RAVELLING RESISTANCE OF UK THIN ASPHALT SURFACE COURSE SYSTEMS UNDER A LARGE-SCALE ACCELERATED TEST METHOD

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ABSTRACT

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Material loss due to surface disintegration, commonly termed 'fretting' or 'ravelling', is one of main defects suffered by asphalt surface courses. Whether the cause can be attributed to mixture design, quality of installation or tyre interaction in service, the magnitude of scale of material loss is not easily predicted during the stages of mixture design and construction. Large scale laboratory accelerated testing, when used effectively, can lead to more accurate predictions of how materials might perform on the network. This paper presents findings from recently completed research designed to assess the suitability of a range of large-scale laboratory test methods to predict material loss from Specification for Highway Works Clause 942 thin surface course systems (TSCS). The research included a literature review of ravelling mechanisms and the main factors affecting it, a laboratory test programme, statistical analysis of accelerated tests on TSCS samples, and the impact of mixture variables such as nominal aggregate size and air voids to ravelling resistance.

INTRODUCTION

Material loss at the road surface caused by the scuffing action of tyres - commonly called 'fretting' or 'ravelling' - is a potential cause of defectiveness in surface course materials. Ravelling is primarily the loss of the coarse aggregate particles (see Figure 1) whereas fretting has been defined as loss of fine material (mortar) (Nicholls et al., 2016). 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 (Nicholls et al., 2016). Fretting and ravelling are the most common distress mechanisms (responsible for over 60% of all defects) experienced by Thin Surface Course Systems (TSCS), commonly used on the UK strategic road network (SRN) (Ojum, 2016). Approximately 45% of the network is surfaced with TSCS, which are currently the material of choice for any resurfacing work (Ojum, 2016).

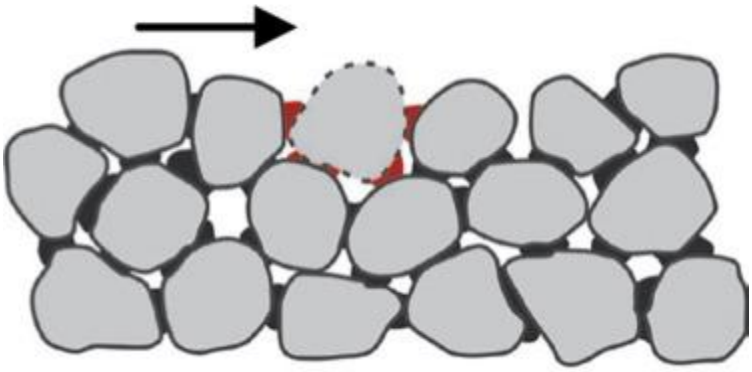

Figure 1. Illustration of the ravelling mechanism - De Visscher and Vanelstraete (2017)

The ability to assess the potential resistance to ravelling of a TSCS prior to any re-surfacing works could be useful for inclusion in material specifications or as a quality criterion by those designing and specifying highway schemes. In this respect, a test able to discriminate between good and bad performing TSCS could be invaluable.

There are several ways to assess the resistance of asphalt surface course to the scuffing action of tyres, which may lead to ravelling, as described in the PD CEN/TS 12697-50 (PD CEN/TS 12697-50:2018, 2018). However, the suitability of these tests to test the susceptibility of asphalt materials to ravelling varies with material type. Furthermore, previous studies (Nicholls et al., 2016) have focused on testing European asphalt materials, and none of these materials incorporated TSCS samples typically used in the United Kingdom.

This paper reviews the main factors affecting the ravelling phenomenon and presents findings from laboratory tests carried out on different TSCS samples using one of the large-scale scuffing devices, namely the Darmstadt Scuffing Device (DSD).

Ravelling Mechanism and Main Factors Affecting It

The mechanism of ravelling of an asphalt surface course consists of the loss of fine and then coarse aggregate from the road surface by the passage of vehicles or weathering (Nicholls et al., 2016). Ravelling occurs when the bond between binder and aggregate reaches a critical point due to the shear forces of traffic (De Visscher & Vanelstraete, 2017). This is due to excessive deformation (and therefore stress) in the binder, which leads to a fracture (either cohesive, adhesive or a combination of the two) and consequent loss of aggregate particles from the surface. Once the mechanism has been initiated, the deterioration becomes progressively faster until failure. This failure mechanism is restricted to the surfacing, which is subjected to the scuffing forces from vehicle tyres changing direction and/or braking/accelerating (Nicholls et al., 2016). However, other causes/factors can initiate or accelerate the ravelling process. These include lack of sufficient binder, inappropriate aggregate grading, poor adhesion between the binder and the aggregate, poor compaction, aggressive scuffing by the traffic, bitumen ageing and effect of climatic conditions, amongst others. These causes are often interdependent, making it difficult to assess the theoretical potential to ravel of an asphalt mixture in the design stage. The Development of Ravelling Test (DRaT) project provided a comprehensive review of these factors (Deliverable D.2 (Nicholls et al., 2016)). Table 1 summarises and provides further analysis of the findings from the DRaT project.

