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Development of a Ravelling Test for Asphalt

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ABSTRACT: The test methods for four scuffing devices had been written up as technical specification PR CEN/TS 12697-50, Resistance to scuffing, which was reviewed by the DRaT project, under CEDR Call 2014: Asset Management and Maintenance. Existing knowledge on scuffing was reviewed and a round robin testing programme was undertaken with four replicate samples of three variations each of three mixture types. A statistical analysis found that results from the different devices could not be accurately correlated, either for specific asphalt mixture types or overall, nor could specific designs of scuffing equipment be identified as being best for identifying the scuffing-resistance of asphalt mixtures. Nevertheless, enhancements to PR CEN/TS 2697-50:2016 were identified that can be made to make a better and more unified document without rejecting any of the designs of scuffing apparatus. A copy of the revised version of the standard was given in the final report.

1 INTRODUCTION

Ravelling is a common mode of early failure for many types of asphalt pavement. Recently several simulative laboratory tests have been developed to give an indication of the ravelling potential of an asphalt mixture. These tests use scuffing machines that repeatedly apply a scuffing action to specimen samples to replicate in service loading. The test methods for four such scuffing devices had been written up as a draft technical specification by Comité Européen de Normalisation (CEN) as CEN/TS 12697-50, Resistance to scuffing, subsequently published with minor revisions as a technical specification (CEN, 2016A).

The four machines were the Aachener Ravelling Tester (ARTe, Figure 1), the Darmstadt Scuffing Device (DSD, Figure 2), the Rotating Surface Abrasion Test (RSAT, Figure 3) and the TriboRoute Device (TRD, Figure 4). Each device and most of the method using them were written up in separate Annexes. Ideally, these methods need to be culled or combined so that there is only one (harmonised) test method for this one property before the technical specification can be converted into a test standard.

The Conference of European Directors of Roads (CEDR) has an interest in developing the test into a truly harmonised standard. Therefore, in its transnational research programme “Call 2014: Asset Management and Maintenance” included one to investigate which should be the preferred option(s) for



Figure 1. Aachener Ravelling Tester (ARTe)



Figure 2. Darmstadt Scuffing Device (DSD)



Figure 3. Rotating Surface Abrasion Test (RSAT)



Figure 4. TriboRoute Device (TRD)

the test. The national road authorities funding this call were Belgium-Flanders, Finland, Germany, Ireland, Norway, the Netherlands, Sweden, United Kingdom and Austria. The resulting “Development of Ravelling Test (DRaT) project was led by TRL with TNO, BRRC, BAM, Heijmans, IFSTTAR, Technische Universität Darmstadt and ISAC in RWTH Aachen Universität.

The DRaT project looked at the methods of testing and the results produced for the four scuffing devices in order to identify:

- The extent to which sample preparation needs to be standardised, such as compaction level, evenness, storage conditions and age when tested.
- The most effective method of measurement in terms of extent of differentiation, validity as a measure of ravelling and practicality.
- Whether the results from one or more scuffing devices can be validated from experience on site.
- Whether the results from different scuffing devices can be converted to a common measure.
- Estimates of the precision of the results with each scuffing device or, if the results can be converted to a common measure, of the common measure.
- Whether the results from either pair of similar devices are comparable and their results are reproducible.
- A procedure to identify if other scuffing devices can be used for the standard test.

It was not known at the start of the project whether these findings would be the same for all asphalt mixture types or different for different types.

2 REVIEWS

A review was carried out into the parameters influencing the propensity of asphalt to ravel (Nicholls et al., 2015). The review found a dearth of literature on ravelling rather than just giving references to it. However, many factors were identified that had affected the potential for ravelling, including:

Materials:

- Hydrophobic aggregates are preferred with better potential affinity to bitumen.
- Aggregates should be clean when mixed into asphalt.

Mix design:

- The binder content should be as high as practicable without causing other problems such as 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 polymer-modified bitumen is uncertain.
- Both larger maximum aggregate size and 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.
- Segregation will also 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 sufficient hot when compacted is liable to ravel.
- Asphalt should not be laid in the wet.

