Health & Safety

Improving the skid resistance of asphalt surfacings using lightweight aggregate

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Abstract

In this study, friction properties of various types of commonly used mineral aggregates for road surfacings have been determined by means of the polishing stone value (PSV) and the friction after polishing (FAP) tests. A manufactured lightweight aggregate produced by the sintering process has also been evaluated in the study. Results showed that the lightweight aggregate had superior polishing and friction characteristics compared to conventional aggregates. Furthermore, friction properties of blends of conventional and lightweight aggregates were estimated theoretically based of the friction properties of the individual components and the proportions of the blends. An optimum aggregate blend was then used to design a thin asphalt surfacing material for high speed and high volume roads. Friction of the asphalt surfacing was then determined in the laboratory using the friction after polishing test. Results showed that the thin surfacing material containing a relatively small proportion of lightweight aggregate significantly improved friction and skid resistance of the asphalt surfacing. Small scale field trials were then carried out to evaluate production and installation of asphalt containing lightweight aggregate. Furthermore, in-situ friction measurements were performed on the laid materials and showed that the skid resistance of the asphalt surfacing increased with the incorporation of lightweight aggregate.

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1. INTRODUCTION

Skid resistance of a road is defined as the contribution of the road surface to the overall friction available between the tyre and the road surface and it is an important factor regarding road safety. The skid resistance of a surfacing however deteriorates with time as a result of polishing of the aggregate microtexture and wear or abrasion of the road surface macrotexture, due to the action of traffic.

The polishing resistance of an aggregate is typically assessed by a standard laboratory test known as the polished stone value [1]. Aggregates with high PSV values are typically specified for situations where high skid resistance is required such as, approaches to junctions, roundabouts and high traffic volume roads like motorways. In the UK, the specifications for asphalt surfacing materials include minimum PSV requirements for different site categories and traffic levels [2]. However, the number of quarries with high-PSV aggregate in the UK is limited [3]. Furthermore, haulage of these aggregates from their sources results in significant transport costs and environmental concerns. Also, in recent years, the demand for high PSV aggregate in the UK has increased rapidly due to the increased popularity of thin surfacing materials. These have resulted in increased materials costs, supply availability issues and construction programme delays.

Alternative aggregate sources have also been used to improve friction and skid resistance. For instance, in the US, artificial lightweight aggregates like expanded clay, slate and shale have been shown to provide high levels of skid resistance when used in surface dressings or chip seals [4]. Furthermore, in Europe, expanded clay lightweight aggregate has also been used in asphalt concrete mixtures as a replacement of some of the natural aggregate. It has been shown that the incorporation of expanded clay lightweight aggregate improved friction levels and reduced stopping distances [5].

The Wehner Schulze (WS) test, developed in the 1960s at the Technical University of Berlin (TUB), is an alternative method to the PSV to evaluate the polishing properties of aggregates. After some modifications, the test is now an EN standard method known as the Friction after Polishing (FAP) test [6]. It is used for determining the friction properties of both aggregate mosaics and asphalt specimens. It has been extensively employed in Europe in the last 15 years to characterise both friction and polishing properties of aggregates and asphalt mixtures. Furthermore, the FAP test has been found particularly useful for predicting the friction properties of blends of aggregates of different polishing characteristics [7]. It has been suggested that blending of aggregates with different frictional properties might enable better use of local and alternative aggregate sources when designing new surface courses to current specifications.

In this work, the friction properties of various types of natural mineral aggregates for asphalt surfacings have been determined by means of the friction after polishing (FAP) test. A manufactured lightweight aggregate produced by the sintering process has also been evaluated in the study. Friction properties of blends of natural mineral aggregates and sintered lightweight aggregate (SLWA) have then been estimated theoretically based of the friction properties of the individual components and the blend ratios. Selected blends of aggregates have been used to design asphalt surfacing materials with enhanced friction. Friction of the asphalt surfacing materials produced with various blends of natural mineral aggregate and lightweight aggregate have been determined in the laboratory using the friction after polishing test.

