Secondary binders like Ordinary Portland cement (OPC), hydrated lime, or fly ash are often added to improve mechanical properties and allow for earlier opening to traffic [6]. The addition of Ordinary Portland Cement enhances short-term and long-term mechanical properties while facilitating faster breaking of the asphalt emulsion [11]. The binder content of dense-graded (DG) and open-graded (OG) CMAs was determined by oven-drying samples to a constant mass and burning them in an ignition furnace. The average binder content of DG and OG CMAs was found to be approximately 4.66% and 4.39%, respectively [12]. The cement employed was a type of General Use (GU) cement (CSA A3000) with a compressive strength at 28 days of 43.9 MPa (ASTM C109) [22]. Using SEM image analysis, it was observed that the higher water content allowed a higher bitumen dispersion. In mixes with cement, more water led to a higher cement hydration, which at the same time prevent a full contribution from the bitumen phase [11].

Aggregates and Reclaimed Asphalt Pavement (RAP) Usage

The use of RAP has gained popularity in pavement construction due to cost savings and environmental benefits. In cold in-place recycling projects, RAP is the primary component of the aggregate blend, with its presence improving mechanical properties by acting as a cushion between aggregate and bitumen. The properties of CRMs vary depending on the source and gradation of RAP [17]. While RAP utilization is well established, there is ongoing research to maximize its use, particularly through cold mix recycling techniques [21].

In one study conducted by École de technologie supérieure (ÉTS) in Montreal, Canada, and ETS Ingeniería de caminos, canales y puertos (ETSICCP) of the Universidade da Coruña (UDC) in Spain, examined the impact of RAP from different sources and particle sizes on the volumetric and mechanical properties of CRM [17]. In general, it was observed that different sources of RAP affected compaction efforts, water evaporation trends, and resistance properties of the mixtures. The interaction between binding phases and aggregate surface varied with different RAP sources, highlighting the need for further research on viscoelastic properties and field applications [22]. Gradation, a critical factor influencing load-bearing and rutting resistance, was addressed in several studies. One study utilized an aggregate blend composed of 94.4% RAP and 5.6% limestone filler [11], while another incorporated RAP aggregates with adjustments made to the water content to optimize compaction and void saturation, totaling 4.5% water in the mix [22]. RAP gradation influences workability and mechanical properties, with higher filler-sized particles enhancing workability, and optimization methods like the compressible packing model (CPM) have been employed to achieve distributions close to the maximum density curve [14].

In another study by Hasanuzzaman et al. (2018), twelve different CMAs were categorized into open graded and dense or well/ dense graded (types, further divided into proprietary cold mix (PCM) and conventional cold mix (CCM) [7]. Each mix was designed for specific temperature ranges and applications, with variations in aggregate types, asphalt content, and additives to meet performance requirements. Asphalt content and aggregate grain size distribution were determined through testing according to AASHTO standards, with moisture content assessed using AASHTO T329 and asphalt content verified by burning samples in an ignition furnace [7]. In another project involving CIREAM, samples revealed variations in asphalt cement content and mix designs, leading to adjustments during construction. Despite challenges in meeting moisture criteria, quality control results for CIREAM were satisfactory, ensuring acceptance without a price reduction [18]. Another investigation on CBTM mixtures included an aggregate distribution comprising 94% RAP and 6% limestone filler, with a fixed dosage of 1.5% ordinary Portland cement by mass of dry aggregates [15].

CMA Mix Design

Various mix design methods, including Marshall and Superpave Gyratory Compaction (SGC), have been employed for cold mix asphalt mixtures. Determining Optimum Water Content (OWC) and Optimum Emulsion Content (OEC) are crucial for successful CMA mix design, along with considerations for compaction energy and curing conditions. The transition to using SGC instead of the Marshall hammer is a significant development in mix design, with challenges including selecting the proper number of gyrations for compaction, with recommendations ranging from 25 to 75 gyrations. Recent studies suggest that 50 gyrations can provide satisfactory air void levels [21]. Current standards lack specific minimum production temperatures for CBTM, with recommendations varying based on experience and project specifics. Production temperatures vary widely, with some studies even conducting tests at room temperature to mimic field conditions, particularly relevant in cold regions like Canada, North-East USA, or North-Europe [1].

