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Original
Asphalt-based cold patches for repairing road potholes – An overview / Hafezzadeh, Raheb; Autelitano, Federico; Giuliani, Felice. - In: CONSTRUCTION AND BUILDING MATERIALS. - ISSN 0950-0618. - 306:(2021), pp. 124870.1-124870.19. [10.1016/j.conbuildmat.2021.124870]

Availability:
This version is available at: 11381/2902412 since: 2021-11-05T17:58:23Z

Publisher:
Elsevier

Published
DOI:10.1016/j.conbuildmat.2021.124870

Asphalt-Based Cold Patches for Repairing Road Potholes- An Overview

Cold Mix Patching Materials (CMPMs) are usually used instead of Hot Mix Asphalt (HMA) to repair potholes and localized distresses. Although these materials provide immediate serviceability, they have a relatively short life. However, worldwide interest in these solutions, which started as fragmented industrial initiatives, is growing. This article provides a critical comparison between several aspects regarding using CMPMs and HMA in repairing potholes. Specifically, repair techniques, productivity and costs were investigated in detail. Plus, the impact of the main crucial factors, i.e., workability, bonding, water susceptibility, stability, and storageability, on the performance of CMPMs was investigated through an overview.

Keywords: Cold mix asphalt, Pothole, Patch materials, Serviceability, Pavement maintenance

1. Introduction

Road asphalt pavements suffer from various deteriorations during their life-cycle, which requires technical and economic resources for repair and maintenance. One of the most common forms of this distress is potholes [1]. Repairing potholes costs millions of euros annually and imposes a budget constraint on the maintenance organizations. In many cases, especially for local authorities, funding for maintaining road surfaces is the most important matter. Potholes often appear towards the end of the winter season, after prolonged periods of rain or during thawing periods, as a result of defects in the preventive maintenance of wearing courses (sealing) favored by sub-bases with poor bearing capacity or poor drainage. They can influence road users' operations and traffic safety and increase the number of crashes with resulting injuries and even fatalities [2-7]. A report by the ministry of road transport and highways of India shows more than 1% of the accidents and deaths in 2018 and 2019 have occurred due to potholes [8]. Besides, the durability and life span of the pavement are affected by the occurrence and subsequent spread of potholes. This is especially true during the winter months, when potholes grow rapidly, making it extremely difficult to repair countless breakdowns in adverse weather [7, 9], and also when there are no adequate strategies and budgets for a preventive maintenance program. The repair operations in warmer weather conditions are usually applied by conventional Hot Mix Asphalt (HMA) that has a low initial cost but desired performance [10, 11]. However, the availability and application of HMA in wintertime are strongly affected by low temperatures, which induce its thermal dissipation during hauling to the jobsite. Besides, the repair materials come into contact with stagnant water and the closure of the traffic should not last for a long time. Thus, road maintenance agencies are propelled to use appropriate temporary repair methods to restore the serviceability of the pavement in a short time [12-14].

In recent years, Cold Mix Patching Materials (CMPMs) have become popular for temporary repairs due to their ease of handling, affordability, few required labor and equipment, and long storage time. Plus, they have lower environmental impacts. However, at the time of writing this paper, there was no precise information about the percentage of unused bagged CMPMs. Also, the environmental implications in terms of increases in special waste and management of packaging waste are not known [15-18]. These mixtures have a short application time and are potentially suitable for repairing potholes in different climates. Plus, as they can be produced in various quantities and stored for several months in sealed containers or stockpiled around the road, repairing scattered distresses that require small quantities of materials can be facilitated with them [16, 19]. However, despite all of the mentioned advantages, CMPMs have the lowest quality of all the patching materials. Repaired potholes during adverse weather conditions, especially in wet winter and spring, withstand only a few freeze-thaw cycles and are sometimes physically removed even by the first traffic actions. They usually have a short lifetime and need frequent treatment operations [6, 19]. Additionally, CMPMs deal with different types of deficiencies, such as poor workability, less durability, rutting, poor skid resistance, adhesion and cohesion problems during the stockpile and under in-service conditions [15, 20]. Since there are no standards for designing and evaluating CMPMs, the state of practice experiences a heterogeneity of product types, and various CMPMs with different test methods have been employed by researchers to design the CMPMs and investigate their performance.

Thus, after a detailed description of pothole formation mechanisms and their general maintenance and rehabilitation techniques, the paper focused on the development of CMPMs over the past years in comparison to conventional hot patch mixtures with specific attention to their components, curing, and performance evaluation.

2. Pothole description

2.1. Definition, formation mechanism, and severity levels

Although several definitions have been proposed to identify a pothole, it can be simply described as “a bowl-shaped hole of various sizes in the pavement surface” [21] or in greater detail as "a localized deterioration of road pavement resulting from a loss of material or depression in the pavement surface" [1]. Potholes are caused by a combination of physical, mechanical, and environmental stresses. Specifically, water infiltration and traffic loads play the main roles in the initiation and growth of potholes. Continuous traffic, especially in adverse weather conditions, leads to cracks in the pavement, which are the prerequisite for pothole formation [22-24]. The cracks in the pavement facilitate water seepage into the road structure. Then, the occurrence of freezing and thawing cycles due to water ingress leads to loss of support in the road layers, and consequently, more serious damage is caused [25-27]. Despite water permeability and traffic, other factors, such as poor mix design or inadequate construction methods [28], defective geometric design of the road [12], material failure, raveling, stripping, bleeding and shoving of the pavement [27, 29], lack of information and defective workmanship, excavation and reinstatements by utility companies [30], inappropriate pavement repair and winter maintenance practices, especially snow removal [31, 32], reduction in lifespan of the road structure, fatigue and interconnected alligator cracks, etc., simplify the formation of potholes and various damages [33-35].

Road management classifies potholes and their severity levels based on their dimensions, surface area, and depth [28]. These parameters are further influenced by other factors, such as climate conditions, speed and intensity of traffic, vehicle type, and the presence of pedestrians and bicycles [5]. According to the U.S. Federal Highway Administration (FHWA), holes with a minimum width of 150 mm and a depth of 2.5 mm, 2.5-5.0 mm, and greater than 5.0 mm are considered low, moderate, and high-severe potholes, respectively [21, 23]. The ERA-NET ROAD pothole project has established a depth of at least 30 mm and a diameter of 100 mm up to 1 m for typical potholes depending on road specific conditions. Potholes with a depth of more than 40 mm are instead regarded as severe [5] and must be repaired in less than 24 hours [26]. Based on Norwegian standards, any damage wider than 100 mm for a vehicle lane and 30 mm for a bicycle lane must be repaired within a week [34]. A conducted study by the Strategic Highway Research Program (SHRP) in the U.S. classifies 0.93 square meters and 150 mm as the maximum surface size and the maximum depth of a pothole [7]. The maximum recommended depth by UK Haringey Council standards is 50, 60, and 25 mm for major roads, unclassified roads, and places that may be dangerous for pedestrians or cyclists, respectively [28]. Also, based on the answers to a questionnaire by approximately 80 local authorities in 2014 in the UK, 67% of respondents considered 25–40 mm, 12% selected 40–50 mm, and 14% considered a depth of greater than 60 mm as a typical pothole depth [21]. Furthermore, as follows (Table 1), the Swiss Road Maintenance and Management Association classifies potholes based on the severity of the distress [26].

Table 1. Potholes' classification based on the severity of the distress [26]

Damage condition	**Severity**	**Depth (mm)**	**Diameter (mm)**
Starting to form single potholes	Low	-	< 100
Single potholes	Medium	< 40	100-300
Slightly connected potholes	High	≥ 40	≥ 300

The severity of the potholes is ranked slightly differently by Shahin [36]. According to Table 2, for potholes with an average diameter of up to 762 mm, both the depth and the diameter are considered to classify the pothole severity. If the diameter is higher than 762 mm, the pothole area is determined and divided by 0.47 square meters. If the result is higher than 25.4, the severity is considered high, otherwise medium [36]. If the distance between the potholes is less than 200 mm, they should be measured together and considered one big pothole [3].

Table 1. Classification of potholes based on depth and diameter according to Shahin [36]

Maximum Depth (mm)	**Average Diameter (mm)**		
	102-203	**203-457**	**457-762**
12.7 – 25.4	Low	Low	Medium
25.4 – 50.8	Low	Medium	High
> 50.8	Medium	Medium	High

2.2. Maintenance and rehabilitation

Road pavements deteriorate under various vehicle traffic and weather conditions. Thus, they need to be rehabilitated to restore serviceability [37]. This rehabilitation technique generally adopted for potholes is called patching (Fig. 1), which is the process of filling potholes in the road pavement with a suitable material to control further deterioration of the pavement and restore the users' safety and comfort [6].

Pothole patching covers a wide range of methods, from temporary procedures in emergency situations to permanent (or semi-permanent) interventions performed during corrective and routine maintenance operations [38]. It is the most obvious and sensible sign of road maintenance to the public and road users [39]. As stated by O'Flaherty [29], patch operations should be performed in good weather before potholes spread throughout the pavement, worsening its condition. Nevertheless, before patching, the cause of the failure must be determined [40].

Prompt repair can limit expenditures and prolong the service life of a pavement. However, this maintenance and rehabilitation strategy is costly and time-consuming, especially in the cold and wet winter months. Therefore, potholes need urgent attention by road maintenance authorities to cut down on further pavement deterioration, vehicle damage, and user costs [20].

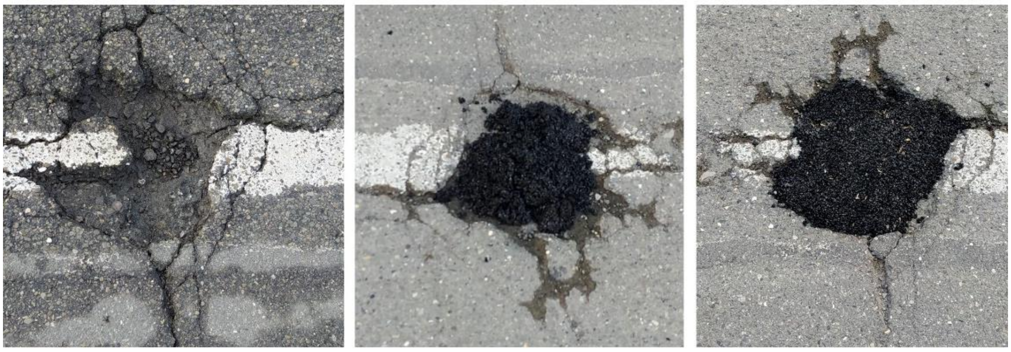

Figure 1. Patching a pothole with CMPM

Despite improvements in mix design and the development of enhanced materials, pavement failures still happen. However, when the distresses are close and occur in relatively isolated locations or on low-traffic roads, the most common maintenance technique used to repair and restore the serviceability is patching [41, 42]. In good patching practices, material quality, repair method, and compaction level are the most important parameters [43, 44]. Nevertheless, the decision to patch is influenced by various factors, such as [38]:

- The temporal frequency of routine maintenance of pavement resurfacing or overlay
- Traffic level
- The hierarchy of the road and the possibility of setting up a temporary construction worksite
- The availability of the equipment, materials, and labor
- Public negative view

Additionally, running time, the climate condition, size of the pothole, properties of the host pavement, and the overall expenditure can affect the patching operations [26].

2.2.1. Repair Procedures

Pothole repair operations include several temporary and semi-permanent to permanent approaches, which are as follows [44, 45].

- Temporary repairs

    - Throw-and-dump or throw-and-go: The cold mixture is just shoveled into the pothole without any heavy compaction and removing the water and debris. The patch is compacted by normal traffic.
    - Throw-and-roll: The cold patch is placed into the unprepared pothole and compacted using a hand tamper and the truck tires.
    - Edge seal method: The repair method is similar to throw-and-roll, but after compaction, the perimeter of the repaired section is covered with a tack coat and sand. Then, it is left for about one day to dry.
    - Spray-injection: The mixture of aggregate and heated asphalt emulsion is sprayed into a prepared pothole, then the patch is covered with aggregates to prevent tracking by vehicles.
- Semi-permanent repair: In this partial-depth repair, the edges of the prepared pothole are vertically cut with a saw and filled with a cold mixture or, in some cases, with HMA. Then the patch is compacted with a roller.
- Permanent or full-depth repair: This approach is used to repair structural damage and may involve the rehabilitation of the subbase and base layers.
    - Infrared: The new asphalt is blended with the existing -Infrared Heated-Pavement material and compacted.
    - Microwave: The hole and its surroundings are pre-heated, and after cleaning loose debris, the pothole is overfilled with patch material and heated and compacted.

