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CICLO XXXV

*Caratterizzazione avanzata
di miscele bituminose a freddo per
la riparazione celere di dissesti di pavimentazioni stradali*

*Advanced characterization
of cold asphalt patching materials
in repairing road pavement potholes and cracks*

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Abstract

Cold mixed patching materials (CMPM) consist of a combination of aggregates with special binders and additives that are commonly used for repairing potholes, cracks, and small-scale patches in road pavements when the outside temperature is too cold for applying hot mix asphalt. Although these affordable products have a short application time and less environmental impact, they often associate with several defects and drawbacks, such as raveling, water sensitivity, poor bonding, workability, and stability. Among all patch materials, CMPMs have the lowest quality and usually offer relatively poor mechanical and functional performance in the field. Repaired potholes during adverse weather conditions, especially in wet winters and springs, withstand only a few freeze-thaw cycles and are sometimes physically removed even by the first traffic actions. If the CMPM used to repair potholes is of high quality and is correctly applied, it can last longer. However, there aren't any global standards or guidelines for evaluating the performance of these materials, thereby determining their quality. Therefore, in this research specific laboratory test methods and procedures, including Marshall stability, indirect tensile strength, Hubbard-Field stability, indentation stability, shear bond, locking point, and brush test, were proposed to provide a tool for advanced technical analysis of the expected performance of CMPMs in practice and better-specialized production for different climates and usage conditions. Different types of CMPMs available on the market, belonging to three main CMPM categories, including solvent-containing mixtures (SC), membrane-containing mixtures (MC), and water-reactive mixtures (WR), were selected and characterized using the mentioned procedures to qualify their performance in pothole repair operations and to observe the performance of test methods and approaches on the materials. In addition, a field study was set up by making potholes and filling them with different materials using manual and

machine compacting strategies to investigate the performance of CMPMs in patching operations. The laboratory findings showed that the proposed test methods led to more reasonable and reliable outcomes compared to the currently used procedures. In every test, WR materials performed far better than other mixtures. Among all materials, the SC material performed the least well. Although the field results occasionally conflicted with the laboratory findings, they nevertheless demonstrated that even poorly evaluated materials in the laboratory last longer when the proper application repair procedure is applied. Moreover, the workability and compactability of the mixtures were more decisive factors in providing the durability of the patches compared to other properties.

Keywords: Pothole, Cold mix asphalt, Patch materials, Pavement maintenance, Roadwork quality

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Introduction

This study aimed to evaluate the characteristics of cold mix patching materials (CMPMs), which are frequently used in place of hot mix asphalt (HMA) to patch potholes in road pavement. To provide a tool for advanced technical analysis of CMPMs in practice and raise awareness among designers and users about the effectiveness of CMPMs in various weather and traffic conditions, the functional and mechanical performance, as well as issues regarding the use of CMPMs in repair operations, were investigated through currently available and proposed test methods. The outcomes enable manufacturers to improve the characteristics of their products through the availability of an experimental framework.

The development and subsequent spread of potholes, especially in winter, affect the durability and life span of the road pavement. Also, potholes have the potential to impact road users' operations, compromise traffic safety, and raise the risk of accidents leading to injuries or even fatalities. Therefore, they should be repaired as soon as possible, but repairing them could have a noticeable financial impact on road maintenance organizations, costing millions of euros per year. Generally, conventional is used as a durable material to repair potholes. However, HMA treatments face difficulties in the winter. In recent years, CMPMs have become popular for repairing potholes, especially in the cold seasons, thanks to their ease of handling, cost-effectiveness, low labor and equipment requirements, lower environmental impact, and longer storage time. Despite their benefits, CMPMs are the worst patching materials in terms of quality and show relatively poor mechanical and functional performance in the field. As a result, repaired potholes with CMPMs typically offer a short lifespan and require regular treatment operations. However, employing a proper method and high-quality materials to repair potholes can extend their longevity.

Nevertheless, there are no accepted test methods in the literature to assess the properties and characteristics of these materials, thereby determining their quality. Currently, the qualification of the commercially available products is based on a set of performance parameters derived from conventional HMA techniques (i.e., density and Marshall stability requirements). However, these requirements are not representative of the various service life stages of CMPMs, and still, there is a conflict between the lab and field results.

Therefore, the thesis is divided into six studies to cover the requirements of CMPMs' performance evaluation in pothole repairs. The first chapter presents a comprehensive literature review to identify the issues and methods for analyzing CMPMs in the lab and during repair practice. According to the findings of the literature review, chapter 2 proposes new test methods and settings to assess the performance of different CMPMs on the market. Chapter 3 displays the performance of test methods and approaches, identifies crucial factors for CMPM, and qualifies the products based on their performance in the lab. The effects of mixture components and densification are shown in chapters 4 and 5. Finally, chapter 6 involves a field study to evaluate the performance of the CMPMs in actual conditions.

Chapter 1

Literature review

1.1. Introduction

Cold mix patching materials (CMPMs) are frequently used instead of traditional hot mix asphalt (HMA) to repair potholes and localized distress, particularly in inclement weather [1, 2]. Although these patching products provide immediate serviceability, they have a relatively short life [3]. Potholes repaired with CMPMs experience different types of damage following repair operations until the patches deteriorate completely. However, several aspects and parameters can affect patches' life spans and increase their longevity, including the size and dimension of the pothole, the preparation of the pothole before patching, the quality of the material, the repair method, weather conditions, the experience of the crew, etc [4, 5]. Although global interest in CMPMs as a rapid solution to repair potholes is growing, a lack of knowledge, issues related to the products, methods of measuring their performance, etc., raise consumer uncertainties about them [5]. This chapter describes a critical comparison between several aspects of using CMPMs and HMA in repairing potholes. Specifically, repair techniques, productivity, and costs were investigated in detail. In addition, the impact of the main crucial factors, i.e., workability, bonding, water susceptibility, stability, and storageability, on the performance of CMPMs was reviewed.

1.2. Pothole description

1.2.1. Definition, formation mechanism, and severity levels

Although several definitions have been given to identifying a pothole, it can be simply described as "a bowl-shaped hole of various sizes in the pavement surface" [6] or, more precisely, as "a localized deterioration of road pavement resulting from the loss of material or depression in the pavement surface [7]." Physical, mechanical, and environmental stresses all work together to create potholes. However, water infiltration and traffic loads play critical roles in the initiation and expansion of potholes. Constant traffic, especially in adverse weather conditions, results in cracks in the pavement, which is a necessary precondition for pothole formation [8-10]. The cracks in the pavement facilitate water penetration into the road structure. Then, the recurrence of freezing and thawing cycles due to water penetration causes a loss of support in the road layers, which results in more severe damage (Fig. 1.1) [4, 11, 12].

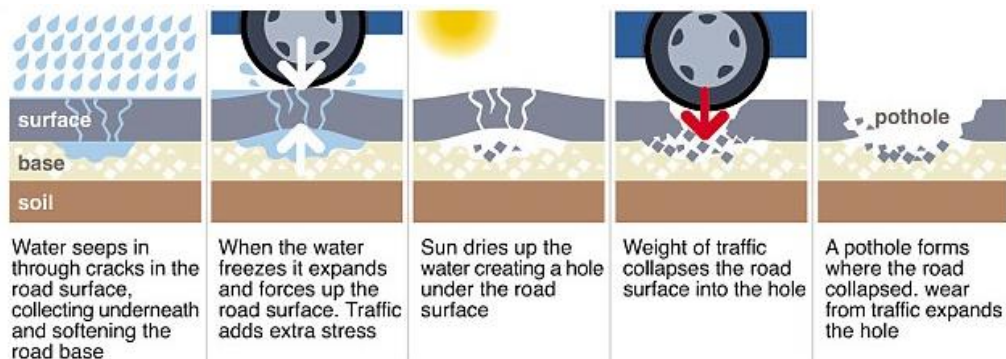


Figure 1.1. The formation process of a pothole [13]

Despite water permeability and traffic, other factors, such as material failure, poor mix design or inadequate construction methods [14], defective geometric design of the road [15], stripping, raveling, bleeding, and shoving of the pavement [12, 14, 16], a lack of knowledge and poor workmanship, excavation and reinstatements by utility companies [5], incorrect pavement, repairing and

winter maintenance operations, especially snow removal [17, 18], reduction in the longevity of the road structure, fatigue, and interconnected alligator cracks, etc., simplify the formation of potholes and various damages [19-21].

Potholes and their severity levels are classified based on their dimensions, surface area, and depth [14]. Additional variables that affect these parameters include the climate, speed and intensity of traffic, the type of vehicle, and the presence of pedestrians and bicyclists [22]. The U.S. Federal Highway Administration (FHWA) considers holes with a width of at least 150 mm and a depth of 2.5 mm, 2.5-5.0 mm, or greater than 5.0 mm to be low, moderate, and high-severe potholes, respectively [6, 9]. The ERA-NET ROAD pothole project has determined a minimum depth of 30 mm and a maximum diameter of 1 m for typical potholes, depending on road conditions. Instead, potholes that are deeper than 40 mm are considered severe [22] and must be repaired in less than 24 hours [4]. Based on Norwegian regulations, any damage that is wider than 30 mm for a bicycle lane and 100 mm for a motorcar lane should be repaired within a week [20]. In a study, the Strategic Highway Research Program (SHRP) classified 0.93 square meters and 150 mm as the maximum surface size and depth of a pothole [23]. The maximum recommended depth by UK Haringey Council guidelines is 50, 60, and 25 mm for major roads, unclassified roads, and locations that could be dangerous for pedestrians or bicyclists, respectively [14]. In addition, according to responses to a questionnaire given to about 80 local authorities in the UK in 2014, 67% of respondents considered 25–40 mm, 12% selected 40–50 mm, and 14% believed a depth of more than 60 mm as a typical pothole depth [6]. The Swiss Road Maintenance and Management Association also categorizes potholes according to the severity of the distress, as shown in Table 1.1 [4].

Shahin [24] ranks the severity of potholes slightly differently. According to Table 1.2, for potholes with an average diameter of up to 762 mm, both the depth

and the diameter are considered when determining pothole severity. The pothole area is measured and divided by 0.47 square meters if the diameter is more than 762 mm. The severity is rated high if the result is higher than 25.4, and medium if it is below [24]. Potholes should be measured as one large pothole if there is less than 200 mm between them [25].

Table 1.1. Potholes' classification based on the severity of the distress [4]

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

Table 1.2. Classification of potholes based on depth and diameter according to Shahin [24]

Maximum depth (mm)	Average diameter (mm)		
	102-203	203-457	457-762
12.7 – 25.4	L	L	M
25.4 – 50.8	L	M	H
> 50.8	M	M	H

L=Low; M=Moderate; H=High

1.2.2. Maintenance and rehabilitation

Road pavements deteriorate over time due to traffic loads and weather conditions. As a result, they require rehabilitation to restore their serviceability [26]. This rehabilitation procedure generally adopted for potholes is known as “patching” (Fig. 1.2), which involves filling potholes in the road pavement with the appropriate material to prevent further deterioration of the pavement and restore the safety and comfort of road users [3]. Pothole patching covers a variety of techniques, from temporary ones in emergencies to permanent (or semi-permanent) ones performed during corrective and routine maintenance operations [27]. It is the most sensible sign of road maintenance to the public

and other road users [28] and should be performed in good weather before potholes spread throughout the pavement, worsening repair operations [16]. Nevertheless, before patching can be carried out, the cause of the pavement failure must be identified [29]. An early and routine repair can limit expenditures and extend the pavement's lifespan. However, rehabilitation and maintenance strategies are typically costly and time-consuming, particularly during the cold and wet winter and inclement weather. Therefore, it is crucial for road maintenance authorities to give urgent attention to potholes to prevent further pavement deterioration, vehicle damage, and user costs [30].



Figure 1.2. Using a CMPM to patch a pothole

When distresses are localized and appear in relatively remote areas or on low-traffic roads, patching potholes is the most common maintenance procedure used to repair pavement and restore serviceability [31, 32]. The most crucial factors for good patching techniques are material quality, repair technique, and compaction level [33, 34]. However, several factors affect the decision to patch, including [27]:

- The temporal frequency of routine maintenance of pavement (resurfacing or overlay)
- Traffic level

- The hierarchy of the road and the potential for establishing a temporary construction site
- The availability of the equipment, materials, and labor
- Public negative view

The patching operation can also be affected by running time, weather conditions, pothole size, host pavement characteristics, and total cost [4].

1.2.2.1. Repair Procedures

Pothole repair operations include several temporary and semi-permanent to permanent approaches, which are as follows [34, 35].

- Temporary repairs

- Throw-and-dump or throw-and-go: The cold mixture is simply shoveled into the pothole without extensive compaction and removing the water and debris. The Traffic compacts the patch.
- Throw-and-roll: The cold patch is placed into the unprepared pothole and compacted using feet, a hand tamper, and a truck wheel.
- Edge seal method: The repair method is similar to throw-and-roll, but after material compaction, a tack coat and sand are applied to the repaired section's perimeter. Then, it is allowed to dry for about one day.
- Spray-injection: A hot asphalt emulsion and aggregate mixture is sprayed into a prepared pothole, and the patch is then coated with aggregates to prevent it from sticking to the wheels of vehicles.

- Semi-permanent repair: In this partial-depth repair, the edges of the prepared pothole are sawed vertically, then filled with a cold mixture or, in some situations, HMA. After that, a roller is used to compact the patch.

- 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: After removing loose debris, the hole and the area around it are pre-heated. Then, the pothole is overfilled with patching material and heated and compacted.

Road maintenance organizations should prioritize permanent repairs over temporary ones and use temporary methods only for emergencies to provide safety quickly [21]. Studies have shown that while the semi-permanent approach is more durable, its higher equipment and labor costs and the effort required for patching reduce its productivity compared to temporary methods such as throw-and-roll and edge seal [23]. Spray injection has a high productivity range depending on labor abilities, but also comes with high equipment expenses. Additionally, spray injection materials are less expensive. The throw-and-roll technique uses hand tools to fill the hole instead of specific equipment. This approach can be used as a substitute for semi-permanent repairs because it offers satisfactory repairs with high-quality materials [27, 36]. Wilson's 1993 study [37] found that spray injection provides more durable patches than other procedures and is the most productive technique in terms of tons/person-day (Table 1.3) [37, 38]. Another study revealed that, in terms of tons/day, the throw-and-roll and spray injection procedures are 4 and 2 times more productive than the infrared method. Furthermore, Nazzal et al. [23] investigation of winter pothole patching procedures revealed (Table 1.3) that, considering the required time for repairing potholes, throw-and-roll, spray-injection, edge seal, and semi-permanent techniques have the highest productivity, respectively. However, recent market data shows that there is considerable interest in the convenience of single-use packaged products for throw-and-roll, although higher unit prices are offset by increased ease of handling and speed of use. Table 1.4 displays the general characteristics of the patching methods.

Table 1. 3. Average productivity values for different repair techniques

Repair technique	Average productivity (tons/hour)	Labor (person)	Average productivity (tons/person-day) [37]	Average required patching time (min) [23]
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 1.4. 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	[19, 23, 39, 40]
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	[23, 32, 38, 41]
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	up to 2 years at summer ≥3 years	[10, 23, 42, 43]

		formation of a cold joint requires well trained and experienced operators higher equipment costs		
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	[23]
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	[19, 23, 26, 34, 44]
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	[10, 23, 32, 45]
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	[23, 44, 46, 47]
microwave	using RAP and RAS strong interface bonding	requires long heating time		[48, 49]

1.2.2.2. Patching materials

The materials that can be used to repair potholes are numerous. However, they are classified into the following main categories [22, 32]:

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

Asphalt-based products (hot and cold) are utilized for both asphalt and concrete pavements, while cement-based materials are usually used for permanent patches on rigid pavements. Besides, there are also other kinds of repair materials, like epoxies, synthetic binders, polymeric materials, and resins, that are not commonly used in repair operations, especially throughout Europe [22, 32].

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

The manufacturing of cold-mixed asphalt mixes does not involve heating. The liquid asphalt-based binder and aggregates are mixed in a plant or on the job site before being stored or used cold in pavement treatments. They perform poorly and are of worse quality than HMA mixtures [3, 50]. In general, these kinds of products, also known as CMPMs, are typically divided into the following groups [4, 29]:

- The cold mix is produced by a local asphalt plant; The cold mixture is produced using the available components without considering the binder-aggregate compatibility test.

- The cold mix is made following the guidelines established by the agency; the maintenance agency's criteria for acceptance and approval of the binder-aggregate are considered before purchasing the material.
- Proprietary cold mix: These materials, which include specially formulated binders, can be manufactured in bulk and packed in sealed bags or buckets weighing 20–25 kg or stockpiled in large quantities outdoors after passing some acceptance tests.

The majority of road repair activities use hot and cold asphalt-based materials, which offer a fair price, acceptable quality, adequate stability, and simple application. Generally, hot-prepared and applied materials provide a long-lasting and effective solution for repairing potholes [4]. Previous studies demonstrated that HMA materials outperform CMPMs and offer the best repair due to their high initial stability, minimal permanent deformation, efficient bonding to the existing pavement, and ease of compactibility [51, 52]. To fill potholes, the New Jersey Department of Transportation (NJDOT) used three different CMPMs and one type of HMA. The outcomes demonstrated that HMA performs significantly better than the other mixes [53]. Similar findings were reported in investigations by Dong et al. [31] and Marasteanu et al. [45]. In a 1986 study, Feighan et al. [32] assessed the performance of patching materials comprising hot mix, cold mix, cold mix with fibers, and fiber mix heated in a Porta-patcher in repairing shallow potholes. They analyzed their service lives and repair procedures and compared them on roads with poor, fair, and good conditions. According to the findings, hot mix asphalt outperformed all other mixes in terms of performance, and CMA was also less efficient. Moreover, HMA is the preferred method of road maintenance organizations for patching operations due to its higher durability, even though applying HMA requires more equipment and is less environmentally friendly [54, 55]. The results of a survey conducted in 2014 in the UK (Fig. 1.3), which included answers to questionnaires from about 80 local

authorities, revealed that 31% of the agencies prefer to use HMA for pothole repair, and 69% of them employ both cold and hot materials [11]. Another survey received responses from 49 US states, 20 local agencies in 8 US states, and 33 local and national highway agencies in the UK and Ireland. The findings (Fig. 1.4) showed that HMA is the most popular material for permanent patches [32]. Despite the durability of these materials in patching potholes, their limited use in adverse weather, and their long and specific application methods, maintenance organizations have recently started to consider the use of CMPM. While CMPMs generally perform worse and have lower quality than HMA, they are workable in most weather conditions [56, 57] because their workability is achieved using solvents rather than heat [58]. Therefore, they are easy to use in inclement weather and challenging circumstances. Particularly in difficult situations like high-speed roads and intersections like roundabouts, the application of CMPM is quick and takes less time, leading to a safer repair operation with less traffic disruption [5].

To assure durability, utilizing a high-quality mixture is crucial but insufficient [5]. If the mixture is applied under improper circumstances, it will not work well, and the service life will be limited [4]. The following are three main concerns of CMPMs to attain maximum performance [59, 60]:

- high air-void content or a moderate level of densification
- weak initial stability and strength
- prolonged curing to reach peak performance.

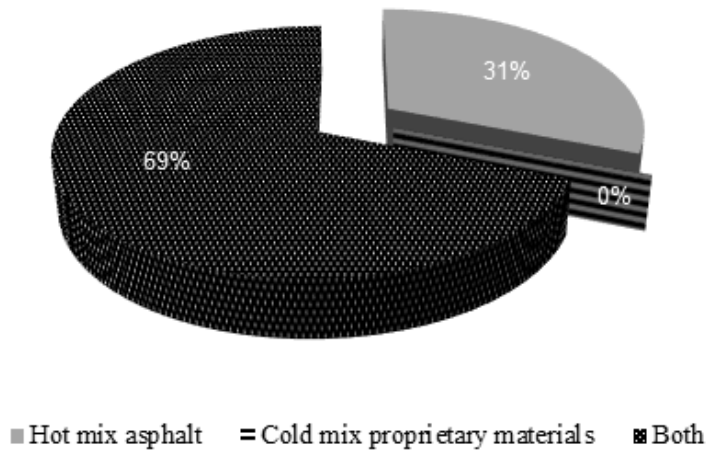


Figure 1.3. Materials were used for patching based on responses from local authorities [11]

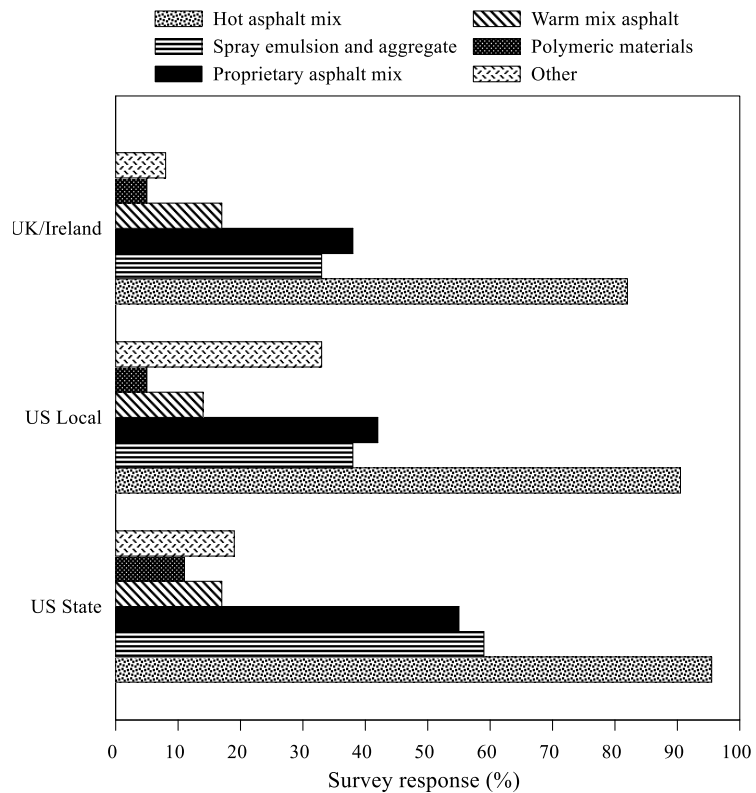


Figure 1.4. Materials used to repair potholes according to responses from agencies [32]

1.2.2.3. Durability of the repaired potholes

The longevity of the patch usually depends on the patching method, the quality of the patching material, and climatic conditions (high or low weather temperature) [31]. Therefore, if the patching procedure is performed satisfactorily under warm or fair-weather conditions, with high-quality material, the patch can last longer [23]. When compared to spring, the lifespan of the patch is typically reduced by a few days to a few months in winter patch practices [4]. The purpose of a winter patching operation is only to provide traffic safety by restoring rideability, not to make a permanent repair. Nevertheless, patched potholes in the spring are anticipated to endure as long as the surrounding pavement [27]. In six Canadian provinces (Alberta, Manitoba, Ontario, Quebec, Saskatchewan, and New Brunswick), laboratory research and a questionnaire were used to evaluate the durability and survival time of winter and summer repaired potholes. According to the findings (Table 1.5), winter-patched potholes survive for no more than 12 months. This value was more than one year for patched potholes over the summer [18, 43].

Table 1.5. Survival time of repaired patches in six Canadian provinces (months) [18]

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

HMA is not the only material that provides durable patches. The use of high-quality CMPMs also results in long-lasting repairs [31]. Patching potholes with high-quality CPAMs in China led to desirable outcomes, but the cost of the high-quality mixtures was three to five times higher than that of HMA [1]. Nevertheless, past experiences show that high-quality materials offer a longer service life even if they cost more. Using high-quality materials reduces the expense of regular repairs that should be made frequently when using low-

quality ones [61]. In addition to the material and application circumstances, the patching procedure (temporary, semi-permanent, or permanent) also has a significant effect on the longevity of the patch. The expected life of a temporarily repaired patch is up to one year. It can endure up to 18 months if high-quality materials are applied [14]. This time frame is restricted to three to six months by the NCHRP study [32]. The lifespan will even be extended if the patching mixture can be compacted to the same density as the existing pavement [62]. Throw-and-go pothole repairs are the least durable and last from a few hours to a few weeks [39, 40]. This repair procedure is typically not advised due to its limited lifespan, frequent re-patching, and high cost [32]. Throw-and-roll pothole repair techniques are more durable than throw-and-go ones. If the repair procedure is applied correctly, the patch can last up to 12 months for spring repairs and 6 months for winter repairs [14, 19]. Potholes filled in the winter using the throw-and-roll technique did not endure longer than three months in the abovementioned study conducted in six Canadian provinces. However, summertime pothole repairs lasted more than two years [18]. Also, winter-repaired potholes with the throw-and-roll method in Tennessee exhibited a reduced life duration and failed only after a few weeks in a 14-month field survey [63]. In general, if a product offers patch durability of more than nine months, the throw-and-roll approach can be a good substitute for the semi-permanent repair procedure [18].

The edge seal method of patching is comparatively durable in all seasons and lasts more than a year. The spray injection approach, if employed appropriately, can serve as a permanent repair and last for up to two years, although it performs poorly when exposed to consistently moist environments [14, 32]. The predicted patch life for the semi-permanent repair method is up to two years [19]. The most durable repair technique, lasting between three and six years, is permanent

patching. The lifespan can be 15 years or longer if a permanent approach using HMA is applied correctly in an appropriately prepared pothole [10, 34, 45].

According to past studies, the durability of patches falls into the following categories [35, 64]:

- Short-lasting patches: those that persist for less than a year.
- Medium-lasting patches: patches that last between one and three years.
- Long-lasting patches: those with a three-year survival lifespan or longer.

However, patch life is still measured in days or months rather than years [65].

Due to one or a combination of the already-mentioned factors, the patch fails after a short period. Table 1.6 shows the most significant causes of patch failure in more detail [66].

Almost all of the symptoms and issues indicated in the Table 1.6, including binder content, poor-graded aggregates, and improper repair by the non-specialist crew, were also covered by Kandhal and Mellott [67]. However, the effect of these factors on patch failure can vary based on specific circumstances. Water infiltration and poor-quality mixtures have the biggest and lowest influences on patch failure, respectively, according to responses provided by over 80 local authorities from throughout the UK to a questionnaire on the primary causes of patch failure (Fig. 1.5) [11].

Table 1. 6. Cold patching materials' failure symptoms and mechanisms [66]

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

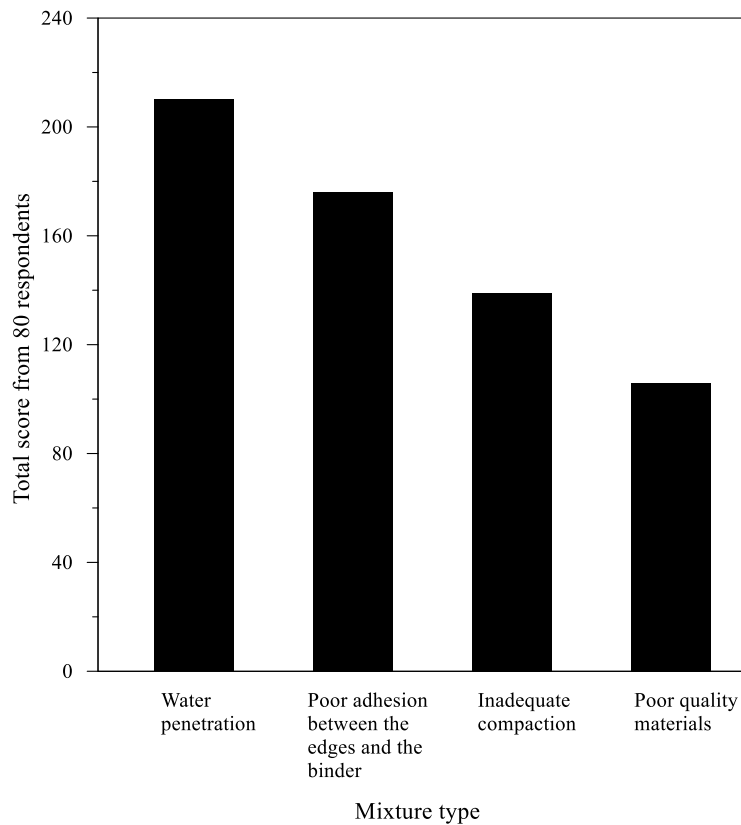


Figure 1.5. The main factor in failing of potholes in UK (least likely reason=1, most likely reason=4; the score is the sum of all weighted rank counts) [11]

1.2.3. Cost analysis

Since patching is an expansive and large-scale repair operation, road agencies must spend millions of dollars annually [3, 65]. Materials, labor, and equipment are the three main costs involved with patching potholes. However, other expenses associated with pothole repairs, such as lane closure and user delay costs, vehicle damage, and insurance costs, cannot be disregarded [51].

Research conducted in 2010 estimated that the cost of accidents and car damage exactly due to potholes over a rainy season in the UK was more than £10 billion (\$13.8 billion), which is four times the total annual road budget of South Africa [29]. In another study, the Local Government Association (LGA) estimated the

money required to repair damaged cars due to potholes in 2014 in the UK was £1 billion (\$1.38 billion). Additionally, a study by the international research data and analytics group (YouGov) revealed that businesses in England and Wales experience an incremental loss of £5 billion (\$6.9 billion) annually due to poor road conditions, which is greater than the budget allocated for road maintenance [11].

As a result, considering the repair lifespan when calculating the benefit-cost ratio (BCR) is crucial, and durable patches, particularly those with a survival life of over a year, can dramatically lower total costs because they don't need to be patched as frequently [54]. According to earlier research, cost-effectiveness increases significantly by preventing the replacement of failed patches [32]. Therefore, preventative maintenance programs can ultimately be less expensive than routine patch operations while considerably extending the life of the patches [14]. A preventative maintenance program can be at least 20 times more affordable than reactive maintenance, according to a 2012 study by ALARM [5]. However, planned maintenance activities are typically given less thought because of a lack of funding. According to responses from about 80 local authorities across the UK to a questionnaire, 25% of the annual pothole repair budget is spent on "planned maintenance," 59% is spent on "reactive maintenance," and the remaining 16% is for routine operations [11].

In repair operations, staff and equipment are typically the most expensive parts. According to research done in 2013, Dong et al. [63] claimed that between 50 and 60 percent of the overall cost of patching is spent on labor costs. The equipment also contributes significantly to the overall cost. The dedicated expenses for temporary techniques with CMA, however, differ slightly. Depending on the method used to repair potholes, the price of materials and equipment might be significant, as Lukas Hammel's research demonstrated (Fig.

1.6) [68]. As a result, the cost of patching can be altered by using expert workers, standard equipment, and patching materials [52].

The cost of the materials typically only makes up a minor fraction of the overall patching expenditures [26, 31]. Studies have revealed that this value accounts for 15 to 25% of the total operating expenses [69]. It also accounts for less than 10%–20% of the total cost if the repairs are carried out correctly [39].

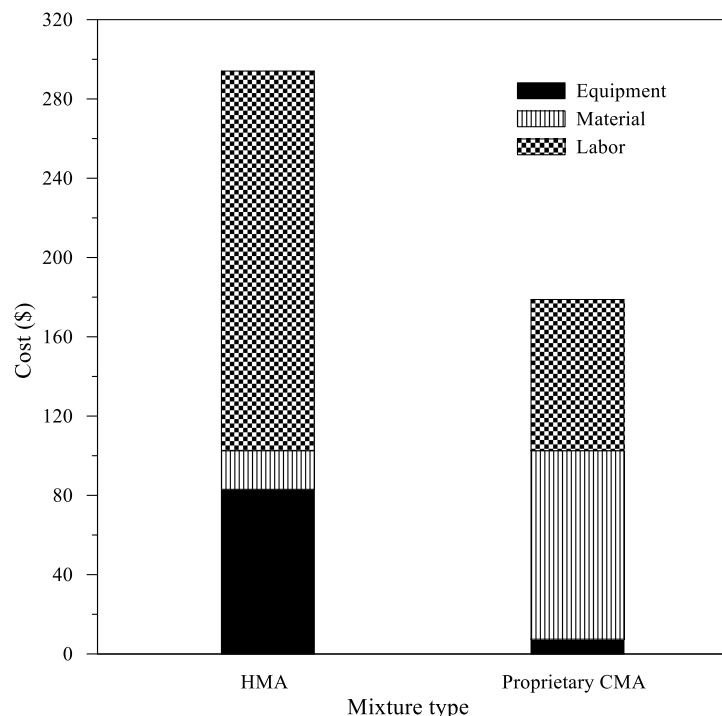


Figure 1.6. The comparison between dedicated costs in 2015 for HMA and a proprietary CMA (The original cumulative costs were expressed in euros) [68].