Table 1. Potential causes/factors initiating or accelerating ravelling (review of Nicholls et al., 2016)

Category	**Cause/ Factor**	**Description**	**Prevention/ mitigation**	**Comments**
Presence of water	Permeability	Water permeability influences moisture damage. Mixtures with higher air voids content are likely to be interconnected allowing water to travel through the mat, stripping the bitumen from the aggregate particles. This can result in a loss of bond that leads to ravelling.	Use of asphalt mixture with low air voids content.	As additional factor to be considered, hydraulic pumping 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. Low voids mixtures are more prone to suffer from this mechanism.
	Surface macro-texture	If water is removed from the surface by interconnected voids, the pressure is reduced and so damage is less. However, when negatively textured surfaces are filled with detritus, damage occurs due to water retention.	Use of asphalt mixture with adequate macro-texture.	HRA[1] is less permeable than SMA[2] and BBTM[3].
Materials	Aggregate-binder affinity	Poor aggregate-binder affinity increases the likelihood of ravelling. The presence of water molecules reduces the affinity of aggregate-binder.	The type of aggregate influences the degree of affinity. Aggregates such as basalt and limestone generally have more affinity to bitumen than quartz and granite. Hydrophobic aggregates are preferred.	Silicates absorb water and reduce the affinity between the constituents.
	Aggregate cleanliness	When aggregates are dirty their adhesion ability is reduced due to the presence of dust of fine aggregate.	Aggregates should be cleaned before mixing.	Ability to do this depends on the site set up and where mixing occurs.
Mix Design	Air Voids	Ravelling is closely related to in-situ voids, with the higher the voids the greater the ravelling.	Design towards low air voids content.	This factor has to be balanced with other factors such as permeability and macro-texture.
	Binder content	Low binder content (1-2% below the optimum) results in a lack of "glue/bond" between constituents: low binder film thickness. Damage in asphalt mixtures can occur within the mastic (cohesive failure) or at the aggregate-mastic interface (adhesive failure). However, thicker bitumen films do not noticeably increase the resistance to ravelling.	Use of optimum bitumen content without negatively influencing rutting/bleeding.	Most likely, for a given asphalt mixture, there is a threshold film thickness (and binder content) below which the expected ravelling increases as thickness decreases.
	Binder grade	Typically, binders with lower stiffness (or viscosity) improve the resistance to ravelling, as reported in several studies. According to Hunter et al. (Hunter et al., 2015), ravelling is most likely to occur at low temperatures and at short loading times when the stiffness of the binder is high. Apparently in contrast, it has been reported by Van Loon and Butcher (Van Loon & Butcher, 2015) that along with decrease in stiffness of the asphalt mixture is associated an increased potential for ravelling (R-value of 0.38). See comments.	DRaT D.2 concluded that the use of more viscous binders will reduce the tendency for ravelling.	The conclusion of D.2 is possibly based on Van Loon and Butcher study. This study focused on asphalt including different % of RAP[4]. The correlation (relatively low) reported by Van Loon and Butcher refers to the initial modulus of the asphalt mixture – not necessarily related to the binder stiffness (and therefore viscosity). In addition, the same study reported no correlation between viscosity and ravelling.