In a study at ÉTS and UNIVPM, mixing procedures were standardized, with manual mixing at ÉTS and mechanical mixing at UNIVPM. The process involved initially mixing the dry aggregate blend to achieve desired gradation, followed by the sequential addition of water, cement, additional water, and asphalt emulsion until homogeneity was achieved, typically taking 5-10 minutes. Compaction parameters were adjusted to achieve desired compaction properties, with residual bitumen from emulsion considered fully effective due to low absorption values of RAP aggregates, and water content adjusted to achieve specific voids in the mixture (V_m) values, fixed at 2% by mass of aggregates at ÉTS and varying at UNIVPM depending on the mix type [5]. In a study by Orosa et al. (2022), laboratories at both ÉTS and UDC followed a similar mechanical mixing procedure involving RAP incorporation, emulsion addition, and compaction. It was observed that CRMs with lower RAP nominal maximum sizes (NMS) from ÉTS required higher compaction energy to achieve similar air void contents compared to mixes with higher RAP NMS, indicating a significant impact of particle size distribution on volumetric properties. While UDC's RAP had a higher NMS, it lacked intermediate particles, resulting in lower maximum density and higher air void content after compaction compared to ÉTS mixes [17].

CMA Curing Characteristics and Water Content

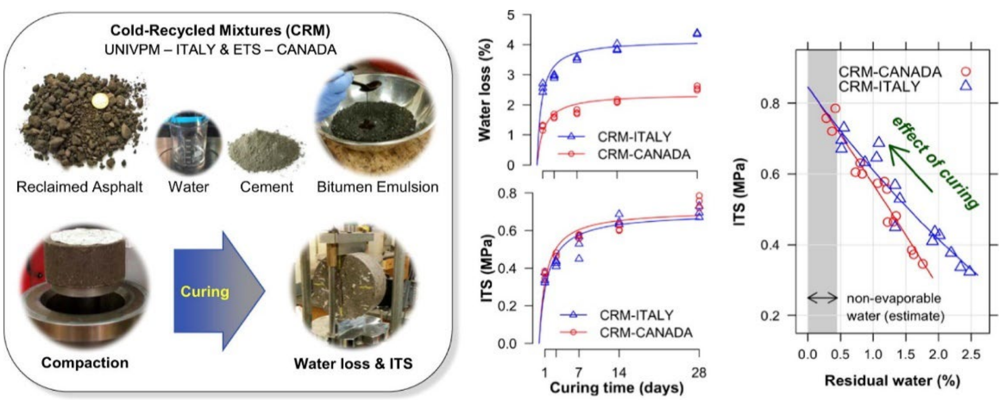
The volumetric properties of bituminous mixtures, whether hot or cold, significantly impact their mechanical performance and durability. In cold mixtures like CRM, changes in volumetric composition occur during curing due to water evaporation and Portland cement hydration, with the solid phase consisting of reclaimed asphalt, virgin aggregate, filler, and cement. Curing leads to an increase in voids and solid phase volume while reducing water volume, causing measurable mass loss in the laboratory and field to monitor curing progress, with volumetric properties characterized by voids in the mixture and voids filled with liquids (V_{FL}), calculated based on various volume components [6].

Understanding the curing processes and strength development over time is essential for CMAs, which can impact factors like traffic opening times and pavement performance. Thus, controlling water content is essential. One project aimed to identify suitable laboratory test methods for evaluating the curing of bitumen-emulsion treated materials used in CIR mixes. The methodology involved a literature review of national and international practices, followed by a four-stage approach: Pilot study, Exploratory laboratory study, Focused laboratory study, and Data analysis. Tests utilized static compression strength, time domain reflectometer (TDR) for water content, nuclear gauge for density, and falling weight deflectometer (FWD) testing for rutting depth correlation [23].

In the 2018 study by Graziani et al., CRM samples were monitored for water loss and tensile strength over 28 days. The Michaelis-Menten (MM) model was utilized to quantitatively describe the curing process of

CRM samples, analyzing the development of physical and mechanical properties over time. This model captures the asymptotic increase of material properties such as water loss by evaporation (WL) and indirect tensile strength (ITS) as functions of curing time (t) as shown in Figure 4 [6].

Figure 4. Effect of curing on water loss and indirect tensile strength (ITS) from [6].