Studies show that CMPMs contribute 20% of the total cost of repairs, compared to 2-5% for hot mix asphalt [52]. Despite being affordable, the materials have a noticeable impact on the patch and the overall expense. Poorly performing CMPMs usually result in higher staff, equipment, traffic control, and user delay costs. Therefore, using high-quality materials is advised to improve longevity, avoid the need for re-patching procedures, and lower total expenses [37, 39, 41].

The cost of using high-quality materials and an appropriate repair technique is much lower than the cost of frequent patching [66]. Through research in 1988, Anderson et al. [66, 69] calculated the annualized expenditure per repair for various patching materials costing from \$30/ton to \$120/ton (Fig. 1.7). By considering the critical condition, if the most expensive mixture (\$120/ton) lasts in the pothole until the second year, the cost required to repair it after the second year will be less than the first-year repeated repair costs of the hole patched with the cheapest material (\$30/ton). Therefore, utilizing expensive mixtures with a long lifespan results in significant cost savings over time [39].

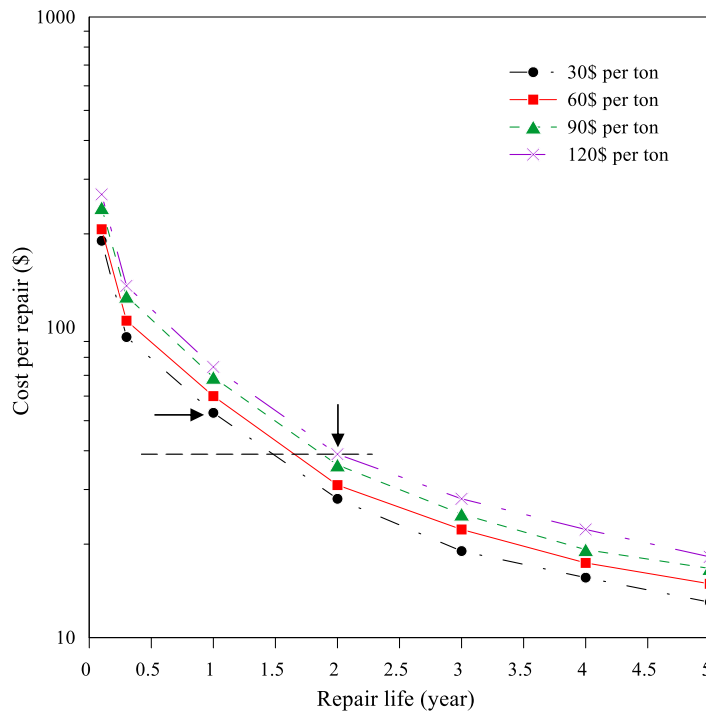


Figure 1.7. Annualized cost for standard repair procedure in 1998 [69]

However, a study at the University of Minnesota found that temporary solutions and less expensive materials are more cost-effective for short-term needs, while long-term patching techniques provide great effectiveness in the long term. Additionally, the advantages are considerably higher if user expenses are considered in the study [45].

It is clear that the patch's longevity cannot be guaranteed just by high-quality materials. It will operate poorly and not survive long enough if the high-quality material is used improperly and in bad condition. According to a two-year European study called POTHOLE, using cold mixtures to patch unprepared potholes costs the most compared to the other patching repair strategies. The most economical repair method is a regular operation that involves cutting, cleaning, filling, and compacting the patch [45]. Compared to other repair techniques, the "throw-and-go" approach, which is a traditional repair technique without pothole preparation, is not cost-effective. The expense of this patching procedure is around three times that of a conventional patching technique, according to Thomas and Anderson's research [39].

Following the results of a questionnaire survey in 2011, in Tennessee, despite the longer operating time and higher initial costs of labor and equipment, the semi-permanent method is the most economical strategy over the long term. In addition, the throw-and-roll treatment method used in spring is cost-effective, but not in winter [19]. The semi-permanent method is considered to be more cost-effective than throw-and-roll. SHRP's most extensive pothole repair research project (H-106) 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 economical than the semi-permanent method due to reduced labor and equipment [37]. Under ideal circumstances, the throw-and-roll and permanent methods' respective labor costs for patching and traffic control can be estimated at two and four workers, respectively [26]. Pothole repair employing a semi-permanent technique costs over 2.5 times more than the throw-and-roll technique, which is consistent with other research of a similar nature [18]. Another study done for Tennessee DOT by Dong et al. [63] demonstrated these price differences between throw-and-roll

and semi-permanent approaches. The findings showed that the throw-and-roll method for patching potholes with different cold mixtures is substantially less expensive in terms of both labor and equipment (Fig. 1.8). Nazzal et al. [23, 31] evaluated the performance and lifetime costs of infrared patching operations in a different study and compared them with spray injection and throw-and-roll repair techniques. The comparison showed that if user expenses are disregarded, the throw-and-roll method will be less expensive than the infrared method for short-term repairs (less than 12 months). But over time, particularly for winter repairs, the infrared technology is more economical than the alternatives.

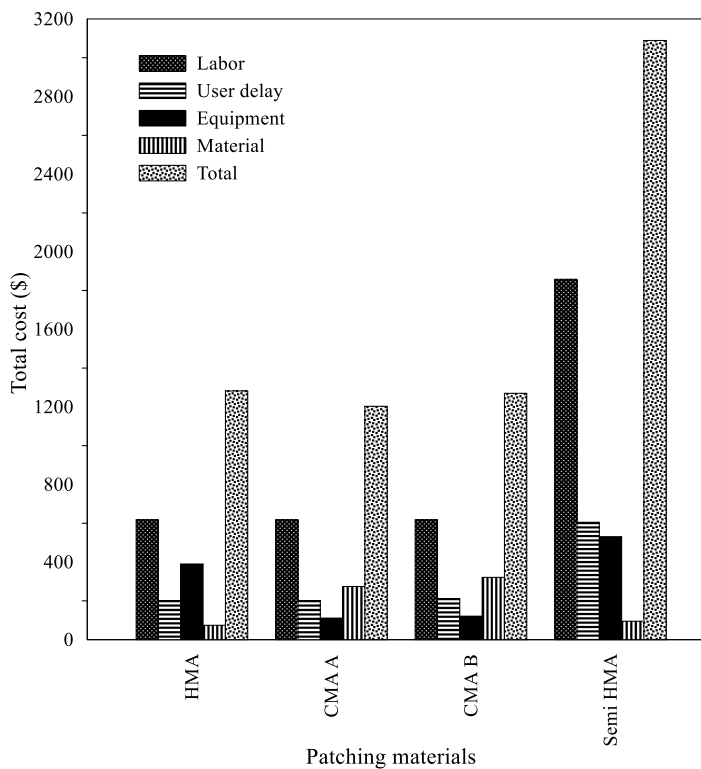


Figure 1.8. Total patching cost differences between cold mix and hot mix asphalt in 2014 [63] Wei and Tighe [70] used various techniques to assess the durability and affordability of patched potholes (Table 1.7). They discovered that the spray injection patching approach is less efficient financially. Unlike the hot mix pathing procedure, which 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 quick and effective deployment in small- or large-scale repair practices [71]. Finally, it is interesting to highlight that, according to the research, cost-effectiveness appears in enhanced productivity and higher service levels, not primarily in cost savings for the agency [72].

Table 1.7. Longevity and cost of different patching methods in 2004 [70]

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

1.3. Cold Mix Patching Materials (CMPMs)

CMPMs are typically used in an emergency as a temporary solution until a more acceptable and definitive practice is applied [73]. These asphalt-based products are a mix of aggregates, additives, and special binders (asphalt emulsion, cutback, and proprietary binders) [74]. However, in recent years, there has been an increase in interest and focus in the mix design of CMPMs regarding the use of waste materials such as reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) to modify the binder or as a replacement for aggregate or mineral filler [75, 76]. Despite the advantages of using cold mixtures in maintenance programs, they have drawbacks which are evident in their poor performance or premature failures. The main issues with these mixtures are poor workability in cold weather, low stability, especially in deep holes, and moisture susceptibility [77]. In addition, since they cannot be compacted at the same level as hot mixes [64, 77], they lead to higher air void contents and patch porosity (up to 30%) and, eventually, poor mechanical performance [60]. The SHRP

manual suggests a few procedures as compatibility and acceptance tests to satisfy the minimal requirements for using these materials, even though there are no standards or detailed instructions for using and evaluating CMPMs [78, 79]. Compatibility tests involve coating, stripping, and drainage tests, whereas acceptance tests include workability and cohesion experiments [54, 73]. The tests stated are used to identify materials that might perform poorly in the field rather than to ensure the success of patching mixtures [27].

1.3.1. Components

The literature has shown the importance and impact of cold mix components on the performance of patched potholes. Below is a description of how various ingredients influence the mixture and how they do so.

1.3.1.1. Binder

The cold mix design uses cutback, asphalt emulsion, and special binders to satisfy the CMPM specifications [60]. By improving the mix design, both in the type and dosage of components, workability and stability—two significant problems for CMPMs—can be controlled. A soft binder with low viscosity is required in the mixture to provide satisfactory workability for extended storage and in cold weather. However, high binder viscosity is preferred for better cohesion and stability of the patch after repair [73]. Therefore, binder viscosity should be comparatively low at low temperatures to give the mixture desirable workability [80]. The cutback binders in cold patching materials make them less temperature-sensitive, allowing them to be used in cold and rainy weather. Traditional solvent cutbacks like gasoline or diesel reduce the binder viscosity and make the mixture workable even with a relatively low initial strength. However, as the solvent evaporates, the strength of the patch gradually increases [2, 20]. Despite its benefits, using cutback-based products in cold weather can be challenging and usually requires warming up with the sun before the

treatment [29]. Plus, as the volatilization of the solvents takes several months, the repaired areas may be damaged during evaporation and curing [81, 82]. Additionally, cutback-based mixtures emit more hydrocarbons than emulsion-based mixtures, pollute the atmosphere by contributing to the greenhouse effect, consume non-renewable energy resources, and are flammable, endangering the workers' health [83, 84].

As a result, new European environmental restrictions have limited or even prohibited existing cutbacks, and using environmentally friendly alternative solvents is currently emphasized [85]. Compared to cutback, asphalt emulsion has considerably fewer ecological issues [26]. However, their relatively short breaking time is the main limitation that drives producers to use slow-setting emulsions in cold asphalt mixtures [4, 86].

In parallel, proprietary binders and environmentally friendly alternatives to petroleum solvents are under consideration by manufacturers and researchers [55]. In a recent study by Wang et al., [87] mineral spirits and isoamyl acetate were used as alternative solvents in designing cold mixtures. New solvents exhibited better solubility and faster evaporation. Compared to diesel mixtures, utilizing new solvents improved curing and initial strength, adhesion, rutting resistance, and resistance to water sensitivity. In another study, Dong et al. [55] used turpentine as an alternative to diesel in cutback binder. Although the solubility of solvents was comparable, turpentine vaporized more quickly than diesel. Besides, utilizing turpentine in the mixture led to higher initial strength and lower abrasion and moisture sensitivity. In research conducted by Zhang et al., [88] similar performances were obtained by modifying cutback with waterborne epoxy resin (WER). The test outcomes, however, showed that the improper addition of WER can result in poor storability and low-temperature performance. The authors recommended 1.2–1.8 wt% WER as the optimal dosage to enhance the performance of the cold mixtures. Vegetable oils such as

sunflower are also used in place of petroleum solvents to reduce 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 [83, 85, 89]. Cooking waste oil (CWO) was used by Geng et al. [1] as a diluent in the cold mixture. The observations revealed adding 15% to 35 wt% CWO to a cold mix containing 21% to 23% diluent improves adhesion and workability. But the influence of CWO on the strength of the patch was not noticeable. Furthermore, there are commercially available special CMPMs whose curing and strength evolution occur in the presence of water via chemical action rather than solvent evaporation. In these water-based cold patching materials, the strength evolution is faster than in traditional CMPMs, and the strength development process starts by adding water or even air humidity. As a result, they must be stored in totally sealed containers and used up to a temperature of 0 °C [68, 81]. They are expensive and unsuitable for large-scale repair operations, although they provide better patch performance [90]. According to the author's laboratory experience with one of the widespread water-reactive CMPMs on the market, the cure rate of the WR material dropped significantly after a few hours of compaction at room temperature, and the material reached the majority of its stability during this time. Additionally, even after being opened for a few days, the remaining material in the sealed bucket did not exhibit high sensitivity to humidity and maintained its quality. Eventually, for all CMPMs that foresee an evolution or reaction of the binder, the packaging and the relative workability of materials are fundamental and define the success or failure of treatment. The inefficiency of CMPMs' workability, which is very frequent following their storage on pallets or shelves, results in lower demand for materials and is a severe discrimination factor in commercial competition [136].

No matter the kind of binder, a high amount of residual binder is needed to achieve a thicker film on the aggregates to improve cohesion and adhesion and, subsequently, the durability of the patch; however, binder drain-down during the stockpile should also be taken into consideration [67]. The higher binder percentage yields a sticky mixture, especially in the winter, but it also causes bleeding, poorer skid resistance, rutting, and drain-down in the stockpile. Nevertheless, an inadequate binder can lead to moisture susceptibility, poor cohesion and adhesion, and subsequently unstable patches but better workability in cold temperatures [73, 91]. Previous studies showed that at least 4.5 percent residual binder is needed for aggregates with less than one percent water absorption to achieve the CMPM specifications. This value varies depending on how much water is absorbed; for instance, if water absorption increased by 5%, the residual binder should have grown by the same percentage [67].

1.3.1.2. Aggregate (type and grain size distribution)

Aggregates, like binders, are essential to the performance of cold mixes. Various forms of virgin and recycled aggregates, including crushed stone, silty sand, RAP [92], RAS [75, 76], slag, and fly ash, are used in the CMPM mix design to mix with the binding materials and make the mixture [58].

Shape and gradation are the most critical requirements for aggregates. The stability and workability of the cold patching mixtures are greatly affected by gradation and aggregate morphology [66]. A high degree of aggregate angularity in the mix design is necessary to provide higher stability, even though angular aggregates do not offer adequate workability. The influence of angularity on workability may be reduced if the mixture contains a predominance of one-sized fine aggregates [67]. Although using specified aggregates such as uncrushed gravel, sand, and rounded aggregates can improve workability, it also increases the risk of pavement failure due to rutting and shoving under traffic loads [30,

73]. Despite the shape, the susceptibility of the aggregates to moisture can also lead to additional issues. Higher water-absorbing aggregates should not be included in the mixture since they can produce stripping and drain-down problems during the stockpile [67]. Therefore, aggregate water absorption should be considered and limited to almost 1 percent [54]. The Ontario Provincial Standard Specification (OPSS) sets a limit of 2% [93].

Dense-graded and open-graded aggregates are usually used in cold mixtures to ensure appropriate performance in patched potholes. There are advantages and disadvantages to each gradation [20]. A well- or dense-graded aggregate offer a low air-void and relatively impermeable mixture, resulting in a stable and long-lasting patch. As opposed to dense-graded gradation, open-graded aggregates provide better workability than dense-graded ones. Besides, their high porosity makes them more workable at freezing temperatures and can speed up volatilization and cure times. However, dense-graded cold mixtures have good performance at warm and hot temperatures [30, 73]. In addition to the gradation type, the size of the aggregates, which is affected by the depth of the pothole, plays a fundamental role in the design of the mixture [22]. For filling cracks and patching small potholes, cold mixtures with fine aggregates work better as they can be applied thinly and prevent raveling on the edges of the hole [14, 54]. Conversely, if the aggregate size is too small compared to the pothole depth, there is a considerable likelihood that the patch will displace or rut [32]. On the other hand, coarse aggregates are better suited for filling deep potholes as they produce more stability and durability [14, 54]. Large aggregates, however, may result in inadequate compaction, poor bonding at the edges of potholes [32], increased abrasion, and quick deterioration [41]. To attain high durability and stability, utilizing 12.5–19 mm coarse aggregates in stockpiled mixtures had previously been promoted. But to apply such a mixture successfully, a perfect patching technique involving saw cuts to produce a vertical and clean edge,

utilizing a tack coat, and appropriate patching material are required. Nevertheless, repairing potholes takes a lot of effort, and the best patching approach is rarely applied. Patches containing coarse aggregates are more prone to premature failure owing to raveling under traffic stresses. Otherwise, if fine aggregates, which offer more flexibility than coarse aggregates, are utilized in the mixture, the patch should be stable to a depth of less than 76 mm [67].

Mixtures containing finer gradations usually do not provide adequate workability. However, if they are made predominantly of single-size aggregates that mostly remain on the 1.18-mm sieve, curing and workability are improved. A cold mix consisting of fine gradation where 100% of the grains pass through 9.5 mm or 4.75 mm sieves produces a workable and pliable mixture that offers increased durability and flexibility over time [54]. Furthermore, using fine aggregates (with a maximum particle size of 11 mm) in cold patching mixtures allows them to be applied in thin layers within a range of 25 mm [4, 86]. The FHWA suggested crushed angular aggregates with sizes ranging from 2.38 mm to 12.7 mm as the ideal aggregate size to achieve the highest levels of workability and stability [66]. According to other studies, the aggregate utilized in CMPMs should not exceed a nominal size of 4 to 10 mm. In 1981, Kandhal and Mellott conducted a study on asphalt stockpile patching mixtures, which led to the gradation shown in Table 1.8 [67]. The recommended gradation for DIY cold patch mixes is reported in Table 1.8 of another FHWA study. Moreover, the mixture's dust content affects its performance, as unclean aggregates may exacerbate moisture damage [73]. An excessive amount of filler (particles that pass through the 0.075-mm sieve) makes the mixture brittle, less tacky, and less workable. For this reason, producers of cold patching materials use clean aggregates with a low percentage of dust (typically less than 1%) to improve the cohesive and adhesive characteristics of the material. In a study on CMPMs, Kandhal and Mellott recommended a dust content limit of 2% [67].

Table 1.8. Recommended aggregate gradations for CPAMs

Sieve size (mm)	Percent passing				
	[73]	[7]	[40]	(Specified) [67]	(preferred) [67]
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

Franklin and Prowell [7] somewhat altered the gradation suggested by Kandhal and Mellott and raised the content of coarse aggregates in their investigation of the 17 proprietary cold mixtures to improve stability. They increased the fine particles to 3% (Table 1.8). Also, Minnesota DOT limited the maximum fine to 3 percent, and the suggested gradation has been reported in the same table [40]. To obtain adequate mixture workability, a maximum of 1 to 2% of dust was proposed in a study by Anderson et al. [66] in 1986. Berlin and Hunt [30], however, set higher standards for dust content in their research. They recommended a value of less than 5% for dust particles in the mixture following six months of laboratory analysis and field assessments of multiple CMPMs. Other studies have recommended a similar dust content value (less than 5%) [45, 54].

1.3.2. Curing

Climate conditions, curing time, and curing rate have a remarkable impact on the performance of the CMPMs. Biswas et al. [43] came to this outcome during their study on cold mixtures in Canada. A rapid curing rate provides better stability and cohesion, while a slow curing rate enables the desired workability.

The curing rate is affected by numerous variables, including climate conditions (windy, rainy, temperature, etc.), binder quantity, binder type, binder grade, etc. Since each mixture's volatile evaporation rate varies and premature curing results in unworkability, the curing rate should be taken into account and managed based on the mixture's qualities. Furthermore, a longer curing time or higher temperature provides better stability than a shorter curing time at a lower temperature [73]. Thanaya et al.'s [59] findings in a study showed that, under fully curing circumstances, the stiffness of CMPMs and HMAs made with the same penetration grade binder is comparable. However, the full curing process is time-consuming. According to studies by Chevron Research Company, the time it takes for cold-mix asphalt to cure fully varies from 2 to 24 months, depending on the weather temperature. Usually, compacting materials at lower temperatures or for shorter periods of time produces unstable specimens [30]. Additionally, there are CMPMs on the market that, even after five or six months, do not achieve adequate stability. For these materials, the stability of the laboratory-made specimens is low even after compacting with higher pressure. Since the specimens collapse instantly after demolding, their demolding without long-term curing is almost impossible. Still, these low-quality materials are bought and utilized by 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 [94]. This procedure, however, reflects the patch condition after several months in service [86], whereas patch durability may be less than a few months, and the patch deteriorates quickly after patching. Consequently, evaluation of the mixture after long-term curing cannot indicate its performance after patch operation.

1.3.3. Performance evaluation

As was already established, patch failures frequently result from a lack of acceptable qualities. As a result, assessing the mixture qualities can assist in determining which kinds of materials deteriorate quickly and should not be used in treatment operations. The main factors that can lead to poor or good CMPM performance are workability, water susceptibility and stripping, stability and strength, adhesion and cohesion (bonding properties), and storageability. How these features work together and operate as a whole determines how durable the mixture will be [95, 96]. The only way to evaluate a material's qualities is through laboratory tests and protracted field research because there are so many materials on the market touting their superior performance [30]. Field evaluation is usually performed through visual evaluations by maintenance engineers. However, as described in the following sections, laboratory testing is more quantitative.

1.3.3.1. Workability

Workability is one of the main characteristics of a cold mixture, which makes it possible for the patching material to be easily handled, plied, and compacted during stockpiling and field placement [97]. The workability of CMPMs is more influential than their performance since they are utilized for temporary repairs [98]. According to earlier studies, the workability of cold mixtures can be affected by their main components, including aggregates and asphalt binders. Using rounded aggregates or uncrushed gravel in the mix design can improve the workability of the mixture. Mixtures with a maximum aggregate size larger than 12.7 mm or containing excess filler also negatively affect workability. Furthermore, the temperature during storage or application can impact the binder's viscosity and the mixture's workability [3, 73]. Poor mixture workability usually leads to insufficient compaction, decreased stability, and patch failure in

a short period. Therefore, to have a durable patch, factors that improve workability must be considered, as they may oppose stability [73, 77]. Table 1.9 summarizes the effects of aggregate and binder on the mixture's workability and patch durability [30].

Table 1.9. Aggregate and binder impact on patch workability and durability [30]

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

In their 1981 study, Kandhal and Mellott [7, 67] evaluated cold patching materials using a spatula. The results of the test, which involved dipping a spatula into the mixture, were classified as "good," "fair," and "poor." The research team also employed a cement-concrete penetrometer, known as the PTI method, to get quantitative results. The lower the workability, the more force is needed to penetrate the tool into the sample. The test failed to measure workability, and the results were inconsistent. The test may also be affected by the presence of large aggregate particles or the level of sample compaction. They proposed that perhaps using a mixer, like a Vane-Shear device, results in more precise outcomes. In a 2019 study [20], using a mixer to quantify the workability of cold mixtures was successful. The average torque measured in one minute was also employed as an index to assess workability. The higher the torque, the worse the workability. Marvillet and Bought originally suggested the concept of utilizing torque to measure workability in 1979 to evaluate the workability of

HMA. They achieved this by using the torque required to rotate the paddle inside the HMA sample [99].

In research by Prowell and Franklin [7], the PTI test resulted in similar results. No strong correlation between laboratory and field outcomes was obtained during their study of 14 different kinds of proprietary cold mixtures. However, Berline and Hunt [54] found a good correlation between field and lab data in their research in 2001. To assess the mixture's workability in 1986, Anderson et al. [66] employed the PennDOT subjective spatula method. They discovered that this method was unacceptable from the perspective of comparability, particularly inter-laboratory results. Therefore, they modified the PTI method by attaching a 9.5 mm by 75 mm extension to the penetrometer foot and assessed the workability of the mixture. The outcomes of the two approaches showed a good correlation. PTI and blade resistance test methods were employed in the SHRP H-106 comprehensive repair project of more than 1250 potholes to assess the mixture's workability in the lab and field. The Blade Resistance tool is similar to the PTI probe, but it uses a blade instead of the bullet-shaped connection in the probe. The findings demonstrated that the values produced by the blade resistance method were about five times greater than the values obtained by the PTI method due to the greater contact area of the blade with the sample. As a result, they discovered that the PTI method's narrow cross-section makes it appropriate for stiffer mixes. On the other hand, the blade resistance technique works well with soft patching materials. Since the workability of the mixture is the main issue when it stiffens, the PTI approach can produce more meaningful results [37]. In NJDOT studies, the blade resistance test delivered varying results for mixture workability. Therefore, this test was not recommended for future research [3]. In contrast to the NJDOT findings, a study by Liao et al. [78] found that the workability of the 24, 96, and 168-hour cured specimens at 25 °C showed a confident linear correlation with cure time. However, compared to the range

suggested in ASTM D 6704, the required resistance to penetration of the blade into the mixtures was minimal. The same PTI method was applied in 1995 by Estakhri and Button [28, 77] to evaluate the workability of patching materials. However, the results obtained from different mixtures did not demonstrate noticeable differences. To get more reasonable results, the PTI test method was modified twice by changing the box shape and the location of the hole on the box wall. The modifications led to some improvements over the previous PTI method; however, the results didn't show a good correlation with field workability evaluations. Afterward, they tried to measure the workability with a Texas gyratory compactor. The total number of mold gyrations required to reach a certain compaction pressure was utilized for this purpose. Again, no correlation between laboratory and field data was obtained. Triaxial and unconfined compression tests were employed to determine the material's workability because none of the earlier methods were effective. The Mohr circles and Mohr failure envelope-based approaches displayed a generally acceptable workability value. In addition to taking longer and requiring more expensive equipment than the other procedures, it also uses more materials [100].

In a study by Lesueur in 2002 [101], using the Nynas device for measuring the workability of cold mixtures was recommended. This study found that the Nynas device could differentiate the effects of many parameters, including water content, temperature, aggregate type, and binder content. The maximum shear force applied to the loose mixture was a measure of workability. In a different investigation, the workability of warm mix asphalt (WMA) was examined using the Nynas device and gyratory shear compactor (GSC). The GSC was not temperature-sensitive and produced identical findings, in contrast to the Nynas device, which led to data that could be quantified [102]. According to a study conducted by TxDOT, a substitute for measuring the workability of a cold mixture is the slope of the GSC compaction curves and the amount of work done

by the shear force during compaction (the area under the curve) [30]. Ferrotti et al. [103] considered these recommendations to assess the workability of high-performance fiber-reinforced cold mixtures. They used the intercept and slope of the regression compaction (void-number of gyrations) curves to analyze the air-void content and workability of mixtures, respectively. Additionally, TxDOT researchers attempted to develop a technique for determining workability by adapting the concept from the concrete slump test. The length of time needed for a cold mixture to slump under its own weight during an experiment known as the "cold patch slump test" (CPST) was considered a measure of workability. As a result, reduced slumping time translates into increased workability, and vice versa. A good linear correlation was found between the field and laboratory data after testing six proprietary CMPMs at three different cold temperature levels [30]. Abaffyová and Komačka [104] used the slump test to assess the storageability of the CMPMs, rather than their workability. Through their research, the cold mixture 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 [105] determined the locking point and evaluated the workability of the mixture using densification curves of compacted HMA. The locking point is the number of gyrations after which, after three continuous gyrations, no noticeable changes in the height of the samples are detected. In the research, lower than 30 and more than 70 gyrations were considered easy-to-compact and hard-to-compact mixtures, respectively. In other studies, the cold mix workability was evaluated using this method, and the locking point of the mixtures was obtained below 100 gyrations [106, 107].

Table 1.10. 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)	[7, 67]
	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	[20]
Anderson et al	Modified PTI method (changing the bullet-shaped connection of the probe)	Maximum penetration force	[66]
SHRP (H-106)	Using a blade to penetrate into the mix	Maximum penetration force	[37]
Estakhri and Button	Modified PTI method (changing the box)	Maximum penetration force	[28, 77]
	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	[101, 102]
TxDOT	Using a Gyratory Compactor to compact the mixture	The slope and the area under the compaction curve	[30, 103]
TxDOT	Cold Patch Slump Test (CPST)	Required time for a cold mixture to slump under its own weight	[30]
Hemsley	Using a Gyratory Compactor to compact the mixture	Locking point of the mixture during the compaction	[105, 107]
Bahia et al.	Using a Gyratory Compactor to compact the mixture	Energy required to compact the loose mixture (Energy index)	[108]

Additionally, in another investigation, the workability and compactibility of the mixtures were assessed using the area under the compaction curves. The following energy indices (Eqs. (1.1) and (1.2)) that measure the mixture's workability were introduced as a result of the energy necessary to compact the loose materials to 92% density (equivalent to an 8% air void in the target mixture) [108].

$$\text{Volumetric Energy index from intercept to 92\% } G_{mm} \cdot EI_{(92\%)} = P \times \frac{\pi d^2}{4} \times \sum_{N=1}^{N_{92}} \Delta h \quad (1.1)$$

$$\text{Workability Energy index from intercept to 92\% } G_{mm}: WEI = \frac{EI_{(92\%)}}{N_{92}} \quad (1.2)$$

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 Eqs. (1.1) and (1.2), when a mixture is hard and has low workability, more energy is needed to compact it. On the other hand, an increase in the number of gyrations indicates a lower WEI, and vice versa. Table 1.10 summarizes the methods used for measuring the workability of CMPMs.

1.3.3.2. Adhesion and cohesion characteristics

CMPMs should provide adequate cohesion and adhesion to prevent patch failure. Cohesion is the feature that makes the mixture components stick together and work well together, while adhesion improves the stickiness of the patch to the surface of the existing pavement [109]. The patch will prematurely fail due to the weakness of each of these characteristics, particularly if the pothole is not dried up and not prepared for repair before patching [97]. Initial patch stickiness is usually low and increases over time. Applying a bond coat to the inner and surrounding areas of the hole is advised to achieve adequate bonding between the patching material and the pothole [110]. This bond coat, which is usually a cationic emulsion containing at least 60% asphalt binder, prevents future water seepage and patch debonding [64, 111]. The literature suggested preheating the

pothole and heating the mixture to extend the endurance of the repair and prevent the patch from debonding. Numerous methods utilizing infrared heat [112, 113], radiant heat [49], and high-frequency electromagnetic fields for mixtures containing fibers have been investigated in many research studies to accomplish this goal [36, 56]. The Indiana State DOT found that heated patches outlasted unheated ones in a trial of 324 fixed potholes using heated and unheated mixes [114].

According to earlier research, a tack coat is required to repair potholes and will increase patch longevity. It also increases crack resistance [115]. However, CMPMs should have self-tacking capabilities to eliminate the requirement for a tack coat. In 1998, Anderson et al. [66] conducted an experiment to evaluate the bonding quality. The self-tacking feature was assessed using the maximal shear force necessary to initiate bond breakdown at the interface between the base and the compacted cold patch. The findings of the tests conducted in both dry and rainy environments lacked validity and reliability.

The Leutner shear test apparatus has been used in numerous studies to evaluate the bonding properties at the interface layers. By applying a vertical load over the reinforced interface layer, Lee et al. [116] discovered that a rough surface enhanced bonding, but the temperature rise (in this example, from 25 °C to 60 °C) harmed the bond feature. Sudarsanan et al. [117] also investigated the bonding strength across the interface layer at various temperatures using the same method. Additionally, similar effects of temperature on the bonding characteristics were discovered by Collop et al. [118], West et al. [119], and Bae et al [119, 120].

In addition, the inclined shear test was performed to mimic the effect of vertical and horizontal loads (vehicle tire and braking loads) on the interlayer bonding strength of the composite asphalt. The results showed that the interface layer requires the use of a sticky substance. Also, the thickness of the tacky coat,

temperature, and freeze-thaw cycles affect the interface shear strength [121]. The study by Chen et al. [122] on the HMA and cold patching materials' bonding strengths yielded similar outcomes. High temperatures and humidity deteriorate the bonding properties at the interface layer. As a result, the interface shear resistance decreased by 98.6% as the temperatures rose from -5 to 55 °C. Additionally, their findings indicated that the surface roughness and type of tacky substance had the most influence on the interface bonding. Virginia DOT employed a different technique to evaluate how sticky the mixture was. Through this procedure, the oven-aged (4 hours at 60 °C) CMPM is compacted on the HMA specimen and inverted (Fig. 1.9), and the amount of time needed for their debonding is taken into account to determine 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 [31, 43]. Less than 5 seconds may point out excessive binder content. Longer than 30 seconds could indicate a low- 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 [7].



