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Executive summary

ERA-NET ROAD initiated a transnational research project titled “Optimization of thin asphalt layers”. A consortium consisting of the Danish Road Directorate/Road Institute (DRI), the Belgian Road Research Centre (BRRC) and the Swedish National Road and Transport Research Institute (VTI) was trusted with carrying out the project. The project began with a State-of-the-Art review of literature and an inventory of experience obtained with using thin asphalt layers (TAL).

This phase of the project was documented in a separate report, concluding that the application of TAL is most certainly worthwhile, in particular as a renewable “skin” of a stable road construction having sufficient bearing capacity. This skin serves road users’ need for skid resistance and other important functions.

The general conclusion of the project is that TAL are widely applicable and are being used in most if not all ERA-NET ROAD member countries.

The use of TAL in Europe seems to increase although available statistics make it difficult to distinguish between TAL and other hot mix asphalt. Policies on applying TAL vary substantially from country to country.

A main reason why the use of TAL increases is road administrations’ need to have cost effective maintenance of their road infrastructure which, in many ways, coincides with their needs for providing lower traffic noise levels in residential areas near major roads. This may be one of the positive effects when a TAL is applied.

Among advantages of TAL, compared with standard DAC 11 or SMA 16, the most important seem to be the noise reduction obtained and the generally lower cost of TAL when applied properly. Also the smaller required working space, including less need to adjust kerbs and the larger free height under bridges, are advantages. TAL provide good skid resistance and are fast to build. A particular advantage of Ultra-Thin Layer Asphalt Concrete is that the spraying of large amounts of polymer modified emulsion seals cracks in the old surface.

The most important disadvantage is the higher sensitivity of TAL to weather conditions during paving. This may be counteracted by combining TAL technology with the Warm Mix concept, a topic for future research and development.

TAL may also be more susceptible to cracking related to substrate deficiencies, and TAL are less applicable at places like urban road crossings or steep climbs where vehicles exert high shear forces on the surface layer.

The present report gives guidance on where to use TAL and where not to. The contribution of TAL to the bearing capacity of the road structure is marginal in many cases. In order to make TAL resistant to wear from studded tyres, one should use large maximum aggregate sizes, in which case their thickness normally would need to be relatively large.

The life cycle cost of TAL compared with the cost of thicker overlays such as DAC 11 or SMA 16 cannot be assessed accurately until TAL lifetime and performance over time has been documented. Until then we must rely on calculation based on engineering judgement concerning the TAL lifetime.

Optimization of TAL may be attempted by varying different aspects of the mix design. The effects of such development should be investigated more extensively. The recommendations given in the present report for further research reflect some of the possible ways to optimize TAL and their application.
The sensitivity of TAL to weather conditions during the paving operation has been mentioned as a major disadvantage. Road administrations and contractors are often forced to pave TAL during cold weather and then its durability may be reduced. This may be counteracted by optimizing the laying process by using additional heaters and special pavers or perhaps by combining hot mix TAL with WMA technology, see the recommendations for future research.

One needs to collect data systematically to obtain time series of the functional properties of TAL (e.g. skid resistance, noise reducing effect and general durability) in order to have solid foundation for future decisions on the development of optimized TAL.

The aggressive action of studded tyres on surface layers with small nominal maximum aggregate size needs focus. Aggregate quality and the proportion of large aggregate are the main parameters determining wear resistance of dense and gap graded asphalt concrete wearing courses. Using TAL with polymer modified bituminous binder or thin layer Asphalt Rubber (AR) pavement might give minor positive effects against wear from studded tyres but the main factor is the aggregate size.

The Warm Mix concept can be applied in an alternative manner. Instead of lowering the mix temperature, Warm Mix technology can be applied to produce mix at almost "normal" temperature. This will extend the time available for hauling, paving and compaction because of enhanced mix workability at lower temperature. There is no experience yet on the durability of such pavements. Systematic follow-up on durability etc. associated with this combination of TAL with WMA technology is desirable, even though no reduced carbon footprint can be achieved when applying WMA technology in this way. In literature a number of WMA techniques are described which have been developed since the mid-1990s, including the use of organic or chemical additives (such as waxes) and foaming techniques to reduce the viscosity of the binder or to reduce the friction force within the asphalt mix, to allow the production and compaction of mixes at reduced temperature compared to HMA.

Rollers equipped with GPS equipment can be instrumental in obtaining optimum compaction of TAL. Such assistance would be particularly important for night-time paving.

Applying premium bituminous binders is presumably of vital importance for TAL durability. Polymer modified binders seem to have good potential, and “in situ” blended polymers have proven beneficial for limiting equipment investment cost.

The use of and experience gained with crumb rubber from tyres applied as AR, possibly with a SAMI, still needs verification concerning the potential savings with all factors included in the analysis. More research and field documentation is required to provide such verification.
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Preface

ERA-NET ROAD is a consortium comprising national European road administrations. Its purpose is to strengthen European road research by coordinating national and regional research programmes and policies.

In 2009 ERA-NET ROAD issued a call for tenders on a transnational research project titled “Optimization of thin asphalt layers”. The project is coordinated by a Project Executive Board with representatives of six European road administrations:

- Mats Wendel (chair), Swedish Transport Administration, Sweden
- Thomas Asp (secretary), Swedish Transport Administration, Sweden
- Tony K. Andersen, Ministry of Transport, Danish Road Directorate, Denmark
- Jostein Aksnes, Norwegian Public Roads Administration, Norway
- David Lee, Department for Transport, Highways Agency, United Kingdom
- Christian Pecharda, FSV; Austrian Association for Research on Road - Rail – Transport, Federal Ministry of Transport, Innovation and Technology, Austria
- Christiane Raab, Empa, Swiss Federal Laboratories for Materials Testing and Research, Swiss Federal Roads Authority, Switzerland

The Project Consortium consisting of the Danish Road Institute, the Belgian Road Research Centre and the Swedish National Road and Transport Research Institute won the tender and the project was initiated 1 July 2009. The researchers carrying out the project are the authors of the present report with support from colleagues with special expertise.

The first stage of the project was a State-of-the-Art review concerning the use of thin asphalt layers. The present report on the second stage of the project contains the results of an analysis of the cost of applying thin asphalt wearing course systems and recommendations on how to optimize thin asphalt layers, including necessary future research.

Essential aims of the present report are to compile experience with and advice on the proper use of thin asphalt layers; to discuss how thin asphalt layers can be improved; to suggest for road administrations not yet applying thin asphalt wearing course systems how they could introduce this concept, and to describe where it is applicable.
Abstract

ERA-NET ROAD initiated a transnational research project titled “Optimization of thin asphalt layers”. Thin asphalt layers have been used extensively and with promising results for more than 15 years in several countries in Europe and abroad. They seem to be cost effective, fast to build and may have good surface properties. In recent years thin asphalt layers have been shown to imply reduced traffic noise levels, increased traffic safety (skid resistance and forward visibility during wet condition) and to be durable compared with traditional alternatives.

The DRI-BRRC-VTI Consortium was trusted with carrying out the ERA-NET ROAD project and began with a State-of-the-Art report covering, among other things, a literature study and an inventory of experience with using thin asphalt layers. The results of this phase of the project were documented in a separate project report.

The main conclusions were that the application of thin asphalt layers is certainly worthwhile, in particular as a renewable “skin” of a stable road construction having sufficient bearing capacity. The skin serves road users’ need for skid resistance and other important functions. Compared with more conventional and traditional surfacing such as dense asphalt concrete 0/11 or stone mastic asphalt 0/11, thin asphalt layers in general come out somewhat better in most respects; for example concerning cost, use of nature resources, rolling resistance, and traffic noise emission. However, there are also drawbacks or problems under special traffic that need to be handled, for example TAL durability when exposed to wear from studded tyres. The availability of premium quality aggregate is a prerequisite for applying thin asphalt layers, and good quality aggregate may be difficult to procure.

The present report looks at possibilities to optimize the application of thin asphalt layers, including an analysis of the cost of applying thin asphalt layers compared with the cost of applying more conventional solutions. The study has been limited to thin asphalt layers with a maximum thickness of 30 mm.

Recommendations are given concerning the best practice in applying thin asphalt layers and suggestions are given for future research needed to fill the gaps in available knowledge.
Abbreviations and acronyms

Acronyms and abbreviations used in the report are:

AADT Annual Average Daily Traffic
AC Asphalt Concrete
APL Analyseur de Profil en Long
AR Asphalt rubber (binder with minimum 15 % by weight of rubber granules) as defined by ASTM
ARAN Automatic Road ANalyzer
ASTM ASTM International, originally known as the American Society for Testing and Materials
BBTM Very thin asphalt concrete (used in CEN, abbreviation from the French name Beton Bitumineux Tres Mince)
BBUM Beton Bitumineux Ultra Minces (ultra-thin asphalt concrete) (≡ UTLAC)
CBA Cost-benefit analysis
CEN European Committee for Standardization
CPX Close Proximity (method) (tyre/road noise measurement close to a test tyre, often using a trailer)
DAC 11 Dense(-graded) asphalt concrete, with maximum aggregate size 11 mm
dB decibel, unit for sound pressure level, re. 20 μPa. dB(A) indicates that the sound signal has been weighted by a standard (A-weighting) filter
EOTA European Organization for Technical Approval
ESAL Equivalent standard axle load
ETAG European Technology Assessment Group
GPS Global positioning system
HMA Hot mix asphalt
IRI International Roughness Index
ISO International Organization for Standardization
LCA Life Cycle Assessment
LCC Life Cycle Cost
<table>
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>LCCA</td>
<td>Life Cycle Cost Analysis</td>
</tr>
<tr>
<td>MPD</td>
<td>Mean profile depth according to ISO 13473-1</td>
</tr>
<tr>
<td>MTD</td>
<td>Materials transport device or Mean texture depth</td>
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<tr>
<td>NMAS</td>
<td>Nominal Maximum Aggregate Size (typically the smallest sieve size which allows all the aggregate to pass the sieve).</td>
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<tr>
<td>OGFC</td>
<td>Open Graded Friction Course</td>
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<tr>
<td>PEB</td>
<td>Project executive board</td>
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<tr>
<td>PmA</td>
<td>Polymer modified Asphalt. Asphalt materials with &quot;in situ&quot; blended polymer directly into the mixer</td>
</tr>
<tr>
<td>PMB, PmB</td>
<td>Polymer modified bitumen (typically related to EN 14023)</td>
</tr>
<tr>
<td>PMS</td>
<td>Pavement management system</td>
</tr>
<tr>
<td>PSV</td>
<td>Polished stone value</td>
</tr>
<tr>
<td>RR</td>
<td>Rolling resistance</td>
</tr>
<tr>
<td>RUMG</td>
<td>revêtement ultra-mince grenu (grenu = adjective ≈ grainy (UK))</td>
</tr>
<tr>
<td>SAMI</td>
<td>Stress Absorption Membrane Interlayer</td>
</tr>
<tr>
<td>SBR</td>
<td>Styrene butadiene rubber</td>
</tr>
<tr>
<td>SBS</td>
<td>Styrene butadiene styrene</td>
</tr>
<tr>
<td>SCRIM</td>
<td>Sideway-force Coefficient Routine Investigation Machine</td>
</tr>
<tr>
<td>SMA</td>
<td>Stone mastic asphalt (Europe), or Stone matrix asphalt (USA)</td>
</tr>
<tr>
<td>SoA</td>
<td>State-of-the-Art</td>
</tr>
<tr>
<td>STA</td>
<td>Swedish Transport Administration (Trafikverket), formerly Swedish Road Administration</td>
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<tr>
<td>TAL</td>
<td>Thin asphalt layer or Thin asphalt layers</td>
</tr>
<tr>
<td>UTLAC</td>
<td>Ultra-Thin Layer Asphalt Concrete, according to EN 13108-9, EOTA Guideline, or proprietary product</td>
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<tr>
<td>WG</td>
<td>Working Group (such as in CEN or ISO)</td>
</tr>
<tr>
<td>WMA</td>
<td>Warm mix asphalt, “lower temperature hot mix asphalt”</td>
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1 Introduction

Thin asphalt layers have been used extensively and with promising results for more than 15 years in several countries in Europe and abroad. They seem to be cost effective pavements, fast to build and may have good surface properties. Development in recent years has shown that applying thin asphalt layers leads to reduced traffic noise levels, increased traffic safety (skid resistance and forward visibility during wet condition) and durable surface layers compared with traditional alternatives.

In the frame of ERANET ROAD II, a call was issued in 2009 for a comprehensive study of this type of road surface. The overall purpose of the study should be to optimize thin asphalt surfacing, 10 - 30 mm thick, not including surface dressing and slurry seal.

The first phase of the study of such surface layers consisted in gathering detailed information on the use of thin layers, and on the experience obtained in Europe and elsewhere. A literature review was carried out for this purpose. This review was supplemented by an inventory amongst asphalt specialists to collect information on knowledge and experience not published in regular literature, but available for example as unpublished research results from institutes and contractors.

The outcome of this first phase of the project is documented in a report on the State-of-the-Art [Sandberg et al., 2010]. The main results are summarized in Chapter 3 and 4 of the present final project report.

Chapter 5 gives qualitative and quantitative descriptions of the cost induced by applying TAL, while Chapter 6 points at ways to optimize their use. An essential challenge has been to identify conflicts between interrelated asphalt technology aspects and performance characteristics and to propose how to optimize the systems.

Chapter 7 gives recommendations concerning the best practice in applying TAL and suggests future research needed to fill the gaps in available knowledge.

A summary of the report findings is given in Chapter 8 which concludes by pointing at important steps to be taken on the way to introduce and apply TAL.

2 Purpose and limitations

2.1 Purpose

The general purpose of the project has been to collect, analyse, summarize and report information on 10 - 30 mm thick asphalt surface layers, including all types of hot mix design and application methods. Proprietary and special products, like types with rubber-modified bitumen should be dealt with. Focus should be on asphalt technology aspects and on performance characteristics assessed to be important for future application of thin layers.

The aim of the study reported here has been to twofold, i.e. to

1. describe the present “Best Practice” in applying TAL, covering all ERA-NET ROAD member countries, not only the six participating countries

2. recommend future activity in attempts to optimize thin asphalt layers, especially in countries where TAL have not reached their full potential.

In this connection, gaps in available knowledge should be identified and directions should be pointed at for research needed to fill such gaps.
2.2 Limitations

The study was limited to thin asphalt mixtures, which means that surface dressings or slurry seals were outside the scope of the project.

Focus was on hot mix asphalt. In this connection, so-called warm mix asphalt was considered a special hot mix application.

The maximum thickness was more or less arbitrarily defined to be 30 mm.

Double layers are composite constructions and they have not been considered TAL. Thus double layer wearing courses, even the top layer of such pavements, were outside the scope of the present project.

3 State-of-the-art on the use of and experience with thin asphalt layers

3.1 Introduction

In the first part of this project, a State-of-the-Art report on thin asphalt layers (TAL) was drafted, covering, among other things, a literature study and an inventory of experience with using TAL. This was later updated in the second part of the project [Sandberg et al, 2010]. This chapter summarizes the State-of-the-Art report.

3.2 Present use of thin asphalt layers

Policies on applying TAL vary substantially from country to country. For example TAL represents 95% or so of all new Danish hot mix surface courses, while in Belgium this percentage is much lower and differs between regions. Also in Sweden, there is a substantial difference in the use of TAL between regions; not necessarily correlated with climatic conditions.

The use of TAL in Europe seems to increase although available statistics make it difficult to distinguish TAL from other hot mix asphalt surface layers. In many countries, there is no statistics regarding TAL use in urban areas; only for the national or regional highways.

The EAPA collects information on the production of each type of asphalt divided according to the EN 13108-series of product standards. Data are expressed as a percentage of the total amount of surface courses, and no data are available concerning their nominal layer thickness. In Figure 1 TAL usage statistics are shown for some countries within ERA-NET ROAD. The data shown in the figure have been collected from questionnaires and interviews with experts.
Figure 1 Area in millions of square metres of thin and very thin asphalt layers in some countries.

Note: Not all roads in the countries concerned are included in these estimates, so the estimated areas must be considered minimum values. Note that according to the interviewed Italian expert, there are no TAL at all in Italy.

Figure 2 shows the percentage of the main road network (highways and motorways) covered with TAL for some countries.

Figure 2 Percentage of the main road network covered with TAL; estimates based on interviewed experts. No data are available for GB.
3.3 Questionnaire and interviews

The project group sent out a questionnaire to a number of experts and received rather limited response. A subsequent round of interviews was slightly more successful. Respondents often mentioned noise reduction as their primary motivation for applying TAL. Cost reduction and fast paving operations also seem to be important motivation, like good resistance of TAL to skidding and rutting. A few respondents mentioned durability problems as a disadvantage.