The MM model is captured in equation 1 below:

$$y(t) = \frac{y_A . t}{h_y + t} \qquad \text{Equation 1}$$

where y_A represents the asymptotic value of the property and h_y indicates the curing time needed for the property to reach half its long-term value. Lower values of h_y signify faster initial increase rates. The MM model can also depict the relationship between different material properties, revealing how factors like cement hydration and emulsion breaking influence property increase rates. When h_{ITS}=h_{WL}, the model degenerates into a straight line with a slope indicating the ratio of the asymptotic values of ITS and WL [6]. In a complementary study completed by Graziani et al. (2020), mixing was carried out gradually adding water, cement, and asphalt emulsion to a pre-prepared oven-dried aggregate blend. Compaction was performed using a gyratory compactor [3]. Another study adjusted the water content of the mix to achieve a target air voids content of 15% without high compaction energy. Compacted specimens underwent a curing process before testing [15]. In the study by Raschia et al. (2020), four mixtures were prepared with the same gradation following the Fuller-Thompson maximum density curve, consisting of 94.4% RAP aggregate and 5.6% limestone filler, with a fixed asphalt emulsion content of 5.0% by aggregate mass resulting in a residual bitumen content of 3.0%. Two cement contents were tested along with two different dosages of intergranular water, and the mixtures were produced using manual mixing and compacted using a SGC under specific conditions before storage at a fixed temperature and humidity [11]. In another study, after both 1 day and 14 days of curing, water loss was lower when curing temperature was 5°C if compared to 25 °C. However, after the long-term curing (28 days), all mixes lost almost the same amount of water, which means that it was not negatively affected by the production temperatures or the emulsion source [1].

Characterization of CMA in the Laboratory

Laboratory tests are essential for analyzing CMA properties and facilitating their wider application as high-performance materials. In the laboratory, several key aspects such as workability, water absorption and loss, cohesion and adhesion, and draindown properties of CMAs have been explored.

Workability and Compactability

Assessing the workability of cold patching materials, especially at low temperatures, is crucial for effective road repairs. The Blade Resistance Test (BRT) as shown in Figure 5 was used by Manolis et al. (2013) to quantify workability, showing that both low volatile organic compounds (VOC) and conventional High Performance Cold Mix (HPCM) remained workable over five months, meeting specified criteria at -10°C. Initial results favored low VOC HPCM, but subsequent stability in workability was observed for both types. Factors such as high binder content, open gradation, and low dust content contributed to satisfactory workability. Further testing is needed to fully understand material property changes and their impact on workability [19].

Figure 5. Blade resistance workability test apparatus from [19].

In study by Raschia et al. (2020), the compaction energy index CEI_T^+ was selected to link both material characteristics. CEI_T^+ is affected by the low transportation temperature rather than low mixing temperature [5]. In fact, results showed that mixes transported and compacted at 5℃ required more energy to reach the target volumetric properties. Analyzing the relationship between CEI_T^+ and the workability parameter V_m, this energy increase can be related to the workability of the mixture, i.e. the amount of voids after 10 gyrations. This evaluation was valid for both emulsion sources used, even if the emulsion produced with a softer bitumen was characterized by a better workability and required less compaction energy [1]. As observed by Raschia et al. (2019), six gradations under study were primarily affected by filler content, which contributed to the workability of the loose mixture. Specifically, a greater filler percentage generally enhanced workability but resulted in reduced compactability. Interestingly, the coarse aggregate portion did not exhibit a distinct impact on the workability and compactability of the mixtures. Additionally, parameters S/Slim and G/Glim, initially devised for Self-Compacting Concretes (SCC), could serve as useful metrics for assessing the workability and compactability of CRM [5].

Raschia et al. (2021) further analyzed the compactability of two RAP sources through two steps: assessing the packing density of the dry RAP aggregate and considering the compaction energy needed to achieve target volumetric properties of CRM mixtures. Despite both RAP aggregates having similar gradation and packing density, image analysis suggested lower compactability for RAP2. However, when mixtures were produced, the opposite trend emerged, with RAP2 mixture requiring less compaction energy than RAP1. This discrepancy suggested that CRM mixture compactability wasn’t directly tied to physical properties of RAP aggregate but rather influenced by chemical interactions between asphalt emulsion and RAP aggregate, along with differences in RAP binders’ properties [14].

Water Absorption and Loss

Water absorption and loss testing is crucial for assessing the durability and performance of asphalt mixtures. In Quebec, the standard mandates the calculation of water absorption on three aggregate fractions: diameters (d) ranging from d = 0/2.5, d= 2.5/5, and d ≥ 5 mm. Each fraction undergoes immersion in water for at least 24 hours to achieve saturation, followed by different procedures to determine absorption values. For instance, the 0/2.5 fraction involves manual water removal and a cone test to establish the saturated surface dried condition. Similarly, the European standard EN 1097-06 requires water absorption calculation on two fractions: d = 0/4 and d ≥ 4 mm, employing procedures similar to Quebec standards. Volumetric analysis compares air void content in the granular mix under compaction with content obtained via gradual water addition, revealing a critical water content range of 0.5% to 1% by mass of RAP aggregate, regardless of compaction energy. Higher aggregate sizes result in greater water loss due to differences in internal structure caused by varying compaction efforts [11] [22].

