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DRaT – Development of the Ravelling Test

Review of parameters influencing the propensity of asphalt to ravel

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DRaT
Development of the Ravelling Test

Review of parameters influencing the propensity of asphalt to ravel

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Executive summary

This report is an output of the Development of the Ravelling Test (DRaT) project. The DRaT project was undertaken under CEDR Call2014: Asset Management and Maintenance in order to investigate the use of standard ravelling tests to predict the sensitivity to ravelling of an asphalt mixture.

The report describes the findings of a literature review into the phenomenon of ravelling (or scuffing or fretting) of asphalt pavement. This failure mechanism is restricted to surface course materials because that layer is the one that receives the full scuffing forces imposed by vehicle tyres when turning or braking.

The review consists of sections on the definition and mechanism of ravelling, the various potential causes of ravelling and strategies for prevention and cure. Testing for the potential of mixtures has not been explicitly covered because the lack of any accepted test for this property is generally accepted in the need for this project. Some correlations of other asphalt or bitumen parameters with a tendency to ravel have been included in the strategies to minimise ravelling.

Whilst there is an acceptance of the ravelling failure mechanism and its importance, there appears to be limited research into the subject. Nevertheless, it has been found that there are a large number of factors that affect the potential for ravelling. These factors include:

<u>Materials</u>:
- Hydrophobic aggregates are preferred with better potential affinity to bitumen.
- Aggregates should be clean when mixed into asphalt.
- Adhesion promotors which improve binder-aggregate adhesion may decrease the ravelling potential.

<u>Mix design</u>:
- The binder content should be as high as practicable without causing other problems such as rutting or bleeding in order to minimise the potential for ravelling.
- The use of more viscous binders will reduce the tendency for ravelling whilst the advantage of using PmBs is uncertain.
- Both larger maximum aggregate size and a coarser grading tend to increase the potential for ravelling.

<u>Construction</u>:
- Poor compaction results in high air voids contents, which reduces the adhesion of particles in the mat.
- Excessive or badly constructed joints and slot cuts can initiate ravelling. Poor quality joints are zones which are more susceptible to ravelling
- Segregation will result in areas with high air voids contents which are more likely to ravel.
- The layer thickness should not be less than twice the maximum aggregate size.
- Asphalt that is not sufficiently hot when compacted is liable to ravel due to poor or bad compaction.
- Asphalt should not be laid in the wet and/or very cold conditions.

<u>In situ</u>:
- Bitumen ageing from overheating during mixing leads to premature ravelling while that from weathering affects the potential for ravelling in the longer term.

- Ravelling damage tends to be more severe during cold weather, particularly in freezing conditions.
- Hot weather may also lead to ravelling, but the mechanism will be different (softening of the binder instead of brittleness)
- Heavy and frequent rainfall can also exacerbate ravelling.
- High shear or torsional forces are the direct causes of ravelling, so ravelling will predominate where braking, acceleration and cornering are present.
- Joints and slot cuts are potential areas where ravelling will start.

Whilst it has been suggested that the best indicators for a propensity to ravel are the phase angle from the flexural fatigue test the fracture toughness from the semi-circular bending test, the use of ravelling tests are better measures of the propensity to ravel.

The basic strategy to minimise ravelling is to produce and lay a material that will overcome these various causes for ravelling, to apply the best possible construction practices and to use only highly resistant mixtures in zones which are subjected to very high shear stresses.

Repair techniques include pothole repairs, removal followed by an overlay and surface treatments depending on the area affected and the precise cause.

1 Introduction

Ravelling is a common mode of early failure for many types of asphalt pavement. The potential causes for this loss of aggregate particles include lack of sufficient binder; inappropriate aggregate grading; poor adhesion between the binder and the aggregate; errors during compacting; aggressive scuffing by the traffic; and ageing, effect of climatic conditions. The number of different causes and their interdependence currently make it difficult to assess the theoretical potential to ravel of an asphalt mixture in the design stage. This is contrary to the general progression towards the design of asphalt mixtures to be resistant to the other principal modes of failure.

Highway authorities need to specify against all the modes of failure that can foreseeably occur. Currently, ravelling is generally attempted to be curtailed by specifying minimum binder content, aggregate grading envelopes and aggregate/binder affinity, but these are indirect assessments that have also been used to counter other aspects of asphalt performance. Recently several simulative laboratory tests have been developed that are claimed to give an indication of that potential. These tests use scuffing machines that repeatedly apply a scuffing action to slab or core samples to replicate in service loading. The test methods for four such scuffing machines have been written up as a draft technical specification by Comité Européen de Normalisation (CEN) as prCEN/TS 12697-50, Resistance to scuffing. However, these methods need to be culled or combined so that there is only one test method for this one property before the technical specification can be converted into a test standard.

There is need for a direct scuffing test to assess the resistance to ravelling of asphalt mixtures, but this method needs to be a single measure that is validated against site performance and has good precision. Therefore, the Conferences of European Directors of Roads (CEDR) has commissioned a project to undertake comparative tests with the four scuffing machines. However, before undertaking the physical testing required, the project has started with a review of the available literature to identify the parameters that can influence the propensity for mixtures to ravel. This report gives the findings of that review.

2 Ravelling

2.1 Terminology

The loss of aggregate from an asphalt pavement surface is called by several different names. The terms are sometimes used to indicate slightly different phenomena whilst at other times each is used to describe the full range.

Fretting has been defined as:
- the loss of fine material from a road surface (Thom, 2014).
- the loss of mortar (binder, fine aggregate and filler) from the surface, usually including the adjacent coarse aggregate (Taggart *et al*., undated)
- defines fretting to describe a surface material that is beginning to lose its surface gradually, usually due to age (Summers, 2000/15).

Ravelling is primarily the loss of the coarse aggregate particles. However, the presence of fretting can develop into ravelling when the support for the aggregate particles is sufficiently reduced to allow the loss of aggregate particles from a road pavement, often described as chipping loss (Thom, 2014).

Therefore, fretting is the loss of the mortar and fine aggregate, which removes the support for larger aggregate particles and hence facilitates their loss, while ravelling is the plucking out of coarse aggregate particles, leaving the mortar exposed to abrasion from passing vehicle tyres. The order may differ, but the final result is the same.

Scuffing is another term that has been used as an acronym for ravelling or fretting, but the term can be confused with tyre scuffing, where tyre rubber is left on asphalt making it look unsightly (Minnesota Asphalt Pavement Association, 2010). Tyre scuffing will not affect the integrity or durability of the pavement surface whereas ravelling will adversely affect performance and durability.

For this review, ravelling will be the term used irrespective of which term was used in the original source.

Stripping can be confused with ravelling because it usually results in ravelling (Taggart *et al*., undated) but it differs from ravelling because stripping removes all the binder from the aggregate while some binder remains with ravelling on detailed inspection (Peterson, 1987). However, the distinction is not usually practical in condition surveys. Nevertheless, stripping is a different failure mechanism because it can give rise to other forms of deterioration such as debonding (Taggart *et al*., undated). Fretting can also be confused with ageing, when oxidation of the binder causes loss of the adhesion (Northwest Pavement Management Association, undated).

2.2 Mechanism

Ravelling is one of the most common, but easily preventable, failure modes of asphalt pavements (Caterpillar Paving Products Inc., 2015). It is the progressive dislodgement and loss of fine and then coarse aggregate from the road surface (Nikolaides, 2015, Caterpillar Paving Products Inc., 2015) by the passage of traffic (Taggart *et al*., undated; Hunter *et al*., 2015) or weathering (Olsen, 1993). Once ravelling of a pavement has been initiated, the deterioration becoming progressively faster with time, with the various stages of ravelling usually being described as light (loss of surface fines), moderate (loss of fines and some coarse aggregate particles), and severe (loss of fine and coarse aggregate) (Caterpillar Paving Products Inc., 2015).

Ravelling has been suggested to be of two types, a short- and long-term ravelling. Short-term ravelling, caused by traffic, is assumed to be caused by intense shearing force at the tyre pavement interface, and is often seen on newly laid roundabouts. Long-term ravelling, which includes any weakening of the pavement caused by ageing and/or weathering, is assumed to be caused by mechanical force where progressive plucking of the aggregate is occurring due to the binder being unable to hold on to the fine and coarse aggregates (van Loon and Butcher, 2003).

Ravelling occurs when the micromechanical bond between binder and aggregate reaches a critical point (Taggart *et al*., undated). The tensile stress (induced in the binder as a result of the movement) exceeds then the breaking stress of the binder and cohesive fracture of the binder will occur, resulting in the aggregate particles becoming detached from the road surface. Thus, ravelling is most likely to occur at low temperatures and at short loading times when the stiffness of the binder is high (Hunter *et al*., 2015).

