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CONSISTEND: A tool to assess the impact of construction process quality on the performance of pavements and its implementation in tenders

WP1-Report 1.1a: Literature Review

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The Netherlands Organisation for Applied Scientific Research (TNO)
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CEDR Call 2013: Energy Efficiency
CONSISTEND
A tool to assess the impact of construction process quality on the performance of pavements and its implementation in tenders

WP1 – Report 1.1a: Literature Review

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D1.1: Final report summarizing the findings of the reviews after quality check.

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Executive summary

Quality control during the construction process is, next to road design and material selection, an important factor that determines the performance of an asphalt road with respect to service life. A longer functional life of a road has an enormous impact on the carbon footprint of that road because it minimizes the use of materials and energy during the life cycle. The road construction sector faces a number of changes that have an impact on quality control.

At this time an important challenge is the limited knowledge available on the influence of the individual construction parameters on the service life of pavements, largely due to traditional and empirical knowledge of road materials and construction. If quality control is brought to the next level it is possible to create a population of roads with a longer and much more predictable average service life. This will also assist with the planning and management of future maintenance interventions.

When the most important parameters of the construction process in relation to the service life are known, quality control can be focussed on controlling these parameters. The next step is to quantify the impact of the use of advanced quality control methods on the average and standard deviation of the relevant service life parameters. When this information is combined it is possible to design a quality control system that is able to realise the required risk level for a specific project.

On completion of the literature review it is clear that there are many factors and mechanisms which can influence the quality and durability of a pavement. It should be acknowledged that many of the factors are interdependent and prove difficult to assess on an individual basis. However, following review of the numerous pavement functions, degradation mechanisms and factors it has been possible to develop a relation matrix to conclude this report. This matrix will also assist with the development of the model and provide the main focus for the industry questionnaire.

1 Introduction

Quality control during the construction process is, next to road design and material selection, an important factor that determines the performance of an asphalt road with respect to service life. A longer functional life of a road has an enormous impact on the carbon footprint of that road because it minimizes the use of materials and energy during the life cycle. The road construction sector faces a number of changes that have an impact on quality control.

Firstly, under the impact of new types of contracts like Design, Build, Finance and Maintain (DBFM), the responsibility for quality control moves from road owner to contractors. These types of contracts have changed the quality control from, a check made by the client to ensure work was realized according to specifications, to a quality system installed by a contractor to minimize financial risks during the project. As a result different prospective investment in advanced techniques for quality control have now become rewarding for contractors.

Secondly, the workforce of construction companies is changing more rapidly, people change jobs, companies are taken over, etc. Subsequently road construction teams are subjected to frequent changes, which reduce the total knowledge of the team and the transfer of this knowledge. As the construction quality of asphalt roads is largely dependent on the empirical experience of the construction workers, this lack of continuity has a negative effect on the service life and performance of a road.

Finally, there are new technologies that have become available over the past decades that can take quality control to a whole new level. With the help of these technologies a wide selection of parameters can now be monitored during construction in real time. For example with the use of infrared sensors the temperature of the whole asphalt surface can be monitored, for example, just after the screed; through GPS the number of roller passes can be monitored at each location; and the foreman can obtain accurate information about the location and expected arrival time of asphalt trucks, the possibilities are endless.

At this time an important challenge is the limited knowledge available on the influence of the individual construction parameters on the service life of pavements, largely due to traditional and empirical knowledge of road materials and construction. If quality control is brought to the next level it is possible to create a population of roads with a longer and much more predictable average service life. This will also assist with the planning and management of future maintenance interventions.
When the most important parameters of the construction process in relation to the service life are known, quality control can be focussed on controlling these parameters. The next step is to quantify the impact of the use of advanced quality control methods on the average and standard deviation of the relevant service life parameters. When this information is combined it is possible to design a quality control system that is able to realise the required risk level for a specific project.

The project will start with the collection of information on the influence of the construction process on the service life of asphalt roads. This information is detailed within this document and forms the basis for deliverable D1.1: Final report summarizing the findings of the reviews after quality check (03/2015).
This report will cover the following key points;

- comprehensive review of literature related to the asphalt pavement construction process,
- the key construction parameters that determine service life performance,
- how they will influence performance for different types of asphalt layers under different climate conditions.

2 Definitions and abbreviations

For the purposes of this report European Standards apply, as do the following terms and definitions [Read, 2003 and BSI, 2006]

Pavement, structure, composed of one or more courses, to assist the passage of traffic over terrain

Layer, element of a pavement laid in a single operation

Course, structural element of a pavement constructed with a single material. A course may be laid in one or more layers

Surface course, upper course of the pavement, which is in contact with the traffic

Binder course, part of the pavement between the surface course and the base

Regulating course, course of variable thickness applied to an existing course or surface to provide the necessary profile for a further course of consistent thickness

Base, main structural element of a pavement. The base may be laid in one or more courses, described as “upper” base, “lower” base etc.

Asphalt Concrete, asphalt in which the aggregate particles are continuously graded or gap-graded to form an interlocking structure

Tack coat (or bond coat), light application of bitumen applied between layers of asphalt to create a strong adhesive bond.

Fretting (or ravelling), the progressive loss of interstitial fines from the road surface.

Stripping, the loss of bond between the aggregates and bitumen, resulting in loose material.

Rutting (or deformation), permanent or unrecoverable traffic-associated plastic deformation often restricted to surface layers, can extend throughout the pavement.

Bleeding (or fatting up), occurs when binder fills the aggregate voids resulting in excess binder on the surface

Cracking, occurs when tensile stress and related strain induced by traffic and/or temperature changes exceeds the breaking strength of the mixture.

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3 Pavements

3.1 Pavement structure and function

A road pavement is a horizontal structure of superimposed layers of selected and processed materials that are placed on the formation soil or subgrade. The main structural function of the pavement is to support and distribute applied wheel loads. Pavement structures can broadly be divided into two groups: flexible and rigid. In the UK the term “flexible” is generally used to describe a pavement construction consisting of bituminous bound surface and roadbase, whereas “rigid” refers to those with slabs composed of pavement-quality concrete with considerable flexural strength.
The structure of a typical flexible pavement found in the UK is shown in figure 1. Essentially, it consists of a bituminous layer (comprising surface, binder and base course) and foundation layer (sub base and subgrade), each of which contributes to the pavement performance.

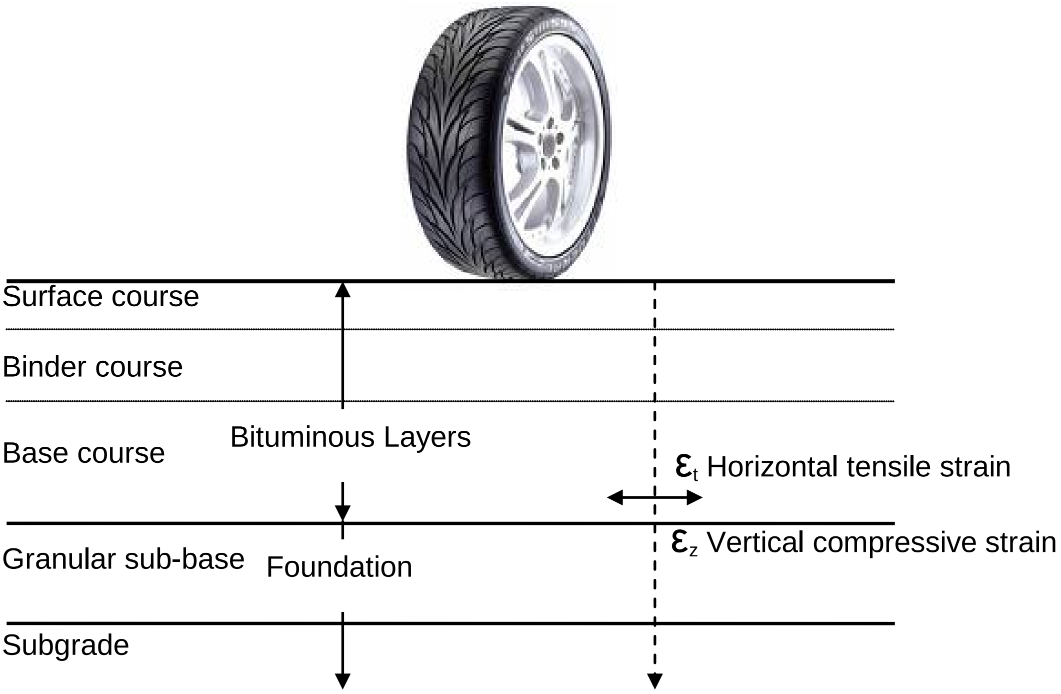

Figure 1: Typical flexible pavement structure found in the UK.

The principal purposes of a pavement are well documented [Pearson, 2012] and the function is believed to be as follows;

1. To facilitate unhindered and free passage to all forms of traffic, by providing a smooth, skid resistant, drained and unhindered surface.
2. To transmit the stresses imposed on it, by a broad range of loading, to the formation in such a manner that the latter does not become overloaded.
3. To minimise fatigue in the various layers due to repeat imposed loading of the pavement and reduce the rate of deterioration of the constituent materials.
4. To ensure water falling on its surface can drain away rapidly and does not hinder free passage.

In designing bituminous materials it has been reported that the following mechanical properties should be considered, Rahman [2004]:

- High elastic stiffness, to ensure good load spreading capability
- High fatigue strength, to prevent the initiation and propagation of cracks due to the repeated traffic load and due to environmental variation, *i.e.* temperature.
- High resistance, to permanent deformation to prevent surface rutting.
- Resistance to low temperature cracking
- Adequate skid resistance in wet weather as well as comfortable vehicle ride.

Furthermore, the durability of the pavement is important in minimising both the environmental impact and the traffic disruption caused by subsequent maintenance. An asphalt material or a pavement can be said to be durable if it maintains its structural integrity and functional properties at a satisfactory level within its nominal design life when exposed to the effects of the environment and the expected traffic loading. However, two distinct definitions are given in Road Note 42 [Nicholls *et al*, 2008] for asphalt durability and pavement durability.
Asphalt durability is defined as 'the maintenance of the structural integrity of compacted material over its expected service life when exposed to the effects of the environment (water, oxygen, sunlight) and traffic loading' and is dependent on;

- The component materials used
- The weather conditions during laying
- The mixture, both the generic type and job mix design
- The workmanship during mixing, transport, laying and compaction
- The site conditions, including geometry, subsequent local weather conditions, drainage and (possibly) traffic.

Pavement durability is defined as 'the retention of a satisfactory level of performance over the structure's expected service life without major maintenance for all properties that are required for the particular road situation in addition to asphalt durability' and is dependent on;

- The asphalt durability
- The traffic and site conditions
- The pavement performance requirements set
- The asphalt performance requirements set

Where the pavement performance requirements could include any or all of the following;

- Stiffness
- Resistance to fatigue
- Texture depth
- Transverse rutting
- Longitudinal ride quality
- Skid resistance
- Noise level
- Colour

Each functional requirement outlined in this section is related to several deterioration/degradation mechanisms; the performance of the most dominant degradation mechanism governs the performance of the functional requirement, the relationship between function and mechanism and associated factors will be discussed further in section 3.2

3.2 Deterioration of pavements (degradation mechanisms)

In order to design and evaluate road pavements, it is necessary to understand modes of deterioration and failure mechanisms. A flexible pavement should not fail suddenly; generally visual deterioration of pavements is apparent after approximately five years of service and worsens over time until a failure condition (defined by unacceptable levels of rutting, cracking etc.) is reached. There are two aspects of material properties relevant to pavement design. Firstly, load deformation or stress strain characteristics which are required for the analysis of the structure. Secondly, the performance characteristics that determine their mode of failure [Read, 2003].

Two main distresses observed directly that are associated to the bitumen matrix are, permanent deformation (rutting),leading to channels in the direction of travel; secondly cracks appearing in the road, as a result of brittle fracture of the bituminous component of the asphalt occurring at low temperatures (generally below 0°C) [Navarro *et al*, 2005].

Under traffic loading, the various layers of bituminous bound materials are subject to repeated stressing. Therefore the possibility of damage by fatigue cracking is usually considered to continually exist. As a wheel load passes over a flexible pavement, each layer responds in the same generic way: an applied stress pulse is caused by the wheel mass whilst the resultant horizontal strain consists of resilient and permanent components (see figure 2). The permanent strain component, although tiny for a single load application, is cumulative. An excessive accumulation of these permanent strains can lead to fatigue cracking and pavement failure [O'Flaherty, 2002].