	Binder type (use of polymer modification)	Some studies indicate that the use of PMBs[5] can increase the resistance to ravelling whilst other studies did not find noticeable influence of PMBs on asphalt life extension.	Overall, the advantage of using PMBs is uncertain.	Most of the studies reported in DRaT D.2 focussed on porous asphalt. None of the studies found negative impact of PMBs on ravelling.
	Aggregate grading and filler content	Larger aggregate size and gap-graded/open-graded mixtures increase ravelling due to larger number of shear planes.	Use of smaller aggregates and/or well-graded mixtures can give a higher number of resisting shear planes, with increased resistance to ravelling.	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. Therefore, rather than the aggregate size itself, the mixture grading is the key factor.
Construction quality	Compaction	Poor compaction results in higher air voids (%) thus reducing the adhesion of particles in the mat. It is claimed that this is the most important factor affecting ravelling.	Compaction must be completed to the specified range. A minimum of 92% of maximum density achieved on site it is claimed to mitigate ravelling and promote a durable pavement. The use of intelligent compaction technologies can assist ensuring quality during work execution.	Excessive compaction can lead to other undesired distress such as rutting. Thus, air voids should be optimised.
	Segregation	Segregation can result in areas with high air voids (%), more prone to ravelling.	Ensure segregation does not occur during construction.	Segregation affects also other types of distress.
	Layer thickness	Excessively thin layer does not provide sufficient room for the aggregate to reorient itself into a dense configuration. This increases the potential of ravelling.	Ensure the layer is at least two times thicker than the nominal aggregate size.	Pavement and mix design should take into account this factor to allow reorientation of constituents and correct compaction.
	Asphalt temperature	If asphalt is not sufficiently hot when laid, poor compaction can occur due to the bonds already formed. This occurs especially at the ends of loads.	Ensure asphalt is at a correct temperature when laying and compacting. Suggested minimum temperature is 145°C at mid-depth of asphalt layer. This ideal temperature depends on a number of factors.	Too hot temperature during construction can lead to excessive bitumen ageing. This factor should be considered during construction works.
	Wet weather	Laying in wet weather impacts the compaction quality and the adhesion, leading to increased potential of ravelling.	Laying should occur in dry conditions (no fog, rain or high humidity).	A warm enough asphalt may be able to evaporate moisture at low levels.
	Joints	Ravelling often initiates where excessive/poor longitudinal joints have been cut.	Joints should be cut to the correct size with care, especially longitudinally.	Workmanship should be controlled. Avoid material segregation. Use pavement joint heater or joint sealant.
In Situ conditions	Bitumen ageing	Premature ravelling can result from overheating during mixing while long term ravelling can result from weathering/brittleness.	There should be no overheating (temperature typically above 165°C) during mixing as this can cause premature aging.	Overheating and its impact on the amount of premature aging depends on the binder type.
	Weather	Cold weather can affect ravelling in different ways: the action of freeze-thaw mechanism can break the bonds in the mixture; low temperatures will make bitumen more brittle. These result in higher ravelling potential. Warm weather can affect ravelling to the extent that softening of the binder can reduce the adhesion strength between constituents.	Ensure that bitumen is adequately designed for the climatic in-situ conditions.	In DRaT D.2 it was reported a study finding that the maximum adhesive performance of porous asphalt was achieved at 0 °C, whereas the adhesion at -10°C was about equal that at +10°C.

	Substrate	For layer thickness lower than two and a half times the nominal aggregate size disaggregation may propagate upwards from the bottom of the layer. Therefore, the substrate stability and bond coat efficiency can influence the ravelling.	Ensure adequate bond coat.	This factor is more relevant for very thin layers.
	Traffic loading	Vertical static or dynamic loading (unless associated with other factors) is not typically related to ravelling. Areas of braking, acceleration and cornering are more prone to ravelling.	If required, surfacing may need specific design in areas of high stress.	Binders with elastic recovery may exhibit better performance in these areas.

Notes:

[1] HRA denotes Hot Rolled Asphalt.

[2] SMA denotes Stone Mastic Asphalt.

[3] BBTM (Béton Bitumineux Très Mince) denotes very thin asphalt layer.

[4] RAP denotes Reclaimed Asphalt Pavement.

[5] PMB denotes Polymer Modified Bitumen.

The review carried out within this research led to the following main findings:

- The presence of water affects ravelling primarily through two mechanisms: (i) stripping of bitumen from the aggregates, mostly in asphalt mixtures with interconnected air voids, and (ii) a pumping effect, caused by the action of tyres on a saturated pavement surface (in low void mixtures). These two apparently contrasting needs could be balanced by using dense mixtures with adequate macro-texture.
- The use of aggregate with good affinity to bitumen reduces the likelihood of ravelling for adhesion failure.
- Open asphalt mixtures tend to be more susceptible to ravelling because the aggregate particles are not embedded in the mortar on all sides. The use of smaller sized, well graded aggregates and low void mixtures could combat this mechanism.
- Binder characteristics affect ravelling in various respects. Binders with low viscosity improve the resistance to ravelling whereas low binder content increases the likelihood of ravelling. The advantages of using PMBs are unclear.
- High quality construction works are essential to improve the resistance to ravelling. To ensure that air void requirements are fulfilled, asphalt should be compacted to the designed density at the optimum temperature range, and possibly in dry conditions, to ensure aggregate re-arrangement the layer thickness should be at least twice the nominal aggregate size. Poorly cut joints can also initiate ravelling.
- The action of traffic loading is relevant to ravelling in areas of braking, acceleration and cornering.

