Evaluation of Laboratory and Field Performance of High Performance Cold Mix Patching Material with Reduced Volatile Organic Compound Content

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ABSTRACT

Laboratory and field performance of a High Performance Cold Mix (HPCM) utilizing a cutback asphalt cement binder that is compliant with potential Volatile Organic Compound (VOC) restrictions anticipated to be implemented by Environment Canada was evaluated.

An HPCM cutback asphalt binder meeting an ASTM D402 distillation test criteria limiting the VOC content to 0.5 percent at 260 degrees Celsius was developed and used in a production trial of reduced VOC compliant HPCM patching material. A conventional HPCM cutback asphalt binder with a VOC of 38.5 percent at 260 degrees Celsius served as the control. Bulk stockpiles of reduced VOC and conventional HPCM were produced in a cold process using a pug mill with wet and unheated aggregates.

A laboratory evaluation of stockpile field samples over a five month period found that both the low VOC content and conventional HPCM materials had acceptable properties in terms of low temperature workability, mix cohesion, moisture sensitivity, compaction at low temperatures, and draindown.

The field performance of the non VOC and conventional HPCM was monitored over a four month period under slow moving heavy construction vehicle traffic. Both materials performed well when evaluated for bleeding, dishing, disintegration of the cold mix material along the edge of the pothole, missing cold patch, raveling, and shoving.

RÉSUMÉ

Une évaluation a été faite des performances en laboratoire et sur le terrain d'un enrobé froid à haute performance (EFHP) utilisant un bitume fluidifié conforme aux restrictions potentielles sur les composés organiques volatils (COV) qui devraient être imposées par Environnement Canada.

Un bitume fluidifié EFHP conforme au critère de distillation de la norme ASTM D402 de 0.5% de COV à 260ºC a été développé et utilisé dans un essai de production d'un EFHP pour colmatage. Un EFHP classique avec un COV de 38,5% à 260ºC a servi de témoin. Des piles de EFHP conventionnels et à basse teneur de COV ont été produites par procédé à froid à l'aide d'un malaxeur avec des granulats humides et non chauffé.

Une évaluation en laboratoire des échantillons de ces piles sur une période de cinq mois a révélé que les deux EFHP, le conventionnel et celui avec une teneur de COV réduite, avaient des propriétés acceptables en termes de maniabilité à basse température, de la cohésion du mélange, de sensibilité à l'humidité, de compaction à basse température, et de fluage.

La performance sur le terrain des EFHP conventionnel et à basse teneur de COV a été suivie sur une période de quatre mois sous des conditions de trafic lent de véhicules de construction lourds. Les deux matériaux ont bien performé lorsque évalués pour le ressuage, la formation de cuvette, la désintégration de l'enrobé à froid en bordure de nids de poule, l'arrachement, et la formation de bourrelets.

1.0 INTRODUCTION

Environment Canada has signaled intent to limit the concentration of Volatile Organic Compounds (VOCs) in cutback asphalt and emulsified asphalt cement products across Canada under a framework that aligns with controls put forth by the United States Environmental Protection Agency (U.S. EPA) and the California Air Resources Board (CARB). The justification for this initiative is that VOCs contribute to the development of smog which is a significant environmental pollutant and contributes to serious health problems across Canada [1].

Smog is a mixture of atmospheric pollutants comprised primarily of ground-level ozone and Particulate Matter (PM). VOCs are precursors to the formation of ground-level ozone and PM. Nitrogen oxides (NOx) react with VOCs in the presence of sunlight in the lower atmosphere to produce ozone. While ozone in the upper atmosphere protects against harmful ultraviolet radiation from the sun, high levels of ground-level ozone presents a serious respiratory health concern that can impair lung function and cause damage to lungs in otherwise healthy adults and children [1].

PM is composed of airborne solid and liquid particles which may be directly released into the atmosphere or formed by the chemical reaction of sulfur dioxides (SOx), NOx, ammonia, and VOCs. Direct sources of PM include combustion emissions from vehicles and industrial processes, smoke from fires, dust that is generated both naturally and from construction activities when the wind blows. Fine particulates with a diameter of less than 2.5 microns (PM-2.5) have been found to have particularly serious health effects with respect to respiratory and cardiovascular functions. Exposure to air pollution has been identified as a risk factor in the formation of lung and heart cancers [1].

In 2003 the Federal Government of Canada listed VOCs as well as sulfur dioxide, nitric oxide, nitrogen dioxide and gaseous ammonia as toxic substances under the Canadian Environmental Protection Act, 1999 (CEPA 1999) due to their involvement as precursors in the formation PM and ground-level ozone. Limits on the VOC content in architectural coatings and automotive refinishing products were introduced in two federal regulations that were published in 2009. Development of a third regulation to control the VOC content in certain consumer products is currently underway [1].

A discussion paper prepared by Environment Canada in 2010 identified further potential initiatives to reduce VOC levels in seven categories of consumer and commercial products during the 2010 to 2020 time period: asphalt cutbacks, portable fuel containers, automotive coatings, adhesives and sealants, aerosol coatings, rubber product manufacturing and plastic parts coatings, and printing [2].

Environment Canada released a subsequent report in 2012 specifically addressing VOC emissions from asphalt cutback and emulsion products across Canada [1]. This was followed by a consultation meeting with industry and government stakeholders in March of the same year. After reviewing actions taken at various government levels in Canada and the US, the report recommends that limits, based on those implemented by CARB, be adopted as these offer the greatest potential for the reduction of VOC emissions. The proposed limit for cutback asphalt is a maximum of 0.5 percent by volume of VOCs evaporating at 260^{o}C based on ASTM D402 [3]. The corresponding limit under consideration for emulsified asphalt is a maximum of 3.0 percent by volume of VOCs evaporating at 260^{o}C based on ASTM D244 [4]. A decision will be made as part of the consultation process as to whether control measures are implemented in the form of a binding regulation, or as a voluntary code of practice with review periods set to ensure substantial compliance. Environment Canada estimates that implementing the limit of 0.5 percent VOC content for asphalt cutbacks would reduce emissions attributed to asphalt cutback products across Canada by 90 percent [1].

An important application of asphalt cutbacks and emulsions includes cold mix patching materials that are used to repair potholes and utility cuts in pavement surfaces. High Performance Cold Mix (HPCM) is a category of cold applied pavement repair materials consisting of an asphalt cement cutback binder and aggregate and differs from regular cold mix patching materials. The cutback binder in HPCM is engineered using chemical modifiers to ensure good adhesion and compatibility between the binder and aggregate in the mix. HPCM materials are often produced with open graded aggregates that have lower fines contents than the dense graded aggregates used in conventional cold mix patching materials. The open graded aggregate and low fines content assist with improving workability and increasing the shelf life in stock pile or bag of HPCM as compared to conventional cold mix. Pavement repairs completed with HPCM are often considered permanent whereas conventional cold patch materials are for temporary fixes.

A portion of the binder in cold mix patching materials consists of a cutter stock that is used as a solvent for the liquid asphalt cement in the binder. The solvent imparts workability to the mix at low ambient temperatures so that it may be applied in a cold, unheated state.

Standard HPCM and conventional cold mix binders do not meet the proposed VOC limits being considered by Environment Canada due to the nature of the solvent in these products. It would be desirable to reformulate these binders such that they comply with the limits for VOC content that are currently under consideration by the Canadian Federal Government, while ensuring that the quality and performance of the VOC compliant cold patching materials is maintained or improved.

This study involved evaluating the performance of an HPCM cutback binder that was developed to meet the proposed VOC content limits under consideration by Environment Canada (QPR® VOC-Free) against a standard HPCM binder (QPR®) with proven and documented field performance [5]. Desirable performance properties in a cold mix patching material would ideally not be compromised in a reformulated product that complies with reduced VOC content limits.

2.0 SCOPE

Laboratory and field performance properties of a low VOC content HPCM (QPR® VOC-Free) were evaluated and compared to properties of a standard HPCM (QPR®) which had documented field performance and served as a control mix. An asphalt cutback binder with a VOC content of less than 0.5 percent at 260^{o}C when tested against ASTM D402 distillation criteria was used to produce the low VOC content HPCM.

Bulk stockpiles of the low VOC content and conventional HPCM were produced with wet, unheated aggregates using a portable pug mill. Stockpiles were sampled and tested over five months for low temperature workability, mix cohesion, stripping, and compaction properties.

Cold patch material field performance was evaluated by repairing potholes with each mix and subjecting the test areas to slow moving heavy construction vehicle traffic over the course of a four month winter and spring timeframe. The performance of the low VOC content and conventional HPCM was assessed for bleeding, dishing, disintegration of the cold mix material along the edge of the pothole, missing cold patch, raveling, and shoving.

3.0 BACKGROUND

Potholes form when water enters a pavement through a crack or other means of infiltration and softens the base so that it is less able to provide structural support. The inadequately supported pavement is damaged and deteriorates under traffic resulting in a pothole [5, 6]. Freeze thaw conditions accelerate the formation of potholes and are an important consideration in Ontario which has been identified as having the most severe type of climate (wet-freeze) with respect to pothole field performance [7]. Water infiltrates through cracks or other deficiencies in the pavement and expands when it freezes. When the ice melts a weakened and unsupported area is left behind which is further damaged under traffic loadings resulting in a pothole. In thicker pavements, consisting of two or more lifts of asphalt, the freeze thaw conditions may cause delamination of the top asphalt lift. This allows water to collect in the resulting pothole subsequently causing damage to lower lifts and to the granular road base [5, 6].

In stockpile storage, mixes must remain workable at low temperatures, resist draindown at higher temperatures, and exhibit good compatibility between the aggregate and asphalt cutback binder in the presence of water so that stripping problems are avoided. Surface crusting, which acts to protect the mix within the stockpile, must not be excessive and the material must have the ability to be reworked so that the mix is free of clumps [8].

The mix must remain workable in low temperature installation conditions so that it may be properly placed and compacted. After compaction stability becomes important. The cold patch must avoid distresses such as shoving, dishing, raveling, and bleeding. Dishing is the excessive continued compaction of the mix under traffic resulting in deformation in the wheel path. The mix should maintain adequate skid resistance and resistance to edge failures caused by inadequate adhesion between the cold patch and the side or bottom of the pothole [6, 8].