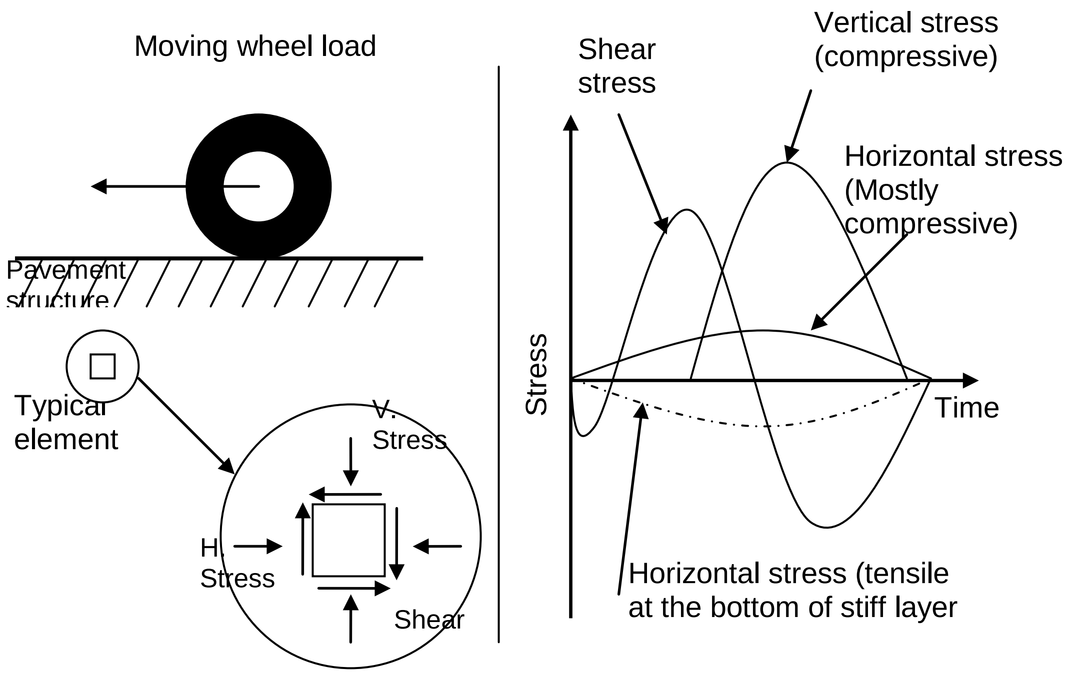

Figure 2: Schematic of stresses and strains induced in pavement layers under loading [(Rahman, 2004), (Read, 2003)].

The factors that affect the deterioration of a highway pavement can be categorised as follows [Ramaswamy and Ben-Akiva, 1990];

1. Pavement characteristics: pavement strength, layer thicknesses, base type, surface type
2. Pavement history: time since last rehabilitation, total pavement age.
3. Traffic characteristics: average daily traffic, cumulative traffic, traffic mix (percentage of trucks)
4. Environmental variables: average monthly precipitation, number of freeze thaw cycles, average annual minimum temperature, and so on.

For the purposes of this project and development of the model, modes of deterioration will be referred to henceforth as degradation mechanisms. A degradation mechanism is a mechanism that causes degradation of function over time, by changes in properties and/or microstructure of a component material. The performance of the most dominant degradation mechanism governs the performance of the functional requirement.

Degradation mechanisms identified as impairing the functional requirements of asphalt pavements are as follows;

- Rutting
- Ravelling/Fretting
- Cracking
- Bleeding/Fatting Up
- De-Bonding
- Ageing (UV)
- Stripping
- Water Ingress/ Moisture Damage

3.3 Degradation factors

Degradation factors are those factors that influence the degradation mechanism (i.e. cause and effect). Each factor is defined by different conditions and each represents a level of acceleration of the speed of degradation. It is recognised that many assumptions are implicit in the design process, over which the design engineer has little or no control [Pearson, 2012]. To achieve the best possible quality in the construction process for an asphalt pavement, a large number of parameters have a strong influence and must be controlled and kept in their optimal range to retain the service life of the asphalt pavement. The degradation factors considered within the scope of this project are discussed in more detail within this section and are taken from literature and do not necessarily represent the view industry in full.

Factors which can affect the generation of tensile strains in the pavement, and therefore considered to impact on service life are:

- Design, appropriate pavement thickness and choice of materials i.e. binder type, mix volumetrics for the strength of the subgrade.
- Environmental conditions: time and temperature/ seasonal variations (low temperature cracking)
- Construction practices and workmanship: lack of compaction leading to increase in air voids, water ingress.
- Traffic conditions: speed and mode of loading (stress or strain controlled). Typically controlled stress is more applicable to thick pavement construction (>150mm) whereas controlled strain is more applicable to thin pavements or surfacings (<50mm).

In addition to these, durability is a key parameter which must not be overlooked, inherent factors affecting durability are reported [Nicholls *et al*, 2010] to be as follows;

- Continuity of supply of asphalt
- Permeability and air void content
- Asphalt temperature
- Layer thickness
- Compaction (equipment, influence of mix constituents)
- Bond

- Joints
- Time of construction

However, many of these factors, whilst important, lie outside the scope of the current project. This project explicitly limits itself to the construction process of asphalt pavements, starting when the asphalt leaves the mixing plant and ending at the completion of asphalt compaction. More explicitly the project covers the Transport, Laying and Compaction (TLC) of asphalt materials, excluding the influences of material selection, mix design, loading during service life etc. This specific focus ensures that quality control during the maintenance and/or reconstruction of existing roads is addressed, as well as a significant element of the quality control of newly constructed roads. The factors directly applicable to this project will be discussed in further detail within this section, however, it is worth noting that many of the degradation factors referred to in this section are interdependent and inextricably linked making it difficult to fully separate out individual degradation factors in relation to mechanism. A relation matrix of degradation mechanisms and factors will be developed and concluded in this document.

3.3.1 Temperature

To create a durable asphalt pavement, the asphalt should be mixed, delivered, laid and compacted within the material temperature limits for a given mixture design. The temperature of the asphalt is critical to its workability and the ability to achieve adequate compaction. Limits on the temperatures, which depend on the mixture type and binder grade, are generally given in standards such as BS 594987 (BSI, 2007a) or recommendations from the designer.

Whilst the mixing temperature is the starting point and critical (i.e. too high temperature damages the binder, whilst too low results in incomplete coating of the aggregate) to the process it falls outside the scope of this project. There are many parameters that influence the temperature of the asphalt mixture throughout the paving process (discussed in further detail in subsequent sections) making it difficult for operators to predict the ideal temperature and adjust operations accordingly. Bijleveld, 2012 reports that such parameters coupled with practical problems such as the temperature over the depth of the asphalt layer rarely remaining constant as the surface of the layer cools down faster than the middle of the layer and the temperature of the bottom of the layer can decrease faster depending on the temperature of the base layer. So, different layers within the height of the asphalt mixture can have different optimal temperature windows. The transport distance and time are important factors in maintaining high mixture temperatures (particularly during cold weather conditions) and will be discussed in section 3.3.6.

The damage that results from extremes of the compaction temperature window are as follows;

- Compaction temperature too low;
  - Incomplete compaction
  - High air void content
  - Susceptibility to fretting, water ingress and binder stripping
- Compaction temperature too high;
  - Difficult to compact due low viscosity of binder, leading to low air void content
  - Fatting up/excess bitumen on the surface

The mixture temperature as it comes out from under the paver screed is important in determining the time available for effective compaction: asphalt temperature has a direct effect on the viscosity of the bitumen and thus compaction. As the asphalt temperature decreases, the bitumen becomes more viscous and resistant to deformation, which results in a smaller reduction in air voids for a given compactive effort. Therefore, mat temperature is crucial to both the actual amount of air void reduction for a given compactive effort, and the overall time available for compaction [Nicholls et al, 2007].

3.3.2 Environmental Conditions

Environmental exposure leads to ageing and weathering of the bitumen and is primarily the result of accumulated ultra-violet radiation and subsequent rainfall erosion. Additionally, oxidation of the bitumen and binder hardening assists the process [Pearson, 2012]. The effect of the environment is most prevalent on the surface course, the result of adhesion loss in the binder due to age hardening results in stripping and fretting and can also lead to cracking.

Environmental factors are determined by when and where paving occurs, and are beyond the control of the contractor. In response to pressure for the timely completion of paving projects, it is impractical for contractors to wait for optimal weather conditions for paving. Mixture and structural design factors are determined before construction and, although they should account for construction practices and the anticipated environment, they often must compromise ease of construction and compaction to achieve design objectives [Nicholls et al, 2012]. In response to this, considerations have been made and are often included in specifications to allow for working windows to be available in relation to weather conditions to allow work to continue. An example of this can be found in figure 3, taken from the UK Specification for Highway Works [MCHW, 2008].

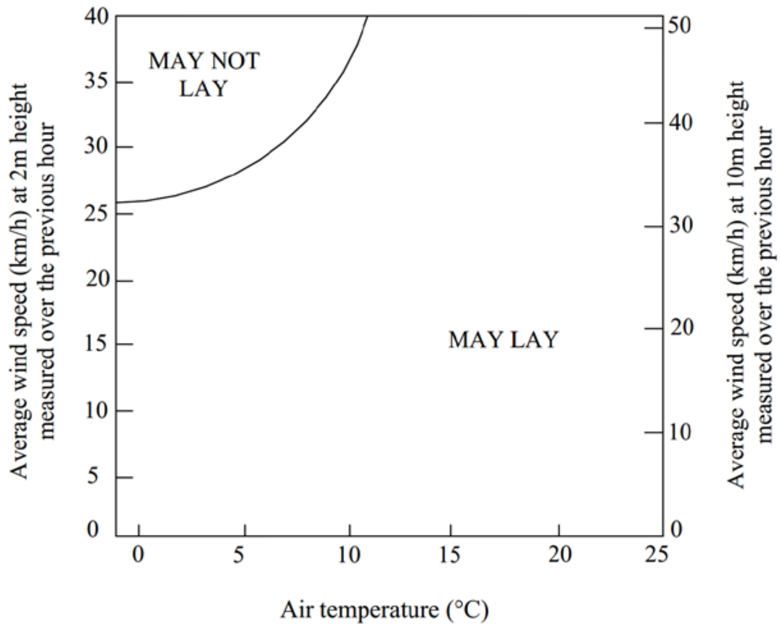

Figure 3: (MCHW, 2008)

In addition to weather patterns, time of working should also be considered. Whilst working at night has the advantage that there may be fewer disruptions because of less traffic, ambient temperatures are likely to be lower which not only cools the material but can often impact on productivity of operatives. It is therefore important when planning to ensure that there is continuity in the supply of material and that there is sufficient availability of equipment and manpower to both undertake the work efficiently and allow for any breakdowns that have a reasonable probability of occurring.

Winter conditions impose tighter working windows on the suitable time available for laying asphalt successfully, whilst at the same time they can reduce the efficiency of operatives. More importantly there is less time available for compaction due to lower temperature and there is the increased possibility of ice and frost. The presence of frozen conditions is more serious as it could result in water being trapped between pavement layers. However, the reduction in compaction time due to low temperature is often not as great as it is for strong winds, so that wintery conditions when it is very still can provide a reasonable time for compaction.

An asphalt layer will cool more quickly in high winds than when it is relatively calm. Wind has more effect on the surface of the layer than its interior. A strong wind can cause the surface to cool so rapidly that a crust forms. This crust must be broken down with the roller before compaction can begin. It is also acknowledged that a mix will cool slower on a sunny day than on a cloudy day (other factors remaining constant), with sunshine affecting the temperature of the underlying base more than mix temperature. The base will be warmer on a sunny day than on a cloudy day with the same air temperature, significantly slowing a new layers cooling rate [WTB, 2014]. On the other hand, a moist base layer significantly speeds up cooling of the over layer. Just as water cools skin faster than air, moisture in the base speeds heat transfer out of the asphalt mix. The moisture may even turn into steam [WTB, 2014]; whilst initially this may assist in lubricating and therefore aiding compaction it ultimately results in reduction in durability of the pavement layer.

3.3.3 Compaction

The degree of compaction of the bound layers is directly related to the service life of the pavement as may be deduced from figure 4, [Whiteoak *et al*, 1990] and is a process whereby the volume of air in an asphalt mixture is reduced using force during the rolling process to enable closer packing of the aggregates within the mixture, thereby reducing air void content and increasing unit density of the mixture. Compaction is regarded [WTB, 2014] as the simplest most economic method of increasing a road's life and improving its load carrying capacity. Done during construction compaction costs very little, and it can reduce future maintenance and add years to the life of the road.

