Aggregate Surface Areas Quantified Through Laser Measurements for South African Asphalt Mixtures

By

Dr. Joseph Anochie-Boateng - Senior Researcher
(Corresponding Author)
Council for Scientific and Industrial Research (CSIR)
P O Box 395, Pretoria 0001, South Africa
E-mail: janochieboateng@csir.co.za
Tel.: +27 12 841 2947, Fax: +27 12 841 2690

Julius Komba - Candidate Researcher
Council for Scientific and Industrial Research (CSIR)
P O Box 395, Pretoria 0001, South Africa
E-mail: jkomba@csir.co.za
Tel.: +27 12 841 3059, Fax: +27 12 841 2690

Dr. Erol Tutumluer - Professor
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign
205 N Mathews Ave, Urbana, IL 61801, US
E-mail: tutumlue@illinois.edu
Tel.: (217) 333-8637, Fax: (217) 333-1924

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Aggregate Surface Areas Quantified Through Laser Measurements for South African Asphalt Mixtures

Joseph Anochie-Boateng[1], Aff. M. ASCE, Ph.D., Julius Komba[2], and Erol Tutumluer[3], M. ASCE, Ph.D.

Abstract: For several decades, efforts have been made by engineers and researchers in the road and airfield pavements, and railroads to develop methods/procedures for accurate quantification of aggregate shape and packing properties. The difficult part of the process has been the fact that aggregate particles have irregular and non-ideal shapes. New research capabilities, including laser-based technology can effectively address the difficulties associated with aggregate shape measurements to optimize asphalt mix design. This paper introduces the use of a three-dimensional (3D) laser scanning method to directly measure the surface area of aggregates used in road pavements in South Africa. As an application of the laser-based measurements, the asphalt film thicknesses of five typical South African mixtures were calculated and compared with the film thicknesses calculated from the traditional Hveem method. Based on the laser scanning method, a new surface area factors were developed for coarse aggregates used in the asphalt mixtures. Overall, the study demonstrated applicability of 3D laser scanning method to characterize coarse aggregates.

Keywords: Asphalt Mixtures; Aggregate Surface Area; Asphalt Film Thickness; Surface Area Factors; Hveem Method; 3D Laser Scanning Method.

[1] Senior Researcher, Council for Scientific and Industrial Research (CSIR), P O Box 395, Pretoria 0001, South Africa; (corresponding author); Tel.: +27 12 841 2947, Fax: +27 12 841 2690; E-mail: janochieboateng@csir.co.za

[2] Candidate Researcher, Council for Scientific and Industrial Research (CSIR), P O Box 395, Pretoria 0001, South Africa; E-mail: jkomba@csir.co.za

[3] Professor, Paul F. Kent Endowed Faculty Scholar, University of Illinois at Urbana-Champaign, Department of Civil and Environmental Engineering, 205 N Mathews Avenue, Urbana, IL 61801; E-mail: tutumlue@illinois.edu

Introduction

Over the past several years, engineers and researchers in pavement engineering and construction have made efforts, and continue to develop methods/procedures for accurate measurement of the surface area of mineral aggregates used in hot-mix asphalt (HMA) design. The total surface area of mineral aggregate particles used to evaluate asphalt film thickness has been either roughly estimated from gradation of the aggregate blends (The Asphalt Institute 1993), or measured using indirect methods such as the Centrifuge Kerosene Equivalent method (Hveem 1942). These methods have been reported to provide low accuracy (Field 1978; Roberts et al. 1996). Research conducted on dependence of asphalt mix durability on film thickness concluded that new and improved methods are needed for accurate measurement of aggregate surface area (Kandhal et al. 1996). Other researchers have also recommended that asphalt film thickness, instead of the voids in mineral aggregates (VMA) and voids filled with asphalt (VFA) be considered in the Superpave volumetric mix design (Hinrichsen and Heggen 1996; Kandhal et al. 1996). Based on these studies, an accurate measurement of surface area of the aggregate particles is needed for a more reliable asphalt mix design.

The recent state-of-the-art in the area of aggregate characterisation has attempted to analyse aggregate shape properties using imaging techniques (Kuo, et al. 1998; Prowell and Weingart 1999; Rao and Tutumluer 2000). These techniques are generally fast, efficient and provide additional benefits of automation that eliminates the subjectivity associated with the traditional manual methods. A number of video imaging systems developed for determining aggregate shape properties is currently available either commercially or as tools in research laboratories (Fletcher et al. 2003; Frost and Lai 1996; Kuo et al. 1998; Prowell and Weingart 1999; Rao and Tutumluer 2000). However, most of these methods capture a two-dimensional (2D) image of the aggregates and provide only 2D information about the geometry of the aggregate particles, which makes it difficult to measure the shape properties in terms of mass or volume.

An accurate way of evaluating three-dimensional (3D) shape/surface properties of an aggregate particle is through the use of X-ray computed tomography (CT) technique. The sophisticated X-ray CT technique is expensive for this purpose (portable X-ray CT could cost > $ 1.4 million). Moreover, X-ray equipment has stringent safety and radiation monitoring requirements. Recently, 3D laser scanning technique for quantifying aggregate shape/surface characteristics has received much attention as a more viable and cost effective alternative to both imaging and X-ray CT (Kim et al. 2003; Lenarno and Tolppanen 2002). The 3D laser scanning technique has been used for characterising the roughness of rock fracture surfaces and rail road ballast materials (Illerstrom 1998; Lenarno et al. 1998). Pan and Tutumluer (2010) used 3D laser scanning to validate surface area factors of crushed and uncrushed natural aggregates of asphalt mixes. The use of 2D tomographic images to reconstruct 3D surface area of an irregular shaped aggregate particle has also been proposed (Masad 1998; Masad et al. 2002; Wang and Lai 1997; Wang et al. 2001).