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.
- Heavy rainfall can also exacerbate ravelling.
- Direct load does not cause, but lateral, shear or torsion forces can cause it so ravelling will predominate where braking, acceleration and cornering are present.
- Joints and slot cuts are potential areas where ravelling will start.

It was concluded that the basic strategy to minimise ravelling is to produce and lay a material that will overcome these various causes for ravelling. Also, 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. Finally, repair techniques include pothole repairs, removal followed by an overlay and surface treatments depending on the area affected and the precise cause.

A review was also carried out into the sites with reported ravelling and any quantitative assessment of the extent (Nicholls, 2016). The review found data on the performance of different sites with different mixtures in the Netherlands, Belgian and the United Kingdom with respect to ravelling. The findings from these studies are as follows:

The Dutch studies showed that:

- There can be a significant scatter in the extent of ravelling with the same asphalt mixture.
- Higher binder contents do reduce the tendency to ravel.
- The use of polymer-modified bitumen does not reduce the tendency to ravel.
- Slag aggregate makes asphalt more susceptible to ravelling.

The Belgian trial showed that twin-layer porous asphalt is more susceptible to ravelling than more dense asphalts.

The British survey showed that:

- Ravelling increases with age, as would be expected.
- The ranking of three mixture types for resistance to ravelling is stone mastic asphalt (SMA) as best, then asphalt concrete for very thin layers (BBTM) and finally asphalt for ultra-thin layer (AUTL).
- Higher binder contents tend to reduce scuffing.
- Larger aggregate sizes tend to reduce scuffing.

However, the last three correlations are very weak and the findings are indicators rather than conclusive.

3 ROUND-ROBIN TEST PROGRAMME

Based on the review into the sites with reported ravelling, the following three asphalt surface course mixtures were select for the trial (Jacobs, 2017):

- a Dutch porous asphalt (PA) in accordance with EN 13108-7 (CEN, 2016b);
- a French BBTM in accordance with EN 13108-2 (CEN, 2016c); and
- a German SMA in accordance with EN 131085 (CEN, 2016d).

However, no quantitative estimate of their propensity to ravel could be identified.

For each generic type of mixture, the design for a typical mixture was identified and then two variations, which were expected to have inferior scuffing resistance, were developed. The variations were a reduced binder content and compaction at a lower temperature. The main parameters are given in Table 1.

The aggregates for each mixture were Listeral Grauwaacke coarse crushed rock, natural sand from Putman river, Moraine crushed sand and factory-produced filler. Cellulose fibres were included as an anti-stripping agent.

Table 1. Mixture parameter and variations for the round robin

Mixture Type	Mixture Code	Binder	Parameters	Variant 1	Variant 2
PA	PA 16 70/100	70/100	Compaction at 150 °C 5.2 % bitumen ±20 % air voids content	Compaction at 105 °C	4.2 % bitumen
BBTM	BBTM 6 50/70	50/70	Compaction at 160 °C 5.6 % bitumen (12 – 19) % air voids content	Compaction at 110 °C	4.6 % bitumen
SMA	SMA 11 PmB	PmB 25/55-55 with 3 % SBS polymer	Compaction at 155 °C 6.8 % bitumen ±3 % air voids content	Compaction at 105 °C	5.5 % bitumen

The asphalt was mixed in a laboratory plug mill mixer and then compacted in 600 mm x 600 mm x 43 mm moulds with a wooden underlayer and metal top frame (Figure 5). The compaction was achieved with a new roller that, therefore, had a perfect round drum (Figure 6). The samples were rotated midway through the compaction procedure in order to ensure uniform compaction.

The slabs were extensively tested in order to minimise any difference between slabs of the same mixture variant:

- The flatness of each specimen was measured at several points to ensure that there were no variations greater than ± 1 mm.