METHODOLOGY

Based on the findings from the literature review, laboratory tests were carried out to assess the potential to ravelling of different TSCS using the DSD.

Darmstadt Scuffing Device (DSD)

The DSD, shown in Figure 2, is a device used to assess the ravelling resistance of full-scale asphalt samples. In this device, a square test plate (260±5 mm × 260±5 mm) is fixed on a moveable platform. A pneumatic tyre is lowered with a controlled vertical force onto the plate surface, while the platform performs several cycles of simultaneous translations and rotations, oscillating in the horizontal plane. The tyre thus simulates the mechanical effect of vehicles when they are turning, accelerating or braking. Each cycle is a combination of five translations and one rotation to an angle of 180°; each movement is considered as a two-way movement.

The test equipment and procedure are described in the Part B of PD CEN/TS 12697-50 (2018) and is summarised in Table 2.

Figure 2. Example of Darmstadt Scuffing Device (DSD) (InfraTest, 2019)

The DSD is currently available in two laboratories: TU Darmstadt (Lab 1) and Belgian Road Research Centre (BRRC) (Lab 2).

Table 2. Summary of DSD characteristics

Sample dimensions (mm):	
Length	260
Width	260
Min. Thickness	25
Max. Thickness	60
Core dimensions	Core samples not explicitly covered but can be tested
Conditioning	(40±1)°C for 2.5 h
Test temperature	(40±1)°C
Initial measurements	Mass and photograph
Test loading	(1000±10) N with a contact area of 33.3 cm^2 for an average contact pressure of 300 kPa

Operation during test	Vacuuming of loose grains and wiping off as required
Test duration	10 cycles (approximately 5 minutes)
Final measurements	Photograph; Residue and loose grains from the asphalt specimen and the tyre
Comments	Developed for testing Porous Asphalt (PA). However, it has the capability of testing Stone Mastic Asphalt (SMA) and very thin surface courses; Binder type has a greater influence if testing is completed at 40°C rather than 20°C

Testing plan

In order to explore how air voids and aggregate size of asphalt Thin Surface Course Systems (TSCS) affect their resistance to ravelling, the testing plan summarised in Figure 3, was adopted.