3.4 Properties promoting the use of thin asphalt layers

The use of TAL seems to be increasing due to the needs of road administrations for cost effective maintenance of the road infrastructure which, in many ways, coincides with the need for lower traffic noise levels in residential areas near major roads. See an example in Figure 3. This may be one of the positive effects when a TAL is applied.

![Figure 3 Surface of a proprietary thin asphalt layer called "Microflex" paved on Kasteelenlaan in Ede; four years old; aggregate size 2-6 mm. Paved primarily due to its noise-reducing capability. Note chippings have a flat surface facing upwards.](image)

The environmental impact of road transport CO₂ emission is currently widely discussed. Road surface characteristics are one of the parameters that influence rolling resistance and hence energy consumption and CO₂ emission. TAL may offer relatively low rolling resistance because of their favourable surface texture, provided relatively small aggregates are used and that high quality paving work ensures an even surface. In such cases, TAL will normally have either a neutral or a positive, reducing impact on CO₂ emission; depending on aggregate sizes and construction, and depending on which thicker surfaces are used as references. This needs further research. Furthermore, since TAL only requires a thin skin of material, superior materials can be used in smaller quantity, thus reducing road administration induced CO₂ emission associated with the extraction, manufacturing and transport of these materials.

In the "perpetual pavement" concept the philosophy is that the pavement base has eternal bearing capacity and is paved with a thin long-lasting "skin" of surface layer which eventually – due to moisture damage, ageing and other climatic action – must be renewed from time to time.
The TAL as a “skin” provides favourable functionalities such as noise reduction potential, relatively low rolling resistance, some anti-spray properties and efficient light reflection. This has accelerated the use of general product categories and proprietary products addressing these demands, also implying relatively high sustainability and low construction as well as maintenance costs. The fast laying of TAL implies shorter closure to traffic and this favours the use of TAL. Provided the pavement base is of appropriate quality TAL offer solutions for many of the functionalities mentioned above and this is probably why there is immense interest in products of this nature.

The SoA report gives general advice and a few examples of published life cycle costs (LCC) compared with the cost of thicker overlays; which are generally favourable for TAL. Nevertheless, this topic needs further investigation, since the LCC of TAL cannot be assessed with any accuracy until TAL lifetime and performance over time has been documented. This topic is further examined in a Chapter 5 of the present report.

3.5 Properties limiting the use of thin asphalt layers

Despite the favourable properties mentioned above one shall not forget problems and limitations associated with TAL. For example, their contribution to bearing capacity is marginal in many cases. To obtain resistance to wear from studded tyres, large maximum aggregate sizes are required. Open-textured or even porous kinds of TAL may offer very good noise properties, but at the expense of limited durability under heavy traffic load; for example in sharp curves or at steep gradients. Their air voids will also quickly get clogged by dirt.

Another problem worth mentioning is that it may be difficult with the techniques at hand to dismantle TAL by cold milling without downgrading the material. Such milling yields additional fines, which strongly hamper their reuse in a new TAL mix since margins for the grading curve are narrow. Nevertheless, TAL recycling remains feasible in other asphalt mixes used as binder or base course. Warm milling (about 100 °C at milling depth) as utilized in repaving and remixing, could possibly overcome the downgrading observed during cold milling, although the feasibility of such warm milling has yet to be demonstrated in practice.

Mostly, TAL were found to have good skid resistance properties, although exceptions were reported. Very little information, however, was found on the durability of skid resistance and noise reduction. There is a need to study time series in the future.

The sensitivity of TAL to weather conditions during paving has been mentioned as a major disadvantage. Road administrations and contractors are often forced – due to numerous factors - to apply TAL during cold weather and then the durability may be reduced. Perhaps this can be counteracted by optimizing the laying process.

3.6 Asphalt rubber – a special type of TAL with promising performance

The report also discusses the concept of using Asphalt Rubber (AR) pavements as thin layers in the various pavement systems. In a broad context, a multitude of benefits of using an AR as a pavement preservation strategy were enlisted, including less reflective cracking in combination with SAMI, reduced maintenance, excellent durability, less ravelling, good rut resistance, good skid resistance and smooth ride, better drainage facilities, reduced tyre/road noise, cost effectiveness, beneficial engineering use for old tyres, and higher energy efficiency. One version of AR is applied as a very thin layer. However, it must be noted that these are the merits of AR typical for some deteriorated pavement conditions in the USA.
In Europe so far, there has been a different scenario when one takes into account the derived benefits of AR, as observed in relation to a few similar pavement strategies of comparable quality.

Three years operation of asphalt rubber pavements on Swedish motorways, highways and some urban arterials have indicated from satisfactory/similar to very good performance in comparison to conventional pavements (SMA), see results and presentations at [Gummiasfalt, 2010]. With regard to noise properties, distinction shall be made between gap-graded and open-graded versions. Only the open-graded version offers any advantage to the reference SMA pavements; an advantage that may be marginally better than that of conventional porous asphalt concrete pavement. Three years is a short service time even in Sweden, so further monitoring, research and practical applications – including further research on the cost effectiveness of AR and its alternatives - will determine whether the AR concept will be a success in Sweden.

3.7 Winter climate concerns

The Nordic countries are highly interested in the effect on TAL of the exposure to traffic with vehicles using studded tyres. The present review concludes that aggregate quality and the proportion of large aggregate are the main parameters determining wear resistance of dense and gap graded asphalt concrete wearing courses.

TAL as defined in this project with layer thickness 10 – 30 mm have approximately 11 mm nominal maximum aggregate size (NMAS) or smaller. When winter conditions call for extensive use of studded tyres and snow chains, TAL may not be an optimum surface layer: “The larger the aggregate the better” is an appropriate advice from a durability point of view.

3.8 Product standards, classification and approval

TAL must be CE-marked in order to be marketed as complying with an EN 13108-series product standard. These standards specify asphalt mixes, not their final application on the road. The ETAG 16 guideline on ultra-thin layers intends to deal with the entire process, including paving operations and final application. Products complying with this guideline will probably pave an additional route for future CE marking. The impact of CE marking on the market still has to be seen in the daily practise of procuring asphalt materials because CE marking has not yet been fully implemented.

At present, classification of pavement acoustic characteristics is limited to declaring product properties in Denmark, the Netherlands and the UK. CEN work on this is at an initial stage. No system exists for checking pavement product conformity of production concerning its noise characteristics.

3.9 Main advantages and disadvantages of TAL

The most important advantages of TAL compared with standard DAC 11 or SMA 16 are:

- Potential for noise reduction
- Lower cost
- Less required working space (height under bridges and need for curb adjustments).
Other advantages include, for example, higher skid resistance (at low and medium speeds), improved sustainability in most respects, better rut resistance and faster laying.

The three most important disadvantages are:
- Weather conditions while laying TAL are more critical
- Dismantling by milling implies downgrading the material
- Susceptible to cracking related to substrate deficiencies.

Other disadvantages include, for example, susceptibility to ravelling, delamination and frost damage; manual laying is not possible; shorter lifetime, and rather low skid resistance in wet weather for some TAL variants. A couple of major problems that may occur (as for thicker pavements too) are illustrated in Figure 4.

![Figure 4 Most common problems with TAL: ravelling (left) and delamination (right) (Photo courtesy of Ian Walsh, Jacobs Engineering (UK) Ltd).](image)

### 3.10 Main conclusions from the State-of-the-Art report

The SoA report indicates that actual achievement of both excellent functional properties and good durability (lifetime) is nothing which comes easily. In practice, it is often difficult to realise both requirements simultaneously since they are frequently in conflict with each other. The information made available through the SoA report should, therefore, serve as a basic guideline for achieving the best compromise between the goals. Learning from laboratory performance tests together with experience in the field will provide useful input. These practical tasks are addressed in the present final project report.

The main conclusion in the SoA report is that the application of TAL is certainly worthwhile on many major types of roads and streets, in particular as a renewable “skin” on a stable road construction having sufficient bearing capacity. The skin satisfies the road users’ need for sufficient skid resistance and energy efficiency, and the roadside neighbours’ needs for a quiet and clean environment, as well as most other important functions.
4 THE FEASIBILITY OF APPLYING TAL

TAL have been used with both good and poor results. Generally, the poor results indicate where and under what circumstances a TAL is not the optimum pavement choice, and the opposite can be said about the good results. The following tables attempt to give an overview of where and under what conditions TAL are feasible or unsuitable to use. Note that this is a generalized assessment, primarily for new construction, since there are many variables in the construction and use which may offset the general picture.

Since the subject is very complicated, and TAL usage must be adapted to special conditions, such as winter conditions where studs are used in tyres, it is necessary to separate the evaluation for two cases: conditions where studs are not used in winter tyres (see Table 1) and conditions when they are used (see Table 2). When studded tyres are used, the TAL shall meet the requirements in EN 13108-20:2005 for resistance to abrasion by studded tyres (EN 12697-16). There are areas which are in a "grey zone" between such cases; i.e. areas where studs are used in winter tyres rather infrequently. In this case, the border between such cases has been set somewhat arbitrarily at 20% of winter tyres having studs.

Table 1 and Table 2 show the evaluation results. There is considerable margin for subjectivity in this average of "expert judgements" made by the authors. Table 3 lists cases where TAL are not feasible in a general sense, within the given circumstances.

Table 1 and Table 2 are based on underlying assumptions of TAL design. For Table 1 the assumptions are:

- On medium and low-speed roads TAL with relatively small NMAS are used. It is assumed that NMAS may normally range between 4 and 8 mm.
- On high-speed roads; especially on motorways, TAL with "medium" aggregate sizes are used, in order to avoid too low skid resistance and aquaplaning hazards. It is assumed that NMAS may then normally range between 8 and 11 mm.

For Table 2 the assumptions are:

- On medium and low-speed roads TAL with "medium" NMAS are used, in order to avoid too much wear by studded tyres. It is assumed that NMAS may normally range between 8 and 11 mm.
- On high-speed roads; especially on motorways, TAL with "large" aggregate sizes are used, in order to reduce wear by studded tyres. It is assumed that NMAS may then normally range between 11 and 16 mm.

In the tables, distinctions are made between high, medium and low volume streets. Since the classification into “high/medium/low volume” varies between countries, it is difficult to quantify these in terms of AADT. However, one may say that arterials or major highways and streets would normally be "high volume", country roads or residential streets would normally be "low volume", and the roads and streets between these extremes would be "medium volume". There would be a considerable overlap which varies from country to country and maybe even from region to region.
In Tables 1-3 the properties of TAL are estimated in comparison to the type of (bituminous) thicker pavement that would be the most common choice on the type of road considered.

Table 1  Evaluation of generalized feasibility of using TAL in different areas and on different types of roads. For conditions where studded tyres are used at a negligible extent. See text for assumptions.

<table>
<thead>
<tr>
<th>Prioritized property</th>
<th>Low cost</th>
<th>Low RR</th>
<th>Low noise</th>
<th>Long life</th>
<th>High skid resistance</th>
<th>Low height</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential streets, low traffic</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Streets with stop-and-go traffic</td>
<td>o</td>
<td>o</td>
<td>-</td>
<td>+</td>
<td>o</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Streets with much turning traffic</td>
<td>o</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>o</td>
<td></td>
</tr>
<tr>
<td>Streets with high grades</td>
<td>o</td>
<td>o</td>
<td>-</td>
<td>-</td>
<td>o</td>
<td>o</td>
<td></td>
</tr>
<tr>
<td>Medium-volume streets</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>1</td>
</tr>
<tr>
<td>High-volume streets, inner-city</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+++</td>
<td>++</td>
<td>1</td>
</tr>
<tr>
<td>High-volume streets, arterials</td>
<td>++</td>
<td>++</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>1,2</td>
</tr>
<tr>
<td>Low volume country roads</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>1</td>
</tr>
<tr>
<td>Highways, max 80 km/h</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>1</td>
</tr>
<tr>
<td>Highways, over 80 km/h</td>
<td>+++</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>1,2</td>
</tr>
<tr>
<td>Motorways</td>
<td>+++</td>
<td>+</td>
<td>o</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>1,2</td>
</tr>
<tr>
<td>Mountain roads</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>1</td>
</tr>
</tbody>
</table>

Ratings:
+++ Highly recommended (best practice), should mean no problem
++ Highly recommended, with caution for certain critical cases
+ Recommended with caution
o Neutral, maybe be feasible and not feasible (high risk of failure)
- Not recommended
- - To be avoided

Notes:
1. TAL types optimized for very low noise properties may be expensive to lay and may use expensive materials. High noise reduction and low cost seem to be incompatible.
2. TAL types with relatively large aggregate sizes (14-16 mm) may provide texture which is excellent for high wet skid resistance, and thus should have +++ in the respective columns, but sacrificing RR and noise reduction.
Table 2 Evaluation of generalized feasibility of using TAL in different areas and types of roads. For climates where studs are used during winter conditions in approximately 20 % or more of the tyres. See text for assumptions.

<table>
<thead>
<tr>
<th>Prioritized property</th>
<th>Low cost</th>
<th>Low RR</th>
<th>Low noise</th>
<th>Long life</th>
<th>High skid resistance</th>
<th>Low height</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential streets, low traffic</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>o</td>
<td>++</td>
<td>+++</td>
<td>1</td>
</tr>
<tr>
<td>Streets with stop-and-go traffic</td>
<td>o</td>
<td>o</td>
<td>++</td>
<td>-</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Streets with much turning traffic</td>
<td>o</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Streets with high grades</td>
<td>o</td>
<td>o</td>
<td>++</td>
<td>-</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium-volume streets</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>o</td>
<td>++</td>
<td>++</td>
<td>1</td>
</tr>
<tr>
<td>High-volume streets, inner-city</td>
<td>+</td>
<td>+</td>
<td>o</td>
<td>-</td>
<td>++</td>
<td>+++</td>
<td>1</td>
</tr>
<tr>
<td>High-volume streets, arterials</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>-</td>
<td>+</td>
<td>++</td>
<td>1,2</td>
</tr>
<tr>
<td>Low volume country roads</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>o</td>
<td>++</td>
<td>+</td>
<td>1</td>
</tr>
<tr>
<td>Highways, max 80 km/h</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>o</td>
<td>++</td>
<td>+</td>
<td>1</td>
</tr>
<tr>
<td>Highways, over 80 km/h</td>
<td>++</td>
<td>+</td>
<td>o</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>1,2</td>
</tr>
<tr>
<td>Motorways</td>
<td>+</td>
<td>+</td>
<td>o</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>1,2</td>
</tr>
<tr>
<td>Mountain roads</td>
<td>+</td>
<td>+</td>
<td>o</td>
<td>-</td>
<td>+</td>
<td>o</td>
<td>1</td>
</tr>
</tbody>
</table>

Ratings:
+++  Highly recommended (best practice), should mean no problem
++   Highly recommended, with caution for certain critical cases
+    Recommended with caution
o    Neutral, maybe be feasible and not feasible (high risk of failure)
-    Not recommended
- -   To be avoided

Notes:
1. TAL types optimized for very low noise properties may be expensive to lay and may use expensive materials. High noise reduction and low cost seem to be incompatible.
2. TAL types with relatively large aggregate sizes (14-16 mm) may provide texture which is excellent for high wet skid resistance, and thus should have +++ in the respective columns, but sacrificing RR and noise reduction.
Table 3  Overriding conditions – conditions when TAL are not feasible.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Reason for TAL not being feasible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base course of arguable strength</td>
<td>TAL is too thin to provide extra bearing capacity</td>
</tr>
<tr>
<td>Base course has cracks</td>
<td>TAL is too thin to prevent reflection of cracks through the TAL (but no problem if SAMI and AR are used)</td>
</tr>
<tr>
<td>Recycling of wearing course is a requirement when repaving</td>
<td>Most TAL materials are not possible to recycle in the same type of layer</td>
</tr>
</tbody>
</table>

5  LIFE CYCLE CONSIDERATIONS

5.1  Introduction to life cycle approaches

This chapter focuses on Life Cycle Cost Analysis, LCCA, but more general approaches to life cycle considerations are also included in sections on carbon footprint, and design aspects on life expectancy are mentioned.

In traditional Life Cycle Cost Analysis, LCCA, all costs during an entire life span of a product or investment is added for the purpose of evaluating strategies for investments, maintenance and operations. If benefits of the investment are included in the analysis, the term Cost-Benefit Analysis, CBA, is often used. In order to reduce the complexity of a LCCA or CBA, the analysis can often be reduced substantially. If, for example, the same external effects, function and performance can be achieved by two different technical solutions, only the cost unique to each solution is needed in the analysis, since everything else is equal. However, if the technical solutions will have an impact on function, safety, environment or health during the product life span, it might be necessary to include these effects in the decision making process. The usefulness of LCCA in Highway and Pavement Engineering depends to a large extent on the responsibility and decision level of its user.