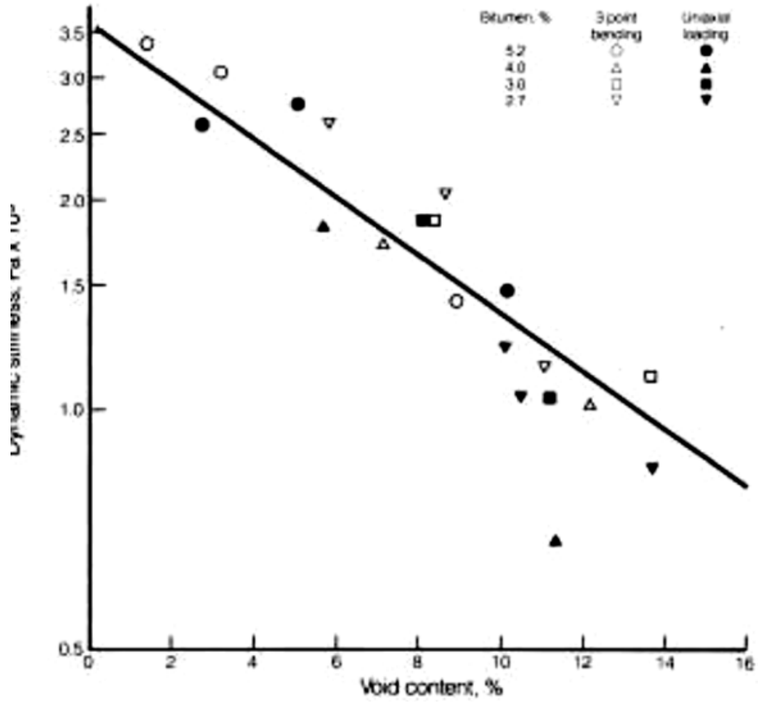

Figure 4: Void content versus Dynamic stiffness [Whiteoak et al, 1990]

An inadequately compacted pavement (i.e. such that density and air void requirements are not met) results in a pavement with reduced stiffness, fatigue and durability, accelerated ageing and increased susceptibility to rutting, fretting, moisture damage and cracking and overall reduction in life.
An approximation for the reduction in life is reported to be for every 1 percent increase in air voids above 8% about 10% of the pavement life may be lost. There is also evidence to suggest that air void content should not fall below 3% air voids during their service life [Pearson, 2012].

Asphalt surfacing is compacted to obtain the desired density for maximum strength and wear, and to provide a smooth, sealed riding surface. Nicholls et al [2007] report that asphalt compaction is influenced by a myriad of factors, some relating to the environment, some determined by mixture and structural design and some under contractor control during construction. The primary factors that affect the ability to compact asphalt are:

- Environmental factors: Wind speed, solar flux, ground and air temperatures.
- Aggregate factors: Grading, size, shape, fractured faces and aggregate volume.
- Binder factors: Bitumen content, film thickness, chemical and physical properties.
- Construction factors: Lift thickness, type of roller, number of rollers, number of passes, speed and timing.
- Other factors: Foundations, mixture temperature, haul distance and haul time.

The construction factors listed above are the most controllable and adaptable of all the factors affecting compaction. Although some factors, such as haul distance/time, asphalt production temperature, lift thickness and type/number of rollers, may be somewhat predetermined, other factors associated with roller timing, speed, pattern and number of passes can be manipulated as necessary to produce an adequately compacted mat [WSDOT, 2000].

As discussed, density is one of the most prominent measures for road quality. Often indirect density gauge measurements are taken during compaction operations. It is expected that the layer will reach the specified properties if the asphalt mixture is compacted within a desired temperature window [Bijleveld, 2012]. Obtaining the desired density optimises the performance characteristics, poor density can result in settlements in a later stage, rutting in the wheel paths and ultimately a shorter life span of the pavement. Factors influencing density and subsequently compaction are the moisture in the substrate, grading and composition of the asphalt mixture all of which fall outside the scope of this project.

Density and air voids are inextricably linked and the task of the roller compactors is to reduce the void content to a target level. If the material temperature is too low during compaction, the bitumen cannot lubricate the mixture anymore resulting in an open surface and high voided mixture. If the mixture is over compacted, i.e. no voids, the mixture can lose stability. Compaction equipment is discussed in further detail in section 3.4.1.

The temperature of the asphalt mixture directly impacts on the compactability and therefore the construction process strategy. Ideally compaction should be done within a certain in-asphalt temperature window, with lower and higher temperature boundaries, to achieve high quality road surface. Vasenev et al, (2012) report that there are no available systems to predict in-asphalt temperature, roller operators have to guess the actual temperatures. This supports reports by Bijleveld [2012] noting that the compaction process as currently practiced is mainly based on experience, in contrast, if the asphalt team works outside their experience-domain, the result is uncertainty with a fair degree of variability.

More recently however empirical studies have taken place which shows that the compaction process for an AC 16 base (conventional bitumen 40/60 pen) should be started at a temperature between 140-150 °C. When the compaction process starts outside this window, it is still possible to reach the target density, but a lower cracking toughness and a higher crack propagation rate should be expected. Despite reaching the target density, compacting outside the optimal compaction window can decrease the cracking toughness to a maximum of 30% and increase the crack propagation rate to a maximum of 40%. So, the temperature at which asphalts are compacted is certainly important. Consequently, if during quality control only the density is used as a criterion, detecting the reduction in quality due to compacting outside the optimal compaction window is not possible. Therefore, it is not sufficient to only steer the process based on the density. The compaction temperature should be taken into account depending on the indicative damage mechanisms. Compaction outside the optimal temperature window can lead to a decrease in quality and a shorter life span of the pavement. The layer thickness and logistics of supply is also extremely important for the cooling rate of the asphalt mixture [Bijleveld, 2012].

3.3.4 Equipment

The mixture should be transported to the paving site as soon as possible and loaded into the paver hopper, or temporarily stored in a surge silo. It is imperative that the transport is done without delay to avoid having a detrimental effect on the material characteristics (excessive binder hardening, binder drainage etc.) and material can be placed within its specified temperature range as described in section 3.3.1. Time delays will be discussed in more detail in section 3.3.6. Nicholls et al, 2007 report that adequately insulated round-bottom delivery vehicles with covered beds can reduce mixture temperature loss whilst tarpaulin-covered trucks can also minimise excessive cooling of the mixture.

Adequate compaction is essential to the durability of an asphalt mixture. The type of equipment used to compact the material has a significant effect on the density that can be obtained with a given number of passes. Equipment should be selected based on its ability to produce a compacted surface to the required density as described in section 3.3.4. For projects within the UK, three primary types of self-propelled compaction equipment are currently being used: static steel wheel rollers, pneumatic tyre rollers and vibratory steel wheel rollers. A combination roller, equipped with both a vibratory drum and a set of four pneumatic tyres, is also sometimes used; however surface course must be finished with a smooth-wheeled roller, which may be a deadweight roller or a vibratory roller in non-vibrating mode. The three types of rollers can be found detailed below [WTB, 2014]

1. For steel-wheel static rollers, axle load, roll diameter, and rolling speed influence compaction performance. Axle load measures the compaction capacity; heavier axle loads compact more. Roll diameter influence surface finish. Smaller diameter rollers tend, more than larger rollers, to shove material ahead of them causing ridges and surface cracks. Rolling speed influences the time available for compaction and the ability of the roller to keep up with the paver. Thicker individual layers require slower rolling speeds or more passes. Thinner layers can be rolled faster or with fewer passes.

2. For pneumatic-tired rollers, contact area, gross weight, and rolling speed influence performance. Compacting effectiveness increases with the area of each tire footprint as well as the gross weight of the roller. Contact pressure, which includes both tire pressure and gross weight, is the primary element in determining the compacting effectiveness of this roller type. As with the steel-wheeled static roller, rolling speed affects compaction time and ability to keep up with the paver.

3. For vibratory steel-wheeled rollers, amplitude, frequency of vibration, and rolling speed influence performance. Amplitude, the amount of vertical movement of the vibrating drum, and frequency, the number of vibrations of the drum per minute, combine to determine the compactive energy generated by the roller. Variable amplitude and frequency controls enable the operator to alter the amount of compactive energy generated in order to achieve specified densities in the fewest passes. The lower amplitude produces less dynamic force which in turn avoids fracturing the aggregate and damaging the finished surface. Thicker lifts require higher amplitudes and lower frequencies.

There are several variables associated with rollers that can be adjusted from job to job to optimise mat compaction, including:

- Roller speed.
- The location at which each roller works (rolling zone).
- The number of roller passes over a given area of the mat.
- The pattern that each roller uses.
- The sequence and number of rollers.

Each of the variables will be discussed in further detail in the subsequent sections.

3.3.4.1 Roller speed

The ability to achieve successful compaction of an asphalt layer is related to the time available for the weight of a roller to exert a compactive effort. Speed will determine the distance between successive impact points on the pavement. The slower the movement of a roller across a point on the asphalt surface, the more time is available for the weight of the roller to place a compactive effort on that point. Alternatively, as roller speed increases, the amount of density gain achieved with each roller pass decreases [Nicholls *et al*, 2007].

The roller speed selected is dependent on a combination of factors, namely;

- Paver speed
- Layer thickness
- Position of the equipment in the roller train
- Number of rollers

The limiting factor on paving output is the rolling capacity rather than the paver speed or the availability of the asphalt. In addition to the maximum speeds achievable with standard compaction equipment, there are several critical variables that limit the speed of rolling [Nicholls et al, 2007]:

- There is a maximum rolling speed, above which the compactive effort applied by the roller is insufficient to achieve the required material density.
- Any variation to the roller speed along the length or across the width of a pavement is likely to cause variations in density and performance.
- The properties of the mixture being placed by the paver can necessitate a reduction in roller speed (ie the tenderness of the mixture).

Typically rollers are expected to move at uniform speed, generally around 5 km/h. Often the roller speed is fixed for a design mixture, unless tenderness of the mixture is observed. Compaction therefore requires skilled operatives to observe and react to changes in the material response rather than react to increased material throughput from the paver as it can alter the effectiveness of the compaction. Paver speed must try and match material production and roller speed to ensure that compaction remains effective.

Nicholls et al, 2007 reports that a “slow and steady” approach will increase both the quality and the long-term durability of the pavement.

3.3.4.2 Number of roller passes

Multiple roller passes are needed to completely compact each point in the pavement surface to the required density over the longitudinal length and transverse width of the lane being paved. The number of required passes depends on many variables, including;

- Position of the roller in the roller train
- Type of compaction equipment.
- Order of the type of rollers.

As each roller type described has different capabilities which in turn can each vary in relation to mat thickness, mixture temperature, and mixture design properties (bitumen content, bitumen stiffness, aggregate characteristics) and environmental conditions. This coupled with the number of variables involved makes it impossible to generalise about the best combination of rolling and roller pattern to use in all cases. For this reason the number of roller passes is considered to be outside the scope of the information available for collection.

3.3.4.3 Over-running of edges

Whilst it remains difficult to quantify the number of roller passes required, it is important that the roller passes are distributed uniformly over the width and length of the mat. Often the edges of the mat receive less compactive effort when compared to the centre of the mat, making wheel track zones more vulnerable to deformation. This outside edge is often the free or unconfined edge where material can break, shove and in more general terms result in lower density as a result of poor compaction.

Compaction of the unsupported edges of the pavement needs experience and care as the type of roller selected can significantly affect the density obtained as material moves transversely under the weight of the equipment. The best location for the edge of a steel wheel roller drum is extended over the edge of the lane by approximately 150mm. No shear loading occurs at the edge of the drum so no transverse movement occurs (Nicholls *et al*, 2007). Furthermore density is achieved as the edge of the drum compacts air instead of shoving the material sideways.

In addition, cutting back of the free edge and proper and adequate application of bitumen can also minimise transverse movement, joints and bond between layers will be discussed in further detail in section 3.3.7 and 3.3.8 respectively.

A further aid to successful compaction of the free edge can be performed by attaching a restraining edge to the roller. This technique utilises an edge-compacting device, which provides lateral resistance at the edge of lane being rolled. The restraining device consists of a hydraulically powered wheel that rolls alongside the compactor drum, pinching the unconfined edge and providing lateral resistance. The restrained edge method produces a fairly consistent edge with a good density. However, it is difficult for the plant operator to see the edge-compacting device, making it difficult to produce a neat and straight edge. Any deviation from the edge line leaves debris in the opposite lane that must be removed before the second mat is placed [Nicholls et al, 2007].

3.3.5 Workmanship

Road infrastructure is a vital component of any transportation system. As growth of the economy is accompanied by increasing travel demand there is a clear need for continuous improvement of road systems. Therefore, construction companies introduce new materials and require new working methods from the personnel on site. The changes often require an asphalt team to perform paving operations under new conditions, where lack of previous experience can make the results of the paving process uncertain. [Vasenev et al, 2012] Despite this it is acknowledged [Bijleveld, 2012] that the current asphalt paving process depends heavily on the skills and experiences of people working on the construction site.
However it should be noted that with the requirement for greater deformation resistance (due to increasing traffic volumes) and retention of high texture depth, asphalts have tended to become stiffer and less workable, with lower binder contents and, hence, they are less forgiving of poor workmanship [Nicholls et al, 2007].
Relying predominantly on craftsmanship, work is mainly undertaken without instruments to monitor key process parameters and no research effort is put into the systematic analysis and mapping of the asphalt paving process and its many and inter-related variables which can often be difficult to predict. This means that it still relies on the experience of operatives to adjust their actions to ensure that materials are laid to achieve required performance.