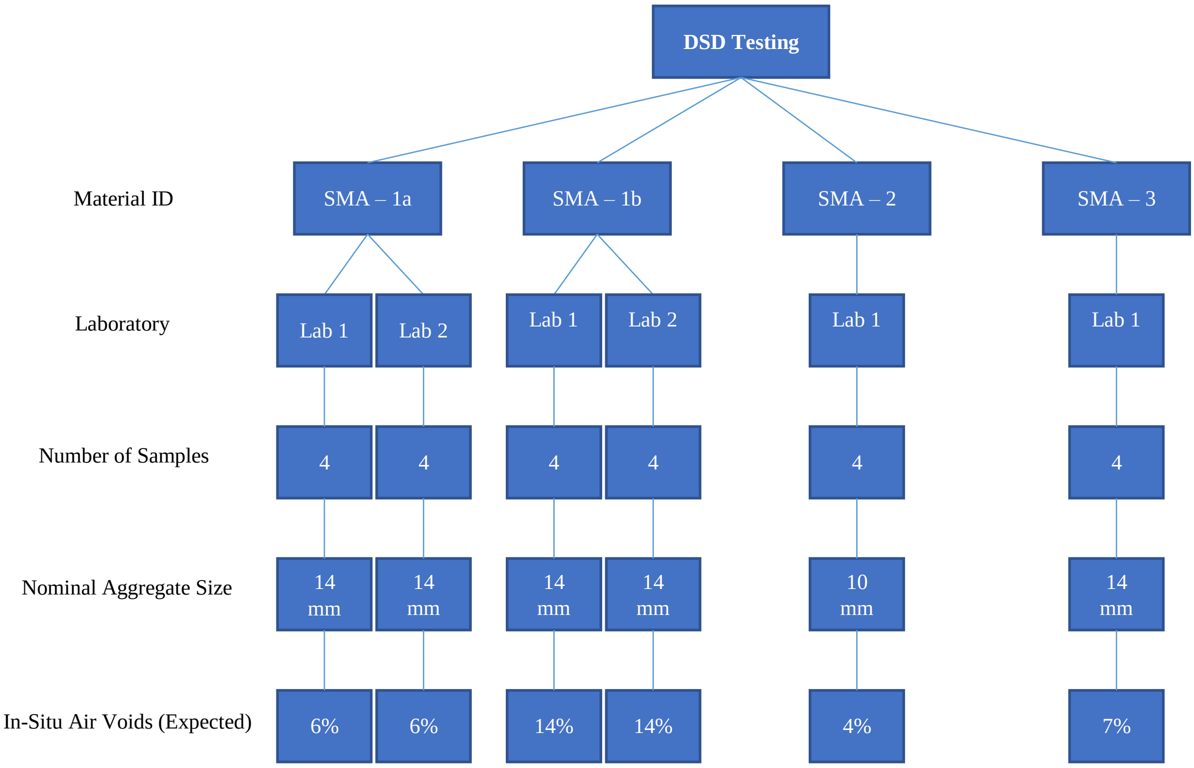

Figure 3. Testing plan overview

Three different Stone Mastic Asphalt (SMA) samples, named as SMA 1, SMA 2 and SMA 3 have been tested. These materials satisfy the requirements of Cl. 942 of Series 900 of the Manual of Contract for Highways Works (MCHW) (MCHW, 2018).

The SMA 1 (nominal aggregate size 0/14 mm) was compacted targeting two different air void contents:

- SMA 1a @ 6% Air Voids,
- SMA 1b @ 14% Air Voids;

in order to simulated good and bad in-situ compaction, respectively.

The other two materials - SMA 2 (nominal aggregate size 0/10 mm) and SMA 3 (nominal aggregate size 0/14 mm) - were compacted targeting their typical in-situ air voids: @ 4% and @ 7%, respectively.

Four samples for each configuration were tested in order to obtain adequate statistical significance in the results.

Sample Manufacturing

All samples were produced in a single laboratory (AECOM Nottingham laboratory) to reduce the variability between specimens. The method to prepare each batch of samples is described below:

1. Pre-coated loose material was provided by the manufacturer of each asphalt type.
2. The pre-coated SMA was pre-heated and mixed with standard equipment specifically designed to replicate mixing in a typical batch mix asphalt plant.
3. The mixtures were poured into moulds of the required size (305 mm x 400 mm x 50 mm). The amount poured was calculated by considering the desired density and the density compensation for shrinkage during the cool-down phase. Temperature was constantly measured during the production and compaction process.
4. Each mould was placed on the bed of the roller compactor and compacted in accordance with BS EN 12697-33 (BS EN 12697-33:2019, 2019).
5. Once compacted, for the determination of quality, various measurements were performed: dimensions, flatness and density. If there is a large variation in the measurements, then new slabs were prepared. At this stage, visual inspection was carried out looking for greasy spots (>2 cm not allowed), scarce and lean spots (>50 cm^2 not allowed) and irregular distribution of the slab mix near edges.
6. The slabs which passed this assessment were selected to be cut/cored to the dimensions required by the DSD (Figure 4).

Figure 4. Overview of asphalt samples cut to 260 mm x 260 mm as per DSD testing requirements

VOLUMETRIC RESULTS

In order to control the slab manufacturing quality in terms of air voids target, the first slab compacted for each variant was used to extract four samples, allowing for an accurate determination of the air voids content - with Method C of BS EN 12697-6 (BS EN 12697-6:2012, 2012). The results are summarised in Figure 5.

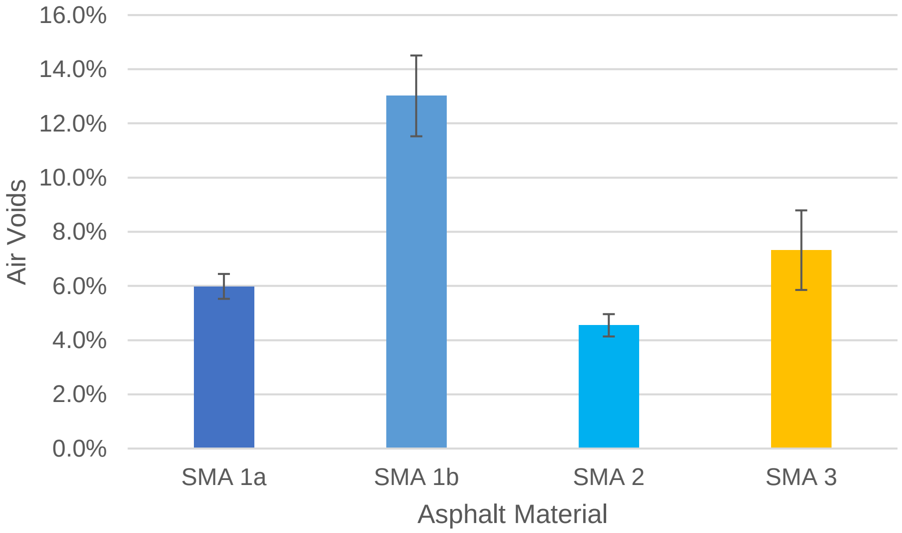

Figure 5. Air voids content for each material, determined as average of four samples extracted per each slab (the error bars display the standard deviation)

Considering the target air voids as described in Section 0, the average results were satisfactory, so the remaining slabs were all manufactured with the same settings and procedures used for the first slabs.