It is recommended that road maintenance agencies should consider permanent repairs as their first choice and use temporary methods only for emergencies to provide safety quickly [35]. Studies show that although the semi-permanent method provides more durability in repairing failures, the high cost of equipment, labor, and higher required effort to patch, reduces its productivity compared to temporary methods like throw-and-roll and edge seal [7]. Spray injection also requires high equipment costs while, depending on the labor skills, its productivity is high. Plus, the materials used in spray injection have a lower price. The throw-and-roll procedure does not require special equipment, but hand tools to fill the hole. This method can be an alternative to semi-permanent that ensures satisfactory repair using high-quality materials [38, 46]. A study by Wilson [47] in 1993 stated that spray injection offers more durable patches than the aforementioned procedures, and in terms of tons/person-day (Table 3), it is the most productive technique [47, 48]. The results of another study showed that the productivity of throw-and-roll and spray injection approaches is 4 and 2 times better than the infrared method in terms of tons/day. Moreover, the investigation of winter pothole patching methods by Nazzal et al. [7] showed (Table 3) that by considering the required time for repairing potholes, throw-and-roll, spray-injection, edge seal, and semi-permanent techniques have the highest productivity, respectively. However, the most recent market data shows that there is considerable interest in the convenience of single-use packaged products for throw-and-roll, albeit higher unit prices offset by greater ease of handling and speed of use. The general characteristics of the patching procedures are shown in Table 4.

Table 3. Average productivity values for different repair techniques

Repair technique	**Average productivity (tons/hour)**	**Labor (person)**	**Average productivity (tons/person-day)** [47]	**Average required patching time (min) [7]**
Spray injection	1.7	2	3.4	2.8
Throw-and-roll	1.6	2	3.2	2.6
Edge seal	1.4	2	2.8	3.2
Semi-permanent	0.3	4	1.2	13.3

Table 4. General features of pothole patching procedures

	Benefits	**Drawbacks or limitations**	**longevity**	**Ref.**
Throw-and -go	• relatively short time • using few workers • simple application • can be used for temporary patching under adverse conditions	• shortest service life	• a few days to few weeks	[7, 33, 49, 50]
Throw-and -roll	• easy and fast • does not require specialized equipment • crew is less frequently exposed to traffic • can be used for temporary patching under adverse conditions • high productivity rate	• labor intensive and repairs can easily fail if the repair is not done correctly	• 3-12 months All-season	[7, 42, 48, 51]

Spray Injection	- fast repair - require fewer people and no compaction - ability to repair potholes in adverse weather - produce a neater and smoother repair - less labor intensive and safe - requires the least expensive materials - does not need to be further compaction	- higher cost of patching for low quantities - requires specialized equipment - need to clean up debris - operator is typically exposed to errant traffic - parked vehicles may become coated with overspray - formation of a cold joint - requires well trained and experienced operators - higher equipment costs	- up to 2 years at summer ≥3 years	[7, 24, 52, 53]
Edge seal	- better connection between the asphalt pavement and new materials - keeps water out	- requires a long recovery time between patching and opening the roadway to traffic	- >1 year All-Season	[7]
Semi-Permanent	- more cost-effective - results in the long life - improving the underlying and surrounding support	- requires more workers and equipment - less effective in winter conditions - has higher labor and equipment costs and lower productivity - involves more preparation and compaction and not feasible under adverse conditions - More patch time is required	- up to 2 years All-Season	[7, 33, 37, 44, 54]

Permanent	• results in the longest life • improving the underlying and surrounding support	• requires more workers and equipment • not applicable in winter	• 3-6 years • With proper preparation up to 15 years	[7, 15, 24, 42, 47]
Infrared	• less crew time in traffic • eliminating or reducing the amount of new asphalt mix, using waste material • provide higher bonding between patch and old pavement	• requires long patching time; 10-20 min	• ≥ 13 years for crack filling	[7, 54-56]
microwave	• using RAP and RAS • strong interface bonding	• requires long heating time		[57, 58]

2.2.2. Patching materials

The materials that can be used to repair potholes are numerous. However, they are classified into the following main categories [5, 42]:

- Hot-mixed asphalt materials
- Cold-mixed asphalt materials
- Cement-based materials

Asphalt-based materials (hot and cold) can be used for both asphalt and concrete pavements, whereas cement-based materials are commonly used for permanent patches on rigid pavements. Additionally, there are other types of repair materials such as synthetic binders, epoxies, polymeric materials, and resins that are not used commonly, especially throughout Europe [5, 42].

Hot-mixed asphalt mixtures are applied hot or cold in the repair operations. The mixture can be produced with well-graded heated aggregates and a hot asphalt binder at high temperatures and used immediately after being produced. Moreover, they are produced in an HMA plant with heated aggregates and liquid asphalt-base binders at a lower temperature than used in the previous procedure. Then, the cold product is stored for later use.

Cold-mixed asphalt mixtures are not heated during their production. The liquid asphalt-base binder and aggregates are mixed in a plant or on a jobsite and stockpiled or used cold in pavement treatments. Compared to the HMA mixtures, they have low quality and poor performance [6, 59]. In general, these kinds of products, also known as CMPMs, are classified according to the following categories [26, 40]:

- The cold mix is produced by a local asphalt plant: The available materials are used to produce the cold mixture without considering the binder-aggregate compatibility test.
- The cold mix is produced based on the specifications that have been set by the agency: The binder-aggregate acceptability and acceptance criteria by the maintenance agency are considered before buying the material.
- Proprietary cold mix: These materials, which include specially formulated binders, after passing some acceptance tests, can be produced in bulk and stockpiled or can be kept in buckets or bags (25-40 kg) to be handled easily on the job site.

Hot and cold asphalt-base materials are the most extensively used for all road maintenance operations. They have a relatively low cost, satisfactory stability, good quality, and easy application. Hot prepared and applied materials provide a more durable and effective solution for repairing potholes [26]. According to previous studies, HMA materials, due to their high initial stability, low permanent deformation, effective bonding to the old pavement, and easy compactibility, perform better than CMPMs and give the best repair [2, 60]. The New Jersey Department of Transportation (NJDOT) used three different types of CMPMs and one type of HMA to repair potholes. The results showed that HMA has far better performance than the other mixtures [61]. Other studies by Dong et al. [41] and Marasteanu et al. [15] indicated similar results. The performance of patching materials involving hot mix, cold mix, cold mix with fibers, and fiber mix heated in a Porta-patcher in filling shallow potholes was evaluated in a study by Feighan et al. in 1986. Their service lives and repair procedures were analyzed and compared on roads with poor, fair, and good conditions. The results indicated that hot mix asphalt has excellent performance in comparison to the other mixes. Plus, CMA was less effective [42]. Moreover, apart from their less workability in adverse climate, dependency on equipment, and being less environmentally-friendly, owing to their higher durability, they are the priority of road maintenance agencies in patching operations [62, 63]. The outcomes of a survey in 2014 in the UK (Fig. 2) included responses of approximately 80 local authorities to questionnaires, and showed that 31% of the agencies prefer to use HMA for pothole repair, and 69% of them use both cold and hot materials [25]. In another survey included responses from

49 states in the USA, 20 local agencies in eight U.S. states, and 33 highway agencies at the local and national levels in the UK and Ireland; the results (Fig. 3) indicated that HMA is the most widely used material for permanent patches [42].

Despite the durability of these materials in patching potholes, their limited applicability in adverse weather and their long and specific application procedures draw the attention of maintenance agencies to the use of CMPMs. Generally, CMPMs have lower quality and poorer performance than HMAs in the face of several benefits. They are workable in most weather conditions [64, 65], since in the CMPMs, the workability is not achieved through heat but by using solvents [11]. Also, their longevity is significantly affected by the quality of the materials [25]. The CMPM application is quick and takes less time, resulting in a safer repair operation with less traffic disruption, especially in difficult conditions like high-speed roads and intersections such as roundabouts [30].

Therefore, using a high-quality mixture is very important to ensure durability, but not enough [30]. If the mixture is used in unsuitable conditions, it will not work well, and the service life will be short [26]. The following are three main concerns of CMPMs to achieve maximum performance [66, 67]:

- high air-void content or a modest level of densification
- weak initial strength and stability
- long curing time to attain their max performance.

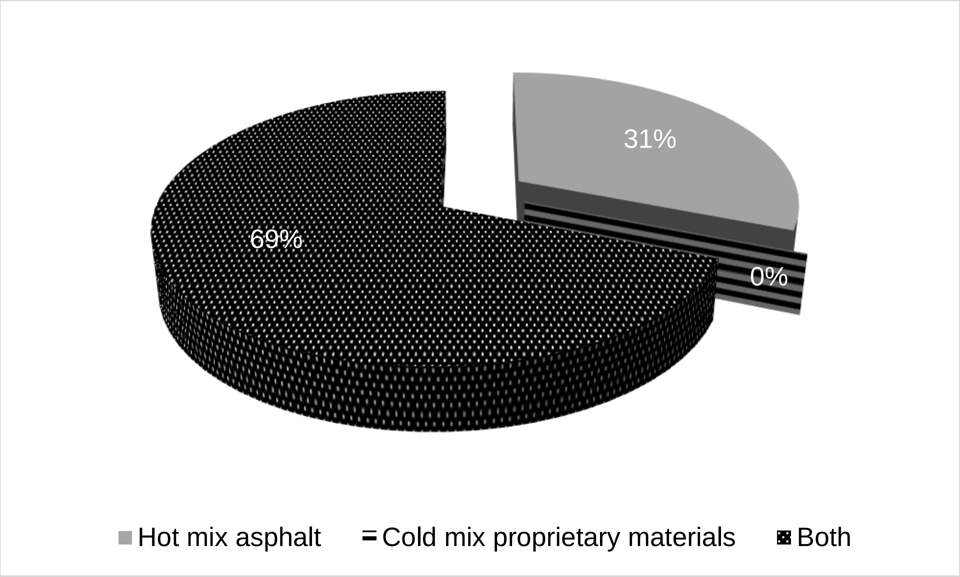

Figure 2. Material used for patch repair based on responses of local authorities [25]

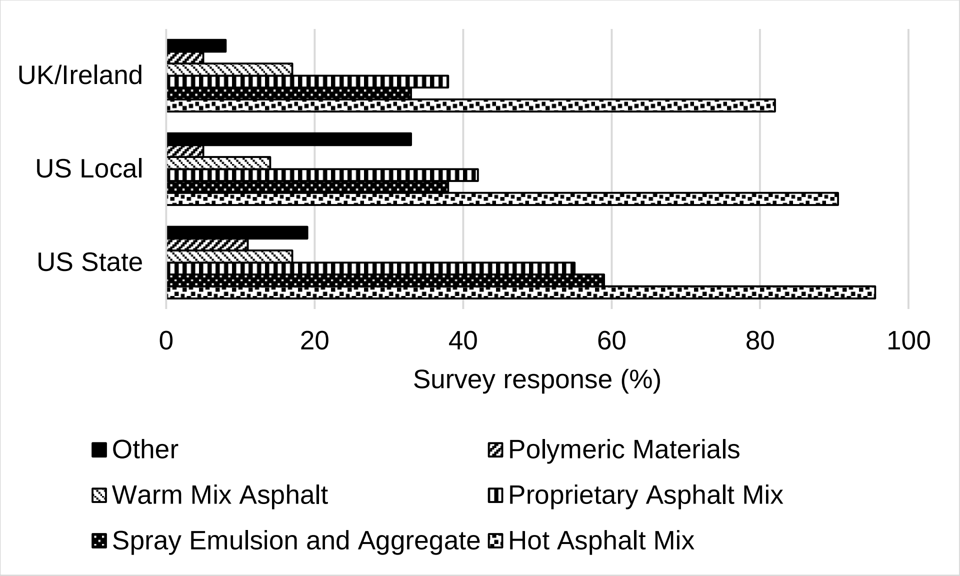

Figure 3. Materials used to repair potholes according to responses of agencies [42]

2.2.3. Durability of the repaired potholes

The patch durability usually depends on repair conditions (high or low weather temperature), the quality of the patching material, and the patching method [41]. Therefore, if the patching procedure is done satisfactorily under warm or fair-weather conditions, the repair method can be very efficient and durable [7]. The patching operation in cold winter compared to spring leads to a shorter life, usually a few days to a few months [26]. In fact, the purpose of repairing potholes in winter is only to provide traffic safety by restoring rideability, not a permanent repair. Nevertheless, repaired patches in the spring are expected to last as long as the surrounding pavement [38]. The durability and survival period of winter and summer repaired potholes were assessed through a laboratory study and a questionnaire in six provinces (Alberta, Manitoba, Ontario, Quebec, Saskatchewan, and New Brunswick) in Canada. The results (Table 5) declared that winter patched potholes survive for no more than 12 months. This value for summer patched potholes was more than one year [32, 53].

