
# POTHOLE

# Final Report

Milestone No. 10

Deliverable 5

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Project Coordinator: Karlsruhe Institute of Technology

Project Partner A: Danish Road Directorate

Project Partner B: Forum of European National Highway Research Laboratories

Project Partner C: Transport Research Laboratory

Project Partner D: University of Žilina

Project Partner E: University of Twente

Project Partner F: Slovenian National Building and Civil Engineering Institute

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# Workpackage 7
# Milestone No. 10 – Final Report
# Deliverable 5

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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:

- Danish Road Directorate (DRD) from Denmark;
- Forum of European National Highway Research Laboratories (FEHRL) from Belgium;
- Transport Research Laboratory (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 freeze–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 base and therefore are not cost-effective.

Immense economic loss results from the damage to the pavement, the increasing numbers of crashes and the injuries and deaths that are caused by potholes. This cost requires an improvement in the materials, methods and techniques that are used for repair of potholes. Moreover, it is desirable to give road agencies some kind of help to deal with these problems.

In this project, typical as well as innovative approaches that target the medium- or long-term repair of potholes are being studied. A catalogue of tests, evaluation methods and experiences based on existing European Standards will be provided to give road agencies an overview of the options for the repair of potholes. Furthermore, testing techniques and materials from existing trial sites will be used to determine which laboratory tests can be, or should be, used to be able to determine which laboratory tests are appropriate for studying pothole repair materials.

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

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

- WP 1 – Definition of the term “pothole”
- WP 2 – Selection of tests and evaluation methods for use in the laboratory and in situ
- WP 3 – Study of existing standards, techniques, materials and experience with them on the European Market
- WP 4 – Evaluation of techniques and materials from existing trial sites
- WP 5 – Laboratory testing of selected materials
- WP 6 – Life Cycle Cost and Benefit Analysis (LCCBA)
- WP 7 – Development of guidelines including catalogues of materials – Final Report

The main objective of this WP 7 is to summarise the findings of all Workpackages and to give guidelines for the durable pothole repair based upon the findings within the project. The guidelines are given in annex 1 of this report.

# 2 Questionnaire (Workpackage 1)

In the beginning of the project a web-based questionnaire has been set up to gather information about potholes and their definition around Europe, distress mechanisms, used materials, maintenance techniques as well as repair methods. The responses received were mainly used as the basis for the first two Workpackage of the project, but also for the identification of test sites throughout Europe (see Workpackage 4). The detailed results are documented in the report of Workpackage 1 and 2 which can be downloaded on www.fehrl.org/pothole.

# 3 Definition of the term pothole (Workpackage 1)

In this project a definition of the term “pothole” was needed to be able to undertake the research, to select the appropriate tests and to give recommendation for the right choice of techniques and materials for a durable repair of potholes.

Therefore the results of the above mentioned questionnaire have been taken into account and analysed. Based upon this and further knowledge of the involved partners a definition of “pothole” has been developed which also takes the mechanisms of pothole development into account. In the following the discussion leading to that definition is described as well as the compiled definition.

## 3.1 Discussion

The definition of “pothole” seems to vary considerably across Europe, or even across individual countries. There is neither any generally accepted definition nor agreement about the need for one. It is probable that there are contracts and policies about the repair of potholes using a particular definition which, if a formal definition were introduced, would have to change in order to provide the same level of performance.

If there is to be a formal definition of pothole, whether for this project or wider, an understanding is needed as to what constitutes a pothole. The main feature of potholes is their relatively rapid appearance in a surfacing that had previously been considered to be performing well. If there is a known problem with the pavement, such as a deficiency in the bearing capacity, it is not considered to be a pothole. Similarly, deformation or other displacement of the surface is not considered a pothole because the cause can be clearly identified as traffic loading. The development of a hole caused by extensive fretting if there is fretting over a wide area of the pavement can be ascribed to binder hardening. To be a pothole, there has to be a defect in the body of the pavement that is relatively localised or whose appearance is relatively localised – there should really be a difference between the pothole itself and the surrounding area of pavement.