The mechanisms which cause the bond to become inadequate are complex and frequently interactive but are likely to be triggered by environmental factors. Rapid failure can occur with water pressure and suction effects on the surface resulting from the passage of vehicle tyres. In matrix dominated materials, the process tends to occur slowly because generally the asphalt is impermeable and environmental intrusion is very limited. However, in aggregate dominated materials, once the lateral support of one particle is lost, ravelling can occur swiftly and progressively (Taggart *et al*., undated).

Taggart *et al*. (undated) have put forward that the processes leading to ravelling comprise:

- A surface being subject to a critical horizontal loading, usually applied directly onto the coarse aggregate particles.
- The loaded aggregate being loosened and eventually displaced wherever the bond of the loaded aggregate to the adjacent matrix or other coarse aggregate is inadequate.
- The process being accelerated, or initiated if the bond is only marginally adequate, when pore water pressures are present within the layer.
- Adjacent aggregate particles and/or matrix being deprived of lateral support once a single aggregate particle has been displaced and progressive deterioration taking place.
- The binder oxidisation rate and adhesion properties taking on greater significance during the deterioration process than initially important features such as mixture grading, air voids content, proportion of voids filled with bitumen.
- The risk of ravelling increasing where the aggregate size/layer thickness ratio is less than 2,5, particularly for larger sized aggregates.
- The rate of progress of the ravelling also being influenced by such factors as substrate movements, bond to substrate and substrate condition.

Roe and Dunford (2012) showed that the contact area between tyre and road surface is lower for coarser aggregate sizes and that higher point stress also occur which would be more likely to precipitate ravelling.

Dehdezi (2015) proposed that ravelling is generally initiated by the loss of a single particle of coarse aggregate from a critical horizontal load, which then allows water more easy access to the matrix of the layer. The critical load occurs when the micro-mechanical bond between binder and aggregate reaches a critical point.

2.3 Consequences

The effect of ravelling is an open surface appearance, loose aggregate on and around the carriageway and the remaining aggregate particles being easily removed from the surface (Olsen, 1993). As the ravelling progresses, the surface becomes rough and “pock marked”, with those “pock marks” developing into potholes if left untreated (Thom, 2014; Nikolaides, 2015). Ravelling also results in loose debris (usually aggregate) on the pavement, roughness and water collecting in the depressions left by ravelling, which can result in vehicle hydroplaning and/or loss of skid resistance (Pavement Interactive, undated; Road Science, undated). The consequences of ravelling include less evenness in the rut where the traffic goes, less skid resistance (especially with ravelling on thick surfaces and old surface treatments), less comfort for road users and more noise for the road user and environment (Coldmix, undated). Furthermore, over time with more aggregate particles lost from the asphalt, the asphalt loses load-bearing capability and will begin to prematurely fail in the areas that have exhibited the most ravelling and bears the most traffic-loading (Mr Pothole, undated).

Surface dressed pavements tend to look ravelled with the inherent nature of the surface but loss of aggregate (ravelling) in them actually results in flushing up of the binder (Northwest Pavement Management Association, undated).

2.4 Asphalt mixtures affected

Ravelling can occur on any type of bituminous road surfacing including all types of asphalt and surface treatments. However, surface treatments, including surface dressings and slurry surfacings, are not being considered in this review. Generally, the more open asphalt mixtures tend to be more susceptible to ravelling because the aggregate particles are not “protected” by being embedded in the mortar on all sides. Open-graded mixtures can provide adequate surface texture but can ravel in high lateral stress areas, usually initiated by the loss of a single particle of coarse aggregate. The loss of a single particle is not, in itself, too serious but the resulting indentation gives water ready access to the matrix of the layer (Taggart *et al*., undated). The exception to this statement is hot rolled asphalt with pre-coated chippings, where ravelling can readily occur if the pre-coated chippings are not adequately embedded before the asphalt mat cools sufficiently to prevent further embedment.

Taggart *et al*. (undated) identified five distress features that form the basis of condition evaluation for the existing road (oxidisation, ravelling, cracking, loss of texture and rutting) of which they found ravelling and cracking to be the most significant mechanisms of deterioration. Martin (1988) made a detailed analysis of all the streets that required resurfacing in North Carolina municipalities with the causes and cost of the pavement distress mechanisms as given in Table 1.

Table 1: Distress mechanisms requiring resurfacing in North Carolina (Martin, 1988)

Pavement distress mechanism	Length (miles)	Proportion of length (%)	Cost/mile ($)	Total cost ($)
Block/transverse cracking	24,45	8,8	27 350	668 705
Alligator cracking – minor rutting	19,49	7,0	40 722	793 674
Ravelling	9,70	3,5	20 339	197 286
Alligator cracking plus moderate or severe rutting	1,84	0,6	62 867	115 675
Patching	0,20	<0,1	42 590	8 518
Ride Quality	3,62	1,3	21 999	70 638
Severe rutting	0,18	<0,1	15 483	2 787
Total	59,48	–	–	1 866 283

It can be seen that ravelling was the third most common defect and the repair costs were also third most costly to repair, taking 10,6 % of the total repair costs.

An extended study of UK sites (Nicholls *et al*., 2010) found ravelling was the most prevalent category of defect, occurred from year one on the surface treatments but from a relatively limited number of sites with these treatments. With asphalt, the defect started to appear after one to three years other than for 10 mm stone mastic asphalt (SMA), from which there was no discernible ravelling from any site until seven years. Overall, of the three asphalt types examined, asphalt for ultra-thin layer (AUTL) generally had the largest proportion of sites with ravelling and asphalt concrete for very thin layers (BBTM) had the smallest, but this was not consistent at all ages across the range of sites monitored. Ravelling in early life was fairly common on high speed sites.

3 Causes of ravelling

3.1 General

There are many reported potential causes of ravelling. Ravelling is caused by one or, more often, a combination of the following contributing factors (Nikolaides, 2015; Hunter *et al*., 2015; Caterpillar Paving Products Inc., 2015; Thom, 2014; Dunning, 2012; Olesen, 1993; Coldmix, undated; Road Science, undated; Pavement Interactive, undated):

a) Materials
- Poor aggregate-binder affinity
- Use of disintegrating or dirty aggregates

b) Mix design
- Low bitumen content in the asphalt
- Use of harder grade and unmodified binders
- High filler content in the asphalt
- Discontinuous aggregate grading

c) Construction
- Inadequate production practices
- Inadequate compaction
- Segregation of the mixture during construction
- Over-thin layer thickness
- Construction at low temperatures (the weather or the asphalt)
- Construction during rain
- Bitumen or asphalt being overheated
- Poor interface bond (only where aggregate size is large relative to layer thickness)
- Slot cuts for induction loops

d) In situ
- Presence and retention of moisture
- Presence of ruts
- Binder ageing
- Cold weather
- Wet weather
- Substrate instability causing surface strains
- Heavy traffic (lateral and fatigue stresses)
- Mechanical dislodging (studded tyres, snowplough blades or tracked vehicles).
- Fuelling spillage (causing debonding of the aggregate)

Most of these factors are described in the sub-sections of Sections 3.2 to 3.5.

No strength parameters were found to have a significant influence on ravelling initiation (Peterson, 1984), but the analysis was on data for surface treatments rather than asphalts.

Ravelling is often observed at intersections, locations with turning movements, curved sections and other adverse geometric locations subjected to intense tangential forces during driver manoeuvers (braking, acceleration, direction change) (Hamlat *et al*., 2007). The extent of stone loss depends on parameters including road geometry; axle type; nature and surfaces characteristics of the materials in contact (i.e. tyre tread and asphalt surfacing); and environmental conditions. The forces imposed either:

- cause an immediate break in the mastic of the asphalt (particularly in cold conditions through brittle fracture or in hot conditions with inadequate bonding) followed by aggregate stripping, or
- produce progressive damage that wears away the material with time.

Furthermore, multitude local cracks occurring within high-deformation zones may lead to aggregate loss at the surface (Hamlat *et al*., 2007).

Ravelling occurs with stripping when the micro-mechanical bond between binder and aggregate deteriorates, which is primarily due to the action of moisture (Dehdezi, 2015). Main factors influencing moisture damage are summarised in Table 2 and Table 3. These tables show that the aggregate type and shape, binder content and the air voids content are the main factors influencing the moisture damage and hence the ravelling in asphalt.