Since costs and life spans of different TAL vary considerably from object to object, a general analysis has not been considered possible. Instead, this chapter begins with an overview of the methodology and then a number of examples are given to highlight common questions.

Life cycle considerations can also be made by applying Life Cycle Assessment methodologies, LCA. LCA focuses on environmental impact and can be used at various levels of ambition from simply mapping activities to assessing a range of different environmental impacts of which climate change is the most well-known. In this chapter, the intentions are to contribute to life cycle inventory by discussing carbon footprint issues, which are related to the impact category climate change.
5.2 Methodology and approaches to LCCA

5.2.1 LCCA by addition of discounted costs over a time period

The principle of adding all costs during a product or investment life span is straightforward. However, the aspects of discounting and the time period actually used for calculations add complexity.

Discount rates are necessary to account for, that it costs less to spend money in the future than spending money today. This could be explained in different ways depending on who is spending the money. Private investors might argue that they can save the money in a bank or invest the money and then get an interest or yield. Another reason to postpone an investment is uncertainty on the long term utility (and costs) of an investment that is difficult to sell. Social discount rates are mostly based on the preference to enjoy utility today rather than tomorrow and on expected economic growth, but also to some extent on risks ahead [HEATCO, 2004]. The discount rate differs between European countries. Germany is reported to use 3% and France 8% social discount rate [OECD, 2001]. The following formula is used for discounting costs over a number of years to present values:

\[
\text{Cost}_{\text{present}} = \text{Cost}_{\text{year}} \cdot \frac{1}{(1 + dr)^{\text{year}}}
\]

where \(dr\) is the selected discount rate. The life span of an investment and the period over which LCCA is performed is important for the result and for the outcome of comparing alternatives. If two alternatives have the same life span and the same standard at the end of the life span in terms of function and future needs for maintenance, the problem becomes trivial. If this is not the case, either a residual value or a calculation time period can be introduced. A residual value is the sum of remaining discounted benefits and costs beyond a certain time. The difference between alternatives can be adjusted with respect to residual values. Calculation time periods can be equal to economic life spans of roads (functional design life). When using calculation time periods, all costs are added during the whole period, with residual values excluded. Calculation time periods vary from 30 years to infinity [OECD, 2001].

LCCA requires different alternatives to be analysed. By simply looking at one alternative, the results may be misleading. For example when comparing initial, large investment costs to future maintenance costs. Instead, a marginal cost approach or a comparison should be used. In both cases it is the total cost that is of interest and should be minimised. In the marginal cost approach, the effect of spending extra on the total sum is analysed, i.e. the total cost if spending one extra Euro today. This gives a hint if today's investments should increase or decrease.

5.2.2 Sensitivity analysis of present and future costs

All investments are associated with risks regarding e.g. costs, timing and performance. In LCCA, the fact that future costs are worth less in present values, means that long term risks are less disturbing compared to present risks. These effects should be considered when choosing pavement type and maintenance strategy.
Sensitivity analysis can reveal if the degree of variation in performance and cost parameters may pose problems or opportunities for improvement (due to low probability but high consequences, or vice versa, and the abilities to control these factors). For example, delamination due to a combination of insufficient tack-coat, high air voids, severe climate (frost or water), turning traffic, etc. In this case, each elementary event is being fairly common, while the combined event is uncommon, but the resulting consequence is substantial and real in terms of serviceability and maintenance costs. Control of materials properties, paving and cross fall are obvious means of avoiding consequences in this example.

5.3 Costs of TAL and common alternatives

The cost of TAL might be assessed by actually completed projects, but in order to contribute to understand the costs of TAL, the analysis will look more into the origins of costs.

5.3.1 Materials and manufacturing

The cost of bitumen is a substantial part of the materials cost. Obviously, this cost depends on the binder content. The price of bitumen is closely related to the price of heavy oils, which means that future price fluctuations are expected. Using modifiers may substantially add to the cost of binder.

Aggregate costs differ with availability (transport distance, source, etc.) while other production costs are more or less fixed.

The need for an improved tack coat might be an additional factor to consider while analysing costs.

5.3.2 Transport and paving operations

The price of asphalt mixes, being relatively low cost per unit weight, is heavily dependent on hauling distances. The price is fairly well related to ton-kilometres. However, shorter distances and lower volumes handled will raise the unit price for effectiveness reasons. Since TAL requires less weight per length of road subject to maintenance, compared to conventional surface courses, TAL cost should be less sensitive to hauling distance.

Effectiveness aspects such as volumes produced, size of objects, employment of advanced equipment, competition, type of procurement etc. have strong impact on prices, regardless of the type of surface course. These parameters can to a large extent be controlled by national road administrations when planning and calling for tenders.

5.3.3 Total costs

Cost data derived from actual projects where only total costs are provided is an important source of information, however difficult to obtain for public use. Looking at data from Sweden, there is no evidence that the cost per tonne of asphalt mixture differs for lifts down to 35 mm, while a limited number of cases show approximately 30-40 % higher cost per tonne for considerably thinner lifts. This is to be expected since the costs of production become much larger in relation to the cost of asphalt mixture.
5.3.4 Performance and future maintenance needs

Based on the contents of the State-of-the-Art report it is evidently difficult to generalise the performance of TAL. The common denominator is the thickness of the asphalt surface layer. One accepted approach in life cycle methodology is to compare alternatives with a similar function (cf. functional units in LCA). This means that the efforts needed in terms of maintenance intervals will differ between alternatives. No further elaboration on this matter is fruitful here, since it would end in the conclusion stated elsewhere in the present report and in the State-of-the-Art report, that the success of TAL is dependent on a number of factors.

For road managers it is important to think beyond the life span of the current treatment. Long term aspects of pavement management, such as the contribution to bearing capacity, crack prevention; reclamation process and recyclability need to be considered from a life cycle perspective.

5.3.5 External costs

Monetary valuations of external effects such as environmental effects (noise, air pollution and global warming), safety, vehicle operation, and time etc. for European countries can be found in the HEATCO report [HEATCO, 2004]. Since noise is of special interest in the context of TAL it will be given further attention, whereas the valuation procedure is similar in principle and the same approach to calculation can be taken to any of the external effects.

Evaluating costs from noise first needs an inventory of the number of persons affected by noise and the noise levels they are subject to. This needs to be done for each alternative solution (e.g. TAL and alternative surface course). Costs for noise per person and noise level probably exists for most European countries, see [HEATCO, 2004]. Valuations are derived by various methodologies such as “stated preference”, “revealed preference” or “hedonic price” and “willingness-to-pay” studies uncovering monetary perception of noise. With these monetary valuations, the cost for each and every person can be summed over the entire calculation time period for each alternative. The outcome is then the difference in cost for noise between the alternatives.

If an alternative leads to significantly different traffic delays in conjunction with maintenance, this should also be considered.

5.4 Performance of TAL and common alternatives

In Table 4 a generalized qualitative comparison is made between the performance of porous and dense TAL and that of some common pavements for each of 21 criteria.
Table 4  Generalized comparison between porous and dense TAL performance and that of some common pavements.

Reference is DAC 0/16

++: much better than reference for this criterion; +: better than reference for this criterion; 0: comparable with reference; -: worse than reference for this criterion; --: much worse than reference for this criterion.

<table>
<thead>
<tr>
<th></th>
<th>TAL (dense)</th>
<th>TAL (porous)</th>
<th>DAC 0/16</th>
<th>SMA 0/11</th>
<th>PA 8/11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life time</td>
<td>-</td>
<td>--</td>
<td>0</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Construction cost</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Maintenance cost</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Initial noise reduction</td>
<td>+</td>
<td>++</td>
<td>0</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Loss of noise reduction during lifetime</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Initial skid resistance</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Skid resistance during lifetime</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Rutting resistance</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Rolling resistance</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Risk for aquaplaning</td>
<td>0</td>
<td>++</td>
<td>0</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Splash/spray</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Debonding from sub layer</td>
<td>--</td>
<td>--</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Speed of construction</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dependency on weather conditions during construction</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Space needed for construction</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Winter maintenance</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Recycling possibilities</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Energy consumption during laying</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sustainability (use of natural resources for construction)</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Resistance to wear by studded tyres</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Local repair of damaged zones</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>
5.5 LCC and construction aspects

5.5.1 General
The optimization of TAL is linked to advantages and disadvantages of surface layers in this category and some of the conditions which shall be fulfilled when applying TAL. In economy terms, focus of LCCA will be on the total pavement structure rather than on the TAL itself. This focus is not a disadvantage for the application of TAL. On the contrary, some pavement design concepts can be beneficial for using TAL when drivers' costs (especially drivers' delay costs) are introduced into the equation. The following paragraphs discuss qualitative aspects of this.

Figure 5 Laying noise reducing TAL; 31 August 2010 at Ugerløse, Denmark.

Note: The water vapour originates from a steel roller outside the picture, using water as an environmentally friendly aid to prevent the surface layer from sticking to the roller. Photo: Hans Bendtsen.

5.5.2 TAL in new road construction
TAL thickness is small compared with the rest of the bituminous part of the total pavement structure, and the surface texture and void structure of TAL are often quite open. The surface layer then contributes only marginally (if at all) to the overall bearing capacity in spite of the
thickness it represents. At the same time TAL for medium to high capacity roads are normally tailor-made mix designs with high priced constituents in order to provide the desired functionality (friction, rut resistance, anti-splash effect, noise reducing ability etc.). This typically brings the price of the same thickness of TAL on the high side compared to standard dense graded asphalt concrete. At a first glance this may seem a disadvantage when considering applying TAL, but combining TAL with the so-called "perpetual pavement" concept this economic disadvantage may diminish or even disappear. This beneficial relationship is mentioned here because it has significant impact on the time period to be used as a basis for the LCCA.

The "perpetual pavement" concept is particularly interesting for medium and high capacity roads. These roads need to be well designed from a structural point of view in order to carry the expected traffic loads for years to come. The same classes of roads are also highly prioritized with regard to little traffic congestion, because drivers' delay costs would be heavy if traffic congestion due to repair and maintenance occurs frequently. The philosophy of "perpetual pavement" is that the bearing capacity for almost unlimited traffic loads is ensured through the design of the unbound layers in combination with the lower bituminous base courses and asphalt binder course. The foundation is meant to be a base that shall not encounter any need for maintenance for a really extended period compared to normal design life. On top of this rut resistance base, highly specialized TAL with numerous built-in functionalities towards traffic can be applied. Exposed to traffic and environmental conditions (oxygen, weather and sun) the surface layer needs to be replaced from time to time but, depending on the impact of drivers' delay costs, even extremely expensive surface solutions can be cost-effective in major cities. By accepting a slightly higher drivers' delay cost the application of more "normal" TAL may be cost-effective on lower traffic class roads.

The European Long-Life Pavement Group (ELLPAG), established in 1999 as a FEHRL and CEDR Working Group, has been an essential initiative to study and promote the concept of perpetual pavement. Several reports have originated from this group. While dealing with both design and maintenance, emphasis was on the design part. Later cooperation between OECD and ECMT (European Council of Ministers of Transport) in 2002 initiated the project on Long Life Surfaces for busy roads. The emphasis was on establishing and developing extreme surface layers which were maintenance free for 30+ years for the concept of perpetual pavements. Two candidates – High Performance Fibre Reinforced Cementitious Concrete and Epoxy Asphalt, respectively – are now in a phase of trial sections. Both solutions are beyond the scope of the present report on optimizing TAL, but both ELLPAG and the OECD/ECMT project have evaluated economic aspects for high end traffic classes. More information can be found in [Christensen et al., 2008] for TAL under such extreme conditions.

TAL can become almost cost-neutral as surface layers when they are incorporated into the structural pavement design at the time of planning new construction. The argument is that the lack of bearing capacity the TAL may provide to the total structure can be compensated for in the bottom layers (either in a lime or cement treated base layer and/or in the bituminous base). These latter layers, from a pavement design life point of view, normally have constituents of cheaper materials than the TAL.

Similarly – considering pavement design life and the demand on the conditions of the layers and surface beneath the TAL – the bottom layers at a marginal additional cost may provide what is needed in terms of rut resistance, water/moisture resistance, evenness etc. for later surface layer paving. From a practical point of view it is also easier – without additional cost – to provide proper profiles (longitudinally and transversally) of the foundation for the later paving operation of TAL in a new road construction.
At new construction – for larger road works like 2 by 2 lanes or a motorway – it might even be economically feasible for asphalt contractors to use a double layer / compact paver to apply the TAL at the same time as the layer beneath (presumably a bituminous binder course). This could enable the asphalt contractor to obtain optimum compaction which in its turn would provide the road owner with longer expected service life. Whether or not using a double layer / compact paver could be an option depends on things like job sizes in the market, availability of asphalt from several asphalt plants at the same job site [Krempel, 2010], expected period of no jobs for the particularly expensive paver and payback time of the investment.

5.5.3 TAL for resurfacing an existing road construction

When TAL is considered for a resurfacing job on an existing pavement one of two situations must be distinguished between:

1. Resurfacing and strengthening the pavement to enhance its design life in order to carry future expected traffic
2. Resurfacing due to failure that only involves the old surface layer of an otherwise well-constructed road with respect to bearing capacity and profiles (failure mechanisms like fretting, ravelling and rutting).

The first situation resembles the situation for new construction described in Section 5.5.2. Depending on the condition of

- the bearing capacity of the existing road versus the desired design life of the strengthened and resurfaced pavement able to carry the expected traffic load
- the existing surface layer with respect to its state of deterioration (fretting, ravelling, wear from studded tires etc.),

the need for removing the old surface layer shall be evaluated. The chosen maintenance strategy will then lead to a decision on which time period will be reasonable to use in the LCCA. This will also be influenced by such time periods appropriate for alternative solutions. The options open in this case to a wide extent follow the conditions described in paragraph 5.5.2.

If the resurfacing is solely due to deterioration of the existing surface layer, the LCCA time period is governed by the durability of the TAL. Like in the strengthening situation, time periods for other alternatives will influence the final choice of time period for the LCCA.

This implies that the bituminous binder course is designed to be resistant to moisture and tough enough to withstand milling operation without deteriorating further due to the aggressive action of milling teeth. In addition it will not have any consequence for the durability of the underlying structure if the milling operation touches the bituminous binder course when the even profile for the renewed surface layer is provided. With the application of sufficient tack coat for the TAL, this new surface can be applied without any additional costs and with no loss of the overall intended durability of the perpetual pavement.

If – on the other hand – it is not a perpetual pavement or in case the milling has not resulted in a proper profile for TAL paving, LCC calculations must include items such as

- spot repair
- levelling layers on parts of the area
- moisture or water protecting measures to prevent the layer beneath the new TAL to be damaged by exposure to moisture/water.
In such situations LCC calculations become tricky. The results depend very much on local weighting of factors in the LCC. Even at the best level of details the input will be a sum of many values based on "engineering judgement" made at some point. This implies severe difficulty in quality assurance, and the LCCA may have difficulty in being recognised as a "true" estimate, unbiased by policy decisions or other issues. In cases of this kind, LCCA may not be relevant because general maintenance strategies on road network level - or practical considerations forced by locally needed utility works - tend to overrule such calculation concerning the pavement structure itself.

5.5.4 LCC and carbon footprint

Few solid facts are available for quantitatively assessing carbon footprints, and the level of optimization in such calculations (job site, contractor, road administration, society, national/global) may influence the outcome. However, a few qualitative statements may be made.

TAL are often highly specialised products consisting of good quality materials. This is a drawback which cannot be denied. Due to their desired functionalities (for example noise reduction) the possibility of using reclaimed asphalt (RA) does not exist. Virgin aggregate – a non-renewable resource – has to be used, and perhaps it must be hauled in over long distances to provide the necessary resistance to polishing effects or studded tires. TAL can be recycled to new asphalt materials by either downgrading (i.e. to be used in lower bituminous layers) or be recycled into a more coarse, dense graded asphalt concrete surface layer, a material type with a diminishing market share. So there are "expenses" on carbon footprint and non-renewable resources when pursuing the improved functionalities of TAL.

TAL in combination with the perpetual pavement concept in new construction can be beneficial for the total pavement carbon footprint. The increased bearing capacity of the lower layers needed when applying TAL as a surface layer can be provided by upgrading local materials (by stabilising soil or unbound materials). Another way is to increase the amount of local aggregate in bituminous base layers where the aggregate can fulfil the purpose even though it may not have sufficient strength or polishing characteristics needed in a surface layer. Using local materials will have positive impact on the carbon footprint.