Figure 1.9. Adhesion test on the inverted complex specimen

The maximum diametric load applied to a complex briquette made of half cold mix and half HMA (Fig. 1.10) was used in a study at the University of Minnesota to evaluate the bonding qualities [45, 123].

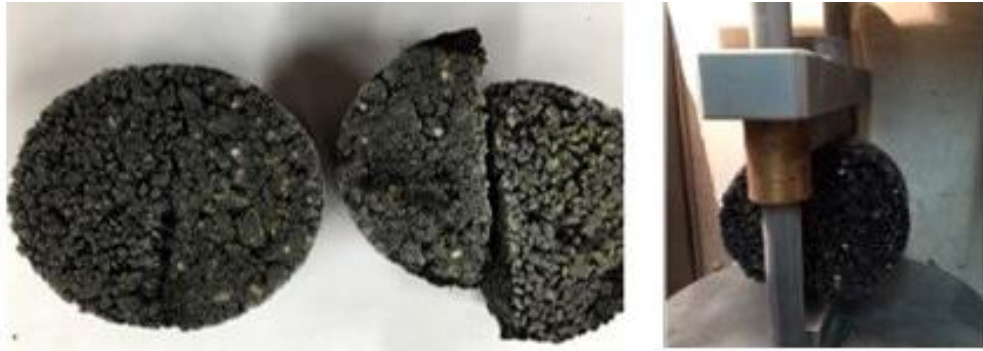


Figure 1.10. Interface shear strength test by applying a diametric load [45]

The stickiness characteristics of CMPMs have also been evaluated in the literature using the modified Cantabro test. The Los Angeles machine rotates the Marshall briquette 100 gyrations, and the mass lost during abrasion is used to calculate the stickiness index [88]. Another study conducted by Ferrotti et al. [103] in 2014 used a similar methodology. However, rather than 100 gyrations, the cold mix specimens were subjected to 300 gyrations. The Cantabro test was also employed to evaluate the cold mixtures' susceptibility to raveling and moisture susceptibility. Bi et al. studied the raveling characteristics of a waterborne epoxy-emulsified asphalt mixture in 2020 [124]. Additionally, the mass loss difference between the abraded wet specimens and dry specimens showed the moisture susceptibility of the cold patching materials [96].

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 capping sieve for 20 seconds. The remaining weight of the sample after rolling compared to its initial weight is calculated to determine the mixture's cohesiveness, which should be more than 60% [26, 43, 54]. According to the MTO report, a loss of more than 35% is

unacceptable [94]. Although this test does not guarantee the success of a mixture, it does indicate the possibility of poor performance [5, 30].

1.3.3.3. Water sensitivity

Water sensitivity generally, called "stripping," is one of the main concerns of asphalt pavements. This issue can occur in various forms, such as loss of binder-aggregate bonding, cohesion failures within the aggregates, binder emulsification, and freeze-thaw cycles due to trapped water [125]. Moisture affects the interactions between the aggregate and the binder in CMPMs, leading to bond failure, which is the main problem with cold patches [58]. Therefore, to reduce 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 noted [45].

Cold patch compatibility and moisture susceptibility were investigated using techniques comparable to those previously used to assess HMA. Thomas and Anderson [69] used a subjective evaluation to estimate the mixture's water sensitivity. The percentage of aggregates coated with a binder in a mixture was considered an indicator of water sensitivity; the minimum allowable value was set at 90%. Ling et al. [106] used digital image analysis to reduce visual errors in coating evaluation to assess the impact of aggregate coating on the moisture susceptibility of CMPMs. The findings showed that the aggregate coating degree predicted by the quantitative models has a remarkable effect on the moisture susceptibility of CMPMs. In 1993, SHRP [27] employed another visual evaluation technique. In that investigation, 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 contents of the container (water and the mixture) were agitated for 5 seconds before being drained. The coating percentage of aggregates must be at least 90% to be accepted [125]. Following ASTM and

Indian Roads Congress guidelines, 5% is the maximum allowable stripping value [94]. Kandhal and Mellott [67] 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. They decanted the water and then spread the wet mixture for evaluating coatings onto absorbent paper. At least 90% of the aggregate should be coated with the asphalt binder film.

The TxDOT and other researchers measured moisture sensitivity using a boiling-water test. In this method, the mixture is boiled for ten minutes in a container. After draining the sample, a coating degree of at least 90% is required [28, 54]. The findings of the Virginia Transportation Research Council study showed that the boiling water method had a better ability to spot variations in stripping results than the immersion method [7]. Tam and Lynch [126] reported similar outcomes. They argued that the 10-minute boiling water test is an extreme and quick procedure that does not accurately represent the field stripping circumstances in the lab. In another study, Lavorato et al. [93] assessed mixture stripping using a less severe method described in the MTO standard (MTO OPSS 307). The mixture is placed in boiling water and stirred with a rod for three minutes at a pace of one turn per second. The minimum acceptable aggregate coating was set at 75%, in contrast to other test techniques. The mass loss of the cold mixture after being subjected to boiling water was also considered an indicator of stripping and mixture water damage. However, the mass loss values were negligible compared to the sample weight, and the test results in the research were highly inconsistent [106, 127, 128].

TxDOT used the modified Lottman method in addition to the previously indicated techniques to quantify the moisture damage. In contrast to earlier test techniques, this procedure was conducted on compacted specimens, and the tensile strength ratio of two sets of specimens (moisture-conditioned and unconditioned) determined the water susceptibility of the mixture. The TxDOT

study's findings demonstrated that the modified Lottman approach is less logical than subjective judgment using a boiling water test to determine the stripping potential [52, 60]. However, the stripping potential of CMPMs during freeze-thaw conditions has been widely measured in other research using the Lottman method [43, 88, 129]. The binder bond strength (BBS) test, in addition to the Lottman method, has been used in other studies to evaluate the relationship between mixture water damage and coating level. Ling et al. [128] 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 for them, and the bonding loss ratio (BLR) was defined as a measure of moisture susceptibility in Eq. (1.3). The findings of the tests conducted on limestone aggregate and emulsion were comparable to those of the modified boiling test with image processing. This test method was also used to assess the water sensitivity of emulsion-aggregate and mastic-aggregate systems after 2 hours and 24 hours of water conditioning.

$$BLR = 1 - \frac{POTS_{wet}}{POTS_{dry}} \quad (1.3)$$

In other studies, the Marshall stability ratio (MSR), which is the ratio of the Marshall stability values of water-damaged to the Marshall stability of cured specimens (Eq. 1.4), was defined to measure the moisture sensitivity of cold mixtures. Higher values of MSR represent lower moisture susceptibility [87, 96].

$$MSR = \frac{MS_{wet}}{MS_{dry}} \times 100 \quad (1.4)$$

Researchers defined the Moisture Index (MI) (Eq. (1.5)) to represent the moisture damage resistance of open-graded CMPMs, as the moisture sensitivity of CMPMs is related to gradation proportion. The MI is the ratio of the aggregates remaining on sieve no. 4 ($P_{\#4}$) to the aggregates still present on sieve no. 50 ($P_{\#50}$). Consequently, higher mixed porosity, higher water seepage, and more water damage are determined by higher MI values [96].

$$MI = \frac{P_{\#4}}{P_{\#50}} \quad (1.5)$$

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.'s [92] research on cold mix materials containing RAP proved that employing RAP in the mix design improved the mixture's resistance to abrasion loss. Also, even though the Hamburg Wheel Tracking Device (HWTDD) is a severe procedure for cold mixtures, it has been used in wet conditions to measure the water damage of CMPMs [27]. Table 1.11 shows the summary of methods used for measuring the water sensitivity of CMPMs.

Table 1.11. 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	[67, 69]
Omar et al.	Static immersion		[26, 125]
Manolis et al.	Boiling water test		[54, 93]
Ling et al.	Digital imaging analysis	Level of aggregate coating	[106]
Ling et al.	Boiling water test	Mass loss	[127, 128]
Dong et al.	Modified Lottman method	Tensile Strength Ratio (TSR)	[52, 88]
Ling et al.	Binder Bond Strength (BBS)	Bonding Loss Ratio (BLR)	[128]
Wang et al.	Marshall stability	Marshall stability ratio of water-damaged to the cured samples	[87, 96]
Huang et al.	Moisture Index= P(#4)/P(#50)	Mixture porosity	[96]
Kwon et al.	Wet track abrasion test	Abrasion loss	[92]
Smith et al.	Hamburg wheel tracking device	Rut depth	[27]

Finally, as CMPMs are typically applied during the cold and wet seasons, they should be able to survive adverse weather conditions and traffic loads that cause debonding, dislodging, and patch failure [97]. For this reason, antistripping additives such as Portland cement, flue dust, hydrated lime, fly ash, etc., should be added to the cold mix to minimize moisture damage throughout the stockpile, practice, and in-service [52, 73, 95].

1.3.3.4. Stability and initial strength

Stability is one of the main characteristics of patch materials because it provides sufficient ability to resist vertical and horizontal displacement of the patch under traffic [3, 43]. This property is particularly noticeable immediately following a patching operation when the repaired pothole is more sensitive to the traffic flow. The patched area after compaction should be stable enough to prevent rutting and shoving caused by vehicles [30]. Aggregate gradation and compaction level are the main factors in achieving this early performance criterion. Yet, the long-term performance of the patch is related to its stability after traffic compaction [124, 129]. Therefore, different factors that affect the stability of the mixture, such as aggregate gradation and compaction level, binder quality and quantity, and curing rate, should be taken into consideration [43, 130]. Additionally, since excessive stability usually results in low workability, precautions should be considered to strike a balance between the stability and workability of the mixture. An acceptable stability level is obtained gradually by curing the mixture, but 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 [51, 54, 98]. Although the technical literature lacks any standardized test methods for evaluating CMPM stability [66], indirect tensile strength (ITS), Marshall stability (MS), and resilient

modulus (RM) protocols are frequently used to do so [28, 78]. Despite the mentioned experiments, a few ground-breaking techniques are utilized to evaluate the stability of the cold repair mixtures, including the screwdriver penetration test and steering wheel rotation using a passenger automobile. Although these tests result in useful information, the lack of standardized methods makes it difficult to evaluate the potential performance of CMPMs [98]. As most experiments have been designed to assess the performance of HMA, the researchers considered an initial aging procedure to provide specimens with enough stability. The specimens made without the curing and aging processes usually collapse as soon as they are demolded and during the test [131]. Manolis et al. [93] could not evaluate the compacted specimen's bulk density during the evaluation of the performance of CMPMs since it had collapsed upon demolding. A similar occurrence was observed in Marin's study [132] on different types of CMPMs, although the samples were confined during curing to prevent them from collapsing before the test. Furthermore, according to another investigation, the gyratory-compacted specimens remained unstable even after 96 hours of curing at 25 °C [30]. Anderson et al. [66] tested the stability of the cold mixtures by applying haversine stress via a steel foot to a cylindrically aged specimen. After 1000 cycles, the experiment's results revealed minimal plastic deformation. Plus, the test could not accurately imitate the traffic load and was time-consuming. Consequently, the research team believed that the test was not worth further development. Oven-aged specimens were subjected to RM and MS tests as part of the SHRP project to assess CMPM stability. The test, however, was an indication of in-place or utilized materials after several months of traffic [37]. Maher et al. [3] used the mentioned methods to evaluate the stability of various CMPMs. The study's findings demonstrated that there was no relationship between the IDT test results and field performance. The outcomes of the MS and RM test procedures also revealed a similar conclusion. The

authors concluded that the result is questionable if the RM technique is used to assess CMPMs. Shoenberger et al. [86] selected MS and triaxial compression (confined and unconfined) experiments for different research work. The outcomes of the axial strain in the triaxial test for various mixes were comparable. Also, the research team did not find the MS test a credible indicator for the performance evaluation of CMPM due to its unsuitability for open-graded mixtures. Limited use of the Hveem stabilometer has been reported in the literature to measure the stability of the cold mix [66]. Additionally, research at the University of Minnesota on a standard cold mixture (CCM), one type of proprietary cold patch (QPR brand), and HMA revealed weak MS for the QPR mixture both before and after curing. However, the CCM demonstrated comparable stability to HMA after curing, despite having poor stability before curing [45, 123]. The MS of the unmodified CMA is much lower than that of HMA and WMA, according to the literature [58].

Weimin et al. obtained initial mix stability of not less than 2.0 kN and 1.5 kN at room and low temperatures, respectively, by the MS evaluation of the CMPM. In a similar study by Jiguo, these values were obtained at 2.0 kN and 1.0 kN, respectively. For initial MS and the seventh-day stability after opening to traffic, the Japan Modified Asphalt Association standard mandates a minimum of 0.5-0.8 kN and 3.0 kN, respectively [2]. In other studies, the minimum initial MS for CMPMs before opening to traffic was suggested to be at least 2.5 kN [133]. However, for some kinds of cold mixtures, it takes up to 10 days to reach 3 kN of stability [82, 90]. The MS values for dense-graded and open-graded mixtures in a comparative investigation of untreated cold and hot mix samples were 5.88 kN and 3.44 kN, respectively, while these values were 11.48 kN and 10.71 kN for asphalt concrete and stone matrix asphalt [124, 134]. In separate research, the stability of open-graded and dense-graded cold patching mixtures with modified asphalt cement was assessed using the MS test. Before performing

experiments at 40 °C, ambient curing (24 h at 25 °C) and rapid curing (24 h at 110 °C) processes were taken into consideration. As expected, the results showed that the dense-graded CMPM had higher stability values than the open-graded one.

Additionally, for further confirmation, the wheel track test was performed in both wet and dry situations on aged and non-aged specimens. They discovered that moisture intensified the specimen deformation; however, it provided more accurate results for predicting rut depth, especially in wet weather conditions. Furthermore, they concluded that the stability and rutting resistance of the CMPMs with high viscosity (130 poise) modified binders were comparable to those of HMA [78]. Also, Biswas et al. [43] found similar outcomes in a study on dense-graded and open-graded cold mixtures that had been cured at 65 °C and 135 °C for 14 to 18 h. The authors found that the stability of dense-graded specimens cured at 135 °C is comparable to HMA. Rezaei et al. [74] conducted a similar investigation to evaluate the stability and rutting resistance performance of CMPM in both dry and wet circumstances. The findings demonstrated that the HWTD was a particularly severe test for CMPMs at ambient temperature curing because the specimens had little resistance to permanent deformation. However, the research team discovered that HWTD is an appropriate test method to assess the stability of CMPMs under conditions of accelerated cure (135 °C for 18 h). Additionally, they asserted that the MS test is an effective way to determine the stability of CMPMs. In the investigation of Chatterjee et al. [30], HWTD was also used to assess the stability of CMPM. Due to the harsh impact of HWTD on uncured specimens, the test was performed on 96-hour-cured samples that were compacted at 100 °C. The results revealed that rutting resistance increased with extended curing times. Visser et al. [129] used the same test to evaluate the CMPMs' rut resistance. Although the materials were tested and compacted at various temperatures, the authors did not believe

that HWTB was a suitable test method for forecasting rut depth in the field. Even though the long curing time and compacting of the samples at high temperatures provide stable specimens before testing by HWTB, it significantly alters the mixture's properties [93, 101]. To address this issue, the Texas Stability Test (TST) was developed to evaluate the stability of cold mixtures. The specimens were compacted using the Texas Gyrotory Compactor (TGC) and cured at room temperature for 0, 1, and 2 weeks before 2-day conditioning and testing. The maximum compressive load was employed as a CPM stability indicator after the MS test on the specimens. The research team also used an MMLS3 to evaluate the cold mixture's stability under Accelerated Pavement Testing (APT) settings [101]. Dong et al. [31] evaluated the CPM's resistance to deformation in a study using the Asphalt Pavement Analyzer (APA). According to their analysis of the two types of patches, even though the cold dump materials performed better than the proprietary cold patches after being cured for 96 hours and compacted at 100 °C, their rut depth was incredibly high during low load cycles. Kwon et al. [92] used the APA and Marshall devices to evaluate the stability and performance of cold mixtures containing RAP and virgin aggregates. Their investigation revealed better stability for mixtures containing RAP materials.

In a study by Diaz [98] in 2016, the Modified Cyclic Creep Test (MCCT) and Light Cone Penetrometer (LCP) were used to examine the CPMs' permanent deformation. The data were analyzed using multiple linear regression analysis (MLRA), which produced two prediction equations for estimating the parameters of MCCT as a function of rutting performance with an LCP. According to the findings, to ensure the minimum required initial stability of the cold patch, the LCP can be used to estimate the cold mixture's operational compactibility. In addition, Haipeng et al. [82] used a penetration shear test to mimic patch deformation under vehicle stresses. The deformation resistance is

low at higher temperatures, as shown by the test results of oven-cured Marshall briquettes at various temperatures (Fig. 1.11. a). A similar test, the California Bearing Ratio (CBR), was also used in another study to evaluate the CMPM's short-term premature deformation (Fig. 1.11. b). The findings showed that the CBR index is affected by the stone skeleton and aggregate gradation of the mixtures [109].

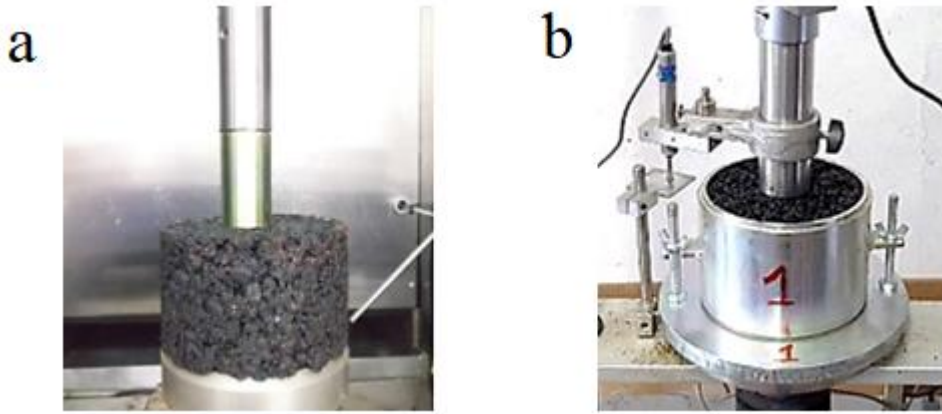


Figure 1.11. a) Conducting penetration shear test [82] b) CBR test on cold patch mix [109]

As mentioned, adequate patch compaction is essential to improve patch stability and prevent premature failure due to deformation under traffic [63]. The area under the compaction curves has been used in the literature to assess the stability of patch materials. The following equations, Eqs. (1.7) and (1.8), were provided for the evaluation of mix stability like the equations given in Section 6.1 [108]:

$$\text{Shear Energy index (EI) from 92\% to 96\% } G_{mm}: EI_{(92-96)} = P \times \frac{\pi d^2}{4} \times \sum_{N_{92}}^{N_{96}} \Delta h \quad (1.7)$$

$$\text{Compactibility Energy Index from 92\% to 96\% } G_{mm}: CEI = \frac{EI_{(92-96)}}{N_{92-96}} \quad (2.8)$$

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 an 8–4% air void in the target mixture) are related to the shear strength of the mix. CEI is the energy needed to compact the mixture to reach a density of 92 to 96%. Mixtures with lower CEI values provide more durability and will be more stable during service life under traffic loads [108].

By using the air void (AV) corresponding to the design number of gyrations (N_{design}) and the linear compaction slope (K), Anderson et al. [135] established another index to measure the HMA stability.

According to the Eq. (1.9), greater stability and rutting resistance are achieved by the higher values of $K \times AV$.

$$S = K \times AV \quad (1.9)$$

The literature has mentioned a maximum of 0.5 and a minimum of 20 for CEI and S, respectively [108].

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's stability [40]. Table 1.12 shows the summary of different methods used for evaluating the stability of CMPMs.

Table 1.12. 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	[40]
	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	[66]
Jain et al.	Marshall stability, Resilient modulus and Indirect tensile strength tests	Compressive strength, Resilient modulus, and Tensile strength	[2, 45, 86, 123]
Shoenberger et al.	Triaxial compression test	Compressive strength	[86]
Anderson et al.	Hveem stabilometer	Degree of plasticity	[66]
Liao et al. Rezaei et al. Visser et al.	Wheel tracking test	Rutting resistance	[30, 74, 78, 129]
Eckmann et al.	Texas stability test	Maximum compressive load	[73, 101]
	Model mobile load simulator	Resistance to deformation	
Kwon et al.	Asphalt Pavement Analyzer	Rutting resistance	[31, 92]
Wang et al.	Penetration shear test	Penetration load	[82]
Riviera et al.	California Bearing Ratio (CBR)	Resistance to applied load	[109]
Bahia et al.	Shear and compactibility energy indices	Energy needed to compact the mixture	[108]
Anderson et al.	Stability index	Compaction curve slope (K) and the air void (AV) corresponding to the design number of gyration (N_{design}).	[135]

1.3.3.5. Storageability

Both stockpiled and containerized CMPMs need to remain workable and resist stripping and binder draindown while being stored. Therefore, this feature,

known as storageability, which 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 [59, 70, 97]. The improper type and content of the mix component can reduce or extend the storageability of the mixture. A mix with too much binder provides a thicker film to coat the aggregates, improving durability and stickiness [67]. 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 issues during stockpiling, while a higher viscosity or rapid volatilization of the diluent leads to poor workability [70]. Additionally, aggregates with higher water absorption lead to stripping and draindown problems during the stockpile. The mixing temperature should be kept as low as possible to prevent binder draindown in the stockpile [91]. Also, storing at a depth of lower than 0.6 meters facilitates the cooling process and minimizes draindown [66, 69]. In addition, covering the stockpile with polyethylene or a tarpaulin sheet can help to increase the storage time. The FHWA and AASHTO test methods have been frequently used in previous studies to assess the CPM 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 remaining binder on the plate indicates binder drainage and shouldn't be more than 4% of the total mass of the binder [26]. However, in research by Prowell and Franklin [7], the draindown of the best-performing mixtures was between 4 and 8 percent. They concluded that the 4% cap might be too strict and suggested an upper limit of 8%. The drainage test findings may also be a little erroneous for the reasons listed below, according to Anderson et al [66].

First, it is difficult to remove all the particles from the plate after 24 hours of aging at 60 °C. Second, in mixtures that include a low amount of binder, the

draindown occurs where the mixture is in contact with the plate. MTO modified the AASHTO test procedure for calculating the draindown materials of uncompacted asphalt mixtures to assess the draindown of CMPMs. In this experiment, a predetermined quantity of the mixture is put in a wire basket and conditioned for one hour in a forced-draft oven. Then, the weight difference between the mixture before and after the conditioning process is calculated and reported as the drained binder of the mixture [93].

1.4. Conclusion

In this chapter, different aspects of CMPMs for repairing potholes were overviewed. The benefits and drawbacks of patching potholes with CMPMs, repair techniques, effects of mixture components on the performance of the patch, and cost, curing, and storageability of these mixtures were investigated. Additionally, as poor workability in cold weather and poor stability, especially in deep potholes, and bonding and moisture susceptibility influence the longevity and performance of repaired potholes with CMPMs, several methods for evaluating these properties were thoroughly reviewed. The following is a succinct summary of the main findings:

- The purpose of repairing potholes with CMPMs is to provide traffic safety by restoring serviceability, not to make a permanent repair. Therefore, these materials are applied in emergencies as a temporary treatment until proper and durable practice is carried out. However, it is not unusual for some road administrations to use these materials with a desire for a more permanent solution.
- Although traditional patching techniques using vertical saw cuts to fill potholes provide more durable patches, they take longer and cause traffic delays. Road administrators, therefore, consider CMPMs that do not require special equipment and considerations to fill potholes.

- Aggregates and binders play a significant role in the workability and stability of the CMPMs. Thus, additional consideration should be given to the aggregate shape, gradation, water absorption, 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. To provide optimal stability and establish traffic flow in the patched region, the CMPM should be cured as fast as possible after placement. 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 temporarily repaired patch with proprietary CMPMs is up to one year. However, the patch's longevity is still considered to be days or months instead of years.
- The main costs associated with pothole patching are supplies, labor, and equipment. Usually, the highest expenditure is devoted to crew and equipment, and the cost of materials is just a tiny portion of the total patching costs. CMPMs contribute 20% of the total 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 have a longer service life, even if they cost more. Because high-quality materials offset the cost of repeated repairs made with poor-quality materials, the cost of high-quality materials with a good repair process is much less than the cost of frequent patching operations. Therefore, using expensive materials with extended longevity leads to significant cost savings in the long run. 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 determine 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.
- Initial patch bonding is often low and gradually rises. Applying a bond layer within and around the hole is advised to achieve appropriate bonding between the repairing material and the pothole. However, CMPMs should have self-tacking properties to eliminate the need for 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.
- The samples are typically aged and cured in the oven to give enough stability to the specimens before evaluating the performance and durability of CMPMs. The patch endurance may be less than a few months, and the patch deteriorates quickly after patching, even though this technique reflects the patch status after several months of use. As a result, the evaluation of the CMPMs after long-term curing cannot indicate their performance immediately after patching. After long-term curing, the mixture may produce satisfactory results, but after a repair operation, the patch distresses instantly under traffic and weather conditions. A comprehensive standard is required to design and evaluate the performance of CMPMs.

To sum up, CMPMs are being developed quickly as viable alternatives to HMA for filling potholes. However, there are still some limitations and issues related to their mix design and performance assessment. Most of the testing procedures

are borrowed from HMA, but they do not always meet the requirements of CMPMs. Moreover, there is a conflict between the mechanical performance required in the field and the simplicity of compaction and application necessary for road maintenance operators. Additionally, most mechanical tests use Marshall briquettes, which are thick specimens requiring extended curing times and unstable after demolding. Patching operations, on the other hand, are carried out in thinner layers with quick curing and traffic reopening. Therefore, it is crucial to develop new techniques and methods to evaluate the performance of these materials. It is hoped that researchers, producers, and operators will collaborate to create durable and superior materials, and establish quality control and assurance measures.

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Chapter 2

Performance-related methods for evaluating the characteristics of cold patching materials

2.1. Introduction

Cold mix patching materials (CMPMs) are commonly used as an alternative to hot mix asphalt (HMA) to repair road pavement potholes, especially in the cold and wet seasons [1, 2]. Although these affordable products have a short application time and less environmental impact, they show relatively poor mechanical and functional performance in the field [3]. The performance and durability of the repaired potholes with CMPMs are strongly impacted by the type of CMPM and its characteristics (workability, curing, storageability, adhesion, and cohesion properties), weather conditions, material quality, storage condition, pothole preparation and repair method, and loading [4, 5]. If the pothole is cleared of debris and water and is repaired with high effort by a highly skilled workforce using high-quality material, it will last longer. However, this ideal procedure is barely applied to patch potholes. Repaired potholes with CMPMs often suffer from several defects and drawbacks, such as raveling, water sensitivity, poor bonding, workability, and stability [6, 7].

Although several failure mechanisms of CMPMs can be encountered, there are no accepted test methods in the literature to evaluate the characteristics and features of these materials, thereby determining their quality [8, 9]. Currently, the commercially available products are qualified based on certain performance indicators derived from traditional HMA practices (i.e., density and Marshall stability requirements). However, these requirements are not representative of

the various service life stages of CMPMs, which range from improving workability at the placement phase to increasing resistance to early traffic and maintaining good adhesion and mechanical strength after compaction [10]. Therefore, specific laboratory tests and new configurations were proposed to provide a tool for advanced technical analysis of the expected performance of CMPMs in practice and better-specialized production for different climates and usage conditions. Modified versions, adapted to the specific nature of CMPMs, of well-known methodologies in the road construction context as well as original procedures have been considered to achieve this purpose.

To observe the performance of test methods and approaches on CMPM, three different types of patching materials were considered, including solvent containing mixtures (SC), membrane-containing mixtures (MC), and water-reactive mixtures (WR). These materials belong to the main categories of CMPMs available on the market, which are categorized by their components, price, and quality.

2.2. Selected materials

Three commercially available products (referred to as SC1, MC1, and WR1), belonging to each of the mentioned categories were selected. Although each product uses a proprietary formulation, some distinctive characteristics can be pointed out. Specifically, the SC material is a mix of aged binder (recovered from RAP aggregates), aggregates (virgin plus RAP aggregates), solvents, and a blend of additives. This type of patching material is the cheapest and lowest-quality product used in the market, but it is widely purchased and used by road maintenance organizations due to its low price. In addition to virgin aggregates, RAP, and additives, the MC product also contains RAS in the mix design. The production and use of this kind of mixture, which has a fair price and almost medium-to-high quality, have grown significantly in recent years. The WR

product contains a special proprietary binder and a blend of additives that ensure rapid hardening of the mixture through a chemical reaction when exposed to water. This type of CMPM often costs more than comparable products but also offers a high-quality patch. WR mixes are packaged in a sealed bucket since they are sensitive to moisture and harden more quickly when in contact with water. The ignition test method (EN 12697-39) was used for the evaluation of mixture composition. Firstly, the binder content of mixtures, expressed as a percentage of the mass of the aggregates, was assessed by ignition; then, the remaining aggregates were used for determining their gradation. Plus, the theoretical maximum density (ρ_m) of the mixtures was obtained according to EN 12697-5. Table 2.1 contains the numerical values of the three parameters for the analyzed products.

Table 2.1. Aggregate gradation of the selected CMPMs

	Sieve size [mm]									ρ_m [g/cm ³]	Binder content [%]
	10.0	8.0	6.3	4.0	2.0	1.0	0.5	0.25	0.063		
	Cumulative passing [%]										
SC1	99.8	99.7	95.3	50.0	19.3	12.0	9.15	7.9	6.4	2.57	4.78
MC1	99.8	99.6	97.6	64.0	24.4	15.8	11.86	8.9	6.2	2.64	6.62
WR1	100.0	99.0	91.8	64.6	36.6	20.2	11.01	7.4	3.4	2.41	6.71

2.3. Methodology

The performance of the proposed methods and procedures was explored by conducting tests on specimens prepared with CMPMs. The mixtures were compacted using a Marshall hammer and a Superpave gyratory compactor (SGC). To assess the mechanical parameters of cold mixtures, researchers usually consider a preliminary aging process to provide enough stability to the specimens and prevent them from collapsing after demolding. However, this aging and curing process does not show the behavior of the CMPMs right after application practices. Therefore, a series of tests and new settings, which will be

detailed in Section 2.3.2, has been proposed to study different physical-mechanical characteristics of the non-aged CMPMs. Specifically, procedures for the assessment of mix workability, stability, raveling, and bonding were selected and adopted.

Therefore, the workability and compactability of the mixes were evaluated using the locking point and density that were determined during the specimen preparation phase. Marshall stability and ITS test methods were employed to assess the stability of non-aged CMPMs to obtain more realistic results. These tests were conducted following the guidelines outlined in EN 12697-34 and EN 12697-23. To address the collapsing issues of briquette specimens after demolding, the modified Hubbard-Field stability test method—which enables testing stability of various CMPMs at reduced thicknesses—was presented. An indentation stability test was also suggested to assess the stability of CMPMs under static weights and localized stress. The objective of this test procedure was to assess the specimens in surrounded condition that was representative of what the patch would encounter in the field by the pothole edges. A brush test was preferred to simulate the raveling properties of the CMPMs under the vehicle wheels. Finally, the bonding characteristics of the CMPMs were assessed using the Leutner shear bond test.

2.3.1. specimen preparation

The compaction of the CMPM in patching potholes is almost an essential part of the repair operation, which is usually performed manually by the road maintenance crew. As a result, the attained density can vary depending on each person's effort and the dimensions of the pothole. Cylindrical specimens with a diameter (D) of 100 mm and a nominal height of 65 ± 5 mm (thick) or 35 ± 5 mm (thin) were prepared using a Marshall hammer and an SGC. Three sets of blows per side, i.e., 35, 50, and 75, were selected to compact mixtures with a Marshall

hammer. For gyratory compaction, the selected pressures were 200 to 600 kPa, whereas the gyrations were set to 100 and 200.