2. LIGHTWEIGHT AGGREGATES

Lightweight aggregates (LWA) are generically defined as those aggregates that have a particle density lower than those of natural mineral aggregates. In Europe, they are specified in EN 13055 [8]. The European standard defines LWA as those aggregates of mineral origin having particle densities not exceeding 2.0 Mg/m^3 or loose bulk densities not exceeding 1.20 Mg/m^3. Lightweight aggregate can be natural (e.g. pumice), manufactured from natural sources (e.g. expanded clay, shale and slate), manufactured from by-products or recycled source materials (e.g. sintered fly ash) and by-product aggregates (e.g. fly ash).

In this study sintered pulverised fly ash lightweight aggregate was used. Fly ash is a waste material generated by coal fired power stations for electricity production. The sintered lightweight aggregate is made by adding a controlled amount of water to the fly ash in specially designed pelletising dish pans. The pellets formed are then heated on a sinter strand where the temperature is between 1000 and 1250 ^{0}C. As the material is heated, it liquefies and carbonaceous compounds in the material form gas bubbles, which expand the material. The expanded product is then cooled by air, forming a porous material. The result is a hard vitrified external crust with an internal honeycombed structure of interconnecting voids within the aggregate. The particles formed are rounded in shape and range in size from 14 mm approximately down to fines. These are then processed to the required grading, depending on the final use.

Particle density (oven dry) and water absorption values for the sintered lightweight aggregate (SLWA) used in the study were found to be 1.49 Mg/m^3 and 14.7 %, respectively. Similar density and water absorption values have been reported for other types of lightweight aggregates used in road construction like expanded clay, shale and slate [9]. It should be noted that particle densities of these lightweight aggregates were approximately 50 % lower than those of natural aggregates. Also, their high water absorption values indicate the porous nature of these types of aggregates.

3. FRICTION OF AGGREGATES

3.1. Friction after polishing test

Laboratory measurements of the friction properties of the aggregates were carried out using the Friction after Polishing test [6]. The test is designed to carry out first accelerated polishing of aggregate or asphalt specimens and then to assess their friction characteristics. Both aggregate mosaic specimens and laboratory prepared asphalt specimens or cores taken from actual roads can be used for testing.

The polishing process is carried out by three rubber conical rollers rotating at 500 rpm, giving a linear speed of 17 km/h, with the contact pressure being 0.4 N/mm^2. The roller head is rotated for typically 1 hour giving a total of 30,000 revolutions or 90,000 roller passes.

The friction measurement process is carried out by three small rubber slider pads attached to a rotating head. The measuring head is accelerated to 3,000 rpm equivalent to a tangential velocity of the rubber sliders of 100 km/h. Water is sprayed on to the surface to give a 0.5 mm water film thickness. When the rotating head reaches 3000 rpm (100 km/h) the motor is turned off and the head drops until making contact with the specimen surface, the contact pressure being 0.2 N/mm^2. The rotating head and rubber slider pads decelerate when making contact with the specimen. Torque transducers mounted in the measuring head measure the reaction force which is then used to determine the friction coefficient at any instant. In the standard method, the friction at 60 km/h is used.

3.2. Friction of natural and lightweight aggregates

In this study seven different natural mineral aggregates from different sources and complying with EN 13043 were used [10]. The mineralogical type of the aggregates is presented in Table 1. Table 1 also includes PSV test results carried out in accordance with the standard method. The aggregates selected cover a wide range of mineralogical types and PSV values typically used in the UK road network.

Table 1. Natural aggregates used in the study

Aggregate ID	Type	PSV	FAP
AG1	Andesite	58	0.39
AG2	Greywacke	63	0.41
AG3	Gritstone	70	0.52
AG4	Granite	51	0.29
AG5	Basalt	56	0.35
AG6	Gritstone	67	0.50
AG7	Tuff	72	0.47

Specimens for friction after polishing test were also prepared using the same aggregates samples (batches) to those used for the PSV tests. Aggregate mosaics specimens of 225 mm diameter were prepared in a similar way to those for the PSV test. Aggregates were sieved through the 10 mm sieve and retained on the 7.2 mm grid sieve. After washing and drying, the individual aggregate particles were fixed in a mould using epoxy resin. Two specimens per aggregate sample were prepared for testing. PSV and FAP specimens are presented in Figure 1.