If potholes are localised defects in the pavement, then their repair as a pothole can be justified because, when undertaken effectively, the material should not break out again. Nevertheless, there are still different distress mechanisms that cause potholes and not all potholes can be repaired durably because of the underlying cause. The presence of different mechanisms can be shown by potholes appearing not just in the winter, but also in the summertime. The distress mechanism may have been initiated in the previous winter, but there are some mechanisms not associated in any way with cold temperatures, as demonstrated by South Africa having a guidance document on their causes, identification and repair (CSIR, 2010).

Overall, there is a general (but not universal) agreement that the dimensions are the best quantitative method to define potholes, even if the actual dimensions to be used are disputed. However, the importance of the dimensions can change with the situation if what constitutes a pothole is to be linked to the associated risks to road users. The size of tyres (bicycle, motorcycle, car or lorry), speed of traffic, road layout including width and many other factors will affect the size before remedial action is desirable / necessary / essential to maintain safety and ride quality. No definition which fixed the dimensions of what constitutes a pothole could allow for such variation, and could have contractual implications where road authorities had policies for pothole maintenance based on different dimensions.

Therefore, it is proposed to offer a more general definition of pothole but to apply guidance notes to cover such issues as the desired standard of safety, the road category, the traffic loads and the distress mechanism.

## 3.2 Definition

The definition of pothole for this project has to be non-qualitative because of the variation in existing definitions, some of which are believed to have contractual implications. The proposed definition of "pothole" is:

> pothole
>
> *a local deterioration of the pavement surface in which the material breaks down in a relatively short time and is lost causing a steep depression*

Notes:

[1] Generally, potholes require rapid remedial action to maintain the safety of road users.

[2] Potholes will also need to be reinstated to maintain the functional requirements and comfort, but the time-constraints on rectification for these requirements will not be as immediate.

[3] Potholes will typically have a depth of at least 30 mm and an area equivalent to a diameter between 100 mm and 1 m with the values for a specific situation depending on several factors including the traffic speed and intensity, the type of vehicle (particularly the presence of bicycles and pedestrians) and the climate.

[4] Potholes can grow once they have emerged, but generally stop growing after a certain time. However, other potholes can appear close to an existing one.

[5] Potholes can occur due to several mechanisms (such as fracture, attrition and seasonal).

# 4 Selection of tests and evaluation methods for use in the laboratory and in situ (Workpackage 2)

## 4.1 Discussion

There is a wide variation in the repair techniques and materials used around Europe. The variation may be influenced by different situations such as existing surfacing material, traffic loads and local climate, but from the variation found within countries some of the variation is likely to be due to lack of knowledge about which are the most appropriate techniques and materials. This conjecture helps to support the need for this project, but does not help to inform it.

Within the methodologies, there was a worrying trend for lack of acceptance that standard assumptions for normal pavements, such as the need for adequate compaction and bonding, seemed to be missing from some recipients. It is suggested that these factors are, if anything, more important for pothole repairs because of the difficulty in achieving the properties with the small scale operation (in particular that the material is hand worked rather than paver-laid) and the already proven adverse conditions that cause the defect initially.

There was not sufficient information to rank different approaches in terms of their effectiveness, although it has to be assumed that organisations would dispense with any found to be obviously inadequate. Nevertheless, there were indications that the methods used did not all use the same material as in the existing pavement. Presumably, the organisations using “foreign” material in the repairs are satisfied that they provide the required level of performance, even when laid in adverse conditions.

One alternative to having materials capable of being laid in relatively adverse conditions is to try to make the conditions benign. One suggestion was the use of a heating device, which should make adequate compaction easier but could lead to premature binder hardening if used too enthusiastically. However, the approach could be considered although it will require additional equipment.

There were mixed views about the need for assessing the materials used for the repairs, and it may be due to consideration of checking compliance on the finished repairs. Given the size of each repair, it is appreciated that either compliance would have to be checked on a limited sample of repairs, requiring a statistical analysis of the results, or the materials would be checked for suitability prior to use. The latter would effectively be a certification system for the material (even if done internally) and would not involve any check on the workmanship on site.

With regard to what should be assessed, the majority who are willing to accept the need for selection criteria tend to support the standard properties required of any surfacing. Such properties include deformation resistance (by wheel-tracking or cyclic compression), texture depth, air voids content, water sensitivity and binder affinity. However, other issues also need consideration because of the particular status of potholes such as the ease of compaction at low temperatures, the setting or curing time needed after completion of the repair prior to traffic on busy roads and the sensitivity to adverse weather conditions during placement.

