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Laboratory studies investigating the use of blended PSV aggregates

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Contents

Executive Summary

Thin Surface Course Systems (TSCS) are now the primary surfacing material used on the Highways Agency's strategic road network. TSCS use more high specification aggregate (aggregate with high resistance to polishing) than older surfacing types such as hot rolled asphalt because it is incorporated throughout the surface course rather than being spread on top. The work described in this report investigates two potential methods for more sustainable use of virgin aggregate resources. Two laboratory experiments were carried out, examining the effect on friction of combining high specification virgin aggregate with either lower-specification virgin aggregate, which is more abundant, or with reclaimed asphalt, use of which in the surface course is currently restricted.

In the first experiment, the effect on friction of combining coarse virgin aggregates from two different sources is investigated. Asphalt specimens were prepared in the laboratory using 26 different combinations of pairs of coarse aggregates, which represented the range of aggregate available in the UK. The asphalt specimens were polished using a Wehner-Schulze (W-S) machine before friction was measured on their surfaces, also using the W-S machine. The results show that, in general, the friction on asphalt with coarse aggregate from two different sources is predictable; given information about the performance of asphalt specimens prepared using aggregate from each source individually. The approach taken could be used to investigate the performance of aggregate combinations not already inspected.

However, the results were more variable than expected, possibly due to the difficulty of preparing small quantities of asphalt in the laboratory. Although this stage of testing gives a valuable indication of performance, and may serve to highlight any potential issues with specific blends, it is recommended that further testing should incorporate full-scale trials on the Strategic Road Network. Trial sites should be allowed by departure from the surfacing materials standard, HD36 (Design Manual for Roads and Bridges, 2006), subject to monitoring of skid resistance. Further, it is recommended that, once performance has been demonstrated for a specific aggregate blend, for a given site category and traffic level, its use should be allowed at similar sites, by departure from the same standard, without additional constraint.

In the second experiment, the effect on friction of incorporating reclaimed asphalt (RA) into the surface course, in combination with virgin aggregates, is investigated. There is a restriction for the use of RA in the surface course of 10% and, if this restriction were relaxed, it may be possible to reduce demand for high specification virgin aggregate at some sites. Asphalt specimens were prepared in the laboratory, combining RA in different proportions, up to 40% by mass, with virgin aggregates. The results suggest that, in most low-risk situations, the addition of RA is likely to have only a small effect on friction, even when the RA contains significant quantities of limestone.

As with the first experiment, it is recommended that trial sites be established on the Strategic Road Network. Specifically, unless the site requires the use of high specification aggregate, RA sourced from surface courses should be allowed without the 10% restriction, subject to further monitoring. Use of RA from mixed stockpiles should also be allowed for trial sites, by departure, provided laboratory testing has been carried out to verify the expected performance of the proposed blend.

It should be noted that, in the second experiment, the results and recommendations do not take into account any additional technical difficulties arising with binder properties or asphalt durability.

1 Introduction

The work described in this report aimed to investigate the effect on friction of blending virgin aggregates with different polish resistance and the effect on friction of incorporating reclaimed asphalt into the surface course, in combination with virgin aggregates.

Thin Surface Course Systems (TSCS) are now the primary surfacing material used on the Highways Agency's strategic road network. TSCS are proprietary hot or cold bituminous materials that have been certified under the Highway Authorities Product Approval Scheme (HAPAS); they can be installed at nominal depths up to 50 mm. According to Construction Product Regulations (CPR), any asphalt product available on the European market must be defined in terms of one of the European standard asphalt types (the BS EN 13108 series of material specifications for bituminous mixtures) and TSCS are usually Stone Mastic Asphalt (SMA), Very Thin Layer Asphalt Concrete (BBTM - Béton Bitumineux Très Mince) or Asphalt Concrete (AC).

Unlike historic hot rolled asphalt, where high specification aggregates (HSA - those aggregates with high resistance to polishing) were rolled into the surface, TSCS have the HSA throughout the surfacing layer. This has led to an increase in the use of HSA and there are reportedly limited stocks of these materials (Thompson, Burrows, Flavin, & Walsh, 2004) that are suitable for use in surfacings. The work described in the following chapters was designed to investigate ways of reducing dependence on HSA and preserve this limited natural resource.

A Wehner-Schulze machine was used to examine the friction after controlled polishing on the surface of asphalt specimens prepared in the laboratory. The results are presented alongside discussions about the implications of blending virgin aggregates and/or reclaimed asphalt, as well as practical implementation.

2 Background

In an attempt to ensure provision of adequate skid resistance, construction specifications require the use of aggregates that resist polishing by traffic. In the UK, this property is assessed by a standard laboratory test that gives a measure known as the polished stone value (PSV). Typically, aggregates with PSV less than 50 are not used as coarse aggregate in the surface course but they may be used in the finer fractions of asphalt materials. Aggregates with the highest PSV (>63) are typically specified for situations where high skid resistance is required, even after the aggregate has been polished by large volumes of traffic.

There are limited stocks of high-PSV aggregate suitable for surfacing materials (Thompson, Burrows, Flavin, & Walsh, 2004). Haulage of these aggregates from their source quarries can result in significant cost and energy consumption for surfacing schemes on many parts of the network. In spite of this, the skid resistance on substantial lengths of the HA strategic road network considerably exceeds the set Investigatory Level (IL). The histogram in Figure 2.1 shows the distribution of network lengths with differences between measured skid resistance (Characteristic SCRIM Coefficient, CSC) and IL for all non-event sections of motorways, dual carriageways and single carriageways. The over performance of the network may be due to over-specification, by engineers, or to the use of aggregate with higher polish resistance than is required, by contractors. Both of these factors may unnecessarily increase the use of high-PSV aggregate.

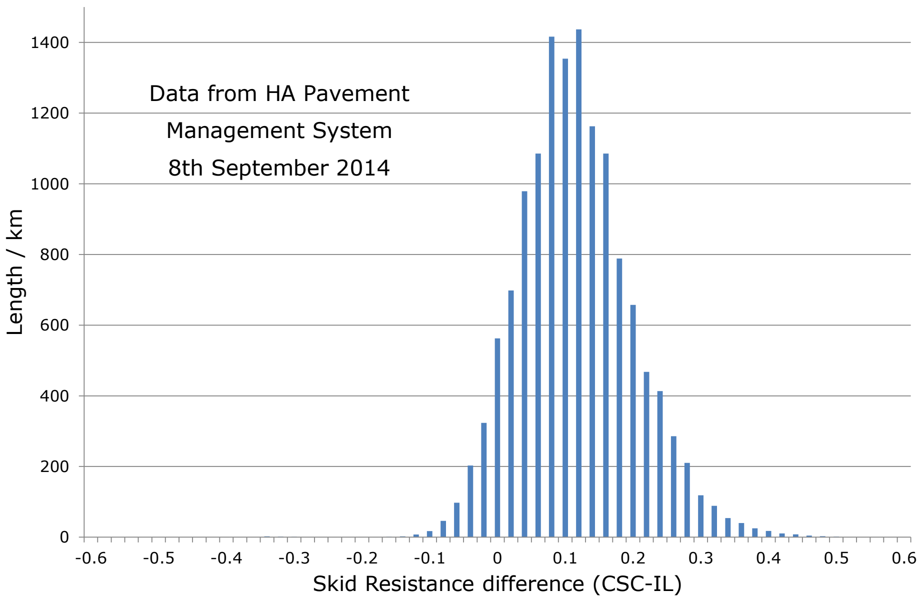


Figure 2.1 Distribution of network lengths (non-event sections) with differences from recommended investigatory level

2.1 Blending virgin aggregates

It may be possible to reduce both cost and haulage distance by making greater use of aggregates that can be sourced locally, instead of importing high specification aggregate. Indeed, aggregates that have PSV high enough to allow their use as coarse aggregate in the surface course, but too low for use in high-demand situations (PSV 50-63), are somewhat more readily available. The most practical use of this more abundant resource, if it is not currently permitted by the specification, might be in combination with a high-PSV aggregate by mixing different proportions of the coarse aggregates.