Figure 5. Moulds used to prepare slabs



Figure 6. Drum roller compacting a specimen

- Nuclear density measurements were taken at four locations but were found to have questionable repeatability and reproducibility. Therefore, the calculated density was determined from the volume and mass and checked to be $\pm 15 \text{ kg/m}^3$ of the target value, although it gives no information about the density distribution over the slab.
- Sand-patch texture measurements were made at four locations on each BBTM and SMA sample with a variation coefficient $\leq 8,8 \%$.
- Visual inspections for binder-rich spots with a diameter greater than 20 mm and lean areas of more than 5000 mm² per slab.

These checks resulted in nine of the 177 slabs produced being rejected.

The slabs were cut into suitable sized slabs for the different devices, with four samples being able to be cut for the DSD and TRD equipment but only one for the ARTe and RSAT. Four samples were required for each variant of each mixture for each laboratory, making a total requirement of 17 slabs per mixture variant.

4 TEST RESULTS

The DRaT test programme deviated from the draft standard (De Visscher, 2017) by increasing the number of replicates tested from two to four in order to have been able to undertake a more accurate statistical analysis. Also, the age of the samples between compaction and testing was extended from below 42 days to (10 ± 1) weeks because of the number of samples to be manufactured, transported and tested.

Further harmonization was made in those requirements not common to all devices in the draft standard. The changes were:

- The conditioning was set at the test temperature $\pm 2 \text{ }^\circ\text{C}$ for at least 4 h.
- The initial measurements were to include at least dimensions and mass together with top view and 45 ° angle view photographs.
- Removal of all loose material by vacuum cleaner initially and during the test.
- Test temperature was set at $(20 \pm 2) \text{ }^\circ\text{C}$ for all devices except the DSD, which was left as

$(40 \pm 2) \text{ }^\circ\text{C}$ (although BRRC repeated the tests with the DSD at 20 °C).

- The final measurements were to include at least the dimensions and mass, top view and 45 ° angle view photographs and the mass of aggregate lost during test.
- Measurements were also required at a quarter, half and three quarters of the number of cycles.

After the testing had been completed, the test conditions achieved were compared with those required. The observed deviations were as follows:

- At ISAC, the enclosure temperature was 23 °C ($> 22 \text{ }^\circ\text{C}$) for the tests on SMA and the sample surface temperature at start of the measurements were not always within range (18 – 22) °C with a maximum temperature of 35 °C for tests on M3.
- At BAM, all test conditions were as specified
- At BRRC, the test load was increased from 1000 N to 2000 N and the number of load cycles to 50 load cycles at the tests at 20 °C because of limited loss of material at the original load. Also, the enclosure temperature was between 20 and 24 °C ($> 22 \text{ }^\circ\text{C}$) during the period of testing and the sample surface temperature at start of the measurement not always within range (18 - 22) °C with, for a few specimens, the maximum temperature at start being 23 °C. Finally, there was a delay of 12 months for PA, 11 months for BBTM and 9 months for SMA samples.
- At TU Darmstadt, the sample surface temperature at the start of the measurement for a few measurements was above 42 °C.
- At Heijmans, the conditioning temperature were different for different mixtures with 20 °C for PA and 5 °C for SMA and BBTM and there was a delay before testing of 1 month for PA and 2 months for BBTM and SMA.
- At IFSTTAR, the enclosure temperature was 24 °C ($> 22 \text{ }^\circ\text{C}$) for all SMA and one BBTM sample and the sample surface temperature at start of the measurement were not measured. Also, there was a delay of approximately 1 month for the BBTM and 2 months for SMA samples.

The detailed results are given elsewhere (De Visscher, 2017). The rate of material loss (slope of the curves) behaved differently depending on the test device. The DSD showed an increasing rate, especially for the PA and BBTM mixtures, while RSAT showed a decreasing rate. The rate is roughly constant for the other two devices.

Plots of mass loss against either density or texture show no correlations. This finding is not surprising because the variations in density and MTD within each series of samples of the same mixture were very small. The conclusion is that the repeatability of the sample manufacturing for this test programme was very good and that the mass loss measurements were not biased by differences in density and texture variations.

Pictures were taken from the test specimens before and after testing. It is very difficult to evaluate the damage from pictures, since the resolution, lighting and angle vary.