Combining TAL with Warm Mix technology presumably will not influence the carbon footprint even though the mixing temperature can be lowered by 10 – 20 ºC. The mix is still operated at a temperature where water needs to be evaporated which accounts for a large part of the consumed energy. In marketing, claims by asphalt contractors have been put forward concerning a reduced carbon footprint due to the lower mixing temperature. However, no solid calculation has been offered yet, and sub-optimization is often seen when the carbon footprint of providing the Warm Mix technology or Warm Mix additive is left out of the equation. Another point is that asphalt producers may apply Warm Mix technology at normal mixing temperatures to deal with extended hauling distance or prolonged paving season – which may have two or three fold negative impact on the carbon footprint (normal or higher mixing temperatures, Warm Mix additives and longer hauling of the produced materials).

In the evaluation of the impact of new developments (like improved binders, Warm Mix technology, solutions with lower carbon footprint) it is often forgotten that there exists a delicate equilibrium between the potential gains by a certain technique and the economic cost. Developers wanting to market their potential solutions of technical or environmental issues make a very tight calculation for the price to purchase the solution. They want to "harvest" almost all the potential gain in economic terms to compensate for their development costs and to obtain earnings for shareholders. Developers are often unfamiliar with the mechanisms of the road sector and end up setting the "price" too high as they do not recognize potential obstacles – practical or bureaucratic – in the introduction of new development. A striking example is that patents in the road sector often have had an impact.
on industry only after patent rights have run out or when the patent rights had been circumvented by chance.

5.6 LCCA - TAL compared to conventional asphalt concrete

In the following example TAL is compared to a conventional, thicker surface layer. In practice, the costs and life span of TAL varies with respect to the type of TAL, traffic, climate, bearing capacity etc. In order to make a relevant comparison and explore the grounds for comparisons, a representative example is given in which the result is neutral. This means that any decision, deviating from this norm of comparison, will show an advantage for one or the other alternative. TAL is believed to show far more beneficial compared to this example during circumstances when TAL is the most suitable solution.

For the example in Table 5, the following conditions are assumed: AADT = 9000 vehicles per day, 2-lane road, 9 metres paved width, approximate life span relation of 2 conventional life spans equal to 3 TAL life spans. In this case the result is neutral (€139 /m for both). In this context, a conventional asphalt concrete is dense graded with maximum aggregate size of 16 mm. The life spans are chosen to achieve a neutral result in Table 5. In reality, given a certain prize per square meter, the need for future maintenance will differ from object to object with respect to all design parameters.

Table 5 Example of LCC for TAL compared with a standard surface layer. $dr =$ discount rate.

<table>
<thead>
<tr>
<th></th>
<th>TAL</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life expectancy [years]</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>Cost per m² [€]</td>
<td>6.7</td>
<td>9.7</td>
</tr>
<tr>
<td>Cost per m, 40 years, 3 % $dr [€]</td>
<td>178</td>
<td>183</td>
</tr>
<tr>
<td>$d:o$ 4 % [€]</td>
<td>139</td>
<td>139</td>
</tr>
<tr>
<td>$d:o$ 6 % [€]</td>
<td>94</td>
<td>92</td>
</tr>
</tbody>
</table>

This example shows that the discount rate is not an important factor when comparing two alternatives to each other. Although the present values for 3 %, 4 % and 6 % discount rates vary considerably in absolute values, the relative difference between TAL and the conventional alternative is negligible. The reason is that the difference in life spans of 8 and 11 years are not long enough to induce differences in LCC.

In this case, since the number of treatments will increase when applying TAL, the external effect to consider should be traffic delays. By the use of a tool recently developed by VTI for the Swedish Transport Administration, traffic delay costs for Swedish conditions have been calculated for the hypothetical case above. AADT of 9000 vehicles per day is purposely chosen since it is a traffic flow when queues develop for normal 2-lane roads when one lane is closed. If stop guards and 500 meters closure are used, only additional time costs of €0.20 per m² becomes the result. However, less effective signals means €4.5 per m² (still 500 m closure) and if guards and 1500 m closure is used, this results in delay costs of €6.0 per m². The results above assume that the maintenance works are done during daytime, that TAL and conventional surface layers are applied at the same pace, and that no redirection of traffic is possible and only one lane is open to traffic. Hence, traffic delay costs should be considered in cases when queues are building up during maintenance works. Night time operations or long life alternatives could be evaluated to mitigate these delay costs.
5.7 Examples of monetary evaluations

Some examples are presented in Table 6 based on a Swedish model for noise cost calculations [STA, 2009]. At present the model is difficult to apply for other countries.

Note: These calculations are valid for countries using studded tyres, since the expected life time for all surface layers in the example is short.

The common conditions for these examples are:
- 2+2 lane Highway, 14 m width of surface course
- AADT 20,000 vehicles per day
- 70 km/h
- 100 private homes, equally distributed on both sides of the road. First row at 10 m from roadside, second row at 30 m from the roadside.
- Reference alternative is Swedish SMA 0/16 (ABS 16) - life span 11 years, €9.7 per m²
- Alternative 1 TAL with 8 mm NMAS - life span 8 years, €6.7 per m²
- Alternative 2 TAL with 6 mm NMAS - life span 6 years, €5.6 per m²

Table 6 Examples of investment cost and noise cost according to [STA, 2009] in selected situations, see text.

<table>
<thead>
<tr>
<th>Example</th>
<th>Length [m]</th>
<th>Investment cost, difference [€]</th>
<th>Noise cost, difference [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-19 % Heavy traffic = Minus one dB relative to SMA 16, Alternative 1</td>
<td>1 000</td>
<td>-12 000</td>
<td>-400 000</td>
</tr>
<tr>
<td>0-5 % Heavy traffic = Minus two dB relative to SMA 16, Alternative 1</td>
<td>1 000</td>
<td>-12 000</td>
<td>-720 000</td>
</tr>
<tr>
<td>6-19 % Heavy traffic = Minus two dB relative to SMA 16, Alternative 2</td>
<td>1 000</td>
<td>-4 400</td>
<td>-720 000</td>
</tr>
</tbody>
</table>

The examples are constructed as being fairly neutral in investment cost while different in noise cost. Since investment costs are neutral, the length of the pavement with lower noise is of less importance. Otherwise this becomes a crucial parameter when maximising utility for certain locations. Given the fairly moderate number of houses and noise reductions, the resulting lower external costs are significant.

As already mentioned, life cycle considerations are tainted with many sources of uncertainty. Discount rate effects are of minor importance to TAL (insensitive), as shown earlier. This is important to state since analysis is greatly simplified by not needing to discount but being able to use present values throughout, and annual costs (cost divided by interval in years) can be used as an approximate indicator. Uncertainties can be characterized as related to:
- Design parameters such as climate, traffic, damage history and bearing capacity
- Mix design, production and paving
- Future evolution or outcome of the above design parameters during calculation period
- Resulting performance indicators and external effects during calculation period
- Evaluations of external effects during calculation period.

Furthermore, uncertainties in the conditions for analysis, such as the length of calculation periods, add to the sensitivity of life cycle analysis results. These uncertainties apply for both economic considerations (LCCA) and environmental impact considerations (LCA). Even though monetary evaluations of external effects and environmental impact assessment are fundamentally different, the inventory part and purpose show similarities.

The above example on noise demonstrates uncertainties and the application of sensitivity analysis. Impacts of noise originate from annoyance and health effects (sleep disturbance and stress). Evaluation of noise will likely change as new evidence reveals the extent of impacts from noise. Doubling or halving costs of noise will have an immediate and proportionate influence on the costs of different alternatives. The monetary evaluations in different European countries varied substantially in 2002, almost one magnitude [HEATCO, 2004], see further Table 7. This variation mainly reflects the price levels but indicates the dynamic nature of the evaluation of noise. Noise is also dependent on the deterioration of the road surface due to combined effects of traffic, climate, durability etc. over life cycles.

Climate is showing both great annual variations and uncertainties over the long term changes. Durability problems due to poor production will always be present, substantially shortening maintenance intervals, even though mitigated by increased knowledge and control measures. Altogether, the uncertainties will lead to substantial differences in the rate of success for individual objects, while analysis on strategic levels will be possible to perform if data are captured systematically. A last general observation is that alternatives with longer pay-back period (large investments expected to last longer) are sensitive to all these combined effects, since the likelihood of, for example, extreme weather occurring during the period is higher and the likelihood of production problems is equal or even increased.

Table 7  Examples of costs for road noise exposure for day-evening-night indicator $L_{DEN}$ (€ per year per exposed person, 2002) [HEATCO, 2004].

<table>
<thead>
<tr>
<th>$L_{DEN}$ [dB]</th>
<th>Estonia</th>
<th>Italy</th>
<th>Switzerland</th>
<th>UK</th>
</tr>
</thead>
<tbody>
<tr>
<td>51-52</td>
<td>2</td>
<td>8</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>65-66</td>
<td>31</td>
<td>126</td>
<td>227</td>
<td>160</td>
</tr>
<tr>
<td>&gt;81</td>
<td>89</td>
<td>363</td>
<td>655</td>
<td>462</td>
</tr>
</tbody>
</table>
6 OPTIMIZATION OF TAL

This chapter deals with optimization aspects and important know-how for successful application of TAL. The intention has been to look in depth at opportunities for further optimizing thin asphalt layers, based on the knowledge gained by drafting the State-of-the-Art report [Sandberg et al., 2010].

Optimization of TAL can be carried out on several levels, including on one hand optimizing the TAL as a part of an entire system and on the other hand optimizing the TAL itself during all stages of use. The first level enables the establishment of check points where the quality of products and processes are controlled; the latter describes detailed knowledge with respect to the design, the production, the performance (testing) and specifications of TAL. Attention is paid to durability issues while meeting the criteria set out with respect to the functional properties of TAL.

The main aim of this chapter is to identify opportunities for further improving the design and the application of TAL. However, disadvantages or limitations (risk assessment) associated with the application of TAL are also dealt with. Input from laboratory testing and from field experience has been utilised to identify remaining knowledge gaps and needs for future research and to provide recommendations in Section 7.5 for follow-up work after the completion of the project.

TAL optimization is explored while dealing with separate stages of TAL application ranging from mix design to its application in the field.

6.1 Mix design

TAL mix design is explored in the following, directly related to the choice of materials: aggregate, binder, additives, use of asphalt rubber, etc. or to the mix design methodology itself. The latter item not only includes the possible impact of grading (e.g. in relationship to the resistance to studded tyres) but also the use of software.

6.1.1 Choice of aggregate

This section describes the importance of high quality aggregates, in particular aggregate with high resistance to surface abrasion, wear (micro-Deval coefficient), fragmentation (Los Angeles coefficient), polishing (polished stone value, PSV) and the resistance to studded tyres (Prall EN 12697-16).

As for all wearing courses, it is important to use high quality aggregates, with a high resistance to:

- fragmentation (Los Angeles coefficient, EN 1097-2)
- wear (micro-Deval coefficient, EN 1097-1)
- polishing (polished stone value or PSV, EN1097-8).

For countries in which studded tyres are used, the resistance to wear by abrasion from studded tyres (EN 1097-9, the Nordic test) is also an important requirement. These characteristics of the aggregate will determine the durability of the surface texture, skid resistance and noise reduction.
The choice of the aggregate shall also consider binder-aggregate affinity, which can be verified using one of the tests from EN 12697-11, Determination of the compatibility between aggregate and bitumen. Good adhesion between aggregate and binder prevents ravelling and therefore also improves the durability. Binder-aggregate adhesion can be evaluated using the boiling test.

Particularly important for the mix design of TAL, the grading and the shape of the aggregates shall be as constant as possible. Changes in grading and aggregate shape have an impact on the volumetric composition, and consequently also on the cohesion and the stability of the skeleton, which is usually a stony skeleton.

The aforementioned demands on quality and constancy of the aggregates set limitations on the use of reclaimed asphalt in TAL.

6.1.2 Choice of binder

Quite often the preferred choice of binder is a polymer modified bitumen or PmB [CROW, 2007]. Especially for TAL, a PmB offers important advantages as compared to unmodified bitumen with respect to resistance to ravelling, binder drainage and durability. Nevertheless, under certain traffic conditions TAL can perform adequately in a cost-efficient way by using a standard grade binder. Also the possible use of asphalt rubber can be considered.

In Austria, the use of PmB is compulsory in order to improve both the adhesive and cohesive properties of the mix [Litzka et al, 1994]. In France, the application of PmB also increased since it allows for an even more discontinuous mix design (less sand and higher bitumen content) [Brosseaud et al, 1997].

Polymer modified bitumen in accordance with product standard EN 14023 is one way of achieving an enhanced binder but for low polymer content binder the effect can be obtained by another route – through polymer modified asphalt (PmA) which in some countries is described as “in situ” blending of polymer modified binder. The production of PmA is a very cost-efficient process as no additional storage tank for polymer modified binder is needed. This lowers the investment at the asphalt plant. It also provides a very neat way of modifying the binder when needed. An example can be that when a paving operation is getting closer to a traffic light, the conventional bitumen is doped by adding polymer directly into the mixer until the paving operation has passed the traffic light area where increased rut resistance might be needed. A drawback of this technique is that it is not possible to test the modified binder before application, and extraction of the binder from the mix might not represent the state the binder has in the asphalt. Due to the very versatile technique it is gaining an increasing part of the modified binder market. In Denmark roughly 95 % of all polymer containing pavements are produced by “in situ” blending.

Generally, for roads with less traffic, an unmodified bitumen is used varying from a 35/50 over a 50/70 to a 70/100 penetration grade binder [Brosseaud et al, 1997]. Depending on the traffic level even softer bitumen can be used. Soft asphalt with bitumen in the hard end of the range specified in EN 13108-4 (e.g. 250/330) are also versatile in TAL for low volume roads.

6.1.3 Grading

For TAL mixes based on a stony skeleton (e.g. SMA or RUMG) the grading curve is rather critical. There is little margin for changes, and a need to keep it as constant as possible. If not, durability aspects may be hampered. This implies a need for quality control of the aggregate and is related to the fact that recycling TAL implies downgrading material and that the use of RA in TAL is highly unlikely.
In the Netherlands [CROW, 2007], France [Setra, 1997 and Brosseauad et al, 1997], the U.K., the U.S. [Bahia et al, 2007], Germany [Graetz, 1998] and Austria [Litzka et al, 1994] TAL mixes are characterized by a very high aggregate content and a discontinuity in the grading curve (stony skeleton).

However, the grading envelope that contains the variety of grading curves used for TAL in practice is still quite broad. This is reflected by the wide overall limits for the grading that are given in EN 13108-2 (AC for very thin layers). To illustrate this, Figure 6 shows these limits for the two possible ranges in case of D = 6.3 mm (6A and 6B), plotted on a graph with two typical TAL mixes used in Belgian practice: an SMA 0/6.3 (for layers of 25 to 30 mm) and a RUMG (revêtement ultra-mince grenu, for layers of 15 mm). The SMA grading satisfies the limits of 6A, while the more open RUMG satisfies the limits of 6B.

Figure 7 shows grading curves typical for Nordic countries using studded tyres, specified in [NPRA, 2009].

![Figure 6: Overall grading limits for two typical very thin layer asphalt layer mixes from Belgian practice, (from EN 13108-2).](image-url)
Figure 7  Grading curves for typical Norwegian TAL mixes.

The fact that the limits on the grading curves are so wide is in line with the idea that the specifications should be more performance related. But this doesn’t mean that the grading curve is not important. Once a mix has been designed with a given grading curve and the performance of this mix has been demonstrated, there is little margin for variations, and a need to keep the grading as constant as possible, because mixes with a stony skeleton are very sensitive to this. Changes in grading could disrupt the stony skeleton and lead to a loss of stability or a loss of cohesion. This implies a need for quality control of the aggregate and is related to the fact that recycling TAL implies downgrading material and that the use of RA in TAL is not recommended.

Only in South Africa [Sabita, 2008] mixes with a sandy skeleton are recommended for TAL. The reason is that they aim at roads with low volume traffic. The focus therefore is on workability, resistance to fatigue and durability, rather than on noise reduction, skid resistance or resistance to rutting.

6.1.4 Mix design methodology

An overview of the mix design methodology for TAL used in different European countries is given here, with particular priority on French experience. Advantages and disadvantages of various approaches are highlighted with respect to the functional properties of TAL and to durability issues (related to performance testing and specifications, see below).

Note 1: Large differences exist between ERA-NET countries concerning their methodology to obtain a mix design. Some depend largely on laboratory type testing while others have confidence in type testing by running quality control. To change such systems has huge impact on contractual relations.

Note 2: During work on the topics mentioned in Section 6.2, attention has been paid on improving TAL durability. In some cases, having in mind the functional properties of TAL described in the State-of-the-Art report [Sandberg et al., 2010], this may result in conflicts (e.g. between noise reduction and durability). The current optimization of TAL should be able to define where the optimum or best compromise lies. Moreover, one should focus on sustainability (including recycling, impact of skid resistance on air pollution) issues and on economic considerations when using TAL (related to LCC).
In France the mix design for BBTM (Beton Bitumineux Très Mince) is based on:
- A gyratory compaction test (in order to discriminate between classes 1 and 2)
- Water sensitivity of the mix (Duriez compression test)
- Resistance to rutting including the evolution of the macro texture.