DSD RESULTS

This section reports and analyses the results obtained from the DSD testing. The analysis is divided into three main sub-sections:

1. Evaluation of the potential for DSD test to discriminate between good and bad compacted material. For this element, the same SMA material was used to produce two variants, differing in air voids: SMA 1a (6%) and SMA 1b (14%).
2. Evaluation of the reproducibility of the findings, by comparing results from the same tests carried out from two different laboratories: Lab1 and Lab2.
3. Evaluation of the influence of air voids and aggregate size on ravelling. For this element, additional SMA materials, differing for air voids and aggregate size were tested (only in Lab1) in order to provide a wider range of data to consider in relation to the findings obtained in the previous phases.

DSD Discrimination Power

Results from DSD testing are expressed as 'mass loss per unit surface area' (g/m^2). An example displaying the cumulative mass loss for each individual test is reported in Figure 6.

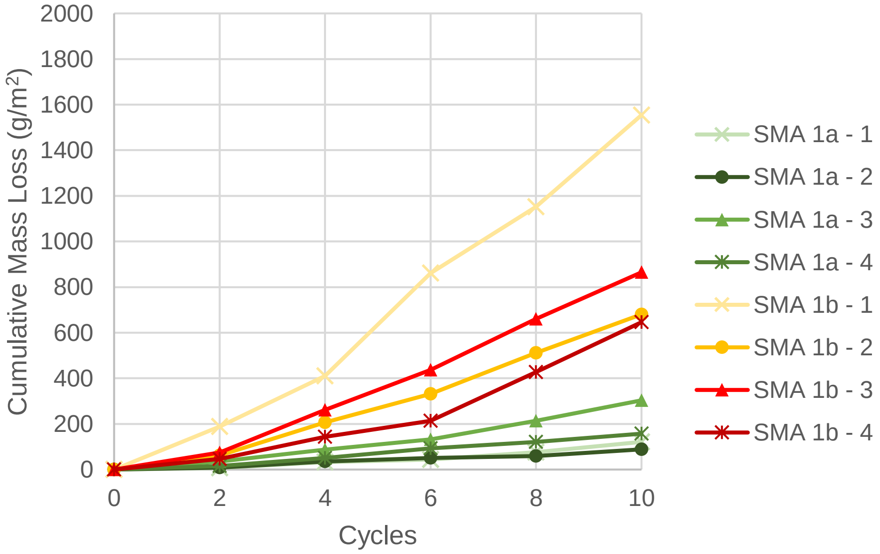

Figure 6. Example of DSD results – Lab 1, SMA 1a and SMA 1b

A difference in mass loss can be observed between SMA 1a (6% AV – good compaction) and SMA 1b (14% AV – bad compaction). This finding is common to both laboratories, as summarised in Figure 7.

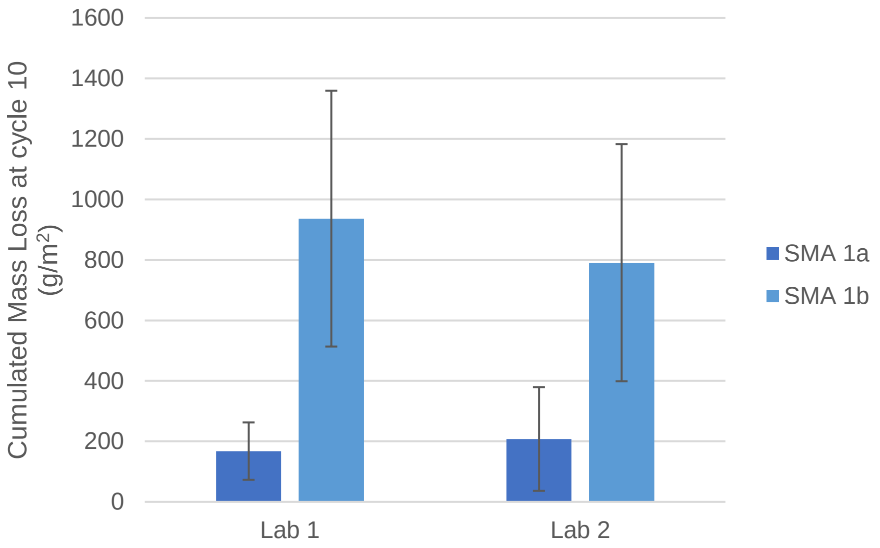

Figure 7. Averaged results for SMA 1a and SMA 1b for DSD testing carried out in Lab1 and Lab2

In order to evaluate if there is sufficient evidence to conclude that different SMA variants (differing in air voids) had a different resistance to ravelling – and to determine whether the DSD test is able to discriminate between good and bad compacted material – a statistical test was run, as described below.