There have been two full scale trials of a limited number of aggregate blends. In one such trial it was shown that thin surfacings comprising more than one coarse aggregate perform at least as well as adjacent thin surfacings using coarse aggregate from a single source (Burton, 2008). In that trial, it was not possible to make direct comparison between the mixtures because of variations in traffic levels between the trial sites. In a second trial (Dunford, 2014), constructed to compare different mixtures under the same level of traffic, a small number of aggregate combinations were shown to provide predictable levels of friction.

The principle has also been demonstrated in the laboratory, using asphalt prepared with combinations of two aggregates (Dunford, 2012). That study used four different aggregate types and blended various combinations of two aggregates in a 10 mm Stone Mastic Asphalt (SMA) mixture. It was shown that the resulting friction could be predicted accurately, based on the friction of the asphalt's constituent coarse aggregates and a mass ratio formula. However, the method of combination, by blending coarse aggregate in the mixture's coarsest fraction (6/10 mm), is probably not easily implementable in practice because of the way aggregate is fed into full-scale asphalt mixing plant. Furthermore, there is a risk that the principle may not extend to a broader range of aggregates.

The experiment described in Section 3.2, and the results presented in Section 4.1, sought to demonstrate the principle across a much broader range of aggregates that may be used in pavement surfacings, in a way that would be easy to implement in practice.

2.2 Incorporating reclaimed asphalt

Highways Agency specifications currently permit the use of reclaimed asphalt (RA), directly incorporated into bituminous surface courses up to a limit of 10% by mass, without specific approval. While RA is often included in base layers in larger proportions, for example during new pavement construction, it is not so widely used in surface course materials. However, since a large proportion of the maintenance of the HA strategic road network now comprises planing off and resurfacing, there is considerable interest in increasing the use of RA in surface courses in order to continue to make use of this valuable resource.

As with the use of blended virgin aggregates, incorporation of RA could contribute to a reduction in transport costs and reduce the reliance on scarce natural resources. This would be particularly true if the RA comprised planings from existing surface courses using high specification natural aggregates. Separation of layers into different stockpiles is encouraged in best practice guidance (Carswell, Nicholls, Widyatmoko, Harris, & Taylor, 2010), but most existing stockpiles of reclaimed asphalt include asphalt from all road layers. Although grading removes the larger particles that are most likely to be from base layers, it is likely that most RA consists of both aggregate that would be used in the surface course, such as various granites and sandstones, and aggregate that would not, such as soft limestone, leading to concerns about friction resulting from its use. It is possible to carry out laboratory testing on the aggregate from RA, and where this has been done the measurements made compared reasonably well with those made on the original aggregate (Carswell, Nicholls, Elliott, Harris, & Strickland, 2005). However, size constraints imposed for laboratory tests (especially for the PSV test) typically limits the amount of testing that can be carried out.

A preliminary examination of the effect on friction of using RA in surface course materials demonstrated that addition of up to 48% RA (by mass) from a mixed stockpile has very little effect on friction (Dunford, 2013). The sample size was very small and there was no measurement of the actual limestone content of the RA used. The experiment presented in this report (Section 3.3) therefore made use of a wider range of RA sources and measured the amount of limestone present before it was incorporated in the asphalt mixture.

It should be noted that the incorporation of RA results in incorporation of used bitumen, which brings additional cost savings but also additional technical difficulties. The durability of surface course materials incorporating RA is beyond the scope of this work and is dealt with elsewhere, for example in Road Note 43 (Carswell, Nicholls, Widyatmoko, Harris, & Taylor, 2010). Further, there are anecdotal concerns that use and reuse of the aggregates themselves may lead to eventual degradation of their structural properties. For these reasons, any final conclusions must be tempered with a caveat that surface courses incorporating RA should be closely monitored for friction and structural properties.

3 Methodology

This chapter describes the methodologies used for laboratory experiments investigating the effect on friction of blending virgin aggregates and of incorporating reclaimed asphalt into the surface course. Common to both experiments is the mix design of the asphalt specimens prepared in the laboratory, so this is discussed first. The test procedure is not presented separately because it has been used many times before in research for the Highways Agency and is now incorporated into a European Standard (CEN, 2011). For both experiments, a Wehner-Schulze machine was used to polish and then measure friction on specimens of asphalt prepared in the laboratory.

3.1 Mix designs

3.1.1 Grading envelopes

The experiments described in this report are concerned with the blending of either virgin aggregates from different sources or virgin aggregates with reclaimed asphalt, in the surface course. The Highways Agency currently recommends the use of hot applied, negatively textured, TSCS for most situations. There are several different mix designs for surface course systems, although some are proprietary. Figure 3.1 shows the grading envelopes for several different surface course mix designs with 10 mm maximum aggregate size. Figure 3.2 shows the same information for designs with maximum aggregate size 14 mm. The solid lines, of various colours, represent the maximum limits for aggregate passing (by percentage mass) each sieve size shown on the x-axis and the broken lines show the minimum limits. The data used for these graphs was sourced from British Standard guidance (British Standards, 2010), from national specifications (Transport Scotland, 2012) and from information appended to construction records in the Highways Agency Pavement Management System (HAPMS).