Table 2: Main factors influencing moisture damage (Dehdezi, 2015)

Damage mechanisms	Descriptions
Aggregate shape characteristics	Aggregate shape characteristics influence adhesion between the aggregate and the binder. Increased aggregate texture and angularity leads to increased surface area, and, therefore, results in increased total bond energy in the mixture. For gradings that are discontinuous (such as SMA), the number of contact points between coarse aggregate particles is important and hence the concentration of producers to control the 2 mm particle size and shape and the fact that 6 mm SMA has greater resistance to ravelling than a variable shaped 14 mm open-graded material.
Binder film thickness	Damage in asphalt mixtures can occur within the mastic (cohesive failure) or at the aggregate-mastic interface (adhesive failure). The thickness of the mastic around the aggregate greatly contributes as to whether cohesive or adhesive failure occurs.
Surface energy	One of the main factors is the type of aggregate. This factor has a considerable influence on bitumen adhesion due to differences in the degree of affinity for bitumen. The vast majority of aggregates are classified as 'hydrophilic' (water loving) or 'oleophobic' (oil hating). Aggregates with high silicon oxide content, e.g. quartz and granite (i.e. acidic rocks) are generally more difficult to coat with bitumen than basic rocks such as basalt and limestone. The phenomenon of stripping of the bitumen in the presence of water can therefore be related to the surface charges.
Air void distribution and permeability	Water permeability is an important factor influencing moisture damage. Mixtures with higher air voids content are likely to be interconnected and hence water can readily access the mixture.
Surface texture	If water is removed from the surface by interconnected voids then the pressure is reduced and so damage is less. However, when negatively textured surfaces are filled with detritus it is reported that damage occurs due to water retention. Much more so on SMA or BBTM than for HRA which is much less permeable.

Table 3: The main adhesivity failure mechanisms in asphalt (Dehdezi, 2015)

Failure mechanisms	Descriptions
Pore pressure	This type of adhesivity failure mechanism is most important in open or poorly compacted mixtures where it is possible for water to be trapped as the material is compacted by traffic. Once the material becomes effectively impermeable, subsequent trafficking induces pore water pressure. This pressure creates channels around the bitumen/aggregate interface leading to loss of adhesion.
Chemical debonding	Diffusion of water through a bitumen film can lead to layers of water at the aggregate surface.
Hydraulic scouring	Hydraulic scouring or pumping occurs in the surface course and is caused by the action of vehicle tyres on a saturated pavement surface, i.e. water is forced into surface voids in front of the vehicle tyre.
Film rupture	At sharp edges on the aggregate surface where the bitumen film is thinnest, it has been shown that water can penetrate through the film to reach the surface of the aggregate.

Moisture diffusion and pore pressure development from entrapped water in the air voids (i.e. pumping action) are the main physical and/or mechanical processes and can ultimately lead to pavement distresses including ravelling (Solaimanian *et al*., 2003). Moisture diffusion through asphalt is a long-term process that affects the durability of asphalt pavements. Moisture will infiltrate into the asphalt mixture and change the physico-chemical properties of the binder, reducing the cohesive strength (Dehdezi, 2015). Additionally, the adhesive bond between aggregate and asphalt binder deteriorates in the presence of moisture, eventually resulting in stripping. In asphalt, some pores are interconnected which allow water to move through the pavement. Dynamic traffic loads can cause high water pressure fields within the pores that are filled with water. These high pore pressures can lead to cracking of the binder film and, hence, the ingress of moisture into the binder/aggregate interface (Figure 1) and an increase of tensile stress within the material (Figure 2). The latter implies that traffic speed can increase the tensile stress (possibly due to increase in pumping action) and lower tensile stresses can be expected on denser asphalt mixtures with less than 5 % air voids content) or porous asphalts with more than 20 % air voids content (Thom, 2014).

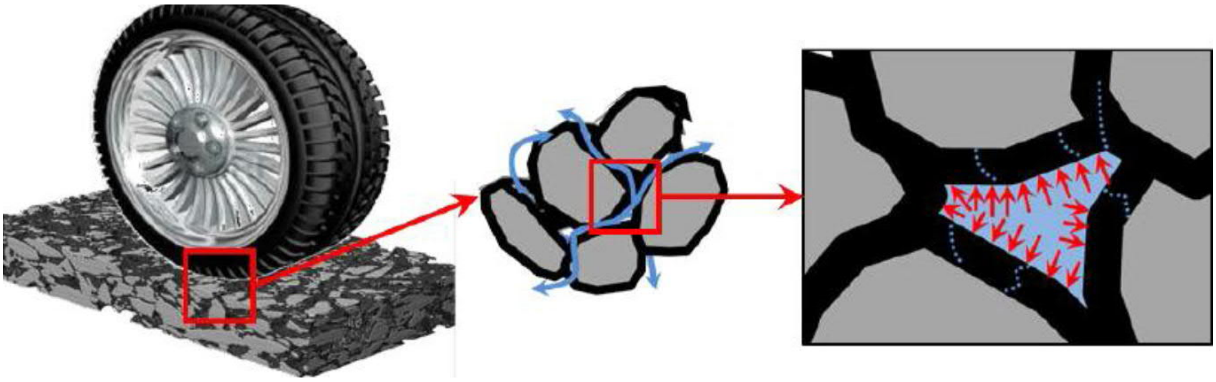


Figure 1: Pore pressure development due to pumping action (Solaimanian *et al*., 2003)

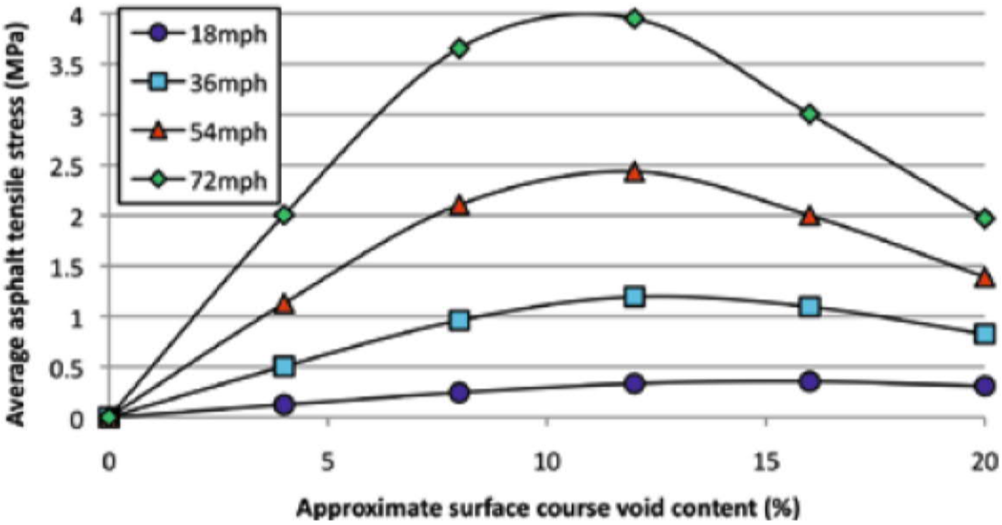


Figure 2: Tensile stress as a function of surface air voids content (Thom, 2014)

For the particular case of hot rolled asphalt (HRA) with pre-coated chippings (PCC), there are two ways the PCC are effectively lost from the HRA mat (Summers, 2000/15):

1) They are submerged into the mat at the time of application and rolling because:
   - HRA is too hot (rolling should be delayed until the temperature is appropriate).
   - HRA mat is being laid too thick (the layer should be split into regulating and surface courses to achieve the correct nominal thicknesses).
   - The HRA is unstable from wet sand (usually after heavy rain) or poor mix proportions.
2) They are lost from the mat due to poor bonding and embedment because:
   - HRA is too cold so that the binder coating the PCCs does not melt to create a bond.
   - HRA mat is laid too thin.
   - An excess of PCCs are laid.
   - The first pass of roller is delayed.
   - The bitumen coating on PCCs is too thin or has been carbonised by over-heating, providing no bond between the PCCs and the HRA.

3.2 Materials

3.2.1 Aggregate-binder affinity

Ishai *et al*. (1984) investigated asphalt mixtures with olivine basalt (which ravelled extensively) and dolomite (which did not ravel) aggregate. The dolomite was a basic carbonate aggregate with about 95 % of ($CaCO_s$ + $MgCO_3$), making it highly hydrophobic, whereas the olivine basalt was on the borderline between basic and acidic with a high content of silicate, making it less hydrophobic. Therefore, hydrophobic aggregates are preferred with better potential affinity to bitumen.

3.2.2 Cleanliness of aggregates

The cleanliness of the aggregate is critical in avoiding ravelling. Any dust or fine aggregate on a coarse aggregate particle can create a barrier to direct contact (bonding) between the bitumen and that particle (Caterpillar Paving Products Inc., 2015). The weakest portion of the resulting mixture will be the adhesion between the aggregate and dust. That bond will break after several repetitions of the physical forces caused by traffic loading, allowing of the coarse aggregate to be more easily dislodging from the mixture.