Currently, there is a lot of work encouraging great use of reclaimed asphalt in new mixtures. Therefore, there is likely to be a need to discourage the use of pothole repair materials that are not suitable for recycling. Further research may be required to find out the maximum extent of pothole repairs with a non-asphaltic material, such as one using epoxy resin, before the pavement becomes unsuitable for recycling. However, the assessment for recyclability does not need to require a physical test, just a check on the data sheet or other information for each of the components.

Whilst there is a logic for assessing pothole repair materials against the properties required for normal surfacing materials, the required levels may not be identical. It has been noted already that the requirements for some properties may need to be raised because of situation, but others may be lowered because the life of the pavement being repaired is already shortened from its original. Any reduction in level can only be for properties for which the damage is cumulative, such as deformation. Properties relating to safety, such a surface friction, cannot be reduced because of the shorter design life.

Furthermore, it could be important to link different kinds of material to their intended use in that, if the pothole repair only has to last a short period of time because the replacement of the pavement is already planned, it might be adequate to use less than the very best material. Such considerations mean that there could be markets for both long-term materials and shorter-term materials.

To convert the properties required into practical specification requirements, there was no dispute about using the relevant CEN test method where there is one. Their use is, in any case, mandatory within Europe. However, the conditions, particularly temperature, may need to be adjusted for some test methods in order to assess the more specific requirements of pothole maintenance. An example is EN 12697-10, compactibility, for which the temperature could be reduced to replicate late winter/early spring conditions.

However, there are no tests suitable in the EN 12697 series, even with adaptation, for some of the properties required of potholes. The need for an assessment of setting or curing time (dependent on the type of material involved) can be important to know how long before the repair has to be left before it can be opened to traffic – very important on busy roads and to allow the gang to move to the next pothole. The simplest option is some form penetration test to see how easily it is to disturb the surface. It has been suggested that a Danish steel-ball depression test would be suitable for this purpose.

The sensitivity to conditions is another important issue for pothole repair materials because their repair is often undertaken in less than ideal conditions. There is no test method explicitly for such a sensitivity analysis, but some existing tests could be repeated with the environmental parameters (such as temperature and humidity) adapted, including freeze/thaw cycle tests which are currently available for aggregates (EN 1367-1) but not for asphalt mixtures. It is understood that a Slovakian guideline for testing bituminous material is available.

## 4.2 List of relevant testing methods

Pothole repair materials and techniques need to be assessed by a procedure, possibly by certification, prior to use because the size of works makes compliance checking impractical. The principal requirements of the materials that need to be assessed in order to ensure durability are:

1. Standard properties for surfacing materials, where the principal properties are:
   - 1.1 Deformation resistance (by wheel-tracking or cyclic compression)
   - 1.2 Texture depth
   - 1.3 Air voids content
   - 1.4 Water sensitivity
   - 1.5 Binder affinity
2. Compactibility in adverse conditions
3. Setting/curing time needed prior to traffic
4. Sensitivity to conditions
5. Adhesion (including the use of tack/bond coat)
6. Recyclability (but only as a consideration at this stage)

The test methods to be used to assess the principal requirements (using the same numbered indents) are:

1. Test referred to in EN 13108 to the levels appropriate to the original specification adjusted for the remaining life of the remaining surfacing
2. EN 12697-10 at low temperature
3. Dependent on material type or test to develop such steel ball depression test (an adaptation of an existing non-CEN test)
4. Repeated tests for different temperatures and humidities and/or freeze/thaw cycles (an adaptation of an existing non-asphalt test)
5. prEN 12697-48, tensile option
6. Desk-top chemical evaluation / data sheet

# 5 Study of existing standards, techniques, materials and experience with them on the European Market (Workpackage 3)

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 to fail again soon after repair.

Two main elements of quality pothole repair 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).

## 5.1 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

Synthetic binders have been also examined within this project (see chapter 7, Workpackage 5), but are not included in this list as they don't belong to the materials mainly used throughout Europe which were the topic of the research of this chapter.