Acronyms (e.g., WR_M75t) were used to label each mixture: the first pair of letters describe the material type (SC, MC, or WR), the letter after the underscore symbol defines the compaction procedure (M = Marshall hammer and G = Superpave Gyratory compactor), the numbers refer to the compaction effort (XX = number of blows for Marshall Hammer; Y&Z = compaction pressure in kPa/100 and gyrations in number/100 for the Superpave Gyratory compactor), and the last letter identifies the specimen height (T = 65 mm; t = 30 mm). The label WR_G2&1T, for example, denotes a specimen of the water-reactive material, which was compacted with the Superpave gyratory compactor at a pressure of 200 kPa for 100 gyrations, yielding a final height of 65 ± 5 mm.

2.3.2. Test methods

Briquette specimens were made using a Marshall hammer or an SGC and tested after different curing times and conditions to observe the performance of test methods on CMPMs. Each time, the compaction quantities (pressure and the number of blows and gyrations) were selected based on the material characteristics and the performance test method. The specimens were cured for up to 30 days in a laboratory setting (temperature $T = 22\pm 2$ °C; relative humidity $RH = 55\pm 5\%$) before the test. Three replicates were considered for each sample. Therefore, the stated number for each test is the average of at least three different measurements.

2.3.2.1. Evaluation of the compactability and workability of CMPMs

Workability is perhaps the most critical feature of CMPM that should be considered during stockpiling and use. The CMPM should be pliable and compactable enough to be used in treatment operations since opening the bag, pouring material into the pothole, and compacting are the first operational

procedures. Researchers have used various techniques to evaluate the workability of the CMPMs, such as dipping a spatula into the mixture [11], using a cement concrete penetrometer (PTI method) [12], the identification of the total number of mould gyrations required to reach a defined compaction pressure in SGC, the triaxial compression and unconfined compression tests [13], the cold patch slump test method [6] and the blade resistance test [3]. However, in most cases, no strong correlation was obtained between laboratory and field results. The workability and compactability of the CMPMs were evaluated in this study using their densities and locking points. The concept of the "locking point," which was originally proposed by William J. Pine, specifies a point on the densification curve beyond which the mix skeleton starts to resist compaction [14]. Unlike the other procedures, these approaches do not require a specific device but a Marshall hammer or an SGC, which are frequently available in road material laboratories. The measurement procedure is also performed during the specimen preparation for other experiments. Thus, no additional materials or costs are required.

Compaction pressure. The compactability of the CMPMs was evaluated using the pressure needed to compact them. A Marshall hammer or an SGC is generally used in the laboratory to densify asphalt mixtures and simulate field activities. The SGC well mimics the HMA roller compaction in the field. However, the pothole repair method performed by the crew is very similar to the impact compaction performed by a Marshall hammer. Nevertheless, the compaction pressure and the number of blows required to compact CMPMs for laboratory simulation of field densification are unknown. For this purpose and to investigate the densification of the cold patches, squared potholes with a size of 450×450 mm and a depth of 35–40 mm were made on road pavement and filled with the CMPMs ($T = 25\text{ }^{\circ}\text{C}$) and compacted using a hand tamper. The density of the laboratory-prepared specimens was measured using the EN 12697-

6 standard and following the sealed-specimen procedure. Also, a non-nuclear electromagnetic density gauge was employed to measure the density of the field patches.

Table 2.2. Densification obtained from field practice and laboratory specimens

	Laboratory									Field
	65±5 mm (Thick)					35±5 mm (Thin)				
Compaction method	S2&2	S6&2	M35	M50	M75	S6&2	M35	M50	M75	HT
Material	Densification [%]									
SC1	74.0	79.0	73.0	74.9	75.6	75.3	73.8	75.6	78.9	77.7
MC1	70.8	77.4	67.0	69.8	71.5	76.1	70.5	71.5	73.7	79.5
WR1	86.3	90.3	86.6	87.8	89.3	90.0	88.0	88.5	89.0	86.2

HT = hand tamper

Table 2.2 shows the outcomes of the densification of CMPMs, both in the lab and in the field, which included the following results:

- A high number of blows (75 blows of the Marshall hammer) or great compaction pressure ($P = 600$ kPa, $N = 200$ using SGC) were needed to reach the density of the repaired potholes in the laboratory. Lower compaction energy did not result in a density corresponding to the field.
- Thick specimens (65±5 mm) were compacted better than thin (35±5 mm) specimens by SGC, as they led to increased density or lower air-void content. However, depending on the workability and compactability of the CMPMs, thin specimens compacted by the Marshall hammer resulted in better or worse compaction than SGC. Therefore, the characteristics of the material and the thickness of the specimen can help to select the suitable compaction method or device.
- The air-void contents or densification percentages of the thick and thin specimens compacted by the Marshall hammer were not significantly different, although thin specimens resulted in lower void contents.

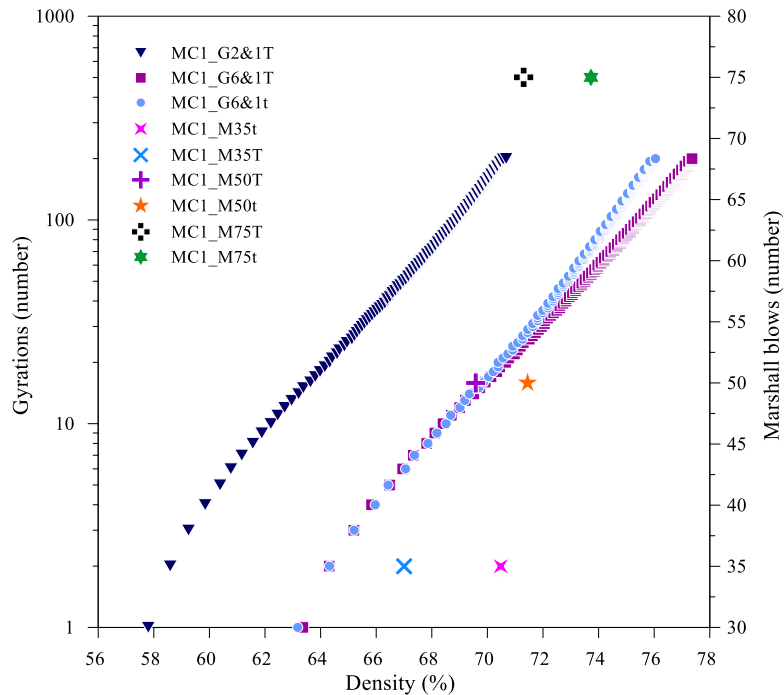


Figure 2.1. The density of MC1 specimens compacted by the SGC or Marshall hammer

As an illustration, Fig. 2.1 exhibits the impact of the compaction energy on the density of the MC1 mixture in more detail. The graphs show that the air-void content decreased as compaction pressure increased. This influence is much more noticeable when a pothole is deep, and the patching materials need to be compacted well with more effort by the crew to provide a denser patch. Poor compaction results in higher air-void contents and increases the potential for patch failure in a short time. This trend was much more noticeable when mixtures were compacted by an SGC rather than a Marshall hammer, as densification or air-void contents differed significantly between mixtures compacted using an SGC at the same number of gyrations but different compaction pressures. This difference was lower for mixtures compacted using a Marshall hammer at the same number of blows. For instance, the air-void content differences between mixtures compacted by a Marshall hammer at 35

and 75 were not as high as the air-void differences between mixtures compacted by an SGC at 200 and 600 kPa at each gyration.

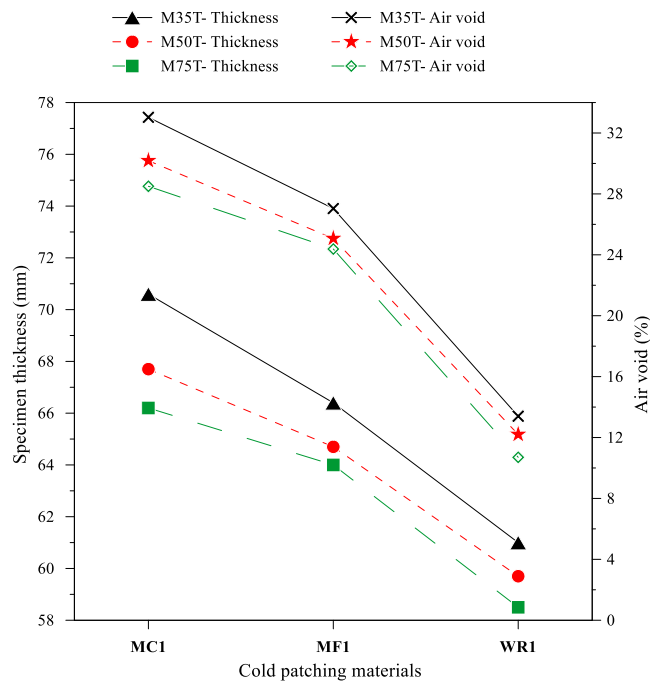


Figure 2.2. The density and air-void results of CMPMs compacted by the SGC or Marshall hammer

Focusing on the impact compaction, Fig. 2 shows the thickness vs. air-void content of specimens compacted with 35, 50, and 75 blows per side. As anticipated, the workable mixture resulted in thinner specimens at each set of hammer blows, indicating better densification or lower air-void content. WR1 and MC mixtures highlighted the highest and lowest height reduction at each set of blows, which means that WR1 and MC1 had the best and worst workability, respectively. In other words, considering the equal number of hammer blows for compacting the CMPMs, the WR1 and MC1 mixtures were compacted better and worse than the others, as the achieved thickness and, subsequently, their air-void content were the lowest and highest, respectively. Although the thickness or air-void content of the specimens (resulting from compaction pressure) is

beneficial for comparing the compactability of different CMPMs, it does not offer a measuring range for categorizing the workability of the cold patching materials.

Locking point. The concept of the "locking point" was defined by Hemsley as the number of gyrations during material compaction by an SGC at which no discernible variations in the height of the specimens are detected after three continuous gyrations. Therefore, a workable material needs fewer gyrations or lower compaction energy to achieve its locking point. In other words, a lower locking point indicates a more workable material and vice versa. To determine the CMPMs' locking point, loose mixtures were conditioned for 24 hours at 20 ± 1 °C and 2 ± 1 °C before being compacted by SGC. Additionally, the low temperature was considered since workability is much more evident during the cold seasons when pothole repair operations are performed. After compacting the samples, the locking points of the SC1, MC1, and WR1 mixtures at 20 ± 1 °C were 59, 75, and 51, respectively. Instead, the values referred to as 2 ± 1 °C stood at 77, 82, and 49. Considering the SC product as an example, the results indicated that, by achieving 59 gyrations during compaction, the other three gyrations did not alter the sample's height. The obtained locking points at 2 ± 1 °C were higher than the locking point at 20 ± 1 °C because mixture workability declines at lower temperatures. In other words, it requires more energy or many gyrations to compact a poorly workable material. The result of the tests and laboratory observations indicated that the materials with locking points of 50 to 60 and 40 to 50 had good to excellent workability. Plus, materials with a locking point higher than 60 were rough and hard to compact. Hemsley also recommends a lock point range of 30 to 70 for workable cold mixtures [15]. Considering the recommended ranges, measuring the locking point of the CMPMs provides adequate information to evaluate their workability.

2.3.2.2. Evaluation of the CMPMs stability

Researchers used a variety of test procedures to determine the stability of the CMPMs, such as resilient modulus, Marshall stability (MS), indirect tensile strength (ITS) [3], triaxial compression (confined and unconfined) [16], Hamburg wheel tracking [17], and penetration shear [18] tests. These tests, however, could occasionally be too challenging for CMPMs, resulting in shaky conclusions and poor concordance between laboratory and field data. Additionally, the known methodologies for evaluating CMPM stability frequently used oven-aged mixtures to ensure they were stable enough before the test. However, the oven-aged samples may not show the behavior of the materials immediately after patching. Also, the oven-aging process may not be suitable for testing and evaluating water-reactive patching materials. Therefore, in this study, non-aged materials were employed and tested under current and new proposed testing methods.

Marshall stability. The Marshall stability test was conducted following EN 12697-34 standard procedures to assess the specimens' resistance to plastic flow. The mixtures were compacted using an SGC at 200 kPa for 100 gyrations. The prepared thick specimens were demolded, left to cure for up to 30 days at room temperature, and then conditioned (at 20 ± 1 °C and 60 ± 2 °C) for 30 minutes before the test. Then, the specimens were loaded at 20 ± 1 °C with a constant deformation rate of 50.8 mm/min in a direction perpendicular to the cylindrical axis. The peak resistance load obtained during the loading sequence indicated stability. The findings (Table 2.3) demonstrated that using the Marshall stability approach to assess the stability of the CMPMs did not produce accurate outcomes. During conditioning at 60°C, the specimens collapsed. At 20 °C, the SC1 briquette specimens were not stable enough on their weight and started losing adhesion between aggregates and binder (segregation) and collapsed.

Table 2.3. Marshall stability results of CMPMs

Material	Conditioning temperature					
	20 °C			60 °C		
	Curing time [day]					
	0 days	7 days	30 days	0 days	7 days	30 days
	Marshall Stability [kN]					
SC1_G2&1T	1.16	1.88	1.71	*	*	*
MC1_G2&1T	2.70	2.82	3.27	0.74	0.80	0.94
WR1_G2&1T	7.39	11.33	12.17	1.74	1.75	2.34

* The specimen failed and collapsed before testing.

As a result, the stability decreased over time due to insufficient adhesion between the binder and aggregates. Also, higher than 200 kPa pressure was applied to compact the samples, but after a short time, the specimens showed the same outcomes. Thus, the Marshall stability test method did not cover testing all types of CMPMs. It is advised to make thinner specimens to maximize the possibility of their survival after demolding and to acquire considerably more reliable results if the Marshall stability method is employed to assess the performance of CMPMs right after demolding. Moreover, as mentioned before, if the patch is compacted well enough with high effort, the potential for facing rutting and patch failure due to losing stability in the first few weeks after the repair operation is not high. Therefore, in the case of an ideal patching operation, stability evaluation would be much more reliable for CMPMs a few weeks after patching rather than immediately. In this case, the specimens are cured long enough (in the mold) to provide sufficient stability after demolding. However, ideal patch placement is barely considered by the repair crew. At room temperature and 60 °C, the minimum suggested values for the initial Marshall stability of the cold patch materials are nearly 2.0 kN and 0.5 kN, respectively.

Indirect tensile strength. The specimens were compacted using the SGC at 200 kPa for 100 gyrations and tested four hours after demolding. The experiment was conducted at 20±1 °C at a constant deformation rate of 50 mm/min to measure the ITS of the laboratory-prepared specimens and followed the EN 12697-23 standard procedure. The peak load at failure was recorded to calculate the ITS value (Eq. 2.1).

$$ITS = \frac{2000 \cdot P}{\pi \cdot D \cdot H} \quad [\text{kPa}] \quad (2.1)$$

where P is the peak load (kN), D is the diameter of the specimen (mm), and H (mm) is the height of the specimen. The ITS results (Table 2.4) for SC1 mixtures showed a similar pattern to that achieved for Marshall stability. Therefore, the strength of SC specimens decreased over time. As already mentioned, the thick specimens were not stable enough at their weight. Thus, the lack of enough adhesion and stability resulted in lower ITS values over time. Again, this test method did not cover testing all types of CMPMs.

Table 2.4. ITS results of CMPMs

Material	Conditioning temp. [20 °C]		
	Curing time [day]		
	0 days	7 days	30 days
	ITS [kPa]		
SC1_G2&1T	16.06	26.78	20.46
MC1_G2&1T	50.13	58.41	60.56
WR1_G2&1T	130.12	256.16	264.53

Similar to the results obtained for Marshall stability, the likelihood of experiencing strength loss in the first few weeks after the repair operation is modest. Therefore, for a more accurate evaluation of the initial strength of the well-compacted patch, a longer curing time and thinner specimens are needed.

Hubbard-Field stability. The Hubbard-Field method is an outdated procedure to determine the optimum asphalt content for a particular blend or gradation of aggregates [19]. The specimens used in this test method have a diameter of 50.8 mm and a height of 25.4 mm. The diameter and height in the modified version were 152.4 mm and 69.85 to 76.2 mm, respectively. The test specimens and testing mold assembly are immersed in a water bath at 60 °C for at least one hour before the test. Then, the test specimen is placed in the mold seated on the shelf produced by the testing ring. The water bath and the testing assembly are positioned on the Hubbard-Field stability machine, and a compressive loading is applied at a constant deformation rate of 1.016 mm/sec. The maximum load resistance developed during the test is expressed as the stability value of the specimen.

Another modified version of this test procedure was taken into consideration to assess the stability of the CMPM specimens that were not stable enough after demolding. Contrary to the original method, the testing mold assembly was customized for our purpose, and cylindrical specimens with a diameter of 102 mm and a height of 25.4 mm were considered based on the mold size requirements.

380 g of CMPM were compacted using an SGC at 200 kPa for 35 gyrations (their locking point). The specimens were cured for up to 30 days in lab conditions, and they were conditioned in a water bath at 60 ± 2 °C for 30 min before testing. Then, according to the described procedure, the prepared specimens were placed in the mold and squeezed through a plunger and a ring slightly smaller than the specimen diameter (Fig. 2.3). Evaluating the stability of SC1 specimens through the Hubbard-Field test method led to logical and trustworthy results. The thin specimens were stable at their weight before testing, and the stability gain rate displayed a rising trend. Hubbard-field thin specimens were much more similar to the field patch and provided fast curing compared to the Marshall briquettes.

The findings revealed that the stability of all three types of materials increased over time. However, the SC1 was sensitive to the high temperature, and the specimens collapsed during conditioning in a water bath at 60 °C.

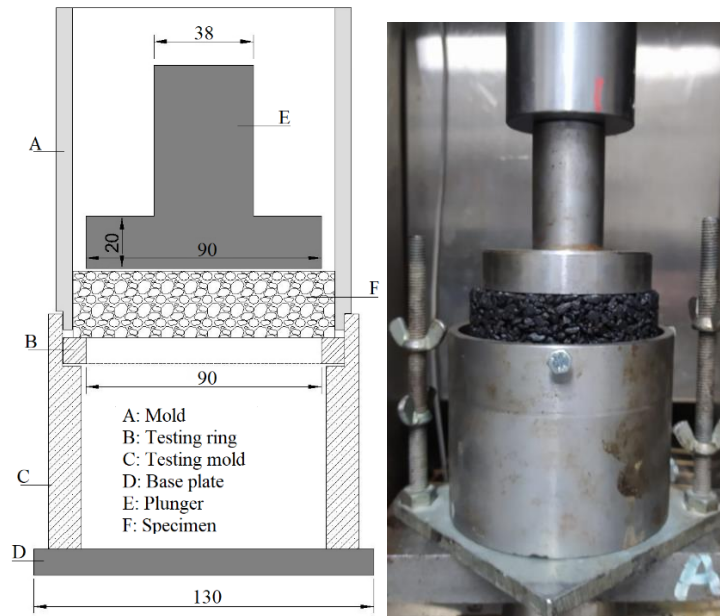


Figure 2.3. The Hubbard-Field stability test device (the dimensions in the scheme are based on mm)

Despite the possibility of evaluating the stability of the CMPMs, the Hubbard-Field test method delivered more functional information about the resistance of the specimens to load and deformation. According to the results presented in Table 2.5, WR materials displayed better stability than the others, and this fact was also evident in the geometry and shape of the tested specimens. After the specimen failed, the more stable and durable product displaced the raised edges (Fig. 2.5-b). However, the specimen edges were not discernible for the other poor materials (Fig. 2.5-a). Therefore, despite other stability testing methods like Marshall stability, the Hubbard-Field stability method provided a better view of evaluating the performance of the mixture by analyzing the shape of the examined specimens.

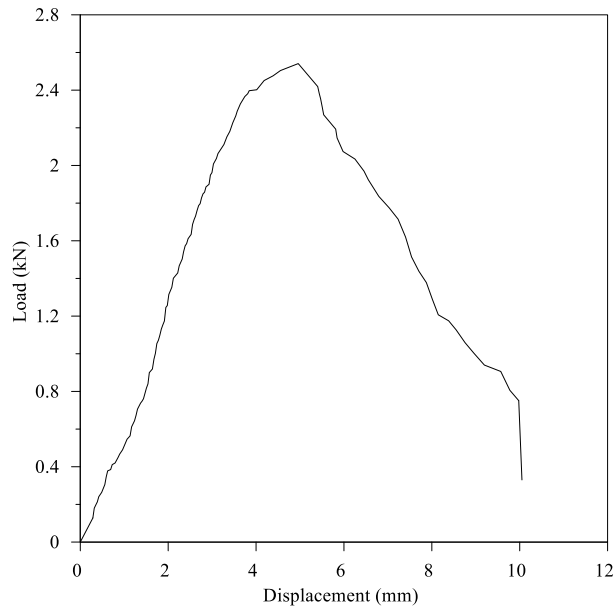


Figure 2.4. The compressive load applied to a WR1 specimen through the Hubbard-Field test method

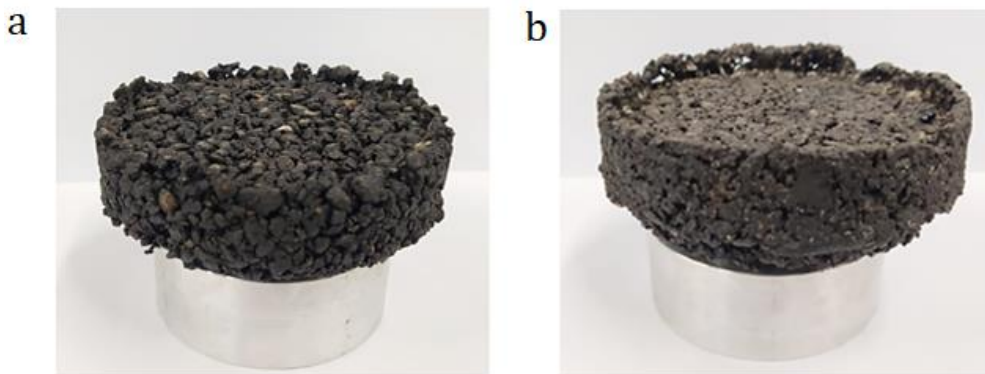


Figure 2.5. The Hubbard-Field specimens after conducting the test: a) MC1; b) WR1

Table 2.5. Hubbard-Field stability results of CMPMs

Material	Conditioning temp. [°C]					
	20 °C			60 °C		
	Curing time [day]					
	0 days	7 days	30 days	0 days	7 days	30 days
	Hubbard-Field stability [kN]					
SC1_G2&1t	2.05	2.62	3.19	*	*	*
MC11_G2&1t	3.04	3.54	3.91	0.91	1.39	1.73
WR1_G2&1t	8.70	12.23	12.54	2.57	5.62	5.93

* The specimen failed and collapsed before conducting the test.

Indentation stability. The indentation test procedure (EN 12697-20) is used to determine the indentation depth of mastic asphalt and other asphalts (with aggregates having a maximum nominal size of 16 mm) when the load is applied to specimens via a cylindrical indenter pin with a flat-ended circular base. For asphalt mixtures used in road construction, specimens are compacted using the Marshall hammer by applying 50 blows per side. Before the test, the prepared specimens are kept on a flat surface at a temperature of not more than 25 °C for 24 h to 42 days. Without demolding the specimens, they are mounted on the device and conditioned for 60 min in water (40±1 °C). The indenter pin is vertically placed on the specimen, and a force of 550 N is applied through the flat-ended cylinder with a base of 500 square millimeters, corresponding to a diameter of 25.2 mm. The cylindrical indenter is attached to a dial gauge that measures the indentation depth. A time-indentation graph showing the indentation depth over time (1, 2, 4, 8, 15, 30, and 60 min) is prepared to report the results.

The concept of this standard was employed to assess the stability of CMPMs. Since the patch is surrounded by the edges of the pothole, in addition to the moldless specimens, mold-surrounded specimens were also considered.

Therefore, the mixtures were compacted by an SGC at 200 kPa for 100 gyrations and cured for 24 hours in laboratory conditions (no water-bath conditioning). Then, the specimens were placed on a plate under the indenter pin, and static weights of 53 kg were applied through the flat-ended cylinder with a base area of 500 square millimeters at 25 ± 1 °C (Fig. 2.6). The indentation depth of the cylinder was recorded and reported as a measure of CPM stability.

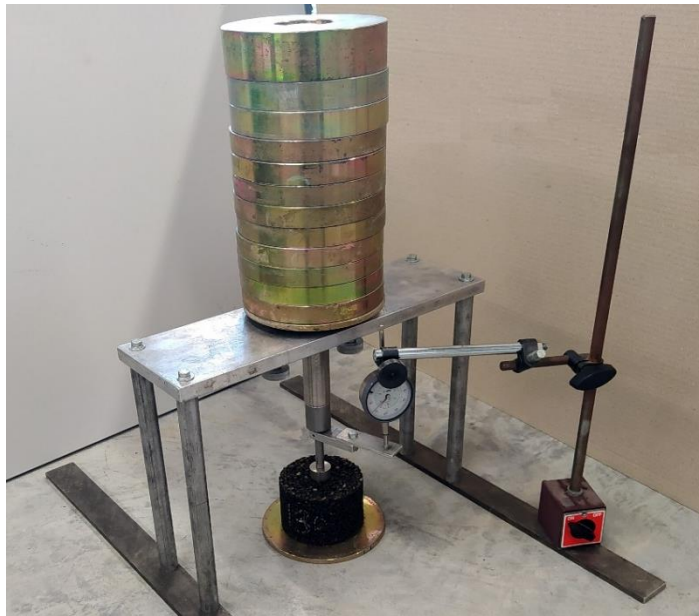


Figure 2.6. Indentation test device

The results of the mold-surrounded specimens (Fig. 2.7) revealed that the cylinder's indentation into the different samples grew over time but was not greater than 6 mm in one hour (Fig. 2.8-a). The incredibly stiff WR1 specimens withstood the static stress and exhibited no effects of indentation under the load. In other words, for WR1 CPM, the recorded indentation depth was zero. However, SC1 and MC1 CPMs only demonstrated a maximum of 6 mm of indentation at 60 minutes and were less resistant than WR1 materials. Under the applied force, MC1 specimens performed the worst.

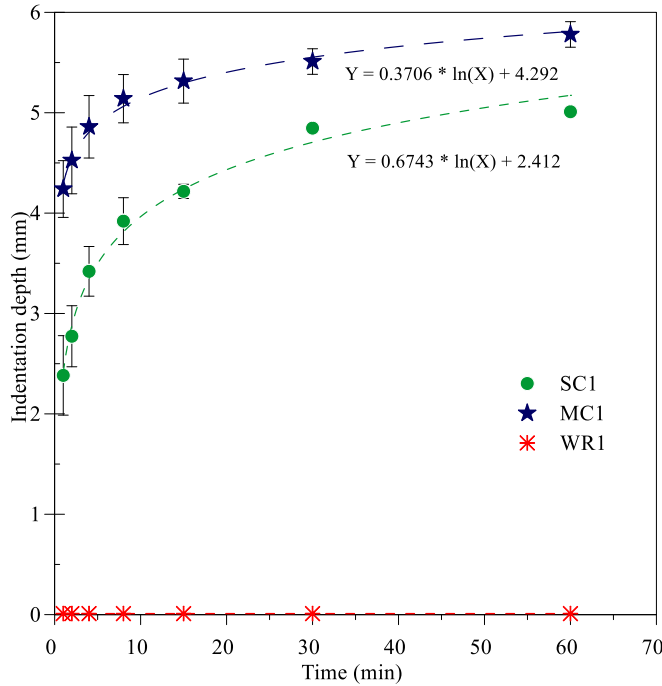


Figure 2.7. Indentation test results obtained from mould-surrounded CMPMs

In addition, less than a few minutes after being subjected to the applied load, MC1 and SC1 moldless specimens lost their stability. The SC specimens showed poor performance and collapsed a few seconds after loading. However, MC1 materials resisted more and collapsed a few minutes after loading (Fig. 8-b). It seems that the distance between the loading place and the edge of the specimens was not long enough to prevent rapid crack propagation, which led to the failure of the specimens in a short time. Nevertheless, WR1 specimens resulted in the best performance. The WR1 specimens were rigid and showed no signs of indentation even after 24 h.

The results obtained from the two approaches indicated that the mold-surrounded specimens led to more reasonable outcomes than the moldless ones. The SC moldless specimens collapsed a few seconds after loading, whereas the materials used to patch potholes demonstrated adequate stability when compacted well in good conditions. Therefore, the failure of the specimens a few

seconds after loading cannot give us a better view of assessing their performance in the lab. Additionally, the results attained from mold-surrounded samples may be affected by the presence of the mold, as crack propagation after loading is restricted by it. Using larger specimens may reduce the impact of rapid crack propagation and mold presence, leading to more reliable results. Plus, the effect of the loading impulse at the start of the test should be removed to avoid influencing the results.

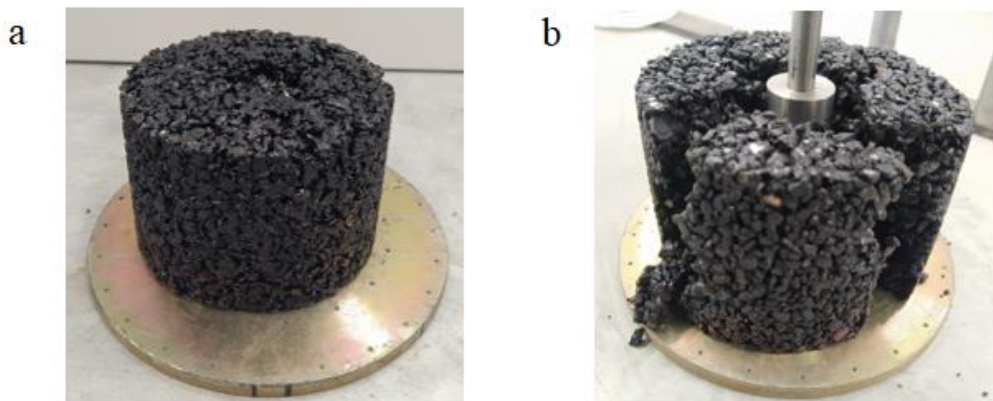


Figure 2.8. Tested specimens: (a) mold-surrounded SC1 specimen (b) moldless MC1 specimen

2.3.2.3. *Evaluation of CMPMs Raveling*

Raveling is generally caused by a loss of bonding between aggregates and binders, as well as mechanical dislodging from specific types of traffic, such as snowplow blades or tracked vehicles. Since CMPMs are typically applied in cold seasons, the potential for poor bonding due to inadequate compaction of the patch and mechanical dislodging due to winter maintenance equipment is high. Usually, the Cantabro loss, i.e., a test method for determining the abrasion loss of compacted HMA mixtures, has been used to investigate the raveling properties of CMPMs [20]. So, the authors suggested the brush test to assess the raveling features of CMPMs, which can better simulate the abrasion and raveling properties of the cold patches in the lab.

Brush test. The original version of this test method (EN 12697-43) is employed to determine the resistance of an asphalt mixture or pavement to fuels. In this test procedure, the specimens are prepared and stored for 14 to 42 days in a dry condition at room temperature before being soaked in the fuel. After curing, half of the test specimen is immersed vertically in the fuel for 24 h (72 h for severe conditions) at room temperature. Then, the specimens are removed and washed carefully with water and a soft brush until the loose particles on the immersed surface are removed. The mass loss of the specimen due to exposure to fuel (A) is calculated, and if it is greater than 5%, the fuel resistance of the specimen is evaluated as "poor resistance" and the test is stopped. Otherwise, the specimen is placed on the brush test device with the clean and washed surface facing up. The surface of the specimen is brushed by a rotating wire brush (the outer diameter and inner diameter of the wire brush are 60 mm and 30 mm, respectively), and the mass loss is calculated after 30, 60, and 120 seconds (B). The total mass loss after chemical (A) and abrasive loading (B) is reported as the resistance of the specimen to fuel and is described as follows:

- $A \leq 5\%$ and $B < 1\%$: good resistance
- $A \leq 5\%$ and $1\% \leq B \leq 5\%$: moderate resistance
- $A > 5\%$ or $B > 5\%$: poor resistance

This test method, without chemical loading or soaking of the specimens in the fuel, was used to evaluate the resistance of CMPMs to raveling. Relationships between the specimens' compaction level, curing time, and resistance to raveling were investigated by subjecting the specimens to the rotating wire brush (Fig. 9).