The Council for Scientific and Industrial Research (CSIR) in South Africa has recently acquired a portable 3D laser scanning device to characterize the shape/surface properties of mineral aggregates for pavement analysis and design. The 3D scanning device has been evaluated for precision and accuracy, to effectively address the difficulties associated with the characterization of shape/surface properties of natural, recycled and marginal aggregates for asphalt mix design in South Africa. This paper presents the evaluation results of the 3D laser scanner, and direct measurement of aggregate surface area for the five typical South African asphalt mixtures. The surface areas obtained directly from the laser scanning method are used to compute asphalt film thickness of the mixtures to demonstrate potential application of laser-based scanning in HMA mix designs.

Aggregate Surface Area Computation

The traditional Hveem method for determining aggregate surface area is currently used in South Africa. In this method, the surface area of aggregate particles is estimated based on gradation and surface area factors (The Asphalt Institute 2007). The Hveem method does not take the aggregate shape into consideration, i.e., mineral aggregates are assumed to be spherical shaped. Using the surface area factors and sieve analysis results, the Hveem method calculates the aggregate particle surface area by Eq. (1).

$$SA = \frac{1}{100} \sum PC \qquad (1)$$

where,

SA = Surface area of the aggregate (m^2/kg)

P = Percentage by weight passing sieve sizes

C = Surface area factor (m^2/kg)

The assumption that all mineral aggregate particles are spherical clearly introduces inaccuracies in the computation of surface areas. An attempt has been made to improve the Hveem method. For instance, Radovskiy (2003) reported that the surface area factors used in the Hveem method are also based on the assumption that specific gravities of the coarse aggregates (particle sizes larger than 4.75 mm or No. 4 sieve size) and fine aggregates (particle sizes smaller than 4.75 mm size) are close to 2.34 and 2.44, respectively. A more rational approach will be the use of direct measurements to compute the aggregate particle surface area. The current research shows that obtaining the surface area of the fine aggregates is a daunting task. However, major advances have been made to directly measure the surface area of the coarse aggregates. Table 1 shows the surface area factors used in South Africa as specified in the Technical Recommendations for Highways (TRH) for hot-mix asphalt design (TRH 8 1987), and also recommended by the Hveem method (The Asphalt Institute 2007).

Table 1. Specified Surface Area Factors

Sieve sizes (mm)	Surface area factor (m^2/kg)
26.5	
19.0	
13.2	0.41[a]
9.5	
6.7	
4.75	0.41
2.36	0.82
1.18	1.64
0.600	2.87
0.300	6.14
0.150	12.29
0.075	32.77

[a] Surface area factor for plus 4.75 mm material is 0.41

Asphalt Film Thickness

The influence of asphalt film thickness on performance of HMA mixtures have been thoroughly investigated (Li et al. 2009; Roberts et al. 1996; Sengoz and Agar 2006). These researchers indicated that film thickness can be used as a criterion for good performance of asphalt mixtures. A comprehensive study conducted by Kandhal et al. (1996) indicated that the viscosity and complex modulus of asphalt binder, and resilient modulus of the HMA mixtures increase when the average thicknesses of the asphalt film coating the mineral aggregate particles get thinner. As mentioned earlier, film thickness, instead of voids in mineral aggregates and voids filled with asphalt has been recommended for HMA volumetric mix design. Eq. (2) is used to compute asphalt film thickness around an aggregate particle (Roberts et al. 1996).

$$T_F = \frac{V_{asp}}{SA \times W}(1{,}000) \quad (2)$$

where,

T_F = Film thickness (μm)

V_{asp} = Effective volume of asphalt (liters)

SA = Surface area of the aggregate (m^2/kg)

W = Weight of aggregate (kg)

It is well known that the film thickness of hot-mix asphalt mixture is a computed number that cannot be obtained by direct measurement. Therefore, asphalt film thickness is seen as an index, rather than fundamentally measured value. It is a priority for researchers and the industry to accurately calculate film thickness for asphalt mixtures. The current method for calculating asphalt film thickness is based on the surface area factors of Hveem asphalt mix design method. In this method, the asphalt film thickness calculations are based on the assumptions that the effective asphalt binder is coating the aggregate particle surface with equal film thicknesses and that all aggregate particles are spherical in shape. In reality, the film thicknesses obtained from this method are average values.

The procedure for calculating effective volume of asphalt binder in South Africa is contained in the Technical Methods for Highways manual (TMH 1 1986). The weight of aggregate particles can be measured in the laboratory with accuracy. However, the same cannot be said about the surface area, because of the assumptions associated with its computation. Therefore, the aggregate particle surface area is the critical parameter for the accurate determination of asphalt film thickness. Leading to this observation, several research efforts should focus on the determination of aggregate surface area. In the current study, asphalt film thicknesses of five South Africa asphalt mixes were computed based on the aggregate surface area obtained from direct measurement from a 3D laser scanning method.