### 5.1.1 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.

### 5.1.2 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), , 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, Stone Mastic Asphalt): lower bitumen content, higher permeability, higher compaction energy required (especially for more continuous –

denser gradations), quicker distress progress, failure distress is by attrition or fatigue cracking.

### 5.1.3 Cement based materials

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

As repaired patch deflection under the traffic should be similar to the surrounding pavement, the repair using strongly cement-based materials is not recommended. Significant differences in the deflection could lead to cracking at the joints between patches and the road under traffic loading. This would make the ingress of water possible 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.

## 5.2 Pothole repair techniques

### 5.2.1 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 often there is no alternative solution and when a defect should be repaired 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, normally with cold-mix-asphalt.

- 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, normally with cold-mix asphalt.

- 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.

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

Semi-permanent procedures include the following steps:

- 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 effect of shorter durability.

### 5.2.3 Permanent or more durable repair

Permanent procedures include the following steps:

- preparation including edge formation (by saw cutting)
- cleaning excavation with removing all debris, loose material and water (drying)
- (optional) heating of surrounding area of pothole
- 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. Heating the surrounding area of pothole helps to increase the adhesion of the filling material.

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.

# 6 Evaluation of techniques and materials from existing trial sites (Workpackage 4)

As part of the questionnaire distributed in WP 1 and WP 2, five questions were incorporated to find trial sites of pothole repairs in Europe. Based on these responses reported in Deliverables 1 and 2, a second questionnaire only concerning trial sites of pothole repairs was sent to selected contact persons.

The detailed description of the examined trial sites can be read in the report of Workpackage 4.

## 6.1 Discussion

The purpose of this project is for road authorities to optimize their maintenance strategy so that the life time of repair of potholes correspond with the life time of the existing pavement to prevent repeated repairs of the same pothole. This would reduce the costs to maintain a safe road network as well as reducing the inconvenience to drivers.

From the trial sites examined in this report, it is difficult to compare the durability of repair materials between the different trial sites, because the materials have been subjected to different traffic and climate stresses and because different methods for evaluation have been used.

In order that a common assessment system for pothole repair can be applied in practice across Europe, it is advisable to establish such a system with durability categories for pothole repair, including in situ evaluation and laboratory tests with associated material requirements. These durability categories shall be related to the climate (areas with many freeze/thaw cycles, areas with very high temperatures, etc).

It is recommended that durability categories for climatic zones described in Deliverables 1 and 2 – Central, North, South and West – are established. In addition, these durability categories should also be related to different traffic classes. With regard to the differentiation of durability categories related to traffic classes, it can be difficult to find a common system, while in Europe there are already different well established systems for traffic classes.

There is already an established assessment system in HAPAS [1] framework, although not particularly adapted for pothole repairs. It would be useful to extend this system to explicitly applies to pothole repairs. In this connection, it is of great importance for the in situ assessment that there is a clearly defined guideline for when any damage is judged sufficient to have a negative effect on the functional properties of the repaired road.

Given the relatively low number of assessments it is suggested that the durability of pothole repair materials is categorised as follows:

Category I: Durability less than 1 year (short-term durability)

Category II: Durability between 1-3 years (medium-term durability)

Category III: Durability more than 3 years (long-term durability)

This means that the repair materials in Category I are intended as emergency repairs of potholes that can last until the weather conditions allows the application of a more durable repair material. Repair Materials in Category II are intended for repair of potholes where there are plans to replace the surface layer within a few years, while repairing materials in Category III are intended for repair of potholes in relatively new surfaces with a durability of more than 3 years.

In order not to be limited to the types of repair materials/methods that are already tested in trial sites, it would be appropriate that new repair materials/methods can be tested by laboratory tests to categorize repair materials by their durability.
It has not been possible to classify the different generic types in durability categories, due to the great variation in the durability of each repair materials within the same durability category. It is, therefore, recommended to select a repair material from each generic material type and from each durability category, giving a total of 12 repair materials

## 6.2 Conclusions

From the relatively limited number of assessments based on one trial site from Denmark with 19 repair material and trial sites from the United Kingdom with four repair materials, from which information from only three were available, a summary of the results is given below.