Based on the results of the gyratory compaction, test mixes are separated into two classes as defined in NF EN 13108-2. Class 1 corresponds to mixes characterized by a void content (following 25 gyrations) of 12 – 19 % for a BBTM 0/6 or of 10 – 17 % in case of a BBTM 0/10. Class 2 mixes correspond to a void content (following 25 gyrations) of 20 – 25 % for a BBTM 0/6, or of 18 – 25 % in case of a BBTM 0/10. Mixes meeting the criteria of class 1 are most commonly used. Class 2 mixes, which are very similar to thin porous asphalt mixes, are less used.

For the determination of the minimum binder content, the French did specify in the past a minimum value for the ‘module de richesse’ of 3.5 according to NF P 98-137. Nowadays, a minimum binder content of 5 % is specified according to EN 13108-2.

In France, one recognizes that gyratory compaction of BBTM is more an indicator for surface texture than for the void content [Delorme, 1993]. Indeed for TAL, void content is less meaningful as compared to thicker asphalt layers due to border effects and its open texture. Also, the measurement of the void content of road samples of TAL is difficult, and large differences occur between void contents determined either by geometry or by hydrostatic weighing.

In case of BBTM, the rutting test is done not only to evaluate the rutting resistance, but rather for the evolution of the surface texture as a function of the number of wheel passes.

In France, there is no specific mix design for BBUM or ‘Beton Bitumineux Ultra Mince’. The mix composition is normally derived from BBTM formulations with minor modifications. The latter includes the decrease of the sand fraction by 5 to 15 % and a small decrease of both the filler as well as the binder content [Brosseaud et al, 1997]. In this way, the surface texture is increased and the water drainage is further optimized [Brosseaud et al., 1996]. Generally, one makes less use of the 0/14 fraction in order to minimize the risk of ravelling. PmBs are recommended for roads with heavy traffic.

In Austria, the mix design of TAL starts with a fixed discontinuous grading curve while the optimal binder content is determined based on void content and Marshall stability [Litzka et al, 1994].

Sridhar and co-workers reported on the mix design of Open Graded Friction Courses (OGFC) [Sridhar et al, 2005]. OGFC are quite similar to a thin porous asphalt layer or a BBTM of class 2 in France. The binder content is optimized based on the test results of the Schellenberg drainage test, the Cantabro test and a permeability test. One considers OGFC as thin layers, although a specific layer thickness is not stated.

In an American report the mix design of an ultra-thin bonded hot mix asphalt wearing course is described [Hanson, 2001]. The Superpave gyratory compactor is used in order to optimize the binder content for a given grading (void content of 10 % at 100 gyrations). Following this optimisation step, the water sensitivity of the mix and the possible binder drainage are checked.

A very detailed mix design procedure for ultra-thin hot mixes is described by the Texas Department of Transportation [Tex-247-F, 2008]. It starts from combining the aggregates to obtain a grading curve within an envelope (also rather wide). The optimum binder content is then determined on the basis of a required film thickness (similar to the idea of the French
“module de richesse”). Finally, a number of performance related tests (binder drainage, water sensitivity and durability) are made.

Sabita guidelines suggest that one should be careful with the results of a TAL mix design performed in the laboratory [Sabita, 2008], since larges discrepancies can occur between samples compacted in the laboratory and samples derived from road works due to:

- The very quick cooling of TAL during paving and compaction operations on the road
- The occurrence of border effects, especially with larger size aggregates.

Consequently, the Sabita guideline suggests using only TAL mixes for which the field performance has been successfully validated.

To summarize, although there is at present not a common mix methodology for TAL (but this can also be said for bituminous mixes in general), some general trends are seen in the mix design of TAL:

- The grading curve is mostly discontinuous (to ensure a stony skeleton). The few exceptions encountered are meant for low volume roads for which noise reduction is not an issue. The limits on the grading curve are rather wide, probably because there is no strong link between the exact grading curve and the mix performance
- The binder content also varies from mix type to mix type. Mixes with high filler content usually contain more binder. The binder content can be determined as a function of the film thickness of the bituminous mortar needed to ensure sufficient aggregate coating. Mix design methodology used in France and by Texas DOT
- Void content is only considered in mix design as a way to classify mixtures, not in relation to the void content expected on the road
- There is a strong emphasis on performance related testing as a way of validating the mix design. The use of performance testing for optimizing TAL, as part of the mix design procedure, is addressed in section 6.4.

6.2 Production

Utilization or increasing the potential operating range of TAL can be achieved by applying new techniques (like Warm Mix Technology) in the production process at the asphalt plant. On the other hand the delicate balancing of fractions and the introduction of even specially manufactured fractions of aggregates for the production of noise reducing TAL calls for even better understanding and optimization of the materials flow through the plant from the feeding bins to loading the asphalt on the lorries from the hot storage bins. This section of the report discusses such aspects having general impact on asphalt production but providing important contributions to TAL.

6.2.1 Warm mix asphalt technology

The asphalt paving industry is constantly exploring new technologies to improve on materials performance, to increase the construction efficiency, to conserve resources and to reduce its environmental impact. Current and future legislation or regulations on both emissions and energy conservation are making the reduction in temperature at which asphalt mixes are produced and compacted very attractive (increased workability). Consequently, warm mix
asphalt (WMA) has gained a genuine momentum across Europe as well as the U.S. While using WMA technology, asphalt is produced at temperatures slightly above 100 °C with properties or performance equivalent to that of conventional HMA. A typical WMA is applied at a temperature around 20 – 40 °C lower than HMA (see Figure 8).

Several organic additives can be used to lower the viscosity of the binder at temperature above 90 °C. The nature of the additive must be selected carefully so that its melting point is higher than the expected maximum in service temperature in order to avoid any risk for permanent deformation and to minimize embrittlement of the asphalt mix at low temperatures. Typical examples include waxes or fatty amides by which a temperature reduction of 20 – 40 °C can be obtained.

Chemical additives do not change the viscosity of the binder but as surfactants they are active at the interface of the aggregate and the binder. They reduce the frictional forces at a wide range of temperatures and therefore allow the production and subsequent compaction of asphalt mixes at lower temperatures (typically 20 – 40 °C lower in comparison with HMA).

Foaming techniques employ the controlled introduction of small amounts of water into the hot binder. Since the water is turned into steam, its volume is largely increased and therefore its viscosity is also reduced for a short period of time, allowing the production of asphalt mix at lower temperatures (as low as 90 °C). Two major techniques are used for foaming: the injection by foaming nozzles or the addition of mineral compounds such as zeolites.

In the literature a large number of WMA techniques are described which have been developed since the mid 1990’s including [Prowell et al., 2007; D’Angelo et al., 2008]. The most common techniques include organic or chemical additives and foaming techniques [EAPA, 2010].
The immediate benefit of lower temperatures is the obvious reduction in energy consumption and therefore greenhouse gas emissions (CO₂, NOₓ, SO₂, VOC,…), in fumes and dust emissions and in odours generated at both the asphalt production plant and during paving operations. But in spite of the immediate benefit of Warm Mix technology the added impact on energy consumption and greenhouse gas emission providing the applied technology is often forgotten in the “environmental marketing”. If the WMA is produced at normal Hot Mix Asphalt temperatures the impact on these factors are negative even though this application of the technique gives other potential benefits (larger operation range or larger time window to achieve necessary compaction).

Beside the environmental benefits the use of WMA offers several other important advantages, not only for the asphalt mixtures themselves but also for the paving operations. Lower asphalt temperatures result in less ageing/hardening of the bitumen during production. It will also lower the amount of dust extraction because the aggregate is heated at a lower temperature. The improved handling properties of WMA create a more comfortable working environment for the asphalt workers and the public near the work sites.

Moreover, the increased workability of WMA offers benefits or new opportunities with respect to the paving operations:

- WMA can be compacted at a lower temperature than conventional HMA for an equivalent degree of compaction
- WMA can be used in deep patches where the site is restricted
- WMA possibly enables the introduction of higher percentages of RA in new asphalt mixes due to the increased workability at normal HMA temperature, especially if the RA is similar to the new TAL.

Taking into account the lesser thickness of TAL applications and the subsequent potential faster cooling of the material prior to attaining the required density or whenever temperature conditions are unfavourable, makes TAL a promising match with WMA technology. It allows for minimising risks with respect to TAL performance in the field or even provides an edge in extending the window for compaction. Consequently, cold weather paving applications have been suggested as a possible extension for WMA applicability [Kuennen, 2010].

The advantages of WMA cited above have recently been illustrated by a 2009 TRB paper [Mogawer et al., 2009] where high percentages of RA and WMA technology were combined into thin hot mix asphalt overlays to be utilized as a pavement preservation strategy. Moreover, cold weather paving of a 25 mm surface layer while using WMA techniques in Ottawa, Canada was reported recently [Manolis et al., 2008]. The application of WMA ultra-thin pavement in China in 2009 at cold air temperature has also been described [Tao et al., 2009].

Despite the high expectations and the recent applications in the field of WMA with respect to TAL no reported field trials or experiments inside Europe could be retrieved at present from the literature. However, it is clear that the application of WMA technology in the case of TAL will further contribute to both the sustainability as well as the durability of TAL applications in the future across Europe as well. Therefore, WMA technology is considered to constitute an integral part of the optimisation of TAL.
Possibly, there may also be some risks in transferring WMA technology to TAL. The effect of many additives on binder coating, binder/aggregate adhesion and especially low temperature behaviour (thermal cracking) needs to be investigated more thoroughly. If there should be a negative effect, this would be especially critical for TAL, more than for other types of layers, because the sensitivity to ravelling is already important.

6.2.2 Fine tuning asphalt plant operation

Asphalt production associated with TAL by and large can be seen as any other asphalt production, but there are some instances where special optimisation of the processes at the production site and in the plant is required. As TAL normally are linked to asphalt materials with a relatively small NMAS (Nominal Maximum Aggregate Size) asphalt producers must be capable of handling a limited number of fractions of aggregate and yet achieve the desired gradation. The amount of fines (fillers and sand – either natural sand or crushed rock) need be controlled efficiently in order to avoid variation in the bituminous mortar part which eventually can show up as fat spots in the surface after paving.

A special problem is associated with noise reducing TAL. Here the surface texture is often obtained by a minute control of aggregates in special produced fractions, which normally is not needed for the bulk asphalt concretes for thicker lifts. Sometimes the required surface texture is the result of mixing special fractions or adding one fraction of a different aggregate source than the main bulk of material. The reason is that selected crushing of mineral type – within certain limits – can produce more or less cubical particle. This will enable the asphalt producer in his mix design to obtain different volumetric configuration and eventually different surface textures which in the end will optimize the noise characteristics of the pavement.

If the asphalt producer cannot purchase the desired special fractions directly at the aggregate supplier, he has to produce them himself by adding a special screening operation as pre-processing prior to the materials entering the asphalt plant. This implies additional cost, equipment and space. In order to have a cost efficient operation, the screened off material must also be utilized as the aggregate presumably originates from a premium source for surface layers (strength, polishing resistance etc.).

In asphalt batch plants – especially on sites operating in a market with frequent mix changes in production to satisfy various customer needs – the interaction between fraction sizes going into the plant and sieves sizes of the screens in the tower above the mixer is important. Here there is a need for optimizing the operation. In many asphalt plants you can bypass the screens and depend on the accuracy of the feed bins by introducing dried aggregate directly into the mixer. If you do not have confidence in this type of control you must introduce rinse-out operations between the individual mixes in order to have appropriate control of the delicate mixes. Such rinse-out operations imply that already heated and dried material will go to the recycling stock pile for later reuse. This creates a challenge in optimizing cost and fuel economy and in maintaining a high asphalt plant capacity.

6.3 Paving operations

In Section 5.5 some aspects of the preparation of the foundation for a paving operation is mentioned in general terms as preconditions for TAL. In this paragraph some practical aspects of the paving operations for TAL are highlighted.
6.3.1 GPS guidance system

The base for TAL needs to have a proper profile (both transversally and longitudinally) and in case of a resurfacing job the old surface layer will often be removed by milling. Milling machines can be run on GPS which will be helpful to obtain the required profile. GPS has been used with success for levelling unbound base layers but here the precision in the vertical direction matches the tolerances in the layers, and in the following bituminous layers any inaccuracy can be compensated for. It is possible to use GPS controlled milling operations, but here the precision in the vertical direction can be an obstacle unless a local fix point is available.

Another problem which you often face in a milling operation in spite of GPS levelling control is variation in the material you mill. Even though you can hit the right level it is very likely that you in some spots will have deterioration in the layer beneath – either by slip in an old tack coat layer or by crumbling material due to moisture induced damage. In an optimized paving operation you must be prepared to do some spot repair or even to introduce replacement of the layer beneath (perhaps several square meters) because the defects were not found during the preparatory investigation of the pavement before milling and resurfacing.

GPS can be a part of the documentation of the subsequent compaction operation where the term “intelligent compaction” is now presently being used. The documentation shows which lanes and how many roller passes have been used, so the impact of vertical precision does not matter that much. “Intelligent compaction is sometimes used for (thicker layers of) unbound materials while the compaction of TAL cannot be controlled this way.

6.3.2 Thermography

Correct compaction of hot mix asphalt is decisive for the pavement quality. The compaction process or mechanisms are highly dependent on the workability of the mix and on the compaction equipment.

One of the most important workability parameters is the temperature of the hot mix asphalt during the compaction process. If the temperature is too high the mix is too workable for correct compaction and if the temperature of the mix is too low the mix is too stiff for correct compaction. After laying the asphalt mix will cool down. The rate of cooling depends on mix and air temperature, wind speed and the mix layer thickness. If the rate of cooling is high the time available for compaction is short. That means that the control of the temperature during laying and compaction of hot mix asphalt is important, in particular for TAL.

The temperature of the hot mix asphalt during laying and compaction is easily controlled by infrared thermography using an infrared camera to measure the surface temperature and to locate areas with deviating temperature. Taking such photos at regular intervals (e.g. 25 or 50 metres) contributes to ensure the TAL quality during construction. This technique is also useful for checking asphalt temperature during transport, laying and compaction. The temperature of the hot mix asphalt during compaction can be monitored when rollers equipped with infrared temperature sensors enable drivers to read the surface temperature off the dashboard. Simpler and much cheaper - but without obtaining detailed thermograph information – is to sample surface temperature using an infrared thermometer.
6.3.3 Paver equipment

UTLAC (Ultra-Thin Layer Asphalt Concrete) is one of the important material types in TAL. Asphalt contractors need to recognise that a special paver is needed for laying this material. The paver must be fitted with spray bars that allow for spraying a thick amount of polymer modified emulsion - also where the traction device of the paver is travelling – prior to placing the loose asphalt material before the tamping knife and the levelling screen. This paver must be purchased or in some cases an existing paver can be refitted with emulsion tanks and spray bars. Such equipment cannot heat pure hot bitumen to a sufficiently high temperature to allow it to be sprayed. The paving crews need to acquire skill for using this type of paver because the quality of the produced pavement depends very much on the interaction between the control of the type and amount of emulsion and on the driving speed of the paver.

In new construction or when an additional strengthening layer is needed, the asphalt contractor has the possibility of using a double layer paver (or compact paver) which paves two materials hot-in-hot. This technique has the potential of minimizing the risk of premature cooling of the surface layer before the necessary compaction level has been achieved. It is an intriguing technique but the equipment will not be generally available due to cost/investment in the equipment, the pay-back time and the logistic nightmare of running synchronously two or three asphalt plants [Krempel, 2010].

6.3.4 Logistics of the paving operation

Having good logistics around the paving operation is often the key to success. When paving TAL it is a vital element. Due to the small thicknesses of TAL the speed of the paver can be higher than usual, and that requires special attention – perhaps best highlighted by a paving operation with normal traffic passing the site.

The smaller thickness of TAL means lower heat content and due to this fact extra care shall be taken concerning associated issues. In order to optimize smooth delivery of materials, avoid unintended paver stops, and to obtain better preservation of the heat content of the materials delivered to the site it can be advantageous to use a shuttle buggy. This device can act as a buffer in the unloading process and normally its thermal insulation is better than that of the delivery part of a standard paver. With long distance from asphalt plant to paving site or with traffic congestion/traffic management on the route involving high risk of disturbing smooth delivery logistics, a shuttle buggy can be a good investment to lower the risk for sub-optimum paving operation.
Figure 9  Thermography using an infrared camera shows the asphalt surface temperature during laying.
The low heat content of the material necessitates having sufficient amount of various types of rollers available. Warm Mix technology – used in a non-energy preserving manner – has the potential described earlier to improve the compaction and through this achieve better durability. The long term durability associated with such use of Warm Mix still lacks documentation, but expectations are positive.

