POTHOLE

Study of existing standards, techniques, materials and experience with them on the European market

Deliverable No. 3

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Project Coordinator: Karlsruhe Institute of Technology
Project Partner A: Danish Road Institute
Project Partner B: Forum of European National Highway Research Laboratories
Project Partner C: TRL Limited
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Executive summary

POTHOLE is a project being undertaken for ERA–NET ROAD by a consortium led by Karlsruhe Institute of Technology (KIT) Institute of Highway and Railroad Engineering Department Highway Construction Technology from Germany. The other partners are:

- Danish Road Institute (DRI) from Denmark;
- Forum of European National Highway Research Laboratories (FEHRL) from Belgium;
- TRL Limited (TRL) from the United Kingdom;
- University of Zilina (UNIZA) from Slovakia;
- University of Twente (UT) from the Netherlands; and
- Slovenian National Building and Civil Engineering Institute (ZAG) from Slovenia.

The main objective of the project is to address the need of road agencies for durable construction and maintenance methods for the repair of damage which occur after hard winters due to repeated frost–thaw cycles. All European countries are faced with the problem of potholes and how to repair them. Many approaches just deal with repair methods which are durable only on a short–term basis and, therefore, are generally not cost–effective.

Regarding the immense economic loss due to the damage, the repair of potholes with materials that are only good on a short–term basis and, most importantly, the increasing numbers of crashes, injuries and deaths caused by potholes requires an improvement in the methods and techniques and especially to give road agencies some kind of help to deal with these problems.

In this project, normal together with new approaches which target the medium– or long–term repair of potholes will be studied. A catalogue of tests, evaluation methods and experiences according to existing European Standards will be listed to give road agencies an overview of the possibilities for the repair of potholes. Furthermore, the testing of techniques and the use of materials from already existing trial sites will be used to determine laboratory testing which can or should be used for the correct testing of materials for this purpose.

The gained knowledge, including the European experiences, will be used to develop guidelines for road agencies to enhance their maintenance needs, allowing them to select a repair technique and/or material with a durability corresponding to the estimated lifetime of the existing pavement. The great advantage of this approach is the corporation of seven countries which ensures that many views and experiences throughout Europe are considered.

This report is the deliverable for the Work Package WP3 – Summary of existing standards, techniques, methods and materials for pothole repair and experience with them.

Two main elements of quality pothole patching are

- material selection and
- repair procedures.

The repair material and technique selection is based on time available for repair, local climatic conditions and actual weather conditions, pothole size and depth, characteristics of adjacent pavement, availability of equipment and workers and, finally, the overall cost-effectiveness determined for the particular circumstances (including material, labour and equipment costs).

The main type of materials used for pothole repair are:

- bitumen-based cold-mix materials (cold-mix asphalt CMA)
- bitumen-based hot-mix materials (hot-mix asphalt HMA)
- cement-based materials

Cold-mix asphalt is mostly used as temporary repair but, with quality material and proper installation, it could be more durable. CMAs can consist of different types of binder: cutback bitumen, bitumen emulsion and proprietary products.

Hot-mix asphalts present a more durable solution; it is easy to install and to compact and it enables more effective bonding with existing asphalt pavement. There are two generic types of HMA: matrix dominated (Hot Rolled Asphalt, Mastic Asphalt) and aggregate dominated (Asphalt Concrete, Split Mastic Asphalt).

Cement-based materials – these fast-setting or rapid-hardening cementitious materials are intended for rapid pavement repair.

Pothole repair techniques:

1.) Temporary repairs
In most cases the pothole is filled with cold asphalt mixture. This is used in emergency circumstances or in harsh winter conditions.

Methods:

- throw-and-go (normally performed with CMA, the worst durability)
- throw-and-roll (normally with CMA)
- edge seal method
- spray-injection patching

2.) Semi-permanent procedure

- removing water and debris from the pothole
- forming the vertical edges (edges cut back to sound surrounding pavement)
- placing the mixture in the hole (hot or cold-mix asphalt)
- compaction using vibratory plate compactors, drum vibratory rollers or tamper

3.) Permanent or more durable repair

- preparation including edge formation (by saw cutting)
- cleaning excavation with removing all debris, loose material and water
- application of bond coat to base and sides
- infilling with asphalt material (mostly hot-mix, but cold-mix asphalt and cement-based material are also used)
- compaction with vibrating plates, drum vibratory rollers or tamper

The proper preparation of pothole is essential for a good repair. No matter how high-quality and durable a material that is used for pothole infilling is, it will not perform well and will not last long enough if it is applied in inappropriate circumstances. The prepared patch area (normally in a rectangular shape) must include the whole area affected by the pothole and any associated distress in surroundings. The cut edges should be clean and neat. All unsound and debonded material should be removed.

This method using hot-mix asphalt represents the most durable solution for pothole repair and it should ensure the service life as of surrounding pavement.

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1 Introduction

POTHOLE is a project being undertaken for ERA–NET ROAD by a consortium led by Karlsruhe Institute of Technology (KIT) Institute of Highway and Railroad Engineering Department Highway Construction Technology from Germany. The other partners are:

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There are seven Work Packages in the project plan as follows:

- WP1 – Definition of the term “pothole”
- WP2 – Selection of tests and evaluation methods for use in the laboratory and in situ
- WP3 – Study of existing standards, techniques, materials and experience with them on the European Market
- WP4 – Evaluation of techniques and materials from existing trial sites
- WP5 – Laboratory testing of selected materials
- WP6 – Life Cycle Cost and Benefit Analysis (LCCBA)
- WP7 – Development of guidelines including catalogues of materials – Final Report

This report is the deliverable for the Work Package WP3 - Summary of existing standards, techniques, methods and materials for pothole repair and experience with them. The report is based on study of existing literature, standards and other technical regulation, techniques and practical experience with materials used for pothole repair. The survey was three-pronged and it included a literature search, an internet search and direct approaches to road authorities, contractors, producers, suppliers and users. Therefore, the information in this summary has been obtained through review of written documents and papers (given in the Sources list) and current practices of pothole repair.

Although the idea at the beginning was to gather information from European countries only, it has been realized later that in the collected documents about repair techniques and materials there was not enough relevant and detailed information. For this reason, the survey and study have been extended to some papers originating from the USA and South Africa which describe wider range of different procedures and various sorts of pothole repair materials. Many of these types of materials and methods are already used in European countries but their application is not well prescribed and documented.

The draft of this report was discussed by the consortium at the meeting in Brussels on 16th and 17th July 2012.

2 Pothole repair management

2.1 European experience

As asphalt pavements age and deteriorate, the need for corrective measures to restore safety and rideability increases. Potholes occur on all kind of asphalt-surfaced pavements. They are generally caused and developed by moisture and ingress of water, winter freeze-thaw cycles, traffic, poor underlying support, inadequate drainage or some combination of these factors.

Road authorities responsible for asphalt-surfaced pavements eventually perform pothole patching. Pothole repair is necessary in those situations where potholes compromise safety and pavement rideability. As stated in the Manual of Practice [source 1, FHA SHRP, USA, 1999] the decision to patch potholes is influenced by many factors:

- the level of traffic
- the time until scheduled rehabilitation or overlay
- the availability of personnel, equipment, and materials
- the tolerance of the travelling public

Pothole patching is generally performed either

- as an emergency repair under harsh winter conditions, or
- as routine maintenance scheduled for warmer and drier periods.

Regardless of climatic conditions, the potential safety and rideability problems that could result from the unrepaired distress must be considered when deciding whether a pothole should be patched. A highway agency or road authority must repair potentially hazardous potholes as soon as it becomes aware of them.

As described in the ADEPT Final report [source 3, UK, 2010], local highway authorities in the UK use a wide range of solutions to repair potholes. Hot mix asphalt is the most commonly used solution, but also cold asphalt mixtures are used, particularly as a temporary repair. Although various authorities have trialled products and processes, there is no comprehensive guidance as to what repair solution and material is the most durable and cost-effective. However, it is supposed that hot materials provide a more durable solution because they are easier to compact and they bond more effectively with existing road surfaces. That sorts of asphalt laid hot from hot-box equipment are the most widely used method for permanent repair in the UK. Proprietary cold materials are probably less durable, but their installation time is shorter which is beneficial for minimising the traffic disruption.

The effectiveness of pothole repairs varies with the quality of workmanship of the maintenance crew and the durability of repair materials chosen. Engineering selection of the pothole repair material and its proper installation is crucial to ensure continued strain compatibility with the surrounding road structure. Since the repair should be an integral aspect of the road structure its engineering characteristics should be selected to match the existing construction as closely as possible. As most thin road structures are flexible by nature the repair medium needs to reflect this engineering feature [source 3, ADEPT, UK, 2010].

HMEP Potholes Review [source 2, UK, 2012] states that, as part of the UK new Asset Support Contracts, the UK Highways Agency has set new requirements for repairs to paved area defects, such as potholes, on the motorway and trunk road network. There is an overarching requirement to make safe any defect, but as a minimum requirement, potholes greater than or equal to 150 mm in diameter, in the thickness of surface course or 40 mm depth, must be repaired within 24 hours.

Well-maintained Highways - Code of practice [source 5, UK Roads Board, UK, 2012] defines two categories of defects:

- category 1 – those that require prompt attention because they represent an immediate or imminent hazard or because there is a risk of short term structural deterioration.
- category 2 – all other defects.

Well-maintained Highways advises that category 1 defects should be made safe at the time of inspection. If this is not possible, which is often the case, repairs of a permanent or temporary nature should be carried out as soon as possible and in any case within 24 hours. Permanent repair should be carried out within 28 days. Some local highway authorities also define an emergency or urgent response of two or three hours in certain circumstances.

Category 2 defects are those which, following risk assessment during an inspection, do not present an immediate or imminent hazard or risk of short term structural deterioration. These defects are not required to be urgently repaired and may be categorised as high, medium or low priority with local target response times. The majority of these defects will form part of planned programme maintenance within an authority's asset management strategy.

In Norway, a standard definition for a pothole is adopted. Anything wider than 100 mm for a road and 30 mm for a bike lane should be repaired within a week. However, in practice a risk assessment is applied to these defects before repair.

In the German guidelines for maintenance of road constructions [source 15, Germany, 2009] maintenance measurements depending on the condition of the construction and the aimed maintenance status are being described. The pothole fillings belong to short-term measures of maintenance which can be done immediately after the occurence of a locally restricted damage. It is not said but it implies that long-term measures for potholes do not exist.

Erhaltungsmanagement der Fahrbahnen (EMF) [source 16, Switzerland, 2003] provides instructions for visual condition survey and evaluation using a damage catalogue.

The potholes are classified according to the severity of the damage:

- severity of damage - slightly: starting forming of single potholes with diameter < 100 mm
- severity of damage - middle: single potholes, diameter 100 to 300 mm, depth < 40 mm
- severity of damage - high: partly connected potholes, diameter ≥ 300 mm, depth ≥ 40 mm

It is proposed that potholes are mostly the result of cracks or cracking out of single grains. They can also be provoked from other kind of damages (rutting, shear strain, subsidence, uplifting due to freeze and thaw changes, open joints, patches, spalling and longitudinal, transversal and other cracking).

Manual of the city of Basel Handbuch Strassenbau [source 17, Switzerland, 2010] is an addition to their technical regulations and a basis for all contracts of the building authorities in Basel. It mentions that due to cold temperature sometimes potholes can not be repaired immediately; therefore, a temporarily solution is to fill the potholes with cold asphalt mixtures. However, later maintenance measure is, in most cases, inevitable.

The Czech Catalogue of distress of flexible pavements TP 82 [source 6, Ministry of transport, 2010] consists of various parts. One of them contains catalogues sheets describing different distresses of flexible pavements, of which Catalogue sheet No. 8 deals with potholes. As well as pothole descriptions (causes for formation, visual appearance) there are general requirements for pothole repair mentioned in the sheet. They are related to repair procedure and material used - hot asphalt in suitable weather conditions, cold asphalt and mastic asphalt in bad (winter) conditions. Moreover there is a recommendation for local repair of pavement, overlay or reconstruction in case of combination of potholes with other structural pavement distresses.