**Table 1: An overview of repair materials for potholes classified by generic material types.**

| | Hot applied asphalt | Cold applied asphalt | Cement | Synthetic binder |
|---|---|---|---|---|
| **Estimated durability** | Cat. I, Cat. II, Cat. III | Cat. I, Cat. II | Cat. I, Cat. II | Cat. I, Cat. II, Cat. III |
| **Working equipment** | Comprehensive | Limited | Limited | Limited |
| **Limitations for application** | None | None | Pothole < 0,5 m | Temperature > 10 °C |
| **Ready for traffic** | Shortly after application | Shortly after application | < 3 h after application | < 3 h after application |
| **Working environment** | Special education | None | None | Special education |
| **Possibility of recycling** | Yes | Yes | No | No |
| **Typical type of damage of repaired pothole** | Cracks in repair, adhesion failure, immersed chippings | Loss of material, fretting | Cracks in repair, adhesion failure | Cracks in repair, adhesion failure, cracks in the pavement, loss of chippings, loss of material |

The result from this evaluation is as follow:

[1] The same conditions (traffic and climate) and evaluation methods are not used for the different trial sites and, therefore, it is difficult to determine the actual durability of the various repair materials. It is, therefore, important to develop a common evaluation system that uniquely determines when damage is being assessed to have a negative effect on the functional properties of the repair.

[2] If the assessment system is to be applicable throughout Europe, it will be necessary to define categories of durability with reference to the different climate zones and different traffic classes.

[3] It has not been possible to classify the different generic types in durability categories based of the evaluated of the trial sites because, within each generic type of material, great variation exists in the estimated durability for each repair material.

[4] It appears that each generic type of repair material has an associated set of typical damage. It may, therefore, be necessary to differentiate the laboratory tests relative to each generic type of repair material.

[5] It appears that some of the generic types of repair materials have limitations on their application, such as size of the pothole and the temperature during application.

[6] It is suggested that the durability of pothole repair materials are categories as follows:

Category I: Durability less than 1 year (short-term durability)
Category II: Durability between 1-3 years (medium-term durability)
Category III: Durability more than 3 years (long-term durability)

# 7 Comparison of the performance of common and new materials for pothole repairs (Workpackage 5)

The consortium divided the requirements for pothole repair materials into basic and supplementary (see Table 2).

**Table 2: Recommended laboratory tests**

| **Basic tests** | **Test method** |
|---|---|
| Aggregate gradation and maximum size of aggregate | EN 12697-2, EN 933-1 |
| Binder content | EN 12697-1 |
| Air voids content | EN 12697-5, 6, 8 |
| Compactibility (workability) | EN 12697-10 |
| Indirect tensile test (stiffness - strength) | EN 12697-23 |
| Water sensitivity | EN 12697-12 |
| Sensitivity to conditions (freeze/thaw cycles) | EN 12697-12 (modified, see report of Workpackage 5 for details) |
| **Supplementary tests** | |
| Deformation resistance | EN 12697-22 |
| Macrotexture depth | EN 13036-1 |
| Skid resistance (pendulum test) | EN 13036-4 |

In this Workpackage only the tests related to the basic requirements (workability, indirect tensile strength, water resistance and sensitivity to freeze-thaw cycles) could have been performed.

Three types of materials (hot asphalts, cold asphalts and synthetic-binder mixtures) were tested. The hot asphalts (AC 11 and SA 8) were chosen as a benchmark for comparison with the cold asphalts and the synthetic-binder materials. Synthetic binders have been tested because they seem to be a relatively durable solution (see Table 1), but haven't been used often in situ so far. No cement based materials have been tested within the project.

Fourteen cold asphalts currently available in the European market were tested. Tests of particle size distribution, binder content and air voids content were used to select one cold asphalt from each country involved in the testing (UK, GER, SL and SK) for further investigation. The results of the tests demonstrated the following:

- Only a few of the cold asphalts have more than one aggregate fraction and continuous particle size distribution; one or two fractions of aggregate predominate in most of the tested cold asphalts.
- The cold asphalts with unsuitable aggregate gradations have high air voids contents that may negatively influence their performance.
- No cold asphalt with an air voids content lower than 10 % was found.
- Some of the cold asphalts contain binders that do not become hard after application of the material; the mixtures stay soft, and they have little or no resistance to loading (and some of them even disintegrating spontaneously).
- Intensity of compaction is critical to cold asphalt performance; low compaction decreases the values of the performance parameters and shortens the service life.
- Cold asphalts differ with regard to compactability; the differences between the compaction curves prove that mixture composition (aggregate gradation and binder) is more important

than compaction temperature. (It appears that the viscosity of the binders in the tested cold asphalts did not change significantly in the temperature range from 5°C to 20°C.)