Two of the most common pothole repair methods, owing to the expediency in which they can be completed in the field, are the throw-and-go and the throw-and-roll procedures. In the throw-and-roll method, material is placed into the pothole and rolled with the wheels of a service truck such that a 3 to 6 mm crown is left after compaction. Water and debris is not removed from the pothole. With the throw-and-go method, the mix is not compacted by the repair crew and is left for ensuing traffic to compact [9]. The edge seal method involves applying a tack coat around the edge of the pothole in order to seal the interface between the cold patch repair and the existing pavement [9].

A semi-permanent repair involves clearing out water and debris and using a pavement saw to square the edges of the pothole such that the vertical sidewalls are structurally sound. Mix is then placed and compacted with a vibratory plate compactor or a single drum vibratory roller. The spray injection method involves blowing hot asphalt binder and aggregate, which mix in-situ, into a pothole followed by a cover aggregate. The storage and delivery means for the materials consist of a self-contained vehicle or are towed behind a vehicle [7, 9].

The Strategic Highway Research Program (SHRP) H-106 pothole repair experiment found the throw-and-roll technique to be as effective as the semi-permanent repair method when high quality patching materials were used. The throw-and-roll method was recommended for working in inclement weather [7]. Prowell and Franklin, along with several suppliers of proprietary cold patch products including the mixes evaluated in this study, recommend placing and compacting mix in two lifts for potholes that are greater than 5 cm deep order to avoid dishing [8, 10].

4.0 MIX PRODUCTION

Stockpiles of low VOC content and standard HPCM were produced at the Coco Paving Nebo Road Plant in Hamilton, Ontario during the week of December 10, 2012. Sunny conditions prevailed with an ambient air temperature of 1 to 3^{o}C during production.

Bulk tanker loads of the cutback asphalt binders were supplied from the Coco Asphalt Engineering Clarkson Plant in Mississauga, Ontario at 95 to 105^{o}C. A 100 percent crushed and washed limestone aggregate with a maximum size (defined as the smallest sieve size through which all of the aggregate passes) of 9.5 mm was supplied from the Lafarge Dundas Quarry in Dundas, Ontario.

The cutback asphalt binders were mixed with wet and unheated aggregates using a portable pug mill in a cold manufacturing process. A front end buck loader loaded aggregates into a cold feed bin. The aggregates were then fed into the mixing chamber of the pug mill using a conveyor weigh belt. A metered positive displacement pump was used to pump the asphalt cement cutback binder from the rear of the supply tanker into the mixing chamber of the pug mill.

Figure 1 shows the bulk stockpiles low VOC and conventional HPCM produced at the Coco Paving Nebo Road Plant for the purposes of this study. Both mixes had fully coated aggregated with a shiny black appearance and good workability. The low VOC HPCM was found to be more workable than the conventional HPCM.

Figure 2 illustrates typical production of HPCM with a portable pug mill.

Low VOC HPCM Conventional HPCM

Figure 1. Stockpiles of Low Volatile Organic Compound (VOC) and Conventional High Performance Cold Patch Material (HPCM) Produced at the Coco Paving Nebo Road Plant in December 2012

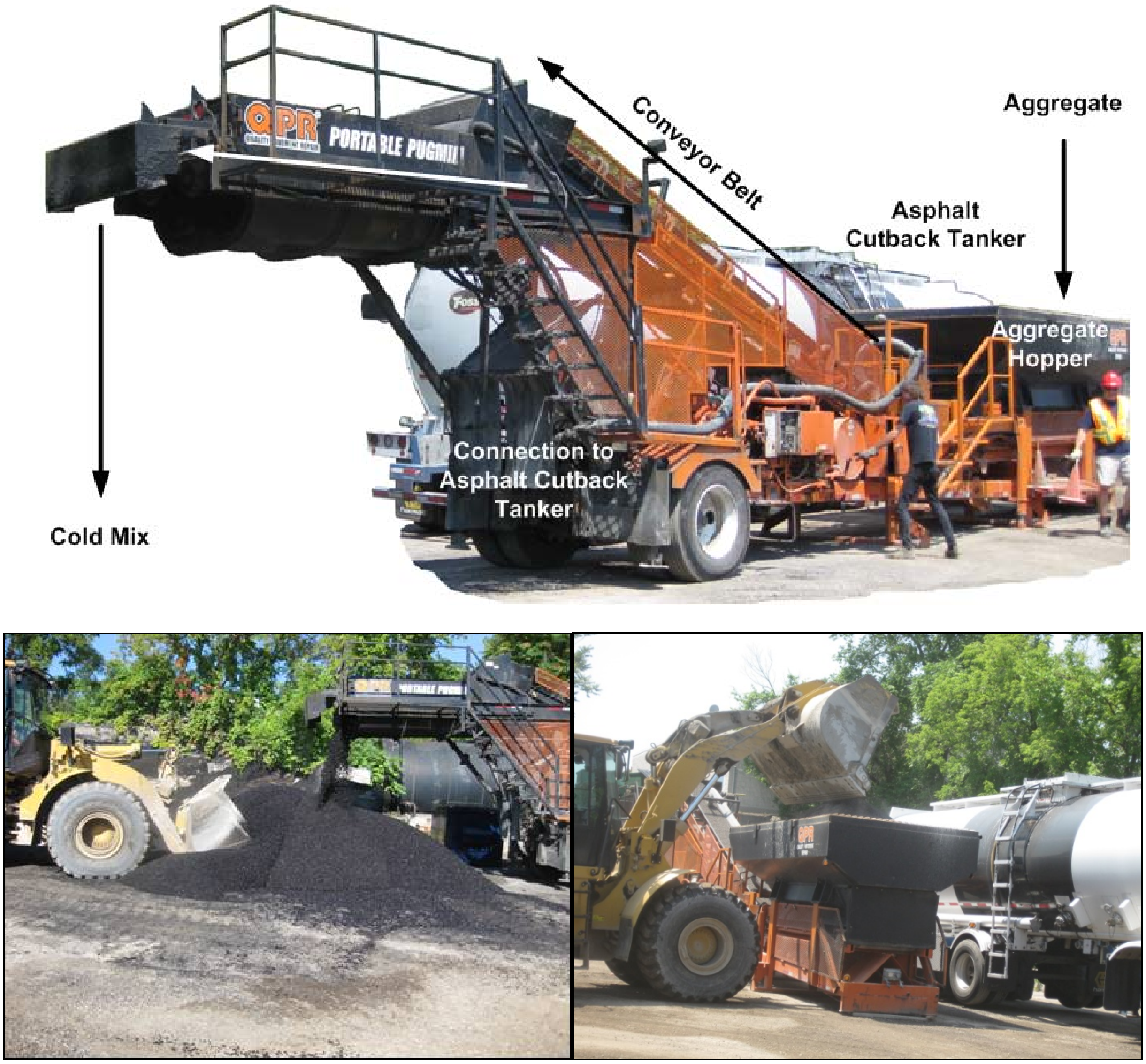


Figure 2. High Performance Cold Patch Material (HPCM) Production Using Pug Mill

5.0 LABORATORY TEST RESULTS AND DISCUSSION

5.1 VOC Content of HPCM Cutback Asphalt Binders

The low VOC and conventional HPCM binders were distilled according to ASTM D402 in order to quantify VOC content. In this test a 200 mL sample of cutback binder is distilled in a 200 mL flask at controlled rate of 50 to 70 drops per minute to a temperature of 360°C. Condensed distillate volumes are recorded at specified temperature intervals (225, 260, and 315°C) and the VOC content is reported as a volumetric percentage at each temperature [3].

A VOC content of 0 percent at temperatures up to 315°C was obtained for the low VOC HPCM cutback binder. These results satisfy the VOC content limit of 0.5 percent at 260°C that Environment Canada is proposing [1]. In comparison, the distillate content of the conventional HPCM cutback binder of 38.5 percent at 260°C exceeded the proposed Environment Canada limit (Figure 3 and Table 1).