Figure 1: PSV and FAP specimens

Friction values of the aggregate mosaics after 90,000 polishing passes are presented in Table 2. It can be seen that Gritstone aggregates (AG3 and AG6) had the highest friction values, followed by Tuff (AG7), Greywacke (AG2), Andesite (AG1), Basalt (AG5) and Granite (AG4). It has been reported that sedimentary aggregates such as gritstone, composed primarily of hard quartz minerals weakly cemented to a mineral matrix have superior frictional properties because of the differential wear and de-bonding of the individual particles under traffic. Whereas, igneous aggregates with a crystalline structure, such as granite are comprised of a large proportion of tightly bound single minerals and have a lower resistance to polishing [11].

The relationship between PSV and FAP values after 90,000 polishing passes for the aggregates evaluated in the study are presented in Figure 2. It can be seen that there is good correlation between PSV and FAP values as seen by the value of R^2 ($R^2 = 0.90$). Work carried out by TRL [7] using four different aggregate types has also showed a similar trend to the one found in current study (see Figure 2).

The following Equations were obtained from this study to describe the relationship between PSV and FAP of the aggregate,

$$FAP = 0.01 \times PSV - 0.22 \tag{1}$$

$$PSV = 88.40 \times FAP + 25.47 \tag{2}$$

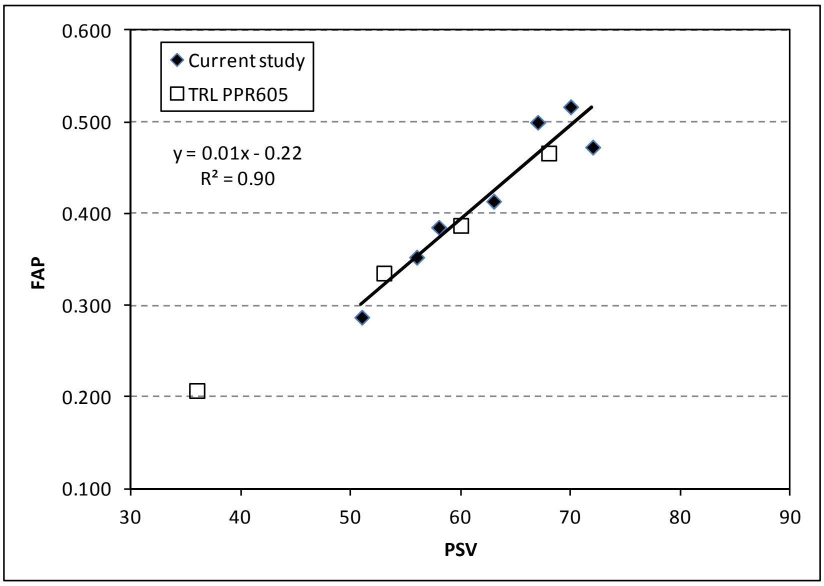

Figure 2: Relationship between FAP and PSV for natural minerals aggregates

Friction values at different number of polishing cycles ranging from 0 to 90,000 for sintered lightweight aggregate (SLWA) were also determined by means of the FAP test. Friction of selected natural aggregates including Andesite (AG1) and Greywacke (AG2) were also determined at different polishing stages. Figure 3 shows the evolution of friction with number of polishing cycles. It can be seen that, as expected, the friction decreased with increasing number of polishing passes. Also, the friction values for the SLWA were considerably higher than those for the two natural aggregates. Furthermore, the friction value at 90,000 polishing, i.e. 0.75, was significantly greater than any of the natural aggregates tested in the study.