TAL is also becoming a candidate for high traffic corridors in the congested Europe. For this reason many paving operations are required to be performed at night or at least outside day and rush hours which as an example in Denmark can be from 18:00 to 06:00 hours. This time window of course also includes the period needed for setting up and removing traffic signs and temporary barriers. This puts even more stringent demands on the managing of the logistic. When night time operation is required, it will normally be associated with a higher risk of cooling the layer before ensuring the necessary compaction level. Here Warm Mix may offer an extra benefit. Not by lowering the initial energy consumption, but using the technology at normal hot mix temperatures will allow a longer time window for the paving operation and reduce the risk of logistic problems resulting in poorer quality of the work. At present there are limited knowledge on WMA used in this manner and the impact on the durability of the pavement. As a rule of thumb the Danish expectancy of impact of paving at night is a two years reduction in durability of the surface layer (like 13 years instead of 15 years expected).

6.4 Performance testing and specifications

6.4.1 General

Laboratory testing of asphalt mixtures in general and TAL in particular is performed at the start of any project and could be considered an integral part of the mix design process. Laboratory testing enables validation of the mix design and provides feedback to change the original design if needed, and therefore to further optimizing the mix in terms of its envisioned performance (functional properties) and durability.

Field testing may be performed immediately after the construction to check the quality of the work of the contractor or after some time in order to monitor the state of the road.

Assessing TAL performance (including durability) is often related to CE-marking (see SoA report § 3.2 on terminology and standards), to certification criteria (e.g. HAPAS in the U.K.) or to meeting tender specifications. The latter frameworks already set out a series of both empirical and performance related test methods.

Additionally to existing test methods the development of new performance tests (e.g. bonding to base layer - performance of the tack coat) is discussed, and, finally, an overview is given for some European countries with respect to the specifications set out for TAL.

6.4.2 Laboratory testing

Normally, such an exercise can also be considered part of the mix design. The assessment of the performance (including durability) is related to either CE-marking or meeting tender specifications (or certification criteria). The development of new performance tests (e.g. bonding to base layer - performance of the tack coat) will be discussed.
Resistance to rutting

In general, very little attention is paid in the literature to the rutting resistance of TAL as probed by the wheel tracking test (EN 12697-22). Especially in the case of a stony skeleton, the high internal friction in combination with an elevated void content, provide a satisfactory resistance to rutting [CROW, 2007; Serfass, 1995; Laurent, 2006]. Tests carried out while using the accelerated loading facilities at LCPC in Nantes did confirm the low risk for rutting if the base layer is well performing [Brosseau, 1996; Vivier, 1990]. It is generally accepted that the use of PmB further minimizes the risk [Sybilski, 1996] (see also mix design: choice of binder).

It is obvious that rutting can still occur in the case of asphalt concrete characterized by a sandy skeleton where the void content is too low taking into account that a surface layer is exposed to the highest temperatures [Judycki, 2003] or the thickness of the TAL compared to the NMAS of the mix is unfavourable (too high). In this context, one proposes in the Netherlands to use voids filled with bitumen and the ratio void content/voids filled with bitumen as an indicator for the risk assessment with respect to the rutting resistance of TAL characterized by a stony skeleton (e.g. SMA 6.3) [CROW, 2007].

Testing the rutting resistance by a cyclic compression test according to EN 12697-25 is not straightforward since the required specimen height exceeds the nominal layer thickness of TAL in the field. Therefore, one has serious doubts about the predictive value of the test result in the case of TAL [CROW, 2007]. But the test can be used for relative comparisons when the same mix design from gradation point of view is tested against a suite of bituminous binders providing varying degree of rut resistance potential.

Water sensitivity

In the literature the results of three different methodologies for measuring the water sensitivity of TAL according to European standards are discussed including:

- EN 12697-12 part A in combination with EN 12697-23: measurement of the indirect tensile strength of cylindrical specimens of bituminous mixtures before and after water conditioning (72 hours at 40 °C)
- EN 12697-12 part B: measurement of the compression strength (Duriez test) of cylindrical specimens before and after conditioning (7 days at 18 °C)
- EN 12697-26 part C: measurement of the stiffness modulus of cylindrical specimens before and after water conditioning or retained stiffness (6 hours at 60 °C followed by 16 hours at 5 °C).

The first method is widely used throughout Europe although several approaches with respect to sample preparation may occur (e.g. compaction energy). This phenomenon unfortunately hampers the comparison of test results. Another problem which has been highlighted in the recent study conducted in the Netherlands and which is typical for TAL consists of the fact that the required sample dimensions for carrying out the indirect tensile test exceeds (minimum 35 mm required) the layer thickness of TAL in the field [CROW, 2007]. Consequently, attention should be paid to the validation of test results.

The Duriez test which has been integrated in the latest version of EN 12697-12 (November 2008) is only used in France (based on the old French standard NF P 98-251-1). The dimensions of the test specimens deviate largely from field applications in the case of TAL.
The measurement of the retained stiffness modulus is taken up as an indicator for the water sensitivity of thin and ultra-thin asphalt mixes in the HAPAS certification system in the U.K. The reader is referred to the HAPAS guideline document (Appendix A.2) for further details of the test protocol. Moreover, since field validation is still lacking, no specifications are set based on test results obtained in the laboratory while using this test method.

In addition to the above test methods the rolling bottle test according to EN 12697-11 part A has been proposed as a possible indicator for the resistance to ravelling and therefore indirectly to the water sensitivity of a TAL [CROW, 2007]. The rolling bottle test allows probing for the affinity or adhesion between an aggregate and bitumen. Therefore, one should be careful while drawing conclusions from test results with respect to the performance of the entire asphalt mix.

**Low temperature cracking**

The evaluation of the resistance of thin asphalt wearing courses to low temperature cracking can be carried out while using one of the methodologies described in prEN 12697-46 “Bituminous mixtures – Test methods for hot mix asphalt – Part 46: Low temperature Cracking and Properties by Uniaxial Tension Tests”.

Since the above described test methods are quite new, very little experience is currently available in the literature. Moreover, low temperature properties of surface courses in general are not included within a priority list of performance testing for a large part of the European countries due to climatic conditions.

**Cohesion – resistance to wear**

TAL characterized by a low void content usually show good to excellent resistance to wear by traffic, as long as the bonding with the adjacent underlying layer is assured, and therefore no delamination occurs (see discussion on tack coats). Typical examples include asphalt concrete or SMA.

However, TAL as designed according to EN 13108-2, or porous asphalt mixes, are very much prone to wear by traffic due to their high void content and therefore open structure. It is generally recognized that these types of asphalt mixes are not suitable for paving at locations such as intersections, roundabouts, and locations with turning movements (e.g. parking lots, bus stops, etc.), sharp curves or other adverse geometric sections. In latter cases, surface damage can occur quickly due to the high tangential forces that may take place. Such forces cause the loss of aggregates at the surface resulting in ravelling. It should be noted however that ravelling is a complex phenomenon and other parameters such as for example the ageing of the binder, the stripping of the binder from the aggregate (loss of adhesion) or the exposure to low temperatures during winter may contribute as well.

Finally, too high tangential forces may even cause the displacement of asphalt material at the surface, especially at sections with slowing traffic.

Several test methods, some of them still under development and undergoing field validation, reflect the importance of the impact of traffic on TAL. Illustrative in this context are:

- The Cantabro test described in EN 12697-17 used to evaluate the cohesive strength of porous asphalt [VBW, 2004] or Open Graded Friction Courses [Sridhar et al, 2005]
- The tribometer or T2R developed at LCPC in France [Hammoun et al, 2008], see Figure 10
- The Rotating Surface Abrasion Test or RSAT designed by Heijmans in the Netherlands [Hartjes et al, 2008], see Figure 10
- The Aachener Rafeling Tester (ARTe) developed by the ‘Institut für Strassenwesen – RWTH’ in Aachen [Schulze et al, 2008], see Figure 11.

At present the CEN TC227/WG1/TG2 task group on test methods for bituminous mixtures is collecting all possible experience and/or available test results with respect to performance.

![Figure 10: Rotating Surface Abrasion Test (RSAT) (left); Tribometer (T2R) (right).](image)

![Figure 11: Aachener Rafeling Tester (ARTe).](image)

Obviously, the objective of this campaign is to develop further the performance related testing and specification framework in the near future.

**Adhesion/bonding with base layer or substrate**

The testing principle and specific test methods described in the following paragraphs may be used for assessing the bond strength. For very thin TAL some adaptation of the techniques may have to be applied.
**Torque test method**

The protocol of the torque test method is described in the annex D of the ETAG guideline for the European technical approval of UTLAC. The test method allows for determining the bond strength between a thin surfacing system (such as TAL) and its substrate, which may be bituminous or cementitious, by measuring the peak shearing torque at a known temperature (usually at 20 °C). The test shall only be carried out on thin surfacing systems which have been installed for a period between 28 and 56 days.

An important advantage of the test method is the opportunity to carry out both in the laboratory while using cores as well as on site. Therefore, the test allows probing for the risk of delamination of TAL following road works. Delamination of TAL is a frequently occurring failure mode of TAL due to the lack of bonding with its substrate. A good bonding between the adjacent layers is required to ensure the durability of TAL. Moreover, the visual assessment of the interface following the test allows evaluating the nature of the failure mode: adhesive (tack coat) or cohesive (surface or base layer).

A significant drawback of testing in the field is the lack of control of the test temperature, although corrections can be made [Leclerc, 2005].

Although the torque test method is very promising test, at present the test lacks still precision and should therefore be further developed (not yet commercially available on the market).

**Shear testing**

In the literature, several test methods are reported for measuring the bonding between multiple layers in shear mode. The best known is the Leutner test as developed at the university of Karlsruhe in 1979 [Leutner, 1979] (see Figure 12).

![Figure 12 Leutner shear test.](image-url)
Several variants of the Leutner shear test have been developed and reported in the literature, see Table 8.

Table 8 Shear tests listed in the literature.

<table>
<thead>
<tr>
<th>Shear test</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer-Parallel Direct Shear (LPDS)</td>
<td>[Raab &amp; Partl, 2006]</td>
</tr>
<tr>
<td>Double shear test</td>
<td>[Diakhaté et al., 2007]</td>
</tr>
<tr>
<td>Laboratory Bond Interface Strength Device (LBISD)</td>
<td>[Buchanan &amp; Woods, 2004]</td>
</tr>
<tr>
<td>Simple shear test based on Marshall press set up</td>
<td>[Vacin et al., 2006]</td>
</tr>
<tr>
<td>Shear test in combination with normal forces</td>
<td>[Mohammad et al., 2002]</td>
</tr>
<tr>
<td>Ancona Shear Testing Research and Analysis</td>
<td>[Santagata et al., 1993]</td>
</tr>
<tr>
<td>Leutner test (modified) (draft CEN method)</td>
<td>prEN 12697-48 Part 3</td>
</tr>
</tbody>
</table>

The variety of test methods reflects the wide interest and importance of the bonding of TAL with its substrate to guarantee the durability of the whole system. However, the diversity of test methods urges harmonization and in a later stage field validation of the test results.

Direct tensile test methods

In the literature, two types of equipment are described to measure quantitatively the bonding between adjacent layers (e.g. surface layer and base layer) and therefore to evaluate the efficacy or performance of the tack coat: the direct tensile test and the dynamometer. The use of the direct tensile test is limited to the laboratory (although it can be performed on core extracted from the road). The dynamometer can be utilized both in the laboratory as well as in the field.

The protocol of the direct test method is described in the annex E of the ETAG guideline for the European technical approval of UTLAC. The procedure is used to ascertain the adhesive strength (pull-off resistance) between thin layers in hot and cold installation and their substrate. The test is carried out on drilling cores using a tensile testing machine (see Figure 13).

The objective of the protocol described in the Austrian standard ONORM B 3639-2 is quite similar although the test set up differs slightly.

In an extended study of Washington State University conducted in collaboration with the U.S. Department of Transportation, Federal Highway Administration [Tashman et al., 2006] three types of dynamometers were used for measuring the bond strength between a tack coat and its substrate (before applying a top layer) in situ. Testing included the use of the Florida DOT Shear Tester, the UTEP (University of Texas at El Paso) Pull Off Test and the Torque Bond Test. Factors known to influence the adhesive bond provided by the tack coat at the interface were studied such as the surface treatment, curing time, residual application rate.
6.4.3 European TAL specifications

Belgium
At present, for all TAL mixes being used in Belgium, specifications are set with respect to the grading curves (only stony skeleton are used), the binder content and the type of binder. There are no performance related specifications for ultra-thin surface courses.

France
For BBTM mixes (20 to 25 mm layer thickness) the old French product standard NF P 98-137 has been replaced by the European standard EN 13108-2. The minimum values set for the ‘module de richesse’ have been substituted by minimum binder content (e.g. 5 %). Additionally, specifications are defined for the appropriate choice of the type of binder which depends on the traffic volume of the road. With respect to BBTM (< 20 mm layer thickness) no product standard is available at present.

Austria
The use of PmB binders is compulsory in Austria. The maximum size for aggregate is defined between 4 and 11 mm. Furthermore, specifications are described with respect to the grading. The binder content is a result of the mix design: based on tests run with varying binder content, the optimum is considered to be the best compromise between void content and Marshall stability (usually around 6 to 6.5 %).
Other countries

In the Netherlands one states that there are too many variations or choices possible in the materials to be used in TAL in order to describe specifications. Therefore, the route of functional specifications has been chosen [VBW, 2004].

UTLAC is specified by EN 13108-9, but another approach can also be used. In the Danish national annex for the product standards in the EN 13108 series, the specification for the asphalt materials of the UTLAC is taken from the specification for the open graded asphalt concrete of the EN 13108-1. As the tack coat is not part of the product standards it is possible to describe this special application for the UTLAC concept as part of the works (not covered by CEN standards).

Also in the HAPAS system used in the U.K. no specifications with respect to materials or recipes are described [British Board of Agreement, 2008].

European standard

The European standard EN 13108-2 for very thin layers (20-30 mm) allows specifying the binder as a function of the climatic conditions, the traffic load, etc. With respect to the grading, a table is presented allowing several choices for the mix design. However, the main focus is clearly on discontinuous mixes.

It is worthwhile to note that the European standard does allow the use of Reclaimed Asphalt or RA in TAL. Nevertheless, it also states that the use of RA makes it very difficult to obtain the discontinuous grading of such mixes as discussed in Section 6.1.3.

6.4.4 Field testing

Once a TAL road section has been built, a posteriori test can be carried out. This may be done shortly after the construction, in order to check the quality of the work of the contractor (conformity of production) and/or after some time (typically a few years) in order to assess the state of the road (monitoring). Which parameters are checked, when this is done and the measurement method/device which are used vary strongly from country to country (see results of the interviews in Appendix A of the State of the art report [Sandberg et al., 2010]).

The main parameters are skid resistance, noise, texture, evenness (transversal and longitudinal) and rolling resistance. These parameters are mentioned in the following sections.

Skid resistance

Skid resistance is one of the more commonly checked parameters as it is crucial for road safety\(^1\). TAL generally performs very well for this criterion. There are a variety of measurement methods and devices for the dynamic measurement of skid resistance, most of them are listed and described in the recent technical specification CEN/TS 13036-2:2010. Limit values are dependent on the device. As an example, in Flanders, Belgium, a minimum SCRIM value of 0.48 is required for each 100 m and 0.43 per 10 m.

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\(^1\) it is clearly correlated with accident rates
Noise

Noise reduction is a main reason for applying TAL and this property is checked in some countries. It may be measured by means of the "statistical pass by method" (ISO 11819-1:1997), which yields a precise and representative measure for the acoustical quality of the road. It has as the disadvantages that it is a spot method (one gets only information about the road surface near the measuring point) and that the measurements are tedious and costly. A better method to check the acoustical quality of a TAL section is the close proximity method (CPX), as described in ISO/TS 11819-2. CPX measurements require little time and yield information about the whole tested section.
The acoustical quality of a road is expressed as the noise reduction/increase relative to a reference surface, which is country dependent, but often DAC 0/11, SMA 0/11 or DAC 0/16 are used. The noise reduction typically obtained with TAL is in the range from 2 to 4 dB.

Indirect information about the acoustical quality can be obtained by means of texture measurements (see the following section). A model for predicting rolling noise emission from texture data is in that case necessary. In practice, the use of such a model introduces an extra uncertainty on the result.

The acoustical absorption properties of porous TAL types may be tested in a non-destructive way by means of the extended surface method (ISO 13472-1:2002).

**Texture**

Texture measurements on TAL can be carried out with a laser profilometer, fixed on a vehicle for high efficiency, or as a portable device for spot measurements. Profilometers, texture measurement and the processing of the results are described in the standard series ISO 13473-1, -2, -3, -4 and -5. The profilometer yields a two- or three dimensional image of the road surface, from which valuable information can be extracted.