- The type of cold asphalt, the temperature conditions and the cure time influence the indirect tensile strength of the cold asphalts.
- The highest indirect tensile strength values of cold asphalts were found for the compaction and conditioning temperatures of (20 ± 1)°C, and the lowest for (5 ± 1)°C.
- Differences in the indirect tensile strength among the cold asphalts can be high (double or more) and depend on the temperature conditions before and after application; better results are achieved at elevated compaction and curing temperatures (20°C).
- Cure time is a positive factor because the values for indirect tensile strength increase over time; the amount of change depends on the temperature conditions and can be significant (up to 50 %).
- Only one of the tested cold asphalts was water resistant in all the tested scenarios of compacting and conditioning temperatures; the others had little or no resistance to the influence of water. (The test samples were soft or disintegrated before or during testing.)
- Only one of the tested cold asphalts proved resistant to freeze-thaw cycles; the others have little or no resistance. (The test samples were soft or disintegrated before or during testing.)
- Taking into account all the ways of comparing compactability and indirect tensile strength (dry, wet, freeze-thaw), it appears that compactability should be removed from the list of relevant properties that should be tested for cold asphalts.

The following findings emerged from the comparison of the test results for the cold and hot asphalts:

- A large difference exists only in the first stage of compaction; thereafter, the ratio of the changes in height increases slowly. The increase means that the change in height of the compacted cold-asphalt specimens is faster.
- The total changes in height of all the tested cold asphalts were higher than for SA 8; two of the cold asphalts had a greater change in height and two had lower when compared with AC 11.
- Only one cold asphalt had values of indirect tensile strength, water sensitivity and freeze/thaw resistance that were close to the hot asphalt values; even this material is comparable only with SA 8 with the soft 250/330 bitumen. The other tested cold asphalts were significantly weaker than the hot asphalts.

Taking into account the findings mentioned above, it seems useful to determine some requirements for the components of cold asphalts and the properties of the final mixture. These could include

- A minimum number of aggregate fractions that should be used in a mixture;
- limitations on the particle size distribution (minimums and maximums passing through defined sieves);
- required air voids content;
- binder properties; and
- required values for the results of the selected tests.

Different approaches could be used to apply the requirements above. All of the requirements could be accepted, or only some of them could be used. Moreover, various formulations of the requirements for each parameter are possible. Numbers, limits, and descriptive requirements are suitable. One of the possible sets of requirements was recommended by the consortium as follows:

- The maximum nominal size of the aggregate used in a mixture should be in the range of 4 mm to 10 mm
- The air voids content of a cold asphalt should be as low as practicable so that it is as similar to the original surrounding material as possible.
- The indirect tensile strength (ITS) of a cold asphalt, as determined according to EN 12697-23, should be at least 20 % of commonly hot asphalts ITS. The ITS requirement should be evaluated for cold-asphalt specimens under the following conditions:
    1. temperature of the cold asphalt before compaction of +5 $^{o}$C;
    2. compaction of the specimens by an impact compactor according to EN 129697-30;
    3. storage and conditioning of the specimens before testing at +5 $^{o}$C; and
    4. test temperature of +5 $^{o}$C.

New knowledge about synthetic-binder materials has been gained. Two materials with different compositions and synthetic binders were tested. From experience and the test results, the following can be concluded:

- The workability time of the synthetic-binder mixtures is very short, so the mixture must be prepared and compacted within a few minutes.
- It is recommended to prepare at one time only the quantity of a mixture that is needed for one pothole.
- The workability of the mixtures is lower and shorter at elevated temperatures (20°C).
- Both tested materials had comparable strength values regardless of differences in the material composition.
- The temperature conditions before and after compaction of the specimens had a only small influence on the indirect tensile strength.
- Both materials are resistant to water and frost.
- Approximately the same values of indirect tensile strength were found at test temperatures of 5°C and 25°C; it seems that the stiffness of the tested synthetic-binder mixtures is independent of temperature.
- The tested synthetic-binder materials had higher indirect tensile strength than the tested hot asphalts.