Cohesion and adhesion test:

Cohesion, vital for patching material integrity, is evaluated through the rolling sieve method, showing higher cohesion in cold mixes at elevated temperatures. Dense graded mixes vary in cohesion at different temperatures, while open graded mixes generally have lower cohesion due to low bitumen viscosity. Stiffer bitumen typically results in better cohesion. However, not all mixes meet the minimum adhesion limit, indicating differences across various cold asphalt mixtures [7]. Additionally, both low VOC and conventional cold patching mixes consistently exceed the MTO's minimum specification for cohesion over five months of testing (Figure 6), possibly due to the use of clean aggregates with low dust content. Field evaluations remain crucial for validating cold patch material performance [19].

Figure 6. Procedure of the adhesiveness test: (a) CMA compaction on top of HMA, (b) sample extrusion, (c) weighing the remnants after inverting the sample and measuring the separation time from [19].

Adhesiveness, essential for bonding existing pavement with new patching materials, depends on asphalt binder and fines in the mortar composition. Poor adhesion leads to edge disintegration and washing-out. The adhesiveness test measures the time for cold mix separation from the HMA surface and assesses the remnant material on the HMA surface, with optimal adhesion time recommended between 5 to 30 seconds. Some mixes exceeded the recommended adhesion time, possibly due to insufficient or stiffer binder, while others met it, indicating sufficient bonding strength with existing asphalt. However, some mixes showed adhesion times below the recommended range, suggesting inadequate bonding strength, with bitumen type and additives influencing the results. Some mixes, with softer bitumen, exhibited lower adhesion compared to others [7].

Draindown Properties and Drainage Test

Draindown, where the binder in the mix flows and accumulates at the stockpile bottom, is a concern in warm weather. Two test methods were used to assess draindown properties in the 2013 study by Manolis et al.: the AASHTO T305 method and the FHWA drainage test. Both low VOC and conventional HPCM mixes showed acceptable draindown results at temperatures of 25 and 60°C. The FHWA drainage test also confirmed their suitability, meeting the 4 percent maximum draindown requirement. Monthly stockpile examinations over five months corroborated these findings, with no evidence of binder pooling. The study underscored the importance of ensuring acceptable draindown characteristics, particularly given the high binder contents used [19].

CMA Rheological Analysis

In a specific study, researchers measured the complex modulus for both the mixture and a Fine Aggregate Mortar composition after two curing stages at 25°C for 14 days and 40°C for an additional 14 days. Specimens were prepared using a gyratory compactor in a 100 mm mold, reaching a final height of 130 mm, and then cored to a diameter of 75 mm post-curing, employing an AMPT PRO system with axial stress measured using a load cell and axial strain measured at the specimen's midsection via three LVDTs positioned 120° apart. Testing temperatures ranged from 0 to 40°C, and frequencies varied from 0.1 to 10 Hz, with each frequency subjected to 20 loading cycles [3]. In this particular study, complex modulus analysis revealed similar thermo-rheological behavior between the mixture and Fine Aggregate Mortar (FAM), despite volumetric composition differences, with curing impacting stiffness modulus and phase angle similar to changes in frequency and temperature, indicating aging phenomena within bituminous binder films formed during emulsion setting. To model these results effectively, a new proposed model considered both viscous and hysteretic dissipation components, potentially arising from cementitious bonds or interparticle friction due to incomplete bituminous film coverage during emulsion setting [3].

The stiffness of mixtures was found to be primarily influenced by the composition of the binding phase (including asphalt binder, cement, water, and air), with aggregate size having negligible effects on modulus values and temperature sensitivity [22]. The complex modulus tests confirmed the influence of RAP binders' properties. The DBN (Di Benedetto-Neifar) model, chosen for its reliability in cold mixture applications, accounted for both viscous and non-viscous dissipations under cyclic loading. While LVE dissipation parameters remained consistent for both RAP sources, one of the RAP mixture showed lower non-viscous dissipation and higher phase angle values, indicating the greater impact of residual bitumen in RAP aggregate on non-viscous dissipation over viscous dissipation [14]. Similarly, modulus measurements by Raschia et al. (2020) demonstrated a significant in the first 7 days for all the mixes due to cement curing. After 14 days, mixes with cement had higher modulus than the mixtures without cement, which were not different regarding the water content [8]. Mixtures underwent various curing processes, including both sealed and unsealed conditions, followed by rheological property measurements. Results indicated that stiffness evolution was likely influenced by the type of residual binder in the emulsion source, emphasizing the importance of this aspect in mix design [15].