Figure 2.9. Conducting the brush test to assess the raveling of CMPMs

The specimens were compacted using an SGC for 100 gyrations at 200, 400, and 600 kPa of pressure (2&1, 4&1, and 6&1 conditions). This pressure range was selected to consider the field compaction, which varies from poor to excellent depending on the effort used by the crew. Cylindrical specimens with a diameter of 102 mm and a height of 60-70 mm were prepared and cured at room temperature for 30 days. A Hobart mixer with a circle mold attached to its bottom side was used to perform the test. The specimens were mounted on the mold, while an air pressure of 150 kPa (1.5 bar) was applied to the bottom of the mold to lift the system of the mold and specimen. Less than 150 kPa was not able to lift the samples. At higher pressures, the specimens were compressed between the wire brush and the mold, resulting in abnormal weight loss. After applying the air, the specimen comes into contact with the 60-rpm rotating wire brush. Then, the mass loss was calculated after 30, 60, and 120 seconds.

Table 2.6. The weight loss of the CMPMs after conducting the brush test

		Curing [day]								
		0	7	30	0	7	30	0	7	30
		Test time [sec]								
		30	60	120	30	60	120	30	60	120
		Weight loss [%]								
MC1	2&1T	11.65	>15	>15	7.26	>15	>15	4.89	10.92	11.91
	4&1T	2.34	3.63	4.00	0.92	7.26	>15	>15	4.89	10.92
	6&1T	0.64	1.32	1.61	0.27	0.92	1.30	2.13	0.66	1.15
SC1	2&1T	>15	>15	>15	>15	>15	>15	>15	>15	>15
	4&1T	>15	>15	>15	13.9	>15	>15	12.80	>15	>15
	6&1T	>15	>15	>15	>15	>15	>15	>15	>15	>15
WR1	2&1T	0.22	0.36	0.59	0.00	0.00	0.00	0.00	0.00	0.00
	4&1T	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	6&1T	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

* The mixture aggregates were broken under the pressure of 600 kPa.

The results reported in Table 2.6 indicated that the performance of SC1 mixtures was not satisfactory under different compaction and curing conditions, as the specimens immediately showed a high rate of abrasion and raveling. However, increasing the pressure and curing time improved the raveling resistance of WR1 and MC1 materials. It seems that the influence of increasing the compaction pressure was greater than the curing time, especially in the short time since the weight loss noticeably decreased with increased compaction pressure. For example, the average weight loss of the MC1 specimens compacted at a pressure of 200 kPa (MC1_2&1T) after seven days of curing decreased from 11.65% to 7.26% (a 4.39% percent difference) while increasing the compaction pressure from 200 kPa to 400 kPa resulted in a 2.34% (9.31% percent difference) weight loss. Again, it was noticed that compaction pressure and densification were crucial for enhancing patch durability.

Nevertheless, if the compaction energy is too high, it can lead to worse abrasion results. Applying a compaction pressure of 600 kPa to SC1 mixes (SC1_6/1T) resulted in aggregate breakage and, subsequently, a higher abrasion rate. Therefore, the mix design and the quality of the mixture components should be considered when applying higher energy to compact the material. Furthermore, since the raveling of the patch starts immediately after the repair operation and the compaction effect is higher than the curing time, evaluating the raveling by brush test after making the specimens can provide a better view of the performance of the patch. If the patch survives after filling the pothole, the curing and the associated traffic compaction will improve the patch's resistance to raveling. In addition, the wide range of motion of the wire brush (with an external diameter of 60 mm) on the specimens (with a diameter of 102 mm) increased the stress concentration at the specimen edges, which led to rapid and premature failure of the specimen. Considering larger specimens (with a diameter of 150 mm) can provide a wider surface for the wire brush movements and prevent the stress concentration at the edges, leading to more reliable results.

2.3.2.4. CMPMs Bonding evaluation

CMPM should provide satisfactory bonding with the old pavement to prevent patch failure. Different test methods were used by researchers to assess the bonding features of the CMPMs compacted on the existing pavement [21, 22]. A maximum shear force at the interface of a composite specimen (HMA and CMPM compacted on HMA) was considered by Anderson et al. [23] to investigate the bonding characteristics of the CMPM and existing pavement. The results were not reliable and conclusive in wet and dry conditions. In other studies, inclined and oblique shear tests were used to assess the bond properties of the CMPMs. Plus, the maximum diametric load applied to a complex specimen (half HMA and half CMPM) was employed to evaluate the bonding

properties. Despite the results, preparing that kind of composite specimen was not easy and comfortable [24]. The Virginia Department of Transportation (VDOT) considered the required time for debonding an inverted complex specimen to assess the interface bonding characteristics. The compacted CMPM in this method was an oven-aged mixture that provides better adhesiveness. Also, this test may not reflect the adhesion characteristics of CMPMs [25].

Considering these considerations, the shear bond test (SBT), also known as the Leutner test, was considered by the authors to evaluate the bonding characteristics of the CMPM. Unlike the other test methods, this procedure allows the bonding properties of the field cores and laboratory specimens to be investigated. Moreover, there is no need for specific equipment, and the Leutner head can be mounted on a Marshall load frame.

Shear bond test. This test method, which is codified by the EN 12697-48 standard, is used to determine the interface shear bond between two asphalt layers. Composite specimens, i.e., an asphalt-based overlay (minimum thickness of 20 mm) placed on a reference layer (minimum thickness of 70 mm), are cored from an in-service pavement or manufactured in the laboratory to measure the bonding features. The specimen is conditioned at 20 ± 1 °C for a minimum of 4 h before performing the test. Then, it is placed on the Leutner head, and the load is applied at a rate of 50 ± 2 mm per minute (Fig. 2.10). When the shear force drops to 70% of the maximum shear force, the test is stopped, and the recorded shear force (F) versus the displacement (δ) is plotted to calculate the required parameters, such as shear energy (the area under the shear force-displacement graph) and the slope of the line graph (the linear part of the graph in Fig. 2.11).

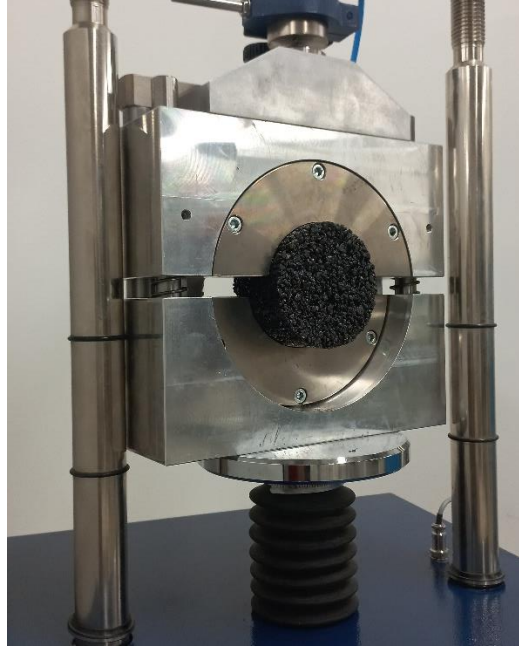


Figure 2.10. Using the Leutner head to evaluate the interlayer shear bond

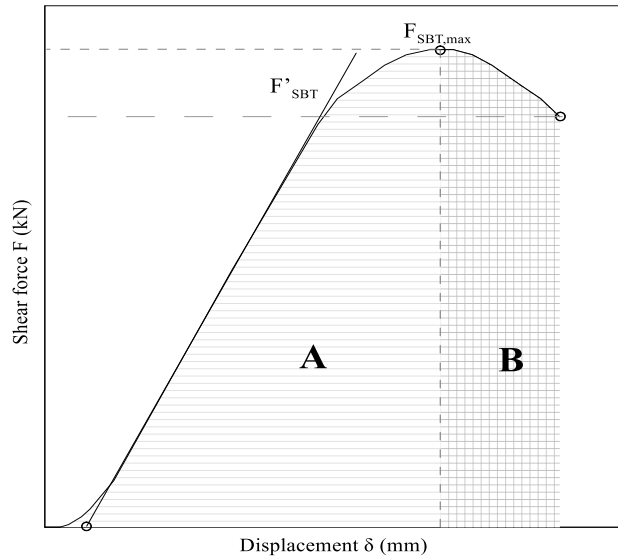


Figure 2.11. The shear force vs. the displacement obtained from the shear bond test

Then, the maximum shear stress at the interface ($\tau_{SBT,max}$) and the interface shear stiffness modulus ($K_{SBT,max}$) are calculated according to Eqs. 2.2 and 2.3.

$$\tau_{SBT,max} = \frac{F_{SBT,max}}{\left(\frac{D}{2}\right)^2} \cdot 1000 \text{ [kPa]} \quad (2.2)$$

$$K_{SBT,max} = \frac{F'_{SBT}}{\pi \cdot \left(\frac{D}{2}\right)^2} \text{ [MPa/mm]} \quad (2.3)$$

where $F_{SBT,max}$ is maximum vertical shear force (kN), D is the initial diameter of specimen in the interlayer (mm) and F'_{SBT} is the slope of the linear part of the force-displacement graph (kN/mm). The shear energy (Eng_i) is expressed by dividing the area under the shear force-displacement curve (the work of failure) by the cross-sectional area of the specimen.

This test procedure was considered to evaluate the interface bonding characteristics between CMPMs and the existing base layer. 600 g of the CMPM were compacted onto a reference dense-graded HMA specimen using an SGC at a pressure of 200 kPa for 100 gyrations. The resulting thickness of the compacted CMPM layer was 35 to 40 mm, which is equal to the depth of a medium-sized pothole. The prepared specimens were conditioned at 25 ± 1 °C for 24 h before the test. Then, they were placed on Leutner's head to conduct the test. The load was applied to the specimen at a rate of 2.5 mm per minute rather than 50 ± 2 mm per minute because of the poor initial bonding characteristics of CMPMs. Table 2.7 shows the test results of different CMPMs.

Table 2.7. Bonding results of the selected CMPMs

Material		$F_{SBT,max}$ [kN]	F'_{SBT} [kN/mm]	$\tau_{SBT,max}$ [kPa]	$K_{SBT,max}$ [Pa/mm]	Eng_A [N·mm]	Eng_B [N·mm]
SC1	Average	0.41	0.40	50.11	48.42	283.96	367.59
	STDEV	0.03	0.00	3.55	0.75	63.80	78.52
MC1	Average	0.34	0.58	41.98	71.05	85.74	127.30
	STDEV	0.05	0.20	6.26	24.11	21.75	35.06
WR1	Average	1.55	2.54	189.32	310.32	673.46	566.68
	STDEV	0.12	0.05	14.71	6.18	63.10	42.37

Bonding was used to describe the quantity of energy needed to break the adhesion between two layers. The findings demonstrated that the WR1 materials resulted in improved bonding performance against the applied shear load compared to the other materials. Although WR1 specimens absorbed a higher quantity of energy before starting to fail, they showed higher stiffness and brittleness compared to the others, as the initial slope and the quickly descending post-peak curve observed for WR1 specimens were steeper than those observed for MC1 and SC1 specimens (Fig. 2.12). Additionally, SC1 materials that performed poorly in other evaluation tests had a stronger interface connection than MC1. The quantitative values of the parameters and the shape of the curve F versus δ support these findings.

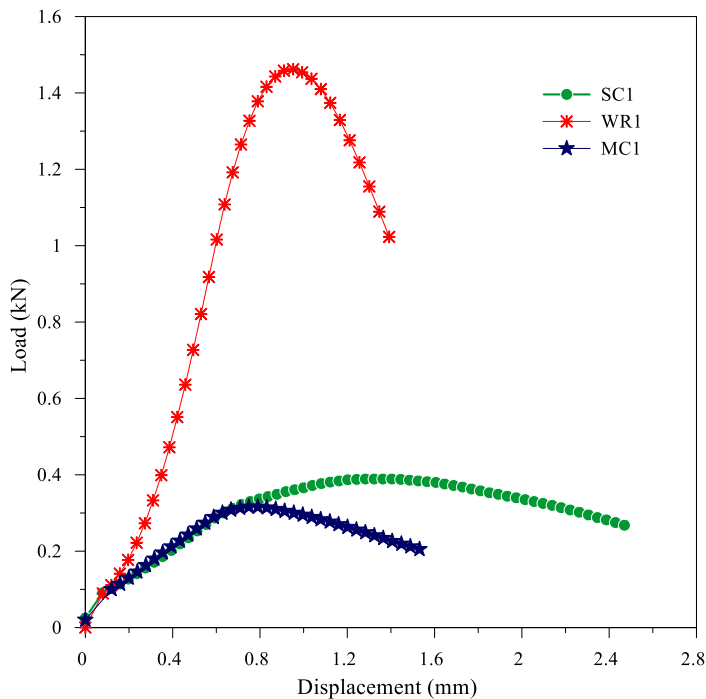


Figure 2.12. The bond shear test results obtained from the examined CMPMs

After a repair operation and reopening to traffic, the patch may debond quickly, leading to the premature failure of the patch. Although the materials' curing and

compaction strengthen the bond between the patch and the existing pavement, time and a higher compaction effort are required to see their effect on the interface bond. Therefore, assessing the material bonding properties after patch operation is advised to prevent premature failure of the patches.

2.4. Conclusions

In this study, new laboratory tests or new settings for existing tests, including Marshall stability, indirect tensile strength (ITS), Hubbard-Field stability, indentation stability, Leutner shear bond, locking point, and brush tests, were proposed to evaluate the properties and performance of cold mix patching materials (CMPMs). To observe the performance of these tests on CMPMs, three different types of patch materials that belong to the main categories of CMPMs available on the market were examined. The specimens were prepared using a Superpave gyratory compactor (SGC) and Marshall hammer, considering a compaction pressure of 200 to 600 kPa and 35 to 75 blows. The main outcomes can be summarized as follows:

- Thicker specimens ($t = 60\text{--}70$ mm) were compacted more effectively than thinner ones ($t = 35\text{--}40$ mm) by the Superpave gyratory compactor (SGC), as thick specimens resulted in higher density or lower air-void content. However, depending on the workability and compactability of the CMPMs, thin specimens compacted by the Marshall hammer led to better or worse compaction than SGC. The suitable compaction method or equipment is thus chosen based on the specimen's thickness and the material's properties.
- The density of patch mixtures was strongly affected by the compaction energy. As a result, it should be considered, especially when a pothole is deep, and the patch materials need to be compacted well with more effort to provide a dense patch.

- With the same number of gyrations but different compaction pressures, mixtures compacted by an SGC showed greater variances in air-void content. This difference was lower for mixtures compacted with a Marshall hammer at the same number of blows. The air-void contents of the thick and thin specimens compacted by the Marshall hammer did not differ significantly, although the thin specimens had better densification.
- Although using the thickness or air-void content of the specimens was beneficial for comparing the compactability of different CMPMs, it did not offer a measuring range for categorizing the workability of CMPMs. However, the locking point of the materials provided a classification range to measure the workability of the mixtures. The materials with locking points of 50 to 60 and 40 to 50 had good to excellent workability, while those with locking points greater than 60 were rough and hard to compact.
- The Marshall stability and ITS test methods did not cover testing all types of CMPMs. If these methods are used to evaluate the performance of CMPMs immediately after demolding, it is advised to make shorter specimens, as the probability of collapsing the specimens after demolding is reduced, which provides much more reliable results. Additionally, the risk of experiencing rutting and patch failure due to losing stability in the first few weeks following repair operations is not high if the patch is compacted effectively with great effort. Therefore, in the case of an ideal patching operation, measuring stability for CMPMs would be significantly more reliable a few weeks later rather than right away following patch installation. In this case, the specimens are cured long enough to provide sufficient stability after demolding.

- Compared to the Marshall stability and ITS test techniques, the Hubbard-Field test method produced more logical and trustworthy results when evaluating the stability of poor materials. The thinner specimens, even after demolding, were stable at their weight before the test, and the stability gain rate was a growing trend. Except for the possibility of evaluating the stability of the materials, the Hubbard-Field test method provided more functional information about the resistance of the materials to the load and deformation. Unlike the poor specimens, the more stable one showed raised edges following failure.
- Evaluating the mold-surrounded specimens through the indentation stability test method resulted in more reasonable outcomes than the moldless ones. Nevertheless, utilizing larger specimens may reduce rapid crack propagation and mold effects and lead to more reliable results.
- Since the raveling of the patch starts immediately after the repair operation and the effect of mixture compaction was higher than the curing time, evaluating the raveling by brush test after making the specimens can provide a better view of the performance of the patch. Because if the patch survives after pothole repair, curing along with the wheel load will improve the patch's resistance to raveling.
- The specimens failed quickly and prematurely because of the wire brush's wide range of motion, which exacerbated the stress concentration at their edges. Using larger specimens (with a diameter of 150 mm) can provide a wide surface for the wire brush movements and prevent stress concentration at the edges. As a result, the test's results may be more reliable.
- Finally, Hubbard-Field, indentation, Marshall stability, and ITS test methods were proposed to evaluate the strength and stability of the CMPMs. For evaluating the workability of the mixtures, measuring the

locking point of the specimens during compaction was recommended. A brush test and an interface shear bond test were recommended to assess the raveling and bonding properties of the CMPMs, respectively.

The outcomes of this study provide greater awareness to CMPM designers and users about the performance of CMPMs in various weather and traffic conditions and enable manufacturers to improve the characteristics of their products by considering various kinds of tests. Moreover, this study opens new windows for researchers to consider different aspects of CMPMs' performances and leads them to improve test methods to analyze and evaluate the patching materials.

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Chapter 3

Performance of cold mix patch materials in laboratory investigation

3.1. Introduction

There are many producers of cold mix patching mixtures on the market who claim their products are an ideal solution for patching potholes in asphalt pavement. However, these mixtures fall far short of their advertised performance. CMPM-repaired potholes frequently face several defects and drawbacks, including raveling, water sensitivity, poor bonding, workability, and stability. It may be challenging to assess the quality of a product solely based on its product data sheet [1, 2]. Besides, there aren't any global standards or guidelines for evaluating the performance of these materials in the laboratory or field [3, 4]. Nevertheless, more municipalities and other users of cold-mix asphalt patching materials are searching for suppliers or producers who can provide an additional level of quality. In this study, the performance of various commercially accessible products was examined using existing and newly proposed testing methods to qualify their use in pothole repair operations.

3.2. Materials

Six distinct kinds of patching materials (referred to as MC1, MC2, MC3, MC4, SC1, and SC2) were considered to evaluate their function and mechanical performance. These products fall within the two main classifications of commercially available CMPMs, including solvent-containing mixes (SC) and

membrane-containing mixtures (MC), which are categorized based on the components, price, and quality. The SC materials were a mix of reclaimed asphalt pavement (RAP) binder, solvent, and virgin aggregates. This type of CMPM is the cheapest and lowest-quality product on the market, which makes it widely purchased and utilized by road maintenance organizations due to its low price. The MC products, which have a fair price and almost medium-to-high quality in the market, contain RAP, recycled asphalt pavement (RAS), and virgin aggregates in their mix design. The mixture composition was determined using the ignition test method (EN 12697-39). First, the binder content of the mixtures, which is expressed as a percentage of aggregate mass, was calculated by burning the binder of the mixture samples at high temperatures. Then, the sieve analysis was performed on the residual aggregate to determine the gradation of the mixtures. Table 3.1 presents the results obtained for each product.

Table 3.1. Binder content and grain distributions of the mixtures

Material	Sieve size [mm]											Binder [%]
	12	10	8	6.3	4	2	1	0.5	0.3	0.01	0.1	
	Cumulative passing [%]											
MC1	100.0	99.8	99.6	97.6	64.0	24.4	15.8	11.9	8.9	*	6.3	6.6
MC2	100.0	100.0	100.0	94.4	63.3	22.1	13.7	10.5	8.4	*	6.2	6.5
MC3	100.0	100.0	100.0	97.1	58.2	28.6	21.2	15.6	13.6	*	9.1	6.4
MC4	100.0	100.0	100.0	97.0	52.4	24.2	16.9	13.9	12.0	10.0	8.5	5.9
SC1	100.0	99.8	99.8	95.4	50.0	19.4	12.0	9.2	7.9	*	5.9	4.8
SC2	100.0	100.0	99.8	97.9	64.4	15.8	8.0	6.3	5.3	*	3.9	4.4

3.3. Methodology

A laboratory study was performed to evaluate the physical-mechanical characteristics and performance of CMPMs. First, the mixture samples were prepared using a Superpave gyratory compactor (SGC) and a Marshall hammer.

Then, several tests, including Marshall stability, ITS, Hubbard-Field stability, indentation stability, densification and locking point, brush test, and shear bond test, were employed to assess the workability, stability, releveling, and bonding qualities of the chosen products.

3.3.1. Specimen preparation

Cylindrical specimens with a diameter (D) of 100 mm and a nominal height of 65 ± 5 mm (thick) or 35 ± 5 mm (thin) were prepared using a Marshall hammer and an SGC. For compacting 1000 g of sample mixtures with a Marshall hammer, 35, 50, and 70 blows per side were considered. The chosen pressures for SGC compaction were 200 to 600 kPa, and the gyrations were set to 100 and 200.

Acronyms (e.g., MC1_M75t) were used to label each mixture: the first pair of letters and number describe the material type (SC or MC), the letter after the underscore symbol defines the compaction procedure (M = Marshall hammer and G = Superpave Gyratory compactor), the numbers refer to the compaction effort (XX = number of blows for Marshall Hammer; Y&Z = compaction pressure in kPa/100 and gyrations in number/100 for the SGC), and the last letter identifies the specimen height (T = 65 mm; t = 30 mm). The label MC1_G2&1T, for example, denotes a specimen of the membrane-containing material, which was compacted with the SGC at a pressure of 200 kPa for 100 gyrations, yielding a final height of 65 ± 5 mm.

3.3.2. Test methods

Briquette specimens were prepared and tested after being cured and conditioned. Each time, the performance test method and the material properties were taken into consideration while choosing the compaction quantities (pressure, number of blows, and gyrations). The specimens were cured for up to 30 days in a laboratory setting (temperature $T = 22\pm 2$ °C; relative humidity $RH = 55\pm 5\%$)

before the tests. Three replicates for each sample were considered. Thus, the reported value for each test represents the mean of at least three independent measures.

3.3.2.1. Evaluation of the compactability and workability of CMPMs

The most important aspect of CMPM that should be considered when stockpiling and using is workability. Since opening the bag, dumping the contents into the pothole, and compacting are the first operational steps, the CMPM should be pliable and compactable enough to be employed in treatment operations. Researchers have used various techniques (Chapter 1, Section 1.3.3.1) to evaluate the workability of the CMPMs. However, in most cases, no strong correlation was obtained between laboratory and field results. The workability and compactability of the CMPMs were evaluated in this study using their densities and locking points.

Locking point. Hemsley defined the "locking point" as the number of gyrations during material compaction by an SGC at which no discernible changes in the height of the specimens are detected after three continuous gyrations [5]. Therefore, a workable material needs fewer gyrations or lower compaction energy to achieve its locking point. In other words, a lower locking point indicates a more workable material and vice versa. To specify the CMPMs' locking point, loose mixtures were conditioned at 20 ± 1 °C and 2 ± 1 °C for 24 hours before being compacted by SGC. The low conditioning temperature was also considered since workability is considerably more challenging during the cold seasons.

Compactability. The energy required to compact the CMPMs was used to assess their compactability. The mixture is more compactable and workable if it requires less compaction pressure to densify it, and vice versa. A Marshall hammer and an SGC were used to densify the samples mixtures and investigate

their compactability. The mixture that results in a higher densification percentage after a determined pressure indicates better compactability.

3.3.2.2. Evaluation of the CMPMs stability

The stability of the CMPMs was assessed using several test methods, including ITS and Marshall stability (Chapter 1, Section 1.3.3.4). But often, these tests could be too challenging for CMPMs, leading to questionable conclusions and poor concordance between laboratory and field results. In addition, to make sure the mixes were stable enough before the test, the studied procedures for evaluating CMPM stability usually employed oven-aged mixtures. However, the oven-aged samples may not reflect the short-term behavior of the patched materials. Therefore, the specimens were made and examined using non-aged materials.

Marshall stability. The Marshall stability test was conducted following EN 12697-34 standard procedures to evaluate the specimens' resistance to plastic flow. The mixtures were compacted using an SGC at 200 kPa for 100 gyrations. The prepared thick specimens were demolded, left to cure for up to 30 days at room temperature, and then conditioned (at 20 ± 1 °C in air and 60 ± 2 °C in water) for 30 minutes before the test. Then, the specimens were loaded at 20 ± 1 °C with a constant deformation rate of 50.8 mm/min in a direction perpendicular to the cylindrical axis. The peak resistance load obtained during the loading sequence indicated stability.

Indirect tensile strength. The specimens were compacted using the SGC at 200 kPa for 100 gyrations and tested four hours after demolding. The experiment was conducted at 20 ± 1 °C at a constant deformation rate of 50 mm/min to measure the ITS of the laboratory-prepared specimens and followed the EN 12697-23 standard procedure. The peak load at failure was recorded to calculate the ITS value (Eq. 3.1).

$$ITS = \frac{2000 \cdot P}{\pi \cdot D \cdot H} \quad [\text{kPa}] \quad (3.1)$$

where P is the peak load (kN), D is the diameter of the specimen (mm), and H (mm) is the height of the specimen.

Hubbard-Field stability. Following the explanation given in Section 2.3.2.2, the Hubbard-Field method was adjusted to assess the stability of the CMPM that was not sufficiently stable after demolding. As a result, in contrast to the original procedure, the testing mold assembly was tailored to our needs, and cylindrical specimens with a diameter of 102 mm and a height of 25.4 mm were made following the mold size specifications.

The specimens were created by compacting 380 g of the sample mixture using an SGC for 35 gyrations (their locking point) at 200 kPa. Then, they were cured for up to 30 days in lab conditions, and before testing, they were conditioned in a water bath at 60 ± 2 °C for 30 min. The test specimen was placed in the mold seated on the shelf produced by the testing ring, and the testing assembly was positioned in the universal testing machine (UTM) (Fig. 3.1). A compressive load at a constant deformation rate of 1.016 mm/sec was applied to the specimen through a plunger. The maximum load resistance developed during the test is expressed as the "stability value" of the specimen (Fig. 3.2).

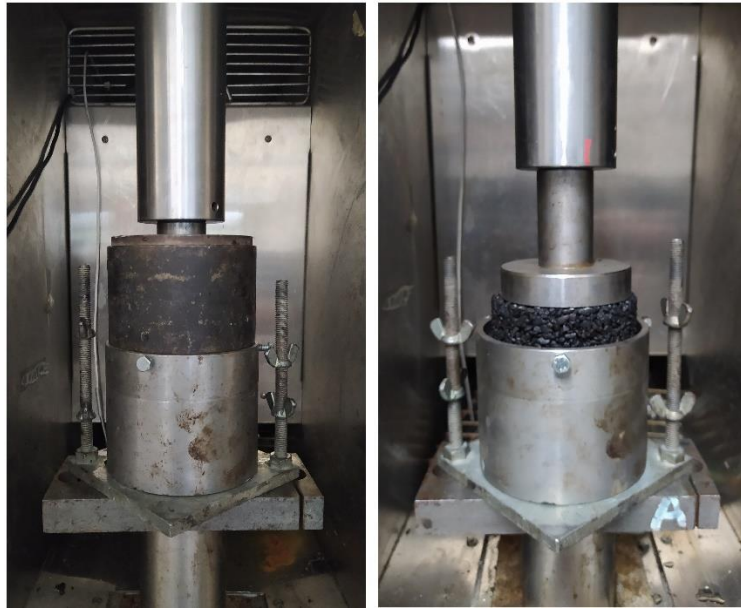


Figure 3.1. The Hubbard-Field stability test device

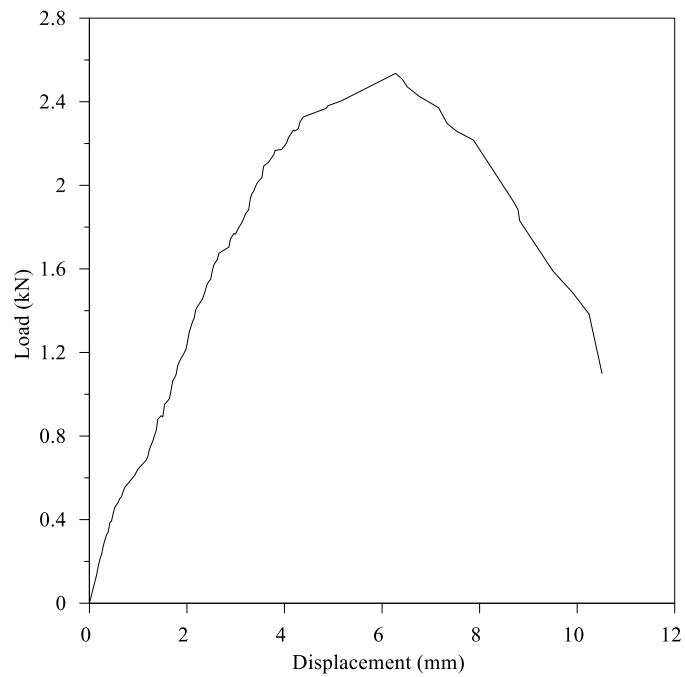


Figure 3.2. SC1 specimen loading through the Hubbard field test method

Indentation stability. According to the procedures outlined in Section 2.3.2.2, the concept of the indentation test (EN 12697-20) was employed to assess the stability of CMPMs under localized stress. Since the patch is enclosed by pothole edges, in addition to the moldless specimens, mold-surrounded specimens were also considered to quantify the stability of the products.

To prepare the specimens, 1000 g of the sample mixtures were compacted using an SGC at 200 kPa for 100 gyrations and cured for 24 hours in laboratory conditions. Then, the specimens were placed on a plate under the indenter pin, and static weights of 53 kg were applied to the specimen through the flat-ended cylinder with a base area of 500 square millimeters at 20 ± 1 °C (Fig. 3.3). A dial gauge was attached to the cylindrical indenter to measure the indentation depth. A time-indentation graph displaying the indentation depth over time (1, 2, 4, 8, 15, 30, and 60 min) was drawn to report the results.



Figure 3.3. Indentation test device

3.3.2.3. *Evaluation of CMPMs Raveling*

Raveling is typically brought on by mechanical dislodging from particular forms of traffic, such as snowplow blades or tracked vehicles, as well as a lack of bonding between aggregates and binders. Since CMPMs are frequently applied during cold weather, there is a substantial risk of poor bonding from insufficient patch compaction and mechanical dislodging by winter maintenance equipment. Usually, the Cantabro loss, i.e., a test method for determining the abrasion loss of compacted HMA mixtures, is used to investigate the raveling properties of CMPMs [6]. However, in this study, the brush test was advised to assess the raveling qualities of CMPMs, which can more accurately mimic the abrasion and raveling characteristics of the cold patches in the laboratory.

Brush test. The procedure of this test method was modified (Chapter 2, Section 2.3.2.3), and only the abrasive loading (B) step was employed to evaluate the raveling resistance of CMPMs and their relationship with compaction level and curing time.

The sample mixtures were compacted using an SGC for 100 gyrations at 200, 400, and 600 kPa (2&1, 4&1, and 6&1 conditions). This pressure range was selected to consider the field compaction, which varies from poor to excellent depending on the effort used by the crew. Therefore, cylindrical specimens with a diameter of 102 mm and a height of 60-70 mm were prepared and cured at room temperature for up to 30 days before the test. A Hobart mixer (Fig. 3.4) with a circle mold attached to its bottom side was used to perform the test. The specimens were mounted on the mold, while an air pressure of 150 kPa (1.5 bar) was applied to the bottom of the mold to lift the system of the mold and specimen. Less than 150 kPa was not able to lift the samples. At higher pressures, the specimens were compressed between the wire brush and the mold, resulting in abnormal weight loss. After applying the air, the specimen came into contact

with the 60-rpm rotating wire brush, and its surface was brushed. The mass loss of the tested specimen was calculated after 30, 60, and 120 seconds to assess its abrasion resistance. The following mass loss ranges are recommended for HMA mixtures while subjected to chemical and abrasive loading.