South African HMA Mixtures Studied

Five wide ranging asphalt mixtures commonly used in South Africa road pavements were selected for this study. The mixtures include bitumen treated base coarse mix with 40/50 penetration grade bituminous binder, coarse and medium continuously graded mixes with Styrene Butadiene Styrene (SBS) modified binder, medium continuously graded (dense graded) mix with 60/70 penetration grade bituminous binder, and bitumen rubber asphalt semi-open graded mix. Thus asphalt mixtures used for wearing and base (binder) courses as well as rehabilitation of road and airfield pavements in South Africa are all represented in this study. Different types of mineral aggregates; andersite (mixes 1 and 4), dolerite (mix 2), dolomite (mix 3) and quartzite (mix 5) were used for this study.

Sieve analysis tests were conducted on the blended aggregates using the standard South African sieve sizes. The nominal maximum aggregate sizes (NMAS) were 19 mm for mixes 1 and 2, 9.5 mm for mixes 3 and 4, and 13.2 mm for mix 5. Table 2 shows the gradation results of blended aggregates for the five mixtures. Following the gradation analyses, aggregate samples were split on a sampling splitter until the number of particles required for scanning was achieved in this study. The goal was to scan a sample size of 30 from the population of aggregates retained on each sieve size for each mixture in order to obtain a statistical representation of the aggregate samples except for the larger sieve size (i.e. 19 mm) where less than 30 particles were retained but additional samples were scanned to increase the sample size to 30 particles.

Table 2. Sieve Analysis (% Passing) Results and Properties of Mixtures Used in the Study

Sieve sizes (mm)	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
26.5	100	100	100	100	100
19.0	93	93	100	100	100
13.2	82	80	100	100	96
9.5	71	73	95	97	74
6.7	58	67	80	75	43
4.75	51	50	62	59	27
2.36	36	34	40	42	17
1.18	25	23	28	30	11
0.600	18	17	21	21	7
0.300	14	12	16	14	5
0.150	8	9	10	9	3
0.075	5.4	5.7	5.5	5.8	2.6

Mix 1 = Bitumen treated base coarse mix with 40/50 penetration grade binder

Mix 2 = Coarse continuously graded mix with SBS modified binder

Mix 3 = Medium continuously graded mix with SBS modified binder

Mix 4 = Medium continuously graded (dense graded) mix with 60/70 penetration grade binder

Mix 5 = Bitumen rubber asphalt semi-open graded mix

Laser-Based Aggregate Scanning

Three-Dimensional Laser Scanning Device

The 3D laser scanning device used for this study was originally designed by Roland DGA Corporation in the United States for solid shape modeling in medical and manufacturing applications.

The device uses an advanced non-contact sensor to scan objects in three dimensions, and up to a 0.1-mm (100-μm) scanning resolution.

The 3D laser device offers direct measurement of surface area properties of regular and irregular shaped objects. The device operates in both rotary and plane scanning modes to make it suitable for different types and sizes of mineral aggregates. In the rotary mode, spherical and smooth-surfaced objects are scanned on a fully integrated rotating table using a laser beam, which travels vertically up the rotating object to generate a digital scan file. The plane scanning mode captures flat areas, hollow objects, oblique angles and fine details of objects with the laser beam, and can scan up to six surfaces at right angles.

An integral part of the 3D laser device is advanced data processing software, which allows users to merge scans for increased quality, change the shape around curved surfaces, sharpen edges, extend shapes, add thicknesses and perform Boolean operations on polygon surfaces. These features are essential for obtaining accurate morphological properties of the aggregates. The 3D laser device at CSIR has been improvised and calibrated to determine shape and surface properties of different types of aggregates including natural (mineral), recycled and marginal aggregates.

Validation of Surface Area of Regular Objects

Fifteen spherical shaped objects of different materials including steel, ceramic, rubber and plastics, and twelve cubic shaped objects of steel, aluminum and brass with known theoretical surface areas were scanned using the laser device. The purpose was to evaluate and verify the capability and precision of the laser device for accurate measurements of the surface area of mineral aggregate particles. The spheres had diameters in the range of 5 mm to 63.5 mm, and the cubes had sizes ranging from 8 mm to 50 mm. The theoretical surface areas of the spheres and cubes were computed and compared with the surface areas obtained from the 3D laser scanner. Eqs. (3) and (4) were used to compute the theoretical surface areas of the spheres with diameter (D), and the cubes with size (L)

$$Surface\,Area\,of\;a\;Sphere\;=4\pi r^2=\pi D^2 \qquad (3)$$

$$Surface\,Area\,of\;a\;Cube\;=6L^2 \qquad (4)$$

Table 3 shows the surface area validation results of measured and theoretical surface areas of the spherical and cubic objects, and Fig. 1 compares the surface areas in a graph. As seen from Fig. 1, there is an excellent correlation (R^2 = 1.000) between the 3D laser measurement and the theoretical values obtained for both spherical and cubic objects scanned. The laser scanner provided essentially the same surface areas as the theoretical or computed values with overall mean absolute errors of 0.33 % and 0.57 % for the spheres, and cubes, respectively. The evaluation results suggest that the 3D laser scanning device would provide accurate surface area measurements of individual aggregate particles for a reliable computation of asphalt film thicknesses for asphalt mixtures.

Direct validation of the measured aggregate surface area with 3D laser scanning device was already accomplished in previous studies (Pan 2006; Pan and Tutumluer 2010). Pan (2006) validated 3D laser based surface area computations using regular shaped objects such as different sized perfect spheres and cubes. Then, Pan and Tutumluer (2010) used the 3D laser based surface area results of irregular shaped aggregates to validate the imaging based surface area index.