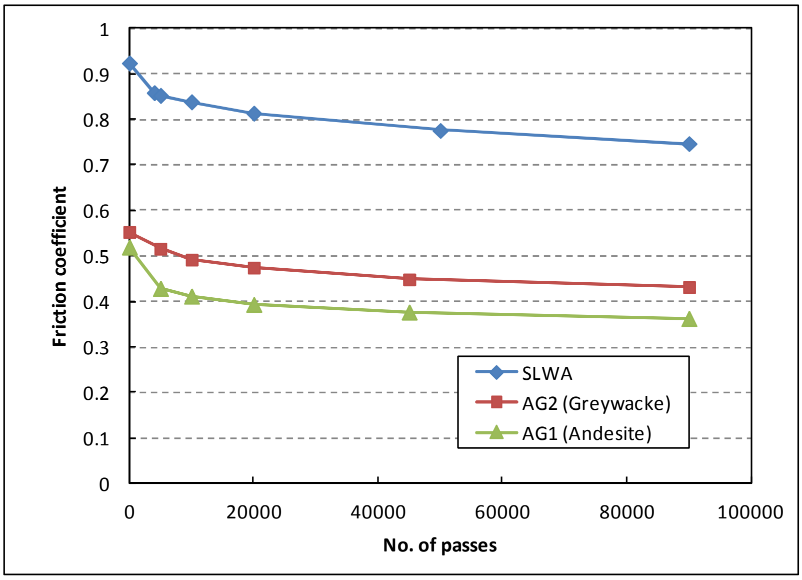

Figure 3: Evolution of friction of natural mineral aggregates and SLWA

3.3. Friction of aggregate blends

The friction characteristics of blends of aggregates can be predicted theoretically based on the simple relationship proposed by Dunford [7]. In the TRL work, the FAP test was used to polish and measure friction of specimens made by blending different pairs of aggregates in various proportions. Friction measurements made on specimens using coarse aggregate from a single source were used, in a simple mass ratio formula, to calculate the friction expected of specimens made using coarse aggregate from two sources. Calculated friction values were then compared with actual friction for all blended specimens. Good correlation was found between the calculated and measured friction values.

Based on the TRL work, the friction of a blend of coarse aggregates from two sources, A and B, can be predicted using Equation 3 [7]:

$$FAP_{AB} = m_A \times FAP_A + m_B \times FAP_B \quad (3)$$

Where m_A and m_B are the proportions (ratio) by mass and, FAP_A and FAP_B are the friction values of the individual components.

Predicted friction values of selected aggregate blends incorporating SLWA are presented in Table 2. It can be seen that the friction values of blends of natural aggregates (AG1 and AG7) and SLWA increased as the proportion of SLWA increased. Also, friction values of blends with AG7 were higher than those with AG1, as the friction value for AG7 was higher than that for AG1.

Theoretical PSV values of the aggregate blends were calculated using the predicted friction values calculated using Equation 3 and the relationship given by Equation 2. It can be seen that, for example, by replacing 15 % of the aggregate AG1 (PSV58) with SLWA, the predicted PSV of the blend increased from 60 to 64. Thus, theoretically the performance of this blend is equivalent to that of an aggregate with a PSV of 64. Therefore, this blend could be used in situations where the specified minimum requirement is PSV>63, for instance, for thin surfacing systems in motorways with traffic levels higher than 6000 commercial vehicles per lane per day (cv/lane/day) [2]. Similarly, by replacing 25 % of the AG7 aggregate with SLWA the predicted PSV of the blend increased from 67 to 73. Thus, this aggregate blend could, in theory, be suitable for sites where high PSV aggregate (PSV>68) or high friction surfacing (HFS) are employed.