3.3.6 *Time*

For the contractor, time is the most important factor. It is necessary to have a well-planned coordinated production process to ensure even flow of hot material to the paving site as the time it takes the asphalt to cool down is essential to achieving performance. Material logistics can often present significant challenges, haulage time is key to delivering material within the correct temperature range for paving operations, as is sufficient loads to prevent frequent stops in the construction process. Non uniform supply can result in material being delivered at varying temperatures which results in varying degrees of compaction and the need to lower and lift the screed on the paver which can result in an uneven finish to the surface layer and in extreme cases additional and unnecessary joints. Ideally only one load should be waiting whilst another is discharging and supply should be matched to equipment and operative capability. Good communication between the plant and site is essential to maintaining steady flow as the vagaries of traffic can make it difficult to predict, operators must then deal with the issues of temperature and cooling by adjusting the lag time between the paver and the roller.

The time available for compaction is defined as the time for a mixture to cool from its temperature when it passes out from under the paver screed to a minimum compaction temperature. Depending on environmental conditions, the insulation provided in the wagon and the length of the haul, the mixture can decrease in temperature from 3 °C to 14 °C between the plant and the paver [Nicholls et al, 2007].

Depending on the cooling rate of the asphalt mixture, there is an optimal time window to compact. If the asphalt mixture is compacted outside of these windows the asphalt mixture will be under stressed (if the mixture is compacted at too low temperatures) or overstressed (when the mixture is compacted at too high temperatures as discussed in section 3.3.1). These conditions are illustrated in figure 5, which schematically shows the temperature of the mixture as a function of time. For different mixtures and different conditions, the ideal compaction window shifts along the timescale [Bijleveld, 2012].

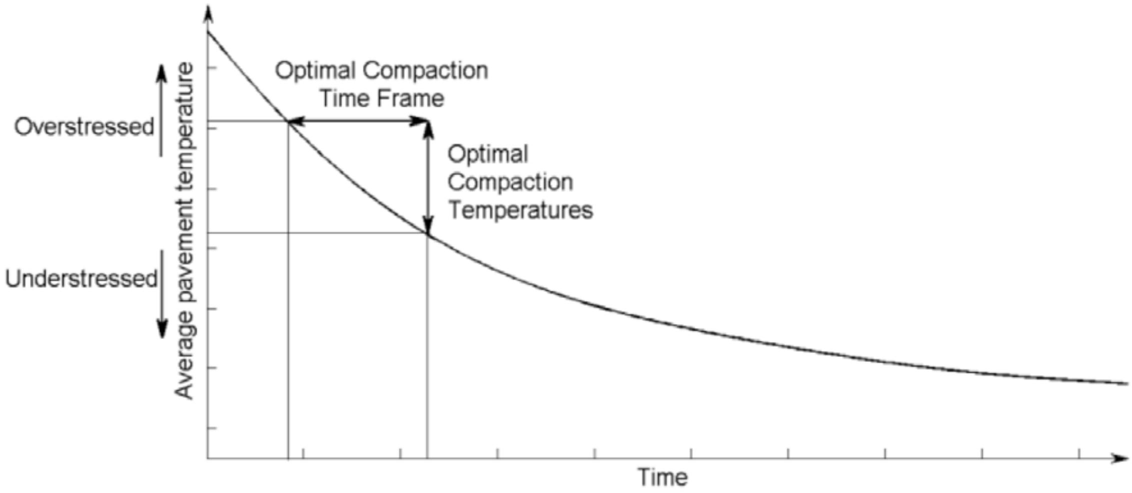

Figure 5: Cooling rate asphalt mixture and optimal compaction temperature and time frame. [Bijleveld, 2012].

The major factors affecting time available for compaction are [Nicholls et al, 2007, WTB, 2014]:

- Initial material temperature.
- Mat or lift thickness, with thicker lifts, having a smaller surface-to-volume ratio, losing heat more slowly and hence increasing the time available for compaction.
- Base or substrate temperature, with hotter surfaces removing heat from the mat at a slower rate and hence increasing the time available for compaction.
- Base or substrate moisture content
- Ambient temperature, with hotter air temperatures removing heat from the mat at a slower rate and hence increasing the time available for compaction.
- Wind speed, with higher wind speeds increasing the mat heat loss by convection and hence decreasing the time available for compaction.

3.3.7 Joints

3.3.7.1 General

On all but small jobs, regardless of the surface course used, it is necessary to construct a number of joints, both longitudinally and transversely to the direction of the pavement. A longitudinal joint occurs when a lane of hot asphalt is placed alongside an existing lane of asphalt at ambient temperature (or at any temperature below the minimum material compaction temperatures), whereas transverse joints are required at the end of a day's work and following any interruption in laying pavement layers that prevents continuity of rolling at, or above, the minimum compaction temperature of the mixture. Limiting the number of joints limits the weakest part of the pavement, this is influenced by a number of factors such as construction methods and matching supply to resources as discussed in section 3.3.6 (time). Parallel joints in the layers are to be avoided as they can create lines of weakness through the depth of the pavement structure, both longitudinal and transverse joints must be offset. Longitudinal joints must also coincide with either the lane edge or lane marking and lie outside of the wheel track zones.

With the advent of new stiffer, less workable materials poor workmanship can manifest itself initially as fretting at joints, so that joint sealing within the first few years of the life of a surfacing is not unusual. The main causes of joint fretting are poor compaction, low binder content and over-raking at the joint. Therefore, it is vitally important that asphalt is adequately compacted in the joint area.

3.3.7.2 Influence of job size

As joints are considered an area of weakness continuous supply reduces this problem. This can be facilitated through paving over longer lengths to reduce the number of transverse joints or paving multiple lanes (perhaps in echelon) to reduce the number of longitudinal joints. Influence of working time can also have a significant effect on the number of joints as possession time can often restrict the amount of material to be laid in any given shift. Although the size of the job can influence the paving operations, it remains subject to client needs and remains outside of the sphere of control.

3.3.7.3 Echelon paving

Echelon paving is potentially the optimum method for ensuring continuity and joint reduction as it ensures that the full width of the road surface (minimum two lanes) is laid and compacted at the same temperature and environmental conditions as shown in figure 6.

Figure 6: Echelon paving [worldhighways.com, 2011]

The Specification for Highway Works in the UK [MCHW, 2008] permits the utilisation of two or more pavers operating in echelon, where this is practicable, and in sufficient proximity for adjacent widths to be fully compacted by continuous rolling. The continuous rolling process ensures a high density is achieved at the joint.
Paving in echelon has the following benefits;

- It eliminates the formation of exposed pavement edges other than day joints
- Minimises exposed pavement edges ensuring less opportunity for ingress of detritus or moisture
- Reduces problems associated with paving when the mat/joint temperatures have dropped as the existing edge will not cool the newly material
- Reduces wastage, cost and time as no cutting back or trimming
- Improved uniformity, consistency
- Contributes to enhanced asphalt durability
- Potential reduction in construction time and whole life cost

The benefits of paving in echelon are offset with the need for closure of two or more lanes which can force increased disruption to the public.

3.3.7.4 Paving against a cold joint

Paving against a cold joint can result in numerous problems, namely reduction in density and increased permeability. Use of a joint heater allows formation of longitudinal joints to be formed when the adjacent width is being laid, but without cutting back or coating with binder. The purpose of the joint heater system is to raise the temperature of the full depth of the initially paved surface course (cold lane) to within the specified range of minimum rolling temperature and maximum temperature at any stage for the material (i.e. the plastic state) prior to the new adjacent hot mat being laid ensuring continuity of compaction across the joint and minimising the density gradient across the joint.

The disadvantages of using a joint heater system are increased time and energy resulting in increased costs to the contractor and premature ageing of the binder if not carried out in a controlled manner.

3.3.7.5 Paving against a free edge

The mixture placed by the paver will have a slope on its outside edge which will vary depending on the type of end plate on the paver screed. This edge material does not receive the same amount of compaction as the rest of the mixture due to its shape and position relative to the roller. Adequate compaction of this free edge is required to ensure durable joints.

Problems associated with inadequacies when paving against a free edge include;

- Poor bond
- Longitudinal crack
- Increased roughness at the joint
- Moisture/water ingress

In the UK the conventional method of construction of a longitudinal joint and compaction against a free edge is the industry standard butt-type joint. This technique achieves a high density at the joint and reduces the density gradient. The butt joint is a well-established construction technique that does not require any new equipment. However, the densities in the joint area are typically lower than those in the surrounding mat and this method has a history of ravelling at the joint [Nicholls et al, 2007].

3.3.7.6 Cutting back free edges

In the UK the Specification for Highway Works [MCHW, 2008] allows for the unconfined edge of the cold lane to be cut back to sufficiently compacted material, thereby removing the unconfined and low-density pavement edge. The exposed edges should be carefully cut back and trimmed to firm material in the compacted lane, or for a minimum equal to the layer thickness, whichever is the greater, and all loose material arising from this operation to be removed from the pavement before the cut edge is painted.

After cutting back, trimming and removal of loose material, the exposed vertical edge or face should be completely coated with binder (hot bitumen, cold-applied polymer modified intermediate or premium-grade bitumen emulsion, polymer modified binder combined with filler or polymer-modified adhesive bitumen strip) before the adjacent width is laid. Similarly, existing asphalt surfacing against which new surfacing is to be laid also needs to be cut back as necessary to remove all loose or weathered material, finishing with a vertical edge as do transverse joints.

Cutting back free edges results in an increase in density at the joint and a reduction in density gradient across the joint. In completion, the joints must present the same texture as the remainder of the surface and provide a uniform pavement surface. However the quality of the joint construction is dependent upon the skill of the operator and can often increase the cost of the pavement due to increased construction time, and discarded materials.

3.3.7.7 Influence of density

In general, the density of the asphalt will be less on the side of the joint that was laid first (cold lane) compared with the side laid second (hot lane). This difference is primarily due to the unsupported edge of the first lane placed not being able to fully resist horizontal movement during its compaction, whereas that free edge of the cold lane is able to resist any horizontal movement of the hot lane during the latter's compaction. This reduces the tensile strength of the pavement and leads to both longitudinal cracking and a high air voids content, which, in turn, leads to ravelling of the pavement along the longitudinal joint. Nicholls et al, 2007 notes that the performance of the longitudinal joint appears to be influenced by the overall density achieved at the longitudinal joint based on field trials undertaken in three US states. The best performing joints demonstrate a density at the joint that is within 2% of the material density [Nicholls et al, 2007].

3.3.8 Bond

Interlayer bond of asphalt pavements has been recognized recently as one of the critical variables affecting the pavement long term performance [Raab et al, 2012]. This bond;

- Prevents sliding surfaces between layers
- Enhances mechanical properties (including bearing capacity)
- Improves long term performance
- Allows the pavement to act as a bound layer as designed (rather than a series of thinner – semi- independent structures)
- Stops movement of water between asphalt layers

Problems associated with inadequate bond between layers include;

- Pumping due to water ingress
- Stripping due to water ingress
- Delamination or debonding
- Cracking
- Potholes
- Rutting

Bond coats, or at least tack coats, need to have adequate stability and viscosity in order both to properly penetrate the surface onto which they are applied, and to be able to deposit a good film at the surface. They are required to be applied [HA et al., 2009]:

- between all pavement layers;
- on areas that can be covered by the same day's paving; and
- on all vertical surfaces of existing pavements, kerbs, gutters and joints where new pavement material will is likely to be placed.

Tack and bond coats should be applied uniformly across the entire pavement surface and result in good surface coverage. Application rates will vary based on the condition of the pavement; too little tack/bond coat can result in inadequate bonding between layers whereas too much tack/bond coat can create a lubricated slippage plane between layers, or cause the tack/bond coat material to be drawn into the pavement layers above, negatively affecting mixture properties and even creating a potential for bleeding in thin pavement layers.

3.4 Materials and anticipated life span

3.4.1 Lifespan of materials

Materials have a wide range of in service lives, lifespan of a material is generally considered to be the time before major maintenance is required [ADEPT, 2013]. Historically there have been various theories relating to classical analysis that relied on homogeneity of materials in relation to design life. More recently [Nunn et al., 1997], thinking has been changed by the realisation that cracks start at the top of the pavement and goes down rather than the reverse. In practice, the surface layer is generally the only location where the binder is exposed to oxidation, so that the surface becomes more brittle than the rest and therefore, more susceptible to cracking. Under classical analysis, the structural pavement was generally designed for a design life of 40 years with strengthening after about 20 years. Under the revised approach a well-constructed pavement built above threshold strength was considered to have a very long life. The threshold strength is, in effect, a minimum thickness. Such structures are known as long-life pavements in Europe, or perpetual pavements in the USA. Deterioration in these pavements is assumed to be confined to the uppermost layers of asphalt and manifests itself as surface cracking or deformation, [Nicholls et al, 2007]. This project reviews lifespan of surface course materials only as not only do these materials require replacement for maintenance or reconstruction they are also exposed to climatic and traffic conditions.