- $A \leq 5\%$ and $B < 1\%$: good resistance
- $A \leq 5\%$ and $1\% \leq B \leq 5\%$: moderate resistance
- $A > 5\%$ or $B > 5\%$: poor resistance



Figure 3.4. Conducting the brush test to assess the raveling of CMPMs

3.3.2.4. *CMPMs Bonding evaluation*

CMPM should offer adequate bonding with the old pavement to avoid patch failure. Researchers evaluated the bonding properties of the CMPMs compacted on the existing pavement using various test methods (Chapter 1, Section 1.3.3.2). However, the outcomes of these tests were frequently in doubt. The shear bond test (SBT), also known as the Leutner test, was taken into account to assess the bonding properties. Unlike the other test methods, this procedure enables an

investigation into the bonding qualities of field cores and lab specimens. Additionally, no special tools are required, and the Leutner head can be mounted on a Marshall load frame.

Shear bond test. This test method, which is codified by the EN 12697-48 standard, was considered to evaluate the interface bonding characteristics between CMPMs and the existing base layer. For making the specimens, 600 g of the CMPM were compacted onto a reference dense-graded HMA specimen using an SGC at a pressure of 200 kPa for 100 gyrations or 70 blows with the Marshall hammer. The resulting thickness of the compacted CMPM layer was 35 to 40 mm, which is equal to the depth of a medium-sized pothole. The prepared specimens were conditioned at 20 ± 1 °C for 24 h before the test. Then, they were placed on Leutner's head (Fig. 3.5) to conduct the test. Since CMPMs have poor initial bonding qualities, the load was applied to the specimen at a rate of 2.5 mm per minute rather than the rate specified in the recommendation guideline (50 ± 2 mm per minute). When the shear force dropped to 70% of the maximum shear force, the test was stopped, and the recorded shear force (F) versus the displacement (δ) was plotted to calculate the required parameters, such as shear energy (the area under the shear force-displacement graph) and the slope of the line graph (the linear part of the graph in Fig. 3.6).

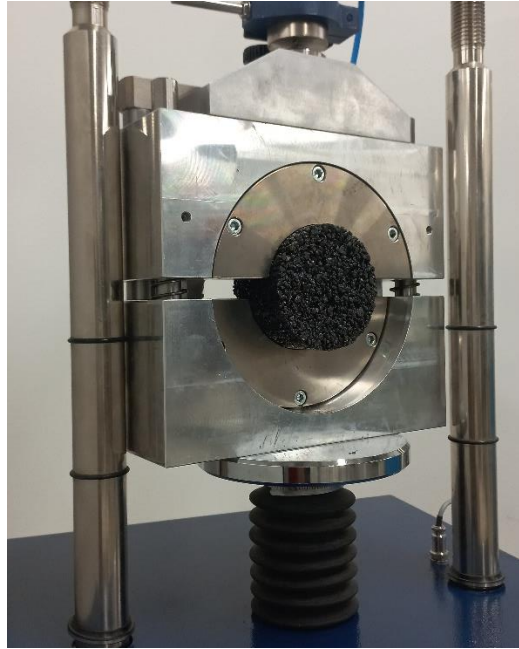


Figure 3.5. Using the Leutner head to evaluate the interlayer shear bond

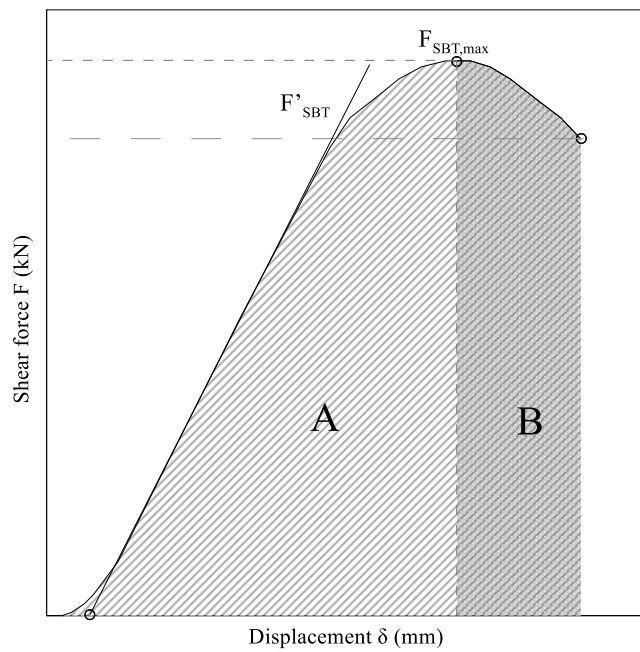


Figure 3.6. The shear force vs. the displacement obtained from the shear bond test

Then, the maximum shear stress at the interface ($\tau_{SBT,max}$) and the interface shear stiffness modulus ($K_{SBT,max}$) are calculated according to Eqs. 3.2 and 3.3.

$$\tau_{SBT,max} = \frac{F_{SBT,max}}{\left(\frac{D}{2}\right)^2} \cdot 1000 \text{ [kPa]} \quad (3.2)$$

$$K_{SBT,max} = \frac{F'_{SBT}}{\pi \cdot \left(\frac{D}{2}\right)^2} \text{ [MPa/mm]} \quad (3.3)$$

where $F_{SBT,max}$ is maximum vertical shear force (kN), D is the initial diameter of specimen in the interlayer (mm) and F'_{SBT} is the slope of the linear part of the force-displacement graph (kN/mm). The shear energy (Eng_i) is expressed by dividing the area under the shear force-displacement curve (the work of failure) by the cross-sectional area of the specimen.

3.3. Results and discussion

The tests were performed to qualify the performance of CMPMs. The results are as follows:

3.4.1 Compactability and workability

The locking point and compactability of the mixtures were used to determine the workability of the CMPMs. The results are as follows:

3.4.1.1 Locking point

The results reported in Table 3.2 showed that the locking points obtained for mixtures were substantially affected by conditioning temperature and compaction pressure. The materials with locking points of 50 to 60 and 40 to 50, respectively, had good and excellent workability, according to the obtained locking point values and laboratory visual observations. Additionally, materials with a locking point greater than 60 were rough and hard to compact.

Table 3.2. Locking point and density of the CMPMs compacted under different pressures

Material	200 kPa				600 kPa			
	locking point	Density [%]	locking point	Density [%]	locking point	Density [%]	locking point	Density [%]
	20±1 °C		2±1 °C		20±1 °C		2±1 °C	
MC1	75	70.8	82	68.3	72	77.4	75	70.9
SC1	59	72	81	70.9	69	77.4	73	77.1
MC2	58	75	75	72.4	60	80.5	66	79.1
MC4	58	76.7	77	75.8	59	81.5	74	81.9
MC3	58	77.2	67	75.7	57	82.8	68	81.7
SC2	45	70.9	64	71.9	44	74.5	61	75.3

As expected, changing the conditioning temperature and compaction pressure affected the locking point values noticeably, meaning that increasing the compaction pressure or temperature can improve the compactability and workability of a mixture if it is not sufficiently workable at lower temperatures. To put it another way, patching materials that were workable enough at a higher temperature (20±1 °C) or under a higher compaction pressure exhibited decreased workability at a lower temperature (2±1 °C) or a lower compaction pressure. For instance, the locking point of the workable SC2 mixture at 20±1 °C and 600 kPa was 44, whereas its locking point increased to 61 at 2±1 °C conditioning temperature, indicating a hard-to-compact patch. Reducing the pressure from 600 to 200 kPa even increased the lock point and ultimately worsened the workability of the mixture. In other words, a higher compaction pressure or many gyrations were needed to compact the material conditioned at a lower temperature. This circumstance might reflect the difficulty of utilizing CMPMs in cold and rainy seasons when the temperature is low and higher compaction energy is needed to compact the rough materials.

3.4.1.2 Compactability

The compactability of the mixtures was employed to evaluate their workability in repair programs. As previously indicated, increasing the conditioning

temperature or compaction pressure resulted in a higher density of the specimens, showing improved compactability and workability of the materials. According to Table 3.2, except for the SC2 mixture, the locking points of all CMPMs showed a direct relation with the percentage of densification at every temperature and pressure condition. The higher locking points, or, in other words, not workable enough mixtures, led to poor densification and vice versa. The MC1 sample mixtures with the highest locking point and lowest workability exhibited higher air-void contents or poor densification. Contrary to expectations, SC2 mixtures with the lowest locking points, or, more specifically, the best workability, had lower densification percentages or higher air void contents at 20 ± 1 °C and 2 ± 1 °C under various compaction pressures.

Although the relationship between compactability and workability is striking, it is not the only determining factor. Workability seems to be more influenced by the mixture's components than other elements. Furthermore, while the densification or air-void content of the specimens is beneficial for comparing the compactability of different CMPMs, it does not offer a measuring range for categorizing the workability of the cold patching materials.

3.4.2 Evaluation of the CMPMs stability

Several test methods, including Marshall stability, ITS, Hubbard-Field stability, and the indentation stability test, were employed to evaluate the strength and stability of CMPMs. The regular operating procedures for conducting the tests were modified to satisfy the CMPMs' requirements. Following are the test findings from the experiments:

3.4.2.1 Marshall stability

The Marshall stability test was performed on the CMPMs specimens at 20 ± 1 °C after conditioning them at 20 ± 1 °C and 60 ± 1 °C. Fig. 3.7 presents the outcomes.

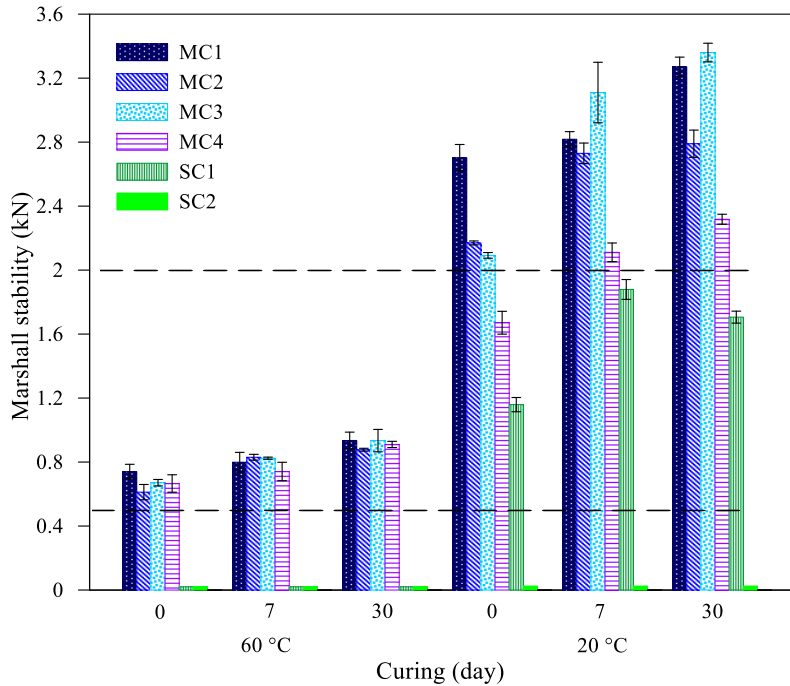


Figure 3.7. The impact of the curing time on the Marshall stability of CMPMs

The findings indicated that the SC materials (SC1 and SC2) displayed lower stability than the MC materials at both conditioning temperatures. The test was unsuccessful since both SC materials were soft while conditioning at $60\pm1^{\circ}\text{C}$ and collapsed despite being created at a pressure of 600 kPa. Even at ambient temperature, the SC2 specimens collapsed, but testing was possible with the SC1 specimens. The results showed that the SC materials performed extremely poorly in terms of stability and were sensitive to higher temperatures. In addition, after seven days of curing at $20\pm1^{\circ}\text{C}$, the stability of SC1 materials declined. The stability initially increased and subsequently decreased over the first week of curing, which may have been caused by a lack of adhesion between the aggregates and binder. Unlike SC, MC specimens were more stable after demolding and yielded better outcomes.

The improvement in Marshall stability due to specimen curing ranged from 8 to 62 percent for various CMPMs when compared to their initial stability. The MC3

and SC1 specimens were affected the most by curing time, as their stability at $20\pm1^{\circ}\text{C}$ improved by almost 62% (Table 3.3).

Table 3.8. Improvement of Marshall stability due to curing

Marshal stability improvement [%]				
Material	Conditioning temperature [°C]			
	60±1		20±1	
	Curing [day]			
	7 days	30 days	7 days	30 days
MC1	7.97	26.35	4.29	21.06
MC2	35.62	43.30	25.81	28.57
MC3	22.80	39.20	48.66	60.61
MC4	11.26	36.64	26.33	38.72
SC1	*	*	62.12	47.20
SC2	*	*	*	*

* The test failed due to the specimen collapsing.

The minimum recommended values for initial Marshall stability of the cold patch materials at room temperature and $60\pm1^{\circ}\text{C}$ are almost 2.0 kN and 0.5 kN, respectively. By referring to this recommendation, all MC specimens achieved stability higher than the recommended values at both conditioning temperatures. The stability results obtained from CMPMs conditioned at $20\pm1^{\circ}\text{C}$ were nearly four times greater than those conditioned at $60\pm1^{\circ}\text{C}$. Moreover, based on the field observations and laboratory results, the compaction energy used to patch medium-sized potholes in the field is higher than the pressure used to make the specimens in this study. Therefore, patching potholes with MC materials can even lead to better results, as the effort employed to compact them in the field is higher than the effort used in the laboratory.

3.4.2.2 Indirect tensile strength (ITS)

Following the procedure mentioned in the EN 12697-23 standard, the specimens were made and tested in laboratory conditions after being kept at $20\pm1^{\circ}\text{C}$ for four hours. According to Fig. 3.8, the outcomes for CMPMs are as follows:

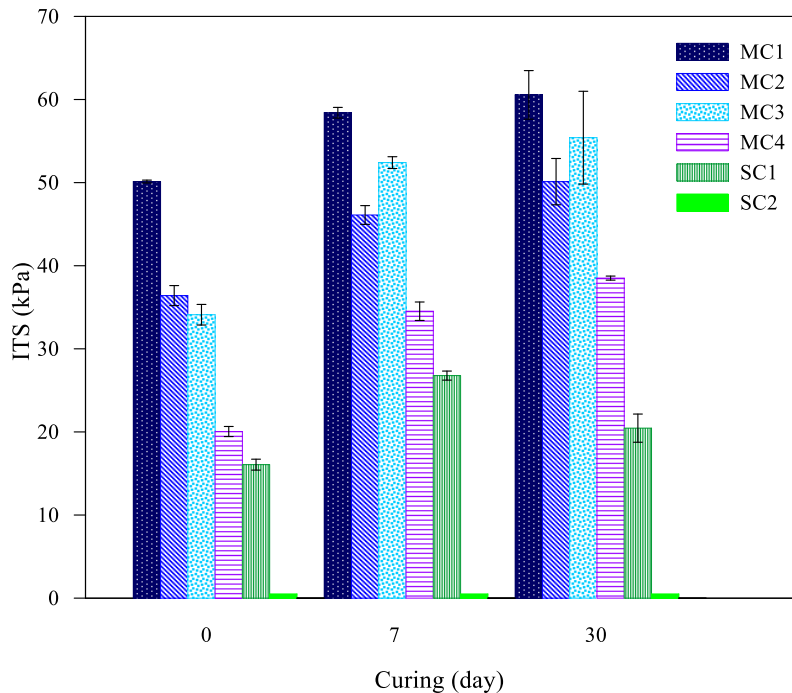


Figure 3.8 The ITS results obtained for CMPMs

Similar to the Marshall stability test, the SC2 specimens collapsed before performing the test. A similar improving trend to that shown in the Marshall stability test was also evident in the findings for SC1 mixtures. Despite not collapsing, the specimens' strength improved until seven days of curing and then decreased due to a loss of adhesion between aggregates and binder. Unlike SC specimens, MC specimens demonstrated an increased rate of strength acquisition with time, and their strength increased with curing time.

The strengths of the MC specimens increased with curing, as shown by the values provided in Table 3.4, which were calculated with respect to the initial

strengths of the specimens (ITS after demolding). For instance, the ITS values obtained for the MC1 materials increased by 16.51% and 20.79%, respectively, after 7 and 30 days of curing, whereas the strengths of the SC1 specimens dropped after one week of curing from 66.71% to 27.34%.

Moreover, the strength of the materials rose sharply in the first week of curing, and then the gain rate dropped. For example, the MC1 specimens' strength increased by 16.51% in 7 days of curing, and then after 7 days to 30 days, the improvement was only 4.28% (differences between 20.79 and 16.5%1).

Table 3.4. The impact of curing on the strength improvement of the CMPMs

Material	ITS improvement [%]	
	Curing time [day]	
	7	30
MC1	16.51	20.79
MC2	26.64	37.67
MC3	53.68	62.47
MC4	72.19	92.06
SC1	66.71	27.34
SC2	*	*

* The test was failed due to the specimen collapsing.

3.4.2.3 Hubbard-Field stability

The Hubbard-Field stability test was performed to evaluate the stability of the CMPM samples that were not stable enough after demolding. The tests were conducted on the thin specimens, and the outcome of the investigation is as follows:

The Hubbard-Field test method produced more reliable findings when evaluating the stability of SC specimens. Hubbard-field thin specimens, as opposed to Marshall briquettes, offered quick curing and were considerably more akin to the field patch. They continued to be stable at their weights, and over time, their stability increased. As previously mentioned, after seven days of

curing, the Marshall stability and ITS values for SC1 specimens dropped. But even after seven days of cure, the Hubbard-field stability data showed a growing stability gain rate (Fig 3.9).

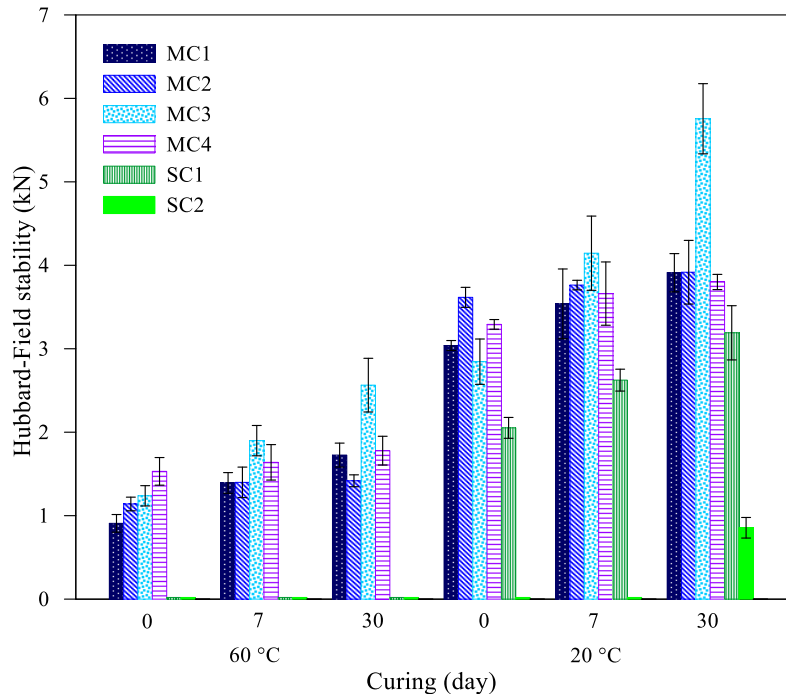


Figure 3.9 The Hubbard-Field stability results obtained from CMPMs cured up to 30 days

In addition, evaluating the SC2 specimen was possible through the Hubbard-Field method after 30 days of curing, whereas the previously mentioned methods yielded no results. The Hubbard-Field test and the findings from the earlier methods revealed that the SC materials are susceptible and vulnerable to conditioning at higher temperatures. There was no way to assess the stability of the conditioned thick and thin SC specimens at 60 °C as they collapsed in every test. Considering this, it would appear that applying SC materials at higher temperatures causes significant rutting in the field while reducing the patch's ability to survive for an extended time. However, MC specimens produced better findings and showed increasing stability. After 30 days of curing, the MC3

specimens provided the best result, whereas the stability of the other specimens almost equaled.

The stability improvement of CMPMS affected by curing time and conditioning temperature is described in Table 3.5. As expected, due to the shortness of the specimens utilized in this test, the impact of curing and stability improvement were higher than the Marshall stability and ITS test methods. In contrast to the previous evaluation tests, after 7 days of curing, the stability increase rate did not decline, and the trend was upward. At both condition temperatures, the stability of all CMPMs was approximately twice as high after 30 days of curing as compared to the values attained after just 7 days.

Table 3.5. The impact of curing time and conditioning temperature on the stability improvement of CMPMs

Hubbard-Field stability improvement [%]				
Material	Conditioning temperature [°C]			
	60		20	
	Curing time [day]			
	7	30	7	30
MC1	53.30	90.09	16.42	28.69
MC2	22.72	24.39	4.07	8.32
MC3	53.39	107.11	45.69	102.32
MC4	7.05	16.20	11.21	15.43
SC1	*	*	27.88	55.51
SC2	*	*	*	-

* The test failed due to the specimen collapsing.

3.4.2.4 Indentation stability

The test was carried out on briquette specimens at room temperature in a dry condition. The results (Fig. 3.10) of the mold-surrounded specimens showed that the indentation of the cylinder into the various samples increased over time but was not greater than 6 mm in one hour. The SC2 and MC2 specimens performed the worst under the imposed force, with an indentation depth of about 6 mm after

60 minutes. The SC1 specimens also did not perform well and showed a 5 mm indentation. The performance was highest with MC3 specimens, which demonstrated less than a 3 mm indentation depth. The shape and slope of the curves showed no appreciable difference between the indentation depth of the SC2 specimens after loading and before stopping the test, indicating that the specimens were not sufficiently stable to withstand the load as the indentation appeared suddenly rather than gradually. The MC3 stable specimens also exhibited this tendency, but their indentation depth was not as great as that of the SC2 specimens. Following loading, the SC1 and MC2 specimens were gradually penetrated by the indentation pin, showing improved stress bearing because the air void contents or densification percentages for these mixtures were lower than those for the SC2 mixtures.

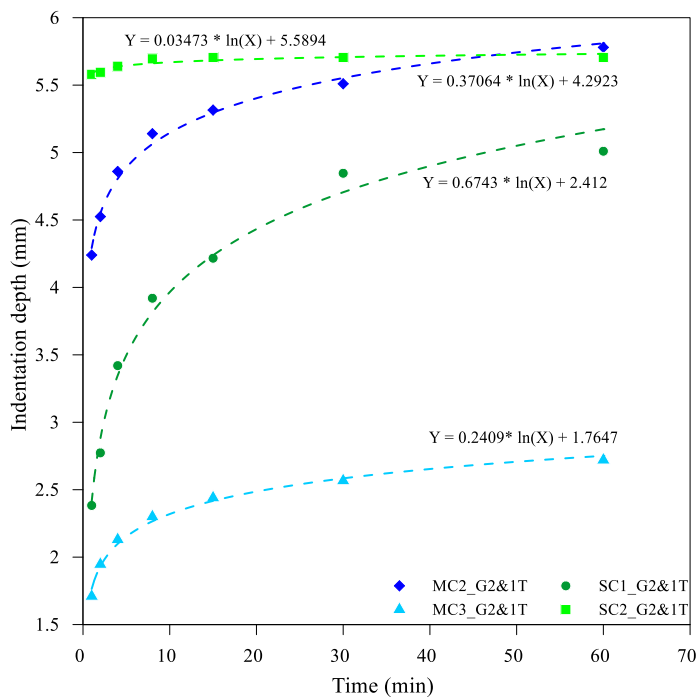


Figure 3.10 Indentation test results for different CMPMs (P200/N100)

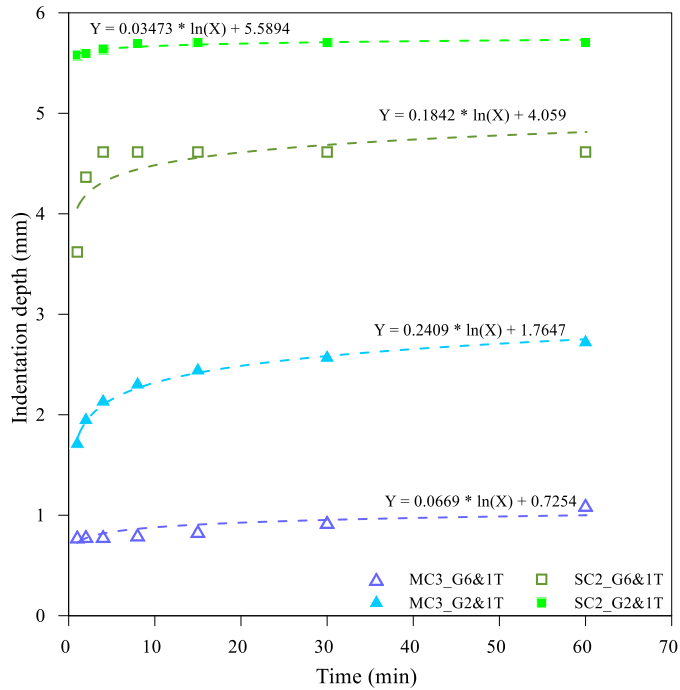


Figure 3.11 The effect of compaction pressure on the stability of CMPMs

The stability results of the MC3 and SC2 specimens, which produced the greatest and worst performances under the applied static stress, are shown in Fig. 3.11. The curves show that the ultimate indentation depth of the specimens decreased as the compaction pressure increased from 200 kPa to 600 kPa. The depth of MC3 specimens was reduced by over 60%, whereas this value for SC2 specimens was just 19%, making the difference between the two considerably more pronounced. The findings for MC2 and SC1 specimens compacted at 600 kPa pressure were 46% and 42%, respectively, indicating improved stability against the applied load. The results emphasized that improved workability does not necessarily lead to better compactability and densification. As a result, even when using a compaction pressure of 600 kPa to make the specimens, the performance of SC2 specimens was not affected in the same way that other materials were.

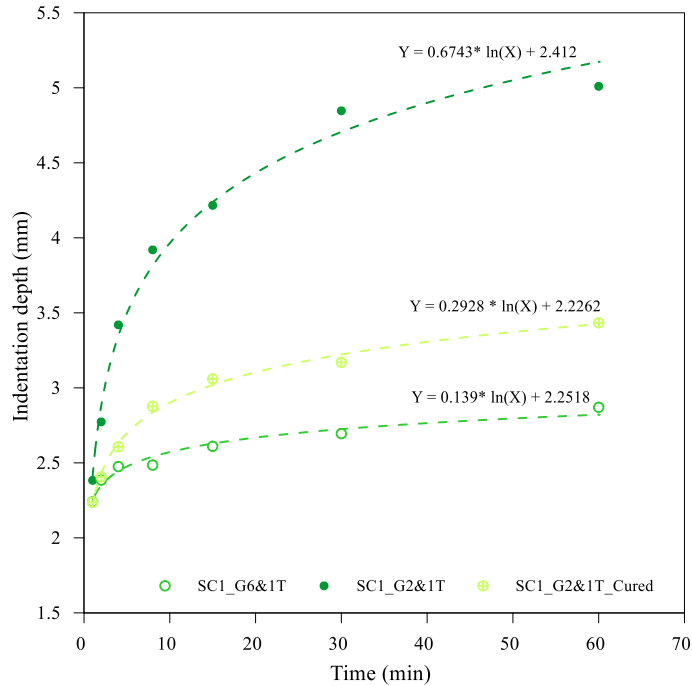


Figure 3.12 The effect of curing and compaction pressure on the stability of CMPMs

Fig. 3.12 shows the impact of compaction pressure and curing time on the stability of the SC1 specimens. A few SC1 specimens were compacted at 200 kPa and cured before testing under laboratory conditions for 110 days. According to the graphs, the impact of raising the compaction pressure from 200 kPa to 600 kPa when making the specimens was higher than the effect of curing them, as the indentation depth obtained for the samples made at the compaction pressure of 600 kPa compared to the indentation depth of the 110-day curing specimens was less. The slope of the trendlines revealed the same results, as increasing the stability of the specimens reduced the slope of the trendline. Compaction pressure and curing have a noticeable impact on the specimens' stability. Because of this, if the specimens are not sufficiently compacted or cured for a long enough period to provide greater density, they will not be able to withstand the imposed stress, resulting in quick penetration of the indenter pin into the specimen. Therefore, more penetration in a short period due to poor

stability led to steeper slopes for the weak specimens. Again, it was found that the effect of compaction pressure is higher than the influence of curing time in terms of providing stability for CMPMs.

The indentation depth values were also measured for moldless specimens. MC and SC moldless specimens lost their stability after being subjected to the applied load. The SC specimens exhibited poor performance and collapsed a few seconds after loading. However, MC materials withstood a few more minutes before collapsing (Fig. 3.13). It seems that the distance between the loading spot and the edge of the specimens was not long enough to prevent rapid crack propagation, which led to the specimens' failure in a short time. The results from the two methods showed that the mold-surrounded specimens led to more reasonable outcomes than the moldless ones, as the values obtained from the moldless specimens did not result in logical conclusions.

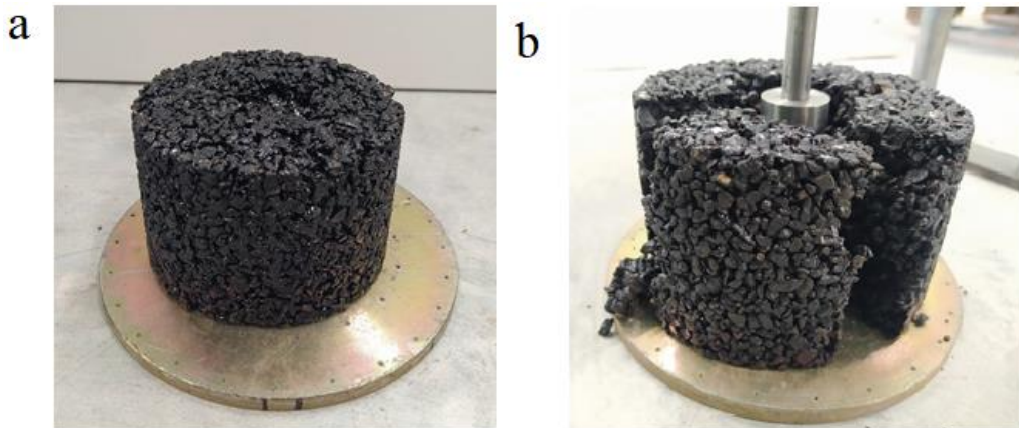


Figure 3.13. tested specimens a) mold-surrounded SC specimen b) MC moldless specimen

3.4.3 Evaluation of the CMPMs raveling

To evaluate the resistance of the CMPMs to raveling, the brush test was used. The findings are as follows:

3.4.3.1 Brush test

Table 3.6 presents the results of the brush test for CMPM specimens. The findings showed that SC specimens did not perform satisfactorily under any compaction and curing settings because they quickly developed a high rate of abrasion. Although the mass loss of the SC1 specimens was decreased by curing the specimens and increasing the compaction pressure to 400 kPa, this reduction was not desirable. However, raising the pressure and cure time increased the MC materials' resistance to raveling. Nevertheless, the compaction pressure and cure time had varied effects on each of them (MC1, MC2, MC3, and MC4). Generally, the effect of compaction pressure on the material's resistance to raveling and abrasion was higher than the influence of curing time; however, the severity of this effect varied for MC specimens. For instance, after curing for 30 days, the MC1 2&1T specimens' abrasion loss dropped from 11.65 to 4.89 (6.76 percent difference), whereas raising the compaction pressure to 400 and 600 led to variances of 9.31% and 11.01%, respectively. Nevertheless, the best abrasion resistance was attained when the curing time and compaction pressure worked together. For example, when the sample mixture was compacted at 600 kPa rather than 200 kPa and allowed to cure for 30 days, the mass loss dropped to 0.27%.