Table 2. Friction of selected blends of natural aggregates and SLWA

Blend (A/B)	m_A	m_B	FAP_A	FAP_B	FAP_{AB}	PSV_{AB}
A: AG1 / B: SLWA	100	0	0.39	0.75	0.39	60
	95	5			0.40	61
	90	10			0.42	63
	85	15			0.44	64
	80	20			0.46	66
	75	25			0.48	68
A: AG7 / B: SLWA	100	0	0.47	0.75	0.47	67
	95	5			0.49	69
	90	10			0.50	70
	85	15			0.52	71
	80	20			0.53	72
	75	25			0.54	73

4. DESIGN OF ASPHALT SURFACINGS CONTAINING LIGHTWEIGHT AGGREGATE

4.1. Materials and mixtures

The mixtures used in the study were asphalt concrete thin surfacing materials, 14 mm nominal size with a polymer modified binder (AC 14 surf PMB). These types of mixtures are generally used in high speed roads where relatively high surface texture and good noise reduction and skid resistance properties are required. The materials are characterised by a semi-porous structure with a gap graded particle size distribution and a relatively open texture.

Two asphalt surfacing materials were first designed in the laboratory with two natural mineral aggregates, AG 1 (Mix 1) and AG7 (Mix 2). Two mixtures were also designed by replacing some of the coarse aggregate with SLWA. Mix 1A was designed using aggregate AG1 and 15 % SLWA by mass of the dry mixture. Mix 2A was designed using aggregate AG7 and 25 % SLWA by mass of the dry mixture. Furthermore, a polymer modified binder was used in all of the mixtures.

Single size 8/14 mm SLWA and four different aggregate sizes, 6.3/14 mm, 4/10 mm, 2/6.3 mm and 0/4 mm were used. Filler was also added to the mixtures at different proportions. Particle density and water absorption values of the aggregates were determined in accordance with BS EN 1097-6 [12] and are presented in Table 3.

The composition by mass of the dry mixtures is presented in Table 4. Composition by volume was also calculated using the particle density of the individual components (see Table 3) and the dry mix proportions. It can be seen that the % by volume of SLWA was considerable higher than the % by mass as a result of its lower particle density.

Table 3. Particle density and water absorption

Aggregate type	Particle density (Mg/m^3)			Water absorption (%)
	Oven dry	SSD	Apparent	
SLWA	1.49	1.71	1.90	14.7
AG1 (coarse)	2.81	2.82	2.84	0.4
AG7 (coarse)	2.70	2.72	2.75	0.7
Filler	2.75			-

Table 4. Composition of the dry mixtures

Component	% by mass (% by volume)			
	Mix 1 (AG1)	Mix 1A (AG1-15% SLWA)	Mix 2 (AG7)	Mix 2A (AG7-25% SLWA)
8/14 mm SLWA	-	15 (26)	-	25 (39)
6.3/14 mm	45 (45)	39 (34)	43 (43)	27 (22)
4/10 mm	18 (18)	3 (3)	17 (17)	-
2/6.3 mm	8 (8)	14 (12)	12 (12)	12 (10)
0/4 mm	25 (25)	25 (22)	26 (26)	33 (27)
Filler	4 (4)	4 (3)	2 (2)	3 (3)

4.2. Design binder content

Design binder content was determined using a gyratory compactor [13]. Proportioned aggregate blends and binder were mixed at 170 ^{0}C and then compacted in 100 mm moulds using the gyratory compactor. The number of gyrations selected was 100. Three compacted specimens per mixture were manufactured.

In order to determine air voids of gyratory compacted specimens, the maximum densities of the mixtures were first determined as per EN 12697-5 Method C (Mathematical Procedure) [14]. Furthermore, the mathematical procedure can be used to determine the extreme limits of the expected maximum density of the mixtures for 100 % and 0 % binder absorption by the aggregate, by applying, respectively, the apparent particle density and the dry particle density of the aggregates in the calculation. In this work, it has been assumed that the 50 % of the voids within the lightweight aggregate have been filled with bitumen and therefore the particle density value of the lightweight aggregate used for the calculation of the maximum density was the average of the apparent and oven dry densities.