Inspection of the pictures did not reveal anything special. However, a few general points were noted. The PA test specimens from the DSD showed the most heavily damaged surface while those from the TRD showed no damage, both consistent with the relative stone loss measure. The BBTM test specimens were similar except that the aggregate size was smaller and those from the TRD show some raveling/abrasion in the middle of the specimen. It was more difficult to see stone loss on the SMA test specimens because the texture of the surface is more closed.

5 STATISTICAL ANALYSIS

Separate statistical analyses are conducted for each type of asphalt and each laboratory (Schoen *et al.*, 2017) in order to establish whether the weight loss in the low temperature (*lt*) and low bitumen (*lb*) sets of slabs were higher than in the standard (*s*) set. One-sided *t*-tests were made on the differences between the low temperature and low bitumen sets with the standard set using log-transformed data. The *t*-test results in the correct probability values when:

- individual weight losses in each set of slabs are normally distributed; and
- the standard deviation of the data is the same for each set of slabs.

Data were collected for both the primary results (determined as the difference between the mass of the slab before and after testing for all laboratories) and the secondary results, which varied with laboratory. For TUD, BRRC and Heijmans, the secondary result was the weight of the material recovered during the test (aggregate and mortar for TUD and BRRC or aggregates > 2 mm for Heijmans) while for IFSTTAR it was the weight loss of PA and SMA slabs after 6,000 cycles and for BAM it was weighings including the wooden frame. There was no secondary result for ISAC.

The reports from the six laboratories showed deviations from the measurement in three cases. The results of these measurements were disregarded in the data analysis. Three further possible outlying weight losses in the data were also identified.

With regards to precision, the devices show large coefficients of variation (often more than 30 %), limiting the discrimination potential strongly without increasing the number of slabs tested. The four replicates tested in this project permitted discrimination between poor quality and standard materials in 14 of the 36 combinations of laboratory and mixture variant.

The primary purpose of the round robin was to make out whether the scuffing devices can be used interchangeably and, if not, which of them gives the most informative results. The presence or absence of a statistically significant increase in weight loss between the different qualities of an asphalt type based on four replicates is tabulated in Table 2.

Table 2. Statistically significant differences in the round robin tests

Device	Laboratory	Asphalt type					
		PA		BBTM		SMA	
		<i>lt</i>	<i>Lb</i>	<i>lt</i>	<i>lb</i>	<i>lt</i>	<i>lb</i>
ARTe	ISAC	0	1	0*	0*	0	0
	BAM	1	1	0	1	1	0
DSD	TUD	0	1	0	0	0	0
	BRRC	0	1	0	0	0	0
RSAT	Heijmans	1 ²	1	0	0	1 ¹	1
TRD	IFSTTAR	0	0	0	1*	1	1 ²

1 Only for primary weight loss

2 Only for secondary weight loss

* After removal of statistical outliers

All devices except the TRD showed an increased weight loss for the PA/*lb* slabs while only two laboratories showed an increased weight loss for the PA/*lt* slabs. The implication is that there was a quality difference which was not picked up by four of the laboratories.

No increased weight loss for the BBTM/*lt* slabs was established, possibly due to the good quality of these slabs. Two laboratories showed an increased weight loss for BBTM/*lb* slabs which again suggests a quality difference which was not picked up by four of the laboratories.

There were quality differences with respect to the standard in both SMA/*lt* and SMA/*lb* slabs although they were not picked up by all the laboratories. It appears that the current test procedures for each device are insufficient to cause ravelling to a properly designed SMA material.

When looking at the results by device rather than mixture type, the DSD appeared insensitive for detecting differences in PA/*lt*, BBTM and SMA mixtures. The RSAT was sensitive for detecting differences in PA and SMA but not BBTM samples, but there were inconsistencies in the primary and secondary weight loss results. The TRD seems sensitive for BBTM and SMA to detect designed quality differences, but the detection is not consistent for *lb* and *lt* differences. Also, the number of cycles for the TRD test needs to be unified from the different materials different loading times for different asphalt types.