Table 3. Surface Area Validation Results for the 3D Laser Scanning Device

Spherical objects				Cubic objects			
Object # (Diameter in mm)	Surface area (cm^2)			Object # (Size in mm)	Surface area (cm^2)		
	Measured	Theoretical	Error (%)		Measured	Theoretical	Error (%)
1 (5.0)	0.78	0.79	-1.28	1 (8)	3.73	3.84	-2.95
2 (12.7)	5.08	5.08	0.00	2 (12)	8.60	8.64	-0.47
3 (15.9)	7.89	7.90	-0.13	3 (15)	13.60	13.50	0.74
4 (19.1)	11.44	11.43	0.09	4 (20)	23.86	24.00	-0.57
5 (20.0)	12.64	12.57	0.55	5 (21)	26.46	26.46	0.00
6 (22.0)	15.27	15.22	0.33	6 (25)	37.28	37.50	-0.59
7 (25.0)	19.56	19.62	-0.31	7 (28)	46.99	47.04	-0.11
8 (25.4)	20.14	20.19	-0.25	8 (30)	53.87	54.00	-0.23
9 (32.0)	32.25	32.21	0.12	9 (35)	73.25	73.50	-0.34
10 (36.5)	41.96	41.82	0.33	10 (40)	95.65	96.00	-0.37
11 (38.1)	45.76	45.50	0.57	11 (45)	122.03	121.50	0.43
12 (44.5)	62.32	62.13	0.31	12 (50)	149.95	150.00	-0.03
13 (50.0)	78.82	78.66	0.20	-	-	-	-