# 8 Life Cycle Cost and Benefit Analysis (LCCBA) (Workpackage 6)

Pothole repair can be done with different materials and techniques both of which will have an influence on the patching survival and, thus, on the repair costs. For road agencies it is therefore important to select a repair strategy which, compared to other strategies, incurs the lowest cost. That not only requires knowledge on the expected patching survival associated with materials and techniques, but also knowledge on the pothole progression on a particular road section. In a life-cycle-cost benefit analysis (LCCBA) this knowledge will be brought together, in order to determine the most cost-effective repair strategy.

Workpackage 6 of the project “Durable Pothole Repair” addressed this challenge of road agencies and conducted a LCCBA for different strategies for the repair of potholes consisting of a combination of different materials and techniques. Table 3 shows the different repair alternatives which those repair strategies were based on. Two different response times were examined for each repair alternative (see table 4), therefore 12 repair strategies have been tested (see also Table 3) These strategies were applied to four scenarios which represented typical, but contrasting repair situations (see Table 5). Main differences were traffic intensity, remaining service life of the road section and number of potholes to be repaired. For each scenario the most cost-effective repair strategy was determined. Due to the numerous variations of considered repair situations it was not possible to compute results which can be directly implemented at road agencies. The intention was to provide guidance on conducting a LCCBA for pothole repair and give general recommendations for selecting a cost-effective pothole repair strategy. Road agencies have to consider the peculiarities of their road networks in the LCCBA, in order to obtain managerial relevant results.

**Table 3: Tested repair alternatives and repair strategies**

| Repair alternative | Repair material | Repair technique | Repair strategies (See table 4) |
|---|---|---|---|
| 1a | Cold-mix asphalt | Unprepared fill-and-roll | 1a-IR |
| | | | 1a-DR |
| 1b | Cold-mix asphalt | Prepared fill-and-roll | 1b-IR |
| | | | 1b-DR |
| 2a | Synthetic binder | Prepared fill-and-roll | 2a-IR |
| | | | 2a-DR |
| 3a | Hot-mix asphalt | Unprepared fill-and-roll | 3a-IR |
| | | | 3a-DR |
| 3b | Hot-mix asphalt | Prepared fill-and-compaction | 3b-IR |
| | | | 3b-DR |
| 3c | Hot-mix asphalt | Milling and resurfacing section | 3c-IR |
| | | | 3c-DR |

**Table 4: Response times**

| | Response time (months) | | |
|---|---|---|---|
| | minimum | mode | maximum |
| Immediate repair (IR) | | 0 | |
| Deferred repair (DR) | 3 | 6 | 9 |

**Table 5: Pothole Scenarios**

| | **Scenario 1** | **Scenario 2** | **Scenario 3** | **Scenario 4** |
|---|---|---|---|---|
| Thickness of top asphalt layer | 50 mm | 30 mm | 30 mm | 50 mm |
| Remaining service live | 6 years | 3 years | 6 years | 3 years |
| Traffic intensity | High (50 million axles/year) | High (50 million axles/year) | Low (10 million axles/year) | Low (10 million axles/year) |
| Amount of precipitation | High (100 mm/month) | Low (25 mm/month) | Low (25 mm/month) | High (100 mm/month) |

The conclusions that can be drawn from the results of the LCCBA are:

(1) In all four scenarios the agency costs for the immediate repair are higher than for the deferred repair, because traffic management costs can be reduced through the bundling of pothole repairs. On the other hand, user costs for deferred repair are higher than for immediate repair, because the existence of potholes for a longer period increases vehicle operation costs, travel time and accident risk.

(2) In all four scenarios immediate repair strategies are preferable compared to deferred repair strategies. Although deferred repair strategies have lower agency costs, the user costs increase drastically and, thus, the total costs. Even for scenarios 3 and 4 with lower traffic intensity, the user costs are considerably higher compared to the agency costs.