Table 1 contains the current findings of service levels of various asphalt mixtures [Nicholls et al, 2007, ADEPT, 2013]. The information assumes that the surfacing was laid on a good-quality substrate, is reasonably heavily trafficked and will be replaced when it reaches an “Acceptable” visual condition. However, these figures should be treated with care because the actual service life achieved will be dependent on a myriad of other factors such as the inherent suitability of the site and the care and attention in the design, mixing and application of the asphalt.

Table 1: Service levels of various asphalt surface course materials [Nicholls et al, 2007, ADEPT, 2013]

Mixture type	Target Life/Years	Minimum Life (if known)/Years		Maximum Life Expected/ Years (Typical)
		Absolute	Typical	
Paver-laid surface dressing (PLSD) or ultra-thin layer asphalt concrete (UTLAC)			8	11
Thin asphalt concrete (TAC) or béton bitumineux très mince (BBTM)			11	15
Thin stone mastic asphalt (TSMA) or stone mastic asphalt (SMA)			10	16
Multiple surface dressing (MSD)			4	8
Micro-surfacing (MS)			2	6
Surface dressing – Single			3	5
Surface dressing – Double or			4	8

racked in				
Hot rolled asphalt (high and medium stability)			14	24
Hot rolled asphalt (low stability)			8	13
Asphalt Concrete –Open graded macadam			6	10
Asphalt Concrete – Marshall Asphalt			15	25
Porous Asphalt			7	10
High friction surfacing (hot)	4	2	3	5
High friction surfacing (cold)	8	2	6	10
Surface dressing	10	0.01	7	13
Microasphalt	10	3	7	13
Thin Surface Course Systems	15	5	10	20
Asphalt Concrete Surfacing	8	5	6	10
Hot Rolled Asphalt Design Mix	20	10	14	26

As shown in table 1, materials have a wide range of service lives, which depend on a number of factors including;

- Design being appropriate for traffic and substrate conditions (empirical design based on probability of achieving design life)
- Compliance with the materials and installation specification and practice
- Variation in laying thickness
- Budgetary, planning and traffic constraints for installation
- Overlaying onto existing statutory undertakers works where weak spots exist

However these factors all fall outside the scope of this project and will therefore not be included in information gathering exercises.

3.4.2 European surface course mixtures

This section details the surface course material and construction practices most commonly used across the project partner countries in order to provide focus to the study and model development. For the purposes of this report England and Ireland will be treated as one as both countries work to the same specification documentation.

3.4.2.1 England and Ireland

The most commonly used surface course mixtures in England and Ireland are as follows, the most popular being hot rolled asphalt whose mixture composition can be found in table 2;

- EN13108 Part 4 (HRA)
- EN 13108 Part 5 (SMA)
- EN 13108 Part 1 (AC)

Table 2: HRA 35/14 F surf 40/60 material composition, EN 13108-4

Grading (passing)	
20mm	100
14mm	95 to 100
10mm	62 to 81
6.3mm	
2.0mm	61
0.5mm	44 to 63
0.25mm	16 to 46
0.063mm	8
Binder Content,	$B_{min6.6}$
Binder Volume,	B_{vol11}
Void Content-	
-Maximum	V_{max8}
-Minimum,	V_{min2}
Water Sensitivity	$ITSR_{70}$
Temperature of the mixture	150ºC to 190ºC
Reaction to fire	Euroclass Cfl
Stiffness	1800MPa
Resistance to permanent deformation	
-small size device procedure A:	
-wheel tracking rate	$WTS_{air5.0}$
-rut depth	$Rd_{Air7.0}$

3.4.2.2 The Netherlands

The most commonly used mixture in The Netherlands is ZOAB 16+, material composition can be found in table 3. ZOAB 16+ is a porous asphalt conform NEN-EN 13108-7 with a binder content of at least 5,2 %.

Table 3: ZOAB 16+ material composition [RAW Standaard 2010].

Though sieve	**ZOAB 16+**
C22,4	100
C16	96 - 100
C11,2	70 - 85
C8	
2 mm	15 - 25
0,5 mm	Declared Value
0,063 mm	2,0 - 10,0

Materials	
Binder	70/100
Fine aggregate	Crushed sand
Filler	Hydroxide
Anti-stripping agent	
Properties	
Binder content	$B_{min5,2\%}$*
Void Content minimum	V_{min20}
Void Content maximum	V_{maxNR}
Susceptibility to water	$ITSR_{80}$
Drain off	D_{NR}

3.4.2.3 Slovenia

The most commonly used asphalt mixture in Slovenia for surface course is AC11surf B50/70 for main roads and SMA8 PMB 45/80-65 for motorways. Material composition for AC11surf B50/70 can be found in table 4.

Table 4: Material composition for AC11surf B50/70 A2 [SIST 1038-1:2008].

	Standard	**AC 11 surf B50/70 A2**
Though sieve	EN 12697-2	
22,4 mm		0
16 mm		100%
11,2 mm		90 – 100%
8 mm		70 – 90%
4 mm		45 – 70%
2 mm		30 – 55%
0,5 mm		
0,25 mm		10 – 25%
0,063 mm		6 – 12%
Materials		
Aggregate		For surface layers Z2 (characteristics - see Figure 2)
Binder		B50/70
Fine aggregate		Crushed limestone
Filler	EN 933-9	MBF 10 (Crushed limestone)
Filler	EN 13179-1	$\Delta_{R\&B}$ 8/25
Anti-stripping agent		No requirement
Properties	SIST 1038-1:2008	
Binder content	EN 12697-1	B_{min} no requirement

Void Content minimum	EN 12697-8	V_{min} 3
Void Content maximum	EN 12697-8	V_{max} 6.5
Voids in the mineral aggregate filled with binder minimum	EN 12697-8	VFB_{min} 65
Voids in the mineral aggregate filled with binder maximum	EN 12697-8	VFB_{max} 80
Voids content in the mineral aggregate	EN 12697-8	$VMA_{min\ NR}$
Susceptibility to water	EN 12697-12	$ITSR_{NR}$
Drain off		Not tested for AC surf
Wheel tracking (small size device, in air, 60°C)	EN 12697-22	PRD_{AIR} 7,0

Characteristics for produced Asphalt concrete are defined in:

- SIST 1038-1:2008 Bituminous mixture – material specifications – Part 1: Asphalt concrete – Requirements –Rules for implementation of SIST EN 13108-1 (table 6)

Characteristics for laid asphalt mixes are defined in

- TSC_06-300_410-2009_Smernice in tehnični pogoji za graditev asfaltnih plasti http://www.dc.gov.si/si/delovna_podrocja/ceste/tehnicne_specifikacije_za_ceste/izdane_ts/

For laid layer of AC11surf A2 the void content should be between V_{min2} and $V_{max8.5}$

4 Construction Quality and European Practice

4.1 Understanding quality

As changes begin to occur in the European road construction industry, contractors are becoming free to choose the type of asphalt mixture and construction to help drive improvements, innovate and share risk. Road agencies are moving towards performance with longer guarantee periods. Within these new roles and contracts, contractors are directly confronted with shortcomings in quality during the guarantee period. Therefore, it is important for contractors to control the quality of the asphalt pavement during construction. In this search for quality control, the paving process is crucial. To improve control over the paving process, contractors need to measure and monitor their own process, gain more understanding of the important mechanisms during this process and the interdependencies between these mechanisms [Bijleveld, 2012].

Already work has begun to try and address the short comings of quality control through research, Lipke and Ripke (2011) recognise that to achieve best possible quality in the construction process a large number of parameters have to be kept in optimal range. Work undertaken as part of the Process Secure Automated Road Construction project (PAST) identified a number of parameters and analysed in detail weak points that existed during asphalt installation; this led to development of a number of strategies for improvement of the various processes which were implemented in demonstrators. Information technology was used for process control whereas simulation models were used to address segregation problems and material transfer. Results of the study showed that the newly developed demonstrators, whilst not fully tested, will make an important contribution to improving quality [Lipke and Ripke, 2011]. Whilst the improvements relating to asphalt segregation remain beyond the scope of this study, the improvements relating to paving operations should not be overlooked.

This section aims to provide an understanding of the requirements in place in each of the partner countries and provide an overview of the quality control against the European landscape. With the introduction of harmonised European standards, many of the products (asphalt, aggregate, bitumen) can be, or will soon be able to be, purchased with a CE Mark. In some European countries, all products that can be CE Marked will have to be CE Marked before they can be put on the market as a requirement of the Construction Products Directive [European Commission, 1988]. CE Marks are not explicitly intended for quality control, but they do contain the supplier's assessment of how the product meets the mandated properties, for which they are legally liable. Different properties of component materials are important for different mixtures and usages and these are generally listed in the relevant clauses of the appropriate specification, for example the Specification for Highway Works [MCHW, 2008]. However, the properties considered are those required to achieve initial performance and not necessarily long-term durability [Nicholls et al, 2007].

4.2 European practice (partner countries)

4.2.1 England and Ireland

The method used in the UK is the application of Sector Scheme 16 and BS 594987, which imposes certain criteria and measurements that should be taken during the laying process. SSD 16 lays down the needs for a quality manual and what should be in it, such as laying records, together with minimum competencies for the operatives and the frequency of QA audits. BS594987 is the specification that contains such things as delivery, compaction and rolling temperatures. There are no set frequencies for these measurements but the only way to prove you have met the requirements would be take them for every load. Likewise with the comments on rain, wind speed and air temperature, if they are not taken on site then the contractor does not know he has complied with the requirements. On that basis the laying records in the quality plan would include:-

1. Visual inspection of the material
2. Temperature at delivery, laying(behind the screed) and after final rolling for each load
3. Wind speed
4. Air temperature
5. Rain
6. Chainage for load start
7. Chainage for load finish

These are as a minimum with 3-4 being at a frequency decided by the contractor, usually once per shift, unless it is in the contract specification.
All contracts should adopt these conditions if the contractor is claiming to be approved to SSD 16; however how well they are done depends on the contract. If the contract specifies

other site testing then a technician will be on site so they are probably done well, if there is no technician on site the banksman gets the job so they will only be superficial.

The control on compaction would be the use of a calibrated density gauge, but this is only used if specified in the contract so the level of compaction is left to the roller driver in all other cases. The depth of the material laid is often not checked during laying which will also have an effect on the compaction.

All material is delivered in insulated and sheeted vehicles but there is little check on the effectiveness of these items so as control measures they are not good.

BS 594987 is the specification that contains the requirements for laying and compaction and the relevant extracts can be found in Appendix A.

4.2.2 The Netherlands

The most common standard in which Quality control measures are listed as requirements is the "Standaard RAW Bepalingen 2010". The contractor should make a quality plan according to the Standaard RAW bepalingen to register all process control methods and register the application condition. In such plans the measures are more clearly defined. In this document the RAW requirements and an example of measures in a quality plan are presented.

From the Dutch Standard "Standaard RAW Bepalingen 2010", only the most relevant sentences of the RAW relating to quality control measures has been translated and is contained in Appendix B.

4.2.3 Slovenia

Quality control measures that must be taken during the laying process are defined in

- 'General and technical conditions for road construction' - book 3, appendix 2000. ['Splošni in tehnični pogoji za gradnjo cest'] and
- 'Guidelines and technical requirements for construction of asphalt layers' (2009) – TSC ['TSC 06.300/06.410:2009 Smernice in tehnični pogoji za graditev asfaltnih plasti'].

These documents are mandatory for construction of national roads (motorways and main roads), but not for construction of municipal roads (local roads) unless otherwise specified in the contract or design documents.

Before the commencement of asphalting works the Contractor must provide to the Supervising Engineer a 'Technological feasibility study'. The study includes data on

- Description of the works,
- Materials (asphalt mix and its Declaration of Performance)
- Methods of asphalting works – compaction (paver, number and type of rollers), delivery (distance of asphalt plant), schedule of works, competence of asphalt team
- Quality assurance – Quality control programme (number and type of tests for the contracted road section). For new contractors it may also include 'proof paving' of a test section.

The Engineers should approve the 'Technological feasibility study' before the start of works.

The scope of contractor's quality control (type of tests and their frequencies) are set in TSC. Most of the tests are performed on laid asphalt. There are set frequencies for control of asphalt temperatures at laying.
The contractor's laying records should include weather conditions (comments on rain and air temperature), temperature of asphalt at laying. The recommended (priporočena) and minimum (najnižja) temperatures of asphalt mix at laying are defined in TSC as shown in Figure 7. The temperature depends on the type of bitumen used in the asphalt mix.