2.2 Experience from outside Europe

The South African technical guide [source 4, CSIR, 2010] describes the causes of typical potholes and uses a decision key system to identify the appropriate repair methods. Various methods are described to ensure that repair work is appropriate for the specific type of pothole and that the pothole will thus not form repeatedly due to failure to address the cause. Mechanisms for quality control of pothole repairs are also presented. A standard form for use by inspectors during the field rating (assessment) of potholes and identification of repair methods is included.

This guide also mentions that potholes have always been a problem on sealed/paved roads in South Africa, but never to the extent experienced during the summer of 2009/2010. The causes of the large increase in the degree and extent of potholes during this period were many, but can probably be attributed mainly to the following:

- insufficient routine, periodic or preventative maintenance leading up to the summer,
- unusually wet conditions for sustained periods,
- ineffective or no repair of existing potholes.

Potholes are generally associated with the spring thaw that occurs in cold regions. Moisture in the pavement freezes during winter with an increase in volume and a consequent decrease in material density. As the frozen pavement layers thaw out in spring, the moisture content of the material increases (often to saturation), which decreases the pavement support. Under traffic loading, high pore water pressures develop in the wet materials with subsequent failure of the material. The guide states there is no doubt that water is the primary cause of potholes, but the lack of periodic and/or preventative maintenance of roads often leads to the development of surface cracks, which allow rapid ingress of water into the structural layers during rainfall.

Prior to any successful pothole repair, it is essential to have identified and classified the cause of the problem. The surficial repair of potholes, without attending to the fundamental causes, is normally a complete waste of time and resources – incorrectly repaired potholes are likely fo fail again soon after repair. To assist with the identification of the causes of potholes, the South African guide [source 4, CSIR, 2010] includes a decision key process to be used (see section 8.6).

3 Materials and procedures for potholes repair

3.1 European experience

The two main elements of quality pothole patching are
- material selection and
- repair procedures.

It is stated in the Potholes Review [source 2, HMEP, UK, 2012] that in the UK, each highway authority determines its approach to repair. Pothole repairs include temporary, semi-permanent, and permanent treatments, but there are no standard definitions for how long these treatments should be in place.

Temporary repairs are mainly used when a defect is being made safe until a more permanent repair is done (within a few weeks or within the life expectancy of the material used). Some authorities use temporary repairs that will be in place until a wider repair programme is undertaken. The semi-permanent or intermediate repair is sometimes applied in a situation before a wider maintenance treatment is undertaken.

Nevertheless, it is indicated that permanent repairs should be undertaken as the first choice. Temporary repairs should only be used where safety cannot be managed using alternative approaches, and in emergency circumstances.

Repair materials and processes comprise hot-mix and cold-mix asphalt together with proprietary pre-packaged products of various types, injection and indirect heat repair techniques [source 3, ADEPT Final report, UK, 2010]. The materials are used for either 'temporary' (make safe) or 'permanent' repairs.

Hot-mix asphalt owe their engineering performance to good installation and compaction practice. It is essential that the material is maintained above an appropriate viscosity temperature at all times prior to installation because it will generaly be used in relatively small quantities throughout a working day. To ensure its suitability for compaction a portable 'hot-box' is used to maintain material temperature prior to installation.

Permanent cold lay surfacing materials which were developed for utility trench reinstatement applications may also be generally suitable for consideration as pothole repair materials.

Pre-packaged materials are available as a range of products for use in low to high traffic stress situations. Indirect heat and velocity injection methods are also available as proprietary processes for pothole repair.

There are a variety of proprietary products that are supplied in bags or tubs available for repairing potholes. Different aggregate type and size and different polymer additives make it difficult to compare products and there is no central database where such a comparison can be made. Some materials are HAPAS (Highway Authorities Product Approval Scheme) approved for reinstatements and low traffic roads.

3.2 Experience from outside Europe

According to South African guide [source 4, CSIR, 2010], the fundamental principle relating to pothole repair is to produce a patch with a deflection under traffic similar to the adjacent road. Significant differences in deflection will lead to cracking at the interface of the patch. The cracking which develops between patches and the road under traffic loading will lead to ingress of water and additional potholes. Therefore the repair of patches using strongly-cementitious materials is not recommended because in that case, the patch would be significantly stiffer than the surrounding material and it would start to ‘rock’ under traffic. This may result in failure of the surrounding contact areas.

4 Bitumen-based cold-mix materials for potholes repair

4.1 Types of binders and aggregates for cold-mixtures

It is presented in the Army Corps of Engineers report [source 7, USA, 2005] that hot-mix asphalt (HMA) is normally used in pavement construction because heating the asphalt binder and aggregates prior to mixing is the most economical method to get proper coating and achieve the highest degree of compaction. The fact that sometimes satisfactory HMA cannot be purchased locally, the intention to reduce logistics costs and environment impacts of HMA, and the requirement for rapid repairs, lead to use materials which do not require heating. The major limitation of using cold asphalt mixtures is that they can normally not be compacted to achieve the same level of compaction as mixtures that are heated. However, with available additives, cold patch materials have been developed that are capable of durability that approaches that of HMA. Available types of binder in CMA are:

- cutback bitumen
- bitumen emulsion
- proprietary products

Cutback bitumens are most commonly used as the binder for cold-mix asphalt patches. They are combined with well-graded blends of aggregates to produce dense asphalt mixtures. The cutbacks used can be classified by type as either medium curing or slow curing. The shelf life of a cutback is practically unlimited, if it is kept in a sealed container.

Bitumen emulsions are also widely used in the repair of asphalt pavements. In an emulsion, the bitumen binder is suspended in an aqueous solution. A limitation of emulsions is the relatively short time they take to break and cure - therefore, only slow-setting emulsions should be used for cold mixtures. Depending upon storage conditions, the shelf life of a typical bitumen emulsion is limited to between 6 months and 1 year. However, there are colloid asphalt emulsions which are more stable and will have a possible shelf life of several years. It is necessary to provide that mixtures containing bitumen emulsion remain in workable consistency at ambient temperatures.

Manufacturers of proprietary products generally use a cutback or an emulsion and then add some type of antistripping agent, polymer, or fibre. These materials are added to improve the strength, bonding, and durability of the repair material. Proprietary materials are usually available in ready-to-apply containers, varying from small bags or buckets to large containers. Some proprietary material manufacturers also sell the binder itself, which can be combined with suitable local aggregates in the area it is to be applied.

There are also materials for patch repairs which do not contain any bitumen binder material. These are generally rigid materials with low enough modulus values to provide some compatibility with the surrounding HMA pavement. As stated in the Army Corps of Engineers report [source 7, USA, 2005], non-bitumen binders are not susceptible to the large changes in modulus values that occur with bitumen binders during changes in temperature (the modulus value of a HMA pavement can decrease by a factor of 10 as temperatures change from near freezing to 60 ^{0}C or above).

The cold-mix asphalt (CMA) is the material mostly used for small to medium potholes [source 4, South African guide, CSIR, 2010]. The material is usually available in bags (25 to 40 kg) from commercial suppliers. The cold-mix materials with bitumen emulsion or cutback bitumen as the binder cannot be supplied in bulk because such type of binder needs to be sealed from drying out (loss of cutback) or the ‘breaking’ of the emulsion. Even bags that are torn or broken may result in unsuitable materials for patching potholes after a relatively limited time. Most products have a specified shelf life and care should be taken to ensure that the material is still in a workable condition.

No standard specification for the requirements or properties of CMA is available in South Africa, but Agrément South Africa compiled a document recently (in 2010) for the certification of cold-mix materials. This includes certain performance levels for a range of tests (aggregate polishing value, resistance against moisture-induced stripping and permanent deformation, aggregate strength, voids content, permeability, etc.). Materials complying with these requirements and which are Agrément certificated are expected to perform satisfactorily for pothole patching.

As stated in the South African guide [source 4, CSIR, 2010], CMA mixtures with cutback bitumen can be difficult to work at low temperatures and often require 'warming up' in the sun before use. Emulsion-based products do not usually present this problem.

The size of the aggregate used for repair material depends on the depth of the pavement to be repaired. In most cases, repair materials contain aggregates that have a maximum aggregate particle size not more than 11 mm. This allows the patching material to be placed in thin layers of about 25 mm. The grading of the aggregate has a great effect on the performance of the cold asphalt material. The voids content resulting in permeability of the asphalt is one of the major factors affecting its suitability. All asphalt for patching should be as impermeable as possible. This can be assured with the proper grading of the aggregate (as well as the degree of compaction after placement). To ensure a low permeability, a continuous type of grading should be used. Dense-graded aggregates are therefore applied to provide a stable, low void, and relatively waterproof pavement structure. Open-graded aggregates, when properly confined, can be stable and will generally be more porous than dense-graded aggregate structures. Compared with dense-graded asphalt mixtures, open-graded asphalt mixtures are normally more workable when temperatures are at or below freezing. As stated in the South African guide [source 4, CSIR, 2010], in most cases, a dense-graded asphalt mixture would perform well at warm and hot temperatures, but an open-graded asphalt mixture is required for satisfactory workability at freezing temperatures.

4.2 Types of cold-mixtures

The pothole patching with cold-mix asphalt can be performed in any weather conditions ranging from clear spring to harsh winter days. The Manual of Practice [source 1, FHA SHRP, USA, 1999], describes three types of cold mixtures:

A. Cold mix produced by a local asphalt plant – in this case the available aggregate and binder are used, usually without an opportunity to check compatibility or expected performance.

B. Cold mix produced according to specifications set by the agency that will use the mixture. The specifications normally include the acceptable types of aggregate and binder, as well as acceptance criteria for the agency to purchase the material. The aggregate and binder are usually also tested for compatibility before approving certain sources.

C. Proprietary cold mix. A local asphalt plant produces this material using specially formulated binders which are produced by producers that previously test the local aggregate, design the mixtures, and monitor production to ensure the quality of the product. These materials (like other cold mixtures) can be produced in bulk and stockpiled, or they can be packaged into buckets or bags to make the material easier to handle in the field.

4.3 Verifying the quality of used materials

Manual of Practice [source 1, FHA SHRP, USA, 1999] describes two kinds of verifying the quality of materials used for patching with cold mixtures:

- compatibility testing procedures
- acceptance testing procedures

The compatibility of the binder and aggregate should be checked when cold mixes are produced according to agency specifications. When using proprietary materials that are already mixed, some acceptance testing must be done before purchasing the material.

4.3.1 Compatibility testing for new combinations of binder and aggregate

Although the majority of binder-aggregate combinations could produce satisfactory results, some combinations would lead to cold mixtures that do not perform well. Therefore, it is useful to identify potential mixture problems prior to large-scale production. This is specially important when a previously untried combination of binder and aggregate is intended to be used. Beside testing material compatibility, estimating the optimum binder content is recommended.

The following testing methods are intended to provide information concerning combinations of materials or cold-mix materials with no prior experience available. Testing may not be necessary when using cold-mix materials that have been successfully used in the past. However, testing these materials could provide reference values to be compared with other cold mixtures.

According to the Manual of Practice [source 1, FHA SHRP, USA, 1999], the most important demands to produce quality cold-asphalt mixture are:

a) The binder should coat the aggregate well and remain coated, even after being stockpiled and subjected to various climatic conditions.
b) The stockpiled material should remain workable and be easy to handle with shovels. The outside crust of the stockpile may harden as the bitumen binder hardens, but this skin should prevent the inner material from hardening, so that when a loader breaks through the outer skin, the material is workable again.
c) The material should remain in the holes where it is placed.

Simple laboratory tests to determine the ability of a particular binder-aggregate combination to meet all the requirements listed above are presented in the Manual [source 1, FHA SHRP, USA, 1999]. The compatibility testing procedure involves three tests: coating, stripping, and drainage. These tests can also provide us a range of optimum binder content for materials which are determined to be compatible.