14 (50.9)	81.34	81.29	0.06	-	-	-	-
15 (63.5)	127.10	126.60	0.39	-	-	-	-

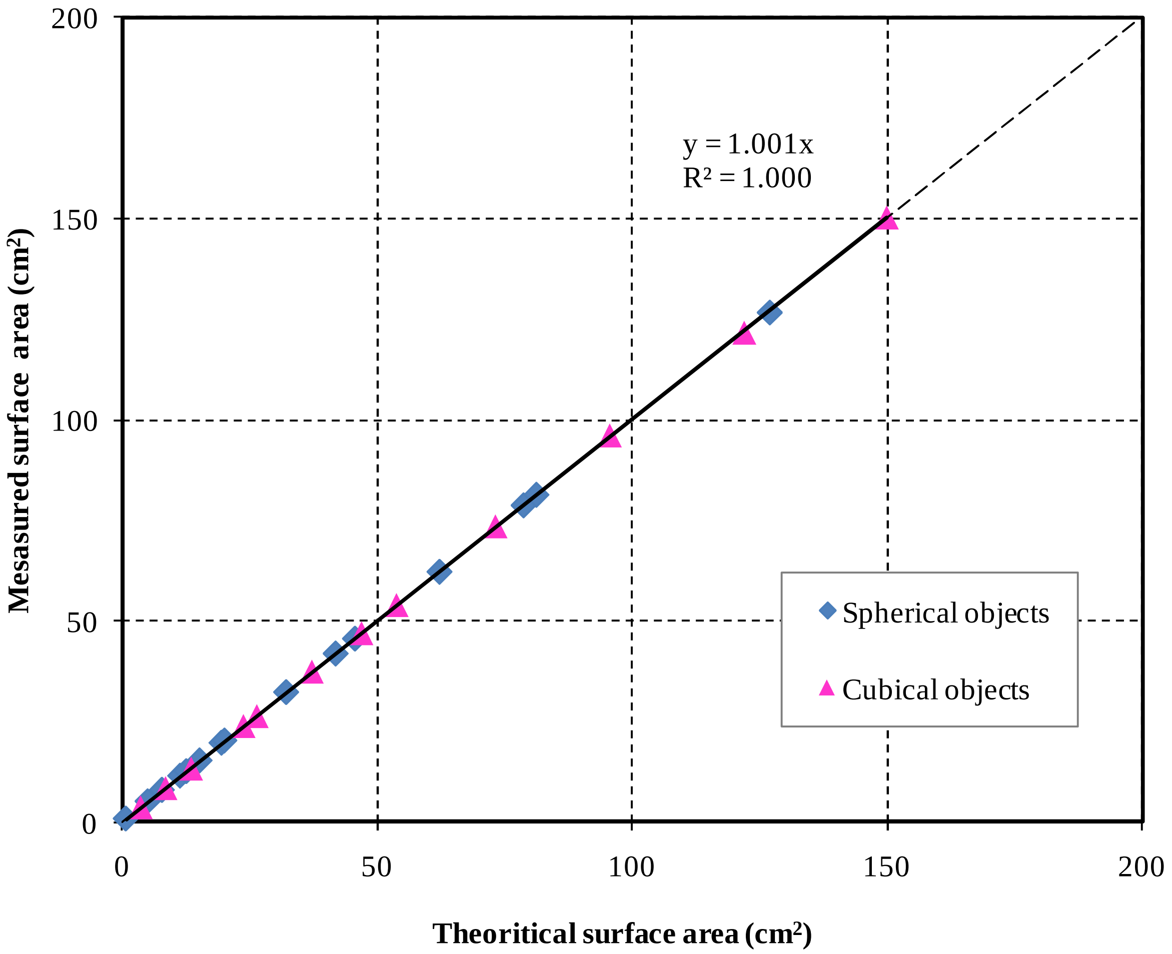


Fig. 1. Comparison of theoretical and measured surface areas of objects scanned

Verification of Accuracy Using Irregular Shaped Objects

The capacity and precision of the laser scanning device to accurately measure surface properties of irregular objects was verified through measurement of volume of aggregate. Aggregate particles originating from the same parent rock are usually assumed to have the same specific gravity hence the mass is equivalent to the volume. Aggregates from five different parent rocks with various bulk densities were used for the evaluation. These are: Andesite-1 (2,815 kg/m3), Dolerite (2,930 kg/m^3), Dolomite (2,873 kg/m^3), Andesite-2 (2,809 kg/m^3) and Quartzite (2,738 kg/m^3). The mass of the aggregates derived from volume of aggregates measured using the laser scanning approach was compared with the actual mass of the aggregates obtained by weighing. Equation 5 was used to derive the mass of the aggregate samples scanned.

$$M = D \times V \quad (5)$$

where,

M = mass of aggregate (kg)

D = density of aggregate (kg/m^3)

V = volume of aggregate (m^3)

Fig. 2 presents a plot of the actual mass of the aggregates (600 overall, for the five different parent rocks) obtained by weighing, and the derived mass of the aggregates obtained from the laser scanning method. It can be seen that the mass of the aggregates estimated from the 3D laser scanning method agree quite well with the physically measured (weighed) values. An excellent correlation (R^2 = 0.9998) exists between the derived and the measured masses although there is an insignificant error, which may be due to the use of bulk densities instead of specific gravities of the individual aggregates in Equation 5.

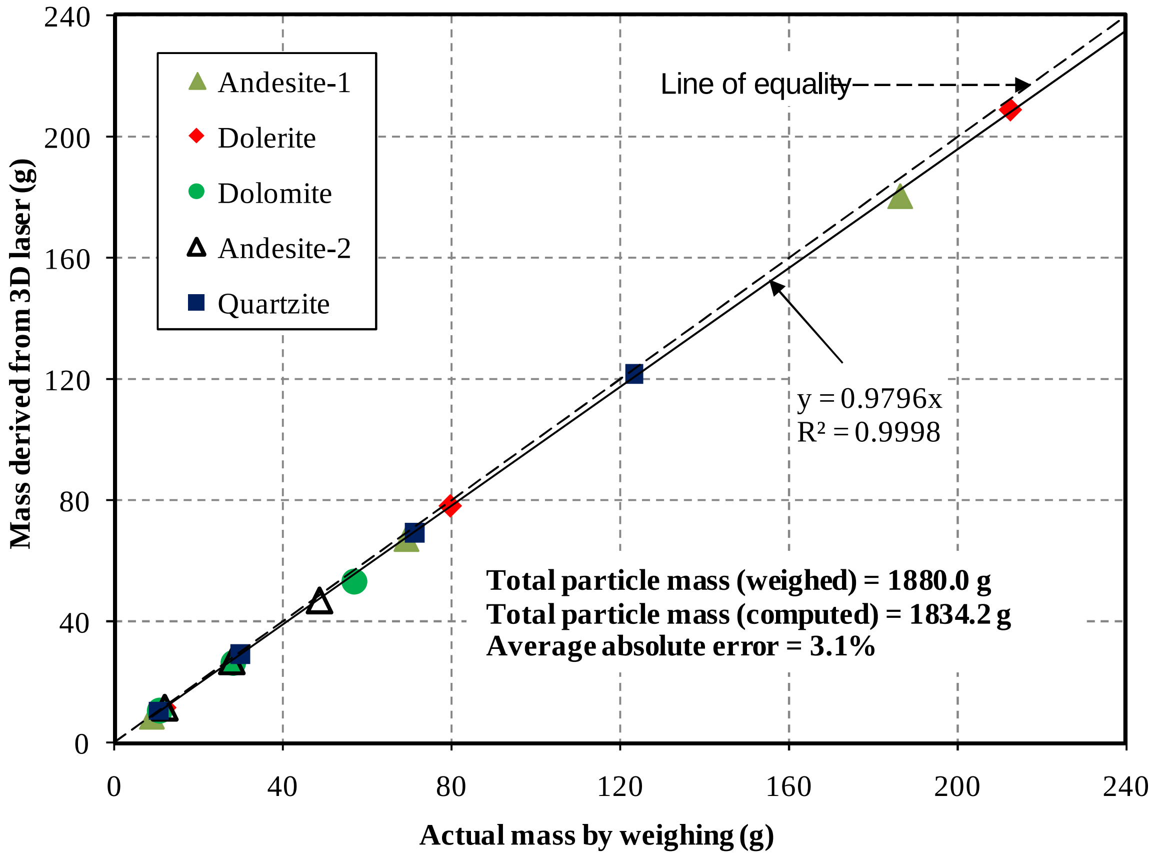


Fig. 2. Comparison of total masses for five parent rock aggregate samples

Scanning of Aggregate Particles

With the proven accuracy in measuring the surface areas of regular shaped particles and verification through aggregate volume measurement, the 3D laser scanner was used next to scan the aggregate particles of the five South African asphalt mixtures. Generally aggregate particles each of the fractions sieved on coarse sieves, i.e., particle sizes larger than 4.75 mm sieve, were sampled to represent each sieve size for this study. All the aggregates scanned were crushed coarse particles.