3.3 Mix design

3.3.1 Binder content

Mix design and, in particular, binder content are critical to mixture performance. A binder content that is too low does not provide enough "glue" to bind the aggregate together (Caterpillar Paving Products Inc., 2015) and allows the particles to be plucked out more easily. Ahlrich (1992) found that the binder contents recovered from two runways that had experienced significant ravelling within a year of resurfacing were low by 1 % to 2 % from optimum and concluded that it was a major contributor to the problem. Voskuilen *et al*. (2004) found that increasing the bitumen content in porous asphalt (PA) from 4,5 % to 5,5 % resulted in less ravelling after 6 to 9 years in service with the expected service life being increased by 2 to 3 years. However, they found that thicker bitumen films (as opposed to binder contents) and polymer-modified bitumens do not noticeably increase the resistance to ageing and, hence, ravelling. However, Taggart *et al*. (undated) believe that binder film thickness is a critical factor for more permeable mixtures in resisting stripping of the binder from the aggregate and, hence, ravelling.

The required binder contents depends on the mixture and aggregate types, the latter in terms of the amount of bitumen that is absorbed into the aggregate so as not to be effective. However, too high a binder content can also create problems with the mixture not being sufficiently homogeneous at low binder contents while segregation may occur at high binder contents (Caterpillar Paving Products Inc., 2015; Voskuilen *et al*., 2004).

Overall, the binder content should be as high as practicable without causing other problems such as bleeding or rutting in order to minimise the potential for ravelling.

3.3.2 Binder type and grade

van loon and Butcher (2003) found that long-term ravelling correlated with binders having lower viscosity, higher phase angle (that is, less elastic and more viscous response) and lower resilient modulus. Watanuki *et al*. (2003) also found from horizontal repeated shear tests that binder with lower stiffness improved the resistance to aggregate ravelling. However, using high quality binder is not always sufficient to control aggregate ravelling. This finding is contrary to the belief that more brittle bitumen leads to a greater susceptibility to stripping, as reported for HRA (Nicholls, 1998).

Nicholls (1998) indicates that the addition of polymers such as styrene-butadiene-styrene (SBS) or styrene-butadiene rubber (SBR) can increase the resistance to ravelling, especially in hot weather. However, Voskuilen *et al*. (2004) found that polymer-modified bitumens (PmB) and thicker bitumen films do not noticeably increase the resistance to ageing and, hence, ravelling. They claim that a PmB does not, in itself, provide a longer service life in PA with the main benefit being in the initial stage when initial damage is reduced and that that reduction may result in a longer service life.

The current average service life of the Dutch standard PA 0/16 is about 11 years with the end of service life being caused by ravelling. Inspections on motorway sites found that relatively cheap modifications (such as fibres) performed better than expensive PmB modifications. The difference in service life between best and worse was two to three years (Voskuilen *et al*., 2004). Conversely, experience in the UK on the M4 motorway near Cardiff showed that PmB porous asphalt gave better performance compared with paving grade bitumen and that the failure mechanism as more gradual (Carswell et al., 2005).

Overall, the use of more viscous binders will reduce the tendency for ravelling whilst the advantage of using PmBs is uncertain.

3.3.3 Aggregate grading

Aggregate size has a significant part in the ravelling process (Taggart *et al*., undated) with ravelling tending to increase as the aggregate size increases. This tendency cannot be explained from the internal geometry of the mixture but could be the result of the large number of shear planes in finer graded mixtures which can resist the ravelling. TRL collaborative research (Roe and Dunford, 2012) showed that the stresses from the contact with tyres was more concentrated with larger aggregate sizes, so that aggregate was more likely to be removed compared to contact with smaller stone sizes where the stress concentrations were reduced.

The practice of reducing aggregate size on laterally loaded sites such as roundabouts to minimise ravelling has been adopted widely.

An extensive investigation into two runways experienced significant ravelling within one year of resurfacing found that the aggrading grading was over-coarse (Ahlrich, 1992). A coarse mixture promotes an open-texture surface which, when combined with a low binder content, allows increased ravelling. Therefore, both larger maximum aggregate size and a coarser grading tend to increase the potential for ravelling.

3.4 Construction

3.4.1 Compaction

van Loon and Butcher (2003) found that ravelling is closely related to the in situ air voids content, with higher voids increasing the risk of ravelling. Their ranking of in situ air voids contents on ten sites with mixtures containing reclaimed asphalt gave a very close correlation to the ravelling ranking. Caterpillar Paving Products Inc. (2015) also claims that the most common cause of ravelling is insufficient compaction of the asphalt mat. They suggest that a minimum of 92 % of maximum density achieved on site will mitigate ravelling and promote a durable pavement. Inadequate compaction results in high air voids contents with the inter-connected void space allowing water to travel through the mat, stripping the bitumen from the aggregate particles, in turn resulting in a loss of bond that leads to ravelling. Inadequate compaction was found on two runways that experienced significant ravelling within a year of resurfacing (Ahlrich, 1992). He found that inadequate compaction resulted in low densities and high air voids contents, making the mixtures water susceptible with a decreased service life. High air voids contents are associated with an excess of interconnected void space so that (Caterpillar Paving Products Inc., 2015):

- There is less contact area between the particles coated with bitumen to form a strong bond; and
- The mixture is permeable throughout to moisture, and subject to the damaging effects of weathering.

Shanmugasundaram *et al*. (2005) found that air voids contents above 8 % in HRA allow moisture and harmful gaseous matters to enter the mixture and, in turn, embrittled the bitumen film so the problems such as ravelling can occur. Nicholls (1998) also reported that higher void content may increase likelihood of ravelling in HRA.

3.4.2 Segregation
Segregation of the asphalt is also liable to result in parts of the mat having high air voids contents (Caterpillar Paving Products Inc., 2015).

3.4.3 Layer thickness
The layer thickness plays a critical role in preventing ravelling because it relates to compaction (Caterpillar Paving Products Inc., 2015). A minimum thickness of twice the maximum aggregate size allows sufficient room for particle reorientation and proper compaction to occur. Lesser thicknesses provide insufficient room for the aggregate to reorient itself into a dense configuration that is impermeable to water as well as increasing the risk of aggregate fracture.

3.4.4 Asphalt temperature
It is generally accepted that the compaction of asphalt when it is too cold makes compaction difficult with the compactive effort breaking the bonds already formed rather than kneading the mixture into a denser mass to allow further bonds to form as the binder cools. A particular instance when asphalt is often compacted cold is at the ends of loads (Nicholls *et al*., 2008). The ends are often significantly cooler than the rest of the mat because of the extra delay before being laid, particularly if the paver is not able to operate continuously. The cooler material can often be inadequately compacted, leading to high air voids contents (see Section 3.4.1) and premature ravelling. The temperature difference can be particularly great when the paver is not working continuously.

The minimum temperature of hot mix asphalt should be 145 °C at the mid-depth of the mat behind the screed when compaction starts (Caterpillar Paving Products Inc., 2015). The ideal temperature will vary slightly depending on the binder type, layer thickness and the time available for compaction (in turn dependant on the ambient conditions of air temperature and wind speed).

3.4.5 Laying in the rain
Laying in wet weather increases the potential of an asphalt pavement ravelling (Caterpillar Paving Products Inc., 2015). The film of moisture that can form on the coated aggregate particles when moisture is introduced during construction, whether through rain, fog or high humidity, can prevent a strong bond from developing. The potential for ravelling can be accentuated when the asphalt that is too cool to rapidly evaporate any moisture it contacts and/or when the compactive effort is perfunctory in the wet weather.

3.4.6 Joints
The initiation of fretting is often associated with the longitudinal construction joints (Dehdezi, 2015) and in particular workmanship in the construction of these joints (McHale *et al*, 2011)

3.5 In situ

3.5.1 Bitumen ageing
Thom (2014) claims that ravelling is an indication that the binder at the pavement surface may have aged, which is supported by Ahlrich (1992) who found the recovered binders, taken from two runways with significant ravelling a year after being resurfaced, had aged more than expected, making the asphalt more brittle with an increased potential for ravelling. The binder will age both during mixing, when it is less dense and at elevated temperature, and with time in service:

- Over-heating a bitumen, typically above 165 °C, will age-harden it so that it loses its effectiveness as a binder (Caterpillar Paving Products Inc., 2015; Summers, 2000/15). The active bonding ingredients, or volatiles, in the bitumen are burned off, resulting in a much weaker binder.
- Asphalt exposed to the atmosphere (generally at the surface) will age with time as it becomes embrittled due to binder oxidation. With reduced flexibility, cracks occur more readily and initiate ravelling at the cracks (Taggart *et al*., undated).

Overheating bitumen leads to premature ravelling whereas long-term ageing affects the potential for ravelling in the longer term.

3.5.2 Cold weather

Cold weather is associated with cracking of the surface course or ravelling of individual particles from the surface depending on the stiffness modulus of the mixture (Nicholls, 1998). High stiffness of the bitumen will lead to cracking being induced which can initiate ravelling.