Table 5. Survival period of repaired patch in six provinces in Canada (months) [32]

Province	**Alberta**	**Manitoba**	**Ontario**	**Quebec**	**Saskatchewan**	**New Brunswick**
Winter	<3	9-12	3-6	6-9	3-6	<3
Summer	>24	>24	12-18	12-18	18-24	>24

Durable patches are not obtained only by applying HMA. The use of high-quality CMPMs also leads to a long patch life. Proprietary cold mixes with a one-year survival period can be considered suitable patches for repairing potholes [41]. The results of the repaired potholes with high-quality CPAMs in China were desirable, but the mixture with high-quality material was 3-5 times overpriced than HMA [18]. Nevertheless, past experiences show that high-quality materials give a longer service life even if they cost more. In fact, high-quality materials offset the cost of frequent repairs that are conducted with poor-quality materials [10].

Despite the material and application conditions, the patching methods involving temporary, semi-permanent, and permanent methods also have an important role in patch longevity. The expected life of a temporary repaired patch is up to one year. However, if a high-quality material is used, it can last up to 18 months [28]. The NCHRP report has limited this period to 3 to 6 months [42]. If the patching mixture can be compacted to an equal density as the existing pavement, the life span will be extended [68].

Repaired potholes with throw-and-go have the worst durability and last a few hours to a few weeks [49, 50]. Owing to the short life, frequent re-patch, and high cost, this repair method is generally not recommended [42]. The durability of repaired potholes by the throw-and-roll method is higher than by throw-and-go. If the patching operation is properly done using this method, it can last up to 12 months for the spring season and 6 months for the winter season [28, 33]. In the aforementioned study in six Canadian provinces, potholes filled by the throw-and-roll method in winter did not last more than 3 months. But summer patched potholes had a lifespan of more than 2 years [32]. In a 14-month field survey in Tennessee, winter-repaired potholes with the throw-and-roll method showed a shorter life span and failed just after several weeks [69]. In general, the throw-and-roll method can be a proper substitute for a semi-permanent repair method if the durability of the product exceeds more than 9 months [32]. Patching by the edge seal method is relatively durable in all seasons and lasts more than one year. The spray injection method, if it is applied correctly, can act as a permanent patch and last up to two years, but shows poor performance if exposed to stable wet conditions [28, 42]. In the semi-permanent repairing method, the expected patch life is up to 2 years [33]. The permanent patching method is the most durable repair method that lasts 3 to 6 years. If a permanent technique with HMA is applied correctly in a properly prepared pothole, the lifespan can also last 15 years or more [15, 24, 44].

Overall, previous studies categorize the durability of the patching materials as follows [45, 70]:

- Short-lasting patches: patches with less than one year of longevity.
- Medium-lasting patches: patches with a 1-3 year lifespan.
- Long-lasting patches: patches with more than 3 years of survival life.

However, the patch longevity is still considered to be days or months instead of years [71]. In fact, owing to one or a combination of the already mentioned factors, the patch fails in a short time. Table 6 gives the most important reasons for patch failure in more detail [9].

Table 6. Failure symptoms and mechanisms of cold patching materials [9]

Symptom	Failure reasons
In stockpile	
Poor workability	High viscosity binder; dirty aggregates or excessive dust; too fine or too coarse gradation
Binder draindown	Low viscosity binder; stored or mixed at high temperatures
Stripping	Aggregates poor coating during mixing; wet or cold aggregate
Lumpy mixture, premature hardening	Higher rate of volatilization and premature curing
Stiffness in low temperature	Binder higher temperature susceptibility, dirty aggregates or excessive dust; too fine or too coarse gradation
During placement	
Poor workability	High viscosity binder; dirty aggregates or excessive dust; too fine or too coarse gradation
Poor stability	High binder content, low viscosity binder, poor aggregate interlock, inadequate voids in aggregate
Hard to compact	Low viscosity binder, higher or lower amount of binder, improper gradation, excessive fine, the shape of the aggregates
In-service	
Shoving, pushing	Poor compaction, low viscosity binder or high amount of binder; Binder moisture and temperature susceptibility; contaminated mixture; long volatilization process; inadequate voids in aggregate; poor aggregate interlock
Rutting	Poor compaction
Raveling	Poor compaction; low viscosity binder; poor mixture cohesion; poor aggregate interlock; aggregate binder absorption; moisture susceptibility; dirty aggregates or excessive dust; too fine or too coarse gradation
Freeze-Thaw deterioration	Poor mixture cohesion; too pervious mixture, moisture susceptibility
Poor skid resistance	Higher binder content; rounded aggregate; too dense gradation
Shrinkage or debonding	Poor pothole preparation; mixture poor stickiness

Most of the symptoms and problems listed in the table, such as binder content, poor-graded aggregates, and improper repair by the non-specialist crew, were also discussed by Kandhal and Mellott [72]. However, depending on different circumstances, the impact of these factors on patch failure can be different. The response of approximately 80 local authorities across the UK to a questionnaire about the main causes of patch failure showed (Fig. 4) that water infiltration and poor-quality mixtures have the highest and lowest impact on patch failure, respectively [25].

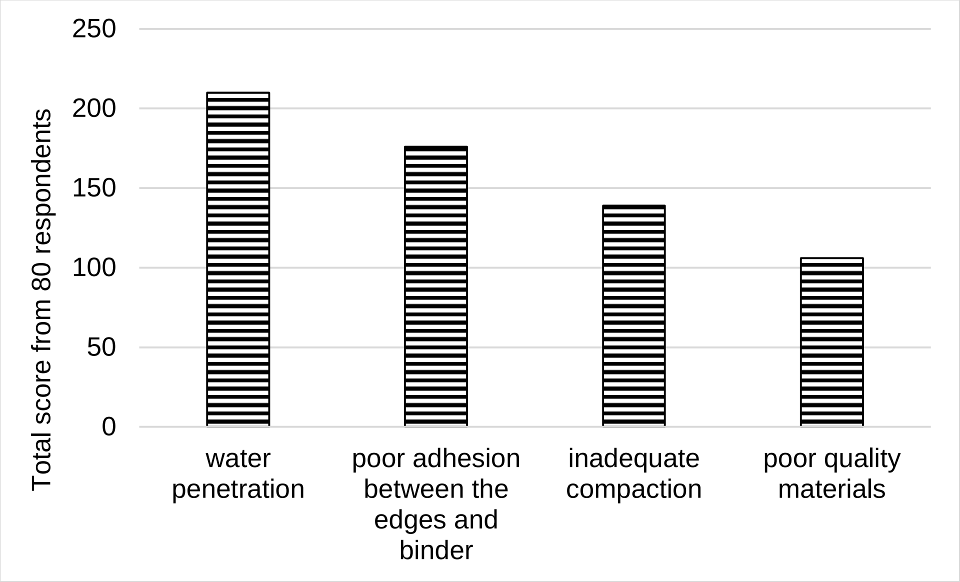

Figure 4. The main factor in failing of potholes in UK (least likely reason=1, most likely reason=4; the score is the sum of all weighted rank counts) [25]

2.3. Cost analysis

Since patching practice is an extensive and large-scale repair activity, road agencies have to spend millions of dollars annually [6, 71]. Pothole patching major costs involve materials, labor, and equipment. However, lane closure and user-delay costs, vehicle damage costs, and insurance costs are also involved with pothole maintenance expenditure and cannot be ignored [2].

According to a study in 2010, the cost of accidents and vehicle damage exactly due to potholes over a rainy season in the UK was more than £10 billion ($13.8 billion), which is four times more than the total yearly road budget of South Africa [40]. In another research, the Local Government Association (LGA) estimated the money needed to repair damaged cars due to potholes in the UK was £1 billion ($1.38 billion) in 2014. Besides, the results of conducted research by the international research data and analytics group (YouGov) showed that businesses in England and Wales face an annual incremental loss of £5 billion ($6.9 billion) due to poor road conditions, which is higher than the road maintenance budget [25]. Therefore, the repair lifespan in determining the benefit-cost ratio (BCR) is essential, and durable patches, especially patches with more than one year of survival life, can significantly reduce the overall costs as they do not need to be patched frequently [62]. Previous studies indicate that by preventing the replacement of unsuccessful patches, cost-effectiveness improves tremendously [42]. Therefore, preventative maintenance programs have an important impact on the longevity of the patches and, in the long term, can be less expensive than routine patch operations [28].

According to a study by ALARM in 2012 [30], a preventive maintenance plan can be at least 20 times cheaper than reactive maintenance. However, due to a lack of budget, planned maintenance operations are usually less considered. Based on responses of approximately 80 local authorities to a questionnaire across the United Kingdom, 25% of the yearly budget allocated for pothole repair is spent on "planned maintenance", 59% on "reactive maintenance" and the remaining 16% is spent on routine operations [25].

Usually, in repair operations, the highest cost is devoted to crew and equipment. Through research in 2013, Dong et al. [69] claimed in patching practices, 50 to 60% of total patching costs account for workforce charges. Plus, the equipment accounts for a significant portion of the total cost. However, the devoted costs in temporary approaches with CMA are a bit different. The materials and equipment costs can be notable based on the employed method for repairing potholes, as Lukas Hammel showed in his research (Fig. 5) [73]. As a result, skilled labor and standard equipment with patching materials can reduce or increase the patching costs [60].

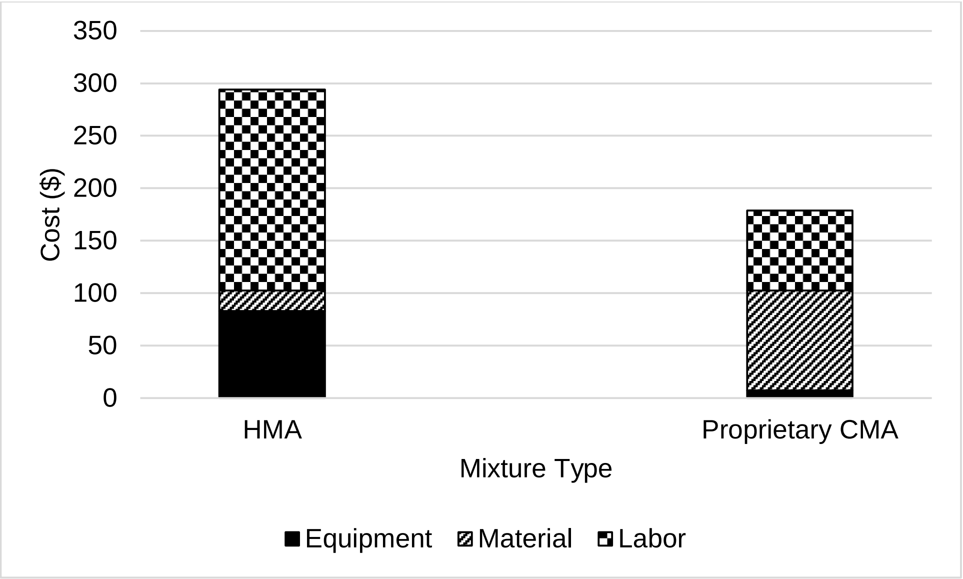

Figure 5. The comparison between devoted costs in 2015 for HMA and a proprietary CMA. (The original cumulative costs were expressed in Euros) [73]

In most cases, the cost of materials is just a small portion of the total patching costs [37, 41]. Studies have shown that this value is 15 to 25 percent of the total operation costs [74]. If the repair process is done properly, it also accounts for less than 10-20 percent of the total cost [49]. According to studies, CMPMs contribute 20% of the overall repair cost, while this value for hot mix asphalt is 2-5% [60]. Despite the low cost, the materials have a significant impact on the patch and the total cost. Usually, CMPMs with poor performance lead to increased labor, equipment, traffic control, and user delay costs. Therefore, utilizing high-quality materials is recommended to increase longevity, prevent re-patching operations, and reduce overall costs [47, 49, 51]. In fact, the cost of high-quality materials and a proper repair method is significantly less than the cost of frequent patching operations [9]. Through research in 1988, Anderson et al. [9, 74] calculated the annualized expenditure per repair for various patching materials costing from $30/ton to $120/ton (Fig. 6). By considering the critical condition, if the most expensive mixture ($120/ton) lasts until the second year, the cost required to repair the damage will be less than the cost needed to patch the pothole with cheap material ($30/ton) after just one year. Therefore, using expensive materials with high longevity leads to a notable cost saving in the long run [49].