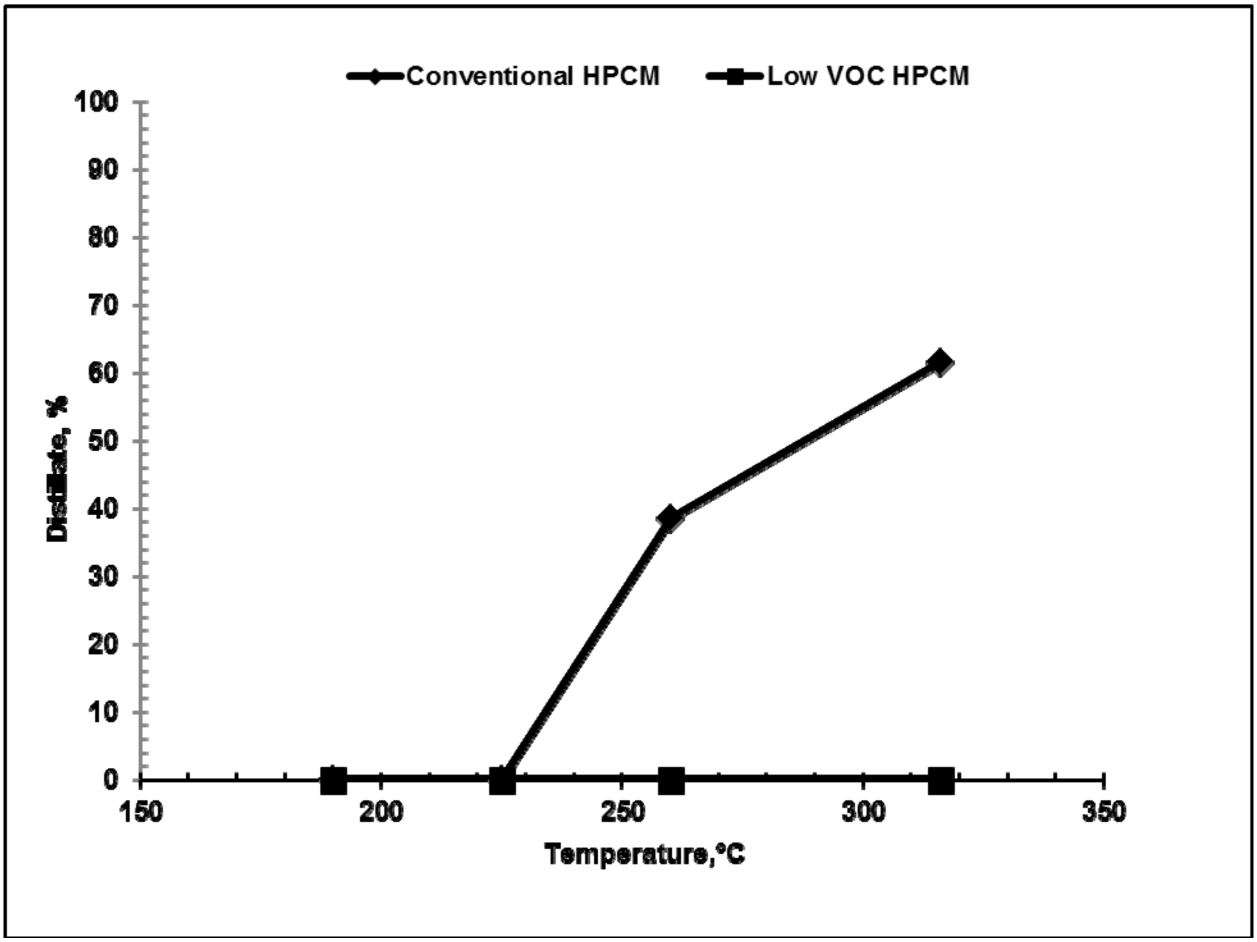


Figure 3. Volatile Organic Compound (VOC) Content of High Performance Cold Mix (HPCM) Cutback Asphalt Binders (ASTM D402)

Table 1. Volatile Organic Compound (VOC) Content of Cutback Asphalt Binders

Distillation Temperature	Test Method	Proposed Environment Canada Requirement	Low VOC HPCM Distillate Content (% by Volume)	Conventional HPCM Distillate Content (% by Volume)
To 225°C	ASTM D402		0.0 %	0.0 %
To 260°C		≤ 0.5%	0.0 %	38.5 %
To 315°C			0.0 %	61.5 %

Note: ASTM is American Society for Testing and Materials.
VOC is Volatile Organic Compound.
HPCM is High Performance Cold Mix.

5.2 Cutback Asphalt Binder Characterization Tests

Further characterization tests were performed on the cutback asphalt binders as shown in Table 2. Of significance is that the low VOC binder had a flashpoint (215°C) which exceeded the conventional HPCM cutback binder flashpoint (97°C) by 118°C.

Table 2. Physical Properties Cutback Asphalt Binders

Test	Test Method	Low VOC HPCM	Conventional HPCM
TOC Flashpoint (°C)	ASTM D1310	215	97
Kinematic Viscosity at 60°C (mm^2/s)	ASTM D2170	475	420
Tests on ASTM D402 Distillation Residue			
Penetration (at 25°C, 100g, 5s) (dmm)	ASTM D5	> 500	> 500
Ductility at 4°C, 5cm/min (cm)	ASTM D113	> 150	145
Solubility in TCE (% by mass)	ASTM D2042	99.9	99.8

Note: ASTM is ASTM International.
TOC is Tagged Open Cup.
TCE is trichloroethylene.
VOC is Volatile Organic Compound.
HPCM is High Performance Cold Mix.

5.3 Binder Content and Aggregate Physical Properties

A determination of cutback asphalt binder content and moisture content was undertaken for low VOC and conventional HPCM stockpile samples taken shortly after production. After extracting the mixes with n-propyl bromide, a sieve analysis was completed on the extracted aggregate in order to determine the gradation of each mix [11].

The total liquid content in the mix, consisting of both water and cutback asphalt binder, was determined with an n-propyl bromide solvent extraction and comparison of the dried aggregate weight after extraction to the starting weight of the mix [11]. It was necessary to determine water content since wet and unheated aggregates were used in production. In order to quantify the water, or moisture content in the mixes, an azeotropic distillation using xylene was performed. This test was adapted from the American Association of State Highway and Transportation Officials (AASHTO) T 110-03 test method for the moisture of volatile distillates in hot mix asphalt [12]. Xylene and water form an azeotropic or constant boiling mixture such that a mixture of xylene and water boils at 90°C compared to the individual boiling points of 100°C and 138.5°C for water and xylene respectively. Since water and xylene and water are not miscible and have different densities (xylene is less dense than water), it was possible to measure the water component of the recovered distillate from the distillation using a receiver with graduated volumetric markings on it. The asphalt cutback binder content was calculated by subtracting the water or moisture content from the total liquid content measured for each mix.

Binder contents of 5.52 percent and 5.39 percent were obtained for the low VOC content HPCM and conventional HPCM respectively (Table 3). The target binder content was 5.5 percent. As a comparison, the recommended binder content for a uniformly graded Texas DOT mix with low absorbing aggregates was 4.5 percent. The high binder contents assist with mix workability and durability properties but must be balanced against good stability and draindown characteristics [13].

A 100 percent crushed and washed limestone aggregate with an open gradation was used for mix production. Gradation results are presented in Table 3 and Figure 4. Both low VOC and conventional HPCM had similar aggregate gradations with mineral dust contents below 2 percent. The low VOC HPCM had a higher dust content of 1.8 percent compared to a dust content of 1.2 percent in the conventional HPCM. Crushed angular aggregate imparts stability to the mix but can decrease workability. Balancing against this are the open gradation and low dust content which increase Voids in the Mineral Aggregate (VMA) and permit a high binder content in order to obtain good workability and durability. The literature also reports that a maximum of 2 percent passing the 0.075 µm sieve is recommended in order to obtain a tacky mix with good cohesive properties [13].

Table 3. HPCM Aggregate Gradation, Moisture and Binder Content

Test	Test Method	Specification	Low VOC HPCM	Conventional HPCM
Liquid Content (%)	MTO LS-282		7.17	7.07
Water Content (%)	AASHTO T110		1.65	1.68
Binder Content (%)	Calculated	5.5% Target	5.52	5.39
Sieve Analysis on Extracted Aggregate Sieve Size, mm	MTO LS 282	QPR® Specification		
9.5		100	100	100
4.75		20-85	67.8	72.8
2.36		2-30	13.3	13.7
1.18		0-10	4.0	3.4
0.075		0-2	1.8	1.2

Note: OPSS is Ontario Provincial Specification Standard.
MTO is Ministry of Transportation Ontario.
LS is Laboratory Standard.
AASHTO is American Association of State Highway Transportation Officials.
VOC is Volatile Organic Compound.
HPCM is High Performance Cold Mix.

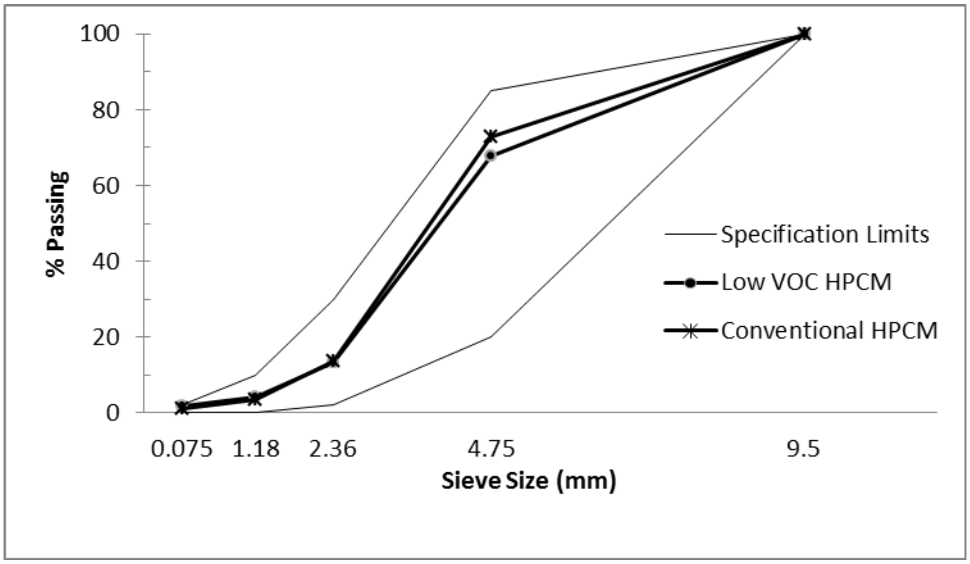


Figure 4. Sieve Analysis of HPCM Mix Design

The Ontario Ministry of Transportation (MTO) requires that aggregates used for proprietary cold patching materials meet the physical properties required for aggregates in a Superpave 12.5 mix [14, 16]. These physical property requirements were met as shown in Table 4. While Ontario Provincial Standard Specification (OPSS) 1003 permits a maximum absorption of 2 percent, the literature recommends 1 percent as the maximum absorption for aggregates used in cold patching mixtures [13, 14]. The aggregate used in this study had a low absorption of 0.86 percent.

Table 4. Physical Properties of Lafarge Dundas Quarry Aggregate Used in HPCM Production

Property	Test Method	OPSS 1003 Aggregate Specification For SP 12.5 Mix	Test Results
Wash Pass 75 µm sieve (%)	MTO LS 601	≤ 2.0	1.6
Absorption (%)	MTO LS-604	≤ 2.0	0.86
Bulk Relative Density	MTO LS-604	-	2.725
Apparent Relative Density	MTO LS-604	-	2.790
Percent Crushed Particles in Coarse Aggregate (%)	MTO LS-607	-	100
Percent Flat & Elongated Particles in Coarse Aggregate (%)	MTO LS-608	≤ 20	10
Micro-Deval Abrasion Loss (%)	MTO LS-618	≤ 17	6.1
Unconfined Freeze-Thaw (%)	MTO LS-614	≤ 6	4.6

Note: SP is Superpave.
MTO is Ministry of Transportation Ontario.
LS is Laboratory Standard.
OPSS is Ontario Provincial Specification Standard.