- The Mean Profile Depth (MPD) and the Mean Texture Depth (MTD) are two closely related parameters (see ISO 13473-1): a not too low MPD/MTD is required on roads with high speed traffic (for impervious TAL types) in order to reduce the risk of aquaplaning. Typical values required on high speed roads are MTD > 0.4 mm (Austria).

- The texture spectrum (see ISO 13473-4) reveals information relevant for the acoustical quality of the road service, as well as the rolling resistance characteristics. The latter relationship is still under investigation.

MTD may also be measured by means of the volumetric patch technique (CEN 13036-1:2001), but this method is rather obsolete, having the disadvantage that it is tedious and its result is not very precise. It is also a spot method.

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3) rather operator dependent
Figure 16  Noise absorption measurement with the extended surface method (Device owned by Dutch consultant M+P).

Figure 17  BRRC dynamic laser profilometer.
Figure 18  Example of texture spectra for three types of TAL and SMA 0/11 measured by BRRC on
the Kloosterzande test track in the Netherlands.

Transversal evenness
Transversal evenness may be checked “manually” with the 3 m straightedge (CEN 13036-7:2003) and/or with a device which digitally records the road profile, designed for the measurement of transverse unevenness (CEN 13036-6:2008). The relevant transversal unevenness indices (like rut depth), based on the measurements made according to CEN 13036-6:2008 and CEN 13036-7:2003, are described in CEN 13036-8:2008.

Longitudinal evenness
The longitudinal evenness may also be checked “manually” with the 3 m straightedge (CEN 13036-7:2003) and/or with a profiling device, designed for the measurement of deviations from the perfect plane in the unevenness and mega texture wavelength ranges (CEN 13036-6:2008). Various possible characterisations of the road profile unevenness such as the International Roughness Index (IRI) are described in CEN 13036-5:2006.

An alternative device for characterizing the road unevenness is the APL (Analyseur de Profil en Long), yielding “evenness coefficients” at wavelengths 2.5 m, 10 m and 40 m, respectively.

Rolling resistance
For the in situ measurement of rolling resistance no standards exist yet, only a few prototypes of trailers which are able to measure rolling resistance based on an angle or a force measurement. Research is still carried out to assess and enhance reproducibility of these methods. No limit values have been fixed yet.

For the in situ measurement of rolling resistance no standards exist yet, only a few prototypes of trailers which are able to measure rolling resistance based on an angle or a force measurement. Research is still carried out to assess and enhance reproducibility of
Figure 19  BRRC ARAN (Automatic Road ANalyzer) for measuring transversal evenness.

Figure 20  BRRC APL device for measuring longitudinal unevenness.
these methods. The lack of standardised measuring equipment means that further optimisation of the mix design to minimise rolling resistance is limited. Asphalt producers / asphalt contractors have no access to recognised/accepted tools for such efforts and no operational limit values are expected to be set in the near future.

Figure 21 Rolling resistance trailer from the Technical University of Gdansk.

6.5 Site logistics – accessibility

Apart from the logistics linked to the paving operation itself (mentioned in Section 6.3.4) some site logistic aspects concern what can be described as logistics for the outer boarder of the paving site. Due to the relatively smaller materials consumption of a TAL paving operation (compared with thick base course layers), the lorry drivers bringing new surface material to the site must be warned of the potentially higher speed of the operation. Depending on local requirements for crash barriers, traffic signs etc. between working operation and traffic, special attention must be paid to the mobility of these security and traffic control measures. The purpose is dual: managing the outer boarder logistics assists in having a smooth paving operation and traffic control is beneficial in minimizing congestion and improving public opinion on road works and maintenance jobs.

Intelligent traffic signs and traffic management together with information to the public through media also contribute to improve practical logistics and accessibility to the site. This is particularly important in urban areas where accessibility means night operations. It is important to have acceptance in the local community for such disturbances.
7 Recommendations

7.1 Process to introduce TAL

7.1.1 Scanning tours and incentives
Referring to replies on the questionnaire, TAL is already in widespread use in many countries. Road administrations could invite contractors to visit some of the countries or regions where TAL is already applied regularly, and afterwards parties discuss between parties how TAL could be applied locally. Many types of TAL can be paved and compacted using standard equipment, and this is a recommended way to initiate the application of TAL technology.

Road administrations could be supportive in introducing new technology, e.g. by providing funding to hire/lease UTLAC pavers for application in pilot projects or to investigate the practical applicability of double layer pavers (compact pavers). Practical application of compact pavers, however, is not straightforward and the purchasing cost will be prohibitive if longer periods of stand still occur. For an UTLAC paver a long period of stand still ought not to occur because this type of paver is also useful for paving ordinary types of asphalt. In this case the emulsion spraying system is used for ordinary tack coat.

7.1.2 TAL types and required paving equipment
The types of TAL which can be paved with standard equipment is asphalt concrete (EN 13108-1), asphalt concrete for very thin layers (EN 13108-2), soft asphalt (EN 13108-3), stone mastic asphalt (EN 13108-5) and porous asphalt (EN 13108-7). All types with a maximum aggregate size (NMAS) of 4, 6, 8 or 11 mm. The easiest type of TAL to begin with is asphalt concrete.

For all types the tack coat emulsion is a standard 50 % emulsion or 60 % emulsion.

Standard paving equipment includes minimum one asphalt paver, one steel roller and one pneumatic-tire roller. Additional equipment is sweeper, emulsion sprayer and trucks for transporting asphalt material.

The UTLAC type of TAL is the Ultra-thin Asphalt Concrete (EN 13108-9). The tack coat emulsion/protective membrane is typically a 70 % polymer modified emulsion. The production and use of this emulsion in combination with spraying with the UTLAC paver is more difficult than paving with standard asphalt equipment.

UTLAC equipment includes minimum one UTLAC asphalt paver, one steel roller and one pneumatic-tire roller. Additional equipment is sweeper and trucks for transport of asphalt material.

The Compact paver is new and complicated to use. Unless the contractor has extensive experience with this paver it is not recommended as a way to introduce TAL.

7.1.3 Contractual relations
For optimizing the contact and relation between the road administration and the pavement contractor, the road administration is recommended to work out tender documents for asphalt pavement constructions which specify TAL pavement for a test section. Furthermore the road administration should ask potential contractors in the country or region to participate.
in building test sections paved with TAL. In this way the road administration gets the opportunity to compare various sections of TAL on longer sections of road.

It is also of utmost importance that road administrations have the legal right or possibility to order specific pavement solutions for test sections in order to gain specific experience on special cases, where it can be almost impossible to tender a very specific solution for a test section by specifying function requirements on a general level. If the road administration has this opportunity it may contribute in risk taking. This will be beneficial for introducing new solutions/techniques which otherwise would not be tried.

For countries or regions where road administrations specify the mix design of TAL, it is recommended also to prepare tender documents specifying performance based requirements on:

- Evenness (e.g. IRI)
- Texture (MPD)
- Skid resistance
- Rutting
- Cracking
- Noise (if required).

In this way it is possible to test results of innovation and development performed by pavement contractors.

7.2 Where and when is it advisable to apply TAL

Recommendations on where and when it is advisable to apply TAL depend on local conditions but nevertheless some general considerations – both positive and negative concerning the applicability of TAL – are highlighted here. The recommendations given can be checked for their adaptability in the specific local situation. See also Chapter 4.

Some of the solutions are mentioned for applicability within a certain range or above or below a given limit. These values shall not be taken as totally fixed values because varying tolerances and/or sensitivities of these parameters can influence the situation either in positive or negative direction. It is also obvious that the mix of traffic (small passenger cars or heavy trucks with either twin tyre mounted axles or with super single tyres) exercises different impacts even though some parameters are the same.

For all findings in the state of the art report regarding positive features that either are present or can be built into the TAL of today, an initial statement is:

“Your first consideration for a new surface layer shall be TAL,
But in some cases TAL is not the optimum choice”

7.2.1 Question: Where?

Every time you consider resurfacing a well-designed, highly trafficked road (e.g. sufficient bearing capacity is available or will be provided through an otherwise necessary strengthening layer) the application of TAL shall be your first consideration. The argument is that regardless of what special functionalities that are built into the TAL, the material will be expensive both from an aggregate and binder point of view. By resurfacing with a thin layer you obtain the best pavement surface/tire interaction for the smallest amount of premium
constituents. For the aggregate this is important because TAL usually consists of virgin aggregate (a non-renewable resource).

In urban areas with kerbs and under bridges the reduced need for correcting kerb heights or the available free height under the bridges are added benefits which in some situations may become essential.

The optimum traffic flow for a TAL is quickly moving traffic exercising little shear force to from tyres on the pavement surface.

If part of the road section has slowly moving traffic (e.g. the last section before or the first section after a traffic light) it is perhaps not ideal, but a properly designed TAL with respect to rut resistance is capable of handling such traffic loads.

Road crossings in urban areas are characterized by sharp curves (very small radii). This will increase the shear forces and in some cases above a limit where TAL is no longer a durable solution. Materials with better shear resistance (more internal friction) are needed. One possible candidate is stone mastic asphalt. Another possibility is the use of a smaller maximum aggregate size.

If – on the other hand – traffic consists of very slowly moving trucks and busses on a climbing lane (perhaps less than 10 km/h), then surface layers with better shear resistance shall be considered. This means asphalt materials with better internal friction like stone mastic asphalt.

A special element in road building which is much used in some countries – both for urban applications and in open countryside – is the roundabout. If the size of the roundabout is reduced the shear forces exerted on the surface by the tyres may exceed a limit where it resembles sharp curves at a traffic light.

Paving smaller roundabouts often involves practical problems of using paving machines that are able to follow the geometry of the roundabout. Many mix design of TAL will only provide the desired surface texture if it is levelled and paved by a machine. Hand spreading application of UTLAC is not possible.

Other elements – especially in urban road networks – are bus stops and bus terminals. These feature heavy traffic load with additional shearing forces from braking at exactly the same spot every time. Oils spill from faulty hydraulic pipes only add to the problem. Almost no bituminous material can cope with this combination of conditions. Here the solution should be a cementitious product or a special product combining the flexibility of porous asphalt with the contact pressure and oil spill resistance of cementitious mortar filling the voids of the porous asphalt.

If bearing capacity and rut resistance of the underlying road structure is insufficient then the road is not suitable for a TAL surface. This is nearly always a road that in its present state is not fit for its purpose. Only lack of capital should prevent you – as a road administration – from immediate action. By improving the lacking characteristics of the road structure you will make it fit for purpose and in that case some of the options may again offer TAL as a solution for the surface layer.

In a special case - almost outside the scope of the present project - TAL can be an optimum choice for providing the necessary surface conditions for traffic, even though the bearing capacity is insufficient. That is very low trafficked, frost heave sensitive roads. The application of TAL consisting of soft asphalt can be a practical solution in Nordic and mountainous areas.
7.2.2 Question: When?

TAL constitute a special group of surface layers and due to the limited heat content of the product compared with thicker surface layers TAL are at higher potential risk for adverse effects of the climatic conditions during paving.

This means a more restricted season compared to normal surface layers. And as usually when considering impact of climatic conditions on paving and compaction it is not only temperature that matters but also wind and moist conditions. As an example, the Danish national road standard states that surface layers ought not to be built later than 1st September in order to obtain optimum conditions for a normal surface layer.

In recent years two technologies have been emerging with a potential to expand the limited time period for TAL paving to the normal period or perhaps even a little beyond:

- The double layer paver or Compact paver
- Alternative use of the Warm Mix concept

In new construction or when building a strengthening/levelling course by means of a newly developed paver or paving train, the asphalt contractor may pave two layers simultaneously. This means that the very thin TAL with respect to heat content can benefit from the heat content of the lower layer (typically a bituminous binder course). Even though this technique is technically feasible, it can be more sensitive to logistic problems and - from an investment point of view - depend too much on local market situations to be cost-efficient for the asphalt contractor.

The other new development is an alternative use of the Warm Mix concept. Instead of lowering the mix temperature, the Warm Mix technology is used to produce a mix at "normal" temperature. This provides the asphalt contractor extended time for hauling, paving and compaction, and TAL can benefit from this because of their enhanced workability at lower temperature. This way of using Warm Mix is novel and there is no experience on the impact on the durability of such pavements, but so far the potential of this technique is viewed favourably. It must be understood that there can be made no claim for a reduced carbon foot print when the Warm Mix concept is used in this way.

7.3 Overall recycling strategy

The application of TAL in combination with asphalt recycling implies technical challenge.

Recycling TAL into new TAL is impossible in practice because the material deteriorates by a higher content of fines when TAL is dismantled by milling.

Recycling of TAL is only possible in other types of asphalt (other wearing course materials, binder course materials or base course materials).

The recycling of reclaimed asphalt other than TAL into new TAL is also in practice impossible because the RA contains too much fines and the grading curve of the RA probably does not meet the grading curve of the TAL.

A recommendation for a road administration would be, before paving with TAL, to evaluate whether its overall recycling strategy fits with applying TAL.

If the Road Administration would like to use reclaimed asphalt in the TAL then use high quality 0/6 mm RA, or 0/6 mm RA in the same quality as the TAL in a quantity of 5 – 10 %. If adding this fraction of RA is successful then increase the quantity of RA to 10 – 20 %.
7.4 Details concerning TAL

7.4.1 General

Based on the work regarding the LCC and optimization of thin asphalt layers, as well as the latest State-of-the-Art report, recommendations shall be worked out with respect to where and under which conditions the application of thin asphalt layers is advisable.

Note 1: It may be argued that it is actually wrong to base this on Swedish LCCA because they are only valid for countries applying studded tyres.

Note 2: Recommendations of where and when to use TAL is described in detail in Section 7.2, see also Chapter 4.

7.4.2 Selection criteria

The design criteria for selecting of TAL is mentioned and listed in Section 7.3:
- Traffic type (Cars and trucks) and traffic level (ESAL)
- Evenness bearing capacity of under layer
- Areas (Urban or open land)
- Climatic conditions.

TAL as surface layer is an excellent and cost-effective pavement which is recommended as pavement for many places where the bearing capacity is sufficient. The following recommendations are given when selecting TAL to obtain successful paving:
- If the underlying layer of asphalt is uneven, paving with UTLAC is not recommended. Instead of UTLAC the use of AC or SMA is recommended.
- On places where hand-spreading application of the asphalt is required UTLAC or SMA are not recommended due to the risk of segregation. If the hand-spreading operations are required then the use of AC is recommended. If sections paved with UTLAC or SMA require hand-spreading operations in roundabouts, such sections are recommended to be replaced by AC.
- On roads with very high level of traffic TAL can be replaced by SMA thicker than 30 mm.
- Also on roads with high levels of traffic the use of modified binder is recommended, because the PmB improves the quality of the TAL compared to unmodified bitumen. Instead of using PmB the in situ modification is an alternative.
- In colder areas or in periods with low temperature there is high risk of quick cooling of TAL during paving and compaction operations. In such circumstances the use of TAL is not recommended. An alternative is TAL in combination with warm mix technology.

7.4.3 Binder

For all types of asphalt and in particular for TAL a polymer modified bitumen (PmB) results in important advantages as compared to unmodified bitumen. The recommended choice of modified binder for TAL is SBS-modified bitumen meeting the requirements in EN 14023, “Bitumen and bituminous binders – Specification framework for polymer modified bitumen”.
The exact choice of PmB from EN 14023 depends on the geographic area (climatic conditions, including minimum and maximum temperatures) and the traffic conditions (ESAL and vehicle speed) and is an integrated part of the mix design and optimization of TAL.

The cost of PmB is higher than the cost of unmodified bitumen. The cost of TAL with PmB is approximately 0.3 – 0.7 €/m² higher than for TAL with unmodified bitumen. The exact price depends on the layer thickness and the type of TAL.

For the UTLAC type of TAL, typically only the emulsion for tack coat/protective membrane is modified. The recommendation for this emulsion is a SBS- or SBR-modified emulsion.

Another type of modifier for the bitumen is crumb rubber from tyres, which is more difficult to mix with bitumen. Unless the contractor has extensive experience with modification using crumb rubber from tyres this technology is not recommended as a way to introduce TAL.

Before road administrations and contractors with little experience with the modification of asphalt with crumb rubber from tyres start up, they will need to investigate the quality of potential types of tyre rubber in detail. Further it is possible to use crumb rubber mixed with warm mix additives to improve the modification.

Instead of modifying the bitumen before mixing the asphalt, it is possible to mix the materials (including the polymer) in the asphalt mixer (in situ modification). This is a more difficult mixing process, and unless the contractor has extensive experience with this mixing process, it is not recommended as a way to introduce TAL.