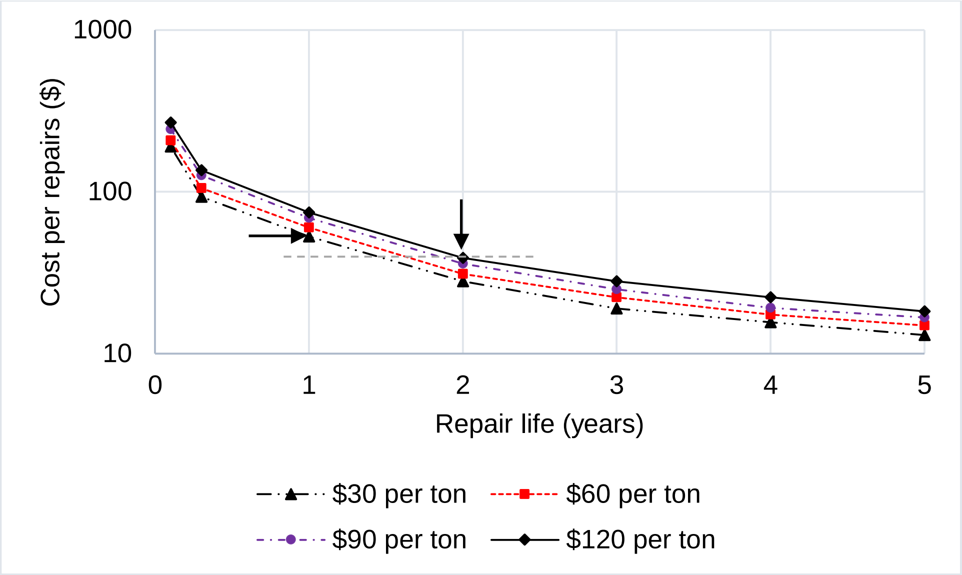

Figure 6. Equivalent uniform annualized cost in 1998 for standard repair procedure [74]

However, the results of a research project at the University of Minnesota showed that for short-term purposes, cheaper materials and temporary methods are more cost-effective, and long-lasting patching methods offer high effectiveness in the long term. Additionally, if user costs are taken into account in the analysis, the benefits are even greater [15].

It is noticeable that high-quality materials alone cannot guarantee the durability of the patch. If used in poor condition with inappropriate technique, it will not perform well and not last long enough. As stated in a two-year European study called POTHOLE, unprepared pothole practice with cold mixtures costs the most compared to other patching repair strategies. Among the repair methods, a standard procedure including cutting, cleaning, filling, and compacting the patch is the most cost-effective repair method [15]. The throw-and-go method, as a common repair method without any hole preparation, is not considered a cost-effective method compared to other strategies. According to Thomas and Anderson's study [49], this patching procedure is roughly three times more expensive than a standard patching method.

Following the results of a questionnaire survey in 2011, in Tennessee, the semi-permanent method is the most cost-effective technique in the long run, despite the increased cost of labor, equipment, and operation time. Plus, the throw-and-roll treatment method used in spring is cost-effective, while the winter season's throw-and-roll procedure is the least cost-effective. The semi-permanent technique is considered to be more cost-effective than throw-and-roll [33]. The most extensive pothole repair research project (H-106) by the SHRP found that for similar patching materials, the throw-and-roll repair method is as effective as the semi-permanent method. However, when the effective cost is considered based on the patch service and analysis period, the throw-and-roll method would be more cost-effective than the semi-permanent one due to reduced labor and equipment [47]. Under optimal conditions, the labor cost for patching and traffic control can be considered as two and four workers for the throw-and-roll and permanent methods, respectively [37]. Confirming other similar studies, pothole repair using a semi-permanent method costs almost 2.5 times more than the throw-and-roll method [32]. These cost differences between throw-and-roll and semi-permanent methods have been shown in another study by Dong et al. [69] for Tennessee DOT. According to the results, repairing potholes with the various cold mixtures by the throw-and-roll technique requires much less cost for equipment and labor (Fig. 7).

In another study, Nazzal et al. [7] assessed the performance and lifecycle cost of infrared patching operations and compared them with spray injection and throw-and-roll repair methods. The comparison revealed that if the user costs are overlooked, for short-term repairs (less than 12 months), the throw-and-roll method will be more cost-effective than the infrared method. However, in the long run, especially for winter repairs, the infrared method is more cost-effective than the other methods.

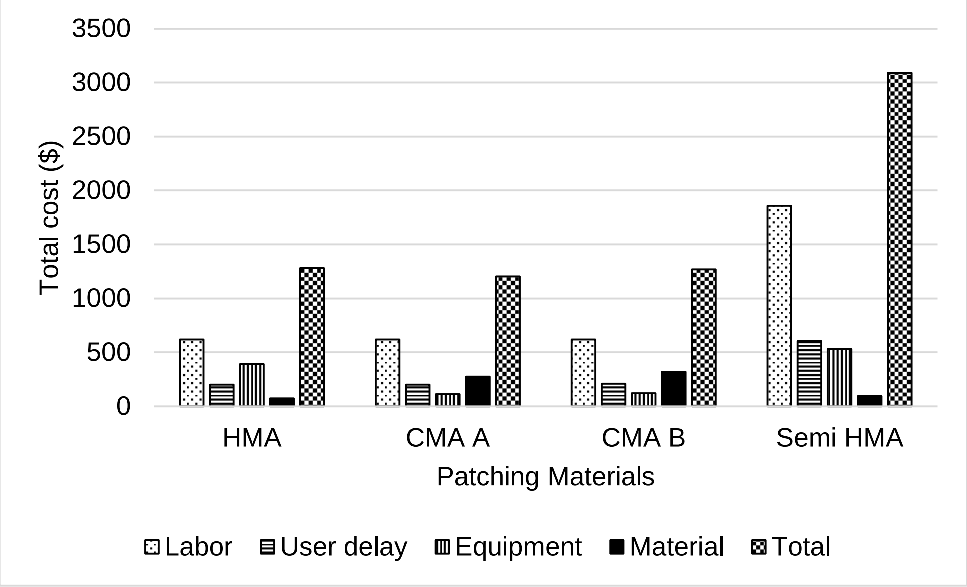

Figure 7. Total patching cost differences between cold mix and hot mix asphalt in 2014 [69]

Wei and Tighe [75] evaluated the durability and cost-effectiveness of repaired potholes through different methods (Table 7). They found that the spray injection patching method is less cost-effective. Although, unlike the hot mix pathing procedure that requires purging the leftover unused materials from the vehicle after the end of repair operations, it is possible to store the mixture on the patch spray machine for fast and efficient deployment in small- or large-scale repair practices [76]. Finally, based on the literature, it is noteworthy that cost-effectiveness appears in increased productivity and higher service levels, not essentially in money-saving for the agency [77].

Table 7. Longevity and cost of different patching methods in 2004 [75]

Patch Technique	**Life span (years)**	**Cost (Canadian $/lane/km)**
Spray injection patching	2	3,375
Machine HMA patching	4	1,386
Manual HMA patching	5	1,246
Mill and patch 10%	6	2,450
Mill and patch 20%	7	4,900

3. Cold Mix Patching Materials (CMPMs)

CMPMs are usually applied in an emergency situation as a temporary treatment until proper and definite practice is done [20, 78]. These kinds of asphalt-based products are composed of a mix of aggregates with special binders (asphalt emulsion, cutback, proprietary binders), and additives [79]. However, in recent years, the use of waste materials such as Reclaimed Asphalt

Pavement (RAP) and Reclaimed Asphalt Shingles (RAS) to modify the binder or as a substitute for aggregate or mineral filler has received growing interest and attention in the mix design of CMPMs [80, 81]. Despite the benefits of cold mixtures in maintenance programs, they have some weaknesses reflected in their poor performance or premature failures. Poor workability in cold weather, poor stability, especially in deep holes, and moisture susceptibility are primary problems associated with these mixtures [20, 82]. Besides, since they cannot be compacted at the same level as the hot mixtures [70, 82], they show high air-void content and porosity of the mixture (up to 30%) and porosity, which, along with an extended curing time negatively affect their mechanical properties [67]. Although there are no standards or comprehensive guidelines for using and evaluating CMPMs [83, 84], a few tests have been recommended by the SHRP manual as compatibility and acceptance tests to meet the minimum requirements for utilizing these materials. Compatibility tests involve coating, stripping, and drainage tests, whereas the acceptance ones include workability and cohesion experiments [62, 78]. It is noticeable that the mentioned tests do not necessarily guarantee the success of patching mixtures but are employed to identify materials that may have poor performance in the field [38].

3.1. Components

The literature has shown the importance and impact of cold mix components on the performance of repaired patches. The influence of these constituents and how they affect the mixture are described below.

3.1.1. Binder

Cutback, asphalt emulsion, and proprietary binders are used in the cold mix design to meet the CMPM requirements [67]. Workability and stability, which are two major issues for CMPMs, can be managed by improving the mix design, both in the type and dosage of ingredients. A soft binder with low viscosity is needed in the mixture to provide satisfactory workability for longer storage time and cold weather. However, for better cohesion and stability after placement of the mixture, high binder viscosity is preferable [78]. Therefore, binder viscosity should be comparatively low at low temperatures to give desirable workability [85]. Cold patches containing cutback binders are less sensitive to temperature and can be applied in cold and rainy weather conditions. Traditional cutback asphalt solvents like gasoline or diesel decrease the binder viscosity and make the mixture workable with a rather low initial strength. However, the strength of the patched material increases gradually by solvent evaporation [14, 34]. Despite their advantages, applying cutback-based materials at low temperatures can be difficult and usually requires warming-up with the sun before the treatment [40]. The volatilization of the solvents takes up to several months, as well, so that the repaired spots may be damaged during this period [86, 87]. Additionally, cutback-based mixtures emit higher hydrocarbons than an emulsion-based mixture, pollute the atmosphere by contributing to the greenhouse effect, consume non-renewable energy resources, and are flammable, which puts the health of the workforce in danger [63, 88, 89].

Thus, the use of current cutbacks has been restricted or even prevented by new European environmental regulations, and using environmentally-friendly alternative solvents is currently emphasized [90]. Compared to cutback, asphalt emulsion has relatively fewer environmental issues [37]. However, the relatively short breaking time is the main limitation that propels producers to use slow-setting emulsions in cold asphalt mixtures [13, 26].

In parallel, environmentally-friendly alternatives to petroleum solvents and proprietary binders are under consideration by producers and researchers [63]. In a recent study by Wang et al. [91], mineral spirit and isoamyl acetate were used as alternative solvents in the cold mixture mix design. The new solvents showed better solubility and higher vaporization rates. Compared to diesel mixtures, using new solvents provided better curing and initial strength, stickiness, rutting resistance, and resistance to water susceptibility, as well. In another study, Dong et al. [63] used turpentine as an alternative to diesel in cutback binder. Although the solubility of solvents was similar, turpentine showed a higher evaporation rate than diesel. Plus, using turpentine in the mixture gave higher initial strength, lower abrasion, and moisture sensitivity. Similar improved performances were achieved by modified cutback with Waterborne Epoxy Resin (WER) in research conducted by Zhang et al. [92]. However, the test results demonstrated that inappropriate addition of WER may result in poor storability and low-temperature performance. The authors recommended 1.2–1.8 wt% WER as the optimal dosage to improve the cold mix performance. Vegetable oils such as sunflower are also used instead of petroleum solvents to decrease the binder viscosity at cold temperatures and make the cold mixture workable. The hardening process of these proprietary binders occurs by oxidative polymerization in the presence of a catalyst, not by evaporation of the flux oil [88, 90, 93]. Geng et al. [18] used Cooking Waste Oil (CWO) as part of the diluent in the cold mixture. The research team found that 15% to 35 wt% CWO in a cold mixture containing 21% to 23% diluent yields better adhesion and satisfactory workability. But, the effect of CWO on the strength of the cold mixture was not noticeable.

Besides, there are special CMPMs on the market that their curing and strength evolution occur with water presence through chemical activity, not by evaporation of the solvents. In these water-based cold patches, the strength evolution is faster than in traditional CMPMs, and the strength development process starts by adding water or even air humidity. Therefore, they must be kept in totally sealed containers during the storage time and used up to a temperature of 0 °C [73, 86]. Although they provide better patch performance, they are expensive and are not suitable for large-scale repair operations [17]. The author’s laboratory experience with one of the most popular water-reactive CMPMs on the market indicated that the curing rate of the material decreases sharply after a few hours of compaction at room temperature, and the material reaches most of its stability during this time. Plus, the remaining material in the sealed bucket did not show high sensitivity to humidity and retained its quality even after a few days of opening the bucket. Eventually, for all CMPMs that foresee an evolution or reaction of the binder, the packaging and the relative workability of materials are fundamental and decree the success or failure of treatment. The inefficiency of CMPMs’ workability, which is very frequent following their storage on pallets or shelves, leads to lower demand for materials and is a severe discrimination factor in commercial competition.