5.4 Coating and Stripping Resistance

Complete coating of the aggregate with binder and resistance to stripping are necessary for good cold mix performance. Fully coated aggregates signal sufficient binder in the mix and resistance to stripping ensures that the bond between the aggregate and asphalt is strong so that the binder will not strip in the presence of water. Stripping problems can lead to raveling under trafficked conditions [8, 13].

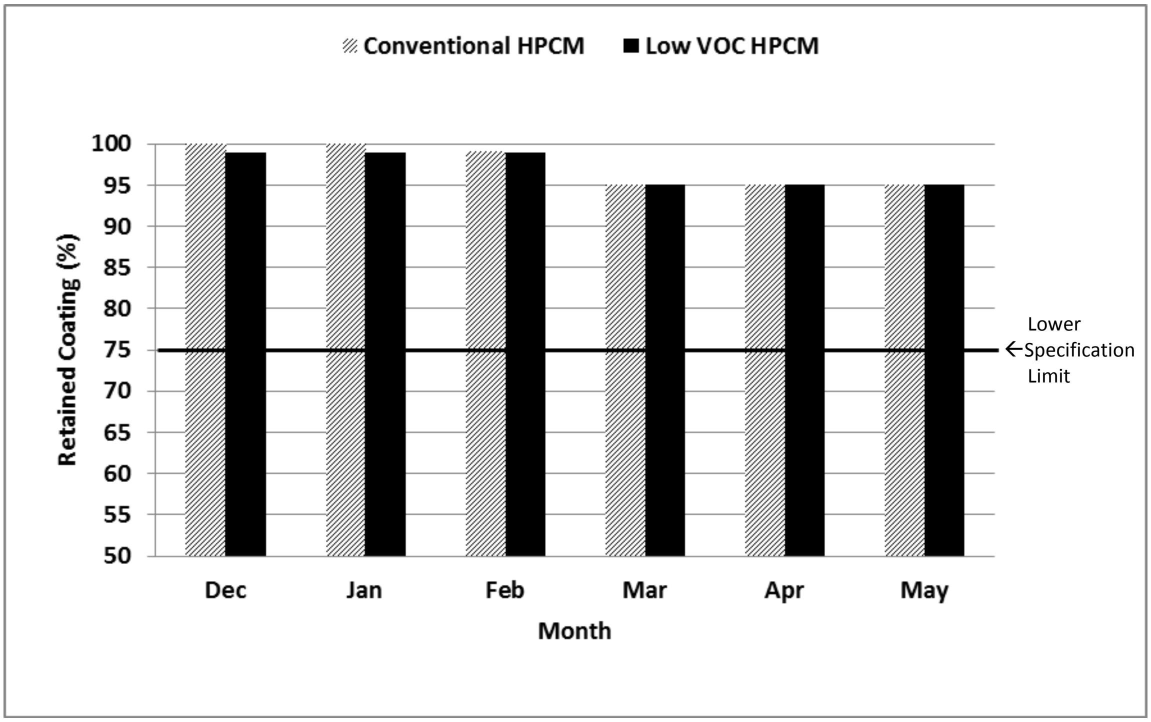
Chaterjee, White et al., report that a 1995 study by the Texas Transportation Institute found that conditioning the mix in boiling water was a better predictor of stripping properties than a Modified Lottman test in which the ratio of tensile strength of the mix before and after conditioning in water is determined [13].

Similarly, a Virginia Transportation Research Council (VRTC) study undertaken by Prowell and White found that a 10 minute boiling water test was able to distinguish differences in stripping results between mixes better than a static immersion test in 60°C water for 16 to 18 hours. The researchers cautioned that a good correlation between stripping results in the laboratory and raveling performance in the field was not found [10]. These comments align with the views of other authors who reference or undertake studies indicating that laboratory testing is not sufficient to predict good field performance but can be used to identify mix that may exhibit poor performance [10, 13, 15].

The stripping resistance of the low VOC and conventional HPCM evaluated in this study was determined using a three minute boil test as prescribed by the MTO OPSS 307 specifications for patching materials [13]. A 1987 study by Tam and Lynch reported that while conditioning the mix in boiling water did not simulate actual conditions in the field, it was a severe test which provided a rapid assessment of stripping potential [15]. In this test, a 50 g sample of cold patching material is placed in 400 mL of boiling distilled water while stirring the mixture with a glass rod a rate of one revolution per second for three minutes. The percent of the mix that remains coated after the boiling procedure is reported as the result of the stripping test. The MTO specifies 75 percent as the minimum acceptable retained coating value [16].

Stockpiles were sampled on a monthly basis and assessed for coating and stripping properties. Both the low VOC and conventional HPCM stockpiles remained fully coated with 100 percent of the aggregate covered over the five month study period. Stripping properties were measured as 98 percent for the low VOC HPCM and 100 percent for the conventional HPCM in samples that were taken shortly after mix production (Figure 5).

Stripping results levelled out to 95 percent in the third, fourth, and fifth months of the study for both the low VOC and the conventional HPCM. These results exceeded the 75 percent minimum retained coating specified in the three minute boil test [16], indicating good moisture sensitivity properties. These are particularly important results given that mixes were produced with wet and unheated aggregates. Moisture contents after production were measured at 1.65 percent for the low VOC HPCM and 1.68 percent for the conventional HPCM.



Note: VOC is Volatile Organic Compound.

Figure 5. High Performance Cold Mix (HPCM) Stockpile Stripping Three Minute Boil Test Evaluation

5.5 Mix Workability

Cold patching materials need to remain workable at low temperatures even after months in stockpile storage. Methodologies that have been devised to assess workability with varying degrees of success include subjectively evaluating the ability to work the material by hand, variations on soil penetrometer tests, and use of a gyratory compactor to determine the number of gyrations required to achieve a target compaction pressure [13]. Chatterjee, White et al., developed the Cold Patch Slump Test (CPST) in which the time for specimens which had been compacted with a Marshall hammer in Polyvinyl Chloride (PVC) tubes to slump once they had been extracted from the tubes was recorded as workability indicator [8,13].

For the purposes of this study, workability was quantified using the Blade Resistance Test [17] which measures the force required for a blade (in order to simulate a shovel scooping into the mix) to penetrate a cold mix sample at -10^{o}C [5]. The procedure was developed by the MTO and is currently part of the provincial specifications for cold patch materials [14, 16].

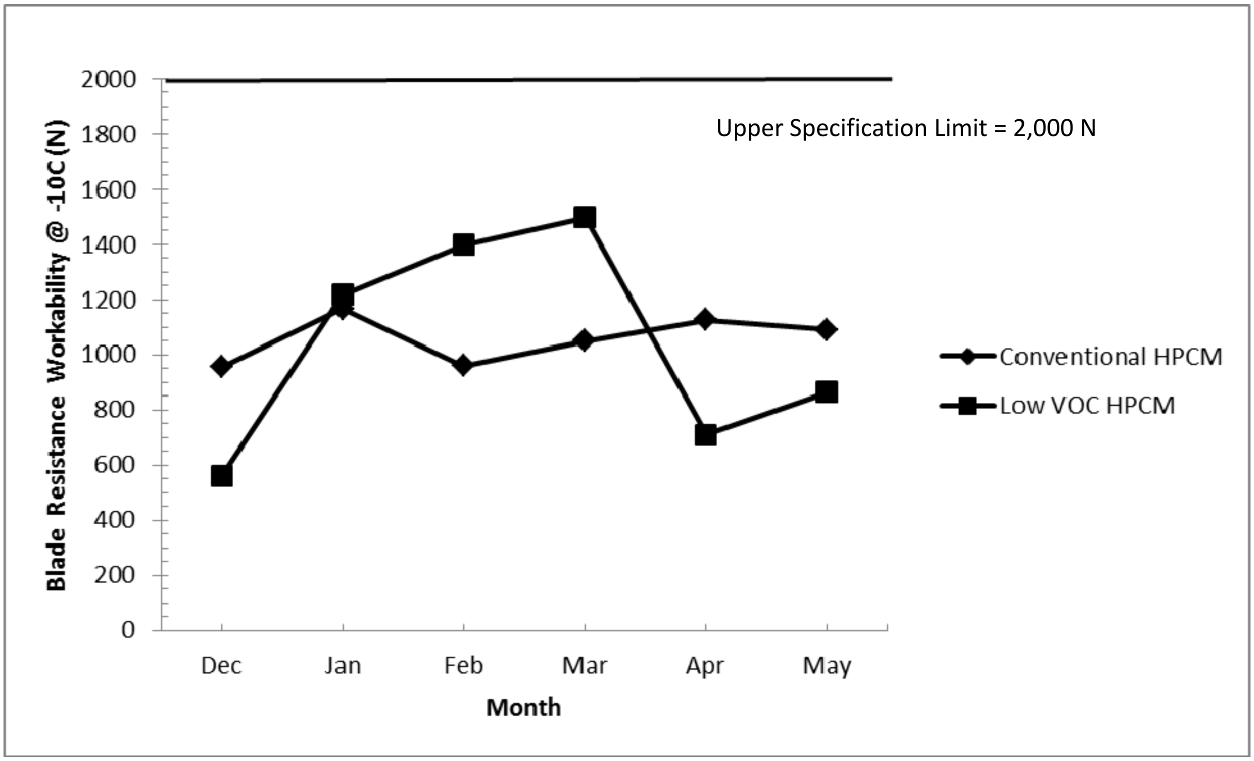
In this test approximately 2 kg of loose mix is placed in a 256 mm long x 165 mm wide x 50 mm high rectangular box and compacted at 21^{o}C with two blows with a Marshall hand hammer that has been modified with steel plate measuring 150 mm long x 150 mm wide x 6 mm high attached to the end of the hammer. The compaction procedure simulates the consolidation that occurs while a mix is in stockpile storage [5]. The compacted mix is conditioned for 12 hours at -10^{o}C in an environmental chamber. The blade resistance is quantified as the force in Newtons (N) measured after 30 seconds of penetration of the mix by a blade measuring 130 mm long x 50 mm high x 6 mm wide (see Figure 6). The loading rate is 50 mm/minute, which is similar to that of a test frame used to measure Marshall Stability [5].