Razpredelnica 3.2.2: Priporočena in najnižja temperatura bituminizirane zmesi pri vgradnji

Tip bitumna	Priporočena temperatura bituminizirane zmesi pri vgradnji (°C)	Najnižja temperatura bituminizirane zmesi za vgrajevalnim strojem (°C)
B 160/220	135	110
B100/150	140	115
B 70/100	145	120
B 50/70	155	130
B 35/50	165	140
PmB	po navodilih proizvajalca PmB	

Figure 7: Minimum temperatures of asphalt laying

Compaction and void content is controlled mainly by drilling of cores and testing in the laboratory and also by nuclear density gauge measurements on site. The target compaction and void content of commonly implemented asphalt mixes (ACbase, ACbin, ACsurf; SMA; PA and MA) are specified in the TSC.

All contractors have to provide the results of tests of produced and/or laid asphalt according to the approved Quality control programme. Contractor's Quality control report for motorway sections includes all the tests required by the TSC and some additional test required by the Investor. For main and regional roads the scope and quality of Quality control testing varies. The scope of the Quality control programme as required by TSC can be found in Appendix C.

5 Conclusions

On completion of the literature review it is clear that there are many factors and mechanisms which can influence the quality and durability of a pavement. It should be acknowledged that many of the factors are interdependent and prove difficult to assess on an individual basis. However, following review of the numerous pavement functions, degradation mechanisms and factors it has been possible to develop a relation matrix to conclude this report. This matrix will also assist with the development of the model and provide the main focus for the industry questionnaire. A copy of the relation matrix can be found supplied separately in a pdf file to be attached in Appendix D. The matrix brings together the information and displays the main function of the pavement at the top of the chart; the colour coding defines whether the function relates to safety, performance or service. Degradation mechanisms and factors form the basis for the matrix and are displayed horizontally and vertically respectively. To broadly link the mechanisms to the degradation factors an 'X' is marked in the correct column. To further define the degradation factors during the phases considered in this project the factors are split into T = transport, L = laying and C = compaction and assigned the following in accordance to the perceived likelihood of the mechanism occurring, H = high, M = medium and L = Low.

6 Acknowledgement

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Appendix A: England and Ireland Quality Control Documentation

BS 594987

BS 594987 is the specification and contains all the requirements for laying and compaction of which the following extracts are the main requirements:-

Transport

Loading of asphalt shall be carried out such that segregation is minimized. Asphalt shall be transported to the laying site in insulated and sheeted vehicles to prevent an excessive drop in temperature and to ensure its protection against adverse weather conditions. Substances that are likely to cause softening or damage to the asphalt (e.g. diesel oil, kerosene) shall not be used on the floor of a vehicle to facilitate discharge of the asphalt.

Delivery

Deliveries of asphalt to the laying site shall be co-ordinated with the rate of laying to avoid interruption to the laying process. Asphalt shall be delivered at a temperature that allows it to be compacted in accordance with the requirements of Clause **9**.

Preparatory Works

Asphalt shall only be laid on surfaces free from loose materials and foreign matter, e.g. mud, slurry or other deleterious material. Prior to commencement of laying, the underlying course shall be prepared to produce a stable surface of appropriate profile on which the asphalt is to be placed.

Resurfacing

An existing surface shall only be used as a base or binder course where the maximum depression under a 3 m straightedge placed longitudinally or under a template placed transversely does not exceed:
a) 25 mm when the resurfacing is to consist of two course work; or
b) 13 mm when the resurfacing is to be a single surface course.

If improvement of the surface is required, it shall be carried out by planning and/or by the addition of a regulating course.

Tack/Bond coats

Table 1 **Recommended target rates of application of tack coat in kg/m² of residual bitumen for newly laid asphalt – New construction**

Binder content upper layer	Binder content lower layer		
	⩽ 4%	4.1–5.0%	⩾ 5.1%
⩾ 5.1%	0.15	0.15	0.15
4.1–5.0%	0.20	0.15	0.15
⩽ 4%	0.25	0.20	0.15

Table 2 **Recommended target rates of application of tack coat in kg/m² of residual bitumen for existing surfaces – Maintenance**

Binder content upper layer	Nature of lower layer/existing surface		
	Fretted/binder lean (see Note 4)	Planed asphalt	Binder rich
⩾ 5.1%	0.20	0.15	0.15
4.1–5.0%	0.25	0.20	0.15
⩽ 4%	0.25	0.25	0.20

Table 3 **Recommended target rates of application of bond coat in kg/m² of residual binder for newly laid asphalt – New construction**

Binder content upper layer	Binder content lower layer		
	⩽ 4%	4.1–5.0%	⩾ 5.1%
⩾ 5.1%	0.15	0.15	0.15
4.1–5.0%	0.30	0.25	0.25
⩽ 4%	0.40	0.35	0.30

Table 4 **Recommended target rates of application of bond coat in kg/m² of residual binder for existing surfaces – Maintenance**

Binder content upper layer	Nature of lower layer/existing surface		
	Fretted/binder lean/concrete (see Note 4)	Planed asphalt	Binder rich
⩾ 5.1%	0.50	0.40	0.25
4.1–5.0%	0.60	0.50	0.35
⩽ 4%	0.60	0.60	0.40

Table 5 **Recommended target rates of application of bond coat in kg/m² of residual binder for improving the relative impermeability of the surface of a lower layer/existing surface**

Binder content upper layer	Nature of lower layer/existing surface (see Note 4)		
	Fretted/binder lean/concrete/ stiff bases	High stiffness modulus bases	Normal asphalt – slightly permeable
⩾ 5.1%	0.60	0.60	0.50
4.1–5.0%	0.60	0.60	0.50
⩽ 4%	0.80	0.70	0.60

Laying

Laying shall not be carried out if standing water is present on the surface to be covered. Laying shall be carried out with due regard to ambient weather conditions so that materials can be properly compacted. The asphalt shall not be laid on any surface which is frozen or covered with ice or snow. Laying shall cease when the air temperature reaches 0 °C on a falling thermometer, except in calm dry conditions, when laying shall cease if the air temperature reaches −3 °C on a falling thermometer.

The paver used shall be capable of laying the asphalt continuously so as to produce an even and compact surface to the required widths, thicknesses, profiles, cambers and crossfalls without causing segregation, dragging, burning, surface defects or irregularities. It shall also be capable of operating at such a speed as to permit continuous laying as far as supply and site conditions allow.

Joints

All longitudinal and transverse joints in surface courses shall be made flush. The following surface course joints shall be made by cutting back the edge to a vertical face that exposes the full thickness of the layer, discarding all loosened material and painting the vertical face completely with a thin uniform coating of hot applied 40/60 or 70/100 paving grade bitumen, or, if approved by the specifier, cold applied thixotropic bitumen emulsion of similar grade or polymer modified bitumen emulsion bond coat, before the adjacent width is laid:
a) all transverse joints;
b) joints where the asphalt abuts an existing surface;
c) all longitudinal joints in mixtures containing paving grade bitumen or polymer-modified binder

Compaction

Rollers and other compaction equipment shall be operated by skilled, experienced personnel.

All rollers shall be fitted with smooth quick-acting reverse mechanisms. Smooth steel wheeled rollers shall have wetting devices of at least the width of the rolls fitted. Rollers used shall be one of the following types:
a) dead weight rollers with smooth steel wheels, a rear roll-width of not less than 450 mm and a weight of not less than 6 t;
b) vibratory rollers of at least equivalent compactive capability as a); or
c) pneumatic tyred rollers of at least equivalent compactive capability as a)
Surface course and binder course mixtures shall be surface finished with a smooth steel wheeled roller, which can be a vibratory roller operating in a non-vibrating mode.

Table 9 **Minimum rolling temperatures for designed asphalt concrete dense, heavy duty and high modulus binder course and base (including EME2)**

Paving grade	Minimum rolling temperature °C
160/220 pen bitumen	60
100/150 pen bitumen	75
70/100 pen bitumen	90
40/60 pen bitumen	105
30/45 pen bitumen	110
10/20 or 15/25 pen bitumen	110

Compaction Control

Cores should be taken for compaction control and the suggested method is specified by material type.

Opening to Traffic

Newly laid sections of asphalt shall not be opened to traffic until they have cooled sufficiently for traffic not to cause undue damage.

Delivery and Compaction Temperatures

Annex A (informative) Recommended delivery and rolling temperatures for recipe asphalt concrete, HRA and SMA to BS EN 13108

Table A.1 **Minimum delivery and rolling temperatures for recipe asphalt concrete, HRA and SMA mixtures**

Material type		Binder grade	Minimum temperature °C	
			On arrival [A)]	Immediately prior to rolling [B)]
Asphalt concrete [C)]	Open surf and bin	160/220	95	75
		250/330	85	65
	Close, fine, medium, dense surf	70/100	130	100
		100/150	120	95
		160/220	110	85
		250/330	100	80
	Dense bin, base [D)]	40/60	130	100
		70/100	125	95
		100/150	120	90
		160/220	110	80
HRA	Surf [E)]	30/45	140	110
		40/60	140	110
		70/100	125	90
		100/150	120	85
	Reg, bin, base	30/45	130	105
		40/60	130	105
		70/100	125	90
		100/150	120	85
SMA	Surf, reg, bin	40/60	130	100
		70/100	125	90
		100/150	120	85

A) In the lorry within 30 minutes after arrival on site.

B) Greater compactive effort will be required to achieve acceptable air void content as temperatures approach the lower limit.

C) For slag mixtures, temperatures may be 10 °C lower than the recommended values.

D) Requirements for temperatures for substantial completion of rolling of designed bin and base asphalt concretes are found in Table 9.

E) Requirements for temperatures for substantial completion of rolling when applying chippings to HRA are found in Table 8.

Appendix B: The Netherlands Quality Control Documentation

31.0 Road pavements II

31.22.08 Requirements for the construction: Preparations

01 The surface should be clean and free of loose parts
02 The adhesive layer should be applied evenly
03 Apply the adhesive layer only on the surfaces as indicated in the specifications
04 Do not apply an adhesive layer on a wet surface
05 On vertical connections an asphalt adhesive should be applied, for Porous Asphalt make sure that the water flow is not prevented.
06 Outside temperatures around 0°C or lower, bitumen emulsion as an adhesive layer should be replaced by an asphalt adhesive layer; the temperature should be measured at 1m above ground level.

31.22.09 Requirements for the construction: Processing conditions

The contractor needs to take appropriate measures for the processing the asphalt. During construction the following conditions need to be recorded:

01 - Weather conditions (wind speed, temperature, rainfall). The temperature and wind speed (m/s) should be measured at 1 m above ground level.
- Weather conditions that adversely affect the processing quality and the measures taken.
- The location and surface of the of the asphalt applied under these weather conditions.

02 Application of Porous Asphalt only when the outdoor temperature satisfies the following formula:

$$t \geq w + 5$$

t = outdoor temperature in °C
w = wind speed in m/s

31.22.10 Requirements for the construction: Processing of asphalt using one or more mixing plant

01 Asphalt may be provided from no more than four mixing plants
02 using asphalt from different mixing plant is permitted under the condition that all mixtures are produced on the basis of the same type testing research.
03 If the asphalt doesn’t meet 02, the asphalt should be processed separately on distinguishable locations and the origin, location of processing, the amount of the different mixtures should be determined.

31.22.11 Requirements for the construction: transport of asphalt

01 The temperature difference of the asphalt should be <25°C. The asphalt should hardly be segregated.

31.22.12 Requirements for the construction: processing of asphalt, general

01 Asphalt should be applied with one or more asphalt pave. The layer should:
- adhere to the lower layer
- the texture should be evenly
- the compression should be evenly

02 The asphalt supply and the speed of the paver should be in line to minimize the interruptions in the work

03 Each layer of asphalt should be applied that the longitudinal and cross joints have an offset of 0.15 m.

04 Loose material should be removed at the longitudinal and cross joints before applying a new layer. The joints should be covered with an adhesive layer. For Porous Asphalt make sure that the water flow is not prevented.

05 Compaction of the asphalt should be done as quickly as possible after laying. Porous asphalt and stone mastic asphalt should not be compacted vibrating. After compaction no roller tracks may occur.

06 When the asphalt layer needs a topping of crushed sand or chippings, this should be done evenly over the surface, and should be pressed firmly at a surface temperature of at least 90°C .

Example

Recording of the construction conditions will be done by the external office. This office provides three employees to perform these activities and this according to Annex 8: Work instruction and the forms (see Appendices 1/5) will be used.

Points of attention: supply and processing:

Cleaning of the underlaying layer

- The road surface must be clean, so no more dirt is on the way, which may reduce the effect of the adhesive layer;
- If the underlying layer has an open structure, clean it as deep as possible.