(3) In all four scenarios the unprepared patching of potholes with cold-mix asphalt (strategy 1a-IR/DR) incurs the highest costs compared to other patching strategies. The low patching survival of this strategy increases the total number of potholes to be repaired.

(4) In all four scenarios the strategies 1b-IR/DR, 2a-IR/DR, 3a-IR/DR and 3b-IR/DR show very similar costs. Although these strategies have different patching survival rates and repair costs, the longer patching survival and higher costs of one strategy is outweighed by the shorter patching survival and lower costs of another strategy.

(5) In scenario 1 and 2 a deferred resurfacing of the road section is more cost-effective than a deferred patching of potholes. The high traffic intensity of both scenarios leads to high user costs which favour the resurfacing option.

(6) In scenario 3 and 4 deferred patching of potholes is more cost-effective than a deferred resurfacing of the road section. The low traffic intensity of both scenarios reduces the user costs which favour the patching option.

Based on the conclusions the following recommendations can be formulated:

(1) If road agencies consider user costs in LCCBA, a pothole should be repaired immediately after occurrence. The longer a pothole exists, the higher the user costs will be.

(2) If road agencies can chose between different repair alternatives for the immediate repair, they should always prevent an unprepared patching with cold-mix asphalt.

(3) In situations with a high number of expected potholes for a road section (scenario 1 and 2), road agencies should choose a repair strategy with an approximate patching survival of at least two-thirds of the remaining service life.

(4) In situations with a low number of expected potholes for a road section (scenario 3 and 4), road agencies should choose a repair strategy with an approximate patching survival of the remaining service life.

(5) In situations with a high traffic intensity (scenario 1 and 2) and if road agencies cannot do an immediate patching repair, a deferred resurfacing of the road section should be done.

(6) In situations with a low traffic intensity (scenario 3 and 4) and if road agencies cannot do an immediate patching repair, a deferred patching of the potholes should be applied.

# 9 Summary and Outlook

The present final report of the project POTHOLE gives a summary of the work done in the project. Further details for each Workpackage are available at the projects webpage (www.fehrl.org/pothole) .

The first steps of the project showed that the problem of pothole is a current topic in all European countries, but still there is no uniform definition. The project suggested a definition for that. Far more important than the missing definition was the fact that a lot of approaches for the repair of pothole which don't ensure durability at all were and still are very common throughout Europe.

Therefore a list of test methods were developed which can help to ensure the use of quality material in the future. Based upon the study of European techniques a compilation of different materials and procedures has been made and developed further, taking the analysing of existing trial sites into account, categories which show an estimated durability if certain materials and procedures are combined. The results of different strategies for pothole repair were shown in a Life Cycle Cost Benefit Analysis.

The guidelines which have been developed based upon all the results of the project can now be easily used by stakeholders which are facing the question which material and procedures should be used for what purpose.

It is suggested to use the given list of laboratory test (Table 2) to distinguish between different materials.

When used and most necessarily spread within stakeholders in Europe, the findings, conclusions and compilation which are collected in the guidelines within this project can be a huge benefit. Still there are some questions that should be dealt with in future projects and research, e.g. suggested in the following:

As stated in Workpackage 3 (see chapter 5) so far almost no requirements for material properties are existing throughout Europe which makes it very difficult for stakeholders to differ and to choose between materials on the market. Also there are no obligatory information which has to be made by the manufacturer about their materials so far. This topics should be dealt with in national papers in the future. So far the geometry of repaired potholes haven't been investigated. Often potholes are repaired as square areas which means the joint is within the direction of the traffic. It is assumed but not yet tested that a square turned 45°degrees (diamond shape) would be advantageous for the durability and maybe also reduce noise.

The geometry of repaired potholes as well as the performance of different materials should be investigated with test sites on a long-term basis.

# 10 Annex "Guidelines for pothole repair"

The "Guidelines for pothole repair" were written as an annex for this report, but has been published as an extra document for a single use and can be downloaded on www.fehrl.org/pothole.

# Literature

[1] BBA, HAPAS Certificate 12/H183, Product Sheet, Hanson Patch Repair Product for Highways, Hanson Road Repair.