A hypothesis test using a two-sample T-test ($\alpha = 0.05$) was used to determine whether two population means are different (Minitab Inc., 2010).

The null hypothesis, H_0, was that the SMA 1a mean is equal to the SMA 1b mean. The alternative hypothesis, H_1, was that the SMA 1a mean is NOT equal to the SMA 1b mean.

The results showed P-values (significance probability) of 0.006 and 0.017 for Lab1 and Lab2, respectively. This indicates that for both laboratories there is moderate to strong evidence against the null hypothesis (see Table 3). In other words, the mean of SMA 1a is not equal to the mean of SMA 1b. Therefore, the DSD can discriminate between good and bad SMA.

Table 3. T-test results interpretation

Significance probability	**Rough Interpretation**
$p > 0.10$	Little evidence against H_0
$0.10 \geq p > 0.05$	Weak evidence against H_0
$0.05 \geq p > 0.01$	Moderate evidence against H_0
$p \leq 0.01$	Strong evidence against H_0

DSD Reproducibility

A usual reproducibility study in the manufacturing industry requires three operators (laboratories), two repetitions and ten samples. In this case, there were only two laboratories (Lab1 and Lab2), four repetitions and two samples. The typical ANOVA analysis would therefore not be statistically significant.

It was considered more appropriate to run a hypothesis test using a two-sample T-test ($\alpha = 0.05$) which is more common for comparing results coming from two laboratories (Minitab Inc., 2010).

The null hypothesis, H_0, was that the mean of SMA 1a (or SMA 1b) from Lab1 is equal to the mean of SMA 1a (or SMA 1b) from Lab2. The alternative hypothesis, H_1, was that the mean of SMA 1a (or SMA 1b) from Lab1 is NOT equal to the mean of SMA 1a (or SMA 1b) from Lab2.

The results showed P-values (significance probability) of 0.696 and 0.631 for SMA 1a and SMA 1b, respectively. This means that there is (both for SMA 1a and SMA 1b) little evidence against the null hypothesis. Therefore, DSD testing on SMA can be considered as having a good reproducibility.

Influence of Air Voids and Aggregate Size on Ravelling

In order to assess the influence of air voids and aggregate size on ravelling, additional SMA materials (SMA 2 and SMA 3) were tested (only in Lab1). These additional tests were conducted to provide a wider range of data to consider in relation to the findings obtained in the previous phases. The results in terms of average mass loss at cycle 10 for all the materials are reported in Figure 8.

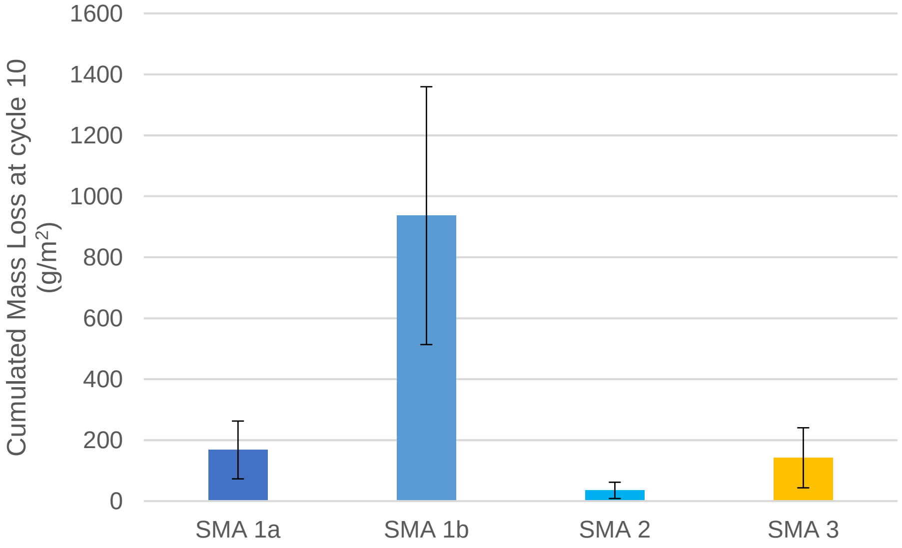

Figure 8. Averaged results of all materials for DSD testing carried out in Lab1

It can be noted that results for SMA 2 and SMA 3 are in line with those obtained for SMA 1; the SMA 3, which presented a higher void content (and higher aggregate size) was more susceptible to ravelling compared to the denser material (SMA 2). It could be noted that SMA 3 exhibited a slightly lower mass loss than SMA 1a (which had slightly lower air voids and same aggregate size). This could be due to the different source of the samples (produced by different companies), although the difference is far below the variability of the test itself.