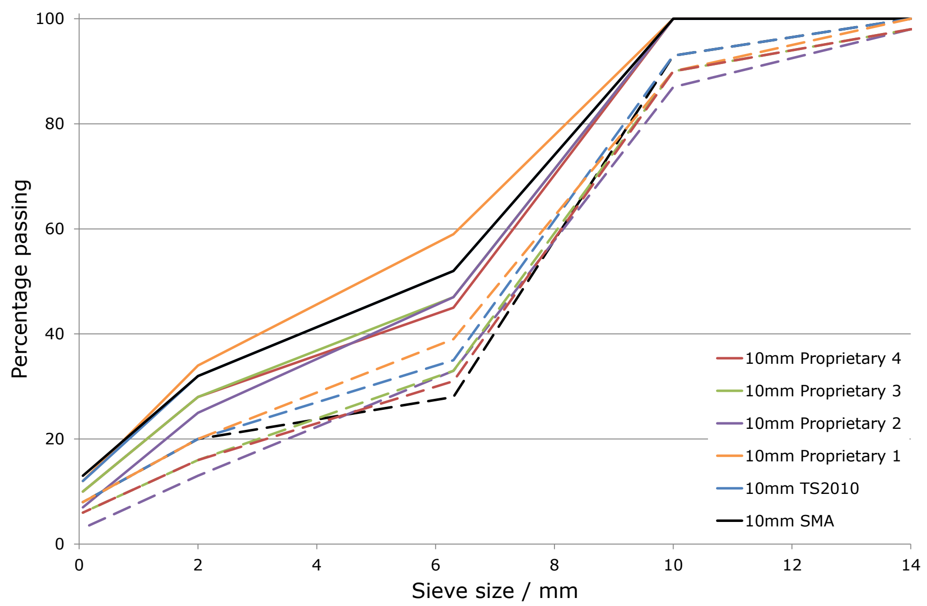


Figure 3.1 Grading envelopes for 10mm thin surface course systems

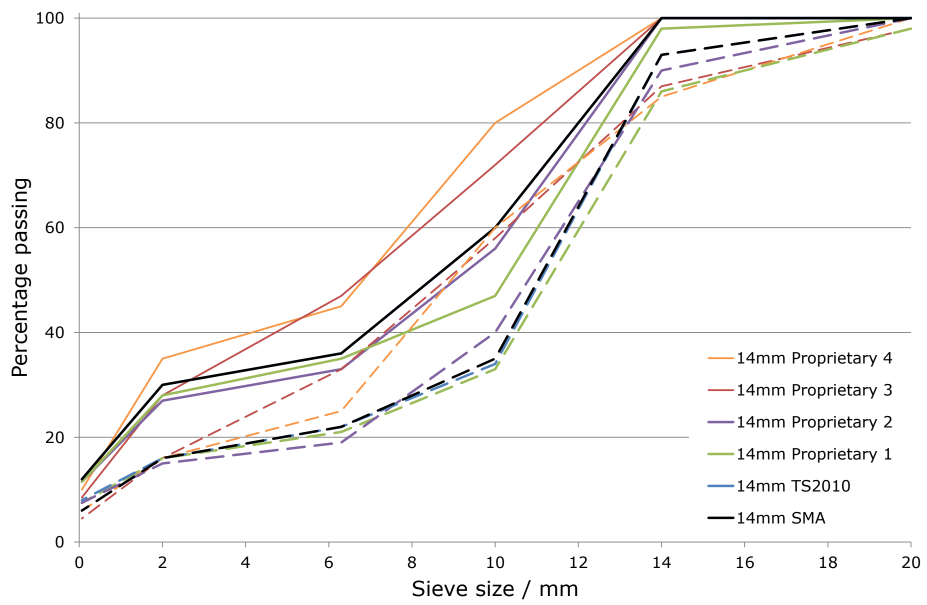


Figure 3.2 Grading envelopes for 14 mm thin surface course systems

For surface courses with 10 mm maximum aggregate size, the standard Stone Mastic Asphalt (SMA) grading envelope (British Standards, 2010) is representative of the proprietary mix designs, as far as information was available. For surface courses with 14 mm maximum aggregate size, the standard SMA grading envelope is representative of proprietary mixtures, although they were slightly more variable: Proprietary mixture 1 is more stringent and Proprietary mixtures 3 and 4 have higher overall aggregate content.

Use of a standard SMA mix design should mean that the results of the experiments described are applicable across the industry and are not favourable to one contractor over another. It is expected that implementation of any of the findings from either experiment would be through the departure from standards process. As part of the departure, skid resistance in service would need to be closely monitored and any deviation from expected performance resulting from a variation in mix design should be identified.

3.1.2 Blending methods and aggregate size

Previous work investigating combinations of virgin coarse aggregates (Dunford, 2012) used an SMA design with maximum coarse aggregate size of 10 mm. Aggregate from different sources were procured in sizes 4/10 mm and 2/6 mm meaning, in the first case, that aggregate passes a 10 mm square sieve but is retained on a 4 mm square sieve. Two different coarse aggregates were combined in different proportions within each coarse aggregate fraction. So, for a 50/50 combination, equal masses of 4/10 mm aggregate from two different sources were incorporated into the mixture and equal masses of 2/6 mm aggregate from the same two sources were also incorporated. The mass of crushed rock fines (from a single, common source) and filler material was adjusted to meet the grading requirement of the SMA.

Blending of different aggregates in that manner was controlled, and served to demonstrate the theory that friction could be predicted using a mass ratio formula. However, it was determined that practical application would be difficult because of the way that mixing plants currently operate. While plants may be able to feed aggregate from multiple stocks of different sizes, it is not economical to double the number of feeds for each coarse aggregate or even to double the number of stockpiles of aggregate for each coarse aggregate size. It would, therefore, be simpler, for the example of a 10 mm SMA, to combine 4/10 mm aggregate from one source with 2/6 mm aggregate from another source.

Using the size gradings for two of the aggregates used in the previous work, and the grading envelope for a 10 mm SMA, it is possible to determine the relative proportions of two different aggregates that could be achieved. It was found that the minimum amount of 4/10 mm aggregate (by mass) could be approximately 60% and the maximum amount of the 2/6 mm aggregate could be approximately 20% of the total dry constituents. For comparison, the same exercise for a 14 mm SMA, using 6/14 mm aggregate from one source, and 4/10 mm aggregate from another source, revealed that the proportions could be more even, at 50% and 30% respectively. This more even split by mass should allow for an easier assessment of the contribution to friction from both aggregate sources, making SMA with 14 mm maximum aggregate size the most appropriate design.

In addition, previous work with RA (Dunford, 2013) found that a mix design with 14 mm maximum aggregate size was appropriate because the size of the RA procured lent itself to better incorporation into a mixture with larger aggregate particles.

3.2 Virgin aggregates

3.2.1 Aggregates

Stocks of aggregate from fourteen different quarries were procured; all were available in size 4/10 mm and thirteen were available in size 6/14 mm. For each of the thirteen sources with both 4/10 mm and 6/14 mm aggregate, pairs of 14 mm SMA specimens were prepared in the laboratory using a common source of crushed rock fines and filler. The resulting asphalt slabs were cored to fit the Wehner-Schulze (W-S) machine; their surfaces were then gritblasted and polished using the W-S machine before friction was measured. Table 3.1 shows the average friction (μ_{PWS60}) after polishing for each of the thirteen sources, along with their nominal PSVs. Consequently, the friction for the source that was available in only 4/10 mm aggregate size has been estimated based on its nominal PSV.

Table 3.1 Aggregate sources, measured friction, and nominal PSV

Aggregate source	Average μ_{PWS60}	Nominal PSV
A	0.30*	49
B	0.32	50
C	0.31	53
D	0.35	54
E	0.34	55
F	0.35	60
G	0.39	62
H	0.38	62
I	0.41	65
J	0.37	65
K	0.42	66
L	0.45	66
M	0.43	66
N	0.45	68

*μ_{PWS60} estimated from nominal PSV

3.2.2 Aggregate combinations

The aggregates were placed in three groups with low PSV (49-53), medium PSV (54-63) and high PSV (63-68) for the purposes of targeting combinations. Combinations of two different aggregates were chosen at random, constrained by three rules:

- Each 6/14 mm aggregate should be used twice, due to limited supply and the demand of the asphalt mix design
- Two aggregates from different 'PSV groups' are preferred to two aggregates from the same 'PSV group'
- Combinations that are likely to result in moderate friction are preferred.

The last two rules were in place because it is anticipated that any practical implementation of the results will target the use of high specification aggregate (HSA) in combination with other, non-HAS, aggregate to create a surface that has moderate skid resistance.

Table 3.2 shows the 26 combinations of aggregates prepared. Alongside the combination number are shown the aggregate source for the 6/14 mm fraction, its nominal PSV, the aggregate source for the 4/10 mm fraction, its nominal PSV, and the expected friction resulting from the combination. The expected friction is simply estimated based on combination of the nominal PSVs of the two aggregates and is categorised as high, medium or low. It can be seen that, due to the blending rules discussed above, the majority of the aggregate combinations should result in an asphalt surface with medium friction.

Table 3.2 Aggregate combinations

Combination ID	6/14 mm		4/10 mm		Expected friction
	Aggregate source	Nominal PSV	Aggregate source	Nominal PSV	
1	B	50	G	62	Medium
2	B	50	J	65	Medium
3	C	53	H	62	Medium
4	C	53	M	66	Medium
5	D	54	A	49	Low
6	D	54	K	66	Medium
7	E	55	C	53	Medium
8	E	55	F	60	Medium
9	F	60	J	65	Medium
10	F	60	I	60	Medium
11	G	62	M	66	High
12	G	62	N	68	High
13	H	62	A	49	Medium
14	H	62	C	53	Medium
15	I	65	D	54	Medium
16	I	65	E	55	Medium
17	J	65	B	50	Medium
18	J	65	E	55	Medium
19	K	66	G	62	High
20	K	66	I	60	Medium
21	L	66	D	54	Medium
22	L	66	H	62	High
23	M	66	F	60	Medium
24	M	66	L	66	High
25	N	68	A	49	Medium
26	N	68	B	50	Medium

Cells coloured red indicate 'high' PSV or 'high' expected friction
Cells coloured orange indicate 'medium' PSV or 'medium' expected friction
Cells coloured green indicate 'low' PSV or 'low' expected friction

3.3 Reclaimed asphalt

3.3.1 Sources and laboratory testing

Four sources of reclaimed asphalt were procured. One, labelled α, was provided after the contractor had carried out their own binder recovery testing and consisted of a range of samples taken throughout a mixed stockpile. Two, labelled β and γ, were from stocks of mixed reclaimed asphalt, used regularly in base layers during on-going construction schemes. The fourth source, labelled δ, was taken directly from local planing operations. The fourth source therefore consisted primarily of surface course material that had been in use on a suburban single carriageway road. Assuming it was specified according to guidance similar to that used by the Highways Agency (Design Manual for Roads and Bridges, 2006), the coarse aggregate should have PSV between 50 and 60.