Coating test

a) Take samples of binder (emulsion or cutback) and aggregate intended for production of a cold mixture. The aggregate should be within the same gradation as the material that will be used for later full-scale production.
b) Dry aggregate samples (approximately 2000 g in weight) at approximately 60^{o}C. Stir the samples to prevent the formation of lumps.
c) After recording the weights of both aggregate and the binder, mix the dried aggregate and binder in proportion so that the residual binder content would be 4.0 %. Continue mixing until the binder is dispersed throughout the mixture.
d) Spread mixture onto absorbent paper to dry. If desired, the mixture can be placed in an oven at 96^{o}C to speed up the drying process.
e) Continue to mix and dry batches of aggregate and binder at higher residual binder contents listed in the appropriate table. Stop mixing batches with higher binder content when the mixture becomes soupy at any binder content.
f) When the mixtures are dry, estimate the proportion of aggregate covered with binder for each mixture. Record the coating values for each mixture.
g) Record the lowest binder content at which the coating value is at least 90 % (the technician performing the test should judge whether the coating is acceptable).

Stripping test

a) Prepare five aggregate samples of approximately 1100 g. Heat the samples to 60°C. Part of each sample will be later used in the drainability test.
b) Beginning with the minimum value obtained from the coating test, mix the aggregate and binder samples, recording the actual weights of aggregate and binder used. Increase the binder content in 0.5 % increments for the remaining samples to be mixed. Do not increase the binder content anymore when the mixture becomes soupy during mixing.
c) Verify that the proportion coated is greater than 90 % for each of the samples mixed.
d) Remove approximately 100 g of mixture and allow to cool to room temperature. Leave aside the remaining 1000 g from each sample for the drainability test which follows.
e) Place the 100 g sample of mixture into a 1-litre jar filled with distilled water. Place jar into an oven at 60°C for 16 to 18 hours.
f) After heating, shake the jar vigorously for approximately 5 seconds, and then pour off the water. Spread the mixture on absorbent paper.
g) As done in the coating test previously, estimate the coating of the mixture. Record the proportion of aggregate coated. Record the minimum binder content at which the coating is greater than 90 % (the technician performing the test should judge whether the coating is acceptable).

Drainage test

a) Record the weights of several 250 mm diameter aluminum pie pans in the appropriate table.
b) Place the 1000 g sample from the stripping test into an aluminum pie pan and record the weight of the sample with the pie pan and the sample alone.
c) Place mixtures (on the pie pans) into a 60 °C oven for 24 hours.
d) After heating, remove the mixture from the pie pan by turning the pan over and tapping the bottom until all aggregate particles are off the pan.
e) Record the weight of the pie pan with binder residue in the table.
f) Determine (calculate) the highest binder content with a drainability of less than 4 proportion of the original weight of binder, and record it.

After completion of all these three tests, the values of the binder contents determined by coating and stripping test represent lower boundaries for the optimum binder content, and the binder content determined by the drainage test represents the upper boundary. At this stage, the compatibility of the binder and aggregate combination becomes apparent. If the binder content for acceptable drainability is below the values for stripping and coating, the tested combination is not supposed to perform satisfactorily in the field.

As said, these testing procedures are intended to give a rough idea of the optimum binder content and to identify those combinations of binder binder and aggregate that would perform poorly in the field in terms of coating, stripping, and drainability. However, even reasonable values for the different tests do not guarantee successful performation at road application.

4.3.2 Acceptance testing for new cold-mix materials by proprietary sources

Acceptance testing is recommended to ensure the quality of the current batches when a previously used cold-mix or proprietary material is intended for use. Although the acceptance test procedure does not guarantee a successful patching material, it is used to identify materials which are likely to perform poorly in the field.

The two tests suggested for acceptance should help the mix-designer to quantify two important characteristics of cold mixtures - workability and cohesion. As with the compatibility testing procedure, these tests do not guarantee success for the materials tested, but they indicate the potential for poor performance in the proposed materials.

Workability test

This test requires a workability box, a pocket penetrometer (normally used for soil testing), and a penetrometer adapter. The workability testing box should measure 102 mm on all sides and should have a 10-mm hole in one side. An acceptable penetrometer has a scale of 0 to 53 metric tons per m^2, with a 6.4-mm-diameter end. The penetrometer adapter increases the diameter of the penetrometer to 9.5 mm.

a) Prepare three samples of cold mix of approximately 2500 g and cool the samples to 4^oC.
b) Place the cooled mixture into the workability box. Drop the mixture loosely into the box, making no effort to pack the material into the box.
c) Push the penetrometer with the adapter through the holes in both sides of the box. Record the maximum resistance as the workability measurement.
d) After repeating steps b) and c) for all three samples, calculate the average workability measurements for all samples.

An average workability reading between 3 and 4 would be considered marginal, whereas a value greater than 4 should be rejected. Values less than 3 are acceptable.

Cohesion test

a) Cool several 1200-g samples of cold mixture to a temperature of 4^oC.
b) Place the cold mixture into a standard Marshall mould (63.5 mm high, with a diameter of 102 mm). Compact the sample using a standard Marshall hammer (4.5 kg) by five blows on each side (drop height of 457 mm).
c) Extrude the sample and record the weight of the compacted sample.
d) Place the compacted sample along the bottom edge of a 305 mm diameter sieve while both the sieve and the sample are standing on end (see Figure 1).
e) Place the cover on the sieve while it is still on end. Roll the sieve (with the sample inside) back and forth 20 times, taking approximately 1 second for each of the 20 passes.
f) Lay the sieve (with the sample still inside) against the edge of a table, allowing room for sample pieces to fall through the sieve openings. Leave the sieve in this position for 10 seconds.
g) Flip the sieve and lid over so that the sample in the sieve falls onto the lid. Weigh the material retained.
h) Determine the average proportion retained by dividing the weight retained by the original weight. A minimum retention value of 60 % is recommended for this test.

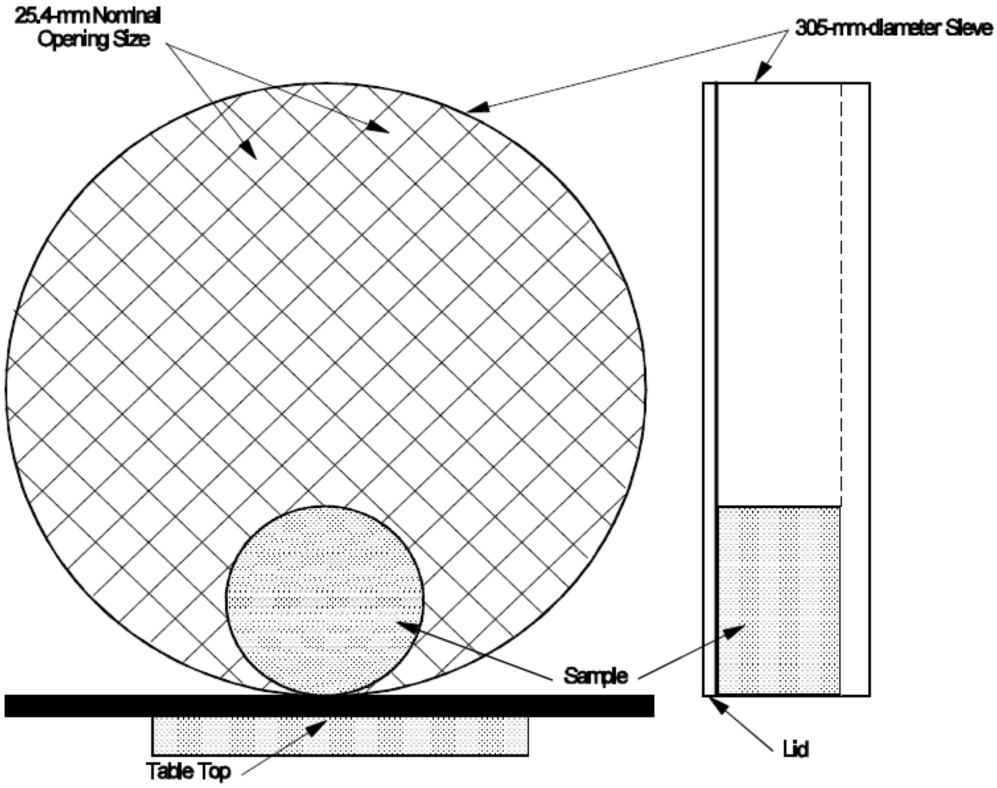

Figure 1: Equipment for rolling sieve cohesion test [source 1, FHA SHRP, USA, 1999]

5 Bituminous hot mix materials for potholes repair

The ADEPT report [source 3, UK, 2010] describes a process for pothole repairs using hot material. It describes the use and characteristics of aggregate dominated and matrix dominated materials and the need to consider both engineering characteristics of these two types of infill materials and compatibility with the surrounding material.

5.1 Hot - mix infill repair materials

Hot-mix asphalt material is found to be the most often applied repair material in use by the UK highway authorities. According to the ADEPT report [source 3, UK, 2010], there are two generic engineering 'family' types of hot-mix asphalt which can be used as infill material - 'aggregate dominated' and 'matrix dominated' asphalt. As the descriptions indicate, the engineering performance of matrix dominated type of asphalt is dictated by the dominance of the 'glue' between the particles (called matrix or mortar), on the other hand, the engineering performance of aggregate dominated type of asphalt is based on the interlocking properties of the aggregate particles. The bitumen binder film thickness for 'matrix' dominated materials is greater than for 'aggregate' dominated materials. Due to their composition, aggregate dominated materials can perform satisfactorily only if all edges are supported by existing intact surrounding material.

5.1.1 Matrix dominated asphalt materials

As stated in the ADEPT report [source 3, UK, 2010], the main characteristics of matrix dominated hot-mix asphalt are as follows:

- Their main engineering performance characteristics result from the properties of the 'glue' matrix which is a blend of fine aggregate (sand), filler (limestone powder) and binder (bitumen of various grades).
- Matrix dominated materials are relatively easy for compaction which results in a largely impermeable material with consequent good durability properties.
- The load transmission is dictated by the characteristics of the matrix.
- The binder content for this material is relatively high, therefore it is more tolerant to strain.
- Its approach to failure distress is through progressive plastic deformation.
- Two sorts of matrix dominated hot-mix asphalts are Hot Rolled Asphalt (HRA) and Mastic Asphalt (MA). The mixture may consist of matrix material only or can have a proportion of single-size coarse aggregate added. The proportions of coarse size aggregate vary depending to purpose. Hand lay application is feasible when the upper limit for coarse aggregate content is 55 % [source 3, UK, 2010]. Material with much lower coarse aggregate contents (about 30 %) is easy to compact but the surface is quite smooth and superimposed chippings may be required to ensure an adequate level of resistance to skidding.

5.1.2 Aggregate dominated asphalt materials

The main characteristics of aggregate dominated hot-mix asphalt are as follows [source 3, ADEPT report, UK, 2010]:

- Their key engineering performance characteristics result from the grain packing properties and interlocking of aggregate particles.
- Binder contents for aggregate dominated mixtures are less than for matrix dominated mixtures because of the smaller aggregate surface area which needs to be coated.

- Aggregate dominated materials are sensitive to strain movement because applied stresses are transmitted through the inter-particle contact points.
- The load transmission is dictated by the characteristics of the point-to-point interlocking of the aggregate particles.
- Its approach to failure distress is through fatigue cracking or unravelling attrition as the inter-particle bond is broken either through induced cracking or environmentally induced embrittlement of the binder. Once a critical ageing point has been reached, there can be rapid degradation over a short time span.
- In the UK, aggregate dominated bituminous materials were known as 'macadam', but in recent technical specifications they are termed as 'Asphalt Concrete' (AC) and Stone Mastic Asphalt (SMA).
- A wide selection of particle size distribution is possible in these materials, ranging from continuous (dense) to single size (open) gradations. Single size gradations are more permeable than continuous gradations. The more continuous (denser) gradations require high levels of energy to achieve full compaction but once installed they provide a very efficient load transfer medium.

5.2 Engineering selection

Engineering selection must consider all conditions and circumstances which affect on the repair material choice.