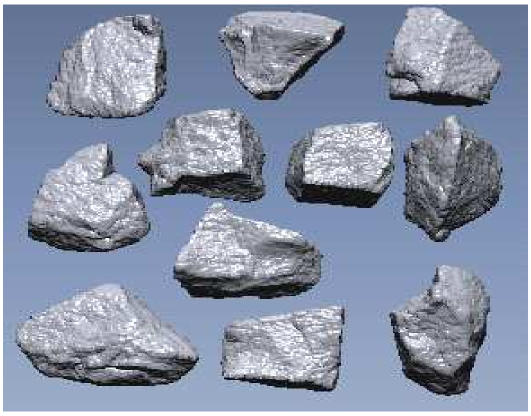
The number of particles scanned was 150 each for mixes 1 and 2, 90 particles each for mixes 3 and 4, and 120 particles for mix 5. The aggregate particles were retained on sieve sizes: 19, 13.2, 9.5, 6.7 and 4.75 mm (mixes 1 and 2); 9.5, 6.7 and 4.75 mm (mixes 3 and 4); and 13.2, 9.5, 6.7 and 4.75 mm (mix 5). Thus, a total of 600 aggregate particles were scanned for the five asphalt mixtures in this study. Although mixes 1 and 2 had 17 and 11 particles (i.e., < 30 particles) retained on the 19-mm sieve size, respectively, additional samples were prepared and scanned to ensure that the sample size of 30 particles was achieved for each sieve size.

The aggregate samples were scanned individually in the laser device. Each aggregate particle was scanned as a three-dimensional solid element (object) with six plane faces. Using the planar mode scanning option in the software, four surfaces of the aggregate particles were first scanned, followed by the top and bottom surfaces to complete the total of six faces for the solid aggregate particle. After the scanning was completed, the software was used to integrate and merge the scanned surfaces to obtain the complete aggregate particle in a six-face bounding box. Different tools including the align, triangulate/merge tools of the software were applied to first bring scanned surfaces together in order to obtain a complete aggregate, and secondly to remove any irregularities, fill holes and merge the scanned surfaces to get a representative scanned aggregate particles.

The time taken for scanning process depended on the resolution and size of the aggregate particle. High resolution and large particle size implied long scanning time. On the average, the total time for pre-processing and post-processing of an aggregate particle was 30 minutes for all aggregate particles scanned. The resolution of the laser device ranges from 0.1 mm to 1 mm. In this study, the highest resolution of 0.1 mm (100 µm), was used to scan all the aggregate particles.

Fig. 3 shows an example of actual sample aggregates retained on 19 mm sieves of mixes 1 and 2 before and after scanning in the 3D laser device. A visual comparison of the actual aggregates and their corresponding scanned images is an indication that the 3D laser scanning method provides a better measurement of aggregate shape/surface properties. Recall that the Hveem method would assume these aggregates as perfect spheres of 19 mm diameter; hence the surface area of these aggregates could be under estimated. Fig. 4 shows the scanned topographies of nine aggregates in 3D axonometric view in bounding boxes.

(a) Actual aggregates - Mix 1



(b) Scanned and processed aggregates - Mix 1

(c) Actual aggregates - Mix 2

(d) Scanned and processed aggregates - Mix 2

Fig. 3. Representative aggregate particles for mixes 1 and 2 - Actual and scanned