One of the reservations about including RA in the surface course is concerned with the introduction of limestone, which is known to polish easily and therefore have very low skid resistance, so the amount of limestone present in each of the three mixed RA sources was examined. To do so, the bitumen was removed from samples of two of the stocks of mixed RA, the first having already been cleaned as a result of binder recovery analysis, before the following brief experiment was carried out.

If possible, a sample of the aggregate was separated into size fractions: 14/20 mm, 10/14 mm, 6/10 mm, 4/6 mm, and aggregate passing a 4 mm sieve. For each of the three coarsest fractions, individual aggregate particles were examined to determine whether or not they were limestone. To aid this process, each particle was either scraped against a glass panel or dropped into a small amount of acetic acid. Limestone will not leave a mark on a glass panel and will start to dissolve in acetic acid (bubbles can be observed coming from the particle's surface). The mass of limestone in each coarse aggregate fraction was measured and expressed as a percentage of that fraction. The overall percentage of limestone found in the three coarsest fractions, in total, was also calculated. For source β it was only possible to calculate the total limestone content, due to the small amount of RA remaining after asphalt preparation. The results are shown in Table 3.3. For the first RA source, four of the samples taken throughout the mixed stockpile were examined.

Table 3.3 Reclaimed asphalt limestone content

RA source	Size fraction	Percentage of limestone	
		Fraction	All coarse
α – 1	14/20 10/14 6/10	53 27 35	35
α – 2	14/20 10/14 6/10	36 28 39	34
α – 3	14/20 10/14 6/10	31 33 45	40
α – 4	14/20 10/14 6/10	70 31 14	30
β	14/20 10/14 6/10	Not measured	3
γ	14/20 10/14 6/10	4 4 7	5

There is a range of limestone content across the four mixed RA sources (the recovered planings contained no limestone), and it is interesting to note that the total percentage of limestone coarse aggregate in the mixed stockpile from source α is reasonably consistent throughout the stockpile. There is some variability in limestone content between size fractions in the four samples of this stockpile, but it is likely to be within the error associated with the test method and the relatively small samples tested.

3.3.2 Blends with virgin aggregate

The various sources of RA were each combined with a single source of virgin aggregate, the choice of which was largely governed by the quantities of aggregate remaining after the previous experiment (Section 3.2) had been completed. If there was still a sufficient amount of the RA remaining, it was blended again with an additional single source of virgin aggregate. In each case, the RA was incorporated in proportions (by mass) of 10%, 20%, 30% and 40%. The final mixture represents the maximum amount of RA that could typically be incorporated whilst adhering to the standard grading envelope for the 14 mm SMA, as before. In principle, more RA could have been included if it had been sieved before use. However, in an effort to maintain the focus of these experiments on realistic practical implementation, this prior screening was not carried out.

Table 3.4 shows the various blends that were prepared, along with the nominal PSV of the virgin aggregate used. Four asphalt specimens were prepared for each of the blends shown (one for each of 10%, 20%, 30%, and 40%). In addition, the case of 0% RA is represented by the virgin aggregate specimens prepared during the previous experiment. The two most abundant RA sources (α and β) were blended with a low PSV virgin aggregate and with either a high or medium PSV virgin aggregate. The two other RA sources (γ and δ) were blended with either a high or medium PSV virgin aggregate.

Table 3.4 RA / virgin aggregate blends

RA source	Virgin aggregate	
	Source	Nominal PSV
α	G	62
α	D	54
β	N	68
β	B	50
γ	H	62
δ	K	66

4 Results and analysis

All of the results shown in this chapter are friction measurements, μ_{PWS60}, made using the Wehner-Schulze machine after the asphalt specimens had been grit-blasted to remove excess bitumen and subjected to a standard amount of polishing. The operation of the machine is described in other reports summarising research carried out for the Highways Agency (Dunford & Roe, 2012), (Dunford, 2013), and its test procedure is documented in a recently published European Standard (CEN, 2011).

4.1 Virgin aggregates

The first specimens to be tested were those using aggregate from a single source. Figure 4.1 shows the average friction measured on the asphalt specimen pairs against the nominal PSV for the quarry from which the coarse aggregate was sourced. The data points are represented by the letter indicating the aggregate source and the colour of the letter indicates the 'PSV group'. Note that the axes do not pass through the origin; this convention will be used for all subsequent graphs because no friction measurements below 0.2 are reported. There is a good relationship between the friction measured on the asphalt specimens and the nominal PSV of the coarse aggregate. This gives confidence in the accuracy of the reported PSV as well as in the relevance of measurements made using the W-S machine.

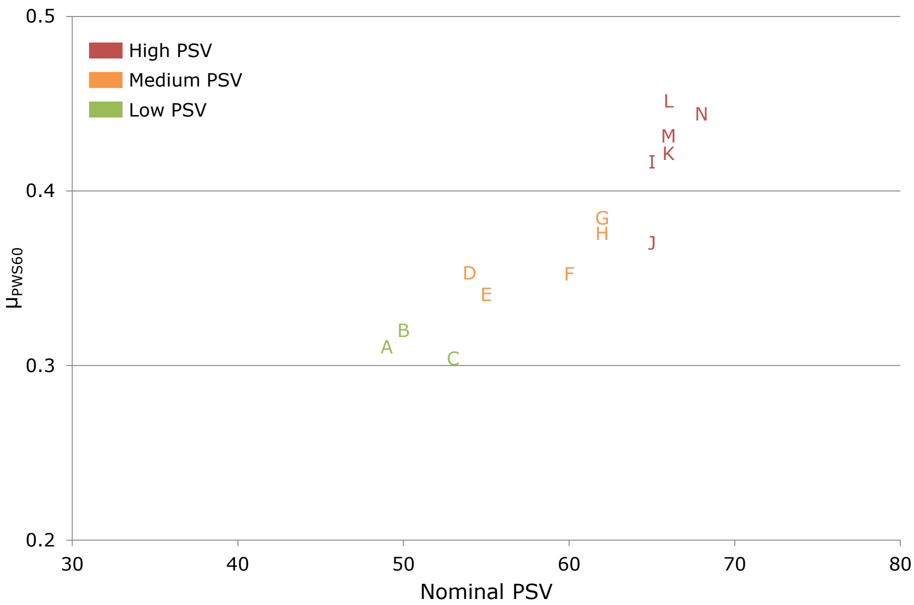


Figure 4.1 Friction measured using the W-S machine against nominal PSV

Table 4.1 shows the friction measured on each aggregate combination. The average friction measured on each of the combination's constituent aggregates is also shown.