Marshall Stability and Flow Test

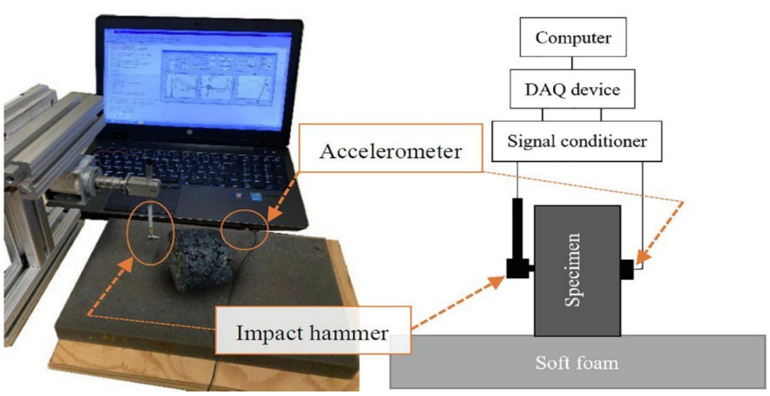
Stability is crucial for patching mixtures to resist deformation from dynamic traffic loading, depending on aggregate type, bituminous binder properties, and compaction effort. The MQ reflects mix stiffness and resistance to shear stress, with higher values indicating better performance, as low stability can lead to various pavement distress issues like rutting and shoving. Marshall flow, indicating vertical deformation, is a key parameter, with high values suggesting a plastic mix prone to rutting under traffic load. A Marshall stability and flow test, following ASTM D6927, was conducted on cured specimens, with almost all dense-graded CMAs exhibiting higher stability values compare to open-graded CMAs and the recommended stability for HMA. The Marshall quotient (MQ), representing the ratio of stability to flow, serves as an indicator of mixture stiffness and resistance to permanent deformation. DG CMAs typically have higher MQ values than open-graded mixes, indicating better resistance to shear stress and rutting. Despite some disparities, MQ values can reflect the rutting resistance of cold-mix materials, with higher MQs associated with greater rutting resistance under dry conditions [12]. Samples cured at higher temperatures exhibited greater stability, with most dense graded mixes showing comparable stability to hot mix asphalt. However, all cold asphalt mixes had higher void content than hot mix asphalt, with open graded mixes generally showing less stability and higher air void content compared to dense graded mixes [7].

Non-destructive Testing on CMAs:

Ultrasonic Pulse Velocity (UPV) testing was performed on six cores collected in 2008 to assess material strength. Previous research showed a strong correlation between wave characteristics and dynamic modulus. The Peak-to-Peak (PTP) amplitude, directly measurable from the oscilloscope, serves as an indicator of material quality. The experimental setup followed ASTM C 597-02. UPV results revealed higher wave amplitudes for CIREAM compared to CIR, suggesting better bonding at the aggregate-binder interface. While not a recognized testing method for asphalt material quality, these findings are provided for informational purposes [10].

As shown in Figure 7, dynamic impact resonance (IR) tests were conducted on specimens previously used for ITSM tests. Following Carret et al. 's methodology, an automated impact hammer with a load cell generated standing waves inside the specimens. The impact induced a maximum strain of approximately 0.1 µm/m. Specimens were placed on soft foam to achieve free boundary conditions. An accelerometer recorded the vibratory response, connected to a signal conditioner and data acquisition device, all linked to a computer. Only the longitudinal vibration mode was considered, with the impact applied at the center of one face and the accelerometer recording at the center of the opposite face. Tests were conducted at –20, 0, and 20 °C, with specimens conditioned for 4 hours. Signals were recorded and transformed from the time domain to the frequency domain using Fast Fourier Transforms (FFT). Frequency Response Functions (FRFs) were calculated from 1 Hz to 15 kHz, with coherence functions used to assess measurement quality. Finite element method (FEM) simulations were conducted assuming linear viscoelastic behavior and free boundary conditions, aiming to match experimental and numerical FRFs' resonance frequencies. The value of the complex modulus (E) was back-calculated for each temperature to match resonance frequencies, with a fixed phase angle (ϕ) of 0.5 ° assumed for simplicity due to low temperatures [17]. Stiffness moduli observed in ITSM and dynamic IR tests showed a strong dependence on temperature, frequency, and air voids content, with dynamic IR tests emerging as a promising alternative to traditional TC tests due to their speed, affordability, and ability to cover a wide range of frequencies and temperatures. Additionally, ITS tests revealed that air voids content had a more significant impact than variations in RAP NMS, emphasizing the importance of air void content in asphalt mixtures' performance [17].