For porous asphalt, Huurman *et al*. (2009) found that the ravelling damage occurring during a particularly cold winter can exceed the damage accumulated in years of less extreme conditions. During 2008/09, the coldest winter for 12 years (Table 4), extremely aggressive ravelling developed along some short stretches of Dutch motorways, requiring traffic measures and emergency repairs.

Table 4: Extremes in temperature data at two locations in the Netherlands (Huurman *et al*., 2009)

Location	Date	T_{min} (°C)	T_{max} (°C)	T_{mean} (°C)	δT (°C)
Eindhoven	06/01/2009	-18.2	-5.3	-11.75	12.9
	07/01/2009	-17.8	-1.1	-9.45	16.7
De Bilt	03/01/2009	-8.9	1.6	-3.65	10.5
	10/01/2009	-10.5	-3.6	-7.05	6.9

Adhesive zones exhibit temperature-dependent behaviour with the performance of zones being maximal at one temperature whilst the performance degrades with increased or decreased temperatures (Figure 3). For the Sandstone and Greywacke aggregates considered (Huurman *et al*., 2009), the maximum adhesive zone performance is achieved at 0 °C. Figure 3 shows that the adhesive zone performance at -10 °C is about equal to the performance at +10 °C whereas Figure 4 indicates that, when there are no temperature fluctuations, the ravelling performance of the asphalt at +10 °C is far better than that at -10 °C (Huurman *et al*., 2009).

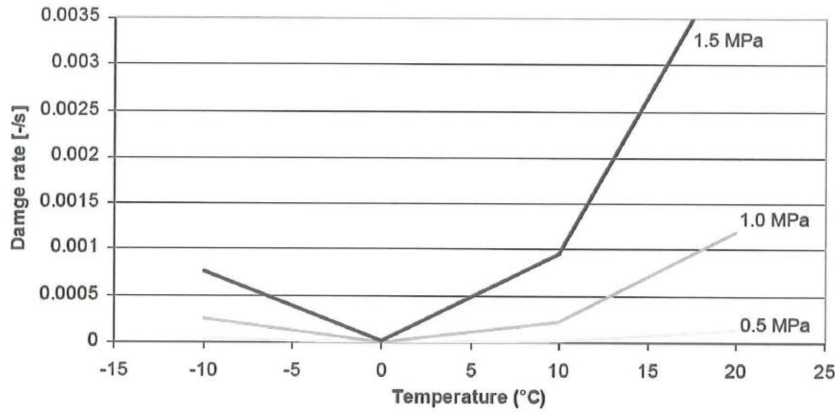


Figure 3: Adhesive zone damage rate as a function of temperature and tensile stress (Huurman *et al*., 2009)

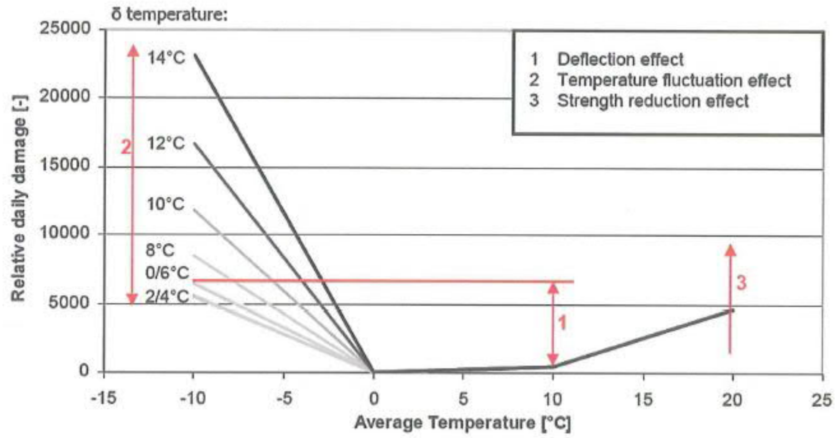


Figure 4: Relative daily damage normalised to 0 °C (Huurman *et al*., 2009)

3.5.3 Wet weather

Taggart *et al*. (undated) suggest that, under conditions of heavy rainfall, the reversals between pressure and suction from passing vehicle tyres may force water through the surface voids and be a factor in initiating binder loss and ravelling.

3.5.4 Substrate

When the layer thickness is greater than two and a half times the nominal aggregate size, the condition of the substrate does not appear to influence the initiation of ravelling (Taggart *et al*., undated). However, for thinner surfaces, disaggregation may propagate upwards from the bottom of the layer and then the substrate stability and bond coat efficiency will influence the ravelling.

3.5.5 Traffic loading

Normal static or dynamic compression loading, other than that caused or triggered by pore water pressure rises, will not generally cause ravelling to occur (Taggart *et al*., undated). However, lateral, shear and tensile forces will generate rotation of the coarse aggregate particles so that the particles can become loosened from the material. Therefore, ravelling will predominate where braking, acceleration and cornering are present, with roundabouts generally suffering the worst ravelling problems, although any roundabout ravelling problems may also be associated with installation difficulties.

Furthermore, each lateral load independently induces strains, some components of which are residual, so it would be expected that (Taggart *et al*., undated):

- Ravelling will occur primarily on heavily trafficked sites or situations with high lateral stresses;
- More fatigue-tolerant mixtures, such as those incorporating binders with elastic recovery properties, may exhibit better performance than conventional materials.

3.5.6 Joints and slot cuts

Taggart *et al*. (undated) noted that saw cut slots for induction loops in the pavement at traffic light approaches can also be a focus for initiation of ravelling. However, that is just an example of all joints and cuts which are generally locations with more air voids and initial damage, respectively, and, therefore, are the weakest link where ravelling is most likely to start.

4 Assessment, prevention and cure

4.1 Assessment of ravelling potential

4.1.1 Indirect measures

A strategy to minimise ravelling is to test the mixtures for their potential to ravel so as to only use mixtures with limited potential. In the absence of a specific test for the property (such as the draft prCEN/TS 12697-50), other tests have to be used.

van Loon and Butcher (2003) reviewed a series of test results with the ravelling observed on mixtures containing reclaimed asphalt from ten sites. The macro- and micro-cracking tests (flexural fatigue and cyclic semi-circular bending), mix stiffness (Resilient Modulus and slope of Indirect Tensile Strength tests) and air voids content all correlated well with the ravelling ranking while viscosity and durability tests (Cantabro and Texas Ball Mill) did not correlate with ravelling severity (Table 5).

Table 5: Ranking summary (van Loon and Butcher, 2003)

Site No.	Visible ravelling	Visible cracking	Air voids content	Cantabro @ 25 °C	Texas Mill @ 25 °C	Fatigue phase angle	Actual viscosity	SCB (cycles)	Res Mod	ITS (slope)
1	4	3	8	8	7	4	3	8	6	7
2	5	4	6	9	9	5	8	7	5	8
3	7	9	7	6	5	2	9	6	10	6
4	3	1	3	5	6	3	7	3	7	4
5	2	10	1	2	3	6	4	1	4	5
6	6	5	2	7	8	7	10	9	8	2
7	9	6	4	3	4	10	1	5	1	9
8	10	7	5	4	2	8	6	10	3	10
9	8	8	9	1	1	9	2	4	2	3
10	1	2	-	10	10	1	5	2	9	1
Av. Diff.	0	2,0	2,3	4,0	4,4	1,4	3,7	2,0	4,2	1,8

The two tests that most successfully indicated the propensity for ravelling were (van Loon and Butcher, 2003):

- Phase angle from the flexural fatigue test (average difference = 1,4) but not the fatigue life itself (possibly because of the large influence stiffness has on the fatigue life result).
- Fracture toughness from the semi-circular bending test (average difference = 2,4).

Early tests designed explicitly to measure the potential of ravelling tended to be for road-marking materials (Nicholls, 1996) or surface treatments (Nicholls, 1997) where the measure of potential to ravel was measured as the proportion of substrate visible through the marking or treatment: such a measure is not appropriate for the potential to ravel of the surfacing material itself which can be 30 mm to 50 mm thick.

4.1.2 Triboroute Device (TRD)

The Triboroute Device (TRD) was developed to test the resistance of asphalt of surface mixtures to tangential forces in the laboratory (Hamlat *et al*., 2007). The test procedure enables the loading to remain constant regardless of the state of surface degradations. However, temperature control is essential to ensuring repeatability of the test.

The TRD has evaluated the ravelling resistance of BBTM mixtures made with conventional 35/50 pen, a polymer-modified and epoxy-modified bitumen. The results for these materials are shown in Figure 5.