### 7.4.4 Test methods

#### Laboratory testing of materials

In order to guarantee the quality and consequently the durability of TAL, the result of the mix design process (as discussed in Section 6.1) should be validated with respect to the performance of the TAL. This performance is also highly dependent on the adhesion of the TAL layer with its substrate. It is therefore recommended to evaluate both TAL and tack coat performance in the laboratory. The most important performance indicators are:

- resistance to rutting
- resistance to cracking at low temperatures
- determination of the adhesion of thin layers to underlying layers (pull-off)
- determination of shear susceptibility, both within the TAL itself and to the substrate
  - tangential forces (in roundabouts and areas with turning traffic)
  - torsion (servo steering in parking areas and at turning points)
- determination of the cohesion of thin layers (fretting resistance)
  - under traffic loading
  - under moist conditions
- influence of the tack coat layer on performance
  - selection of emulsions
  - performance of ultra-thin layers and underlying layers.
The corresponding test methods used to evaluate these performances are dealt with in more detail in Section 6.4. It should be noted however, that some tests are still under development and more importantly still need field validation with respect to TAL (e.g. for the determination of shear susceptibility). Therefore, the definition and subsequent use of performance specifications is far from straightforward.

In 2011, BRRC will participate in the follow-up of the realization of test sections (in collaboration with the Flemish Road Administration) where about ten variants of noise reducing asphalt mixes (all TAL) will be constructed and evaluated. This will not only provide more insight in the mix design of such mixes, but also offer the opportunity to validate laboratory test results related with the field performance of TAL. Moreover, some in situ testing (e.g. adhesion of TAL with its substrate) is planned.

**In situ testing of delivered TAL**

Before laying a TAL, repair of potholes and cracks is urgently needed. Furthermore, sufficient bearing capacity and satisfactory evenness of the binder course or base course is required before paving with TAL.

It is important to document the bearing capacity and evenness of the sub layer, and it is recommended - before paving with TAL - to measure these parameters as a function of the GPS-coordinates. In case the final TAL pavement quality should prove non-satisfactory, then such documentation is useful for the analysis of the problem. GPS logs of which lanes and how many roller passes have been used may be useful documentation of the compaction operation

After having paved with TAL it is recommended to measure the following parameters as a function of the stationing or GPS log, see Section 6.4.4:

- Evenness (e.g. IRI
- Texture (MPD)
- Skid resistance
- Rutting
- Cracking
- Noise (if required).

To supervise the condition of the TAL it is further recommended to monitor these parameters annually.

**7.5 Recommendations for future research**

Road administrations could invite contractors to visit countries or regions where TAL in combination with warm mix technology is already applied. This technology is useful in reducing CO₂ emission and for minimizing potential problems with the compaction of TAL. The combination of these technologies improves the paving of TAL in colder areas with a short season for surface layer work. However long-term experience of the service life of this type of TAL is not available. The service life and quality of this type of TAL is recommended as a major topic for future experiments.

Alternatively, producing WMA at HMA temperatures will permit extended time for haulage and compaction. This can additionally extend the laying season into colder months and/or night work. There is no experience yet on the durability of such pavements. It is important to emphasize that it is not possible to produce all types of WMA at HMA temperatures.
Depending on the types of WMA additives and on the type of WMA, the viscosity of the binder at the HMA temperature could be too low which results in bitumen drainage of the mix.

Due to the fact that WMA technology at present comprises a large number of techniques with a large variety of types of additive it is not possible to recommend a specific WMA technique.

The use of TAL in combination with the warm mix technology increases the potential content of reclaimed asphalt in TAL, especially if the reclaimed asphalt is similar to the new TAL.

Compaction of asphalt can be improved by applying rollers equipped with GPS to assist the compaction process. This technology could be a topic for future experimentation on optimum compaction of TAL. Further the compaction quality can be improved by controlling surface temperature by means of thermography using infrared cameras or rollers equipped with infrared temperature sensors.

Tyre rolling resistance for cars and trucks on pavements has significant influence on the total consumption of fuel and hence on the CO\textsubscript{2} emission from transport. Research in minimizing the rolling resistance of pavements including TAL will be an essential future task for the transport sector.

Other topics for future research activity are:

- Define TAL structural life time under various conditions (traffic load, climate, studded tyres …) in order to be able to perform reliable LCCA
- Extend time history of traffic noise levels (acoustic ageing) to include noise in PMS
- In situ modification of TAL with polymer including crumb rubber from tyres
- Apply the French method mentioned in Section 6.1.4 for mix-design of TAL with the gyratory compactor.

### 7.6 Potential risks in applying TAL

The potential risks involved in applying TAL are summarized in Table 9 together with estimated risk levels. Potential countermeasures to avoid these risks are also given in the table. Finally possible actions to correct failures are also given. The risk levels given in the table are based on the inventory made in the first phase of the project.
Table 9  Potential risks involved in applying TAL and countermeasures to avoid and/or correct the problem.

<table>
<thead>
<tr>
<th>Potential problem</th>
<th>Risk&lt;sup&gt;4&lt;/sup&gt;</th>
<th>Countermeasure to avoid problem</th>
<th>Residual risk&lt;sup&gt;5&lt;/sup&gt;</th>
<th>Countermeasure to correct problem</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ravelling</td>
<td>high</td>
<td>- Avoid applying TAL on sections with frequent and high shearing forces (roundabouts, crossings, exits for trucks and buses, tight parking areas, where servo steering will be used etc.)&lt;br&gt;- Do not construct at too low ambient temperature&lt;br&gt;- Ensure proper compaction; for a quicker compaction one can use more than one compactor and/or one can limit the distance between the asphalt plant and the construction site&lt;br&gt;- Use modified binder and or hydrated lime</td>
<td>Medium</td>
<td>Medium&lt;br&gt;Rejuvenation of the road surface can extend the lifetime of an affected TAL by a few years, otherwise reconstruction is the only option</td>
<td>Porous types of TAL are more sensitive to ravelling than impervious TAL</td>
</tr>
<tr>
<td>Debonding/delamination</td>
<td>high</td>
<td>- Avoid applying TAL on sections with frequent and high shearing forces (roundabouts, crossings, exits for trucks and buses, tight parking areas, where servo steering will be used etc.)</td>
<td>medium</td>
<td>Local repair in case of very little damage, otherwise only replacing tack coat and TAL can be done</td>
<td></td>
</tr>
</tbody>
</table>

<sup>4</sup> This is an expert assessment of the risk encountered if no special attention is paid to this problem  
<sup>5</sup> An assessment of the risk remaining after having taken the countermeasures to avoid the problem
<table>
<thead>
<tr>
<th>Potential problem</th>
<th>Risk&lt;sup&gt;4&lt;/sup&gt;</th>
<th>Countermeasure to avoid problem</th>
<th>Residual risk&lt;sup&gt;3&lt;/sup&gt;</th>
<th>Countermeasure to correct problem</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>o Provide high quality tack coat, especially enough tack coat should be used on a concrete sub layer</td>
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<tr>
<td></td>
<td></td>
<td>o Brush sub layer thoroughly if it is cement concrete before applying TAL (consider using a SAMI in this case). Pay special attention to contamination of the sub layer surface from farming activities in the area during paving</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>o Do not apply tack coat or TAL under wet conditions</td>
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<tr>
<td></td>
<td></td>
<td>o In case of doubt, carry out lab test on bonding strength (e.g. Austrian wedge splitting test)</td>
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<td></td>
</tr>
<tr>
<td>Initial skid resistance too low</td>
<td>medium</td>
<td>o Gritting the freshly constructed TAL</td>
<td>low</td>
<td></td>
<td>This is normally a temporal problem, and one may simply put a warning sign if skid resistance is not extremely low</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>The use of modified binder increases the risk on low initial skid resistance and delays the wearing off of the bitumen layer on the stones, which is necessary to obtain a good grip</td>
</tr>
</tbody>
</table>

<sup>4</sup> Potential problem classification:  
- High  
- Medium  
- Low  
- Very Low

<sup>3</sup> Residual risk classification:  
- High  
- Medium  
- Low  
- Very Low
<table>
<thead>
<tr>
<th>Potential problem</th>
<th>Risk&lt;sup&gt;4)&lt;/sup&gt;</th>
<th>Countermeasure to avoid problem</th>
<th>Residual risk&lt;sup&gt;5)&lt;/sup&gt;</th>
<th>Countermeasure to correct problem</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skid resistance too low long after construction</td>
<td>low</td>
<td>o Use high quality aggregate with sufficiently PSV</td>
<td>low</td>
<td>None, except for reconstruction of the TAL</td>
<td>This risk is even smaller in countries where studded tyres are used</td>
</tr>
<tr>
<td>Rutting</td>
<td>low</td>
<td>o Provide sub layers with sufficient rutting resistance</td>
<td>low</td>
<td>None, except for reconstruction of the TAL</td>
<td>As TAL is by definition thin, rut depth of the TAL itself remains limited. Problem are most often due to problems with the sub layer</td>
</tr>
<tr>
<td>Cracking due to sub layer deficiencies</td>
<td>low to high(*)</td>
<td>o Avoid laying TAL on unstable sub layers, such as not interconnected concrete slabs</td>
<td>low</td>
<td>None, only replacing of unstable sub layers and TAL</td>
<td>(*) the risk depends heavily on which sub layer TAL is applied</td>
</tr>
<tr>
<td>Too high longitudinal or transversal unevenness</td>
<td>low to high(*)</td>
<td>o Make sure the surface on which the TAL will be applied has an acceptable evenness by a proper milling of the sub layer (e.g. with a laser guided device) and/or the application of a levelling layer</td>
<td>low</td>
<td>None, only replacing of unstable sub layers and TAL</td>
<td>(*) the risk depends heavily on which sub layer TAL is applied</td>
</tr>
<tr>
<td>Insufficient initial noise reduction</td>
<td>low</td>
<td>o Ensure an adapted mixture with a maximum aggregate size not higher than 8 mm</td>
<td>low</td>
<td>None, only reconstruction of the TAL</td>
<td>Porous TAL may be expected to yield slightly higher noise reduction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>o Ensure proper compaction</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>o Do not construct at too low ambient temperature</td>
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<td></td>
</tr>
<tr>
<td>Potential problem</td>
<td>Risk(^4)</td>
<td>Countermeasure to avoid problem</td>
<td>Residual risk(^3)</td>
<td>Countermeasure to correct problem</td>
<td>Comment</td>
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<td>---------------------------------</td>
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<td>-----------------------------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Mix cools off too fast</td>
<td>low to high(^6)</td>
<td>o Ensure to have good weather conditions during construction (sufficient temperature/no rain) or mitigate by using heaters</td>
<td>low</td>
<td>None, only reconstruction of the TAL</td>
<td></td>
</tr>
<tr>
<td>Poor durability and/or homogeneity of the compaction</td>
<td>low to high</td>
<td>o Ensure to have good weather conditions during construction (sufficient temperature/no rain) or use heaters</td>
<td>low</td>
<td>None, only reconstruction of the TAL</td>
<td></td>
</tr>
</tbody>
</table>

\(^6\) depending on weather condition
7.7 Education

When introducing new pavement technology or substantial changes to existing technology, it is important that road engineers and representatives of road authorities and contractors receive proper education and information about the new or changed technology. Failing to do so may be costly; partly because a failed road project is always associated with a high cost; partly because failures in successful application of new or changed technology may result in frustration and hesitation to try it again. Therefore, lack of education may cause serious delays in the introduction of better technologies; in this case the wider use of TAL.

Even sharing the new information with the public is worthwhile. This might raise the general interest and understanding among the public of paving operations and policies; the “public” of course including politicians.

It is, therefore, proposed that a wider introduction of TAL in the European road network is accompanied with the following education and information activities:

- Widest possible dissemination of this report and of the State-of-the-Art Report
- The above may include project summaries and links to the reports at each of the participating partners’ websites, also in the FEHRL Knowledge Centre
- Organization of a special one-day seminar at which the results of this project are presented to a European audience
- Promoting the production of conference papers related to this report and newer information about this subject, and presentation of these at both national and international conferences
- Organization of special one-day courses on the selection, application and use of TAL
- A smaller follow-up project ("OPTHINAL 2") in 2012 or 2013, with the aim to update the work in the present project with the recent experience; since we still know too little about the long term performance of several types of TAL. This may be considered as “continuing educating of the educators”.
- Timing of the education activities is important. To raise the interest, it is important to perform activities 1-4 above as soon as possible.
8 Conclusions

The main conclusion is that the application of TAL is indeed worthwhile on many types of major roads and streets, in particular as a renewable wearing course (a "skin") on a well-designed road construction having sufficient bearing capacity. The skin generally satisfies road users’ need for skid resistance and energy efficiency, and roadside needs for a quiet and clean environment, as well as other important functions.

TAL cover a wide range of products. Tradition or historic development have been instrumental to the application of TAL in different countries as demonstrated, for example, by TAL being widely used in Denmark (approx. 95 % of new hot mix surfaces) while it seems that TAL are not at all applied in Italy.

The most important advantages of TAL, compared with standard DAC 11 or SMA 16, are the noise reduction obtained and the potentially lower cost of TAL. Also the smaller required working space, including reduced needs for adjusting kerb heights when repaving the road and the larger free height available under bridges are advantageous.

Spraying large amounts of polymer modified emulsion when laying Ultra-Thin Layer Asphalt Concrete (UTLAC) implies useful sealing of cracks in the old surface.

The most important disadvantage is the higher sensitivity of TAL to weather conditions during paving. This may be counteracted by combining TAL technology with the so-called Warm Mix concept, a topic for future research and development, see below.

With available cold milling techniques the dismantling of at least thinner types of TAL almost inevitably leads to downgrading the material for use in general hot mix asphalt. This means that TAL with high functionality can only be produced from virgin, non-renewable resources or with a small quantity (5 - 10 %) of reclaimed asphalt of the same quality as the TAL. TAL may also be more susceptible to cracking related to substrate deficiencies ("when we have structural problems") and TAL are less applicable at places like urban road crossings or steep climbs where vehicles exert high shear forces on the surface layer.

Life Cycle Cost Analysis (LCCA) can play an important part in the decision making process, but locally applicable conditions (e.g. the use of studded tyres) must be taken into account to obtain unbiased evaluations.

An alternative use of the Warm Mix concept seems to be worth trying out. Instead of looking solely for lowering the mix temperature, the Warm Mix technology could be applied to produce a mix at almost "normal" temperature, allowing an extended time for hauling, paving and compaction because of enhanced mix workability at lower temperature. There is no experience yet on the impact of this on the durability of such pavements.

Applying rollers equipped with GPS systems could assist in developing procedures for optimum compaction of TAL. This is of particular importance for paving done during night time to minimize traffic congestion.

The application of premium bituminous binders is probably of vital importance to TAL durability. Polymer modified binders have shown good potential in Europe. "In situ" blending of polymers (for PmA production) has shown its potential from an investment point of view. Its cost-effectiveness needs verification by further documentation of TAL durability.

The use of and experience gained with crumb rubber – especially as AR with a SAMI – still needs verification concerning potential savings, considering all "pro et con" factors. More research and field documentation is desired for this purpose.
TAL do not constitute a well-defined entity with respect to European specifications but embrace a balance of functional characteristics. Some product standards in the EN 13108 series are more oriented towards tender documents describing composition rather than functionality. A second generation of European product standards might provide better possibilities for performance specification from which TAL can benefit.

The European product standards (EN 13108 series) do not allow specifying a TAL based only on the criteria involved in performance testing (a possible exception may be AC-mixes according to EN 13108-1). This is due to both the lack of validated test results directly related to field performance (e.g. water sensitivity) and the fact that some test methods are still under development (e.g. resistance to ravelling). Some test methods may be applied a posteriori such as the torque bond test used to probe for the adhesion of TAL with its substrate (major durability aspect of TAL applications). Therefore, additional research is needed to fill in these knowledge gaps and to further implement performance based specifications.

9 Acknowledgements

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10 References


Gummiasfalt (2010): “Seminarium om gummiasfalt”. Website presenting the results and presentations of an international seminar on asphalt rubber, held in Göteborg, Sweden, September 2010 (both in Swedish and English), see http://www.gummiasfalt.se/


Manolis, S.; Decoo, T.; Lum, P.; Greco, M. (2008): “Cold Weather Paving Using Warm Mix Asphalt Technology”, Proceedings of the fifty-third Annual Conference of the Canadian Technical Asphalt Association (CTAA), Saskatoon, Saskatchewan, November 2008; Polyscience Publications, P.O. Box 1606, Station St Martin, Laval, Quebec H7V 3P8, Canada


OECD (2001): “Assessing the benefits of transport”, European Conference of Ministers of Transport


STA, 2009: "Råd för val av beläggning med hänsyn till miljö" (Advice concerning the choice of road surface layers considering the environment), Swedish Road Administration (Vägverket), PUBLIKATION 2009:124


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