Tam and Lynch described the development and field validation of the Blade Resistance Test [17]. While the correlation between blade resistance workability at -10°C and field workability was not strong, it was noted that workability in the field was assessed via subjective means and that the field temperature varied. In contrast the blade resistance was always measured at -10°C. Furthermore it was found that blade resistance measurements trended with expected results for mixes which were simulated to have increasing and decreasing levels of workability. It was also reasoned that satisfactory blade resistance cohesion values obtained at -10°C should translate into workable mixes applied at or above -10°C [17].

Figure 6. Blade Resistance Workability Test Apparatus

Stockpiles of the low VOC HPCM and conventional HPCM were sampled and tested for workability on a monthly basis over a period of five months. Results are presented in Figure 7. Lower blade resistance values indicate better workability [17]. Both the low VOC and conventional HPCM maintained acceptable workability values that were less than the maximum acceptable value of 2,000 N at -10°C that is specified by the MTO [16]. Initial workability results showed that the low VOC HPCM had better workability (559 N at -10°C) than the conventional HPCM (954 N at -10°C). The conventional HPCM workability increased moderately to 1,167 N at -10°C after one month in storage than then remained relatively constant ranging between 950 N and 1,200 N over five months. The low VOC HPCM results were more variable and ranged between 559 and 1,500 N at -10°C over the same timeframe. Further testing needs to be done to elicit the extent to which changing material properties versus testing variation contributed to the varying month to month results. The coefficient of variation in the monthly stockpile test results ranged between 5.6 and 25.4 for the low VOC HPCM, and between 8.2 and 17.0 for the conventional HPCM. Maher, Gucunski et al., also reported a high degree of testing variation when evaluating blade resistance of cold mix patching materials in a study completed by the Center for Advanced Infrastructure & Transportation (CAIT) at Rutgers State University [5].

Stockpile workability was assessed on a subjective basis while taking stockpile samples each month for testing. Both the low VOC HPCM and conventional HPCM were found to be workable throughout the five month study period. A very thin crust, which was readily workable back into the mix, formed over each stockpile. Factors contributing to the good workability found in both the low VOC and conventional HPCM included the high binder content, open gradation, and low dust content in these mixes.



Note: VOC is Volatile Organic Compound.

Figure 7. Blade Resistance Workability of High Performance Cold Mix (HPCM) Stockpile Samples

5.6 Mix Cohesion

Cohesion describes the ability of cold patch material to remain together once compacted [18] and is a potential indicator the ability of the mix to resist raveling under traffic loadings [19]. Cohesion was evaluated using the MTO LS-290 Test Method for Cohesion of Cold Bituminous Patching Material by Rolling Sieve Method [19].

In this method approximately 1,100 g of cold patching material is compacted at -10^{o}C in a 100 mm diameter Marshall hand hammer mould with five blows per side using a Marshall hand hammer. Compacted specimen height is 63 ±2 mm. The specimen is rolled back and forth 20 times in a 19 mm sieve (see Figure 8) and the percent by mass that is retained on the sieve after this procedure is reported as the cohesion index. A high cohesion index corresponds to good cohesive properties. The MTO specifies 60 percent as the minimum acceptable cohesive index value for cold patching materials [16].

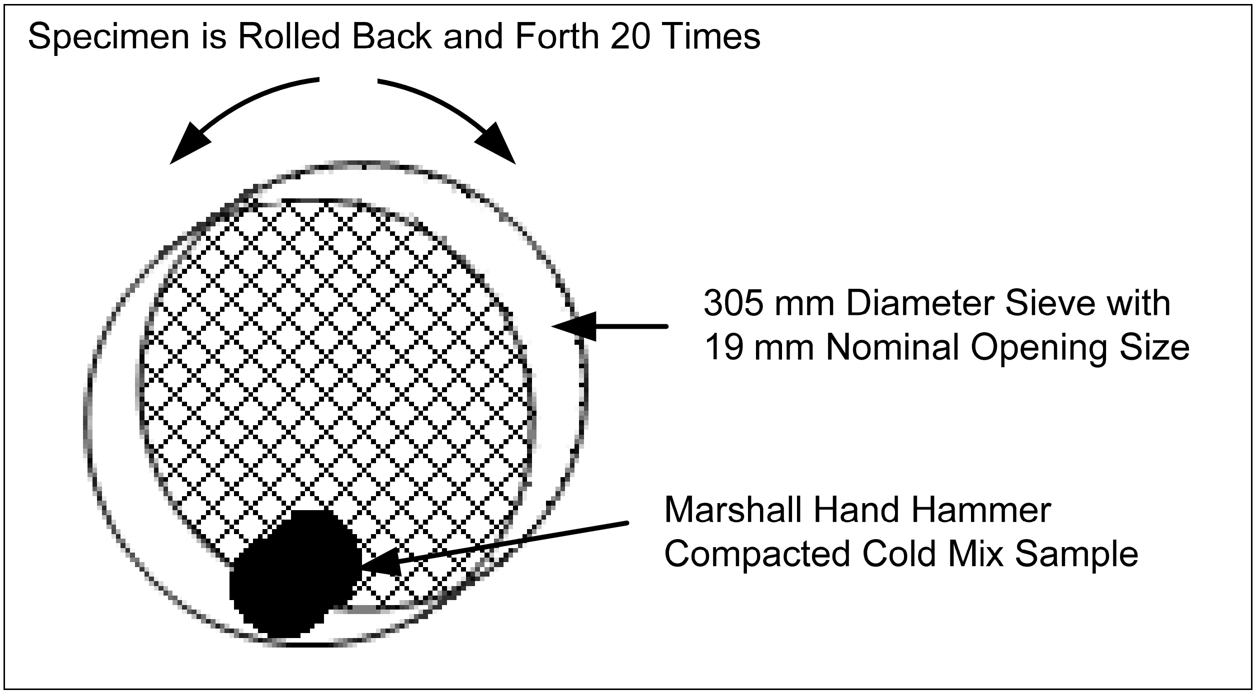
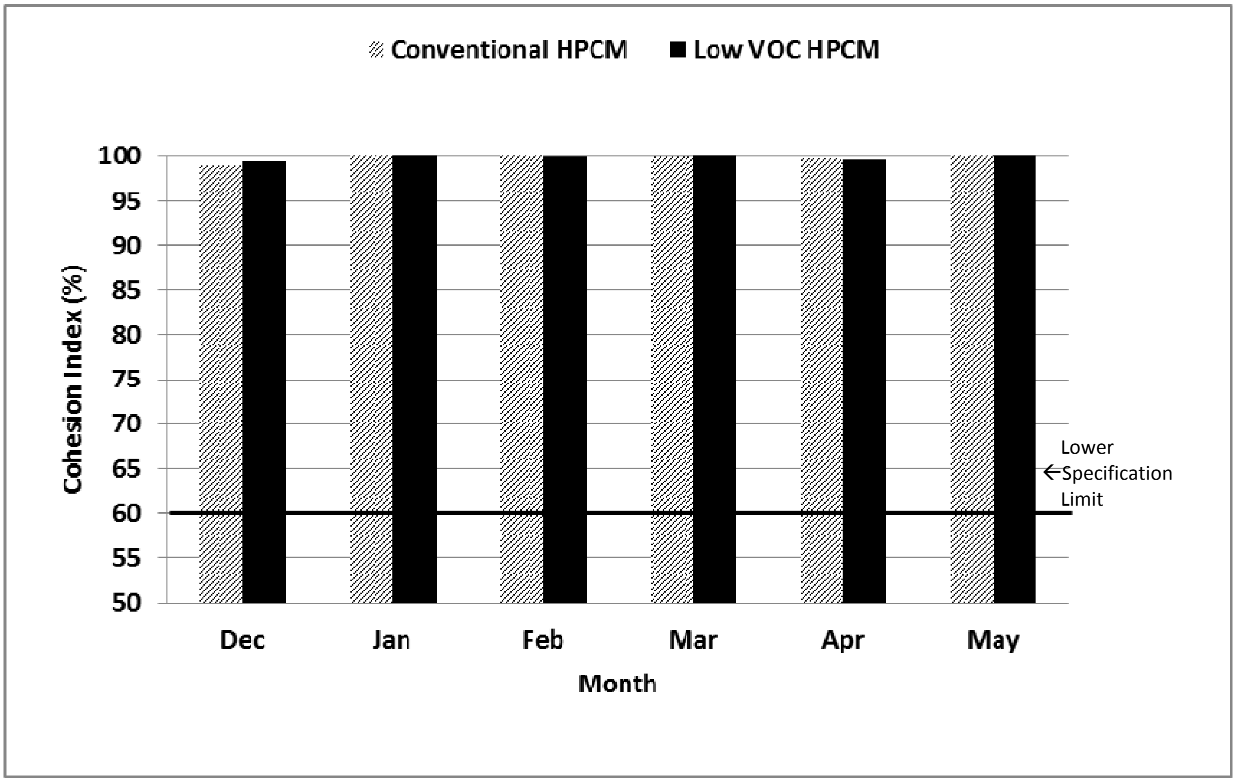


Figure 8. Rolling Sieve Method Cohesion Test

Rolling contact between the sieve and the test sample is reported to partially simulate the effect of vehicle tires abrading against the surface of a cold mix patch. As with blade resistance, a moderate to low degree of correlation was noted between this test method and subjective measures of stockpile cohesion in the field [16].

In a comparison of two cold patch materials which obtained poor results in the rolling sieve test, Maher, Gucunski et al., found that one of the materials exibited excessive distintigration of the cold mix along the edge of the pothole while the other material had good field performance [5]. Estakri, Jimenez, et al., describe results in SHRP Report H-348 which involved testing at a warmer temperature (4°C) and use of a larger 25.4 mm sieve size than the 19 mm sieve used in the MTO test. The authors conclude that while the test can possibly identify poor performing materials, it cannot be used as an assurance that the material will perform in the field [20]. This further supports that field evaluation in addition to laboratory testing is necessary to validate the performance of cold patch materials.