Apply adhesive layer

- Emulsion changed yes/no

Production asphalt mixture

- Temperature
- Request Mill registration
- Production control results
- Additional research
- Extractions (at least 2 per test section)
- Marshall tablets (minimum 4 per test section)
- In advance and during production samples must be taken

Applyng the asphalt mixture

- location, indicate the boundaries of the test sections (start, end, type, see Appendix 1)
- record the speed of the spreader (including changes and stops) including times (see Annex 3A)
-
- assess visually the drain-off and segregation (in the truck / hopper, before the bar and after the bar, see Appendix 3A)
    - weather conditions (Annex 3A and 3B)
    - workability (not absolutely required: can be listed under Special features during construction (Annex 3A) or under comments (Appendix 3B)
    - asphalt temperature (in the truck, hopper, before the bar, after the bar and cooling over time, see appendix 5 and 3B)

- record compaction process (at least 2 times per test section, method: stone on the road, see Appendix 3B). The location of the stone is noted and the stone is clearly visible.
    - different rolling behavior (for example, vibrating tempering)
    - the temperature every 5 minutes (up to asphalt has cooled down to 70 ° C)

- start time
- weather conditions, such as temperature, rain / dry wind speed. (temperature measurement with thermocouple and / or infrared thermometer)
- equipment (Annex 4)
- Photographing the construction process c.q. texture

Points of attention photographing the test sections

- Photo of every machine in its entirety
- In advance of each section: overview
- During construction of the section: use of equipment
- Afterwards: surface / overview
- Surface (with a macro lens)

Recording conditions by contractors

The contractor must record the weather. In case of bad weather conditions for processing the asphalt, the following aspects in accordance with article 31 22 10 of the Standard RAW 2000, have to be recorded:

- the measures taken;
- the position and the surface of the asphalt applied under the relevant weather conditions.

The contractor must record a number of observations according to the Quality plan. Examples are measuring the outside temperature, the temperature of the incoming asphalt and asphalt temperature at the outlet of the hopper and the layer thickness (see Annex II Quality Plan-B point 9).

Recording production conditions

According to a separate work instruction, partner X will randomly record the production conditions in the asphalt mixing plant.

Operating control

The operating control will be carried out in accordance with the "Standard RAW Provisions" of the CROW.

Table 5 Operating control (production/asphalt mixture plant)

action/research	Who arranges this	Who carries out	amount/ frequency	Goal
1. Composition: Grading Binder content	Contractor	Contractor	2 per mixture	Bedrijfscontrole volgens artikel 31 24 03 lid 02
2. Void content plant mixed material (to calculate density mixture)	Contractor	Contractor	4 per mixture	Bedrijfscontrole volgens artikel 31 24 03 lid 02
3. Additional sampling materials (25 kg crushed stone, sand 5 kg, 2 kg filler, bitumen 2 x 2 kg) *	Contractor	External agency	every mixture	Onderzoek DWW en aanvullend onderzoek Extern bureau volgens tabel 7
4. Additional sampling mortar for additional research (2 kg per sample). Deliver mortar samples to Partner X.	Contractor	Contractor	4 per mixture	Onderzoek DWW en aanvullend onderzoek Extern bureau volgens tabel 7

* for the filler and binder, the contractor should ask the supplier to provide samples.

Table 6 Operating control during construction: hopper samples and cores

action/research	Who arranges this	Who carries out	amount/ frequency	Goal
1. Void content* (cores)	Contractor	Contractor	1/1000 m^2	Bedrijfscontrole art 31 24 03 lid 03
2 Degree of compaction* (cores) (bestek proef 67.1)	Contractor	Contractor	1/1000 m^2	Bedrijfscontrole art 31 24 03 lid 03
3. Layer thickness*(cores)	Contractor	Contractor	1/1000 m^2	Bedrijfscontrole art 31 24 03 lid 03. Zie boorschema draaiboek.
4. Additional drilling cores	Contractor	Contractor:	Per test	research

action/research	Who arranges this	Who carries out	amount/ frequency	Goal
(for permeability tests and nuclear density measurements)		provides cores to research institute	section: 5 cores 0,5 m right from core 1 - 5	

Appendix 3a Spreading test sections

SPREADING PROCESS			
date	….-….-……..	Ligging	(volgens BPS, anders tekenen)
Weather	unclouded/ slightly clouded/ cloudy/ fog/ dry/ rain/ snow/ ice storm	track Traffic lane	1 HRL 1 / 2 / 3
Outside temp	…….. °C	Lane width	………… m
Wind speed	…….. m/s	uit kant (strook)	……,…… m
surface	dry/drying/wet	uit kant (berm)	……,…… m
Test section	nr …… code ………	type:	
Road nr	……………………	Spreadmachine 1………………………..	
kilometer	km ………………	Spreadmachine 2………………………..	
Pavement type	…….	Spreadmachine 3………………………..	
contractor	…………………………….		
producer	…………………………….	Speed spread machine ………….. m/min	
processor	…………………………….		
observer	…………………………….		

spreadmachine	Contractor		start/end	stop 1	stop 2	stop 3
1		starttime				
		Endtime				
		location				
2		starttime				
		Endtime				
		location				
3		starttime				
		Endtime				
		location				

	cause:
stop 1	
stop 2	
stop 3	

During construction	

Appendix 3B compaction process

COMPACTION PROCESS			
date Weather Outside temp Wind speed	….-….-…….. unclouded/ slightly clouded/ cloudy/ fog/ dry/ rain/ snow/ ice storm …….. °C …….. m/s	Ligging track Traffic lane Lane width uit kant (strook)	(volgens BPS, anders tekenen) 1 HRL 1 / 2 / 3 …………. m ……,…… m
Test section Road nr kilometer Pavement type contractor producer processor	nr …… code ……… ………………… km ……………… ……. ……………………………. ……………………………. …………………………….	Lower layer/ top layer Mixture lnr. ……….. Roll 1: ………………………………………….. Roll 2: ………………………………………….. Roll 3: ………………………………………….. Roll 4: …………………………………………..	

observer	……………………………					
duration applying asphalt [minutes]	asphalt temperature [°C]	Number of rolls per roller type				Remarks
		roll 1	roll 2	roll 3	roll 4	
starttime: ……..						
5						
10						
15						
20						
25						
30						
35						
40						
45						
50						
55						
60						
65						
70						
75						
80						

Appendix 4 Equipement

Equipement	Mark, type	Year of construction of the equipement	specialties	Operating weight
SPREAD MACHINE 1 SCREED				
SPREAD MACHINE 2 SCREED				
SPREAD MACHINE 3 SCREED				
DOUBLE DRUM ROLLERS				
DOUBLE DRUM ROLLERS				
THREE WEEL ROLLER				
THREE WEEL ROLLER				
. . . .				
. . . .				
. . . .				
SPLIT SPREADER				
Spraying car/ handspray	.. (type emulsion)			

Appendix 5 Temperature measurements

<table>
<tr><td colspan="8">TEMPERATURE MEASUREMENTS</td></tr>
<tr><td colspan="2">date

weather

Outside temperatuur

windspeed

surface</td><td colspan="3">….-….-……..

onbewolkt/ licht bewolkt/ bewolkt/ mist/ droog/ regen/ sneeuw/ hagel

…….. °C

…….. m/s

dry / drying / wet</td><td>Location

Track

Lane

Lane width</td><td colspan="2">(volgens BPS, anders tekenen)

1HRL

1 / 2 / 3

……….. m</td></tr>
<tr><td colspan="2">Test section

Road nr

kilometer

Pavement type

contractor

producer

processor</td><td colspan="3">nr …… code ………

km ………………

…….

…………………………….

…………………………….

…………………………….</td><td colspan="3">Lower layer / top layer mixturenr. ………..

thermometer type: ……………………

nr: …………</td></tr>
<tr><td rowspan="2">km</td><td rowspan="2">time</td><td rowspan="2">License plate

truck</td><td rowspan="2">air

temperature

[°C]</td><td colspan="3">Asphalt temperature</td><td rowspan="2">remarks</td></tr>
<tr><td>hopper
[°C]</td><td>before bar
[°C]</td><td>after bar
[°C]</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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</table>

Appendix C: Slovenia Quality Control Documentation

TSC 06.300/06.410:2009

'TSC 06.300/06.410:2009 Guidelines and technical requirements for construction of asphalt layer' (TSC) contains the requirements for laying and compaction of asphalt mixes that are commonly used in Slovenia (ACbase, ACbin, ACsurf; SMA; PA and MA). Short summary of some of the requirements is given below.

Technical feasibility study (TFS)
At least 14 days prior to the beginning of asphalt laying, the Contractor must provide TFS to the Supervising engineer for approval. TFS must include:

- Data on materials (Certificate of factory production control, Declaration of Performance (before 2014 Declaration of Conformity), for surface layers also report on results of low temperature cracking tests (that is the maximum tensile strength reserve value and the corresponding temperature).
- Description of all phases of asphalting works - compaction (paver, number of rollers), delivery (distance between the asphalt plant and construction site), schedule of works, competence of asphalt team
- Data on equipment (type, capacity).
- 'Quality control programme' – the minimum number and type of tests is defined in TSC. Number and type of tests for the contracted road section must be approved by the Supervising engineer. For contractors, who did not perform similar work yet, it may also include 'proof paving' of a test section.
- Data on a list of responsible and professional staff on site.

All contractors have to provide the results of tests of produced and/or laid asphalt according to the approved 'Quality control programme'. Contractor's Quality control report for motorway sections includes all the tests required by the TSC and some additional test required by the Investor. For main and regional roads the scope and quality of Quality control testing varies. An example of the scope of testing is shown at the end of this annex.

Delivery
Loading of asphalt shall be carried out such that segregation is minimized. Asphalt shall be transported to the laying site in sheeted vehicles to prevent an excessive drop in temperature, to ensure its protection against adverse weather conditions and contamination. Only substances that do not cause damage to the asphalt shall be used on the floor and walls of a vehicle to facilitate discharge of the asphalt.
The number of vehicles shall be adequate and well coordinated to ensure continuous delivery to the site to avoid interruption to the laying process. For transport distance over 70km, only vehicles with thermal insulation shall be used.

Asphalt shall be delivered at a temperature that allows it to be adequately compacted. The recommended (priporočena) and minimum (najnižja) temperatures of asphalt mix at laying (that is behind the paver) are defined in TSC (table 3.2.2) as shown below. The temperature depends on the type of bitumen used in the asphalt mix. For polymer modified bitumens the temperatures shall be defined by the producer. Temperature at laying shall be measured by the Contractor at every 1000t of asphalt mix.

Razpredelnica 3.2.2: Priporočena in najnižja temperatura bituminizirane zmesi pri vgradnji

Tip bitumna	Priporočena temperatura bituminizirane zmesi pri vgradnji (°C)	Najnižja temperatura bituminizirane zmesi za vgrajevalnim strojem (°C)
B 160/220 B100/150 B 70/100 B 50/70 B 35/50	135 140 145 155 165	110 115 120 130 140
PmB	po navodilih proizvajalca PmB	

Preparatory Works

The asphalting works may start only after the underlying course is inspected and approved by the Supervising engineer.
Asphalt shall only be laid on dry surfaces free from loose materials and foreign matter. Prior to commencement of laying, the underlying course shall be prepared to produce a stable surface of appropriate profile on which the asphalt is to be placed.
The evenness shall be checked with a 4m straightedge according to SIST EN 13036-7 and TSC 06.610 (Properties of pavements – evenness). An existing surface shall only be used as the underlying course where the maximum depression under a 4 m straightedge placed longitudinally or transversely does not exceed:
a) 10 mm when overlaying with a wearing course
b) 15 mm when overlaying with a binder course.
c) 20 mm when overlaying with a base course.

Bond coats

To ensure adhesiveness a bond coat shall be applied. The rates of application of bond coat depend on the nature of the exiting surface and shall be defined for every single situation.
To enhance impermeability of asphalt layer under the porous asphalt
- A polymer bitumen shall be applied at 1.0 to 1.5 kg/m^2
- Polymer bitumen emulsion shall be applied at 1.5 to 2.2 kg/m^2.

Laying

The paver used shall be capable of laying the asphalt continuously so as to produce an even and compact surface. The paver shall be capable of compacting to a 85% of the reference density. Deviation from this requirement must be approved by the supervising engineer.

Laying shall be carried out with regard to ambient weather conditions so that materials can be properly compacted. Laying of wearing course shall cease when the air temperature reaches 3°C, laying of base layer shall stop when the air temperature reaches 0°C.
In general the asphalt shall not be laid on any surface which is frozen or covered with ice or snow. Supervising engineer may exceptionally approve laying in calm dry conditions on dry, unfrozen surface at lower ambient temperatures.