There were substantial differences between the results from the two laboratories using the ARTe. The BAM device seemed particularly capable of discriminating between the PA qualities whereas the ISAC device only showed statistically significant

differences for PA/lb slabs from the standard. The differences between the laboratories can only be explained only by a different experimental conduct or by (unknown) differences between the individual devices.

The anticipated ranking of the asphalt types for ravelling propensity under the same loading conditions was PA, then BBTM and finally SMA. This ranking was generally found from the results except with the TRD, which ranked PA last. However, there was a problem with permanent deformation during the PA testing with the TRD causing the limited mass loss.

The potential of different devices to discriminate between standard and poor-quality materials of the same asphalt type were not comparable, so it would appear that the scuffing devices cannot be used interchangeably. In addition, no single device appeared to be capable of detecting all the designed differences between the standard and poor-quality materials according to the current test methods.

The comparison between the devices for the three materials demonstrates that there are clear differences in the design and effects of the testing devices. No uniform correlation between the devices could be found nor could their results be culled or unified for a performance or loading time that would convert to a common measure, or scaling factor to turn the results of one device to another. Furthermore, some of the devices showed a different damage development in time. Therefore, the results of the individual devices could not be converted to a common measure.

6 RECOMMENDATIONS TO UPDATE STANDARD

The research provided no definitive answer (for all or for specific asphalt mixture types) as to whether there are:

- a ‘best’ device to be used universally;
- any ‘bad’ devices to be removed from the list; or
- robust correlation factors to equate results from the different devices.

Nevertheless, it was considered that there was sufficient useful information gained to produce a revised draft of PR CEN/TS 12697-50:2016 (Nicholls *et al.*, 2017).

The main issue with the revision was to put the separate test methods into a single test method with only certain parameters and options defined for the separate devices that cannot be harmonized (such as sample size) still in separate annexes. However, there is a need to normalise the results for each device into a common measure. Although the correlations were not consistent, these values were averaged to give an estimated normalisation factors as shown in Table 3. Separate normalisation factors were not calculated for different asphalt mixtures because that would imply greater precision than is the case.

Given the variability in the values used to produce these values, it was proposed to round them off to 2.8 for the ARTe, 2.6 for the DSD, 1.0 for the RSAT and 10 for the TRD. However, on further reflection the consortium decided that these factors were not sufficiently robust to be included in a standard and they were relinquished to a separate appendix in case the CEN committee felt differently.

It was recommended to increase the minimum number of replicates per test from two to three: four would be better but there was concern that four replicates would make the test too expensive and inhibit its use.

In addition, a normative annex was proposed for alternative devices that may be developed in the future. The annex would cover checking the equivalence of the new device together with the calculation of the normalising factor. However, without normalising factors to calibrate against, the consortium also decided not to include this annex in their proposed draft of the standard.

Most of the harmonisation applied to the round robin programme (Section 3) was recommended for the revision of the standard. Several other aspects included in proposed revision are described below.

The first recommendation to the new draft was to extend the definitions because it was appreciated that terms such as ‘scuffing’ and ‘ravelling’ are not understood to mean the same thing universally. The proposed definitions added included:

- **scuffing**: the action of tyres, particularly when the wheels are rotating about an axis not perpendicular to the direction of travel of the vehicle (or relative motion of the tyres and asphalt surface simulating the vehicle movement) which causes material loss from the surface of the asphalt

Table 3. Rejected proposal for Normalising factors between devices

Device	ARTe				DSD		RSAT	TRD
Laboratory	ISAC	BAM	Mean	TUD	BRRC	Mean	Heijmans	IFSTTAR
PA	5.0	2.4	3.0	0.2	0.2	0.2	1.6	(91.7) †
BBTM	15.2	5.3	10.3	0.7	0.7	0.7	1.9	10.1
SMA	6.9	4.6	5.8	13.3	21.1	17.2	3.5	37.9
Mean		6.6			6.0		2.3	24.0
Normalised		2.81			2.59		1.00	10.3

† Excluding the PA results with the TRD (permanent deformation being observed)