Table 4.1 Friction measurements on virgin aggregate combinations

Combination ID	6/14 mm		4/10 mm		Measured friction
	Aggregate source	Average friction	Aggregate source	Average friction	
1	B	0.32	G	0.39	0.37
2	B	0.32	J	0.37	0.29
3	C	0.30	H	0.38	0.27
4	C	0.30	M	0.43	0.37
5	D	0.35	A	0.31	0.35
6	D	0.35	K	0.42	0.36
7	E	0.34	C	0.30	0.33
8	E	0.34	F	0.35	0.35
9	F	0.35	J	0.37	0.31
10	F	0.35	I	0.42	0.41
11	G	0.39	M	0.43	0.39
12	G	0.39	N	0.44	0.38
13	H	0.38	A	0.31	0.31
14	H	0.38	C	0.30	0.32
15	I	0.42	D	0.35	0.33
16	I	0.42	E	0.34	0.37
17	J	0.37	B	0.32	0.37
18	J	0.37	E	0.34	0.38
19	K	0.42	G	0.39	0.37
20	K	0.42	I	0.42	0.41
21	L	0.45	D	0.35	0.34
22	L	0.45	H	0.38	0.39
23	M	0.43	F	0.35	0.39
24	M	0.43	L	0.45	0.43
25	N	0.44	A	0.31	0.35
26	N	0.44	B	0.32	0.35

In previous work, a mass ratio formula was used to predict the friction measured on asphalt specimens prepared with two different coarse aggregates. It was shown that there was a near one-to-one relationship between the measured friction and the predicted friction. If the same mass ratio formula is used to predict friction for each combination shown in Table 4.1, based on the asphalt containing 50% by mass 6/14 mm aggregate and 30% by mass 4/10 mm aggregate, and the measured friction for each specimen is plotted against these values, the graph in Figure 4.2 can be produced. The broken line is a line of unity, and the solid blue line is a line of best fit whose equation and R^2 statistic are also shown. It can be seen that, while there is some variability in the results, in general there is a positive correlation between measured and predicted friction. However, measured friction is lower than predicted friction, in most cases.

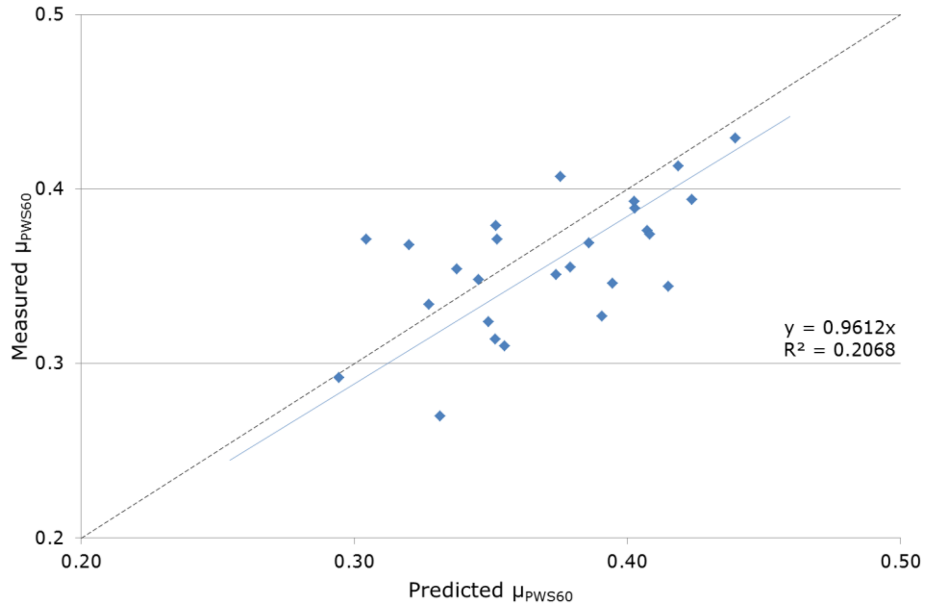


Figure 4.2 Measured friction vs friction predicted using a mass ratio formula

Multiple linear regression can be used to estimate the relative contributions to overall friction from each of the constituent aggregates. Using Microsoft Excel, the friction measured on each of the combinations ($\mu_{measured}$, the dependent variable) was compared to the friction measured on the specimens prepared using each individual aggregate source (μ_{14} and μ_{10}, independent variables). The best fit line returned has the equation:

$$\mu_{measured} = 0.47 \times \mu_{14} + 0.50 \times \mu_{10} \quad \textbf{(1)}$$

where μ_{14} is the friction associated with the 6/14 mm aggregate and μ_{10} is the friction associated with the 4/10 mm aggregate. Using this prediction formula naturally results in a one to one relationship between measured and predicted friction, as well as slightly reduced variability in the results, as shown in Figure 4.3. The linear fit suggests that there is a greater contribution to friction from the 4/10 mm aggregate than expected, given the mass of material present in the mix. Despite the fact that the mass of 4/10 mm aggregate is 60% of the mass of 6/ 14 mm aggregate (30% compared with 50%), its contribution to overall friction is actually greater (0.50 compared with 0.47) than the contribution from the 6/14 mm aggregate.

The repeatability standard deviation of the W-S test was found to be approximately 0.019, including variability in laboratory-based asphalt production (Dunford & Roe, 2012). If the predicted friction is correct, it is useful to consider the number of friction measurements ($\mu_{measured}$) that have been over- or underestimated by more than 0.037 (1.96 times the repeatability standard deviation). If friction measurements are normally distributed and deviation from predicted friction is due solely to W-S test repeatability for $\mu_{measured}$ then 95% of measurements would be within 0.037 of predicted friction. In fact, only 20 of the points (77%) are within this range (six outlying points are circled in red).

There is more variability in these results than can be explained by the repeatability of the W-S test for measurements made on the combinations. Sources of variability include error in the predicted friction (such as the repeatability of the W-S test for μ_{14} and μ_{10}), additional variability associated with the production of the asphalt specimens compared with previous experiments because of the small batch size, and increased variation in aggregate grading because of the use of a large number of different sources.

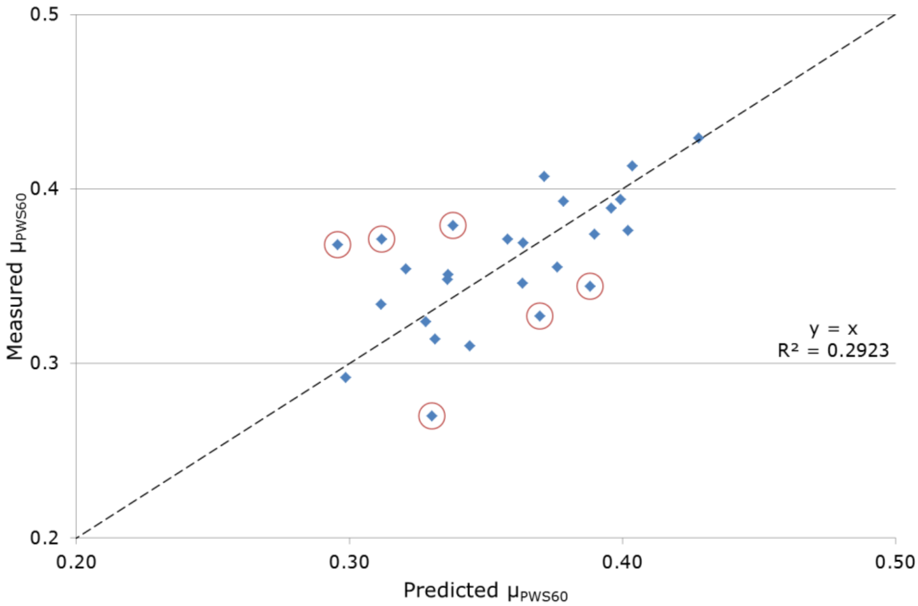


Figure 4.3 Measured friction vs friction predicted using a regression formula

It could be argued that the aggregate in the asphalt can only have an effect on friction if it is present on the surface, regardless of the mass present in the mixture. Researchers in France carried out a study combining different aggregates in mosaic specimens before they were polished and tested using a Wehner-Schulze machine (Senga, Dony, Colin, Hamlat, & Berthaud, 2013). In order to improve prediction, an automatic process was developed to detect the proportion of each aggregate that could be seen in the mosaic surface, because of the different appearance of the two aggregates used.