Table 1: Comparison of engineering performance characteristics [source 3, UK, 2010]

Repair material type	Relative binder content	Failure distress mode	Progress of distress	Relative permeability	Compaction energy required	Service life durability
Matrix dominated	Higher	Deformation	Slower	Lower	Lower	Longer (5-10 years)
Aggregate dominated	Lower	Attrition	Quicker	Medium or higher	Higher	Shorter (1-4 years)
Note: Service life is an estimated range only and may be extended if combined with timely surface area regeneration.						

South African technical guide [source 4, CSIR, 2010] states that hot-mix asphalt (HMA) is probably the best material for patching potholes where potholes occur within a reasonable haul distance from an HMA plant and the quantity of asphalt required to patch the potholes assures an adequate supply (usually in urban areas). A continuously-graded asphalt with low permeability is usually used. The minimum working temperature is a function of the viscosity of the binder (which depends on the binder grade). This temperature should be determined in the laboratory and need to be identified for each different mixture. In most cases, it should not be less than about 135 ℃. The material should not be too cold because compaction would then not be effective.

6 Cement - based (concrete) materials for potholes repair

The final report on Expedient Repair Materials for Roadway Pavements [source 7, Army Corps of Engineers, USA, 2005] states that the need for rapid pavement repair requires the use of fast-setting or rapid-hardening cementitious materials. Although the terms fast-setting or rapid-hardening vary somewhat between producers and are often not well defined, they generally include materials that achieve an initial set in less than 1 hour and a minimum compressive strength of 3.5 MPa (500 psi) within 3 hours. According to the report [source 7, Army Corps of Engineers, USA, 2005], the available types of rapid-hardening cements include:

- Magnesium-phosphate cements are a blend of materials which react with water to form a rapid-hardening concrete. These cements are available in one-component systems (in powder form with water being added to form the concrete) or in two-component systems (a magnesium powder for combination with phosphate in an aqueous solution). These cements can be extended with aggregate. Both hot- and cold-weather type formulations are available on the market.
- High-alumina cements have as their main ingredient monocalcium aluminate. The lime and alumina make up about 80 % of the cement in roughly equal parts. This cement achieves a high early strength, but it has a relatively long initial set time followed quickly by the final set. This cement is commonly used in high-temperature (refractory) applications.
- Regulated-set portland cements are a mixture of a portland cement and calcium fluoro-aluminate. These cements provide high early strengths and rapid set times which can be regulated with admixtures.
- Gypsum cement has calcium sulfate hemihydrate as its main component. Thess cements has a very fast initial set and high early strength. The durability, abrasion resistance and fuel resistance of this cement are low.
- Special blended cements are proprietary materials which contain portland cement and other materials. Of the other available rapid-hardening cements, these blended cements are generally the least expensive and simple to mix.
- Type III portland cement with accelerating admixtures is a mixture of rapid-hardening cement and accelerating admixtures (gypsum, calcium chloride, calcium nitrate or various carbonates). These cements achieve high early strengths and good durability, although they have relatively high heat of hydration and shrinkage.
- Polymer cements are organic in nature and are produced by combining two or three liquid components during mixing. These monomer components can be polymerized with the addition of an aggregate into a polymer concrete. The polymerized monomer (synthetic resin) is used to replace the hydraulic cement as the bonding agent for the aggregates. Types of polymer cements include epoxies, methacrylates, polyesters and urethanes. Polymer cements are very versatile in set time and strength gain, they have high adhesion properties and low shrinkage, and are relatively durable. However, they are generally expensive, relatively difficult to mix, have thermal properties different from conventional PCC, and present a safety hazard for workmen.
- Proprietary materials cover a wide range of fast-setting materials that do not fit into one of the previously listed categories. Some of these materials also contain some amount of waste material, usually fly ash.

7 Repair techniques with cold-mix materials

7.1 Application procedures

Manual of Practice [source 1, FHA SHRP, USA, 1999] describes repair techniques for the cold-mix repair of potholes in asphalt-surfaced pavements:

- throw-and-go
- throw-and-roll
- semi-permanent repair procedure
- edge seal method
- spray-injection patching

7.1.1 Throw-and-go

This procedure is strictly intended for temporary pothole repair only because the cold-mix patching material is shoveled into the pothole with no previous preparation of the pothole. Compaction of the patch is left to traffic (passing vehicles), while the maintenance crew moves on to the next distress location. Generally, this method is used in harsh winter conditions because of its high rate of production.

7.1.2 Throw-and-roll

This is a slightly improved method regarding a simple throw-and-go method. The cold-mix patch material is also shoveled into the pothole with no previous preparation of the pothole. After filling, the the maintenance crew truck tyres are used to compact the patch before the crew moves to the next location. Again, this method is still supposed to be temporary repair.

The throw-and-roll method consists of the following steps:

a) Placing the material into a pothole (which may or may not be filled with water or debris), as shown in Figure 2.
b) Compacting the patch using truck tyres, as shown in Figure 3.
c) Verifying that the compacted patch has some crown between 3 and 6 mm.
d) Moving on to the next pothole location.

Figure 2: Throw-and-roll procedure - infill material placement

Figure 3: Throw-and-roll procedure - patch compaction with truck tyres

Because some effort is made to compact the patches, this method provides a tighter patch for traffic than simply leaving loose material. The execution rate is still high because the extra time to compact the patches (a couple of additional minutes per patch) do not reduce productivity significantly - especially if the patches are spread over a long distance and most of the repair time is spent travelling between potholes.

7.1.3 Semi-permanent repair

The semi-permanent repair method is considered as one of the best for repairing potholes, short of full-depth removal and replacement. This procedure represents an increased level of effort for patching potholes. This extra effort increases the performance of the patches by improving the underlying and surrounding support provided for the patches. On the other hand, it also raises the cost of the patching operation.

Care in the preparation of the pothole for repair is at least as important as the repair itself. The initial key point of preparation is removing all debris and water from a pothole before commencing the repair process. It is necessary to remove all loose and unbonded material as well as material that has been affected by the pothole. If this is not done thoroughly, then the repaired patch will not function as a reinstated part of the pavement and could soon become abraded or dislodged. Sweeping out is the most frequently used method of preparation, but unless this is done thoroughly with appropriate equipment it can be difficult to remove all debris.

This procedure includes the following steps:

a) Removing water and debris from the pothole.
b) Forming the sides of the patch area until vertical sides exist in reasonably sound pavement. A pavement saw, jackhammer or milling machine can be used for edges straightening (Figures 4 and 5).
c) Placing the asphalt mixture.
d) Compacting with a device which should be smaller than the single patch area (single-drum vibratory rollers or vibratory plate compactors) - see Figures 6 and 7.

Figure 4: Semi-permanent procedure - edges straightening using hand-held pavement saw

Figure 5: Semi-permanent procedure - edges straightening using cold-milling machine

Figure 6: Semi-permanent procedure - compaction using vibratory-plate compactor

Figure 7: Semi-permanent procedure - single-drum vibratory roller used for compaction

This repair procedure provides a sound area for patches to be compacted against and results in very tightly compacted patches. However, it requires more workers and equipment and has a lower productivity rate than either the throw-and-roll or the spray-injection procedure.

In practice, for smaller potholes, this procedure is also performed without straightening the edges (Figures 8).

Figures 8: Small pothole repair (without edges straightening, but with base spraying)

7.1.4 Edge seal

This method requires a second pass through the repair area, but this additional effort improve patch performance in older pavements with a lot of cracking.

The edge seal method consists of the following steps:

a) Placing the material into a pothole (which may or may not be filled with water or debris).
b) Compacting the patch using truck tyres.
c) Verifying that the compacted patch has some crown (between 3 and 6 mm).
d) Moving on to the next pothole.
e) Once the repaired section has dried, placing a ribbon of bituminous tack material on top of the patch edge (tack material should be placed on both patch and pavement surfaces).
f) Placing a layer of sand on the tack material to prevent tracking by vehicle tyres.

Because this procedure require a second visit to the repaired section by the crew (to allow water to dry before placing the tack), the repair productivity has been reduced. As a benefit, the placement of the tack material prevents water from getting through the edge of the patch and can glue together pieces of the surrounding pavement, improving support for the patch.

7.1.5 Spray injection patching

Using spray-injection devices for repairing potholes requires higher equipment costs than the other procedures, but it also has a high rate of productivity and lower material costs. This patching technique is successfully used across the United States and Canada.

The spray-injection procedure is normally not performed in any weather. It requires a device that can place virgin aggregate and heated emulsion into a pothole simultaneously; even so, this procedure can be carried out in most weather conditions.

The spray-injection procedure consists of the following steps:

a) Blowing water and debris from the pothole.
b) Spraying a tack coat of binder on the sides and bottom of the pothole.
c) Blowing binder (heated emulsion) and virgin aggregate into the pothole.
d) Covering the patched area with a layer of aggregate.

This procedure requires no compaction after the cover aggregate has been placed. Figures 9 and 10 illustrate the two main types of spray-injection devices available. The first (Figure 9) is a trailer unit towed behind a truck carrying the aggregate, the second (Figures 10) is a unit with aggregate, heated binder tank, and delivery systems all contained in a single vehicle.

Figure 9: Spray-injection device - truck and trailer unit

Figures 10: Spray-injection device - self-contained unit

Similar procedure is applied in Slovak and Czech republics but the term "jetpatcher technique" is used [source 19, Ministry of transport, TP 96, Czech republic, 1997]. It is stated that is not allowed to use this technique for maintenance of motorways and roads with limited access. It can be used for maintenance of 1st class roads in exceptionally cases only.

The jetpatcher technique is determined for local repairs of asphalt pavement surface, mainly to ensure pavement serviceability after the winter period and to prevent distress from developing. The jetpatcher technique is not allowed to be used on cement concrete pavements. This technique can be performed only as a part of operative management on the base requirements resulting from visual inspections. It is recommended to include a trained person with a licence for pavement diagnostics in a team for visual inspections who is able to decide about the suitability of the jetpatcher technique. When a treatment of pavement is planned in a frame of pavement management system, it is necessary to keep in mind that the repairs using the jetpatcher technique should be removed.

Recommended basic principles and conditions for use the technique for pothole patching:

- jetpatcher technique must not be used during warranty period
- asphalt surface with local occurrence of potholes, i.e. total area of potholes is max 1 % of the section area; depth of pothole max 50 mm
- minimum air temperature shall be + 10 °C and the maximum not higher than + 30 °C
- not permitted when the conditions include rain, excessively wet aggregate or a strong wind
- loose material not removed by air has to be removed mechanically
- only trained operators can operate with an equipment for this technique

Virgin crushed aggregate and bitumen emulsion are used for the jetpatcher technique. Fractions 2/4, 4/8, 8/11 and 8/16 are recommended (using the basic set plus set 1 of the CEN aggregate sieve sizes). The choice depends on the thickness of layer (depth of pothole). Properties of aggregate shall fulfill requirements determined in the standard EN 13043 and ČSN 736129 Table 3b - Qualitative parameters of coarse aggregate according to EN 13043.

Cationic bitumen emulsions with minimum bitumen content of 58 % are used as binder. Emulsions C 60 B4, C 60 B5, C 65 B4, C 65 B5, C 60 B6, C 65 B6 are allowed or BP types for polymer modified emulsions. Bitumens B50/70, 70/100 or 100/150 are used for emulsion production.