Table 4. Standard deviations found

Device	ARTe		DSD		RSAT		TRD	
Laboratory	ISAC	BAM	Mean	TUD	BRRC	Mean	Heijmans	IFSTTAR
PA	49 %	24 %	37 %	17 %	18 %	17 %	38 %	53 %
BBTM	42 %	38 %	40 %	15 %	22 %	18 %	28 %	34 %
SMA	18 %	25 %	22 %	37 %	30 %	34 %	12 %	35 %
Mean		33 %			23 %		26 %	41 %
				31 %				

- **material loss**: amount of material that has been lost from the surface of the asphalt due to scuffing divided by the area being scuffed
- **ravelling**: loss of coarse particles from the surface of the asphalt due to scuffing divided by the area being scuffed
- **fretting**: loss of fine material from the surface of the asphalt due to scuffing divided by the area being scuffed

The definitions were deliberately worded in order to apply to the scuffing of a road surface by passing vehicle tyres or to the simulated scuffing of a test sample by the tyres on scuffing apparatus during a test.

It was proposed that the sample preparation requirements should include:

- Checking the bulk density of the slab or core by the dimensions procedure (as already included by the test method) with a maximum allowable difference of 0.050 Mg/m³.
- Checking the thickness of the samples at nine positions with a calliper to ensure a maximum allowable difference of 2.5 mm.
- Checking the overall dimensions and flatness (± 1.0 mm) of each sample.
- Checking the visual condition is acceptable.

It was proposed that the samples should be required to have all loose material removed with a vacuum cleaner initially and before each set of measurements. The material vacuumed off will need to be retained for determining the material lost.

It was proposed that measurement should be made at the end of the test and not less than three equally spaced intervals during the test. At each set of measurements, the following initial measurements should be made:

- Dimensions of the sample.
- Mass of the sample.
- Mass of lost coarse particles (not initially, optional otherwise).
- Photographs of the top surface of the sample from above and at a 45 ° angle.

The location relative to the sample from which the pictures are taken together with the lighting and camera settings also needed to be recorded so that they can be replicated for subsequent photographs

It was proposed to have two test durations, the standard number of cycles and an extended number of about double the standard. However, no investigations have been made as to whether the same nor-

malisation factors should be applied for the extended loading cycle because of the different development in damage over time and loading.

It was found that that the test methods have relatively large geometric standard deviations, often more than 30 % (Schoen *et al.*, 2017), as summarised in Table 4.

These values are for single measurements, so can be reduced by dividing by the square root of three for test results which are the mean of tests on three samples. However, it is proposed that these values will only be given as guidance for repeatability rather than to make estimates of repeatability and reproducibility because of the limited number of devices involved.

A revised draft of PR CEN/TS 12697-50 with recommendations incorporated was produced with the changes highlighted. The highlights were red for major additions, mauve for minor changes in terminology, blue for moved sections, green for a compilation of ideas from the Annexes into the main text and grey across gaps from which text has been removed. However, because these changes were so extensive, the highlighting could only be indicative.

7 GUIDANCE ON SCUFFING

A separate informative annex was also proposed giving advice on scuffing and the choice of scuffing device (Nicholls *et al.*, 2017). The annex starts by discussing the difference between early stage ravelling and ravelling at the end of the service life.

Early stage ravelling results from the shear stresses imposed by vehicles which can be high, particularly at bends, crossings and roundabouts. Depending on the type of mixture, these stresses will be applied primarily to either the mortar fraction or the stone particles in the road surface. For continuous-graded mixtures, this load can generate the loss of fine material from the surface, called fretting. This phenomenon can retard or even stop when the coarser fractions of the mixture are exposed at the surface and help to withstand the traffic load. A different process takes place with stone-skeleton mixtures like SMA or PA where the traffic forces are applied directly to the stone particles at the road surface, both initially and thereafter, to cause ‘ravelling’ (loss of coarse aggregate from the surface).

Ravelling at the end of the service life develops at the end of the life-span particularly of stone-skeleton mixtures like PA and SMA. It occurs in and near the ‘wheel tracks’ of a road surface, those being the places that mostly bear the loads from the vehicle tyres, not only at crossings or curves but also in straight sections of roads.