With the exception of a few combinations, for most of the aggregate combinations in the present study, the appearance of the two aggregates used is very similar, making automatic detection of surface presence difficult. However, one of the aggregates is bright red in colour and it has been possible to inspect the surfaces of the asphalt specimens prepared using this aggregate to examine its presence on the surface. Figure 4.4 shows the surfaces of one combination, where the red aggregate is used as the 6/14 mm aggregate (left), and one combination where the red aggregate is used as the 4/10 mm aggregate (right).

Figure 4.4 Asphalt specimens containing a red aggregate in the 6/14 mm fraction (left) and in the 4/10 mm fraction (right)

Although it is difficult to make an accurate estimate because of the presence of bitumen and fine materials, it is clear that the 4/10 mm aggregate is more heavily represented on the surface than one might expect given that there is 40% less aggregate by mass compared with the 6/14 mm aggregate. In fact, by overlaying a grid and counting the approximate surface area taken by each individual aggregate particle, it is possible to estimate that, on average, the 4/10 mm aggregate in these specimens occupies 82% of the surface area occupied by the 6/14 mm aggregate.

There may be a physical explanation for this, and for the relative contributions to friction suggested by the regression formula, considering the volume and surface area of the aggregate particles within the asphalt mix. For simplicity individual aggregate particles are assumed to be spherical and uniform in size, with diameter equal to the nominal size of the fraction in question, i.e. 10 mm or 14 mm. If all aggregate is assumed to be equally dense, the relative proportions of volume are equal to the relative proportions of mass. So, since 50% of the total mass in each 14 mm SMA asphalt specimen consist of 14 mm particles and 30% consists of 10 mm particles, the total volume of 10 mm particles is 0.6 times the volume of 14 mm particles. Therefore, it is true to say:

$$n_{10} \times \frac{4}{3}\pi {r_{10}}^3 = 0.6 \times n_{14} \times \frac{4}{3}\pi {r_{14}}^3 \qquad \textbf{(2)}$$

And because:

$$r_{14} = 1.4 \times r_{10} \qquad \textbf{(3)}$$

Then:

$$n_{10} = 1.6 \times n_{14} \qquad \textbf{(4)}$$

where n_{10} is the number of 10 mm particles, r_{10} is the radius of 10 mm particles, n_{14} is the number of 14 mm particles and r_{14} is the radius of 14 mm particles.

There are significantly more 10 mm aggregate particles than there are 14 mm aggregate particles. The total surface area of 14 mm aggregate particles is:

$$n_{14} \times 4\pi {r_{14}}^2 \qquad \textbf{(5)}$$

And the total surface area of 10 mm aggregate particle is:

$$n_{10} \times 4\pi {r_{10}}^2 \qquad \textbf{(6)}$$

Or

$$1.6 \times n_{14} \times 4\pi \left(\frac{r_{14}}{1.4}\right)^2 \qquad \textbf{(7)}$$

Or

$$0.8 \times n_{14} \times 4\pi {r_{14}}^2 \qquad \textbf{(8)}$$

This implies that the 10 mm particles have approximately 80% of the total surface area of the 14 mm particles, which matches the estimate provided by counting the number of red particles in Figure 4.4. If the total surface area is proportional to the surface area present at the upper face of the asphalt then the 10 mm particles might have a greater influence on friction than would be expected given their presence by mass (i.e. 80% of the surface area despite being 60% of the mass, compared with the 14 mm particles).

Equation (1) suggests that the 10 mm particles actually have an even greater influence on friction than the 14 mm particles (a coefficient of 0.50 for the friction supplied by the 10 mm particles compared with a coefficient of 0.47 for the friction supplied by the

14 mm particles). This result, emphasising the contribution of the 10 mm aggregate, may be attributable to experimental error or variation, or it may be an as yet unexplained physical phenomenon, beyond the simple treatment of surface area outlined above.

4.2 Reclaimed asphalt

In previous work (Dunford, 2013) it was found that the addition of RA from a mixed stockpile, when compared to the addition of virgin limestone aggregate in the same proportions, had a negligible effect on friction. This is shown in the graph in Figure 4.5, where the friction measured on two sets of asphalt specimens is shown side by side (note that there was no specimen prepared with 48% limestone content).

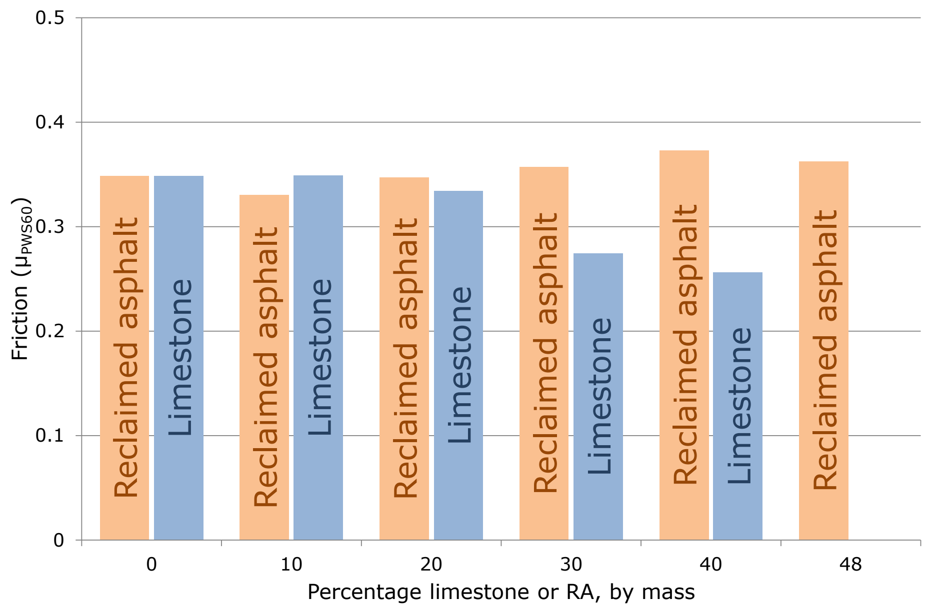


Figure 4.5 Friction measured on asphalt specimens containing either limestone or RA in different proportions

The aim of the present work is to find if the same is true when alternative sources of RA are used, particularly since one of those sources (ɑ) is known to contain a significant amount of limestone.

Table 4.2 lists the combinations of virgin aggregate and RA examined. The friction measurements made on specimens containing 0%, 10%, 20%, 30% or 40% RA by mass are shown and these values are also reported as a proportion of the friction measured on the 0% specimen.

Table 4.2 Friction measurements on RA combinations

RA source	Virgin aggregate μ_{PWS60}	Proportion RA by mass(%)	Measured friction	Friction, proportion of 0% specimen (%)
α	G (0.39)	0	0.39	100
		10	0.34	87
		20	0.38	99
		30	0.38	99
		40	0.38	97
α	D (0.35)	0	0.35	100
		10	0.31	89
		20	0.35	99
		30	0.37	105
		40	0.35	99
β	N (0.44)	0	0.44	100
		10	0.38	84
		20	0.39	88
		30	0.37	82
		40	0.37	82
β	B (0.26)	0	0.26	100
		10	0.25	99
		20	0.27	105
		30	0.26	103
		40	0.29	114
γ	H (0.38)	0	0.38	100
		10	0.33	87
		20	0.34	91
		30	0.30	80
		40	0.35	94
δ	K (0.42)	0	0.42	100
		10	0.39	93
		20	0.42	100
		30	0.40	95
		40	0.39	92

The results are shown in Figure 4.6, where each combination of virgin aggregate and reclaimed asphalt is shown in a series of columns with, from left to right, increasing proportions of reclaimed asphalt. The six series of columns are in order of decreasing friction measured when no reclaimed asphalt was combined with the virgin aggregate. When there is no reclaimed asphalt (0%) the range of friction measured is between 0.26 (orange column, aggregate B) and 0.44 (blue column, aggregate N). When there is significant amounts of reclaimed asphalt present (40%), the range of friction measured is smaller, between 0.29 and 0.39.