Application procedure for pothole repair using the jetpatcher technique is similar to multilayer surface dressing. The pothole patching procedure phases are:

- mechanical cleaning of damaged pavement surface and debris from a pothole
- final cleaning of pothole using pressurized air
- spraying a tack coat of binder (dosage from 0.3 to 0.4 kg/m^2)
- spraying emulsion (using air pressure) into the pothole including its edges (dosage rates from 0.7 to 1.5 kg/m^2 in relation to used fraction of aggregate)
- spraying coarse aggregate (8/11 or 8/16) into the pothole at dosage rates from 8.0 to 13.0 kg/m^2
- after the emulsion has broken, application of the next layer of emulsion and aggregate (a smaller maximal nominal size of aggregate grain relative to the previous layer, the dosage of the emulsion being adjusted in relation to the aggregate size)
- repeating the previous step until the pothole is fully filled-in
- after compaction by vehicles (approximately 2 - 3 days) sweep-up any loose aggregate particles

In Sweden, a “trunk car” spray injection device is used to minimize the cost of the repairs to cracks and potholes [source 14, Sweden]. The use of a spray injection device for potholes repairs at nine different trial sites is described. The benefits of using this vehicle are:

- one-man-operated
- no exposure of workers to danger
- quick method (compared to, for example, asphalt)
- environmentally friendly method
- high-quality repairs with bitumen coated aggregates
- heating of the damage area, so this method can be used at low temperatures
- mobility

7.2 Other specifities about various cold-mix repair materials

Typical cold patch mixtures contain an emulsified or cutback bitumen to maintain workability at ambient temperatures. But some cold-mix patching materials require special treating during application due to the origin of their binder. For example, the Rephalt product [source 9, Virginia Department of Transportation, USA, 2009] incorporates a bio-based component to maintain this workability. This component then reacts with water incorporated into the mixture during placement to ‘cure’ into a stiff pavement layer. Approximately one litre of water needs to be added to each 25 kg of material in order to initiate this reaction and an additional approximately one litre of water is sprinkled on the loose material before compaction. See Figure 11 (multi layer application for a bit larger and deeper patch).

Figure 11: Sprinkling loose material with water

Procedures relating Marshall specimen preparation

As noted in [source 7, Army Corps of Engineers, USA, 2005], the specimens for the Marshall testing (stability and flow values) can be compacted using a Marshall compaction hammer or using a gyratory. Giratory can compact to densities equivalent to those obtained with the Marshall hammer. In order to be able to compact the CMA mixtures for Marshall specimens, the mixtures need to be cured and heated prior to compaction. The curing is required when testing cold mixtures which use either a cutback or an emulsified binder in order to provide workability at ambient temperatures. The method used is to place the mixture in a forced draft oven at 135 ^{O}C overnight (14 to 18 hours) and then compact at that temperature. Specimens compacted under these conditions should represent the condition of the mixtures after being in place for several months.

Some Canadian documents describing cold-mix testing also quote that the samples need to be aged before compaction in order to add stability and obtain more representative results after several months of traffic. Such a procedure is supposed to determine the stability of the cold mixture after it has been exposed to the natural environment for a period of time - ranging from a few weeks in a warm climate to a few months in a colder environment [source 18, Golder Associates Ltd. report, Canada, 2002].

On the other hand, Instarmac from the UK have adopted a rather different test method for the measurement of density, stability and flow for their Ultracrete EMCOL mixtures that has been used for many years by their Japanese Licensee. This procedure is as follows [source 8, Instarmac leaflet, UK, 2005]:

Test 1: Curing 7 days in air at 25^{O}C

1. Using Marshall Compaction Apparatus. Place the mixture into the mould at 25^{O}C, press to harden with 50 blows to both sides (63.5 mm thick). For accuracy, preparing 3 specimens and averaging the results is recommmended.
2. Allow the specimens to stand for 1 day at 25^{O}C and then remove the samples from their moulds.
3. Leave to cure for 7 days in air at 25^{O}C after which time the thickness and weight can be taken to determine the density.
4. Place the samples in a water bath at 20^{O}C to condition for 30 minutes.
5. After this time period, remove the samples and immediately carry out the Marshall stability test.

Test 2: Curing 6 days in water at 25^{O}C

1. Follow the same steps as in 1 & 2 of Test 1.
2. Place the samples in a water bath, set to a temperature of 25^{O}C, and condition for 6 days submerged in water.
3. Remove the samples and placed them in a separate water bath at 20^{O}C to condition for 30 minutes.
4. After this time period, remove the samples and immediately carry out the Marshall stability test.

7.3 Winter and spring repair procedures

Pothole-patching operations are usually performed when potholes have developed at various locations throughout a maintenance area. Most patching operations simply try to repair the distress and restore rideability and safety as quickly as possible. The Manual of Practice [source 1, FHA SHRP, USA, 1999] contains recommendations for improving the overall quality of the patches. Although pothole repairing can be performed throughout the whole year, the majority of these works takes place in two distinct periods:

- in winter, when temperatures are low, base material is frozen, and additional moisture and freeze-thaw cycles are expected before the spring thaw.
- in spring, when base material is wet and soft, and only few additional freeze-thaw cycles are expected.

According to the Manual [source 1, FHA SHRP, USA, 1999] the recommendations for repair operations are therefore divided into:

- winter and
- spring patching and include
    - preparation
    - placement, and
    - compaction alternatives.

7.3.1 Winter Patching

Winter patching operations generally take place during periods of snow melt, when maintenance crews do not perform the winter service (when they do not plough or apply abrasives or salt). Warmer weather during winter not only provides time to repair potholes, but it also creates conditions which can leave to further development of potholes because the warmer temperatures cause thawing and softening of frozen base materials, reducing underlying pavement support. Because winter patching occurs while more winter conditions are expected, the patching materials are subjected to more stress owing to repeated cycling between very cold and warm conditions.

Materials

Aggregates used for winter patching conditions should be high-quality, crushed aggregate with few fines. Binders should be emulsified bitumens with at least an anti-stripping additive (due to water in the potholes). The mixture should be workable at low temperatures to allow both easier handling by the workers and easier compaction in the pothole.

Procedure selecting

Because patching potholes take place under harsh winter conditions, usually there is not enough time for using the semi-permanent procedure (see section 7.1.3). Such a procedure requires more time to patch the potholes which decreases the productivity of the repair work and increases the amount of time during which the maintenance crew is exposed to traffic.

Therefore, throw-and-roll procedure provides a cost-effective means of patching under winter conditions. It is extremely important that a high-quality material is used and that it is compacted by the truck tyres. Leaving the patch to be compacted later by traffic will result in premature patch failures.

Patches placed under winter conditions certainly have a shorter life expectancy than patches placed in the spring – they are supposed to last from several days to several months. The aim of winter patching is to restore rideability and safety as quickly as possible – not to repair the distress more durably or even permanently.

7.3.2 Spring Patching

Spring patching differs from winter operations in that the climatic conditions do not stress the patches to the same degree because freeze-thaw cycling should have finished, so most of the conditions that soften the underlying support have already passed.

Materials

The choice of materials for spring patching should be based on a calculation of their cost-effectiveness with consideration of the experience of the local maintenance crew.

Any material acceptable for winter patching is generally acceptable for spring patching. High-quality crushed aggregate with few fines and an emulsified bitumen should be used for spring patching. Anti-stripping additives are still advisable. The mixtures can be slower setting than winter materials because the higher temperatures allow more rapid evaporation.

Because repair materials are often been stockpiled over the winter, the effects on the mixture and the differences in workability over wide temperature ranges should be considered.

Materials that are workable at very low temperatures tend to be very sticky and hard to use at higher temperatures.

Procedure selecting

Spring patching can be realized by the throw-and-roll, semi-permanent, edge seal or by spray injection (jetpatcher) procedures. The selection should be made on cost-effectiveness determined for the certain circumstances and the availability of equipment and workers. Because the semi-permanent procedures require more equipment and workers, and the edge seal procedure requires a second visit to the repair area, those procedures may be impractical in some instances. In this cases, the throw-and-roll procedure is the best alternative for placing spring patches, having in mind a shorter durability in general.

Because of better climatic conditions patches placed during the spring are expected to last longer than patches placed under winter conditions. Observations from some field tests have been made which indicated that, after the initial setting period (2 to 4 weeks), patches were likely to remain in place until the surrounding pavement begins to deteriorate. The aim of spring patching operations should be to place patches that last as long as the surrounding pavement.

7.4 Patching Costs for cold-mix asphalt

For every combination of material selection and repair procedure, the cost-effectiveness of the overall patching operation will be affected by three main costs for pothole patching [source 1, FHA SHRP, Manual of Practice, USA, 1999]:

- material costs
- labour costs
- equipment costs

There may also be some user-delay costs associated with pothole patching operations, as well as associated lane-closure time. The combinations of materials and procedures that will produce optimum cost-effectiveness vary between different road authorities.

Materials

Cost of materials are usually one of the least significant contributors to the overall costs of a patching operation. However, the material used for patching has influence on the cost of the overall operation when there are differences in performance between several materials. More expensive materials which are placed with less effort and last longer, therefore, reduce the cost of the initial patching effort, as well as the amount of repatching needed. All together reduces also the labour and equipment costs for the overall operation.

Labour

The labour cost for the throw-and-roll technique consist of two workers who do the actual patching, plus traffic control. One of the two workers shovels the material from the truck into the pothole, and the other compacts the patch by driving the truck over the section. In some instances (when patching large areas, for example), the driver of the vehicle can help to shovel the material. This help generally improves the productivity of the overall operation.

The edge seal procedure requires the same two workers and traffic control as the throw-and-roll procedure, but requires an extra pass to place the tack and sand materials at the end.

Experience from maintenance operations have shown that the optimum crew for the semi-permanent patching operation consist of four workers, along with the appropriate traffic control. Two workers clear out debris and square-up the edges, while the other two follow behind, place infill material and compact the patches.

The single-unit spray-injection device requires a single operator. When using the trailer-unit equipment, two operators are recommended – one operates the vehicle, the other places the material.

Labour costs for traffic control should be included when necessary. The cost of traffic control can be handled in several different ways, depending on the site of the patching operation and the requirements of the particular road authority.

Equipment

For the the throw-and-roll, semi-permanent methods and edge seal, shovels, rakes, or other handtools are needed for placing the material. In addition, for the throw-and-roll and edge seal methods, the only major equipment costs are for the truck carrying the material and the traffic control vehicles and signs.

For the semi-permanent repair method, the necessary equipment varies from one maintenance company to another, depending also on the place circumstances, but a basic list includes the following:

- material truck (with handtools)
- equipment truck
- compaction device (vibratory plate and single-drum vibratory roller are generally both the most inexpensive and the most maneuverable)
- air compressor
- edge-straightening device (jackhammer, pavement saw, cold-milling machine)
- traffic control vehicles and signs

The only equipment needed for spray injection procedure is the spray-injection device and the traffic control trucks and signs.

8 More durable repair techniques applied with hot-mix or cold-mix materials

8.1 Main aspects

The main aspects of the quality and durable repair process are:

- Preparation is a key to good repair.
- Clean and dry excavation is essential.
- Debris and water must be removed from the pothole.
- Edge formation, usually vertical edges, provide cleaner surfaces for bond adhesion and is mainly achieved by saw cutting.
- Acute angles should be avoided.
- Application of a bond coat to the base and sides of the excavation for full adhesion and to prevent later water ingress.
- Appropriate infill material must be selected on the basis of ease of installation and good compaction.

The main phases of such repair process include [source 3, ADEPT, UK, 2010, and source 4, CSIR, South Africa, 2010]:

1. preparation including removing all loose material and water
2. edge formation (saw cutting) and removing all debris
3. excavation with cleaning and drying
4. application of bond coat to base and sides
5. infilling with asphalt material
6. compaction with vibrating plate, roller or tamper

8.2 Preliminary treatment and preparation with edge formation

The proper preparation is crucial for a good repair. It is as important as the repair itself. No matter how quality and durable material is used for pothole infilling, it will not perform well and last long if it is applied in inappropriate circumstances.

First, the area which is intended to be patched must be marked using chalk, spray paint or crayons. The depth of the material that needs to be removed depends on the cause of the pothole and the material in which it occurs. The entire distressed area must be included, together with some sound adjacent area. It is essential that the marked area includes the whole area affected by the pothole and any associated distress. The patch should be marked using straight lines because these can be cut more neatly than round or oval patches. A diamond saw is normally used to cut through the surfacing and to give a neat and clean, well-shaped patch (Figure 12). This process avoids too much disturbance to the surrounding material which could otherwise be weakened or dislodged by other methods resulting in inherent weakness around the repair. The formation of neat vertical edges to the pothole excavation provides cleaner surfaces for bond adhesion and better opportunity for infill material edge compaction.