Stockpiles of the low VOC content and the conventional cold patching mixes were sampled and tested once a month for five months. The cohesion results for both mixes were similar and well exceeded the 60 percent minimum specification established by the MTO [16]. Cohesion Index values ranged between 98.9 and 100 percent for the low VOC content HPCM and between 99.4 and 100 percent for the conventional HPCM (see Figure 9). Both mixes were produced using clean washed aggregates with low dust contents (1.8 percent for the low VOC HPCM and 1.2 percent for the conventional HPCM) which may have contributed to the good cohesion values. A maximum of 2 percent passing the 0.075 µm sieve is recommended in the literature for good cohesion and tackiness [13].



Note: VOC is Volatile Organic Compound.

Figure 9. Rolling Sieve Cohesion Stockpile Sample Test Results

5.7 Draindown Properties of Mix

Draindown problems cause the binder in the mix to flow and pool at the bottom of the stockpile. This is of particular concern in warm weather. Potential causes of draindown include high binder contents, soft or low viscosity binders, and production of mix at elevated temperatures which reduces the viscosity of the binder and causes it to drain off of the aggregate [18].

Two different test methods were employed to measure draindown properties. In the first method, the AASHTO T305 test for evaluating draindown characteristics in uncompacted asphalt mixtures [21] was adapted to test cold mix. This was followed by a drainage test used by the FHWA [9].

5.7.1 AASHTO T305 Draindown Evaluation

In the AASHTO T305 method, a known mass of uncompacted mix is placed in a wire basket and conditioned in a forced draft oven for one hour and then weighed again to determine what percent of the binder has drained away from the mix during the test period [21]. This test is normally run on hot mix samples at or above the anticipated production temperature of the mix [22]. The method was adapted for testing cold mixes by evaluating draindown at and above the anticipated stockpile storage temperature during warm weather conditions in Ontario. Temperatures of 25°C and 60°C were selected for the cold mix draindown evaluation. The MTO specification of a maximum 0.3 percent draindown at the production temperature for stone mastic asphalt (SMA) when tested according to AASHTO T305 was used as a guide when evaluating the cold patch materials in this study [23].

Acceptable draindown results of less than 0.3 percent were obtained by the low VOC and conventional HPCM mixes at both 25°C and 60°C. Table 5 summarizes the results.

Table 5. Draindown Evaluation (AASHTO T305)

Draindown	Low VOC HPCM	Conventional HPCM
Draindown at 25°C (%)	0.00	0.00
Draindown at 60°C (%)	0.10	0.12

Note: HPCM is High Performance Cold Mix.
VOC is Volatile Organic Compound.

5.7.2 FHWA Drainage Test

Samples taken from stockpiles of low VOC HPCM and conventional HPCM were also evaluated using the FHWA drainage test. In this test 1,000 g of cold mix is placed on a 25 cm aluminum pan and conditioned in an oven at 60°C for 24 hours. The mix is removed from the pan and the percent by mass of binder that remains affixed to the pan is calculated. FHWA indicates 4 percent as the maximum acceptable draindown result [9].

Prowell and Franklin report that artificially high results may be produced by this test as a result of the difficulty in removing all aggregate that is affixed to the aluminum pan as well as due to the binder that adheres to the pan at the point of contact between the pan and the cold mix [10].

Both the low VOC and conventional HPCM stockpile samples had similar draindown results and met the 4 percent maximum draindown requirement as shown in Table 6.

Table 6. FHWA Drainage Test Results for Low VOC Content and Conventional HPCM

Draindown	Specification	Low VOC HPCM	Conventional HPCM
Draindown at 60°C (%)	≤ 4	1.07	0.92

In addition to laboratory testing, stockpiles were examined on a monthly basis over a five month timeframe with no evidence of pooling binder at the bottom of the pile. The observations were conducted during the winter and spring months. Subsequent evaluations during the warmer summer months are planned in order to further validate the laboratory results with field observations.

Ensuring that the mixes exhibited acceptable draindown characteristics was an important aspect of the study given the high binder contents used to produce the HPCM materials in this study. The open aggregate gradation used in the mixes assisted in providing good draindown characteristics at high binder contents. The study verified that the new low VOC content binder behaved similarly to the conventional HPCM binder with respect to draindown properties.

5.8 Compaction

Compaction properties were evaluated using the Superpave gyratory compactor to compact the mixes to 150 gyrations with a vertical pressure of 600 kPa and an external gyratory angle of 1.25 degrees. A compaction temperature of -10°C was selected to simulate the compaction properties of the mix on a cold winter day. The -10°C compaction temperature also corresponded to the evaluation temperature for workability and cohesion.

Creation of a compaction curve plotting the percent maximum specific gravity (G_{mm}) of the mix against the number of gyrations required a determination of the bulk relative density of the mix after 150 gyrations. It was not possible to measure the bulk relative density as mix specimens were not stable and would not retain their shape when extracting them after compaction with the gyratory compactor. A review of the literature found reports with similar observations indicating instability in compacted gyratory specimens even after curing the mix for up to 96 hours at 25°C prior to compaction (curing at 60°C for 96 hours was recommended in order to obtain stable specimens) [13]. The bulk specific gravity at 150 gyrations was therefore volumetrically calculated based on the height and diameter of the cylindrical specimen.

The following trends were observed in the compaction data obtained by testing stockpile samples of mix each month over a five month period:

- Low VOC HPCM samples had between 1.3 and 1.7 percent lower air voids than the conventional HPCM specimens after 150 gyrations at -10°C.

- High air void (26.3 percent for the conventional HPCM and 24.6 percent for the low VOC HPCM) were obtained on samples taken shortly after production. Air voids dropped each month for the first four months of the study and then levelled out in the fifth month to 20.9 percent for the low VOC HPCM and 22.2 percent of the conventional HPCM.

Figures 10 illustrates a typical compaction curve for HPCM stockpile samples taken in April 2013. The curve indicates that the low VOC HPCM is easier to compact than the conventional HPCM and terminates with 20.9 percent air voids for the low VOC HPCM and 22.2 percent air voids for the conventional HPCM after 150 gyrations at -10°C. A plot of air voids at -10°C after 150 gyrations for monthly stockpile samples is shown in Figure 11.

High air voids in cold mix material compacted with a gyratory compactor have also been reported elsewhere in the literature. In one study air voids ranging between 11 to 14 percent were obtained after compacting at 1.7°C for 200 gyrations. It was necessary to increase the compaction temperature to 100°C in order to reduce air voids to less than 10 percent [13].

Several studies report that compacting at elevated temperatures such as 100°C was necessary to produce specimens that were stable enough and had sufficiently low air voids to test with the Hamburg Wheel Tracking Device (HWTD) [8, 13]. One study cured samples overnight at 135°C in order to obtain samples that were stable enough for Marshall Stability and Flow and Resilient Modulus testing [6].

In the current study, specimens were not cured or compacted at hot mix temperatures for subsequent stability, rutting, or modulus testing as elevated temperatures would significantly change properties of the cold mix materials. Of interest is a 2007 study by Rosales-Herrera, Prozzi et al., which reports success in the use of the Texas gyratory compactor to obtain stable specimens without requiring elevated temperatures for subsequent performance testing [8]. Investigating the stability and related properties for the materials studied in this report using curing and compaction methods that do not require elevated temperatures is of interest for future research.

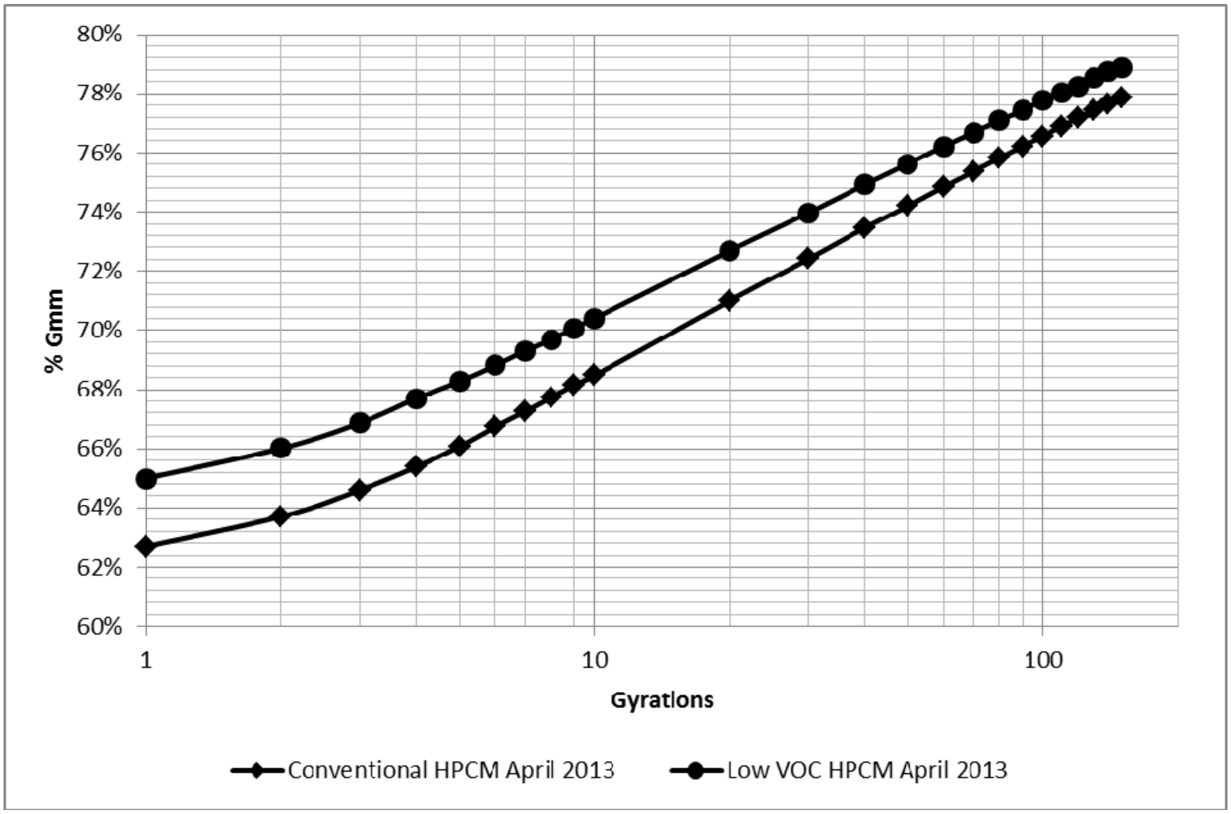


Figure 10. Compaction Curve of Conventional and Low Volatile Organic Compound (VOC) High Performance Cold Mix (HPCM) at -10°C for April 2013 Stockpile Samples