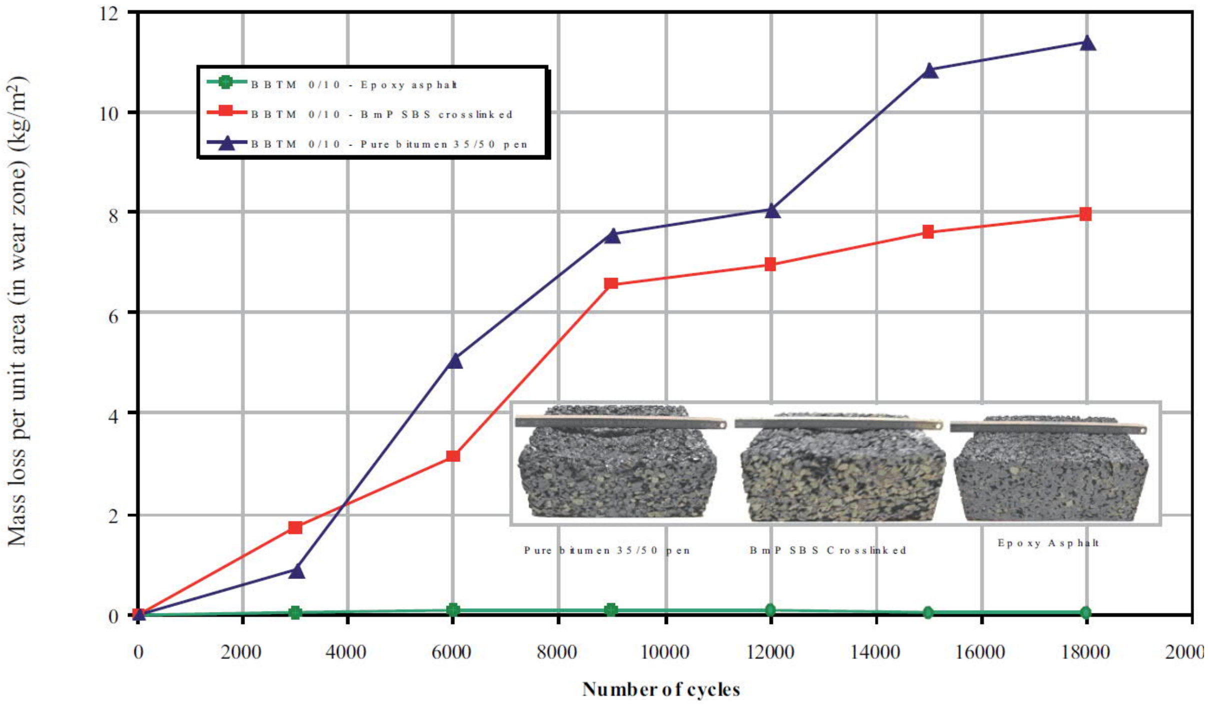


Figure 5: Evolution of mass loss with number of cycles at ambient temperature for different bituminous mixtures (ITF, 2008)

The epoxy asphalt exhibited minimal wear and clearly outperformed the polymer-modified and control bitumens, showing that epoxy asphalt should perform well in open graded friction courses that may otherwise be susceptible to ravelling.

4.1.3 Rotating Surface Abrasion Test (RSAT)

The Rotating Surface Abrasion Test (RSAT) was developed in the late 1990s, allowing about 15 years of experience with RSAT to be collected from over 850 samples (Groenendijk, 2012). Ninety two different materials were tested with the RSAT from 16 projects between 1998 and 2012 with 1 to 5 samples per material, giving over 230 specimens being tested. About 10 % of the specimens had excessive stone loss within 24 h, the tests stopping prematurely at between 2 h and 18 h. The remaining results ranged from 0,1 g/24 h to 233 g/24 h of stone loss.

Early specimens were laboratory-mixed but, since 2007, all tests were undertaken on combinations of three cores taken from in-service pavements. The mean between-specimen coefficient of variation was 0,52 with values ranging between 0,04 and 0,99 for laboratory-made specimens and between 0,11 and 1,21 for 3-core-slabs composed of in-situ specimens.

The correlation between RSAT results on laboratory prepared samples and in-situ ravelling performance on 11 projects on Dutch highways varied, although some of the variability can be attributed to observed differences in mixture composition and/or compaction between lab-specimens and in-situ pavements. The RSAT results mostly correlated fairly well with practical performance and/or engineering expectations.

4.1.4 Rotating Surface Abrasion Test and TriboRoute Device

The TRD and RSAT, together with the brush test for resistance to fuel to EN 12697-43:2005, (as measures of resistance to ravelling) were compared with the indirect tensile strength ratio (ITSR) test method (as a measure of water sensitivity) (Seghers et al., 2010). The brush test was founded not suitable to give an indication of the ravelling capacity of an SMA mixture while the TRD (Figure 6) and RSAT (Figure 7) gave both similar and dissimilar results.

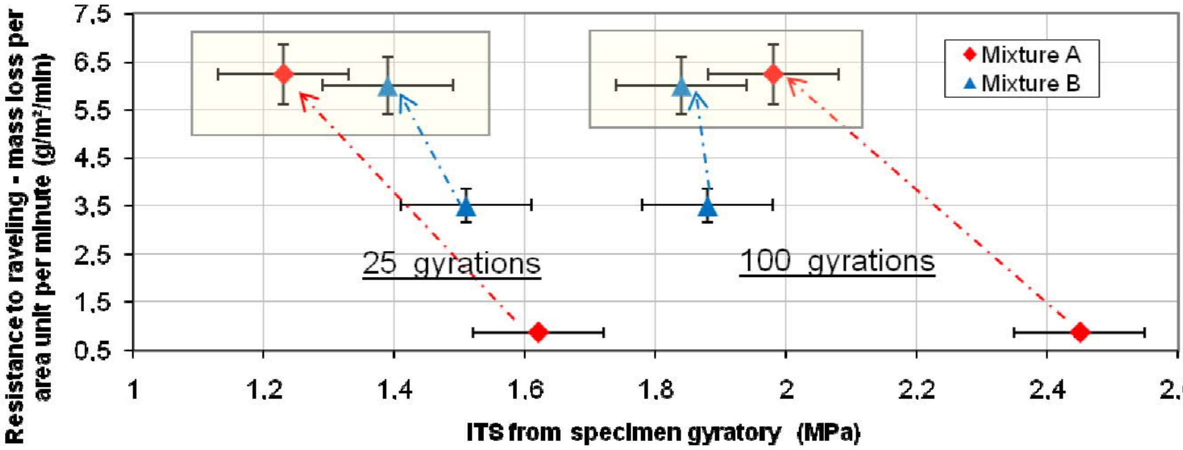


Figure 6: TRD results plotted against ITS results (Seghers et al., 2010)

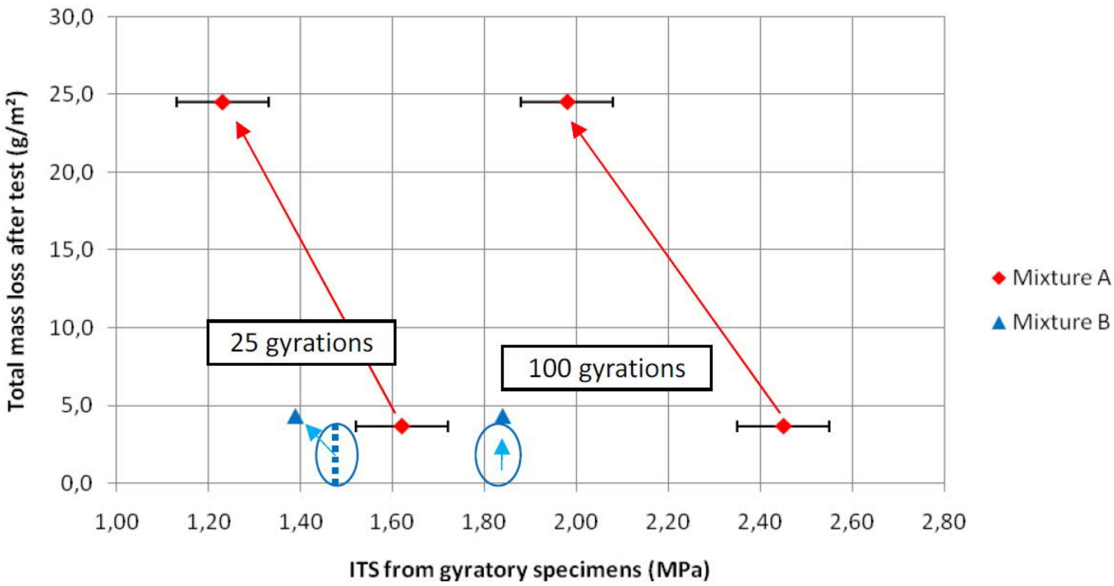


Figure 7: RSAT results plotted against ITS results (Seghers et al., 2010)