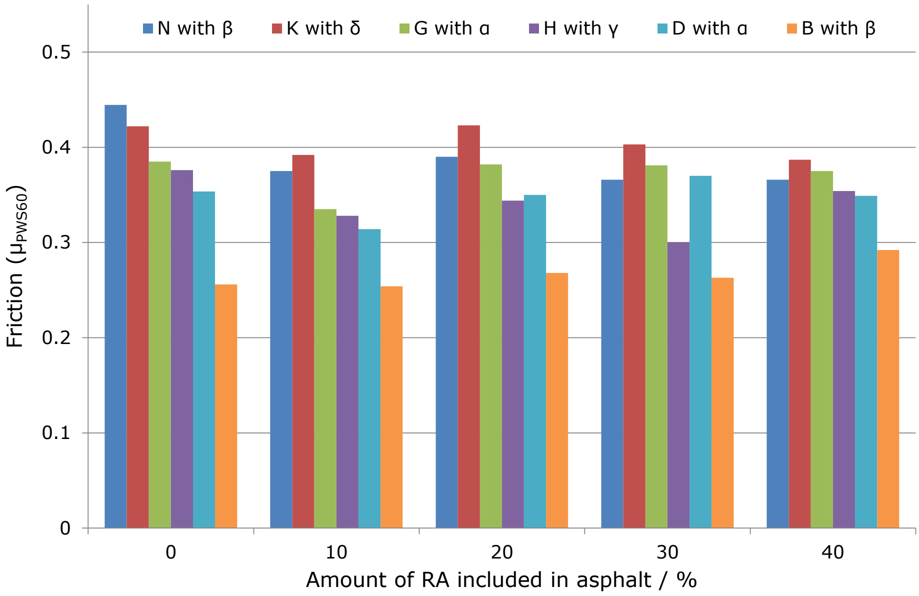


Figure 4.6 Friction measured on asphalt specimens containing RA in different proportions

The results do not dramatically alter the conclusions from the previous work. In general, when RA is combined with virgin aggregate, although the friction measurements are variable, it is difficult to attribute anything more than minimal effects to the addition of reclaimed asphalt. In particular, the addition of RA α to either virgin aggregate D or G resulted in no more variation in friction than would be expected through normal repeatability, despite a large amount of limestone being present in the RA. The same is true for the addition of RA γ and RA δ to aggregates H and K respectively, although the variability in the results is somewhat larger.

However, when RA β was added to aggregate N, there does seem to be a reduction in the friction measured and, when RA β was added to aggregate B, there seems to be an increase in the friction measured. These contradictory results may be due to unplanned variation in mix design but it is more likely that the effects observed are related to the properties of the virgin aggregates rather than of the reclaimed asphalt, as follows. A significant reduction in friction was observed because friction on the virgin aggregate alone was so high, in the case of aggregate N. Conversely, the significant increase in friction was only observed because friction on the virgin aggregate alone was so low, in the case of aggregate B.

5 Discussion

The principle of blending different aggregate constituents into thin surface course systems is common to both experiments reported herein although the desired outcomes differ. For blending virgin aggregates the most useful outcome is that the friction resulting from blending two different aggregates is both adequate and highly predictable. For incorporating reclaimed asphalt, a highly satisfactory outcome is simply that the addition of RA has little or no effect on friction.

5.1 Virgin aggregates

The results obtained suggest that friction on asphalt with two different virgin aggregates in a 14 mm SMA, can be predicted using the friction measured on 14 mm SMA prepared with the individual aggregates. Furthermore, given the relationship between PSV and friction measured on the asphalt, it appears that the PSV of the aggregates could be used to predict an equivalent PSV for the blend, although no attempt has yet been made to develop a formula. There is some significant variability in the results, possibly due to the margin of error involved in preparing small volumes of asphalt. However, the general principle has been clearly shown and would probably be improved by addition of further results.

The range of aggregates tested in the laboratory has spanned the mineralogical diversity of aggregates used in pavement construction in the UK, as well as representing a range of polish resistance. It is therefore reasonable to suggest that the blending principles demonstrated are applicable to any aggregate that would normally be used in thin surface course construction. The work concentrated on practical applicability by mixing aggregates in different sizes and ensuring that the mix design used was representative of designs used in practice. However, it is possible that slightly different mix designs and the aggregate mixing methods used in full-scale asphalt plants (where aggregate feeds are combined, dried, and then separated into fractions again before accurate weighing and combining) may have an effect on the friction of the blended product.

Therefore, it is recommended that this research is moved out of the laboratory and onto full-scale trials. The use of blended aggregate surface courses on the HA strategic road network could be allowed, by departure from HD36 (Design Manual for Roads and Bridges, 2006), with minimal expected risk to road user safety. It should be noted that the polishing of asphalt specimens in the laboratory may be representative of the stress applied by free flowing traffic and it is possible that blended aggregate products may perform differently in locations where traffic stress is higher. To further demonstrate the friction prediction methodology, trial sites should be constructed comprising separate panels, at least 100 m long, of a thin surfacing with, in turn, coarse aggregate from a single source, coarse aggregate from a second single source and with aggregate from both sources blended together.

Barring any unforeseen complications discovered during full scale trials, blended aggregate products could be used in future without specific departure from standards but with a caveat that their use should be preceded by demonstration of cost saving or substantial sustainability benefits. In addition, further assurance checks could be incorporated to ensure proper mixing of the different aggregate sources. These might include laboratory testing in a manner similar to the experiments in this report, or some verification of correct blending by observation at the aggregate mixing stage.

A particularly interesting conclusion from the measurements made so far is that the contribution to friction from the smaller aggregate (4/10 mm) is relatively greater than from the larger aggregate (6/14 m), despite its lower presence by mass. This may be related to the amount of area of smaller aggregate particles present on the surface and could be an important factor when considering sustainability or cost savings using a scarcer or more expensive aggregate source. If the high specification aggregate is used as the smaller aggregate in the mixture its benefit is maximised.

Further study could be undertaken to see if the same theory could be applied to the addition of yet smaller aggregates. For example, the addition of a third coarse aggregate size, 2/6 mm, may have its own effect on friction. However, it is probable that the effect will be less because, although the smaller particles may contribute significantly to total surface area, their presence on the surface is normally reduced. Smaller particles are more likely to be removed by the action of traffic and are more likely to be lost amongst the texture of the surface.

5.2 Reclaimed asphalt

In previous work (Dunford, 2013), the following scenarios were proposed:

> "If RA is reclaimed from an existing thin surface course system, is handled properly, and segregated then, in terms of potential skid resistance:
>
> - Provided the original source is well known and its specification meets the specification required of the new thin surface course then, subject to quality control constraints, no restriction should be placed on the amount of RA used.
> - If the original surface course is well known but its specification does not meet the specification required of the new thin surface course then the virgin aggregate should be chosen carefully. It may be possible to select an appropriate virgin aggregate using a mass ratio formula to predict the result of blending with the RA.
> - If the original surface course is not well known then the advice will depend on the specification of the required new thin surface course. If an aggregate with PSV less than, say, 53 is required then the effect on skid resistance of any surface course RA will be minimal and there should be no restriction on the amount of RA used. If the new specification is for high-PSV aggregate (63 and above) then a restriction of 10% RA might be adopted unless a laboratory investigation can demonstrate results to the contrary.
> - Measurements of skid resistance should be made to verify that the surface is performing as expected initially, and after a period of service.
>
> If the RA is reclaimed from mixed sources then, until further work to assess the effect of variability in RA is carried out, a 10% restriction should remain in place."

The laboratory experiments reported above are not sufficient to warrant a significant change to these scenarios. The limestone content of the RA does not seem to be a strong predictor of its friction performance when combined with virgin aggregate.

The most significant result emphasises the third bullet point in the paragraph above: the intended use of the blended asphalt should be considered before incorporation of any RA. If a high PSV virgin aggregate would normally be required, addition of RA may have a detrimental effect on friction, but if the site is not demanding in nature, owing to its geometry or the amount of traffic it carries, the addition of RA could actually prove beneficial.