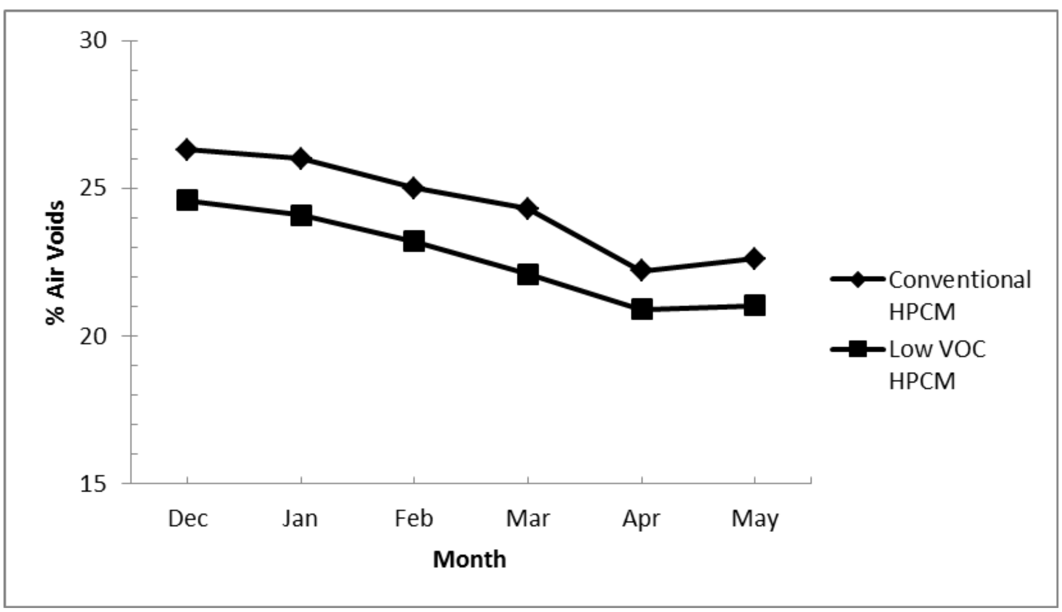


Figure 11. Air Voids of Conventional and Low Volatile Organic Compound (VOC) High Performance Cold Mix (HPCM) After 150 Gyrations at -10°C

6.0 FIELD PERFORMANCE

6.1 Field Performance Evaluation Methodology

Prowell and Franklin developed a semi-quantitative methodology in their VTRC study for evaluating the field performance of bituminous cold patch materials based on the following distress categories: dishing, raveling, debonding (defined as edge disintegration and cold patch material loss), pushing and shoving, and bleeding [10].

Dishing is caused by unstable or inadequately compacted mixes which rut under traffic. Poor workability creates difficulties in achieving proper compaction and may also contribute to dishing [10]. Aggregate loss from the surface of the repaired pothole is defined as raveling. Potential causes include stripping problems, low cohesion, inadequate compaction, a high percentage of fines, inadequately interlocking aggregates, or gradations that are either excessively coarse or fine [8, 10].

Debonding occurs when the mix fails to adhere to the side or bottom of surfaces of the pothole resulting mix that is dislodged from the pothole under traffic. Deterioration or cracking at the pothole edge may be caused by shrinkage issues or excessive loss of volatiles from the binder resulting in inflexibility at lower temperatures. Infiltration by water through the resulting cracks may cause further damage and premature failure. The VTRC study undertaken by Prowell and Franklin separated debonding distresses into two subcategories: disintegration of the pothole’s edge and missing cold patch material [8, 10].

Pushing and shoving are caused by mix instability and may be difficult to distinguish from dishing in minor potholes. Factors which may contribute to an unstable mix include inadequate compaction, a binder content that is too high, a binder that is too soft, low voids in mineral aggregate, or aggregates that do not adequately interlock [8, 10].

Bleeding is excess binder flushing to the surface of the repaired pothole and may result in poor skid resistance. High binder content and low air voids can result in bleeding under heavy traffic loads. Open graded mixes with lower binder contents are reported to assist in mitigating bleeding issues [10].

The framework used in the VTRC study to quantify the performance of repaired potholes is shown in Table 7. Each distress category is assigned a rating from between 1 and 4 depending on the evaluation criteria listed in the table.

The results of the rating evaluation are entered into Equation 1 in order to calculate the Performance Rating (PR) for the cold patch repair [10]:

$$PR = SURx\,\frac{[(0.171W)+(0.177R)+(0.156E)+(0.144B)+(0.180D)+0.204PS)]}{4.0}\,x100 \qquad (1)$$

Where: *PR* is the Performance Rating;
W is the workability evaluation rating;
R is the raveling evaluation rating;
E is the edge disintegration evaluation rating;
B is the bleeding evaluation rating;
D is the dishing evaluation rating;
PS is the pushing and shoving evaluation rating; and
SUR is the survivability (surviving number of patches ÷ original number of patches).

Table 7. Rating System for Evaluating Field Performance of Cold Mix Patching Materials [10]

Distress Category	Rating			
	4	**3**	**2**	**1**
Workability	Very Workable	Good Workability	Fair Workability	Poor Workability
Bleeding	No Bleeding	< 30%	30 – 60%	> 60%
Dishing	No Dishing	< 6.4mm	6.4 –12.5 mm	>12.5mm
Edge Disintegration	No Edge Disintegration	< 30%	30 – 60%	> 60%
Missing Patch	No Missing Patch	< 30%	30 – 60%	> 60%
Raveling	No Raveling	Pock Marks on Surface (Loss of Fines)	Larger Particles Are Loose But Only At Surface	Damage Extends Beyond Surface
Shoving	No Shoving	Localized Bulge < 12.5 mm	12.5 – 25 mm	> 25 mm Depth of Corrugation

6.2 Field Trial

Reports from investigators in the literature, based on their own results or from searches of previously published results, indicated that laboratory tests alone are not currently sufficient to predict field performance [10, 13, 20, 24]. A field trial of the low VOC HPCM was conducted using the conventional HPCM as a control in order to determine if the positive results obtained when testing the mixes in the laboratory would translate into good performance in the field.

An evaluation of the field performance of the low VOC and conventional HPCM was completed by patching five potholes in early January 2013. Test locations were selected at two Coco Paving asphalt plants in Ontario that had ongoing winter operations such that the patches were subjected to slow moving construction vehicle truck traffic throughout the winter and spring. The patches were monitored over a four month period from January – May 2013.

The cold mix was taken from the stockpiles produced in December 2012 and was approximately one month old at the time of placement. Weather conditions were sunny with an air temperature ranging between -1 to 2^{o}C. Both the low VOC and conventional HPCM exhibited good workability during the installation process.

A modification of the throw-and-roll repair method was used to repair the potholes based on recommendations from the supplier of the materials evaluated in this study [8]. Holes were cleared of loose debris with a hand shovel. One of the potholes (labelled as repair area D) had ice adhered to the edge of the pothole which was left in place as attempts to completely remove the ice with hand tools were not successful. Mix was placed into the pothole in two lifts if the hole was deeper than approximately 5 cm. The first lift was compacted with a hand held plate tamper. Additional mix was thrown on top and compacted with a hand tamper and then the wheels of pick up truck such that the hole was left with a slight crown after compaction. Table 8 details the particulars for each test section.

Table 8. Field Trial Test Section Repair Details

<table>
<tr><th>ID</th><th>HPCM Type</th><th>Location</th><th>Pothole Depth</th><th>Number of Lifts</th></tr>
<tr><td>A</td><td>Low VOC</td><td rowspan="3">Coco Paving Wilson Avenue Plant
Toronto, Ontario</td><td>5 cm</td><td>Mix installed in one lift.</td></tr>
<tr><td>B</td><td>Conventional</td><td>5 – 10 cm</td><td>Mix installed in two lifts.</td></tr>
<tr><td>C</td><td>Low VOC</td><td>5 – 10 cm</td><td>Mix installed in two lifts.</td></tr>
<tr><td>D</td><td>Low VOC</td><td rowspan="2">Coco Paving Nebo Road Plant
Hamilton, Ontario</td><td>6 – 8 cm</td><td>Mix installed in two lifts.</td></tr>
<tr><td>E</td><td>Conventional</td><td>8 – 10 cm</td><td>Mix installed in two lifts.</td></tr>
</table>