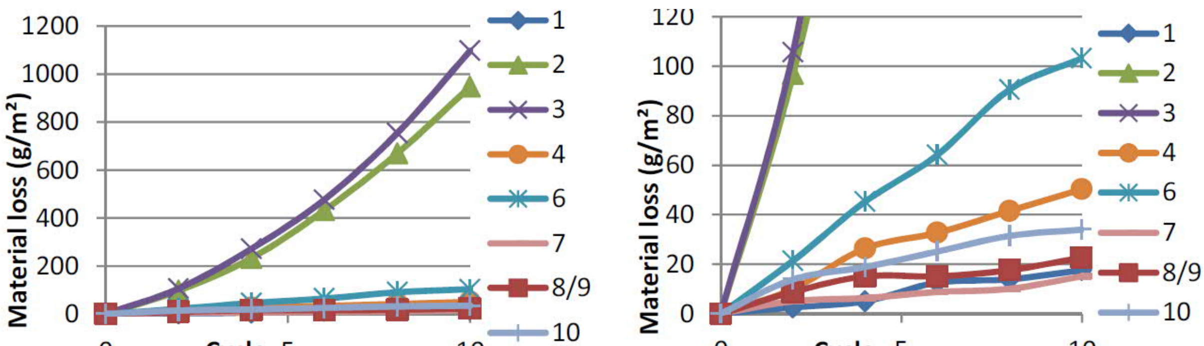
The results of the TRD imply that the ITSR method cannot be used as a ravelling indicator (despite van Loon and Butcher, 2003; Section 4.1.1) because the (limited) results shows that a water sensitive is not necessary a ravelling sensitive mixture. Water-sensitive mixture A was founded to be also ravelling-sensitive using RSAT relative to water-resistant mixture B although still showing a good performance on the resistance to ravelling in practice. If the RSAT results are used as a reference, it was possible for the two extreme mixtures to rank them first by means of the ITSR test method. More results with different SMA mixtures are needed to confirm the usability of the ITSR method as a ravelling indicator.

4.1.5 Darmstadt Scuffing Device (DSD)

The DSD was developed for assessing the ravelling potential of porous asphalt mixtures (Root, 2008) . However, laboratory tests (De Visscher and Vanelstraete, 2015) found that:

- the test is capable of discriminating between different variants of SMA;
- the test is capable of discriminating between different variants of mixtures for very thin surface courses;
- SMA exhibits little loss of material loss in comparison with mixtures for very thin courses;
- binder type has a greater impact on the result at 40 °C than at ambient temperature (around 25 °C);
- the test results are in line with general expectations and/or practical experience and hence confirm the relevance of this test method.

Eight different thin noise reducing and two control asphalt layers were laid in 2012 and studied, mainly to study the acoustical quality, but also other characteristics including potential for ravelling (Bergiers *et al*., 2014). Samples, taken from the asphalt mixtures at the construction site during paving, were reheated, compacted in the laboratory and tested with two tests per variant. The mean results of the ravelling tests are shown in Figure 8 for the SMA-10 (section 1) and for the mixtures for thin layers. Section 5, twin-layer PA (section 5) was not tested in the laboratory while Sections 8 and 9 were paved with the same mixture at different thicknesses. The tests make a clear distinction between Sections 2 and 3, with a lot of material loss, and all the other sections, with only moderate or little material loss. Sections 7, 8 and 9 demonstrated a good resistance to ravelling that is equivalent to that of SMA.



Note: Both graphs are the same with different scales

Figure 8: Material loss in the ravelling tester (Bergiers *et al*., 2014; De Visscher and Vanelstraete, 2015)

The distinction in ravelling resistance made by the laboratory tests was confirmed by the visual inspections after less than two years. Sections 2 and 3 showed ravelling locally, especially in the wheel tracks, while a 100 mm diameter pothole was seen in Section 3. Severe ravelling was detected on Section 5, particularly at the beginning and end of this section.

4.1.6 Aachener Ravelling Tester (ARTe) and Rotating Surface Abrasion Test

A trial with 10 sections was laid and three of the sections were tested by three contractors which had different ravelling tests including ARTe and RSAT (BAM *et al*., 2015). Laboratory prepared test specimens, laboratory prepared and aged specimens and samples from the road were tested by each contractor.

The main findings of the studies were:

- The laboratory prepared and aged specimens showed no clear ranking, although each contractor had different protocols for ageing.
- The site samples showed a lot of dispersion.
- The unaged laboratory prepared specimens are seen as a benchmark for ravelling sensitivity.
- For the regular dense graded mixtures, the standard test duration is sufficient but, for other mixtures, that duration may be insufficient.
- Temperature development in the sample during the test had a substantial influence on the result.
- Monitoring of the test sections with time is required.

4.2 Strategies to minimise ravelling

The basic strategy to minimise ravelling is to produce and lay a material that will overcome the various causes for ravelling put forward in Chapter 3. In particular, according to Road Science (undated), the prevention of ravelling involves the use of:

- Timely preventive maintenance
- Polymer-modified bitumen
- Clean aggregates
- Material transfer devices (presumably shuttle buggies)
- Good compaction
- Good drainage
- Anti-stripping agents

Anti-stripping agents are the most commonly used modifiers in basic asphalt, added at a rate of 0.3 to 0.5 % of the binder content to improve binder adhesion to certain aggregates, typically granites, and hence minimise ravelling (Nicholls, 1998).

Another strategy to prevent ravelling is the staggering of joints in different pavement layers so they do not coincide, allowing moisture to travel through several layers without being impeded (Nicholls *et al*., 2008). The minimum lateral distance between joints in adjacent layers is generally specified as 300 mm, but the distance should be the maximum practical.

The use of a suitable joint construction technique to minimise the air voids content will also minimise or eliminate ravelling at the joint (Nicholls *et al*., 2008). If the joints are not formed to a high standard, the joint interface can become a focus for the commencement of ravelling under trafficking (Taggart *et al*., undated).

4.3 Maintenance procedures

Repair strategies generally fall into two categories, dependant on size (Pavement Interactive, undated). For small, localised areas of ravelling, the ravelled asphalt should be removed back to sound material and the hole patched as for potholes. For large ravelled areas, the damaged pavement has to be removed and the area overlaid, the typical repair being typically 35 mm to 50 mm of fresh asphalt (Mr Pothole, undated).

However, a ravelled pavement should be investigated to determine the root cause of failure (Pavement Interactive, undated). Provided overheating of the binder did not cause the failure, a suitable surface dressing (Summers, 2000/15) or micro-surfacing asphalt (Coldmix, undated) will seal and hold the ravelling surfacing material while, if poor drainage is the cause of the problem, the drainage should be corrected (Road Science, undated).

5 Conclusions

From the large volume of literature available there are a significant number of factors that affect the potential for ravelling. These factors include:

Materials:
- Hydrophobic aggregates are preferred with better potential affinity to bitumen.
- Aggregates should be clean when mixed into asphalt.
- Adhesion promotors which improve binder-aggregate adhesion may decrease the ravelling potential.

Mix design:
- The binder content should be as high as practicable without causing other problems such as rutting or bleeding in order to minimise the potential for ravelling.
- The use of more viscous binders will reduce the tendency for ravelling whilst the advantage of using PmBs is uncertain.
- Both larger maximum aggregate size and a coarser grading tend to increase the potential for ravelling.

Construction:
- Poor compaction results in high air voids contents, which reduces the adhesion of particles to the mat.
- Excessive or badly constructed joints and slot cuts can initiate ravelling.
- Segregation will result in areas with high air voids contents.
- The layer thickness should not be less than twice the maximum aggregate size.
- Asphalt that is not sufficiently hot when compacted is liable to ravel due to poor or bad compaction.
- Asphalt should not be laid in the wet.
- Poor quality joints are zones which are more susceptible to ravelling.

In situ:
- Bitumen ageing from overheating during mixing leads to premature ravelling while that from weathering affects the potential for ravelling in the longer term.
- Ravelling damage tends to be more severe during cold weather.
- Hot weather may also lead to ravelling, but the mechanism will be different (softening of the binder instead of brittleness)
- Heavy and frequent rainfall can also exacerbate ravelling.
- High shear or torsional forces are the direct causes of ravelling, so ravelling will predominate where braking, acceleration and cornering are present.
- Joints and slot cuts are potential areas where ravelling will start.

Whilst it has been suggested that the best indicators for a propensity to ravel are the phase angle from the flexural fatigue test the fracture toughness from the semi-circular bending test, the use of ravelling tests are better measures of the propensity to ravel.

The basic strategy to minimise ravelling is to produce and lay a material that will overcome these various causes for ravelling, to apply the best possible construction practices and to use only highly resistant mixtures in zones which are subjected to very high shear stresses.

Repair techniques include pothole repairs, removal followed by an overlay and surface treatments depending on the area affected and the precise cause.

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7 References

Ahlrich, R C (1992). Investigation of airfield runways at Jacksonville Naval Air Station. *Transportation Research Record 1337, Flexible pavement construction, performance and recycling, pp 51-60*. Washington DC: Transportation Research Board.