Figure 7. Dynamic test set-up for the longitudinal mode of vibrations [17].



CMA Performance Testing

Despite being designed for HMA, various tests, including those for rutting, moisture resistance, indirect tensile strength (ITS), fracture tests, and Hamburg wheel-tracking (HWT), have also been adapted for CMA performance analysis.

Indirect Tensile Strength

The Indirect Tensile Strength (ITS) test assesses asphalt mix durability; it is often paired with moisture and freeze-thaw conditioning to assess moisture resistance, which is crucial for patching durability, especially in cold regions. In one study, an ITS test was conducted on all cured samples according to the AASHTO T283 guideline. It was observed that the moisture susceptibility of dense-graded CMAs is strongly correlated with the percentage of fine particles, whereas in open-graded mixtures, the amount of coarse aggregates in the mix shows significant correlation with rutting and moisture susceptibility [12]. High-performance mixes generally exhibit higher tensile strength, but CMA showed comparable moisture resistance to traditional HMA, albeit with lower tensile strength, possibly influenced by asphalt viscosity and composition [7].

In another study, the effect of voids on mortar composition was evaluated by measuring the ITS of materials. Two replicate specimens were tested for each material composition at 25 °C after 1 day of curing at the same temperature [3]. In a follow-up study, they selected a specific fine aggregate mortar (FAM) composition (*E*) and compared its curing behavior to the curing behavior of the mixture. They produced three replicate specimens for both the mixture and the FAM, having 100 mm diameter and 67.4 mm and 64.7 mm height, respectively. Curing started immediately after compaction, and consisted of a first phase of 14 days at 25 °C followed by a second phase of 14 days at 40 °C. During the curing phases, they measured the water loss due to evaporation after 6 h, 1, 3, 7, 14, 15, 17, 21 and 28 days [9]. On the same specimens, starting from the third day of curing, they also measured the ITSM. The study revealed that both the mixture and the FAM specimens exhibited a similar rate of water loss, indicating a close relationship in their stiffness evolution. Initially, during the first curing days, the mixture demonstrated greater stiffness, but over time, the FAM surpassed it in stiffness. Utilizing the Hirsch model, researchers simulated this phenomenon and determined that the series arrangement of FAM and coarse recycled asphalt aggregate prevailed over the parallel arrangement [3].

In the study by Raschia et al. (2020), higher water content generally decreased mix strength, with cement addition not significantly improving resistance, potentially leading to lower aggregate packing due to reduced compaction energy. Indirect Tensile Stiffness Modulus (ITSM) values highlighted temperature susceptibility, where cement inclusion appeared to counteract emulsion effects, particularly with higher water content, resulting in decreased stiffness, while mixes without cement showed improved bitumen dispersion and higher stiffness with more water [11]. In another study by Orosa et al. (2022), the ITSM test was used to compare different RAP NMS and compaction methods at temperatures of –20, 0, and 20°C [17]. It was also observed that production at 5°C did not significantly affect the long-term strength and stiffness of mixtures, indicating no premature emulsion breaking despite higher compaction energy. Conversely, mixtures produced at this temperature exhibited globally low values for ITS and ITSM, suggesting higher sensitivity to production temperature, underscoring the importance of careful selection during production [1].