Regardless of the type of binder, to improve cohesion and adhesion and subsequently the durability of the patch, a high amount of residual binder is required to achieve a thicker film on the aggregates; however, binder drain-down during the stockpile should be considered as well [72]. The higher content of the binder leads to bleeding, lower skid resistance, rutting, and drain-down in the stockpile, but it provides a sticky mixture, especially in the winter months. Nevertheless, an inadequate amount of binder can result in moisture susceptibility, poor cohesion and adhesion, and subsequently unstable patches, but better workability in cold temperatures [78, 94]. Previous studies indicated that to meet the CMPM requirements, at least 4.5 percent residual binder is needed for aggregates with less than one percent water absorption. This value changes with the percentage of water absorption, as if the water absorption increased by 0.5%, the amount of the residual binder should increase by 0.5% as well [72].

3.1.2. Aggregate (type and grain size distribution)

Aggregates like binders play a crucial role in the performance of cold mixtures. In the CMPM mix design, various types of virgin and recycled aggregates, such as crushed stone, silty sands, RAP [95], RAS [80, 81], slag, and fly ash are utilized to mix with the binding materials and form the mixture [11].

The most significant required features of aggregates are shape and gradation. Gradation and aggregate shape significantly impact the workability and stability of the cold patching mixtures [9]. To achieve better stability, a high degree of aggregate angularity in the mix design is required, even though angular aggregates do not provide good workability. If one-sized fine-aggregates are predominant in the mixture, the impact of angularity on the workability may be decreased [72]. Although using certain aggregates such as uncrushed gravel, sand, and rounded aggregates can improve the mixture workability, it leads to pavement failure, including rutting and shoving under traffic loads [20, 78]. Despite the shape of the aggregates, their sensitivity to moisture can also result in other problems. Aggregates with higher water absorption cause stripping and drain-down problems during the stockpile and should not be used in the mixture [72]. Therefore, aggregate water absorption should be considered and limited to almost one percent [20, 62]. A maximum of 2% is fixed by the Ontario Provincial Standard Specification (OPSS) [96].

Dense-graded and open-graded gradations are usually used in cold mixtures to provide satisfactory performance in repaired potholes. Each gradation has its own benefits and drawbacks [34]. A well or dense-graded gradation provides a low air-void and relatively impermeable mixture that yields a stable and durable patch. On the other hand, open-graded gradation gives better workability than dense-graded gradation. Due to their high porosity, they can facilitate volatilization and curing time and are more workable at freezing temperatures. However, cold mixtures with a dense gradation have good performance at warm and hot temperatures. Overall, from one region to another, the aggregate proportions can be slightly varied [20, 78] Despite the gradation type, the size of the aggregate in the mix design is important and depends on the depth of the pothole to be repaired [5]. Cold mixtures with fine aggregates are more suitable for filling cracks and repairing shallow potholes as they can be applied thin and prevent raveling on the edges of the hole [28, 41, 62]. However, if the aggregate size is too small compared to the pothole depth, the possibility of displacement or rutting in the patch is high [42]. On the other hand, coarse aggregates are more suitable for filling deep potholes as they result in extra stability and durability [28, 62]. Nevertheless, too large aggregates may lead to insufficient compaction, poor bonding at the pothole edges [42], increased abrasion, and fast deterioration [51]. In the past, the use of 12.5-19 mm coarse aggregates in stockpiled mixtures had been promoted to achieve higher durability and stability. Yet, to succeed in applying such a mixture, an ideal patching procedure involving saw cuts to create a vertical and clean edge, using a tack coat, and sufficient compaction is needed. While filling potholes is a time-consuming operation and employing an ideal patching method is not usually used, patches with coarse aggregates due to raveling under traffic loads start to premature failure. Otherwise, if fine aggregate mixtures are used that have more flexibility than a coarse aggregate mixture, the patch should be stable at a depth of less than 76 mm [72].

Mixtures containing finer gradations usually do not provide good workability. However, if they are made mainly of one-sized aggregate mostly kept on the 1.18 mm sieve, the curing and the workability features can be improved. A fine gradation cold mixture consisting of 100% passing 9.5 mm or 4.75 mm sieve can produce a workable and pliable mixture which is characterized by improved durability and flexibility over time [62]. Besides, the use of fine aggregates (maximum particle size of 11 mm) allows cold materials to be applied in thin layers within 25 mm [13, 26]. To achieve maximum workability and stability, the FHWA recommended crushed angular aggregates in sizes ranging from 2.38 mm to 12.7 mm as the optimal aggregate size [9]. Other studies suggest a range of 4 to 10 mm of aggregate as the maximum nominal size of aggregates used in CMPMs [43]. Kandhal and Mellott proposed the gradation reported in Table 8 through their study in 1981 on asphalt stockpile patching mixtures [72]. In another study by FHWA, the recommended gradation for homemade cold patching mixtures is according to Table 8 [78].

Moreover, dust content affects the repaired patch performance as dirty aggregates may increase moisture damage [78]. In fact, an excessive amount of filler (particles passing through the 0.075 mm sieve) makes the mixture brittle, less workable, and less tacky. For this reason, cold patch producers use clean aggregates with low content (usually less than 1%) of dust to improve the cohesive and adhesive characteristics of the patching material. Kandhal and Mellott recommended a maximum dust content of 2% in their research on CMPMs [72]. In the investigation of the 17 proprietary cold mixtures, Franklin and Prowell [1] moderately modified the gradation proposed by Kandhal and Mellott and increased the content of coarse aggregates to improve the stability. The fine particles were increased by up to 3% (Table 8). Also, Minnesota DOT limited the max fine up to 3 percent, and proposed gradation has been indicated in the same table [50].

A maximum of 1 to 2% of dust has been proposed in a study by Anderson et al. in 1986 [9] to obtain sufficient mixture workability. However, Berlin and Hunt [20] have set higher values for dust content in their study. After 6 months of laboratory evaluation and field survey of several CMPMs, they suggested a value of less than 5 percent for dust particles in the mixture. A similar value (less than 5%) for dust content was also suggested in other studies [15, 62].

Table 8. Recommended aggregate gradations for CPAMs

Sieve size (mm)	**Percent passing**				
	[78]	[1]	[50]	(Specified) [72]	(preferred) [72]
12.5	---	---	100	---	---
9.5	95-100	95-100	95-100	100	100
4.75	40-85	75-95	35-50	40-100	85-100
2.36	15-40	10-40	Max 20	15-40	10-40
1.18	6-25	---	---	---	0-10
0.6	---	---	Max 10	---	---
0.075	1-6	0-3	Max 3	0-2	0-2

3.2. Curing

Climate temperature, curing time and curing rate have a remarkable impact on the performance of the CMPMs. Biswas et al. [53] came to this result during their research on cold mixtures in Canada. The rapid curing rate provides good stability and cohesion, while the slow rate enables workability. This curing rate is affected by several factors, such as climate conditions (windy, rainy, temperature, etc.), binder quantity, binder type, binder grade, etc. Therefore, based on the mixture properties, the curing rate should be considered and controlled, since the volatile evaporation rate of mixtures is different, and prematurely curing leads to unworkability. Moreover, a longer curing time or higher temperature provides better stability than a shorter curing time at a lower temperature [78]. The results of research by Thanaya et al. [66] indicated that under full curing conditions, CMPMs and HMA of the same penetration grade binder have similar stiffness. But, the full curing process is time-consuming. Studies by Chevron Research Company [90] showed that, depending on weather conditions, it takes 2 to 24 months for the cold mix asphalt to be fully cured. Usually, materials that are compacted under lower temperatures or short curing times result in unstable specimens [20]. Moreover, there are CMPMs on the market that do not reach sufficient stability even after 5 or 6 months. For these materials, the stability of the laboratory-made specimens is low even after high compaction, and their demolding without long-term curing is almost impossible since they collapse instantly after demolding. Still, these low-quality materials are bought and utilized by the road agencies due to their lower price. Therefore, to evaluate the CMPMs, the samples are cured in the oven to provide sufficient stability for conducting tests [97]. However, this procedure reflects the patch condition after several months in service [13], while the patch durability may be shorter than a few months, and the patch deteriorates in a short time after patching. Consequently, evaluation of the mixture after long-term curing cannot indicate its performance after patch operation.

3.3. Performance evaluation

As before mentioned, patch failures are often due to the lack of desirable characteristics. Thus, the evaluation of the mixture properties can help to understand which types of materials deteriorate in a short time and are not suitable for use in the field. Workability, water susceptibility and stripping, stability and strength, adhesion and cohesion (bonding characteristics) and storageability are the main factors that can result in poor or good CMPM performance. These properties are engaged with each other and the durability of the mixture is achieved under their overall performance [98, 99]. Since there are abundant materials on the market claiming to have the best performance, the only way to assess their properties is through laboratory experiments along with a long-term field study [20]. The field performance is usually carried out through visual evaluations by maintenance engineers. However, the laboratory tests are more quantitative, as explained in the following sections.

3.3.1. Workability

Workability is one of the primary properties of cold mixture that enables the patching material to be handled, easily plied, and compacted during the stockpile and placement in the field [78, 100]. Since CMPMs are commonly used for temporary repairs, their workability characteristics are more noteworthy than their performance [101]. As claimed by previous studies, the workability of cold mix can be affected by its main components, including asphalt binder and aggregates. In fact, using rounded aggregates or uncrushed gravel in the mix design can improve the mixture workability. An excess amount of filler or mixtures with a maximum aggregate size bigger than 12.7 mm also negatively affect the mixture workability. Furthermore, weather temperature during the storage or application time can impact the binder viscosity and the mixture workability [6, 39, 78]. Usually, a mixture with poor workability leads to insufficient compaction, reduced stability, and patch failure in a short time. Therefore, to have a durable patch, factors that improve workability must be considered, as they may oppose stability [78, 82]. The impact of aggregate and binder on workability and, subsequently, durability of the patch can be summarized in Table 9 [20].

Table 9. Aggregate and binder impact on patch workability and durability [20]

Characteristic	Parameter	Workability	Durability
Binder Viscosity	Low Viscosity	Good	Poor
	High Viscosity	Poor	Good
Aggregate Shape	Angular	Poor	Good
	Rounded	Good	Poor
Aggregate Size	Larger	Poor	Good with ideal condition
	Finer	Good	Good if hole depth is less than 76 mm
Aggregate Gradation	Open	Good	Poor
	Dense	Poor	Good

To evaluate cold patching materials, Kandhal and Mellott [1, 72] used a spatula in their research in 1981. The test was performed subjectively by dipping the spatula into the mixture, and the results were reported as good, fair, and poor. A cement concrete penetrometer was also used to obtain quantitative results by the research team and is called the PTI method. The greater the force required to penetrate the tool into the sample, the lower the workability. However, the results were inconsistent, and the test failed to quantify the workability. The presence of large aggregate particles or the degree of sample compaction can impact the test, as well. They suggested maybe using a mixer such as a Vane-Shear device leads to more accurate results. During a study in 2019 [34], the use of a mixer to quantify the cold mixture workability was found to be satisfactory. The average measured torque in one minute was considered as an indicator of mixture workability. The greater the torque, the worse the workability. The first idea of using torque to measure workability had already been proposed by Marvillet and Bought in 1979 to assess HMA workability. They used the torque needed to rotate the paddle within the HMA sample for this purpose [102].

Similar results from the PTI test were achieved in a study by Prowell and Franklin [1]. During their study of 14 types of proprietary cold mixtures, no strong correlation was found between laboratory and field results. However, Berline and Hunt [62], in their research in 2001, obtained a good correlation between the field and lab results. In 1986, Anderson et al. [9] used the PennDOT subjective spatula method to evaluate the mixture workability and found this procedure undesirable from the point of repeatability, especially inter-laboratory repeatability. Therefore, by connecting a 9.5 mm by 75 mm extension to the penetrometer foot, they modified the PTI method and quantified the cold mix workability. A reasonable correlation was obtained between the results of the two methods. In the SHRP H-106 extensive repair project of more than 1250 potholes, PTI and Blade Resistance test methods were considered to evaluate the mixture workability in the laboratory and field. The Blade Resistance device is similar to the PTI probe, except the tool uses a blade instead of a bullet-shaped connection in the probe. The results showed that, due to the greater contact area of the blade with the sample, the values obtained by the Blade Resistance method are almost five times larger than the values obtained by the PTI method. Therefore, they found that the PTI method is suitable for stiffer mixtures owing to its small cross-section. However, the Blade Resistance method is more effective on soft patching materials. Since the mixture workability is the main issue when it becomes stiff, the PTI method can provide more meaningful results [47]. The results of the mix workability were variable by the Blade Resistance test in research conducted by the NJDOT. Therefore, this test was not recommended for future research [6]. Unlike the results of the NJDOT, the workability of the 24, 96, and 168-hours cured specimens at 25℃ showed a confident linear correlation with curing time in a study by Liao et al. [83]. However, the required resistance to penetration of the blade into the mixtures was low compared to the recommended range in ASTM D6704. To quantify the workability of the patching materials, Estakhri and Button [39, 82] used the same PTI method in 1995. However, they couldn’t find noticeable differences in the workability results of various mixtures. To get more reasonable results, the PTI test method was modified two times by changing the box shape and the location of the hole on the box wall. The modifications demonstrated some improvements over the PTI method; however, the results didn’t show a good correlation with field workability evaluations. Afterward, they tried to measure the mixture workability with a Texas Gyratory Compactor. The total number of mold gyrations required to reach the defined compaction pressure was considered for this purpose. Once again, no correlation was obtained between laboratory and field values. Since none of the previous procedures were successful, triaxial compression and unconfined compression tests were employed to quantify the workability of the material. The methods that were based on the Mohr circles and the Mohr failure envelope showed a relatively satisfactory workability value. Aside from using more materials than the other methods, it is also time-consuming and requires costly apparatus [103].