Design binder contents and, maximum density, bulk density and air voids are presented in Table 5. It can be seen that the binder content had to be increased when SLWA was incorporated into the mixtures. This was to compensate for binder absorption by the porous lightweight aggregate. Also, as the proportion of SLWA increased the design binder content also increased. Results also show that both maximum density and bulk density decreased when some of the coarse aggregate was replaced with SLWA. It should be also noted that Mix 4 was designed to give lower voids than the other materials.

Table 5. Mixture design parameters

Property	**Mix 1 (AG1)**	**Mix 1A (AG1-15% SLWA)**	**Mix 2 (AG7)**	**Mix 2A (AG7-25% SLWA)**
Design binder content (%)	5.3	6.8	5.1	7.6
Maximum density (Mg/m^3)	2.595	2.285	2.525	2.105
Bulk density (Mg/m^3) at 100 gyrations	2.213	1.933	2.218	1.968
Voids (%) at 100 gyrations	14.7	15.4	12.2	6.5

5. FRICTION OF ASPHALT SURFACINGS CONTAINING LIGHTWEIGHT AGGREGATE

5.1. Specimen preparation and testing

Friction properties of asphalt surfacings were determined using the Friction after Polishing test [6]. Laboratory prepared asphalt specimens were used for the test. Proportioned aggregate blends and binder were mixed at 170 ^{0}C and then compacted to form slabs (300 mm x 300 mm x 50 mm) using a laboratory roller compactor. Cylindrical specimens, 225 mm diameter and 50 mm height were then extracted from the slabs and used for testing. Two specimens per mixture were prepared.

FAP test on the asphalt specimens were carried out by first sand blasting the surface of the specimens. The sand blasting stage is used to 'roughen' the specimen surfaces in order to simulate the action of winter weather. For this purpose, a sand blasting cabinet was used. The cabinet has several automatic settings which control the duration and evenness of the blasting over the specimen surface. After sand blasting, the specimens were polished for 1 hour or 90,000 polishing, before the friction was measured.

5.2. Friction after polishing test results

Friction test results for the asphalt surfacing materials after sand blasting followed by polishing are presented in Table 6. Results show that SLWA improves the friction of the asphalt surfacing as seen by the friction values after polishing. Furthermore, this enhancement is proportional to the amount of SLWA incorporated into the mixture. Small differences in friction can be also observed between the two mixtures with no SLWA, i.e. Mix 1 and Mix 2. These might reflect differences in the PSV of the aggregates used. Figure 4 shows an asphalt specimen before and after sand blasting and polishing. It can be observed that grit blasting removed some of the bitumen from the surface of the aggregate.

Table 6. Laboratory friction values of asphalt specimens

Mixture	FAP after grit blasting and 90000 polishing cycles		
	1	2	Mean
Mix 1 (AG1)	0.381	0.393	0.39
Mix 1A (AG1-15% SLWA)	0.416	0.442	0.43
Mix 2 (AG7)	0.393	0.401	0.40
Mix 2A (AG7-25% SLWA)	0.539	0.438	0.49

Figure 4: Asphalt specimens before and after FAP testing

Friction values for aggregates mosaics and the corresponding asphalt mixtures have been compared and are shown in Table 7. It should be noted that the values for the blends of aggregate and SLWA are the predicted values determined using Equation 3 and not the measured values. Results indicate that there is good agreement between the friction value of aggregate AG1 and the value for the asphalt mixture with the same aggregate (Mix 1). Furthermore, predicted friction of the aggregate blend containing AG1 and 15 % SLWA is practically the same as the value for the mixture (Mix 1A). It was also found that the friction value of aggregate AG7 was considerably higher than the friction of the mixture (Mix 2). Also, the predicted friction of the aggregate blend containing AG7 and 25 % SLWA was higher than that for the mixture (Mix 2A). These differences could be attributed to the presence of some residual binder on the surface of the aggregate. It is also believed that complete removal of the binder film surrounding porous aggregates might not be achieved during the sand blasting process, particularly where the concentration of porous aggregates on the surface of the specimen is relatively high, like for Mix 2A.