Hamburg Wheel-Tracking Test

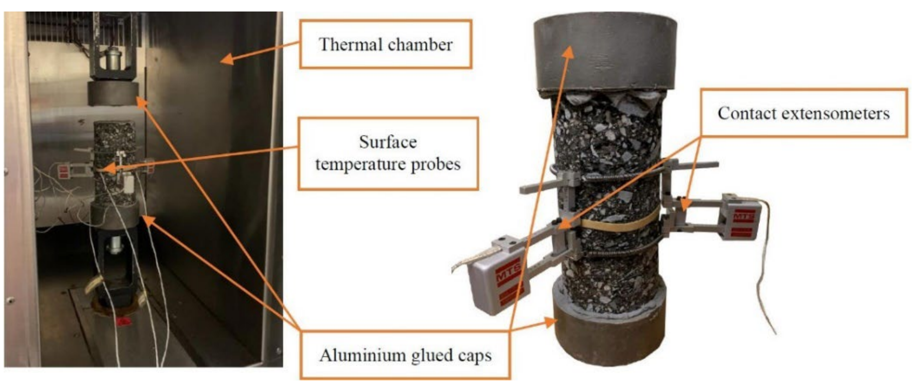
Although the HWT device, primarily intended for HMA, can be harsh on CMA, leading to premature specimen failure, researchers have utilized it to assess the engineering properties and performance of

CMA materials [3] [12]. The Hamburg Wheel-Tracking (HWT) test, as per AASHTO T324-11, evaluates the rutting and moisture susceptibility of asphalt mixtures by rolling a steel wheel over the sample within a temperature-controlled chamber. The number of passes during testing should be adjusted to enable the observation of moisture damage under immersed conditions. Research conducted by the City of Hamburg indicated that moisture damage effects became noticeable after approximately 10,000 passes when samples underwent 19,200 passes. Hence, literature recommendations advise conducting more than 10,000-wheel passes to adequately reveal the impact of moisture damage on asphalt mixtures [12]. A study investigated the effectiveness of polymer modified emulsions in enhancing the performance of cold mix asphalt made from recycled materials. The study found that while there was no significant improvement in strength, moisture damage resistance, or fatigue resistance with polymer emulsion compared to regular emulsion, there was a moderate enhancement in rutting resistance. The study suggests that polymer modified emulsions may offer benefits in improving the rutting resistance of cold mix asphalt [24].

Fatigue Performance

Bituminous materials' linear viscoelastic behavior is often assessed through cyclic TC (Figure 8) tests to measure complex modulus across various temperatures and frequencies as shown in Figure 8. In this study, TC tests were conducted solely on the original RAP source with an NMS of 20 mm. Specimens, obtained by coring a 150 mm diameter SGC specimen at 100 gyrations, had a height of 150 mm and a diameter of 75 mm. Sinusoidal cyclic axial loads were applied using a hydraulic press in controlled deformation mode, with a 50 µm/m amplitude. Axial tension was measured by a load cell, axial deformation from three strain gauges, and radial deformation from two non-contact sensors. Tests were performed at 8 temperatures (-30 to 34°C) and 7 loading frequencies (0.01 to 10 Hz). Experimental results were analyzed using the 2S2P1D linear viscoelastic model, as detailed in previous research [17].

Figure 8. Specimen before (left) and after (right) tension–compression test from [17].



Another study utilized a two-component epoxy to secure cold mix specimens for Uniaxial Tension-Compression Fatigue testing, minimizing its effect on results through room temperature hardening for 20 hours. Testing at 12°C simulated Pennsylvania's colder conditions, with extensometers monitoring fatigue behavior, and experimental techniques like four-point bending and Indirect Tensile (IDT) testing were used for analysis. Studies highlighted the influence of cement content and filler type on fatigue characteristics, recommending stabilizing agents like polymers and Portland cement for improved performance, with polymer-modified emulsions showing promise in enhancing rutting and fatigue cracking resistance in cold recycled mixes. Specifically, stabilizing cold mix asphalt with 1% Portland cement significantly improved fatigue cracking resistance in 100% RAP mixes, while polymer-modified emulsions enhanced fatigue performance by 166% [21].

The paper explores the fatigue behavior of cold bituminous mixes, which is relatively less studied compared to hot-mix asphalt. It discusses results from cold mix beam tests using a four-point beam testing apparatus, focusing on fatigue, strain-at-break, and flexural stiffness properties. Typical cold mixes, consisting of crushed limestone rock and reclaimed asphalt pavement (RAP) millings treated with asphalt emulsion or foamed bitumen, were investigated. The study aims to understand fatigue properties and the relationship between strain-at-break, visco-elastic behavior, and mix performance. Findings suggest linear fatigue relationships on a log-log scale, with the influence of active filler (1% cement) varying based on aggregate blend and binder type [25].