In practice, the most common repair shape is rectangular with sides parallel to the edge of the road and corner angles of 90 degrees. Acute angles should be avoided because they create a situation of extreme difficulty for infill material compaction. Experience has shown that, for smaller areas, a diamond-shaped patch with the upper and lower apices in the direction of traffic movement tends to be more effective and durable. The impact of tyres on the edge of such patches is different and it reduces the risk of cracking at the patch edge or of longitudinal deformation. Therefore, if the opportunity exists, it could be beneficial to form the rectangle in a 'diamond' layout with a lead corner in the direction of traffic because this orientation avoids the sudden transition loading by traffic from existing road to the pothole patch.

Anyway, the ideal repair shape would be circular because this does not result in any corners where compaction of the infill material is inherently more difficult. However, round patches would be more difficult to construct with a reasonable aesthetic quality unless using a large diameter coring rig, as used in the “Core & Vac” technique for utility repairs [source 21, UK, 2012].

Figure 12: Cutting asphalt pavement using saw

8.3 Cleanliness of excavation

After cutting the surfacing, the material which is going to be replaced must be excavated using a pick and spade or jackhammer (Figure 13). A clean and dry excavation is essential for an effective repair and all water in the pothole must be removed. Therefore, the excavated hole needs to be well-cleaned prior to any repair. Without ensuring that all unsound material is removed, even the best repair of the pothole will soon be affected by continued failure of material outside the pothole patch.

The hole is normally cleaned of all loose material by sweeping it. A combination of sweeping and use of absorbent granules or sheets or by the use of air pressure is also applicable (Figure 14).

Figure 13: Using jackhammer at excavation

Figure 14: Cleaning the excavation hole with air jetting

Figure 15: Excavation hole prepared for bond coating

8.4 Bond coating

A bond coat must be evenly applied to both the base and sides of the excavation to ensure full adhesion and continuity of strain transfer (Figure 16). The bond coat is normally a cationic emulsion containing at least 60 % bitumen. It is preferably applied by brush to achieve an even covering. Thorough bond coat application is critical to obtain a sealed joint with the surrounding road material and to mitigate future water ingress.

Some repair asphalt producers require application of spray sealant to pothole edges.

Figure 16: Bond coating

8.5 Infilling with repair material

The selection of the most appropriate type of infill repair material should be based upon the assesed pothole formation mechanism, pothole size and other characteristics and the thickness of exposed remaining bound material. Different types of materials can be applied (cold or hot asphalt mixtures, cement-based materials). Small potholes are usually repaired by filling with cold-mix asphalt material (CMA). Large ones can be repaired more effectively using hot-mix asphalt (HMA), but the location of the potholes needs to be within a suitable haul distance from an asphalt plant. The repair material ordered needs to be of a significantly large quantity to make the delivery cost-effective and within a suitable proximity so that the material can be delivered at a temperature that allows successful placement and compaction without excessive cooling of HMA.

The preferred hot-mix infill material for pothole repair is matrix dominated asphalt (see section 5.1) because of its relative ease of installation and good compaction ability. ADEPT report [source 3, UK, 2010] states that aggregate dominated materials should be an option for consideration only if there is a planned surface regeneration works programme on the surrounding road shortly after the pothole repair is undertaken. The report includes a scheme for infill repair material selection process for hot asphalt mixtures (Figure 17). However, the need to repair surfaces with a material of similar characteristics can be important.

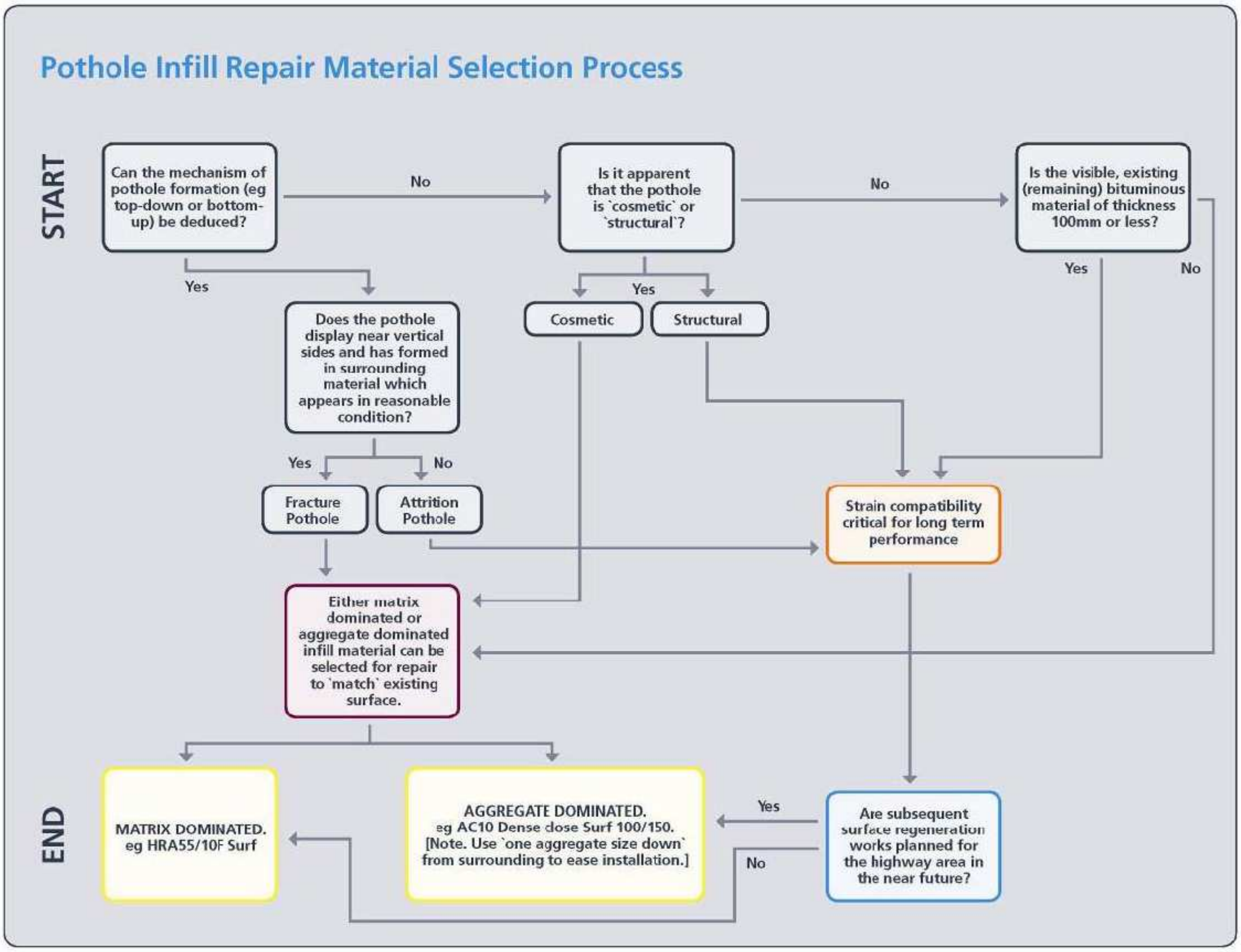

Figure 17: Pothole infill repair material selection process [source 3, UK, 2010]

8.6 Compaction

Every type of infill repair material applied must be fully compacted. Vibratory plate compactors and single or double-drum vibratory rollers are often used, depending on the patch size. For small patches also hand tamper is applicable. If full compaction is not achieved then this would lead to premature distress of the repair through water ingress.

Compaction within the confines of a pothole must be undertaken using either a vibrating plate or tamper. The joints between the patch and the existing road are the areas that fail most frequently, with an open crack developing that allows the access of water and causes the premature failure of an otherwise satisfactory patch. For this purpose, application of a geosynthetic crack-sealing strip over these joints, using a layer of bitumen emulsion to stick the strip and a second layer on top of the strip to 'waterproof' the geosynthetic, is found to be useful. Blinding with some coarse sand over the second layer ensures that the bitumen does not stick to vehicle tyres.

Because the corners of the rectangular patches are the most vulnerable to distress, particular care must be taken also to achieve full compaction in these areas.

While hot-mix infill material is used, it must be maintained above an appropriate temperature to enable full compaction. As mentioned in 5.2, this temperature is a function of the grade of binder used in the mixture. Compaction should be completed before the temperature of the material falls too low. The use of a mobile 'hot-box' to maintain the asphalt at an appropriate temperature is recommended.

As described in 5.1, matrix dominated hot-mix asphalt requires relatively less energy to achieve the full compaction than aggregate dominated material and this fact could also be one of decisive factors for repair material selection.

Figures 18: Repaired potholes

8.7 Current practice and recommendations

South African technical guide [source 4, CSIR, 2010] states that it is normally not recommended that HMA is used to patch potholes with a thickness of more than 75 mm because it is difficult to ensure adequate compaction of thicker layers. It is necessary to ensure that the entire patched area that will be in contact with the HMA is covered with a tack coat, usually bitumen emulsion, to ensure good bonding between the HMA and the excavated hole.

As already mentioned in section 2, the South African guide [source 4, CSIR, 2010] provides a tabulated decision key process for the potholes repair to assist with the identification of the causes of potholes (see Table 2). This table shows that the classification process is purely visual, except for key point 10 where it is necessary to determine whether the top of a cementitiously-stabilised base has carbonated. Similarly, the determination of whether the subgrade is excessively wet requires some judgement, which is gained with experience. The guide also includes a standard form for the field assessment and categorisation of potholes.

Table 3 presents an illustrated key to the identification of pothole repair measures. To use the key, one must start at the top left-hand box and sequentially follow the vertical numbering and horizontal boxes until a repair technique is identified. These techniques then refer to the three types of procedures which are described below :

Shallow asphalt

This type of repair is generally restricted to potholes that occur entirely in one layer of asphalt and will rarely require more than a 75 or 100 mm thickness of asphalt. All loose material should be swept from the patch area. After the patched area has been prepared (identified, marked, cut, excavated and cleaned), the entire exposed area (vertical and bottom exposure) of the patch must be covered (painted) with an appropriate bitumen emulsion coat. The suppliers of certain CMA indicate that tack coats are not necessary (this may possibly apply to those that are emulsion based), but it is recommended that a tack coat is used where a cold mixture and asphalt are in contact and on top of the base layer (bottom). The placed asphalt (CMA or HMA) in the hole is then leveled by rake, normally in a single layer. If the hole is more than about 75 mm deep, it should be filled in layers not exceeding 75 mm, each one compacted separately. The asphalt is then compacted using hand tampers or plate compactors, although small pedestrian rollers can be used for larger patches. It is useful to blind the patch with some fine sand or gravel to avoid adhesion to tyres in the period immediately following compaction. At the end, the patch surface should be checked for level, using a straight edge.

Medium-depth asphalt repair

If the pothole is deeper than one asphalt layer thickness and passes into the binder course, but is no deeper than the bottom of the binder course or the upper part of the base, the pothole should be patched as described above (as shallow asphalt). Also, crushed stone, natural gravel or treated gravel (with cement or bitumen emulsion) could be used as a partial filler for holes deeper than 75 mm if the road is not heavily trafficked.

Deep repair

Deep patches in asphalt-surfaced roads are necessary when the pothole is the result of structure failure at depth. If this is primarily the result of excessive water in the lower layers of the pavement, the source of the water should be eliminated prior to patching (with use of sub-soil drains adjacent to the road).