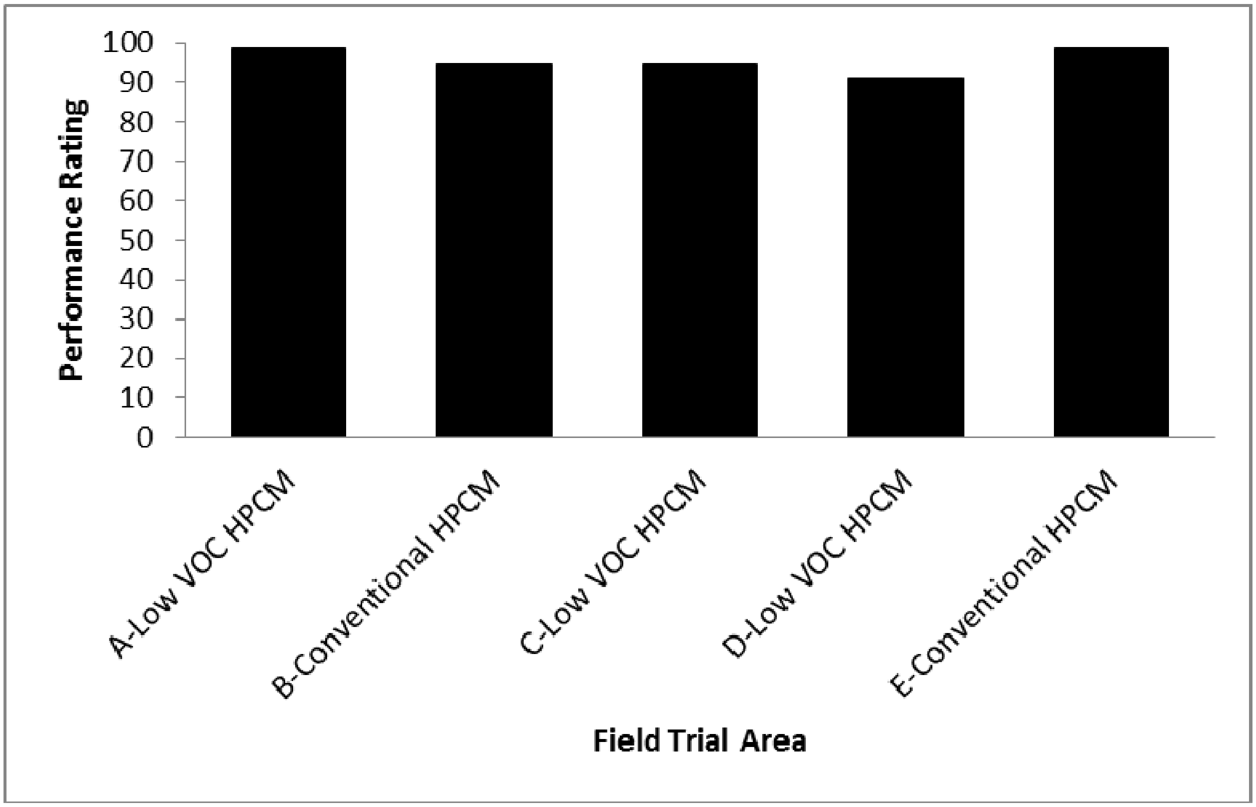
Note: ID is Identification.
HPCM is High Performance Cold Mix .
VOC is Volatile Organic Compound.
VOC is Volatile Organic Compound.

The field performance of the test areas was assessed with the methodology used by Prowell and Franklin in their VTRC study [10] described earlier this report. Potholes were assessed for the following distresses: bleeding, dishing, edge disintegration, missing patch, and raveling, and survivability. It is noted that the survivability was 1 for each field trial area as all potholes survived. The Performance Rating (PR) of each pothole after four months in service is presented in Table 9 and Figure 12.

Table 9. Distress Evaluation of Field Trial Sites After Four Months In Service

Area	W	B	D	ED	MP	R	S	PR
A – Low VOC HPCM	4	4	3	4	4	4	4	98.6
B – Conventional HPCM	4	4	3	3	4	4	4	94.8
C – Low VOC HPCM	4	4	3	3	4	4	4	94.8
D – Low VOC HPCM	4	4	3	2	4	4	4	90.8
E – Conventional HPCM	4	4	3	4	4	4	4	98.6

Note: W is Workability.
B is Bleeding.
D is Dishing.
ED is Edge Disintegration.
MP is Missing Patch.
R is Raveling.
S is Shoving.
PR is Performance Rating.
HPCM is High Performance Cold Mix.



Note: VOC is Volatile Organic Compound and HPCM is High Performance Cold Mix.

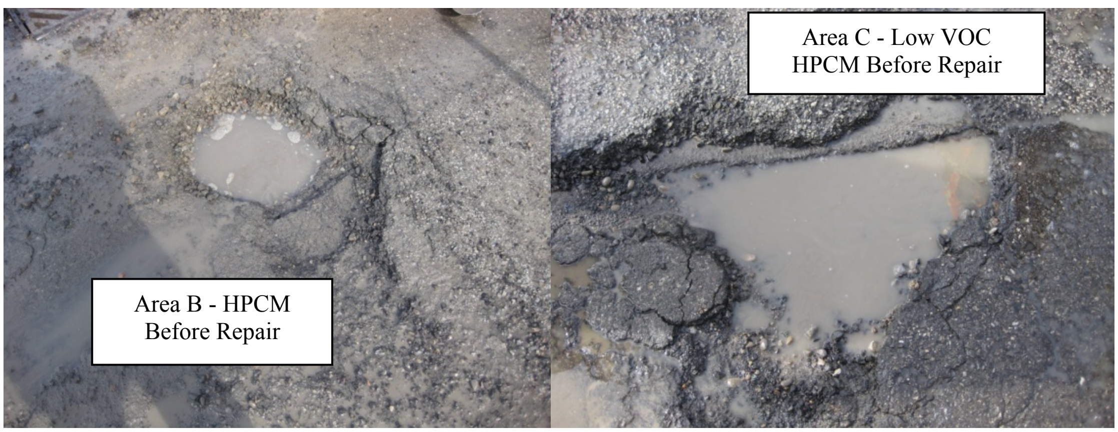
Figure 12. Performance Rating of Field Trial Sites After Four Months in Service

Similar performance was noted between the low VOC and conventional HPCM. All test areas were found to be in reasonably good condition with PR values ranging between 90.8 – 98.6 (100 is the maximum attainable score) over the four month winter and spring study period. During this timeframe the test areas had been subjected to heavy slow moving traffic from construction vehicles and progressively frequent freeze-thaw cycles in the spring months. Ontario was classified as a wet-freeze climate in the SHRP H-106 pothole repair experiment and is considered the most severe type of climatic region in terms of pothole repair performance. The other North American climatic regions were described as dry-freeze, wet non-freeze, and dry non-freeze [7].

Minor dishing, a result of heavy truck traffic, was noted in all potholes. A minor amount of edge disintegration was observed in areas B (conventional HPCM) and C (low VOC HPCM). Moderate edge disintegration was found in test area D, which had been filled with low VOC HPCM. The area of edge disintegration in hole D corresponds to the part of the pothole that had ice that could not be dislodged at the time of repair. This likely made the pothole susceptible to damage during freeze-thaw cycles as water would have been able to enter into the pothole and cause damage upon freezing and expanding. Figures 13 through 17 show the test areas before, immediately after, and four month after being repaired.

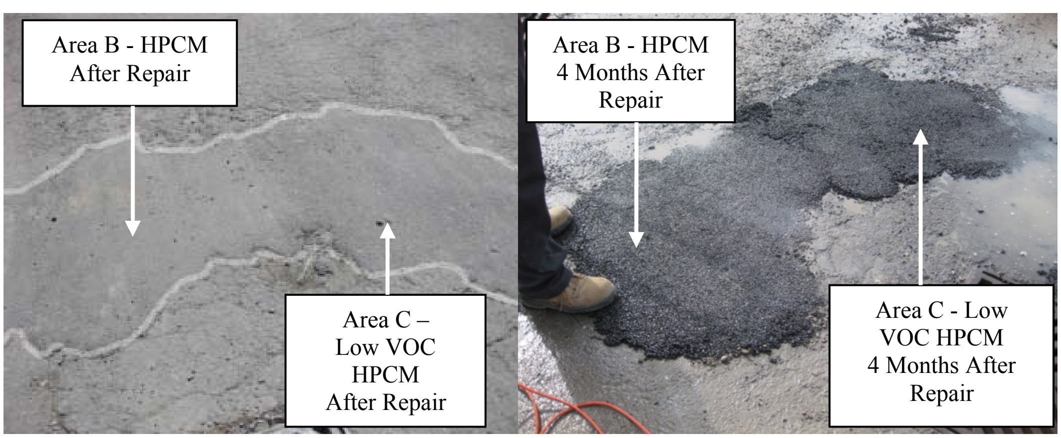
Note: VOC is Volatile Organic Compound and HPCM is High Performance Cold Mix.

Figure 13. Field Trial Area A – Low Volatile Organic Compound (VOC) High Performance Cold Mix (HPCM)



Note: VOC is Volatile Organic Compound and HPCM is High Performance Cold Mix.

Figure 14. Field Trial Areas B and C Before Repairs



Note: VOC is Volatile Organic Compound and HPCM is High Performance Cold Mix.

Figure 15. Field Trial Areas B (Conventional HPCM) and C (Low VOC HPCM) After Repairs

Note: VOC is Volatile Organic Compound and HPCM is High Performance Cold Mix.

Figure 16. Field Trial Area D – Low Volatile Organic Compound (VOC) High Performance Cold Mix (HPCM)

Figure 17. Field Trial Area E – Conventional High Performance Cold Mix (HPCM)

7.0 CONCLUSIONS AND RECOMMENDATIONS

A high performance cutback asphalt binder complying with proposed Environment Canada requirements limiting VOC content to 0.5 percent at 260 degrees Celsius was developed and used in a production trial of reduced VOC HPCM. A conventional HPCM using a conventional high performance cutback asphalt binder with a VOC content of 38.5 percent at 260 degrees Celsius was produced and served as a control. It was found that:

- Stockpiles of the low VOC content HPCM and the conventional HPCM maintained acceptable results when evaluated in laboratory performance tests for workability, coating, stripping, cohesion, draindown, and compaction when tested over a five month period.

- When tested with a Superpave gyratory compactor, the low VOC HPCM was easier to compact than conventional HPCM at -10 degrees Celsius, although it is not clear if this translates into a marked difference in the field.

- Low VOC HPCM performed well in the field and comparably to the conventional HPCM when subjected to slow moving heavy construction vehicle traffic over a four month winter and spring time period. Similar performance was noted with respect to workability, bleeding, dishing, edge disintegration, missing patch, raveling and shoving.

Given the promising results obtained with the low VOC content HPCM it is recommended that future work be performed to further understand and validate the performance properties of this material. Recommendations include:

- Evaluating the laboratory performance properties of low VOC HPCM stockpile samples for an even longer period of time than the five month timeframe in this study.

- Expanded field trial testing to include exposure to fast moving traffic with high traffic counts over an extended period of time.

- Exploring the feasibility of conducting laboratory tests to measure properties related to stability and modulus without the necessity of conditioning or compacting at excessively high temperatures in order to produce specimens that are stable enough for testing. These elevated temperatures, which well exceed the temperatures that cold mix materials are exposed to in the field, may unrealistically alter the properties of the mix.

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