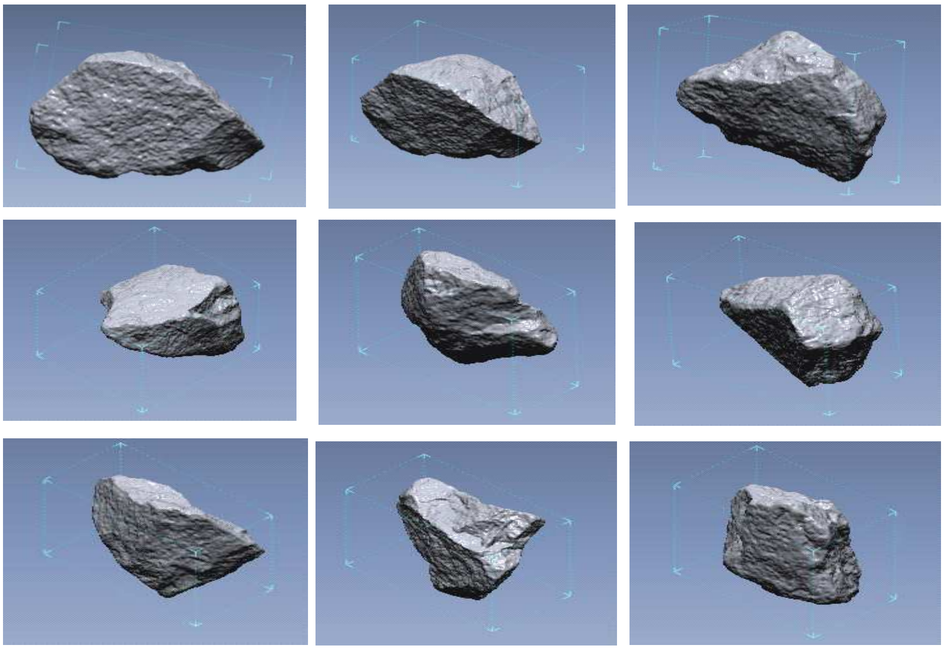


Fig. 4. Scanned topographies of sample aggregates in 3D axonometric view

Discussion of Scanning Results

The results of all the aggregate particles retained on each coarse sieve are presented. Fig. 5 shows the plots of the measured surface areas of individual aggregate particles retained on different sieve sizes for the five hot-mix asphalt mixtures studied. Significant variations in surface areas of individual particles retained on the same sieve size, especially, particles retained on the larger sieve sizes are observed. The plots also show that there are differences in surface areas between the aggregate types used in different hot-mix asphalt mix designs. It is worth mentioning that in gradation analysis, particles retained on the same sieves are assumed to have the same sizes, and these sizes are approximated to spherical shapes by the Hveem method. The observed surface area variations shown in Fig. 5, as captured by direct measurement from the 3D laser scanning method, indicate that the traditional test methods for mineral aggregates could introduce significant errors when estimating specific surface area factors, and subsequently, surface area and asphalt film thickness.

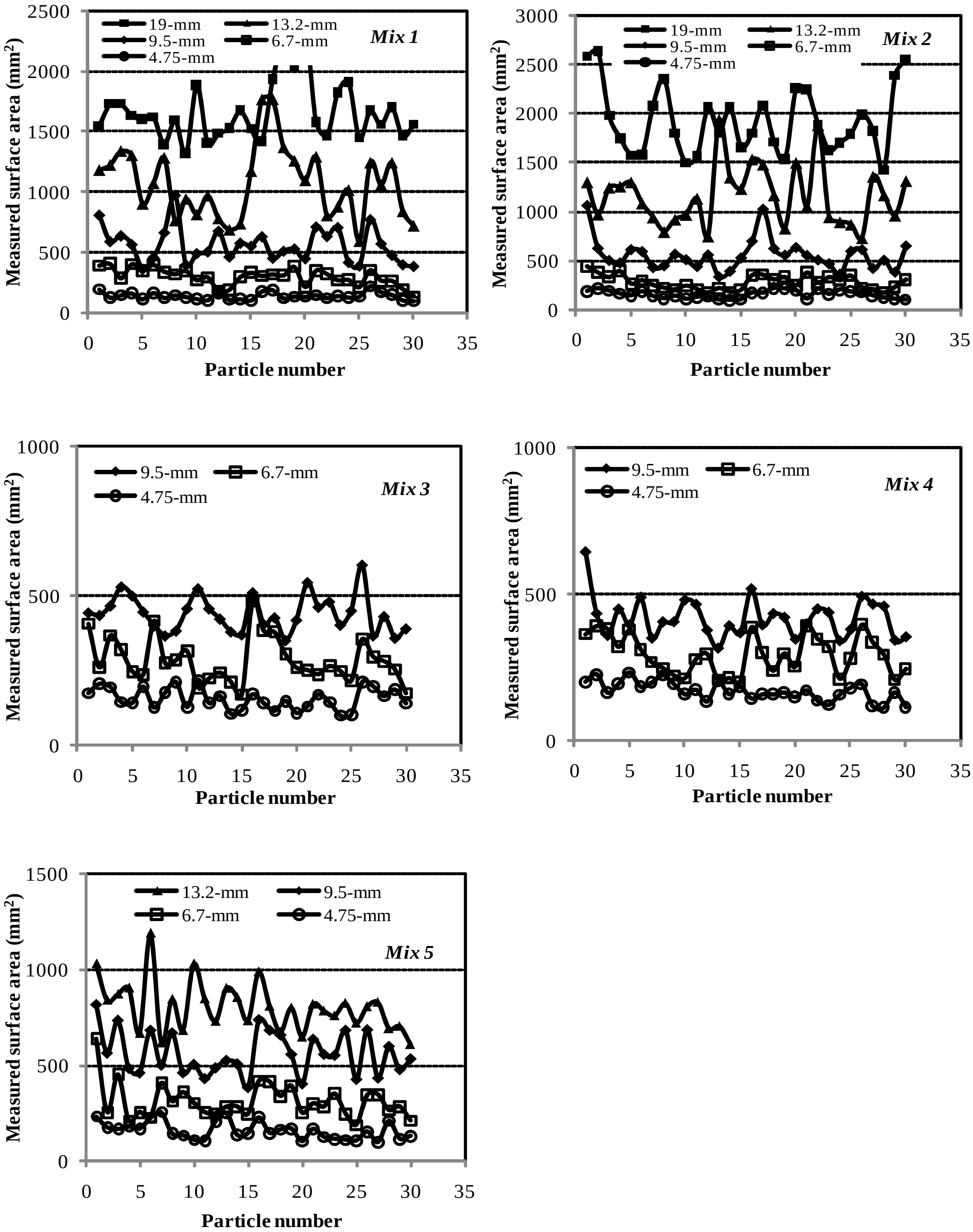


Fig. 5. Measured surface areas of scanned aggregates of the five mixes studied

Large surface area implies thin asphalt film thickness around the aggregate particle, and this has implications on the performance (e.g., rutting and cracking) of the asphalt mixtures. Also, the effect of aggregate morphology is inextricably linked to asphalt mixture durability. The durability of an aggregate particle shows its resistance to weathering/disintegration in response to cycles of environmental effects (e.g., cycles of wetting, drying, heating). It is well known that the asphalt film thickness around an aggregate particle has an effect on durability of the asphalt mix by protecting the aggregate from moisture damage. Generally, low film thickness may increase water permeability and moisture damage to the asphalt mixtures. The effect of film thickness on oxidation hardening/aging of the asphalt mixture is also well known. Hard/aged asphalt binder in particular is susceptible to crack initiation which is more rapidly propagated in asphalt mixtures with low film thickness. If left untreated, cracking could lead to distresses including pothole formation and eventual failure of the pavement. Thus, the use of direct and automated methods such as the 3D laser scanning methods for accurate measurement of surface areas is quite important for improving asphalt mix design and pavement performance.