Asphalt layer shall be compacted from the edge of the road to the centerline and in the upward direction. Roller paths shall overlap by 15 to 20 cm. Stops, change of direction and rapid braking and acceleration of rollers shall be avoided.

Compaction

Rollers and other compaction equipment shall be operated by skilled, experienced personnel.
Maximum temperature of bituminous mixtures at laying may be up to 20°C higher than recommended.
When compacting in windy weather and cold weather the minimum temperature of bituminous mixtures at laying shall be 10°C higher than the minimum required value.

Compaction Control

Quality control is oriented towards control of laid asphalt. Compaction is controlled by drilling of cores and testing in the laboratory and also by a nuclear density gauge measurement at site. The target compaction and void content of commonly implemented asphalt mixes (ACbase, ACbin, ACsurf; SMA; PA and MA) are specified in the TSC. The limit values for ACsurf are given below.

Razpredelnica 5.2.3.5: Mejne vrednosti za prostorske lastnosti vgrajenih bituminiziranih zmesi bitumenskih betonov

Lastnost	Enota mere	Skupine prometnih obremenitev in vrste bituminiziranih zmesi AC surf							Postopek za preskus
		izredno težka	zelo težka	težka	srednja	lahka	zelo lahka	hodniki za pešce, kolesarske steze, ipd.	
		A1	A2		A3	A4		A5	
- zgoščenost plasti	%	≥ 98			≥ 97	≥ 96		≥ 96	TSC 06.711
- vsebnost votlin v plasti	V.-%	$V_{min2} - V_{max8,5}$			$V_{min2} - V_{max9}$	$V_{min1} - V_{max9}$		$V_{min1} - V_{max6,5}$	SIST EN 12697-8
- največja sorazmerna globina kolesnic	%	PRD_{AIR} 7,0							SIST EN 12697-22

Quality control

The quality control of construction of public roads always includes:

Contractor's control
The contractor shall provide laboratory and staff to perform the necessary tests according to the Quality Control programme.

Investor's control
Investor's control shall be performed by accredited asphalt laboratory – the scope of tests is defined in the Quality Control programme.

The frequencies of tests for an example of construction of AC pavement are shown below for ACbase, ACbin and ACsurf course for approx. pavement area of 10000m^2 .

Quality Control programme - Example for Asphalt Concrete

Asphalt mixtures (TSC 06.300/06.410)

	Regulations (standard, TSC,...)	asphaltin works unit of measure	quantity	Contractor's control per unit of quantity	No. of test	Investor's control per unit of quantity	No. of test

1.0 AC base course

1.2 Laid asphalt mix

drilling of cores

	Regulations (standard, TSC,...)	unit of measure	quantity	Contractor's control per unit of quantity	No. of test	Investor's control per unit of quantity	No. of test
Determination of bulk density of bituminous specimen	SIST EN 12697-6	t	1800	1000	2	4000	1
Determination of void characteristics of bituminous specimens	SIST EN 12697-8	t	1800	1000	2	4000	1
Determination of the reference density	SIST EN 12697-9	t	1800	1000	2	4000	1
Determination of the thickness of a bituminous pavement	SIST EN 12697-36	t	1800	1000	2	4000	1
Wheel tracking (small size device, in air, 60°C)	SIST EN 12697-22	t	1800	DoP	0	8000	1
Standard Test Method for Density of Bituminous Concrete in Place by Nucle	ASTM D2950-91	m^2	9783	200	49	400	25

2.0 AC bin course

2.1 Produced asphalt mix

	Regulations (standard, TSC,...)	unit of measure	quantity	Contractor's control per unit of quantity	No. of test	Investor's control per unit of quantity	No. of test
Soluble binder content	SIST EN 12697-1	t	1900	1000	2	4000	1
Determination of particle size distribution	SIST EN 12697-2	t	1900	1000	2	4000	1
Determination of the maximum density	SIST EN 12697-5	t	1900	1000	2	4000	1
Determination of bulk density of bituminous specimen	SIST EN 12697-6	t	1900	1000	2	4000	1
Determination of void characteristics of bituminous specimens	SIST EN 12697-8	t	1900	1000	2	4000	1
Determination of the water sensivity of bituminous specimens	SIST EN 12697-12	t	1900	DoP	0	8000	1
Stiffness	SIST EN 12697-26, annexB		1900	DoP	0	8000	1
Resistance to fatigue	SIST EN 12697-24, annexD		1900	DoP	0	8000	1

2.2 Laid asphalt mix

drilling of cores

	Regulations (standard, TSC,...)	unit of measure	quantity	Contractor's control per unit of quantity	No. of test	Investor's control per unit of quantity	No. of test
Determination of bulk density of bituminous specimen	SIST EN 12697-6	t	1900	1000	2	4000	1
Determination of void characteristics of bituminous specimens	SIST EN 12697-8	t	1900	1000	2	4000	1
Determination of the reference density	SIST EN 12697-9	t	1900	1000	2	4000	1
Determination of the thickness of a bituminous pavement	SIST EN 12697-36	t	1900	1000	2	4000	1
Determination of adhesiveness of bituminous layers	TSC 06.753	t	1900	1000	2	4000	1
Wheel tracking (small size device, in air, 60°C)	SIST EN 12697-22	t	1900	1000	2	8000	1
Standard Test Method for Density of Bituminous Concrete in Place by Nucle	ASTM D2950-91	m2	10327	200	52	400	26

2.3 Extracted bitumen

	Regulations (standard, TSC,...)	unit of measure	quantity	Contractor's control per unit of quantity	No. of test	Investor's control per unit of quantity	No. of test
Determination of softening point - Ring and Ball method	SIST EN 1427	t	1900	4000	1	4000	1
Determination of needle penetration	SIST EN 1426	t	1900	4000	1	4000	1
Determination of the Fraass breaking point	SIST EN 12593	t	1900		-	4000	-
Bustimung der Duktilitat	DIN 52013	t	1900		-	4000	-
For polymer modified bitumens							
Determination of the elastic recovery of modified bitumen	SIST EN 13398		1900		-	4000	-
the force ductility method at 10°C	SIST EN 13589 in 13703		1900		-	4000	-
the force ductility method at 25°C	SIST EN 13589 in 13703		1900		-	4000	-

3.0 AC surf course

3.1 Produced asphalt mixture

	Regulations (standard, TSC,...)	unit of measure	quantity	Contractor's control per unit of quantity	No. of test	Investor's control per unit of quantity	No. of test
Soluble binder content	SIST EN 12697-1	t	950	500	2	2500	1
Determination of particle size distribution	SIST EN 12697-2	t	950	500	2	2500	1
Determination of the maximum density	SIST EN 12697-5	t	950	500	2	2500	1
Determination of bulk density of bituminous specimen	SIST EN 12697-6	t	950	500	2	2500	1
Determination of void characteristics of bituminous specimens	SIST EN 12697-8	t	950	500	2	2500	1
Determination of the water sensivity of bituminous specimens	SIST EN 12697-12	t	950	DoP	-	8000	1

3.2 Laid asphalt mix

drilling of cores

	Regulations (standard, TSC,...)	unit of measure	quantity	Contractor's control per unit of quantity	No. of test	Investor's control per unit of quantity	No. of test
Determination of bulk density of bituminous specimen	SIST EN 12697-6	t	950	500	2	2500	1
Determination of void characteristics of bituminous specimens	SIST EN 12697-8	t	950	500	2	2500	1
Determination of the reference density	SIST EN 12697-9	t	950	500	2	2500	1
Determination of the thickness of a bituminous pavement	SIST EN 12697-36	t	950	500	2	2500	1
Determination of adhesiveness of bituminous layers	TSC 06.753	t	950	500	2	2500	1
Wheel tracking (small size device, in air, 60°C)	SIST EN 12697-22	t	950	DoP	0	8000	1
Standard Test Method for Density of Bituminous Concrete in Place by Nucle	ASTM D2950-91	m^2	10417	100	105	200	30

3.3 Extracted bitumen

	Regulations (standard, TSC,...)	unit of measure	quantity	Contractor's control per unit of quantity	No. of test	Investor's control per unit of quantity	No. of test
Determination of softening point - Ring and Ball method	SIST EN 1427	t	950	2500	1	2500	1
Determination of needle penetration	SIST EN 1426	t	950	2500	1	2500	1
Determination of the Fraass breaking point	SIST EN 12593	t	950		-	2500	1
Bustimung der Duktilitat	DIN 52013	t	950		-	2500	1
For polymer modified bitumens							
Determination of the elastic recovery of modified bitumen	SIST EN 13398	t	950		-	2500	-
the force ductility method at 10°C	SIST EN 13589 in 137	t	950		-	2500	-
the force ductility method at 25°C	DIN 52013, SIST EN 1	t	950		-	2500	-

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Appendix D: Relation Matrix

		Function										Safety	Performance	Service
		Skid Resistance		Noise Level		Ride Quality		Texture		Structural Stability (Stiffness)	Fatigue Resistance			
		Degradation Mechanisms												
Degradation Factors (combination of asphalt and pavement durability)	Phase	Rutting	Ravelling/Fretting	Cracking	Bleeding/Fatting Up	De-Bonding	Ageing (UV)	Stripping	Water Ingress/ Moisture Damage			Influenced/Interdependent on		
Temperature			X					X	X					
	T	L	L	L	L	L	L	L	L					
	L	H	H	M	M	M	L	M	M					
	C	M	H	M	M	H	L	H	H					
Environment			X	X				X						
....Ambient Temperature <5C	T	L	L	L	L	L	L	L	L					
....Wind Chill >15mph (or 24km/h)	L	M	M	M	L	M	L	L	L					
....Ambient Temperature <5C	L	M	M	M	L	M	L	M	L					
....Rainfall	L	L	L	L	L	M	L	M	H					
....Wind Chill >15mph (or 24km/h)	C	M	M	M	M	M	L	M	L					
....Ambient Temperature <5C	C	M	M	M	M	M	L	M	M					
....Rainfall	C	M	M	M	M	M	L	M	H					
Compaction		X		X			X		X			Environmental (wind speed, solar, ground and air temp), Aggregate and Binder factors, Lift thickness, type and number of roller passes, speed and timing of rollers, mix temperature, haulage time and distance		
....Void content	C	H	H	H	M	M	L	M	H					
....Number of roller passes	C	L	H	M	M	M	L	L	M					
Equipment														
....Basic equipment (no insulation)	T	L	L	L	L	L	L	M	L					
....Conventional equipment (thermal insulation)	T	L	L	L	L	L	L	L	L					
....Intelligent equipment (temperature monitoring)	T	L	L	L	L	L	L	L	L					
....Basic equipment (lightweight roller)	L	H	M	H	M	H	L	M	M					
....Conventional equipment (choice of roller)	L	M	M	M	M	M	L	L	L					
....Intelligent equipment (temperature plots)	L	M	M	M	M	M	L	L	L					
....Basic equipment (no vibratory screed)	C	H	H	H	H	H	L	M	L					
....Conventional equipment (vibratory screed)	C	M	M	M	M	M	L	L	L					
....Intelligent equipment (laserline and gps)	C	L	L	L	L	L	L	L	L					
Workmanship														
....New inexperienced operatives	T	L	L	L	L	L	L	L	L					
....Trained operatives	T	L	L	L	L	L	L	L	L					
....Experienced operatives	T	L	L	L	L	L	L	L	L					
....New inexperienced operatives	L	M	M	M	M	M	L	M	M					
....Trained operatives	L	M	M	M	M	M	L	M	M					
....Experienced operatives	L	M	M	M	M	M	L	M	M					
....New inexperienced operatives	C	H	H	H	H	H	L	H	H					
....Trained operatives	C	H	H	H	H	H	L	H	H					
....Experienced operatives	C	H	H	H	H	H	L	H	H					
Travel time and delays												(In relation to cooling rate) Layer thickness, air temperature. Base temperature, base moisture content, mix laydown temperature, wind velocity, amount of sunshine		
....Haulage time from the plant	T	L	L	L	L	L	H	L	L					
....Queue to offload (in relation to leaving the asphalt plar	L	M	H	M	M	M	H	L	L					
....Waiting at paver for next load	C	M	H	M	M	M	H	L	M					
Joints			X	X					X			Poor compaction, low binder content, over raking at the joint.		
....Hot matched or warm painted	L	L	L	L	L	L	L	L	L					
....Cold trimmed and painted	L	L	M	M	L	M	L	L	M					
....Cold and unpainted	L	L	H	H	L	H	L	L	H					
....Number of joints	L	L	H	M	L	H	L	L	M					
Interlayer bond		X		X		X		X	X					
....Contaminated surface	L	L	H	L	L	H	L	M	H					
....No bond coat	L	L	H	L	L	H	L	H	H					
....Target bond coat +0.2l/m^3	L	L	M	L	L	M	L	M	M					
....Target bond coat +0.4l/m^3	L	L	L	L	L	L	L	L	L					