In a study by Lesueur [104] in 2002, using the Nynas device for measuring the workability of cold mixtures was recommended. According to this research, the Nynas device was able to differentiate the influence of different parameters such as binder content, temperature, the nature of aggregates, and water. The maximum shear force applied to the loose mixture was a measure of workability. In another study, the Nynas device and Gyratory Shear Compactor (GSC) were employed to investigate the workability of Warm Mix Asphalt (WMA). Unlike the Nynas device that led to definite results, the GSC was not sensitive to temperature and resulted in similar values [105]. In a research project by TxDOT, it was announced that the slope of the GSC compaction curves and the work done by the shear force during the compaction (the area under the curve) can be used as a surrogate measure of the cold mixture workability [20]. Ferrotti et al. [106] considered the mentioned recommendations to assess the workability of high-performance fiber-reinforced cold mixtures. The intercept and the slope of the regression compaction (void-number of gyrations) curves were used to analyze the air-void content and workability of the mixture, respectively. Besides, TxDOT researchers tried to develop a method to measure workability by taking the idea from the concrete slump test. As a result, during a similar experiment called the Cold Patch Slump Test (CPST), the required time for a cold mixture to slump under its own weight was considered as a measure of workability. So, less time to slump indicates more workability and vice versa. The results of testing six proprietary CMPMs at three different cold temperature levels showed a good linear correlation between the field and laboratory results [20]. Abaffyová and Komačka [107] used the slump test to assess the storageability of the CMPMs, not the workability. Through their research, the cold mix is poured into the inverted Abram cone or the CBR mold for 10 minutes to experience the self-compaction condition. Then, the mold or cone is lifted, and the required time for dropping the whole mixture from the mold is recorded and reported as a measure of storageability.

Hemsley [108] used densification curves of compacted HMA to assess the workability of the mixture, and defined the locking point. The locking point is the number of gyrations that after three continuous gyrations, no noticeable changes in the height of the samples are detected. In their research, less than 30 and higher than 70 gyrations were considered to indicate easy to compact and hard to compact mixtures. This approach was employed to measure the cold mix workability in other research, and they found the locking point of the mixtures below 100 gyrations [109, 110].

Moreover, in another study, the area under the compaction curves was used to measure the workability and compactibility of the mixtures. The energy required to compact the loose mixture to 92% density (corresponding to 8% air void in the target mixture) led to defining the following energy indices (Eq. (1) and Eq. (2)) that measure the mixture workability [111].

Volumetric Energy index from intercept to 92% G_{mm}: $\mathrm{EI}_{(92\%)} = \mathrm{P} \times \frac{\pi \mathrm{d}^2}{4} \times \sum_{\mathrm{N}=1}^{\mathrm{N}92} \Delta \mathrm{h}$ (1)

Workability Energy index from intercept to 92% G_{mm}: $\mathrm{WEI} = \frac{\mathrm{EI}_{(92\%)}}{\mathrm{N}_{92}}$ (2)

Where d is the sample diameter, P is the compaction pressure, h is the sample height during compaction, and N is the number of gyrations.

According to Eq. (1) and Eq. (2), when a mixture is hard and has low workability, more energy is needed to compact it. On the other hand, the increase in the number of gyrations indicates a lower WEI and vice versa [111].

Table 10. The summary of methods used for measuring the workability of CMPMs

Researcher	**Workability measuring method**	**Indicator of the workability**	**Ref.**
Kandhal and Mellott	Dipping a spatula into the mixture	Subjectively (good, fair, and poor)	[1, 72]
	Penetrating a cement concrete penetrometer into the mix (PTI method)	Maximum penetration force	
Han. et al.	Using a mixer to mix the mixture	Torque needed to rotate the paddle	[34]
Anderson et al	Modified PTI method (changing the bullet-shaped connection of the probe)	Maximum penetration force	[9]
SHRP (H-106)	Using a blade to penetrate into the mix	Maximum penetration force	[47]
Estakhri and Button	Modified PTI method (changing the box)	Maximum penetration force	[39, 82]
	Compacting the mixture with a Texas Gyratory Compactor	Number of gyrations required to reach the defined compaction	
	Triaxial compression test	Cohesion value and friction angle	
	Unconfined axial compression test	Unconfined compressive strength	
Lesueur	Using a Nynas device to apply shear force to the loose mixture	Maximum applied shear force	[104, 105]
TxDOT	Using a Gyratory Compactor to compact the mixture	The slope and the area under the compaction curve	[20, 106]
TxDOT	Cold Patch Slump Test (CPST)	Required time for a cold mixture to slump under its own weight	[20]
Hemsley	Using a Gyratory Compactor to compact the mixture	Locking point of the mixture during the compaction	[108-110]
Bahia et al.	Using a Gyratory Compactor to compact the mixture	Energy required to compact the loose mixture (Energy index)	[111]

3.3.2. Adhesion and cohesion characteristics

CMPMs should provide satisfactory cohesion and adhesion to prevent patch failure. Cohesion is the characteristic that makes the mixture components adhere together and work well altogether, while adhesion is a feature that provides better stickiness between the patch and the surface of the existing pavement [112]. The weakness of each of these features will cause the patch to prematurely fail, especially when the pothole is not dried and prepared before the repair operation [100]. The initial patch stickiness is usually low and increases over time. However, to ensure adequate bonding between the patching material and the pothole, applying a bond coat to the inside and around the hole is recommended [113]. This bond coat, which usually is a cationic emulsion containing at least 60% asphalt binder, prevents future water seepage and patch debonding, as well [7, 70, 114]. To prevent the patch debonding and increase the durability of the repair, preheating the pothole and heating the mixture were recommended in the literature. To achieve this goal, various techniques using infrared heat [115, 116], radiant heat [58], and high-frequency electromagnetic fields for mixtures with fibers have been conducted through various studies [46, 64]. The 324 repaired potholes with heated and unheated mixtures in a study by Indiana state DOT revealed that heated patches were more durable than unheated ones [117].

Past studies show that using a tack coat is necessary to repair potholes and will extend patch durability. Plus, it improves crack resistance properties [118]. However, CMPMs should have self-tacking properties to eliminate the need to use a tack coat. The bonding characteristic was assessed through an experiment by Anderson et al. [9] in 1998. The maximum shear force required to bond failure at the interface between the base and the compacted cold patch was considered to measure the self-tacking feature. The results of the tests in dry and wet conditions were not reliable and conclusive.

To evaluate the bonding characteristics at the interface layer, the Leutner shear test device has been employed in other studies. Lee et al. [119] applied a vertical load across the reinforced interface layer and found that a rough surface improves the bonding, but increasing the temperature (in this case, from 25 °C to 60 °C) impacts the bond feature adversely. The same procedure was also used by Sudarsanan et al. to investigate the bond strength across the interface layer at various temperatures [120]. Also, Collop et al. [121], West et al. [122], and Bae et al. [123] found the same impacts of temperature on the bonding properties.

Additionally, the inclined shear test was carried out to simulate the effect of vertical and horizontal loads (vehicle tire and braking loads) on the interlayer bonding strength of the composite asphalt. The results declared that using a tacky material is necessary to apply at the interface layer. Plus, the thickness of the tacky coat, temperature, and freeze-thaw cycles affect the interface shear strength [124]. Similar results were achieved in Chen et al. [125] research on the bonding strength of cold patching materials and HMA. Humidity and high temperatures weaken the bonding characteristics at the interface layer. So, increasing the temperatures from

-5 to 55 °C reduced the interface shear resistance by 98.6%. Also, according to their results, the type of the tacky material and the surface roughness had the dominant impact on the interface bonding characteristics. Another method was used by Virginia DOT to assess the adhesiveness of the mixture. Through this procedure, the oven-aged (4 hours at 60°C) CMPM is compacted on the HMA specimen and inverted (Fig. 9), then the required time for their debonding is considered as the adhesion degree. Mixtures with longer adhesion times or more remnant weight show higher adhesiveness. The 5 to 30 second bonding time is considered the optimum adhesion degree [41, 53]. Less than 5 seconds may point out excessive binder contents. Longer than 30 seconds may indicate insufficient or high viscosity binder. As a result, this experiment may not reflect the adhesion properties of CMPMs but may be useful for measuring mixture quality [1].

Figure 9. Adhesion test on the inverted complex specimen

In a study at the University of Minnesota, the maximum diametric load applied to a complex briquette involving half cold mix and half HMA (Fig. 10), was considered to measure bonding properties [15, 16].

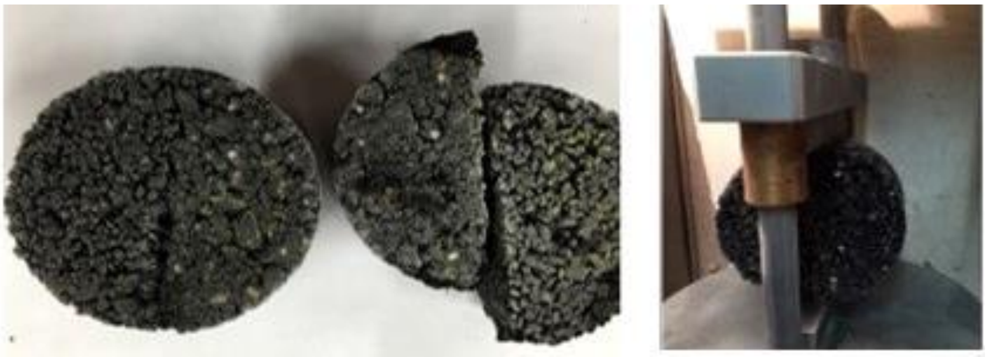

Figure 10. Interface shear strength test by applying a diametric load [15]

The modified Cantabro test has been used to measure the stickiness properties of CMPMs in the literature, as well. The Marshall briquette in the Los Angeles machine is subjected to 100 gyrations, and the mass loss during abrasion is considered the stickiness index [92]. This method was also reflected in another study conducted by Ferrotti et al. in 2014 [106]. But the cold mix specimens were subjected to 300 revolutions, not 100 gyrations. Additionally, the Cantabro test was employed to assess the raveling and moisture susceptibility of the cold mixtures. The raveling properties of waterborne epoxy-emulsified asphalt mixture were evaluated by Bi et al. in 2020 [126]. Plus, the mass loss difference between the abraded wet specimens and dry specimens shows the moisture susceptibility of the cold patching materials [99].

Mixture cohesiveness has also been investigated by the ‘Rolling Sieve Test’ in the literature. This experiment, which simulates the cohesion properties of patching materials under the vehicle tire, is based on the Ministry of Transportation of Ontario (MTO) method. Through this procedure, a compacted Marshall specimen is rolled horizontally in a caped sieve for 20 seconds. The remaining weight of the sample after rolling compared to its initial weight is calculated as a measure of mixture cohesion, which should be more than 60% [37, 53, 62]. The MTO report states that a loss of more than 35 percent is unacceptable [97]. Although this test does not guarantee the success of a mix, it indicates the potential for poor performance of a mix [20].

3.3.3. Water sensitivity

Water sensitivity generally, called stripping, is one of the main concerns of asphalt pavements. This problem can occur in various forms, like; loss of binder-aggregate bonding, cohesion failures within the aggregates, binder emulsification, and freeze-thaw cycles due to trapped water [127]. In CMPMs, moisture impacts the binder and aggregate bonding interactions and results in bonding failure that is dominant distress in cold patches [11]. Therefore, to minimize the cold mixture water damage, the binder-aggregate compatibility, aggregate hydrophobic and hydrophilic features, and overall mix design parameters such as density and air-void should be noticed [15].