The effect of raising compaction pressure to make the MC1 specimens was much more considerable than curing in a short time, as the abrasion or mass loss noticeably decreased with increased compaction pressure, where the specimens had not been allowed to cure. Compaction pressure alone did not significantly reduce mass loss in the remaining MC products (MC2, MC3, and MC4), whereas the combination of compaction pressure and curing increased the specimens' resistance to raveling. The effect of this combination was not seen in SC2 specimens since, as was already noted, they performed incredibly poorly.

Table 3.6. The mass loss of CMPM specimens prepared at different compaction pressure

		Curing [day]								
		0	7	30	0	7	30	0	7	30
		Test time [sec]								
		30	60	120	30	60	120	30	60	120
Specimen		Weight loss [%]								
MC1	2&1T	11.65	>15 *	>15	7.26	>15	>15	4.89	10.92	11.91
	4&1T	2.34	3.63	4.00	0.92	1.30	2.13	0.66	1.15	2.40
	6&1T	0.64	1.32	1.61	0.27	0.35	0.51	0.27	0.42	0.60
MC2	2&1T	>15	>15	>15	>15	>15	>15	>15	>15	>15
	4&1T	>15	>15	>15	13.91	>15	>15	11.76	>15	>15
	6&1T	12.6	>15	>15	2.8	5.17	5.82	1.94	3.55	5.06
MC3	2&1T	>15	>15	>15	>15	>15	>15	>15	>15	>15
	4&1T	>15	>15	>15	12.89	>15	>15	0.69	3.33	11.26
	6&1T	>15	>15	>15	5.65	16.93	>15	0.68	1.93	5.49
MC4	2&1T	>15	>15	>15	>15	>15	>15	>15	>15	>15
	4&1T	>15	>15	>15	>15	>15	>15	>15	>15	>15
	6&1T	>15	>15	>15	>15	>15	>15	14.21	>15	>15
SC1	2&1T	>15	>15	>15	>15	>15	>15	>15	>15	>15
	4&1T	>15	>15	>15	13.9	>15	>15	12.80	>15	>15
	6&1T	>15	>15	>15	>15	>15	>15	>15	>15	>15
SC2	2&1T	>15	>15	>15	>15	>15	>15	>15	>15	>15
	4&1T	>15	>15	>15	>15	>15	>15	>15	>15	>15
	6&1T	>15	>15	>15	>15	>15	>15	>15	>15	>15

* The weight loss was severe, and the thickness of the testing specimens were not tall enough to have contact with wire brush. Therefore, the test was stopped after extremely poor performance.

Furthermore, if the pressure applied to compact the specimens is too high, it can lead to worse results. Compacting the SC1 specimens at 600 kPa (SC1 6&1T) resulted in aggregate breakage and a higher abrasion rate. Therefore, when applying higher pressure to densify the material, consideration should be given to the mix design and the quality of the mixture components.

3.4.4 CMPMs Bonding evaluation

A shear bond test was performed to investigate the interface bonding quality between the existing surface and patched CMPMs. The findings are as follows:

3.4.4.1 Shear bond test (SBT)

Bonding was used to refer to the amount of energy required to break the adhesion between two layers. The results presented in Table 3.8 and on the following graphs demonstrated that the SC materials provided better bonding performance against the applied shear load compared to the MC materials, as the pre-peak, post-peak, and total energy needed to break the adhesion between the SC specimens (SC1 and SC2) and the base HMA layer were greater than what were required for the MC specimens (MC1 and MC2). In other words, SC specimens were stickier than MC specimens and resisted the shear force more effectively; as a result, more energy was needed to overcome this adhesiveness and fail the specimens.

The results (Table 3.7) showed that compared to mixtures prepared at 200 kPa, all sample products (MC2, MC3, SC1, and SC2) compacted at 600 kPa required more energy to overcome interlayer bonding and failure of the complex specimens. At each compacting pressure employing an SGC, the pre- and post-pick energy absorbed by SC products (SC1 and SC2) was greater than the pre- and post-pick energy absorbed by MC mixtures (MC2 and MC3). However, during the Marshall hammer compaction, only the post-pick energy absorbed by the SC specimens was higher than the values obtained for the MC.

Table 3.7. The shear bond test results obtained for tested CMPMs

CMPM	Specimen		$F_{SBT,mc}$ (kN)	F'_{SBT} (kN/mm)	$\tau_{SBT,max}$ (kPa)	$K_{SBT,max}$ (Pa/mm)	Eng_A (N·mm)	Eng_B (N·mm)
MC2	G2&1t	Avg.	0.20	0.23	24.72	28.73	34.52	42.10
		STDEV	0.01	0.04	1.56	4.47	3.24	28.93
	G6&1t	Avg.	0.47	0.83	57.15	102.08	138.62	153.19
		STDEV	0.00	0.04	0.35	5.51	15.81	55.51
	M70&1t	Avg.	0.38	0.59	46.06	71.98	94.72	78.19
		STDEV	0.02	0.02	2.46	2.50	14.40	5.71
MC3	G2&1t	Avg.	0.21	0.20	26.13	24.05	37.92	41.32
		STDEV	0.04	0.06	4.59	7.76	19.23	18.98
	G6&1t	Avg.	0.63	0.89	77.63	109.37	261.54	239.21
		STDEV	0.03	0.09	4.19	11.28	66.21	69.08
	M70&1t	Avg.	0.46	0.71	55.99	86.64	134.00	110.40
		STDEV	0.04	0.03	5.28	4.11	25.70	12.53
SC1	G2&1t	Avg.	0.29	0.34	35.94	41.58	75.61	141.64
		STDEV	0.02	0.03	2.87	4.26	14.76	18.83
	G6&1t	Avg.	0.61	0.85	78.08	103.94	309.97	429.70
		STDEV	0.05	0.11	6.26	12.97	30.65	60.15
	M70&1t	Avg.	0.34	0.39	41.92	47.36	107.11	166.47
		STDEV	0.01	0.01	1.47	0.63	15.70	39.42
SC2	G2&1t	Avg.	0.21	0.20	25.74	24.59	52.66	144.18
		STDEV	0.01	0.02	1.07	1.95	12.24	26.19
	G6&1t	Avg.	0.40	0.41	49.44	50.66	279.75	372.11
		STDEV	0.01	0.05	0.97	5.61	7.32	53.40
	M70&1t	Avg.	0.24	0.23	29.90	28.05	71.71	138.71
		STDEV	0.03	0.04	3.37	4.90	11.71	32.16

Furthermore, the post-pick energy absorbed by SC specimens was greater than their pre-pick energy, whereas the post-pick energy absorbed by MC specimens was nearly equal to their pre-pick energy. This may show that SC materials are more flexible than MC materials.

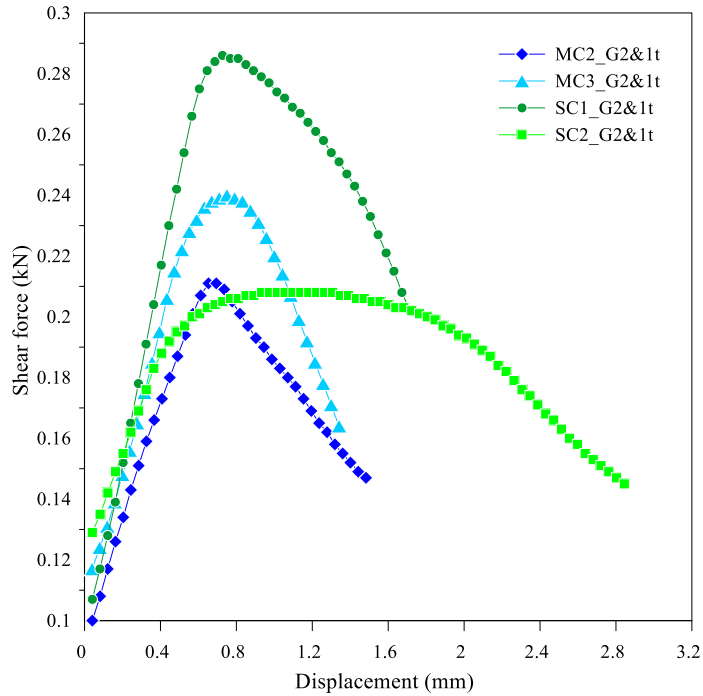


Figure 3.14 The bond shear test results obtained from CPM specimens compacted at 200 kPa

The initial slope and the sharply descending post-peak curve recorded for MC specimens (Figs. 3.14 and 3.15) were steeper than those reported for SC specimens, indicating that even while MC specimens absorbed less energy before beginning to fail, they were stiffer and more brittle. The MC specimens displayed a short displacement following the application of the maximum shear force, in contrast to the SC specimens. However, the SC specimens exhibited a longer displacement, indicating the compacted specimens' flexibility.

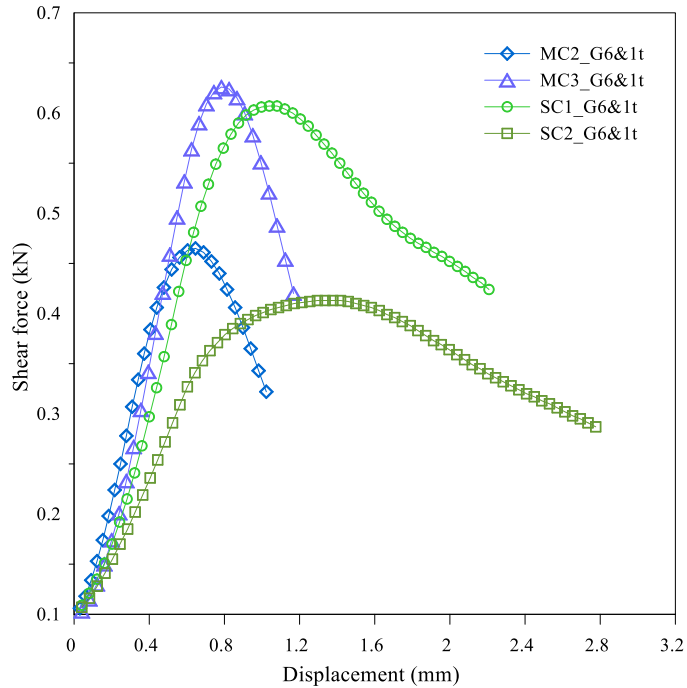


Figure 3.15 The bond shear test results obtained from CPM specimens compacted at 600 kPa. As previously noted, the higher compaction pressure led to better interlayer bonding results. However, the behavior of the materials did not change much, and the brittleness of the MC specimens was higher than the SC specimens. Furthermore, the air void contents were nearly equal whether the sample mixtures were compacted with 70 Marshall hammer blows or SGC at 200 kPa. However, the specimens compacted by the Marshall hammer produced better interlayer bonding than those compacted by an SGC at 200 kPa (Fig. 3.16). This bonding improvement was much more noticeable for MC samples than SC specimens, as the obtained shear forces for the Marshall hammer compacted MC specimens were closer to their SGC-compacted ones at 600 kPa. As a result, when equal compaction pressure was considered, the specimens made by a Marshall hammer produced a stronger bond than the SGC.

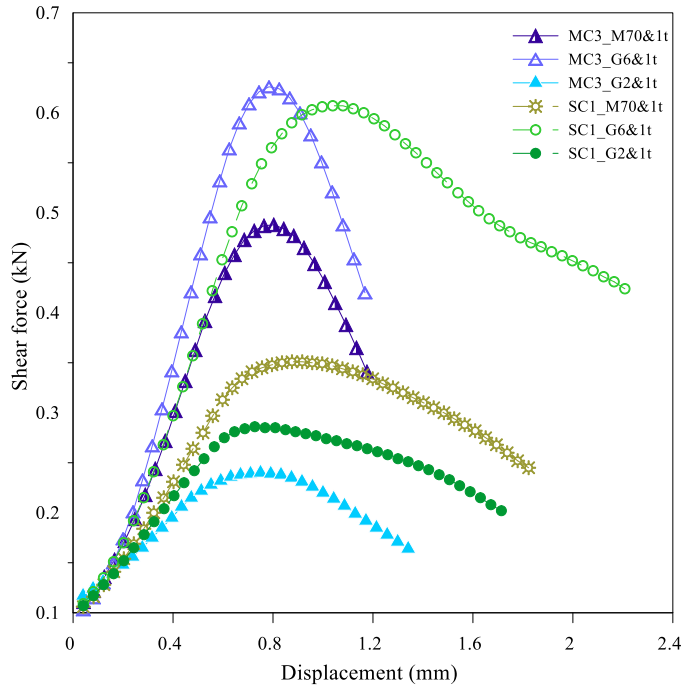


Figure 3.16 The bond shear test results obtained from specimens compacted using the Marshall Hammer and an SGC

3.5. Conclusions

In this chapter, six different kinds of cold patching materials (referred to as MC1, MC2, MC3, MC4, SC1, and SC2) belonging to two main classifications of commercially available CMPMs, including solvent-containing mixes (SC) and membrane-containing mixtures (MC), were considered to evaluate their function and mechanical performance using existing and newly proposed testing methods. The main outcomes can be summarized as follows:

- The locking point of the specimens provided reliable measuring ranges to assess the workability of the CMPMs. The materials with locking points of 50 to 60 and 40 to 50, respectively, had good and excellent workability, according to the obtained locking point values and

laboratory visual observations. Also, materials with a locking point greater than 60 were rough and hard to compact.

- Increasing the compaction pressure or conditioning temperature of the mixtures resulted in a higher density of the specimens, showing improved compactability and workability of the materials.
- The locking points of all CMPMs, except for the SC2 product, displayed a direct correlation with the degree of densification at every temperature and pressure setting. The higher the locking points, the poorer the densification, and vice versa. Contrary to expectations, the SC2 mixture with the lowest locking point, or, more specifically, the best workability, had a lower densification percentage or higher air void contents at 20 ± 1 °C and 2 ± 1 °C under different compaction pressures.
- Although the relationship between compactability and workability is striking, it is not the only determining factor. Workability seems to be more influenced by the mixture's components than other elements.
- Although the densification or air-void content of the specimens is beneficial for comparing the compactability and workability of different CMPMs, it does not offer a measuring range for categorizing the workability of the cold patching materials.
- In the Marshall stability and ITS test techniques, SC materials performed dreadfully in terms of stability and strength and were vulnerable to higher temperatures. The specimens collapsed while being cured at 60 °C, making their movement impossible. Even at ambient temperature, the SC2 specimens collapsed before the test.
- At both conditioning temperatures, all MC specimens outperformed the acceptable levels for Marshall stability. The stability findings from conditioning CMPMs at 20 °C were almost four times better than those from conditioning at 60 °C.

- The Hubbard-Field test method produced more reliable findings when evaluating the stability of SC specimens, and testing the SC2 specimen was possible through this method after 30 days of curing. Hubbard-field thin specimens, as opposed to Marshall briquettes, offered quick curing and were considerably more akin to the field patch.
- The indentation stability test provided more reasonable outcomes when mold-surrounded specimens were used. Using larger specimens to reduce the impact of rapid crack propagation and mold restrictions in the indentation test is advised.
- The outcomes of the brush test showed that SC specimens did not perform satisfactorily under any compaction and curing settings because they quickly developed a high rate of abrasion. However, raising the pressure and cure time increased the MC materials' resistance to raveling.
- The effect of compaction pressure on the material's resistance to raveling and abrasion was higher than the influence of curing time; however, the severity of this effect varied for MC specimens. Nevertheless, the best abrasion resistance was obtained when the curing time and compaction pressure worked together.
- The MC specimens displayed a short displacement following the application of the maximum shear force in the shear bond test, in contrast to the SC specimens. However, the SC specimens exhibited a longer displacement, indicating the brittleness of the MC specimens was higher than the SC specimens.
- Compared to SGC, Marshall hammer compaction produced better interlayer bonding outcomes. When equal compaction pressure was considered, the specimens made by a Marshall hammer provided a stronger bond than the SGC.

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Chapter 4

Compacting of patching materials

4.1. Introduction

Cold mix patching materials (CMPMs) typically offer short-lived patches and demand frequent maintenance [1, 2]. However, employing top-notch patching supplies and a reliable repair technique might increase the durability of the patches [3, 4]. In typical pothole repair practices, the cold mixture is shoveled into the pothole without any heavy compaction, removing the water and debris, or is generally compacted manually using feet, a hand tamper, and a truck wheel [5, 6]. Therefore, the compaction of the mixtures plays an essential part in the patching, which is performed by the road maintenance crew. As a result, the obtained density can range depending on each person's effort and the pothole's dimensions, resulting in varying durability. To evaluate the influence of densification on CMPM-patched potholes, a laboratory-based experimental plan was performed using two compaction methods, i.e., compacting by the Marshall hammer and the Superpave gyratory compactor (SGC). This chapter discusses research on the volumetric properties of CMPMs and the impact of densification on the performance of patches.

4.2. Materials

Eight distinct kinds of patching materials (designated as MC1, MC2, MC3, MC4, MC5, SC1, SC2, and WR1) were employed to assess the volumetric characteristics and compactability of CMPM. These products fall within the three main classifications of commercially available CMPMs, including solvent-

containing mixes (SC), membrane-containing mixtures (MC), and water-reactive (WR) materials, which are categorized based on the components, price, and quality. The SC materials were a mix of reclaimed asphalt pavement (RAP) binder, solvent, and virgin aggregates. The MC products contained RAP, recycled asphalt pavement (RAS), and virgin aggregates in their mix design. The WR product had a unique proprietary binder and a blend of additives that ensured rapid hardening of the mixture through a chemical reaction when exposed to water. The mixture composition was determined using the ignition test method (EN 12697-39). First, the binder content of the mixtures, which is expressed as a percentage of aggregate mass, was calculated by burning the binder of the mixture samples at high temperatures. Then, the sieve analysis was performed on the residual aggregate to determine the gradation of the mixtures. Table 4.1 presents the results obtained for each product.

Table 4.1 Binder content and grain distributions of the mixtures

Material	Sieve size [mm]										Binder [%]
	10	8	6.3	4	2	1	0.5	0.25	0.0125	0.06	
	Cumulative passing [%]										
MC1	99.8	99.6	97.6	64.0	24.4	15.8	11.9	8.9	*	6.3	6.6
MC2	100.0	100.0	94.4	63.3	22.1	13.7	10.5	8.4	*	6.2	6.5
MC3	100.0	100.0	97.1	58.2	28.6	21.2	15.6	13.6	*	9.1	6.4
MC4	100.0	100.0	97.0	52.4	24.2	16.9	13.9	12.0	10.0	8.5	5.9
MC5	100.0	100.0	99.4	67.0	32.1	26.2	22.8	20.5	*	14.8	5.8
SC1	99.8	99.8	95.4	50.0	19.4	12.0	9.2	7.9	*	5.9	4.8
SC2	100.0	99.8	97.9	64.4	15.8	8.0	6.3	5.3	*	3.9	4.4
WR1	100.0	99.0	91.8	64.6	36.6	20.2	11.0	7.4	*	3.4	6.7

* The 0.0125-mm sieve was not used in the aggregate gradation.

4.3. Methodology

A laboratory experiment was performed to investigate the volumetric characteristics of CMPMs. Three different temperatures, i.e., 20 ± 1 , 2 ± 1 , and $-15 \pm 1^\circ\text{C}$, were considered for conditioning and compacting the mixtures. The

sample mixtures and the compaction molds (collar, cylinder, and plate) were initially conditioned in a climate chamber at each mentioned temperature for 24 hours. Then, cylindrical specimens with a diameter (D) of 100 mm and a nominal height of 65 ± 5 mm (thick) or 35 ± 5 mm (thin) were made using a Marshall hammer and an SGC. For compacting sample mixtures with a Marshall hammer, 35, 50, and 75 blows per side were considered. The chosen pressures for SGC compaction were 200 to 600 kPa for 200 gyrations. Before testing, the compacted specimens were dried to a constant weight at laboratory conditions (temperature = $22 \pm 2^\circ\text{C}$; humidity = 55%), and their volumetric properties were measured following EN 12697-5 and EN 12697-6 standards.

Acronyms (e.g., SC1_M75t) were used to label each mixture: the first pair of letters and number describe the material type (SC, MC, or WR), the letter after the underscore symbol defines the compaction procedure (M = Marshall hammer and G = SGC), the numbers refer to the compaction effort (XX = number of blows for the Marshall Hammer; YZ = compaction pressure in kPa/100 for 200 gyrations using the Superpave Gyratory compactor), and the last letter identifies the specimen height (T = 65 mm; t = 30 mm). The label WR_G2T, for example, denotes a specimen of the water-reactive material, which was compacted with the Superpave gyratory compactor at a pressure of 200 kPa for 200 gyrations, yielding a final height of 65 ± 5 mm. The temperature of the specimen will be added to the label if it is conditioned at a temperature other than $20 \pm 1^\circ\text{C}$. For instance, label MC5_M75t_2°C demonstrates that the MC5 sample has been conditioned at $2 \pm 1^\circ\text{C}$ before testing and then compacted in a 35 ± 5 mm layer using 75 Marshall blows.

4.4. Results and discussion

Following the steps outlined in EN 12697-5, the theoretical maximum specific gravity, or Rice density (ρ_m), of the loose mixtures—which depends on the

aggregate specific gravity and asphalt binder content of each product—was first determined to assess the compaction impact on the patch durability and volumetric properties of the CMPMs. The bulk density of the compacted specimens was then calculated at various conditioning temperatures following EN 12697-5 and using the results obtained for ρ_m . The outcomes are as follows:

Table 4.2 Theoretical maximum density results

Mixture	Avg. Rice density [gr/cu.cm]
MC1	2.64
MC2	2.57
MC3	2.68
MC4	2.52
MC5	2.69
SC1	2.58
SC2	2.61
WR1	2.40

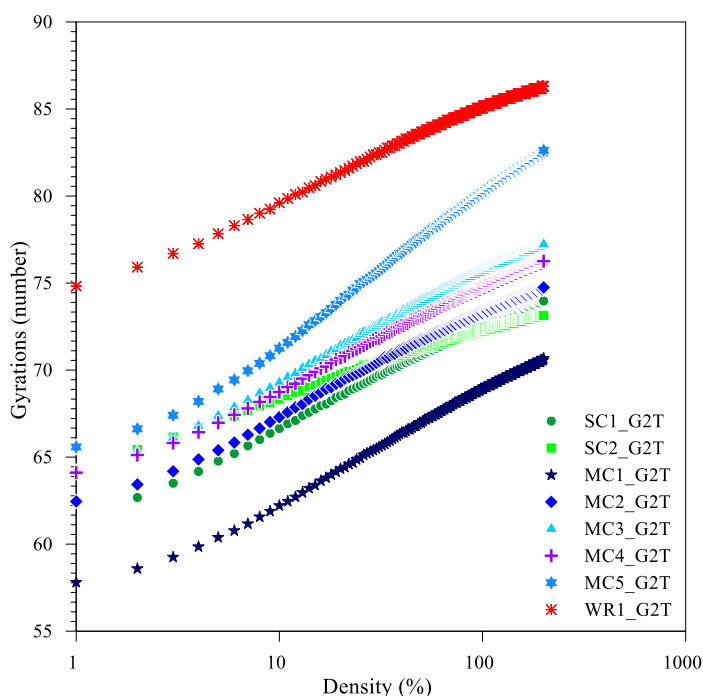


Figure 4.1 The densification of CMPM specimens at 200 kPa compaction pressure

The findings demonstrated that, in contrast to the WR mixture, the Rice density of other CMPMs was almost comparable. Plus, the bulk density of the specimens was affected by compaction pressure and conditioning temperature. The results of the densification of the mixture in Fig. 4.1 revealed that excellently workable WR materials supplied the best densification; however, SC2 samples with excellent workability delivered poor densification compared to the other CMPMs. Additionally, the least workable of the materials, MC1 mixes, demonstrated the weakest compaction, leading to the highest air-void content. Based on Fig. 4.2, increasing the compaction pressure from 200 to 600 kPa enhanced the compactability of the mixtures and produced higher densities; nevertheless, the SC mixtures, especially the SC2, were barely affected by the increased pressure, demonstrating that higher workability is not always accompanied by better densification.

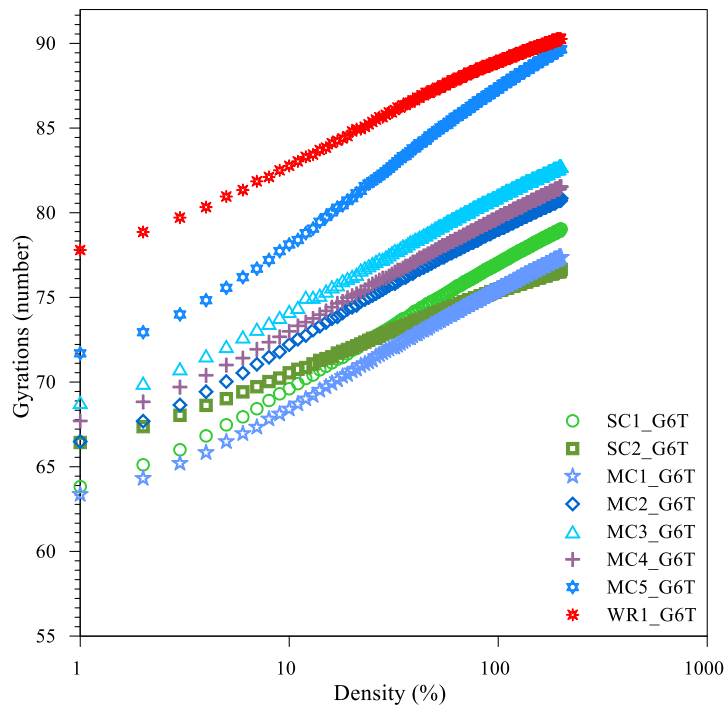


Figure 4.2 The densification of CMPM specimens at 600 kPa compaction pressure

Increasing the compaction pressure and conditioning temperature improved the compactability and densification of the mixtures, resulting in lower air-void contents and more stable specimens. Table 4.4 shows the variations in the void content of the samples at a temperature of 20 ± 1 °C with respect to the reference conditions, i.e., G2T at 20 ± 1 °C. According to the results, increasing the compaction pressure from 200 kPa to 600 kPa at the same temperature (20 ± 1 °C) had the highest effect on the air-void contents. For example, the air-void contents of the MC3 specimens decreased by 24.6% when the compaction pressure increased to 600 kPa.

Table 4.3. Average air-void percentages obtained for thick specimens

Compaction method	Air-void [%]								
	G2T	G6T	G2T	G6T	G2T	G6T	M35T	M50T	M75T
Mixture	Conditioning temp. [°C]								
	-15 ± 1			2 ± 1			20 ± 1		
MC1	*	*	30.0	23.5	29.2	22.6	33.0	30.2	28.5
MC2	31.8	28.5	27.6	20.9	25.2	19.5	28.3	26.5	25.2
MC3	28.5	20.8	24.3	18.3	22.8	17.2	23.0	21.8	19.6
MC4	27.5	19.0	24.2	18.1	23.3	18.5	23.0	22.0	20.4
MC5	*	*	*	*	16.8	10.1	23.2	21.3	19.2
SC1	33.0	25.9	29.1	22.9	26.0	21.0	27.0	25.1	24.4
SC2	32.2	27.4	*	*	27.5	25.5	28.2	26.8	26.4
WR1	*	*	15.7	10.6	14.5	9.7	15.3	13.5	11.6

* There is no data.

However, decreasing the temperature from 20 ± 1 to 2 ± 1 °C did not affect density as significantly as raising the pressure, and the air void content only increased by 6.6% for the MC3 samples. Nonetheless, lowering the temperature to -15 ± 1 °C resulted in the worst densification and roughly the same densification changes as increasing the compaction pressure had on the specimens, but vice versa. The air-void contents of the MC3 specimens at -15 ± 1 °C decreased by 25%.

Table 4.4 Changes in air-void contents with respect to reference conditions i.e., G2T at 20±1°C

Compaction method	Air-void content changes [%]							
	G2T	G6T	G2T	G6T	G6T	M35T	M50T	M75T
Mixture	Conditioning temp. [°C]							
	-15 ± 1		2 ± 1			20 ± 1		
MC1	*	*	2.7	-19.5	-22.6	13.0	3.4	-2.4
MC2	26.2	13.1	9.5	-17.1	-22.6	12.3	5.2	0.0
MC3	25.0	-8.8	6.6	-19.7	-24.6	0.9	-4.4	-14.0
MC4	18.0	-18.5	3.9	-22.3	-20.6	-1.3	-5.6	-12.4
MC5	*	*	*	*	-39.9	38.1	26.8	14.3
SC1	26.9	-0.4	11.9	-11.9	-19.2	3.8	-3.5	-6.2
SC2	17.1	-0.4	*	*	-7.3	2.5	-2.5	-4.0
WR	*	*	8.3	-26.9	-33.1	5.5	-6.9	-20.0

In addition, in most cases, 35 and 50 blows per side had no appreciable impact on the specimens' air-void contents. However, compacting the sample mixtures with 75 Marshall hammer blows per side improved the compaction and produced a higher density with respect to the reference compaction pressure.

Table 4.5. Average air-void percentage obtained for thin specimens

Air-void [%]					
CMPM	G2t	G6t	M35t	M50t	M75t
MC1	*	24.0	29.5	28.6	26.3
MC3	*	17.9	19.2	18.1	16.6
MC4	*	19.9	*	21	18.9
SC1	*	24.7	26.2	24.4	21.1
SC2	*	26.0	27.3	25.3	24.0

Table 4.5 shows the void percentage of thin samples prepared using the SGC and the Marshall hammer and conditioned at 20 ± 1°C. The results showed that thinning the specimens did not change the density values compared to thicker specimens, although the results obtained by the Marshall hammer were higher than those obtained by the SGC. When more compaction energy was applied, using the SGC to compact thick specimens produced better densification than a Marshall hammer. As an example, making thick SC1 specimens using an SGC

at 600 kPa resulted in 21% air voids, whereas compacting with 75 Marshall blows provided 24.4% air void contents. However, considering thin specimens, the Marshall hammer offered better densification than the SGC when more compaction energy was used. For instance, utilizing an SGC at 600 to create thin SC1 specimens produced air-void contents of 24.7%, compared to 21.1% when employing 75 Marshall hammer blows.

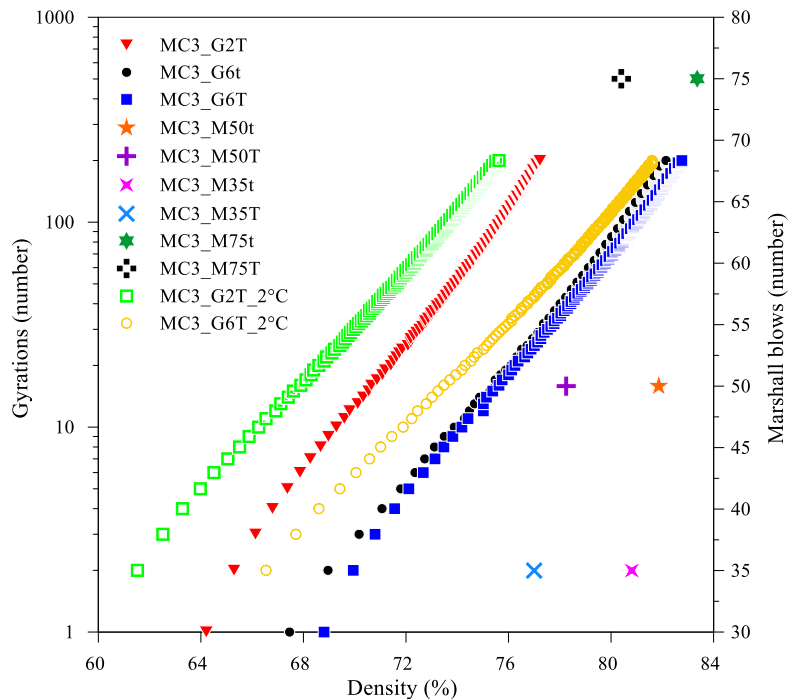


Figure 4.3 The density of MC3 specimens compacted by the SGC and Marshall hammer

For MC3 samples, Fig. 4.3 showed the effect of temperature, compaction pressure, and thickness on the densification of the specimens. As can be seen, higher compaction pressure and conditioning temperature resulted in better densification and lower air-void contents, and vice versa. However, sample mixtures that were conditioned at lower temperatures but compacted at higher pressure displayed improved densification because the influence of compaction pressure was greater than that of conditioning temperature. The densities of the thin and thick specimens did not significantly alter when the samples were

compacted using the SGC, either. But for every set of Marshall hammer blow, the density achieved for thin specimens was higher than that for thick specimens.