Table 2: Key to the decision process for the repair of potholes [source 4, CSIR, 2010]

KEY	DEFECT	REPAIR ACTION	GO TO
1	Surfacing is asphalt		2
	Surfacing is thin bituminous seal		4
2	Pothole is deeper than asphalt wearing course		3
	Bottom of pothole is within asphalt wearing course	Shallow asphalt (HMA or cold mix)	
3	Pothole caused by cracking due to fatigue of asphalt	Deep repair after sub-soil drainage installation	
	Pothole caused by localised surface water ingress with no associated crocodile cracking	Medium-depth asphalt repair	
4	Pothole has exposed an unstabilised base		5
	Pothole has exposed a stabilised base		10
5	Pothole is not associated with cracks		6
	Pothole is associated with cracks		8
6	Pothole affects seal and top of base only (< 50 mm)	Shallow surface repair	
	Pothole extends > 50 mm into base		7
7	Pothole affects only the base	Medium-depth repair	
	Pothole extends below the base		8
8	Pothole does not affect entire pavement structure (only base and sub-base)	Medium-depth or deep repair	
	Pothole affects entire pavement structure		9
9	Pothole is the result of saturated subgrade or support	Deep repair after sub-soil drainage installation	
	Pothole is the result of poor material – no evidence of excessive subsoil water	Deep repair	
10	Top of base has carbonated and is weak		11
	Top of base has not carbonated excessively and is still strong	Shallow surface repair	
11	Pothole is associated with crocodile cracking	Deep repair	
	Pothole is not associated with crocodile cracking	Medium-depth repair	

Table 3: Key to the identification of pothole repair measures [source 4, CSIR, 2010]

1	Surfacing is asphalt .... > 2		Surfacing is thin bituminous seal .... > 4	
2	Pothole is deeper than asphalt wearing-course .... > 3		Bottom of pothole is within asphalt wearing-course **Shallow asphalt** **(HMA or cold mix)**	
3	Pothole caused by cracking due to fatigue of asphalt **Deep repair after sub-soil drainage installation**		Pothole caused by localised surface water ingress with no associated crocodile cracking **Medium depth asphalt repair**	
4	Pothole has exposed an unstabilised base .... > 5		Pothole has exposed a stabilised base .... > 10	
5	Pothole is not associated with cracks .... > 6		Pothole is associated with cracks .... > 8	
6	Pothole affects seal and top of base only (<50mm) **Shallow-surface repair**		Pothole extends > 50 mm into base .... > 7	

7	Pothole affects only the base **Medium depth repair**		Pothole extends below the base .... > 8	
8	Pothole does not affect entire pavement structure (only base and sub-base) **Medium depth or deep repair**		Pothole affects entire pavement structure .... > 9	
9	Pothole is the result of saturated subgrade or support **Deep repair after sub-soil drainage installation**		Pothole is the result of poor material – no evidence of excessive sub-soil water **Deep repair**	
10	Top of base has carbonated and is weak .... > 11		Top of base has not carbonated excessively and is still strong **Shallow-surface repair**	
11	Pothole is associated with crocodile cracking **Deep repair**		Pothole is not associated with crocodile cracking **Medium-depth repair**	

9 Pothole repair cost-effectiveness and evaluation

To evaluate current patching operation, the cost-effectiveness of the overall operation should be calculated. Manual of Practice [source 1, FHA SHRP, USA, 1999] presents a worksheet for calculation of patching operation costs. Such form can be used either for a current operation or for a proposed patching operation, using different materials or procedures. It requires the user to enter information for each material and procedure combination to be evaluated. The following terms are being used:

- Expected Patch Survival – an estimate of the average life of patches to be placed. The value should be entered in months.
- Patching Analysis Period – the duration for which the cost-effectiveness analysis is being calculated (generally a period of between 3 and 5 years). The value should be entered in months.

The most difficult value to obtain accurately is the "expected patch survival." The pavement condition, material quality, climatic influence, crew ability and past repair performance all contribute into this value.

Evaluating Repair Performance

When two or more patch types have been installed for the purpose of comparison, a method is needed to rank the tested patch types from best to worst. The Manual of Practice [source 1, FHA SHRP, USA, 1999] describes two methods for calculating a performance factor.

To determine the effectiveness of a given patch type, the repairs must be monitored for at least one year, preferably longer should the repairs survive. Monitoring repairs simply consists of checking for the presence of the repairs and noting the survival or failure of each one. The time elapsed from installation to monitoring is also noted (patch performance data).

Patch survival rating

The patch survival rate is defined as the area under the patch survival curve over time. To calculate the area, a table can be used for any available patch survival data. One advantage to this method is that the survival rating can be calculated for any time interval and can be updated easily as additional data are collected.

Expected average repair life

The average repair life is needed to calculate the cost-effectiveness of the patching operation using the worksheet and formulas. To calculate the average life, the observed period of performance is needed for each repair that is monitored. For repairs lost to overlays, no survival time is needed. The survival data collected over time are converted into the average life value.

10 Further technical regulations and practical experiences from various countries

Below is some information gained from different papers from various countries which are related to pothole repair materials and techniques, but seem to be more general and, therefore, were not covered in the previous sections of this report.

Assessment and certification procedure in the UK

The assessment and certification procedure in the UK is undertaken in two stages [source 10, British Board of Agrément, UK, 2010]:

- assessment and
- certification

Assessment is onwards conducted through:

- submission for product approval
- quality assurance
- laboratory testing (maximum density, in-situ bulk density, indirect tensile stiffness modulus, resistance to permanent deformation - tests are performed on cores)
- product installation trial
- product performance trial (if required)

Quality control checks are commonly carried out on incoming materials, during production and on the finished product.

The BBA certificate includes the following parts:

- HAPAS requirements
- regulations
- technical specification (product description, manufacturer and quality control, delivery and site handling)
- design data (precautions during installation, durability)
- installation (preparation, application)
- technical investigations (approval trials, investigations)

Austria issued technical specifications for materials used in cold asphalt mixtures [source 11, ÖNORM B 3587, Austria, 2011] which give the requirements for constituent materials (binder, aggregate, filler) and for the CA mixtures (five types of grading from CA 4 to CA 22). There are no given values for tested characteristics (”no requirement” NR for void content, water sensitivity, affinity between bitumen and aggregate, resistance to fuel and to de-icing fluid for application on airfields).

German guidelines for maintenance of road constructions [source 15, Germany, 2009] describe pothole repair procedures with asphalt mixtures. Bonding to the surrounding road can be achieved by using polymer-modified bitumen (PmB), a joint sealing band or a joint sealer.

It is only allowed to implement the pothole repair in dry weather conditions. If a hot asphalt mixture is used, the temperature should not be below +3℃. The temperature of the mixture has to be below +40℃ when the road is re-opened fo r the traffic. For stationery traffic the mixture temperature has to be the same as the surrounding road.

Because the optimal compaction level for pothole patching cannot normally be reached, asphalt mixtures with small grains and low viscosity binder should be used.

Regulations for layer thickness are the same as for normal road constructions (given in other German guidelines).

Slovenian technical specification for public roads [source 12, Ministrstvo za promet, Direkcija RS za ceste: Tehnična specifikacija za javne ceste TSC 08.311/1:2005, Slovenia, 2005] states that, beside the infill material selection, the main difference between temporary and permanent (the term "more durable" is actually used) pothole repair is the edge formation and treatment:

- In harsh winter conditions (snow, rain, low temperatures) the throw-and-roll procedure needs to be used with no preparation of pothole (only loose and unbonded material should be removed). Normally, cold-asphalt mixtures with cutback bitumen and rather fine-grained aggregates are used (because fresh hot asphalt is rarely available during winter). Instead of patch compacting using truck tyres, the back of a shovel is commonly used.
- In a bit more favourable weather conditions (after rain) the pothole should be cleaned and standing water removed. The bond coat needs to be applied to the base and the sides before the pothole is filling with hot or cold asphalt mixture.
- For deeper potholes (more than 40 mm), the asphalt could be applied in more layers (each compacted separately). Also, coarse crushed stone material or cementitious material could be used in the bottom layer.
- For more durable repairs, the pothole should be repaired according to the procedure given in section 8 (with edge cutting or sawing and hot asphalt mixture as the infill material). Heating pothole edges with infrared rays prior infilling is also found to be useful.

This Slovenian document also specifies some conditions for using hot-asphalt repair mixtures:

- minimum base (road surface) temperature is 10 ^{0}C (if a normal vehicle is used to transport the material) or 5 ^{0}C (if an insulated truck is used)
- minimum air temperature is 5 ^{0}C
- minimim asphalt mixture temperature during infilling is 110 ^{0}C (if bitumen binder B160/220 is used) or 130 ^{0}C (if bitumen binder B70/100 is used)

At lower surface or air temperatures, the cold-asphalt mixture should be applied – usually with cutback bitumen (with additives) that is applicable at temperatures below 0 ^{0}C as well (also suitable for temporary stockpiling). If it is intended to apply the CMA immediately, a cationic bitumen emulsion can be used as binder (applicable for use at temperatures above 3 ^{0}C).

The Slovak Catalogue of repair techniques of distress basic type TP 08/2011 [source 20, Slovak Republic, 2011] includes a sheet for pothole repair technique.

Short description of a repair procedure:

- cutting and crushing, or milling the damaged surface of the surface course up to unbroken material
- cleaning the cut area
- tack coat on pothole bottom and edges
- spreading and compaction of asphalt concrete, cold-mix or mastic asphalt (jet-patching method or other certified techniques can also be used)
- testing (visual control and unevenness control) according to the relevant standards

Repair methods are selected according type of pothole:

- distress is in surface course or
- distress is in binder course or base.

According to reliability and durability there are two main groups of repair techniques:

- operational repair (which ensures serviceability temporarily, until a permanent repair can be made)
- permanent repair (which ensures the surface with good properties during the service life of the surface course)

Operational pothole repairs are performed in autumn, winter or early spring months. Spraying techniques like penetrating macadam covered single surface or multiple surface dressings, cold-mix asphalt or hot-mix asphalt (if conditions for transport are appropriate) and jet-patching method are used for this purpose.

On the other hand, hot-mix materials (mostly mastic asphalt and asphalt concrete), specifically cold-mix asphalts, jet-patching or infra-heating technique are used for permanent repair.

Each of the materials used for pothole repair must have a technical sheet containing aggregate size distribution, binder content and binder properties, storage and package instructions.

A suitable mixture is asphalt concrete with maximum aggregate size 11 mm. If the potholes are deep and reach the base layer, the repair should be perform in two phases. Firstly, a coarse grained mixture (asphalt concrete 0/16 mm) fills lower part of pothole up to the binder course, after that an asphalt concrete 0/11 mm is laid.

The repair procedure using hot-mix materials involves:

- cutting the pothole edges to a regular shape
- removing the cuttings, chippings and released aggregate particles and cleaning the pothole
- cleaning the damaged area of any remaining mixtures particles, dirt, silts, etc (using water under pressure and drying under compressed air stream)
- applying a tack coat with bitumen or bitumen emulsion or heating the substrate and adjacent pavement parts by gas-heater or infra-heater
- filling the pothole with asphalt concrete hot-mix and compacting using mechanical compacter (tamper) or smaller hand roller, or
- filling the pothole with mastic asphalt hot-mix (temperature from 190 °C to 250 °C), spreading the chippings 2/4 or 4/8 mm just after levelling and impress this aggregate into the mastic asphalt.

During hot-mix pothole repair, the air temperature shall not drop below + 5 °C.

The surface characteristics and the appearance of the repaired surface course should not be different from the adjacent undamaged pavement surface.

A memo (reminder) from Danish Tuelsø trial section [source 13, Denmark, 2009] describes the procedure for selection of test trial and products. The test trial was divided into 25 test fields. In two of these fields the reference material was used. The reference material was defined as the material the Danish Road Directorate normally uses for repairing of potholes. Further, the report describes the establishment of weather and traffic monitoring station, and the results of the first measurements and inspections.

The South African guide [source 4, CSIR, 2010] describes quality control system of pothole repair in South Africa. For the repair of potholes to be effective, a controlled quality-assurance programme must be followed and implemented. Each stage of the process should be checked to ensure that it conforms to the requirements for that stage. The primary requirements for pothole repairs are:

- The fill materials must be suitable for the specific layers.
- Each layer should be properly and adequately compacted to meet density requirements.
- If hot mix asphalt is used, the compaction temperatures should not be too low.