This compatibility and moisture susceptibility of the cold patches have been investigated through similar methods that were previously used to evaluate HMA. Thomas and Anderson [74] determined the water sensitivity of the mixture by a subjective assessment. The percentage of aggregates coated with a binder in a mixture was considered an indicator of this parameter: 90% was defined as the minimum acceptable value. To reduce the visual error in coating evaluation, Ling et al. [109] used digital imaging analysis to assess the influence of the aggregate coating on moisture susceptibility of the CMPMs. The results showed that the moisture susceptibility of CMPMs is highly dependent on the level of aggregate coating predicted by the quantitative models. Another visual evaluation method was used by SHRP in 1993 [38]. In that study, an over 90% coated mixture was kept in a one-liter container filled with distilled water at 60 °C for 16 to 18 hours (static immersion). Then, the container, including water and the mixture, was agitated for 5 sec and drained. The coating percentage of aggregates should not be less than 90% to be accepted [37, 47, 127]. The maximum acceptable stripping value in ASTM and Indian Roads Congress standards is 5% [97]. Kandhal and Mellott [72] conducted this visual evaluation by pouring 50 grams of the cured mixture into 400 ml of distilled boiling water and stirring with a rod for 3 minutes. Then, they decanted water and spread the wet mixture on absorbent paper for coating level. The aggregate should be at least 90% coated with an asphalt binder film.

The TxDOT and other researchers used a "boiling water test" to measure moisture sensitivity. In this method, the mixture is placed in a container of boiling water for 10 minutes. Then the sample is drained and the coating degree should be more than 90% [39, 62]. The results of a study by the Virginia Transportation Research Council showed that the boiling water method had a better ability to detect differences in stripping results than the immersion method [1]. Similar results were reported by Tam and Lynch [128]. They claimed that the boiling water test for 10 minutes is a severe and rapid process that doesn't simulate the field stripping conditions in the lab. In another research, Lavorato et al. [96] used a less severe method, which has been described in the MTO standard (MTO OPSS 307), to assess the mixture stripping. The mixture is placed in boiling water and stirred with a rod at the rate of one rotation per second for 3 minutes. Conversely, to other test methods, the minimum acceptable aggregate coating was set at 75%. The mass loss of the cold mixture after being subjected to boiling water was also considered as an indicator of stripping and mixture water damage. However, the mass loss values were negligible relative to the sample weight, and the test results were highly variable in research [109, 129, 130].

Besides the mentioned methods, the modified Lottman method was employed by TxDOT to measure the moisture damage. Unlike previous test methods, this procedure is done on compacted samples and the tensile strength ratio of two sets of samples (moisture conditioned and unconditioned) determines the water susceptibility of the mixture. The results of the TxDOT study showed that subjective evaluation with a boiling water test is more logical than the modified Lottman method to measure the stripping potential [60, 67]. However, the

Lottman method has been widely used in other studies to measure the stripping potential of CMPMs under freeze-thaw conditions [53, 92, 131]. In addition to the Lottman method, the Binder Bond Strength (BBS) test has also been employed to assess the relationship between mixture water damage and coating level in other studies. Ling et al. [130] used the BBS test to evaluate the moisture susceptibility of emulsion–aggregate bonding. The Pull-Off Tensile Strength (POTS) in wet and dry conditions was calculated. According to Eq. (3), the Bonding Loss Ratio (BLR) was defined as an indicator of moisture susceptibility. The test results of limestone aggregate and emulsion were similar to the results obtained from the modified boiling test with image processing. Also, this test method was used to assess the water sensitivity of the emulsion-aggregate and mastic-aggregate systems after 2 h and 24 h water conditioning.

$$BLR = 1 - \frac{POTS_{wet}}{POTS_{dry}} \tag{3}$$

The Marshall Stability Ratio (MSR), which is the ratio of the Marshall stability values of water-damaged samples to the Marshall stability of cured specimens (Eq. (4)), was defined to measure the moisture sensitivity of cold mixtures in other studies. Higher values of MSR represent lower moisture susceptibility [91, 99].

$$MSR = \frac{MS_{wet}}{MS_{dry}} \times 100 \tag{4}$$

Given that the open-graded CMPMs' moisture sensitivity is associated with gradation proportion, the Moisture Index (MI) was defined (Eq. (5)) by researchers to represent the moisture damage resistance of open-graded CMPMs. MI is the ratio of aggregates remaining on sieve No. 4 ($P_{\#4}$) to the ratio of aggregates remaining on sieve No. 50 ($P_{\#50}$). The higher MI values determine higher mixture porosity, higher water seepage, and higher water damage, subsequently [99].

$$MI = \frac{P_{\#4}}{P_{\#50}} \tag{5}$$

Besides, the Wet Track Abrasion Test (WTAT), which is usually adopted for slurry seal mixtures, was used to measure the water sensitivity of the CMPMs. The WTAT results of Kwon et al. [95] research on RAP included cold mix materials proved that the RAP introduction in the mix-design improves the mixture resistance to abrasion loss. Also, even though the Hamburg Wheel Tracking Device (HWTD) is a severe procedure for cold mixtures, it has been used in wet conditions to measure the water damage of CMPMs [38]. Table 11 shows the summary of methods used for measuring the water sensitivity of CMPMs.

In the end, since CMPMs are usually applied during cold and rainy seasons, they should withstand adverse weather and traffic loads that lead to debonding, dislodging and failure of the mixture [100]. Therefore, antistripping additives such as Portland cement, flue dust, hydrated lime, fly ash, etc., should be used in the cold mix to reduce moisture damage during the stockpile, practice, and in-service [60, 78, 98].

Table 11. The summary of methods used for measuring the water sensitivity of CMPMs

Researcher	**Water sensitivity measuring method**	**Indicator of the workability**	**Ref.**
Thomas and Anderson	Visual subjective assessment	Coating degree of aggregates	[72, 74]
Omar et al.	Static immersion		[37, 127]
Manolis et al.	Boiling water test		[62, 96]
Ling et al.	Digital imaging analysis	Level of aggregate coating	[109]
Ling et al.	Boiling water test	Mass loss	[129, 130]
Dong et al.	Modified Lottman method	Tensile Strength Ratio (TSR)	[60, 92]
Ling et al.	Binder Bond Strength (BBS)	Bonding Loss Ratio (BLR)	[130]
Wang et al.	Marshall stability	Marshall stability ratio of water-damaged to the cured samples	[91, 99]
Huang et al.	Moisture Index= P(#4)/P(#50)	Mixture porosity	[99]
Kwon et al.	Wet track abrasion test	Abrasion loss	[95]
Smith et al.	Hamburg wheel tracking device	Rut depth	[38]

3.3.4. Stability and initial strength

Stability is one of the main characteristics of patch materials that provides sufficient ability to resist vertical and horizontal displacement of the patch under traffic [6, 53]. This property is especially noticeable immediately after a patching operation is performed, i.e., when the repaired pothole is more sensitive to the traffic flow. In fact, the patched area after compaction should be stable enough to prevent rutting and shoving caused by traffic [20]. To meet this early performance, aggregate gradation and compaction level play a major role. However, the long-term performance of the patch is related to its stability after traffic compaction [34, 126, 131]. Therefore, different factors that affect the stability of the mixture, such as aggregate gradation and compaction level, binder quality and quantity and mixture curing rate should be taken into account [53, 132]. Also, since excessive stability usually leads to low workability, precautions should be considered to strike a balance between the stability and workability of the mixture. An acceptable stability level is achieved over time by the mixture curing, while this process is time-consuming and traffic flow should be established immediately. So, the bonding properties, gradation and internal friction of the aggregates are the main factors in improving stability and, subsequently, mechanical properties [2, 62, 101]. Even though there are no accepted test methods in the technical literature to assess CMPM stability [9], it is often determined by Indirect Tensile Strength (ITS), Marshall Stability (MS) and Resilient Modulus (RM) procedures [39, 83]. Despite the mentioned experiments, a few pioneering procedures, such as the screwdriver penetration test and steering wheel rotation using a passenger car, are used to assess the suitability of the cold repair mixtures. Although these tests result in useful information, the lack of standardized methods makes it difficult to evaluate the potential performance of CMPMs [101].

As most experiments have been designed to assess the performance of HMA, the researchers considered a preliminary aging process to provide sufficient stability for mixture compactibility. Usually, the specimens prepared without the curing and aging process immediately collapse after demolding and during the test [133]. In the evaluation of the CMPM performance, Manolis et al. [96] could not measure the bulk density of the compacted specimen due to its collapse after demolding. A similar occurrence was observed in Marin's study [134] on different types of CMPMs, although the samples were confined during the curing time to prevent them from collapsing before the test. Additionally, another study has reported that the gyratory compacted specimens were unstable even after being subjected to up to 96 h at 25 °C curing condition [20]. Anderson et al. [9] investigated the stability of the cold mixtures by applying a haversine load on a cylindrical aged specimen through a steel foot. The results of the experiment after 1000 cycles showed small plastic deformation. Plus, the experiment could not simulate the traffic load and was time-consuming. Consequently, the research team did not believe that this test warrants further development. In the SHRP project, the RM and MS tests were conducted on the oven-aged samples to assess the CMPM stability. However, the test was an indication of in-placed or utilized materials after being several months under traffic [47]. Maher et al. [6] used the aforementioned test methods to evaluate the stability of various CMPMs. The results of the study showed that there is no correlation between the field performance and the results of the IDT test. The results of the MS and RM test methods showed a similar outcome as well. The authors found that the use of the RM methodology for evaluating CMPMs is doubtful. In another research, Shoenberger et al. [13] selected MS and triaxial compression (confined and unconfined) experiments. The results of the axial strain in the triaxial test were similar for the various mixtures. Also, the research team did not find the MS test as a reliable indicator for performance evaluation of CMPM due to the unsuitability of this test for open-graded mixtures. Limited use of the Hveem stabilometer has been reported in the literature to measure the cold mix stability [9]. Furthermore, the results of an investigation on a conventional cold mixture (CCM), one type of proprietary cold patch (QPR brand) and HMA at the University of Minnesota showed a weak MS for the QPR mixture before and after curing. But the CCM, although it had weak stability before curing, showed comparable stability to HMA after curing [15, 16]. According to the literature, the MS of the unmodified CMA is significantly lower than HMA and WMA [11].

Through the MS evaluation of the CMPM, Weimin achieved an initial stability of mix not less than 2.0 kN and 1.5 kN at room and low temperatures, respectively. In a similar study by Jiguo, these values were obtained at 2.0 kN and 1.0 kN, respectively. The Japan Modified Asphalt Association standard specifies a minimum of 0.5~0.8 kN and 3.0 kN for initial MS and the 7th day after opening traffic stability, respectively [14]. In other studies, the minimum initial MS for CMPMs before opening traffic was suggested to be at least 2.5 kN [19]. However, for some cold mixtures, it takes about 10 days to reach 3 kN stability [17, 87]. China requirements have recommended a strength greater than 3 kN and 5 kN for the initial and forming strength of CMPMs, respectively [126]. In a comparative study on the un-treated cold mix and hot mix samples, the obtained MS values were 5.88 kN and 3.44 kN for dense-graded and open-graded mixtures, respectively, while these values were 11.48 and 10.71 kN for asphalt concrete and stone matrix asphalt, respectively [135]. The stability of open-graded and dense-graded cold patching mixtures including modified asphalt cement was analyzed through the MS test in another investigation. Rapid curing (24 h at 110 ℃) and ambient curing (24, 72, 168, and 336 h at 25 ℃) processes were considered before conducting tests at 40℃. As expected, the results indicated higher stability values for dense-graded CMPM with respect to the open-graded one. Plus, the wheel track test was also carried out on aged and unaged specimens in wet and dry conditions for more verification. They found that moisture intensified the sample deformation; however, it provides more reasonable results for predicting rut depth, especially in wet weather conditions. Furthermore, they inferred that the stability and rutting resistance of the CMPMs with high viscosity (130 poise) modified binders are comparable to those of HMA [83]. Also, Biswas et al. [53] found similar results through a study on dense-graded and open-graded cold mixtures that had been cured at 65℃ and 135℃ for 14 to 18 h. The authors found that the stability of dense graded samples cured at 135℃ is comparable to HMA. A similar study was done by Rezaei et al. [79] to assess the stability and rutting performance of CMPM in dry and wet conditions. The results showed that curing the specimens at ambient temperature, the HWTD turned out to be a very harsh test for CMPMs: specimens showed low resistance to permanent deformation. However, the research team found that HWTD is a suitable test method to evaluate the stability of CMPMs at accelerated-cured (135°C for 18 h) conditions.