Table 7. Friction values of aggregate mosaics and asphalt specimens

Mixture	Aggregate mosaics	Asphalt specimens
Mix 1 (AG1)	0.39	0.39
Mix 1A (AG1-15% SLWA)	0.44 (Eq. 3)	0.43
Mix 2 (AG7)	0.47	0.40
Mix 2A (AG7-25% SLWA)	0.54 (Eq. 3)	0.49

5.3. In-situ skid resistance

FAP measurements can be used to estimate the skid resistance of a road surface determined on-site using, for example, the SCRIM coefficient (SC). Huschek [15] proposed a relationship between SC values determined at a speed of 80 km/h using the German SCRIM and the friction coefficient obtained in the FAP test (see Equation 5). This relationship was determined by performing friction after polishing test on cores taken from the wheel path on locations where SCRIM measurements had previously taken place.

$$SC\ (80\ km/h) = 0.96 \times FAP + 0.06 \tag{5}$$

In the UK, SC values are reported at 50 km/h, so SC values calculated at 80 km/h were corrected to a speed of 50 km/h using Equation 6 [16], as follows,

$$SC\ (50\ km/h) = SC\ (80\ km/h) \times (-0.0152 \times 80^2 + 4.77 \times 80 + 799)/1000 \tag{6}$$

Predicted SC values are presented in Table 8. It can be seen that the predicted SC values are above the UK recommended minimum Investigatory Levels (ILs) for motorways and non event carriageways, i.e. 0.40. Furthermore, the incorporation of SLWA could be used to enhance the in-situ skid resistance performance of asphalt surfacings. It can be seen that asphalt surfacings containing 25 % SLWA could be used in areas (site categories) reserved only to traditional high friction surfaces (HFS), where ILs above 0.50 are required. It should also be noted that experience with the FAP test in Germany has suggested that the final level of friction measure in the test simulates the state of skid resistance that occurs after four to six years of traffic on aggregates in situ.

Table 8. Predicted SCRIM Coefficient values

Mixture	FAP	SC (50 km/h)
Mix 1 (AG1)	0.39	0.42
Mix 1A (AG1-15% SLWA)	0.43	0.46
Mix 2 (AG7)	0.40	0.43
Mix 2A (AG7-25% SLWA)	0.49	0.53

6. CONCLUSIONS

Based on the laboratory tests to evaluate polishing and friction properties of different natural and lightweight aggregates and asphalt surfacing materials containing these aggregates, the following conclusions can be drawn:

- There is good correlation between PSV of the natural aggregates and the friction values determined using the FAP test.
- Friction values of the sintered lightweight aggregate were considerably higher than those of the natural aggregates used in the study, indicating better resistance to polishing.
- Friction of blends of natural aggregates and sintered lightweight aggregate can be estimated using the friction of the individual components and their blend ratios.
- Particle density (oven dry) of the sintered lightweight aggregate was 1.49 Mg/m^3, thus, approximately 50 % lower than that of natural aggregate. Water absorption, on the other hand, was 14.7 % indicating the porous nature of this type of aggregate.
- Asphalt concrete surfacings containing SLWA require higher binder contents to compensate for the amount of binder absorbed by the porous lightweight aggregate. As a general rule, 0.1 % extra binder has to be added for every 1 % of SLWA added to the mixture.
- The incorporation of SLWA into an asphalt surfacing improves the friction of the surfacing as seen by the friction values obtained in the FAP test. Furthermore, this enhancement is proportional to the amount of SLWA incorporated into the mixture.
- Good correlation was found between the friction values of the aggregates mosaics and those of the asphalt mixtures particularly for the asphalt surfacing with 15 % SLWA. For the asphalt with 25 % SLWA, friction measured on the aggregate mosaics was higher than that measured on the asphalt specimens.
- Predicted in-situ skid resistance values determined from FAP tests shows that the in-situ skid resistance of asphalt surfacings is enhanced by the use of SLWA. Furthermore, based on the predicted SCRIM Coefficient values, the in-situ performance of the asphalt surfacing with 25 % SLWA is comparable to that of traditional High Friction Surfaces (HFS).

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