4.5. Conclusions

This chapter discussed research on the volumetric properties of eight distinct kinds of CMPMs and the impact of key factors on patch densification at -15 ± 1 , 2 ± 1 , and $20 \pm 1^\circ\text{C}$. The following conclusions can be derived from the test results:

- The density of the specimens was significantly affected by compaction pressure and conditioning temperature. Increasing the compaction pressure and conditioning temperature improved the compactability and densification of the mixtures, resulting in lower air-void contents and more stable specimens. However, the volumetric characteristics were more impacted by the compaction pressure than by the conditioning and compacting temperatures.
- The SC mixtures, the excellently workable SC2, were hardly impacted by the increased pressure, proving that improved densification is not invariably a result of higher workability.
- Thinning the specimens did not change the density values of the CMPM specimens compared to thicker ones, although making the thin specimens with the Marshall hammer produced better densification than the SGC.

When more compaction energy was applied, using the SGC to compact thick specimens produced better densification than a Marshall hammer. However, considering thin specimens, the Marshall hammer offered better densification than the SGC when more compaction energy was used.

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Chapter 5

The importance of CMPM mix design

5.1. Introduction

Cold mix patching materials (CMPMs) are asphalt repair materials used to patch potholes and cracks in road pavements and other surfaces. These mixtures are widely used as temporary patching materials, especially in the winter months when they can be used in low temperatures [1, 2]. They are affordable, have a short application time, and have lower environmental impacts. Despite their benefits in treatment operations, CMPMs perform poorly overall, notably in terms of stability and workability [3, 4]. This decline in performance and durability can be managed by optimizing the mix design. In recent years, various commercial and waste materials, such as flux oils, RAP, and RAS, have been included in CMPM's mix design to improve their performance, particularly their compactability and stability. Flux oil is used instead of petroleum solvents to dilute the hard or oxidized binder to the required viscosity while retaining the solid mix in a workable condition [5]. However, improving workability by decreasing the viscosity may lead to low stability [6]. As a result, reclaimed asphalt pavement (RAP) or recycled asphalt shingle (RAS) is used in the mix design to improve the mechanical performance of CMPM while also striking a balance between workability and stability [7]. Following the end of the waste model and the paradigm of the circular economy, the introduction of RAP and RAS reduces the demand for virgin and non-renewable resources (binders and aggregates) and increases the affordability and sustainability of these mixtures [8]. Research studies have highlighted how CMPMs containing RAP and virgin

aggregates show higher stability [7]. Furthermore, a recent study discovered that using cooking waste oil as a diluent in cold mix asphalt improved adhesion and workability without significantly increasing the strength of the mixture [1]. This chapter details a study on the effect of various amounts of flux oil and RAP on the mechanical properties of conditioned CMPMs at different temperatures.

5.2. Material

Five different CMPMs were produced using virgin aggregates (VA), RAP, RAS, filler, asphalt binder, and additives. The prepared mixture was of the membrane-containing (MC) type, and the polymer-modified asphalt cement contained in RAS served as the required binder for the mixture. The asphalt shingles used were a combination of post-consumer and manufacturing waste. The mixtures' total binder content, as determined by the ignition test method (EN 12697-39), was 6.4%. To soften the binder and make the mixture workable during storage and application, flux oil, a bio-based product, was utilized. The solid skeleton, in terms of amount and grain size distribution, as well as the RAS type and content, were constant parameters, while the amount of RAP and flux oil were considered mixed design variables. Table 1 shows the proportion of each ingredient as a percentage of the total weight of the mixture. All mixtures had a nearly identical solid skeleton (aggregate type and grading curve). An increase in RAP content countered the decline in VA content. In other words, part of the VA in the mix design was replaced by 13.3% and 30% RAP. The proportion of crushed grit to river sand was 3:2. Additionally, the impact of three different amounts of flux oil (1.13%, 1.3%, and 1.8% by the weight of the mixture) on the workability and performance of the mixture was investigated, starting with the ideal flux oil content (1.6% of the mixture's weight) advised by the CMPM manufacturer. The variation in flux oil content was counterbalanced by very slight changes in VA. Each mixture was identified using an alphabetic code

consisting of the capitalized letters R and F (Table 1), representing the first letters of RAP and flux oil, and a pair of numbers indicating the quantity of each ingredient. For example, R30F1.8 represents a mixture that contains 30% RAP and 1.8% flux oil.

5.3. Methods

The same permanent plant that is used for HMA production was utilized to produce CMPMs. The mixer was charged with hot aggregates (180–190 °C) which were mixed with the RAS blend for 120 seconds. Subsequently, the hot aggregates and binder were mixed with RAP for an additional minute. Then, flux oil and filler were added to the mixture when the temperature dropped to approximately 100°C. The mixture was then cooled (to $\approx 90^{\circ}\text{C}$) and discharged at the end of the drum, where it was stored for a week [8].

Table 5.1. Proportion of each ingredient (percentages on the total weigh of the mixture)

	R13F1.1	R13F1.3	R13F1.6	R30F1.6	R30F1.8
Gravels (6.3-2 mm)	42.93	42.77	42.64	32.52	32.64
Sand (< 2mm)	28.61	28.60	28.43	21.68	21.76
Filler (< 0.075 mm)	7.00	7.00	7.00	7.00	7.00
RAP	13.33	13.33	13.33	30.00	30.00
RAS total	7.00	7.00	7.00	7.00	7.00
Flux oil	1.13	1.30	1.60	1.60	1.80

The mixtures were analyzed on a laboratory scale to evaluate several essential characteristics of cold asphalt patching materials, i.e., Marshall quantities (stability and flow) and indirect tensile strength (ITS), which were investigated using a Marshall compression testing machine. Three different temperatures, i.e., 5, 25, and 40 °C, were considered for conditioning and compacting the mixtures. The prepared sample mixtures and the compaction mold (collar, cylinder, and plate) were initially conditioned in a climate chamber at each temperature for 24 hours. The mentioned temperatures were selected to mimic the cold winter,

warm spring, and hot summer conditions in which CMPMs could be stored and used to fill potholes. The conditioned sample mixtures were compacted using a Marshall hammer (EN 12697-30) by applying 50 blows per side. Before testing, the compacted specimens were demolded and left on a smooth, flat surface for eight hours at laboratory conditions (temperature = $22 \pm 2^\circ\text{C}$; humidity = 55%). Based on the theoretical maximum density (ρ_m) of the uncompacted mixtures (EN 12697-5) and the bulk density ($\rho_{b\text{sea}}$) of the extruded specimens (EN 12697-6: sealed specimen procedure), the air void contents (V_m) of the compacted specimens were calculated according to EN 12697-8.



Figure 5.1. CMPM production, discharge, and storage

The Marshall stability-flow test (EN 12697-34) was performed to assess the resistance of the CMPMs to plastic flow. The briquette specimens were loaded at 25°C with a constant deformation rate of 50.8 mm/min in a direction perpendicular to the cylindrical axis. Three replicates were considered for each test product in each experiment, and the results were reported as Marshall stability (S), Marshall quotient (MQ), and flow (F). where S was the peak resistance load obtained during the loading; F was the vertical deformation at the

failure less the nominal deformation obtained by extrapolation of the tangent of the graph of load against deformation back to the zero load; and MQ was the ratio of S to F. Additionally, the ITS test (EN 12697-23) was conducted at 25°C at a constant deformation rate (50 mm/min) to evaluate the indirect tensile strength of the CMPMs, according to Eq. 5.1:

$$ITS = \frac{2000 \cdot P}{\pi \cdot D \cdot H} \text{ (kPa)} \quad (5.1)$$

where P is peak load (kN), D is the diameter of the specimen (mm), H (mm) is the thickness of the specimen. Similar to Marshall stability test, three replicates were considered for each type of CMPM.

5.4. Results and discussion

The performance evaluation of CMPMs in terms of Marshall and ITS values and volumetric properties was presented in two parts: first, evaluating the effect of RAP on mixtures containing an equal amount of flux oil, and second, assessing the impact of flux oil on mixtures containing the same RAP content. The following paragraphs explain the findings, while Figs. 5.2 and 5.3 and Table 5.2 provide a summary.

5.4.1. *The Impact of RAP on CMPMs*

Two types of CMPM were employed to assess the effect of RAP on the performance of CMPMs. Selected CMPMs were almost identical in all areas, excluding the amount of RAP. The mixtures contained a constant amount of flux oil (1.6%) and two different amounts of RAP (13.3 and 30%). The Marshall stability and ITS tests were conducted on the specimens at different temperatures, and the results were displayed in line graphs in Figs. 2a and 2b. According to the findings, increasing the RAP from 13.3% to 30% resulted in better mechanical characteristics at each conditioning temperature when using

an equal amount of flux oil. In other words, R30F1.6 exhibited better mechanical performances than R13F1.6 in terms of ITS and Marshall quantities (S and MQ). As a result, adding a higher percentage of RAP (30%) to the mixture resulted in a higher effect on the mixture's performance. In general, the sample mixtures were thermo-sensitive and showed better stability and strength when they were conditioned and compacted at a higher temperature. In this conditioning scenario, the CMPM cure rate is high, providing better cohesion and mechanical performance. But as evidenced by the slope of the lines in Figs. 2a and 2b, this growth was noticeably more pronounced for R30F1.6. In other words, a mixture containing 30% RAP was more sensitive to temperature and performed better than a mixture containing 13.3% RAP. However, the flow sensitivity to the temperature of mixtures containing different amounts of RAP was almost the same. Different RAP amounts in CMPMs showed essentially identical flow-decreasing tendencies with rising temperatures. This testing behavior reflected what typically occurs in actual circumstances and had some operational implications. CMPMs applied in warm weather conditions have a longer lifespan and better performance compared to those used in cold weather. Therefore, maintenance operations should be scheduled on milder days during the winter, and storing the materials in a thermally insulated or heated setting is a preferred practice. The compactability and volumetric characteristics of the CMPMs were similarly affected by an increase in RAP. According to Table 5.2, at each conditioning temperature, the mixture containing 30% RAP (R30F1.6) had fewer air voids (V_m) and less porosity than the mixture containing 13.3% RAP (R13F1.6), indicating that R30F1.6 was more compacted and densified than R13F1.6. As a result, raising RAP enhanced the mixtures' mechanical and functional performance. Overall, these gains were 20.7%, 34.4%, and 32.2% for stability at 5 °C, 20 °C, and 40 °C, compared to 35.0%, 19.5%, and 39.3% for ITS.

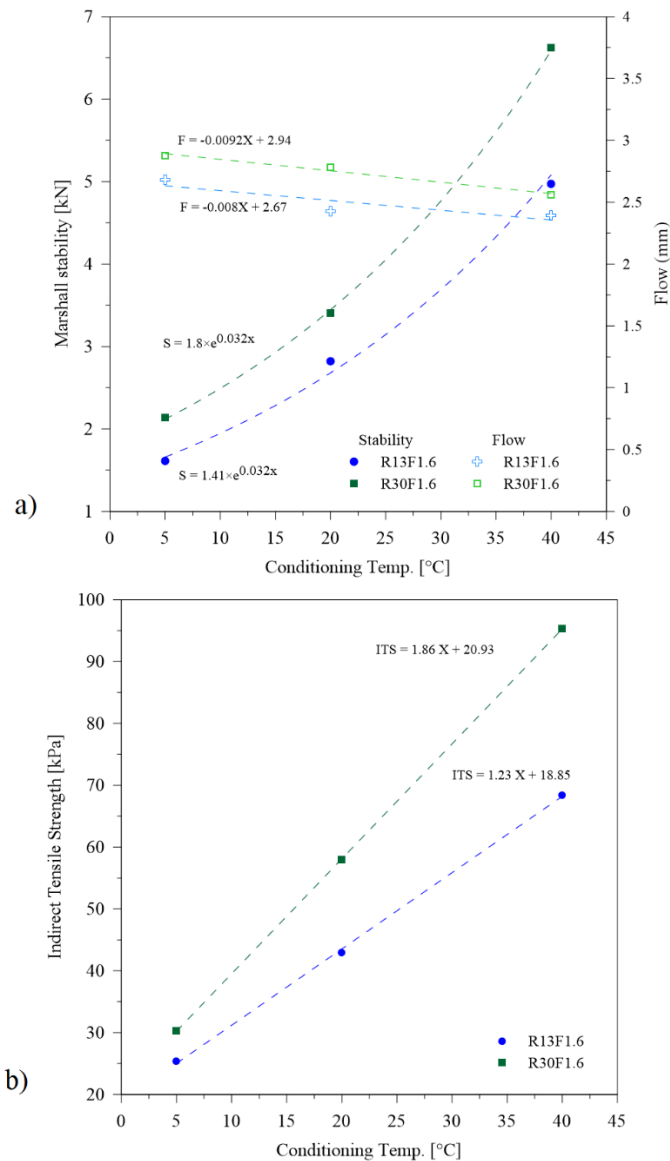


Figure 5.2. Marshall (a) and ITS (b) results of CMPMs containing different amounts of RAP at various temperatures

5.4.2. The influence of flux oil on CMPM

To assess the influence of flux oil on the performance of CMPMs, specimens containing 13.3% and 30% RAP were made using lower (1.1% and 1.3%) and higher (1.8%) than ideal amounts of flux oil (1.6%). The mixtures with the same

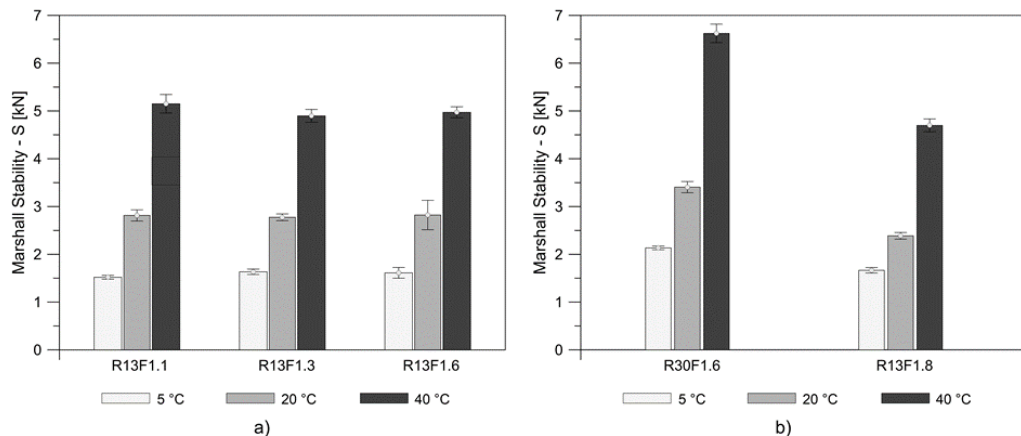
amount of RAP, i.e., R13.3 and R30, were compared to illustrate the results. Due to the low RAP (13.3%) level utilized in the mix design, the effect of flux oil on the mechanical properties of the mixtures at different conditioning temperatures was not discernible. As shown in Fig. 5.3a, when the amount of the flux oil decreased from 1.6% (the ideal amount) to 1.13%, the Marshall stability and Marshall quotient of the CMPMs at various temperatures were nearly constant, registering a 5% standard deviation. However, the flux oil had no impact on the stability of the CMPMs when the RAP in the mixture was minimal. Besides, at each temperature, the volumetric parameters (air voids and compactability) and the ITS were not significantly impacted by the reduction of flux oil (Tab. 5.2).

Table 5.2. Test results of CMPMs at various conditioning temperatures

Material name	Conditioning temperature								
	5 °C			20 °C			40 °C		
	MQ (N/mm)	ITS (kPa)	V _m (%)	MQ (N/mm)	ITS (kPa)	V _m (%)	MQ (N/mm)	ITS (kPa)	V _m (%)
R13F1.1	555.91	30.46	27.49	1126.08	47.60	24.25	2091.68	66.17	22.46
R13F1.3	634.05	26.92	27.00	1117.77	46.02	23.92	2107.98	67.20	22.05
R13F1.6	604.89	25.35	27.30	1116.00	42.96	22.53	2084.22	68.45	20.30
R30F1.6	741.53	30.29	20.77	1225.23	58.00	16.87	2591.23	95.32	14.73
R30F1.8	628.91	25.14	21.81	894.97	45.65	19.27	1891.70	63.79	16.72

However, when the amount of RAP in the mixture was high (30%), the increase in flux oil from 1.6 (R30F1.6) to 1.8% (R30F1.8) decreased the Marshall stability and quotient. Specifically, their Marshall stability dropped by 29.9%, 22.0%, and 29.1%, respectively, at 5 °C, 20 °C, and 40 °C (Fig 5.3 b). Also, the ITS test and volumetric characteristics both showed this pattern. Concerning the R30 mixtures, more flux oil results in a slick state between the aggregates and a reduction in the grains' ability to interlock. Therefore, the aggregates cannot be well compacted, which results in less favorable mechanical properties. The porosity and air-void content of the sample likewise demonstrated the same

tendency. In general, fluctuations in RAP content lead to changes in the flux oil impact. When the amount of RAP in the mixture was considerable, flux oil had a visible effect; however, flux oil did not significantly alter the mechanical performance of the specimens with lower concentrations of RAP. This pattern



may be affected by the amount of oxidized binder diluted by the flux oil.

Figure 5.3. Marshall stability at different conditioning temperatures of cold patches including 13.3%(a) 30 % (b) RAP

5.5. Conclusion

This study used laboratory testing, including Marshall stability, ITS, and density tests, to determine how adding flux oil and RAP affected the mechanical properties of cold mix patching materials. Five different kinds of CMPMs were conditioned at various conditioning temperatures and tested at room temperature to achieve this goal. The following conclusions can be derived from the test results:

- More RAP was employed in the CMPMs, which resulted in improved mechanical performance. Also, CMPMs containing a higher amount of RAP showed better compactability, less porosity, and fewer air voids.
- The impact of using flux oil on CMPMs was noticeable when the amount of RAP used in the mixtures was high. At a higher amount of RAP, raising the flux oil above the ideal amount (1.6%) considerably affected

the CMPMs, while decreasing the flux oil below the ideal amount did not have a noticeable impact on mixtures containing a lower amount of RAP.

- The CMPMs' mechanical and functional properties responded very favorably to conditioning temperatures. Higher conditioning temperatures led to improved performance from CMPMs.
- Mixtures containing different amounts of RAP demonstrated nearly identical flow sensitivity to temperature and had roughly similar flow-decreasing trends.

The findings demonstrated the significance of the mix-design phase as a crucial stage in the production of CMPMs and as the cornerstone for meeting the performance standards that ensure their effectiveness and prolonged service life. The study is therefore meant to serve as a springboard for the growth of symbiotic collaboration between many industries to adopt cutting-edge technological processes to generate durable, valuable, and reasonably priced materials for pothole repair.

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Chapter 6

Field practice

6.1. Introduction

To repair potholes in road pavement, especially during the cold and wet seasons, cold mix patching materials (CMPMs) are utilized [1]. These reasonably priced products offer short-lived patches that necessitate frequent maintenance despite having a quick application time and minimal environmental impact [2]. Employing top-notch patching materials might boost the durability of the CMPM-patched potholes [3]. But there is no accepted test method for evaluating and determining CMPMs' performance before utilizing them, and usually, there is a conflict between laboratory and field assessment outcomes [4, 5]. Producing vertical and clean edges with saw cuts, cleaning potholes from debris, and compacting the patch materials with adequate effort are advised to obtain durable patches [6]. Nevertheless, exposure of the patches to various vehicle traffic, air, humidity, or direct sunlight (UV radiation and/or high temperatures) worsens their performance and declines their durability [7, 8]. To assess the behavior of the CMPMs in patching practices, despite laboratory investigation, a field trial section was set up. This chapter presents a field study to investigate the performance of various CMPMs when employed in patching operations using a proper method.

6.2. Materials

Six distinct kinds of patching materials (designated as MC1, MC3, MC4, SC1, SC2, and WR) were selected to be evaluated in field pothole patching practice.

These products fall within the three main classifications of commercially available CMPMs, including solvent-containing mixes (SC), membrane-containing mixtures (MC), and water-reactive (WR) materials, which are categorized based on the components, price, and quality. The mixture composition was determined using the ignition test method (EN 12697-39). First, the binder content of the mixtures, which is expressed as a percentage of aggregate mass, was calculated by burning the binder of the mixture samples at high temperatures. Then the gradation of the aggregates was determined using the residual aggregates obtained from the ignited mixtures. Table 6.1 presents the results obtained for each product.

Table 6.1 Binder content and grain distributions of the mixtures

Material	Sieve size [mm]										Binder [%]
	10	8	6.3	4	2	1	0.5	0.25	0.0125	0.06	
	Cumulative passing [%]										
MC1	99.8	99.6	97.6	64.0	24.4	15.8	11.9	8.9	*	6.3	6.6
MC3	100.0	100.0	97.1	58.2	28.6	21.2	15.6	13.6	*	9.1	6.4
MC4	100.0	100.0	97.0	52.4	24.2	16.9	13.9	12.0	10.0	8.5	5.9
SC1	99.8	99.8	95.4	50.0	19.4	12.0	9.2	7.9	*	5.9	4.8
SC2	100.0	99.8	97.9	64.4	15.8	8.0	6.3	5.3	*	3.9	4.4
WR	100.0	99.0	91.8	64.6	36.6	20.2	11.0	7.4	*	3.4	6.7

* The 0.0125-mm sieve was not used in the aggregate gradation.

6.3. Methodology

Investigations in the field and the lab were used to assess CMPM performance. For this reason, squared potholes with a diameter of 450×450 mm and a depth of 35±5 mm were created and patched with the CMPMs on a distressed road pavement on Benjamin Franklin Street in Parma (Fig. 6.1). In addition, cylindrical specimens with a diameter (D) of 100 mm and a nominal height of 35±5 mm were made in the laboratory using a Marshall hammer and a Superpave gyratory compactor (SGC). Three sets of blows per side, i.e., 35, 50, and 75,

were selected to compact mixtures with a Marshall hammer. For SGC, the compaction pressure was 600 kPa for 200 gyrations. The density and performance of the patches were investigated immediately following the patching procedure and 1, 8, 30, 90.

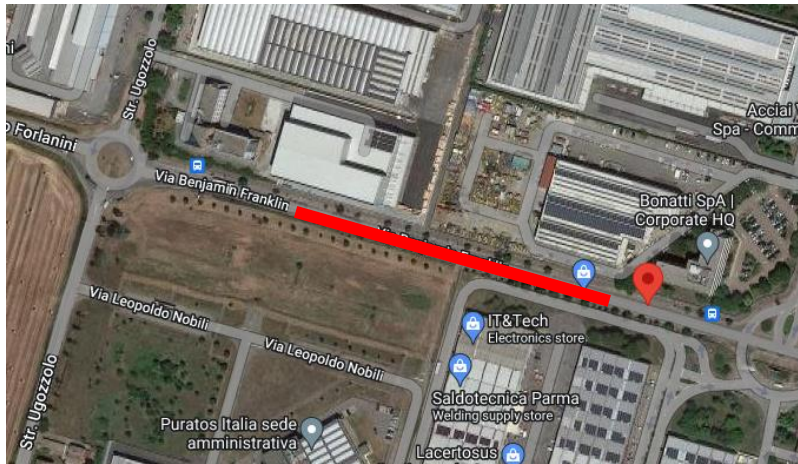


Figure 6.1 The location of the pothole patching case study

6.3.1. Repair procedure

As previously stated, a suitable repair technique is also necessary for a successful repair, in addition to high-quality materials. Nevertheless, repairing potholes takes a lot of effort, and the best patching approach is rarely applied, but a patching technique involving saw cuts to produce a vertical and clean edge and appropriate patching material offers long-lasting patches. The procedures used in this study for creating and filling the potholes were as follows:



Figure 6.2 Creating square potholes using an asphalt milling machine

An asphalt milling machine (Fig. 6.2) was employed to make squared potholes with a size of 450×450 mm and a depth of 35 ± 5 mm. Four potholes were created for each type of material to test their performance in patching operations.



Figure 6.3 Cleaning the potholes by removing dusts and debris



Figure 6.4 Pouring the material into the clean potholes

Then, as seen in Figs. 6.3 and 6.4, after cleaning the potholes of debris, they were randomly filled with patching material.



Figure 6.5 Using feet and hand tamper to compact the patching materials



Figure 6.6 Using feet and a vibratory forward plate compactor to compact the patch

For each type of selected material, two of the potholes were compacted by hand tamper and the other two by a vibratory forward plate compactor (Figs. 6.5 and 6.6). During patching, the weather was sunny, and the temperature of the bottom side of the pothole was 26 °C. The patches were densified with a tamper until it felt like they had sufficiently compacted. Also, three passes were considered for the vibratory compactor to compact the mixtures. Then, truck wheels (Fig. 6.7) were passed over the compacted patches to provide extra compaction.



Figure 6.7 Passing the truck for final compaction

6.3.2 Evaluation methods

The medium- and long-term performance of the patches under traffic and environmental conditions is being monitored. Besides, the densities of the patches were measured over time using a non-nuclear electromagnetic density gauge (Fig. 6.9) to assess the densification level compared to the laboratory condition. Also, following the steps outlined in EN 12697-6, the laboratory specimens' densities were calculated.



Figure 6.8 Measuring the densities of patches with a non-nuclear electromagnetic density gauge

6.4. Results and discussion

The findings obtained from monitoring the patches and laboratory investigations were as follows:

6.4.1 densification

For the case study lane, peak hour traffic was computed and presented in Table 6.2. The results showed that almost 36% of traffic was effective, meaning that the cars drove over repaired potholes and increased densification. Heavy traffic

made up 13.5% of total traffic, yet only 7.8% of it was efficient. The results of the densification of the patches under traffic were summarized in Table 6.3.

Table 6.2 The peak hour traffic for the case study lane

Vehicle	Car		Bus		Truck		Trailer truck	
Time	Not eff.	Eff.	Not eff.	Eff.	Not eff.	Eff.	Not eff.	Eff.
7:30-8:00	127	62	0	1	1	5	8	12
8:00-8:30	142	67	0	1	3	5	14	12
7:30-8:30	269	129	0	2	4	10	22	24
Sum	398		2		14		46	
Total traffic	460							

* Effective traffic: the vehicle passed over the patched pothole.

Table 6.3. Average air-void contents obtained for patches in the field

Compaction method		Air void values [%]							
		Hand tamper				Forward plate compactor			
Material		Measuring time [day]							
		0	1	8	30	0	1	8	30
MC1	Avg	20.54	16.39	13.99	11.48	25.50	19.17	17.03	15.79
	STDEV	3.30	1.95	2.85	3.34	0.33	1.13	1.70	1.05
MC3	Avg	19.40	16.20	14.55	13.71	17.08	11.71	8.20	7.40
	STDEV	0.98	1.84	2.69	2.29	0.76	1.39	0.27	0.38
MC4	Avg	17.21	11.22	8.90	7.88	19.63	15.09	13.39	11.65
	STDEV	0.11	2.74	1.51	1.36	0.97	2.90	3.73	3.97
SC1	Avg	22.34	18.25	15.50	13.80	19.65	17.78	15.09	14.06
	STDEV	1.64	3.38	3.07	3.20	2.11	0.64	1.06	1.08
SC2	Avg	20.63	15.59	13.58	12.36	20.00	16.22	13.90	13.11
	STDEV	0.14	1.17	0.84	1.58	0.67	0.91	0.30	0.41
WR1	Avg	16.96	*	*	*	13.83	*	*	*
	STDEV	0.88	*	*	*	1.20	*	*	*

* Due to the moisture in the patches and the sensitivity of the gauge, measuring the density failed.

Table 6.3 shows the air void values obtained for the patches compacted using a hand tamper and a vibratory compactor machine. As can be seen, the air void decreased over time as the patches were compacted under the traffic loads. According to the air void contents, in the early hours and days, the rate of densification caused by traffic flow was higher, but then it slowed. Except for

MC1 and MC4 mixtures, compacting the patches with a vibratory forward plate compactor provided better densification than doing so by hand tamping. However, the air-void differences obtained from the two methods were less than 5 percent. Additionally, the outcomes of both strategies were nearly comparable for extremely workable SC2 mixtures. As a result, the impact of the compacting method on the compactability and densification of the mixtures depends on the type of material.

Table 6.4 Changes in air-void contents with respect to reference conditions

Compaction method	Air void reduction [%]					
	Hand tamper			Vibratory forward plate compactor		
	Measuring time [day]					
Material	1	8	30	1	8	30
MC1	20.2	31.9	44.1	24.8	33.2	38.1
MC3	16.5	25.0	29.3	31.4	52.0	56.7
MC4	34.8	48.3	54.2	23.1	31.8	40.6
SC1	18.3	30.6	38.2	9.5	23.2	28.5
SC2	24.4	34.2	40.1	18.9	30.5	34.4

Table 6.4 displays the air void content changes in patches due to traffic load over time. According to the data, the patches underwent higher densification on the first day following patching operations, and up to 34.8% of the air void decreased in the patches. However, the compaction increased over time and led to lower air voids; 30 days after the patch operation, the reduction of air voids increased almost twice as much as that experienced after the first day. For example, one and 30 days after the patch operation, the air void contents of the manually compacted SC1 patches decreased by 18.3% and 38.2%, respectively.

Table 6.5 details the densification of thin specimens compacted by SGC and Marshall hammer blows. The laboratory specimens yielded substantially identical air void contents when compressed at 600 kPa for 200 gyrations or by 75 Marshall blows, as the vibratory forward plate compactor did for the patches. 35 and 50 Marshall hammer blows offered higher air void contents or lower

densities compared to field practice. Therefore, more pressure should be employed when compacting specimens to replicate field densification in the laboratory.

Table 6.5. Average air-void percentage obtained for thin specimens

Compaction method	Air-void [%]			
	SGC		Marshall hammer	
	600 kPa	35 blows	50 blows	75 blows
Mixture	Conditioning temp. [20 ± 1°C]			
MC1	24.0	29.5	28.6	26.3
MC3	17.9	19.2	18.1	16.6
MC4	19.9	*	21.0	18.9
SC1	24.7	26.2	24.4	21.1
SC2	26.0	27.3	25.3	24.0

6.4. Conclusions

This chapter described a field investigation to examine how different CMPMs perform when used in patching operations utilizing an appropriate methodology. Square potholes were created and patched using a hand tamper and a vibratory forward plate compactor. Laboratory testing, image processing, and visual observations were used to assess the patches' durability. The findings lead to the following conclusions:

- The impact of the compacting method (i.e., using a hand tamper or vibratory compactor) on the densification of the patching mixtures depends on the type of material. A vibratory compactor did not necessarily provide better densification than a hand tamper, and vice versa.
- The patches achieved up to 34.8% of the air void reduction on the first day following patching operations. The reduction attained after 30 days was nearly twice as great as the reduction realized after the first day.

- To replicate field densification in the laboratory, more compaction pressure (600 kPa for 200 gyrations in an SGC or 75 Marshall blows per side) should be employed when compacting specimens.
- The most workable mixtures offered well-maintained patches without losing more materials since they were densified better toward the edges of the potholes.
- Among the CMPMs, MC1 and WR1, i.e., the worst and the best workable materials, showed the worst and best performance in the field. It seems that the workability of the mixtures was a more decisive factor in the durability of the patches compared to other properties.
- The findings showed that if an appropriate method is used in good conditions, even poorly-evaluated materials in the laboratory last longer.

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Conclusions

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. Currently, the commercially available products are qualified based on certain performance indicators derived from traditional HMA practices (i.e., density and Marshall stability requirements). However, these requirements are not representative of the various service life stages of CMPMs, which range from improving workability at the placement phase to increasing resistance to early traffic and maintaining good adhesion and mechanical strength after compaction. 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. 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.

The outcomes of this study provide greater awareness to CMPM designers and users about the performance of CMPMs in various weather and traffic conditions and enable manufacturers to improve the characteristics of their products by considering various kinds of tests. Moreover, this study opens new windows for researchers to consider different aspects of CMPMs' performances and leads them to improve test methods to analyze and evaluate the patching materials.