Moreover, they claimed that the MS test is an effective way to distinguish the stability of CMPMs. HWTD was also considered to evaluate the stability of CMPM in research conducted by Chatterjee et al. [20]. Due to the harsh impact of HWTD on uncured samples, the test was carried out on 96-hour cured specimens that were compacted at 100 ℃. It was concluded that the longer the curing time, the higher the rutting resistance. The same test was conducted by Visser et al. [131] to assess the rut resistance of CMPMs. The materials were compacted and tested at various temperatures, but the authors did not consider HWTD a suitable test method to predict rut depth in the field. Even though the long curing time and compacting of the samples at high temperatures provide stable specimens before testing under HWTD, it drastically changes the properties of the mixture [96, 104]. To solve this issue, the Texas Stability Test (TST) was developed to evaluate the stability of cold mixtures. So, the compacted specimens with the Texas Gyratory Compactor (TGC) were cured at room temperature for 0, 1, and 2 weeks before 2-day conditioning and testing. Then, the MS test was conducted on the samples and the maximum compressive load was used as a stability measure of CMPMs. Furthermore, the research team employed an MMLS3 to assess the stability of the cold mixture under Accelerated Pavement Testing (APT) conditions [104]. Dong et al. [41] in a study used the Asphalt Pavement Analyzer (APA) to evaluate CMPM resistance to deformation. Their investigation into the cold dump and cold proprietary patches that were cured for 96 hours and compacted at 100 ℃ illustrated that even though cold dump materials had better performance than the cold proprietary patches, their rut depth was very high at low load cycles. Kwon et al. [95] used the APA and Marshall devices to evaluate the stability and performance of cold mixtures, including RAP and virgin aggregates. Their investigation revealed better stability for mixtures containing RAP materials.

The permanent deformation of CMPMs was investigated through the Modified Cyclic Creep Test (MCCT) and Light Cone Penetrometer (LCP) in research by Diaz in 2016 [101]. Multiple Linear Regression Analysis (MLRA) was employed to analyze the data and led to two predictive equations to estimate the parameters of MCCT as a function of rutting performance with an LCP. The results claimed that to ensure the minimum required initial stability of the cold patch, the LCP can be used to estimate the compactibility of the cold mixture during operation. Besides, a penetration shear test was employed by Haipeng et al. [87] to simulate patch deformation under vehicle loads. The test results of oven-cured Marshall briquettes at various temperatures (Fig. 11) demonstrated that at the increased temperature, the deformation resistance is low. A similar test, the California Bearing Ratio (CBR), was also used in another study to assess CMPM short-term premature deformation (Fig. 12). The results revealed that the CBR index is affected by the stone skeleton and aggregate gradation of the mixtures [112].

Figure 11. Conducting penetration shear test [87]

Figure 12. CBR test on cold patch mix [112]

As mentioned, adequate patch compaction is necessary to improve patch stability and prevent premature failure due to deformation under traffic [69]. To evaluate the stability of the patch materials, the area under the compaction curves has been used in the literature. Similarly, to the equations mentioned in section 6.1, the following Eq. (7) and Eq. (8) were presented for mix stability evaluation [111]:

Shear Energy index (EI) from 92% to 96% G_{mm}: $\mathrm{EI}_{(92-96)} = \mathrm{P} \times \frac{\pi d^2}{4} \times \sum_{N92}^{N96} \Delta h$ (7)

Compactibility Energy Index from 92% to 96% G_{mm}: $CEI = \frac{\mathrm{EI}_{(92-96)}}{N_{92-96}}$ (8)

where d is the sample diameter, P is the compaction pressure, h is the sample height during compaction, and N is the number of gyrations.

In the indices, the 92% and 96% G_{mm} (corresponding to 8 to 4% air void in the target mixture) are related to the mix shear strength. CEI is the energy needed to compact the mixture to reach a density of 92 to 96%. Mixes with lower CEI values provide more durability and will be more stable during service life under traffic loads [111].

Another index has been defined by Anderson et al. [136] to measure the HMA stability based on the linear compaction slope (K) and the air void (AV) corresponding to the design number of gyrations (N_{design}). According to the Eq. (9), better stability and rutting resistance are achieved by the higher values of K × AV.

$$S = K \times AV \qquad (9)$$

The literature has mentioned a maximum of 0.5 and a minimum of 20 for CEI and S, respectively [111].

As mentioned before, the stability of the CMPMs is low, especially immediately after their compaction. Therefore, different types of modifiers are used in the mix design to achieve higher stability. Usually, additives such as mineral fillers, fiber, rubber, polymer, sulfur, etc., are used in the proprietary or modified binder production process to improve the mixture stability [50, 137]. Table 12 shows the summary of different methods used for measuring the stability of CMPMs.

Table 12. The summary of methods used for measuring the stability of CMPMs

Researcher	**Stability Measuring Method**	**Indicator of the Stability**	**Ref.**
Diaz	Screwdriver test	Penetration of screwdriver	[101]
	Wheel rotation using a car	Patch resistance against wheel rotation	
Anderson et al.	Applying a dynamic haversine load through a steel foot	The plastic deformation	[9]
Jain et al.	Marshall stability, Resilient modulus and Indirect tensile strength tests	Compressive strength, Resilient modulus, and Tensile strength	[13-16]
Shoenberger et al.	Triaxial compression test	Compressive strength	[13]
Anderson et al.	Hveem stabilometer	Degree of plasticity	[9]
Liao et al. Rezaei et al. Visser et al.	Wheel tracking test	Rutting resistance	[20, 79, 83, 131]
Eckmann et al.	Texas stability test	Maximum compressive load	[78, 104]
	Model mobile load simulator	Resistance to deformation	
Kwon et al.	Asphalt Pavement Analyzer	Rutting resistance	[41, 95]
Wang et al.	Penetration shear test	Penetration load	[87]
Riviera et al.	California Bearing Ratio (CBR)	Resistance to applied load	[112]
Bahia et al.	Shear and compactibility energy indices	Energy needed to compact the mixture	[111]
Anderson et al.	Stability index	Compaction curve slope (K) and the air void (AV) corresponding to the design number of gyration (N_{design}).	[136]

3.3.5. Storageability

Both stockpile and containerized CMPMs need to remain workable and resist stripping and binder draindown during storage. Therefore, this feature, which is called storageability and depends on the environment, storage method, and project size, should be considered for the desired storage period (6 to 12 months) in the mix design [66, 75, 100]. In fact, the improper type and content of the mix component can reduce or extend the storageability of the mixture.

A mixture containing excess binder enables better durability and stickiness due to providing a thicker film to coat aggregates [72]. However, it may lead to binder draindown and accumulation at the bottom of the pile, especially immediately after stockpiling or in warm weather. Besides, a low viscosity binder may cause drainage and stripping problems during stockpile, while a higher viscosity or quick volatilization of the diluent leads to poor workability [75]. Moreover, aggregates with higher water absorption features cause stripping and draindown problems during the stockpile. The mixing temperature should be kept as low as possible and practicable to prevent binder draindown in the stockpile [94]. Also, storage at a depth of less than 0.6 meter facilitates the cooling process and minimizes draindown [9, 74]. In addition, covering the stockpile with polyethylene or a tarpaulin sheet can help to increase storage time [20, 75]. The FHWA and AASHTO test methods have been frequently used in previous studies to assess the CMPM draindown and subsequent storageability. In the FHWA draindown test method, a plate containing 1000 g of the cold mixture is placed at 60°C for 24 h. The plate is then turned over and the mixture is removed. The amount of the remained binder on the plate, which indicates binder drainage shouldn't exceed 4 percent by mass of binder [37]. However, the draindown of the best-performing mixtures in a study by Prowell and Franklin [1] was in the range of 4 to 8 percent. Therefore, they concluded that the 4% limit might be too strict and recommended a maximum of 8%. In addition, Anderson et al. [9] found out that the results of the drainage test could be somewhat erroneous for the following reasons. First, after 24 h aging at 60°C, removing all the particles from the plate is difficult. Second, in mixtures that include a low amount of binder, the draindown occurs where the mixture is in contact with the plate. The AASHTO test method for determining the draindown materials of uncompacted asphalt mixtures was adapted by MTO for evaluating the draindown of CMPMs. In this test, a certain amount of mixture is placed in a wire basket and conditioned for 1-h in a forced draft oven. Then, the weight difference between the mixture before and after the conditioning process is measured and reported as the drained binder of the mixture [96].

4. Conclusion

This study investigated the different aspects of CMPMs in repairing potholes. The advantages and limitations of patching with CMPMs, repair procedures, impacts of patch components, cost, curing, and storageability of these mixtures were assessed through this research. Additionally, since CMPMs' durability and performance engage with poor workability in cold weather, poor stability, especially in deep holes, bonding, and moisture susceptibility, the different procedures for evaluating these properties were investigated in detail. The main outcomes can be summarized as follows:

- The purpose of repairing potholes with CMPMs is to provide traffic safety by restoring serviceability, not a permanent repair. Therefore, these materials are applied in an emergency as a temporary treatment until proper and definite practice is done. However, it is not unusual for some road administrations to use these materials with a desire for a more permanent solution.
- Although repairing potholes by a standard patching method involving vertical saw cuts is more durable, this procedure is time-consuming and interrupts traffic. Therefore, CMPMs that do not need special tools and considerations, are considered by road administrators to repair potholes.
- Aggregates and binders play a significant role in the workability and stability of the CMPMs. Thus, more attention should be paid to the shape, gradation, water absorption of the aggregate, and binder viscosity to provide optimal performance during storage and in-service.
- The volatilization of the CMPM solvents takes up to several months, and the curing process is time-consuming. Still, the CMPM should be cured as fast as possible after placement to provide maximum stability and re-establish the traffic flow in the patched area. However, if the volatilization rate and curing during the stockpile are too fast, the mixture will experience premature curing and become unworkable and impractical.
- The expected life of a temporary repaired patch with Proprietary CMPMs is up to one year. However, the patch longevity is still considered to be days or months instead of years.
- Pothole patching main charges involve materials, labor, and equipment. Usually, the highest cost is devoted to crew and equipment, and the cost of materials is just a small portion of the total patching costs. CMPMs contribute 20% of the overall repair cost, while this value for hot mix asphalt is 2-5%. Therefore, using high-quality materials is strongly recommended for patch operations.
- High-quality CMPMs give longer service life even if they cost more. The cost of high-quality materials with a proper repair method is significantly lower than the cost of frequent patching operations because high-quality materials offset the cost of frequent repairs that are conducted with poor-quality materials. Therefore, using expensive materials with high longevity leads to a significant cost saving in the long run, and the

cost-effectiveness appears in increased productivity and higher service levels, not essentially in money-saving for the agency.

- For all CMPMs that foresee an evolution or reaction of the binder, the packaging and the relative workability of materials are fundamental and decree the success or failure of treatment. The inefficiency of CMPMs' workability, which is very frequent following their storage on pallets or shelves, leads to lower demand for materials and is a severe discrimination factor in commercial competition.
- The initial patch bonding is usually low and increases over time. To ensure adequate bonding between the patching material and the pothole, applying a bond coat to the inside and around the hole is recommended. However, CMPMs should have self-tacking properties to eliminate the need to use a tack coat.
- The gradation and level of compaction have a critical role in the initial stability of the CMPM. Low compaction levels lead to higher air-void content (up to 30%), and the patch is prone to rutting and raveling.
- Through the evaluation of CMPMs' performance and durability, the samples are usually aged and cured in the oven to provide sufficient stability for testing. Though this procedure reflects the patch condition after several months in service, the patch durability may be shorter than a few months, and the patch deteriorates in a short time after patching. Consequently, evaluation of the CMPMs after long-term curing cannot indicate their performance immediately after patching. The mixture may show satisfactory results after long-term curing, but after patching, it distresses instantly under traffic and weather conditions. A comprehensive standard is required to design and evaluate the performance of CMPMs.

In conclusion, CMPMs are quickly developing for patching potholes as suitable alternatives to HMA. However, there are still some limitations and issues with their mix design and performance evaluation. In fact, most of the test methods have been borrowed from the HMA context. However, those approaches do not always meet the requirements of CMPMs. Also, there is a conflict between mechanical performance, which is required in the field and the easiness of application (workability) and compaction that is demanded by road maintenance operators. Besides, most of the mechanical evaluation tests use thick specimens (Marshall briquette) that need longer curing time and are not stable enough after demolding, while in real conditions, patching operations are performed in thinner layers (less than 50 mm) with almost immediate curing and reopening to traffic. Therefore, developing new procedures that can evaluate the performance of these kinds of materials is essential. It is hoped that a connection between researchers, producers and operators will be made in order to develop methods and techniques to achieve durable and superior materials and facilitate the quality control and assurance steps.

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