- The final driving quality should be acceptable (a 5 to 10 mm ‘hump’ above the surrounding pavement will allow for some traffic compaction without causing a significant effect on riding quality in the longer term).
- The patch surface should not form a depression after traffic compaction has been achieved, but rather be slightly raised compared with the adjacent road.
- All joints should be sealed properly. There should be no open joints between the patch and the surrounding material. It is also recommended that a geosynthetic strip is ‘glued’ with bitumen emulsion over the joints and then ‘painted’ with bitumen emulsion and blinded with coarse sand.
- The patch must be aesthetically pleasing.

The Army Corps of Engineers report [source 7, USA, 2005] describes a field evaluation of pothole repair materials. In 2008, a large number of proprietary bitumen based cold-mix materials and cementitious rapid repair materials were subjected to laboratory and field evaluation where patch-holes were made in an asphalt pavement roadway.

The results of the laboratory workability tests indicate that open-graded cold-mix patch materials generally have a higher workability (lower workability number) than dense- or well-graded mixtures. It is assumed that aggregate gradation probably has a greater effect on workability than the grade of the binder. Evaluation of the effect of the penetration or viscosity of the binders on workability is not possible in most cases due to various other mixture additives and other differences between the mixtures.

The results of the Marshall tests indicated that, as expected, the mixtures with the denser or well-graded aggregates and with the harder binders (higher viscosities) tended to have the higher Marshall stability values. However, the Marshall stability test is probably not a good indicator of performance because it is not an appropriate test for open-graded mixtures.

Overall, the maximum compressive stress of the open-graded mixtures is dependent on the confining stress, and compressive stress of the dense-graded mixtures is found to be independent of the confining stress.

Trafficking on the areas repaired with the rigid materials had no effect on the repair materials themselves. The rigid patches showed no distress after traffic. However, after several passes, the HMA between the patched areas started to rut and, eventually, the rigid repairs started to move (rock) under the wheels of the vehicles. This type of failure of rigid repair materials used in surrounding flexible pavement surfaces is typical due to the movement of the flexible material in relation to the rigid patches (because of their relatively high stiffness or modulus value compared with the adjacent asphalt pavement). The severity of this type of problem would probably increase with increasing temperatures and decrease with decreasing temperatures, because of changes in the surrounding asphalt layer and the underlying asphalt base layer.

Each hot-mix asphalt patch experienced some additional compaction under traffic, as evidenced by the slight rutting that occurred (the surrounding asphalt pavement also rutted under the traffic applied).

Virginia Department of Transportation [source 9, USA, 2009] provides a list of approved proprietary high quality cold patch materials which passed an extensive laboratory and field evaluation process (Prowell and Franklin, 1997). A conclusion of their report from 1994-1996 was that laboratory tests alone are insufficient for screening potential mixtures.

Five primary distress types were evaluated in that report used to generate the existing approved list: bleeding, rutting / dishing (further compaction under traffic), debonding, ravelling and pushing & shoving. These distresses were identified by the authors as the primary distress modes of concern for cold mix patching materials in Virginia.

In that report [source 9, USA, 2009] there is also en example of a form for recording the patch condition during routine inspecting and monitoring (at the beginning weekly, later monthly) – see Table 4. In such a form, all kind of stress that would be associated with a weak or unstable mixture must be noticed (signs of pushing, shoving, rutting, cracking, ravelling, tracking).

Eighteen Month Follow up conducted in June 2009 :

Product: Rephalt by Vialit **Hole Dimensions:** See Main body of report
Location: US Route 60 in New Kent County **Hole Condition:** Cleaned and Cleared of debris See Report
Road type / Age / ADT: See Main body of report **Weather at installation:** 30 to 34°F and cloudy See Report

	Evaluation Time (months)	1	2	3	4	5	6	7	8	9	10	11	18	Comments
Criteria														
Cracking	Excellent							-	-	-	-	-		Slight Hair line crack in small extended portion of patch, see photo
	Good													
	Fair													
	Poor													
Raveling	Excellent							-	-	-	-	-		
	Good													
	Fair													
	Poor													
Shoving	Excellent													
	Good							-	-	-	-	-		Slight shoving, due to high center during construction
	Fair													
	Poor													
Rutting	Excellent							-	-	-	-	-		
	Good													
	Fair													
	Poor													
Tracking	Excellent							-	-	-	-	-		
	Good													
	Fair													
	Poor													
Overall	Excellent							-	-	-	-	-		(-) Indicates that the site was not evaluated during this time interval
	Good													
	Fair													
	Poor													

Table 4: Table for recording and evaluating the patch condition during routine monitoring [source 9, USA, 2009]

11 Conclusions

Prior to any successful and durable pothole repair, it is essential to have identified and classified the cause of the distress. Incorrectly repaired potholes, without attending to the fundamental causes, could be a complete waste of time and resources because such potholes are likely fo fail again soon after repair.

Two main elements of quality pothole patching are

- material selection and
- repair procedures.

Even though the climatic and traffic conditions vary across the countries, the materials and methods for placing patches are fairly similar.
The repair material and technique selection is based on time available for repair, local climatic conditions and actual weather conditions, pothole size and depth, characteristics of adjacent pavement, availability of equipment and workers and finally, the overall cost-effectiveness determined for the certain circumstances (including material, labour and equipment costs).

Pothole repair materials

Almost no requirements for material properties were found in the gathered documents. There are some test methods listed in a few standards or technical specifications but no values are given as the requirements (only some broad limits for particle size distribution of aggregate grading).

The size of the aggregate used for repair material depends on the depth of the pothole to be repaired. In most cases, repair materials contain aggregates which have a maximum aggregate particle size not more than 11 mm (using the basic set plus set 1 sieves) or 10 mm (for the base set plus set 2 sieves). The aggregate grading has a great effect on the performance of an asphalt mixture. The voids content results in permeability. Continuous grading leads to low permeable mixture. Therefore, dense-graded aggregate structure provides a stable, low void and relatively waterproof asphalt mixture. On the other hand, open-graded aggregates are more porous and are normally more workable at temperatures at or below freezing. Consequently, dense-graded asphalt mixture is supposed to perform well at warm and hot temperatures, but an open-graded asphalt mixture is required for satisfactory workability at freezing temperatures.

The main type of materials used for pothole repair are:

- bitumen-based cold-mix materials (cold-mix asphalt CMA)
- bitumen-based hot-mix materials (hot-mix asphalt HMA)
- cement-based materials

Cold-mix asphalt

It is mostly used as temporary repair but, with proper installation, it can be more durable. Major limitation for these materials is that they cannot normally be compacted to the same level as hot-mix asphalts. The advantage is short application time and applicability in harsh winter conditions.

CMA can comprise different types of binder:

- cutback bitumen
  CMA mixtures with cutback bitumen can be difficult to work at low temperatures and often require some warm-up time in the sun before use.
- bitumen emulsion
  Limitation of bitumen emulsions is relatively short time to break and cure, so slow-setting

emulsions should be used for CMA. Because these materials contain additives to ensure that the mixture remains in workable consistency at ambient temperatures, attention must be paid to torn or broken bags which may result in unsuitable materials after a relatively limited period.

- proprietary products

Verifying the quality of materials for CMA consists of:

- compatibility testing of new combinations of binder and aggregate (coating test, stripping test and drainage test)
- acceptance testing to ensure the quality when a previously used cold-mix or proprietary materials is intended for use (workability test and cohesion test)

The main demands for a quality CMA are:

- The binder should coat the aggregate well and remain coated also after stockpiling and in various climatic conditions.
- The stockpiled mixture should remain workable and be easy to handle with shovels.
- The mixture should remain in the hole where it is placed.

It has been found that aggregate gradation probably has a greater effect on workability than the grade of the binder. Open-graded cold-mix patch materials generally have a higher workability than dense- or well-graded mixtures.

Hot-mix asphalt

It presents a more durable solution, it is easy to install and to compact, it enables more effective bonding with existing asphalt pavement. Attention must be paid to appropriate mixture temperature for compaction (hot-box equipment is used to maintain material above appropriate viscosity temperature which ensures that material remain suitable for compaction).

There are two generic types of HMA:

- matrix dominated (Hot Rolled Asphalt, Mastic Asphalt): higher bitumen content, lower permeability, easy for compaction (lower compaction energy required), good durability, slower distress progress, failure distress is by deformation. As the surface is often quite smooth superimposed chippings are required to provide better skid resistance.
- aggregate dominated (Asphalt Concrete, Split Mastic Asphalt): lower bitumen content, higher permeability, higher compaction energy required (especially for more continuous – denser gradations), shorter durability, quicker distress progress, failure distress is by attrition or fatigue cracking.

Cement - based materials

These fast-setting or rapid-hardening cementitious materials are intended for rapid pavement repair.

Disadvantage: As repaired patch deflection under the traffic should be similar to the surrounding pavement, the repair using strongly cementitious materials is not recommended – significant differences in the deflection could lead to cracking at the joints between patches and the road under traffic loading. Ingress of water is then feasible which may result in additional potholes. When the repaired patch is significantly stiffer than the surrounding (more flexible) asphalt material, it could start to ‘rock’ under the wheels of the vehicles which leads to failure of the adjacent contact areas.

Pothole repair techniques

Temporary repairs

In most cases the pothole is filled with cold asphalt mixture. This is used

- in emergency circumstances when a pothole represents a potential hazard for safety and rideability or
- in harsh winter conditions when there is no alternative solution and when a defect should be repair immediately or in a short time (a more durable repair will be done later)

Methods:

- throw-and-go (no preparation and cleaning of the pothole, compaction by traffic only, usable in harsh winter conditions, high rate of performing, but the worst durability)
- throw-and-roll (no preparation and cleaning of the pothole, compaction by tyres of maintenance crew truck, usable in harsh winter conditions, high rate of performing)

  Both these methods are normally performed with CMA.
- edge seal method (for improving patch performance): similar to throw-and-roll method (compaction by truck tyres) but then improved by placing a ribbon of bituminous tack material on top of the patch edge (tack material should be placed on both patch and adjacent pavement surfaces). At the end, a layer of sand is placed on the tack material to prevent tracking by vehicle tyres.
- spray-injection patching - placing heated bitumen emulsion (as binder) and virgin aggregate simultaneously into a pothole, no compaction, higher equipment costs, lower material costs, high rate of productivity

Semi-permanent procedure (using hot or cold-mix asphalt)

- removing water and debris from the pothole
- forming the vertical edges (up to sound surrounding pavement) - edges straightening is done by using hand-held saw, jackhammer or cold-milling machine)
- placing the mixture (CMA or HMA) in the hole
- compaction using vibratory plate compactors, drum vibratory rollers or tamper

  An option for smaller potholes is leave out edges straightening, but this omission could have an affect of shorter durability.

Permanent or more durable repair

- preparation including edge formation (by saw cutting)
- cleaning excavation with removing all debris, loose material and water (drying)
- application of bond coat to base (bottom) and sides
- infilling with asphalt material (mostly hot-mix, also cold-mix asphalt or cement-based material is used)
- compaction with vibrating plates, drum vibratory rollers or tamper

The proper preparation of potholes is essential for a good repair. No matter how good quality and durable the material that is used for pothole infilling is, it will not perform well and not last long enough if it is applied in inappropriate circumstances. The prepared patch area (normally rectangular shape) must include the whole area affected by the pothole and any associated distress in surroundings. The cut edges should be clean and neat. All unsound and debonded material should be removed.
Cationic emulsion is normally used for bond coating (it must be evenly applied).
Every type of infill material should be fully compacted. Attention must be paid to the proper mixture temperature when HMA is used. Special care should be devoted to the pothole edges and corners of rectangular patches. Because the joints between the patch and the adjacent pavement are the areas that fail most frequently (open cracks), sealing the joints is advisable for better durability (geosynthetic crack-sealing strip over the joints, using a layer of bitumen emulsion to stick the strip and a second layer on top of the strip to 'waterproof' the

geosynthetic). Finally, blinding with some coarse sand over the second layer of emulsion ensures that the bitumen does not stick to vehicle tyres.

For deeper potholes (more than 40 mm), the asphalt should be installed in more layers (each compacted separately). Also, coarse crushed stone material or cementitious material could be used in the bottom layer.

This method using hot-mix asphalt represents the most durable solution for pothole repair and it should ensure the service life as of surrounding pavement.

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