In addition, SMA 2 exhibited the lowest mass loss. This outcome could be due: i) to the smaller aggregate size (10 mm); ii) to the lowest air voids (4%); or to a combination of these two factors. The large variability between the other materials having the same aggregate size (14 mm) suggest that the air voids appear to play the influent role. The data analysed so far returned a very strong correlation between the average cumulated mass loss and the average air voids for SMA materials, as shown in Figure 9. A wider range of results could more conclusive correlations.

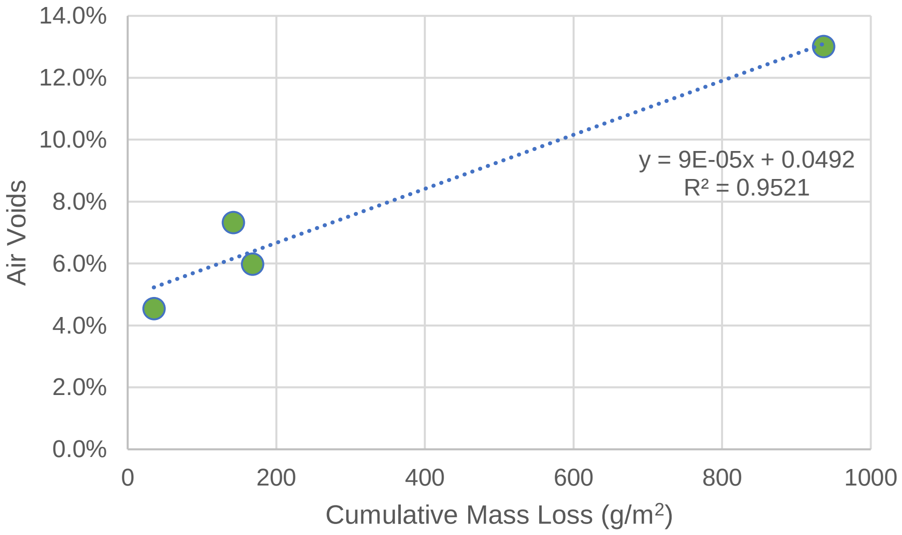

Figure 9. Influence of air voids on ravelling

CONCLUSIONS

This paper has presented the findings from recently completed research designed to assess the suitability of large-scale laboratory test methods to predict material loss from Specification for Highway Works Clause 942 TSCS. The research included a literature review of the ravelling phenomenon and the main factors affecting it, statistical analysis of accelerated tests on TSCS samples, and the impact of mixture variables (such as nominal aggregate size and air voids) to ravelling resistance. The main conclusions are summarised as follows:

- Based on the findings from the initial review, open asphalt mixtures are claimed to be more susceptible to ravelling because the aggregate particles are not embedded in the mortar on all sides. The use of smaller sized, well graded aggregates and low void mixtures could mitigate this mechanism.
- Results obtained from Lab 1 for materials SMA 1a and SMA 1b showed that there is sufficient statistical evidence to conclude that the DSD is able to discriminate between well and poorly compacted SMA.
- Results coming from two different laboratories (Lab1 and Lab2) were statistically comparable in terms of amplitude (mass loss) and outcome (SMA good vs. bad). Thus, DSD can be considered as a highly reproducible test.
- Results obtained from Lab 1 for a wider range of material confirmed that materials with higher air voids and higher aggregate size was more susceptible to ravelling compared to the denser materials.

- In addition, material with lower aggregate size appear to be less prone, although there is a large variability between the other materials having the same nominal aggregate size (0/14 mm).
- The air voids seem to play a key role on the resistance to ravelling; a very strong correlation (R^2 = 95%) between the average cumulated mass loss and the average air voids for SMA materials was found.
- Overall, test results are in line with general expectations and/or practical experience and hence confirm the relevance of this test method and its potential for future use in the Specification for Highway Works (MCHW, 2018).

ACKNOWLEDGEMENTS

This paper presents findings from a recent research project, commissioned by Highways England (HE) and undertaken by AECOM, to assess the suitability of a range of simulative laboratory test methods to predict surface course material loss on the UK network. The views expressed in this paper are the authors and do not necessarily express the views or policies of the organisations that they represent.

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