When RA is used in the surface course, more rigorous testing of that RA is recommended if the amount used is more than 10% by mass and, in Published Document (PD) 6691:2010 "Guidance on the use of BS EN 13108 Bituminous mixtures – material specifications", two specific properties of the RA are required:

- "the upper size of the reclaimed asphalt shall not exceed the upper size of the mixture"; and
- "the aggregate in the reclaimed asphalt shall conform to the requirements for the aggregate in the mixture specification".

The first requirement could be achieved by correct grading but, if no documentation exists to identify the aggregate in the reclaimed asphalt (such as records pertaining to the surface course in the case of RA from planings), it may not be possible to fulfil the second requirement. This could be mitigated by assuming that the reclaimed asphalt has low friction, blending it with a suitably high PSV virgin aggregate, according to a mass ratio formula. Alternatively, the friction performance of the RA could be checked by developing a test protocol, along the same lines as the experiment presented in this report, using laboratory test equipment to polish and test friction on asphalt specimens prior to full-scale paving. In either case, in-situ testing should be undertaken to monitor the skid resistance at the site. It is likely that the amount of RA that can be added will be limited by its effect on the durability of the resulting asphalt rather than by its effect on friction and verification of structural performance would also be prudent.

The experiments reported here give some confidence that, on a trial basis, the restriction of 10% RA (either from surface courses or mixed stockpiles) may be relaxed without undue risk to road user safety on low risk sites. However, each site should be considered individually, and the proposed asphalt blends should be matched to the site's skid resistance requirements. Note, again, that these experiments did not study the effect on durability or the properties of blended bitumen, which has been dealt with elsewhere (Road Note 43).

6 Recommendations

The discussion above can be summarised in a number of specific recommendations either for continuation of the work investigating the materials examined or for limited sanction of their use on the Strategic Road Network.

6.1 General

Given the outcomes and recommendations resulting from both experiments, a streamlined route to implementation is desirable. The process of trial site construction by departure from standards and subsequent intensive monitoring for skid resistance performance, as recommended in each case below, is potentially time consuming and costly. In principle, the laboratory methodologies described could be used for product development, while the performance of full-scale implementation could be assessed by similar laboratory testing (with methodologies currently requiring development) using material taken directly from site.

At present, for skid resistance, the performance of individual components of asphalt materials are assessed and specified. It is recommended that the development of methods for the assessment and specification of the long term skid resistance performance of complete asphalt mixtures is pursued. Initially, this may be achieved by building an evidence base comparing the actual skid resistance performance of asphalt materials (especially those laid as trial sites) with the performance predicted using laboratory tools such as the Wehner-Schulze machine.

6.2 Virgin aggregates

HD36/06 (Design Manual for Roads and Bridges, 2006) is used to specify or recommend a minimum PSV for the aggregate used in the surface course. If two virgin coarse aggregates are blended, it is likely that the PSV of one of them will be lower than is currently specified in HD36. It is recommended that the Highways Agency allow departure from HD36 for:

- Trial sites to demonstrate the performance of Clause 942 materials incorporating coarse aggregates from two different sources, requiring evidence of satisfactory performance in laboratory tests and regular monitoring of skid resistance performance over a period of at least two years. (On the Strategic Road Network this would occur automatically under the normal skid resistance survey regime so would not require additional testing; however, the information should be collated to inform future departures and, ultimately, future standards.)
- The use of Clause 942 materials with combinations of coarse aggregates from two different sources, whose performance under similar conditions have been demonstrated, as above.

In both cases, information detailing the asphalt product, specific aggregates and site location should be submitted to Highways Agency when the departure request is made.

6.3 Reclaimed asphalt

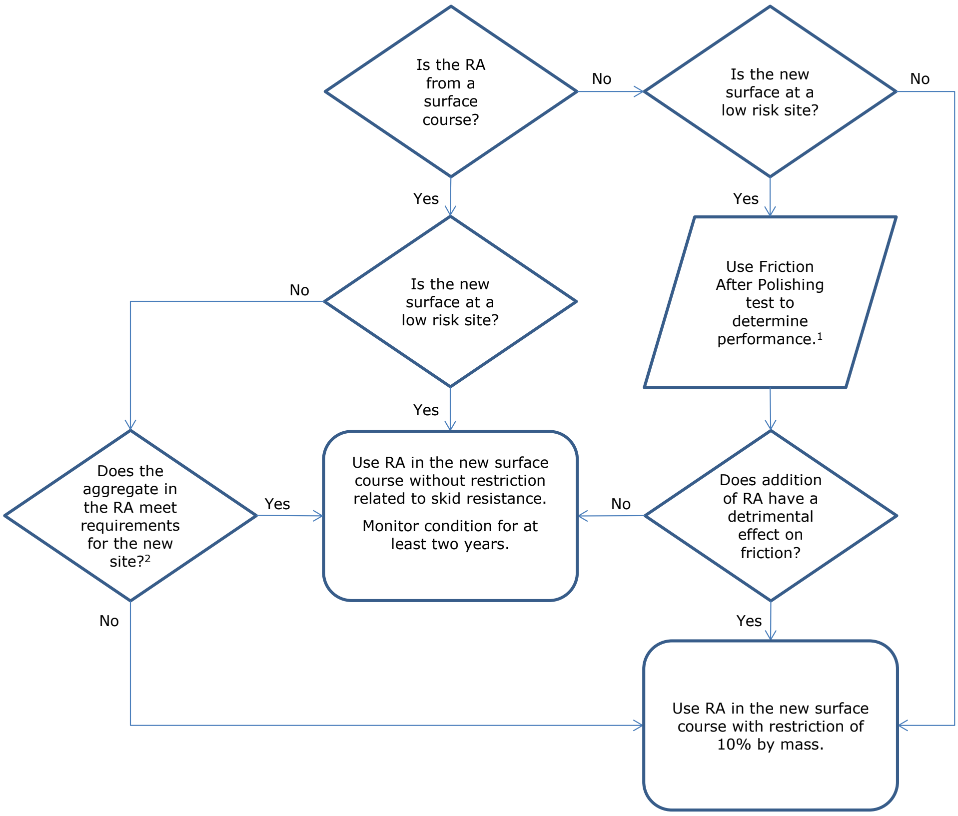
The restriction of 10% RA in the surface course is mentioned in various documents, including guidance for the use of BS EN 13108 (British Standards, 2010), which is referred to in HA's Specification for Highways Work (Manual of Contract Documents for Highway Works, 2008), and in best practice guidelines (Carswell, Nicholls, Widyatmoko, Harris, & Taylor, 2010). Larger proportions are allowed, but only after further testing of RA aggregate, which may not be practicable.

If the use of RA is to be promoted, the additional testing requirements for the aggregates in RA could be relaxed. It is recommended that, subject to existing restrictions on binder content and resulting durability, the Highways Agency should allow departure from SHW Clause 902 for trial sites:

- Using any surface course RA, without restriction, at low risk sites, subject to in-situ monitoring for a period of at least two years
- Using mixed source RA at low risk sites, subject to laboratory testing to verify the friction after polishing of the proposed asphalt blend, and subject to in-situ monitoring for a period of at least two years.

These recommendations are presented in the flow chart in Figure 6.1.

If the results of further site trials support a relaxation of the 10% restriction of RA in the surface course, at least for some sources, it may be necessary to modify other guidance, such as that for use of BS EN 13108 (British Standards, 2010).



Notes:

1. The methodology presented in PPR710, incorporating 10%, 20%, 30% etc. proportions by mass can be used to estimate the effect of RA on friction.

2. If no information about the aggregate is available, or if available information is not reputable, further testing may be carried out (see note 1). If in doubt and for very high risk sites, assume the answer to this question is no.

Figure 6.1 Flowchart summarising recommendations for use of RA

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