Fracture Resistance

Numerous studies have investigated methods to enhance the stiffness of cold-recycled asphalt mixtures compared to HMA, including modifying emulsified asphalt or integrating additives like Portland cement, fly ash, quick lime, silica fume, or waste materials into the mixtures. The type and dosage of additives significantly influence the properties of cold asphalt mixtures, with studies focusing on achieving sufficient strength and bearing capacity of the constructed base layer through treatments with cement and asphalt emulsion. Evaluation of fracture behavior using the semi-circular bend (SCB) test on Full-Depth Reclamation (FDR) materials with varying cement percentages shows that cracking resistance increases with higher cement content, although higher percentages lead to a more brittle behavior, suggesting the need for further research to determine optimal cement dosage and study moisture effects on cracking resistance in FDR mixes [26]. In research, FDR effectively addresses reflective cracking and rutting performance but lacks comprehensive research on its rheology, leading to reluctance in its widespread use. Additionally, the impact of adding cement as a co-binder on FDR's mechanical behavior requires further investigation to determine the optimal quantity without compromising mix integrity [19]. In the study by Orosa et al. (2022), the SCB test was conducted following ASTM D8044–16 on twenty-four semi-circular specimens (Figure 9); specimens were compacted with 100 SGC gyrations, utilizing three different NMS of RAP, each with a 25 mm notch parallel to the vertical axis, tested at temperatures of –20, 0, and 20°C. A monotonic displacement of 0.5 mm/min was applied while recording load and vertical displacement using a data acquisition system. A preload of 45 ±10 N was applied for up to 30 s before testing to ensure contact. Maximum load (P_{max}) before failure and strain energy to failure (U) were calculated and compared for each mixture and temperature [17].

Figure 9. SCB specimens prior to testing from [17].

Environmental Considerations in Canada and Low Temperature Properties

Over the past decade, the construction of road pavements has seen the emergence of new techniques, with a focus on environmental and economic considerations. CRMs have gained prominence for structural layers like binder, base, and subbase layers. CRMs offer the advantage of being producible at ambient temperatures, significantly lower than those required for conventional HMA. This temperature reduction is achieved through the use of asphalt emulsion or foam with lower viscosities, facilitating placement and compaction at lower temperatures, which will be beneficial for the energy saving concept [14]. Furthermore, the aging road network infrastructure has led to increased focus on pavement restoration interventions, particularly in North America where rehabilitation treatments have gained prominence over new constructions since the 1970s due to rising asphalt prices and limited public funding. Full-depth reclamation emerges as a cost-effective technique in Quebec since the 1980s, offering environmental benefits by reducing virgin aggregate usage, greenhouse gas emissions, and energy consumption [19]. Water in CAMs ensures workability, compactability, and the use of wet aggregates, offering significant environmental and energy-saving benefits over HMA or WMA. Sustainability is further improved by incorporating RAP as aggregate material in CRMs, producing high-performing base or binder layers with abundant RAP availability [1]. In a study, CIR is proven to be a cost-effective and environmentally sustainable pavement rehabilitation treatment, reusing existing HMA pavement materials [10].

Conclusions

In recent years, there has been lots of interest in CMA as a rapid solution for pavement repair projects. However, the lack of reliable quality control procedures remains a challenge in the widespread use of these mixes. Researchers have focused on investigating the engineering properties, permanent deformation, and moisture resistance of various types of CMAs.

The comprehensive assessment of asphalt mixtures through various tests and studies sheds light on crucial factors affecting their performance and durability. Studies have shown that densely-graded CMA samples exhibit higher rutting resistance compared to open-graded samples, with factors like dust-to-binder ratio and percentage of coarse aggregates influencing moisture susceptibility. Additionally, the rheological behavior of CRM, including CRM mixtures produced with asphalt emulsion and cement, has been analyzed to aid in pavement design and analysis. Results indicate that the fine aggregate matrix (FAM) of CRM mixtures plays a significant role in controlling curing and thermo-rheological behavior, with different binding agents impacting mechanical properties. The Hamburg Wheel-Tracking test, combined with investigations into polymer-modified emulsions, elucidates the intricate relationship between rutting resistance and moisture susceptibility. Additionally, fatigue performance evaluation through TC tests and SCB samples highlights the importance of temperature, frequency, and additive content in enhancing asphalt mixtures' resilience against cracking. Furthermore, dynamic modulus measurements, binder tests, and SEM analysis provide valuable insights into the material properties and interactions crucial for optimizing asphalt mixture design and performance. These findings underscore the multifaceted approach necessary for achieving durable and sustainable asphalt pavements, emphasizing the importance of continued research and innovation in the field. However, there is a considerable lack on research on the low temperature properties and thermal cracking susceptibility which will be crucial for the widespread use of high-performance CMAs in Canada.

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