These mechanisms, together with other mechanisms such as those for fretting (loss of cohesion of the mortar), are essentially different. They take place in different stages of the life of a pavement, a different combination of mixture parameters and load parameters are relevant to each and different circumstances can be critical (e.g. temperature).

Before using the scuffing test, it would be useful to consider which mechanism(s) is/ are being investigated or their potential monitored and which of the devices is most targeted at the area. To assist in such a review, some aspects to be considered are listed in Table 5 and the aspects for different devices in Table 6.

Table 5. Aspects to be considered in choice of device

Reason for investigation or monitoring		Avoid wear and rough texture	Avoid early stage ravelling	Extension service life	Investigation on the residual life of an existing pavement
Relevant period of service life		Whole pavement life	Beginning of pavement life	End of lifetime	End of lifetime
Damage principle		Fretting	Ravelling	Ravelling	Ravelling
Revelation form of damage		Loss of fine material from the road surface	Loss of coarse aggregate	Loss of coarse aggregate	Loss of coarse aggregate
Type of mixture		Continuous graded mixtures	PA, SMA or thin fine graded SMA	PA, SMA or thin fine graded SMA	PA, SMA or thin fine graded SMA
Requirements on the test device	Type of test pieces	Slab produced in laboratory	Slab produced in laboratory	Slab produced in laboratory	Cores from the road
	Direction of movement	No requirement	No requirement	All directions	All directions
	Length of test run	Measuring wear: moderate/large number of passes	Measuring strength: limited number of passes	Generating fatigue damage: large number of passes	Generating fatigue damage: large number of passes
	Final measurements	Loss of weight of test sample	Loss of fines and coarse aggregate	Loss of coarse aggregate	Loss of coarse aggregate

Table 6. Aspects for different apparatus

Device	Test samples		Direction of movement	Length of test run	Principal measurement methods
	Slabs	Cores			
ARTe	Laboratory produced slab	3 x 150 mm \varnothing cores per sample	All directions	600 cycles in 2 h	Weight-loss of sample Loss of coarse aggregate Change of texture depth
DSD	Laboratory produced slab	3 x 150 mm \varnothing cores per sample Single cores	Forward and back	10 cycles	Weight-loss of sample
RSAT	Laboratory produced slab	3 x 150 mm \varnothing cores per sample	All directions	86.600 cycles in 24 h	Weight-loss of sample Loss of coarse aggregate
TRD	Laboratory produced slab	n/a	Forward and back	6.000 cycles	Weight-loss of sample

8 CONCLUSIONS

The main limitations of the research were that:

- No quantitative measure of scuffing on site was identified to produce data for validation of the various options.
- The round robin did not produce precise correlations, whether between devices for all mixtures or between devices for specific mixtures.
- Neither the ‘best’ device to be selected as the sole one for the test nor any ‘bad’ devices for exclusion were identified, whether for specific mixtures or for all mixtures

Nevertheless, the research forms the basis of an ‘improved’ proposal for PD CEN/TS 12697-50 with the majority of details in the main text rather than in separate annexes for each device. As such, more details are common between the methods for the different devices while retaining separate annexes for details that remain different.

Normalisation coefficients have been calculated to compare results from different devices, although these are not fully validated and are not proposed for the revised standard. Further development is needed when extra data become available with possibly different coefficients for different mixture types.

An additional annex was considered for possible additional devices defining a check for compatibility with existing devices and the calculation of the normalisation coefficient but also discounted.

An additional informative annex for guidance on the choice of scuffing test has been proposed.

The implementation of the ‘improved’ proposal for PD CEN/TS 12697-50 will be with CEN and for the implementation of the test by road authorities, including CEDR members and local authorities.

Therefore, the open questions left by the research programme are:

- Will CEN agree to the proposal?
- Will PD CEN/TS 12697-50 be used extensively?
- Can the Normalisation factors be refined to make them practical?
- Will CEN select a preferred test device, possibly different devices for different situations, or adopt a calibration procedure for alternative devices?

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