BAM, Heijmans and Ooms (2015). Eindrapportage Rafelingsproeven project N346 provincie Gelderland (Final report Ravelling Trials project N346 province of Gelderland).

Bergiers, A, J De Visscher, K Denolf, A Destree, B Vanhooreweder and C Vuye (2014). Test sections to study the acoustical quality and durability of thin noise reducing asphalt layers. Melbourne: Inter-Noise 2014.

Carswell, I, J C Nicholls, R C Elliott, J Harris and D Strickland (2005). Feasibility of recycling thin surfacing back into thin surfacing systems. *TRL Report 645*. Wokingham: TRL Limited.

Caterpillar Paving Products Inc. (2015). Five ways to prevent asphalt ravelling. Minneapolis, MN: Caterpillar www.heavyequipmentguide.ca/article/20924/five-ways-to-prevent-asphalt-ravelling.

Coldmix (undated). Ravelling. www.coldmix.eu/applications/ravelling.

Dehdezi P (2015). Developing a simulative laboratory ageing testing method for thin surfacings. *Report 47074052*. Basingstoke: URS Infrastructure & Environment UK Limited.

De Visscher, J, and A Vanelstraete (2015). A new performance test for resistance to ravelling by traffic: laboratory and field experience in Belgium. *8th RILEM International Symposium on Testing and Characterization of Sustainable and Innovative Bituminous Materials, RILEM Bookseries 11, DOI 10.1007/978-94-017-7342-3_63*.

Dunning, R L (2012). Fundamental causes of cracking, potholes, raveling, and rutting in asphalt pavements. https://asphaltwaterproofing.wordpress.com/2012/05/02/fundamental-causes-of-cracking-potholes-raveling-and-rutting-in-asphalt-pavements/.

Groenendijk, J (2012). Dutch Highways Agency experience with the Rotating Surface Abrasion Test for characterising ravelling susceptibility of asphalt mixes. *Version 1.0*. Delft: Rijkswaterstaat Centre for Traffic and Navigation.

Hamlat, S, F Hammoum, P-Y Hicher and J-P Terrier (2007). Laboratory evaluation of the resistance to tangential forces of road surfacing materials. *Bulletin des Laboratoires des Ponts et Chaussées, No. 267*. Paris: Laboratoire Central des Ponts et Chausées.

Hunter, R N, A Self and J Reid (2015). The Shell bitumen handbook. *Sixth edition*. London: ICE Publishing.

Huurman, M, L Mo and M F Woldekidan (2009). Porous asphalt ravelling in cold weather conditions. *ENVROAD 2009*. www.citg.tudelft.nl/fileadmin/Faculteit/CiTG/__Over_de_faculteit/Afdelingen/Afdeling_Bouw/-_Secties/Sectie_Weg_en_Railbouwkunde/-_Leerstoelen/Leerstoel_Wegbouwkunde/-_Publicaties/-_Publicaties_2009/doc/porous_hu.pdf.

International Transport Forum (2008). Long life surfaces for busy roads. *ISBN 978-92-821-0158-2*. Organisation for Economic Co-operation and Development.

Ishai, I, J Craus and M Livneh (1984). Improvement of stripping resistance of sensitive aggregate in bituminous paving mixtures. *Fourth Conference on Asphalt Pavements for Southern Africa, Vol 1, pp 474-487*. Cape Town: Pritpak (Cape) Limited.

Martin, J B (1988). Pavement management for North Carolina municipalities. *Transportation Research Record 1200, Pavement management and weigh-in-motion, pp 66-70*. Washington DC: Transportation Research Board.

McHale, M, I Carswell and P roe (2011). New surface course specification for Scotland. *TRL Report 670*. Wokingham, TRL Limited.

Minnesota Asphalt Pavement Association (2010). Tire scuffing and indentations of asphalt pavement. http://www.asphaltisbest.com/wp-content/uploads/2014/02/Tire-Scuffing-and-Indentations-of-Asphalt-Pavement.pdf.

Mr Pothole Pavement Restoration Specialists Inc. (undated). Ravelling. **Error! Hyperlink reference not valid.**.

Nicholls, J C (1995). Laboratory testing of road marking materials. *TRL Report TRL121*. Wokingham: TRL Limited.

Nicholls, J C (1997). Laboratory tests on high-friction surfaces for highways. *TRL Report TRL176*. Wokingham: TRL Limited.

Nicholls, J C (Editor) (1998). Asphalt surfacings. London and New York: E & FN Spon.

Nicholls, J C, M J McHale and R D Griffiths (2008). Best practice guide for durability of asphalt pavements. *TRL Road Note RN42*. Wokingham: TRL Limited. www.trl.co.uk/ reports-publications/road-notes/report/?reportid=6317.

Nicholls, J C, I Carswell, C Thomas and B Sexton (2010). Durability of thin surfacing systems, Part 4: Final report after nine years monitoring. *TRL report TRL674*. Wokingham: TRL Limited. www.trl.co.uk/reports-publications/results/?search=TRL674.

Nikolaides, A (2015). Highway Engineering – Pavements, materials and control of quality. London: CRC Press.

Northwest Pavement Management Association (undated). Pavement surface condition field rating manual for asphalt pavements. www.wsdot.wa.gov/NR/rdonlyres/ 4FE2F96D-BFE0-4484-812E-DD5164EB34F5/0/AsphaltPavementBook.pdf.

Olesen, R W (1993). Maintaining blacktop. *The Asphalt Year Book 1993, pp 35-36*. Staines: The Institute of Asphalt technology.

Pavement Interactive (undated). Raveling. www.pavementinteractive.org/article/ raveling/.

Peterson, W D O (1987). Road deterioration and maintenance effects – Models for planning and management. Baltimore and London: The Johns Hopkins University Press.

Road Science (undated). Raveling. www.roadscience.net/services/distress-guide/ raveling.

Roe, P, and A Dunford (2012). The skid resistance behaviour of thin surface coarse systems. *TRL Report PPR564*. Wokingham: TRL Limited.

Root, V (2008). Entwicklung eines Prüfverfahrens zur Beurteilung des Widerstandes von Asphaltdeckschichten gegen Schubbeanspruchungenband der Oberfläche (Development of a test method for assessing the resistance of asphalt surfacing against shear stress stripping the surface). Dissertation, Schriftenreihe des Instituts für Verkehrs, Technische Universität Darmstadt.

Seghers, D, J Stoop, W van den Bergh, S Vansteenkiste, J de Visscher, F Hammoum and R Reynaert (2010). Research to the applicability of the ITS-R test as a ravelling indicator for SMA mixtures. Macao, China: International Society for Asphalt Pavements.

Shanmugasundaram, V, D Thirunakkarasu and R Murugasan (2005). An analysis of causes of premature failure of bituminous pavements in national highways of Tamilnadu State in India. Indian *Highways, Vol 33, No. 9, pp 123-31*. New Delhi: Indian Roads Congress.

Solaimanian, M, J Harvey, M Tahmoressi and V Tandon (2003). Test methods to predict moisture sensitivity of hot-mix asphalt pavements. San Diego, California: Transportation Research Board National Seminar.

Summers, C J (2000/15). The idiots' guide to highways maintenance. **Error! Hyperlink reference not valid.**.

Taggart, A, M Kendrick, S Biczysko, P Cearns, H Potter, J Bullas, V Carter, L Tachtsi and S Finnie (undated). Best practice guidelines for specification of modern negative texture surfaces (NTS) on local authority highways. www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&frm=1&source=web&cd=8&ved=0CEMQFjAHahUKEwib9YLG-cjHAhXHWRoKHXsCAPo&url=http%3A%2F%2Fwww.ukroadsliaisongroup.org%2Fdownload.cfm%2Fdocid%2F5F3A1531-9879-40D0-9D699E0B0E0DC34C&ei=WdjeVdvkMsezafuEgNAP&usg=AFQjCNHxgyG8n6SLzRilt3zqEmHhqZO-bA.

Thom, N (2014). Principles of pavement engineering. *Second edition*. London: ICE Publishing.

van Loon, H, and M J Butcher (2003). Analysis of a thirteen year old RAP site in South Australia. *21st ARRB Transport Research Conference, Cairns*. Melbourne: ARRB.

Voskuilen, J L M, F Tolman and E Rutten (2004). Do modified porous asphalt mixtures have a longer service life? *3rd Eurasphalt & Eurobitume Congress, Book II, pp 1261-1271, Paper 331*. Brussels: EAPA and Eurobitume.

Watanuki, T, K Kougo and T Inoue (2003). A study of resistance to aggregate fretting of porous asphalt pavements. *Journal of Pavement Engineering, JSCE, Vol. 8, pp 65-70*. www.jstage.jst.go.jp/article/journalpe1996/8/0/8_0_65/_article.