Development of Surface Area Factors

An integral part of the 3D laser scanning device is the advanced data processing software, which allows calculation of aggregate surface areas. The workflow for this process involves processing the scanned data through aligning, combining, and merging to produce the aggregate image, then the surface area is calculated via the “Properties Tree” tool in the software according to the selected resolution of the laser scanner.

The surface area results obtained from the 3D laser scanning method were used to develop surface area factors for coarse aggregates scanned. Due to the resolution limitation of the 3D laser device, it was practically impossible to scan the fine aggregates. The surface area factors were computed by; (a) summing up all the total surface areas obtained for the 3D scanner, (b) summing up the total weight of aggregate particles scanned from each sieve size and (c) dividing the total surface area of aggregates (m^2) by the total weight (kg). Table 4 lists the surface area factors developed for the coarse aggregates of the five South African mixes studied. The specified surface area factors for coarse aggregates recommended by the traditional Hveem method are also included in Table 4 for easy comparison. The statistical analysis results indicates that there is a great potential of the 3D laser scanning method to establish surface area factors for different mineral aggregates used asphalt mixtures, although more data would be needed to make a valid conclusion. In the present form, the coarse aggregate surface areas factors for the five South African asphalt mixtures studied range from 0.13 ~ 0.44 m^2/kg.

The developed surface area factors were used to compute surface areas of coarse aggregates for all the five mixtures. Table 5 compares coarse aggregate surface areas based on the newly developed surface area factors from the 3D laser scanning and the traditional Hveem methods. It can be seen that percentage differences between the surface areas of the two methods are in the range of 10 % to 30 % for the five asphalt mixtures studied. Recall that the Hveem method calculates specified surface area factors based on the assumption that all aggregate particles are spherical in shape, which could underestimate the surface area of aggregate particles. On the other hand, the surface areas from the 3D laser scanning method are based on direct measurements from the laser device. As mentioned earlier, the scanning mode of the 3D laser device is able to capture flat areas, hollow objects, oblique angles and fine details of the aggregate particles, thereby improving accuracy in the aggregate shape characteristics. This could be the possible reason of the higher surface areas generally obtained from the laser scanning method when compared with surface areas obtained from the traditional Hveem method.

Table 4. Comparisons of the Specified and 3D Laser Scanner Based Surface Area Factors

Particle size (mm)	Specified surface area factors in TRH8, MS-4 (m^2/kg)	Laser based surface area factors (m^2/kg)							
		Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mean	Standard deviation	CoV (%)
19		0.139	0.122	-	-	-	0.131	0.0120	9.21
13.2	0.41	0.173	0.164	-	-	0.197	0.178	0.0171	9.58
9.5		0.242	0.210	0.233	0.257	0.236	0.236	0.0170	7.23
6.7		0.322	0.301	0.304	0.315	0.315	0.311	0.0087	2.79
4.75	0.41	0.462	0.389	0.435	0.423	0.458	0.433	0.0296	6.83

Table 5. Comparisons of Coarse Aggregate Surface Areas (SA)

Mixture	SA based on specified Factors (m^2/kg)	SA based on 3D Laser Scanner (m^2/kg)	% Difference
1	0.619	0.846	28.4
2	0.615	0.794	22.5
3	0.664	0.734	9.5
4	0.652	0.735	11.4
5	0.521	0.622	16.3

An extrapolation technique, which is theoretically based on the geometrical similarity among the same type of aggregate particles with different sizes, has been used (The Asphalt Institute 1993; Kandhal et al. 1998). The geometrical similarity concept used in fractal analysis defines an object as composed of sub-units and sub-sub-units on multiple levels that statistically resemble the structure of the whole object (Feder 1988). Based on this concept, a second order polynomial equation was used to extrapolate surface area factors of the coarse aggregate material measured by University of Illinois Aggregate Image Analyzer (UIAIA) system to obtain surface area factors of the fine aggregates (Pan and Tutumluer 2010).

In this study, the variations in the coarse aggregate surface area factors with particle sizes for all the five mixtures showed that a power function form would better extrapolate the data when compared to a polynomial equation. Fig. 6 shows a plot of surface area factors against coarse aggregate particle sizes using individual data of the five asphalt mixtures studied, and Eqs. (5)–(9) represent empirical correlation models between the surface area factors and the particle sizes for the individual asphalt mixture data.

Although an excellent correlation exists between the coarse aggregate surface area factors and aggregate particle sizes (R^2 values ~ 0.99), there may be inherent inaccuracies, which could be reduced by scanning large samples of aggregate particles for each sieve size. However, the consistency in surface area factors between all the coarse fraction sieves could imply confidence in extrapolation for the fine aggregates. It should be noted that a minimum of 90 and a maximum of 150 coarse aggregate particles were used to develop the surface area regression equations. Therefore, these equations should not be taken beyond their validity without appropriate cautions in an attempt to do extrapolation to estimate the fine aggregates surface area. Additional data may be required to improve/validate these empirical equations for their final use to quantify surface areas of both coarse and fine aggregates.

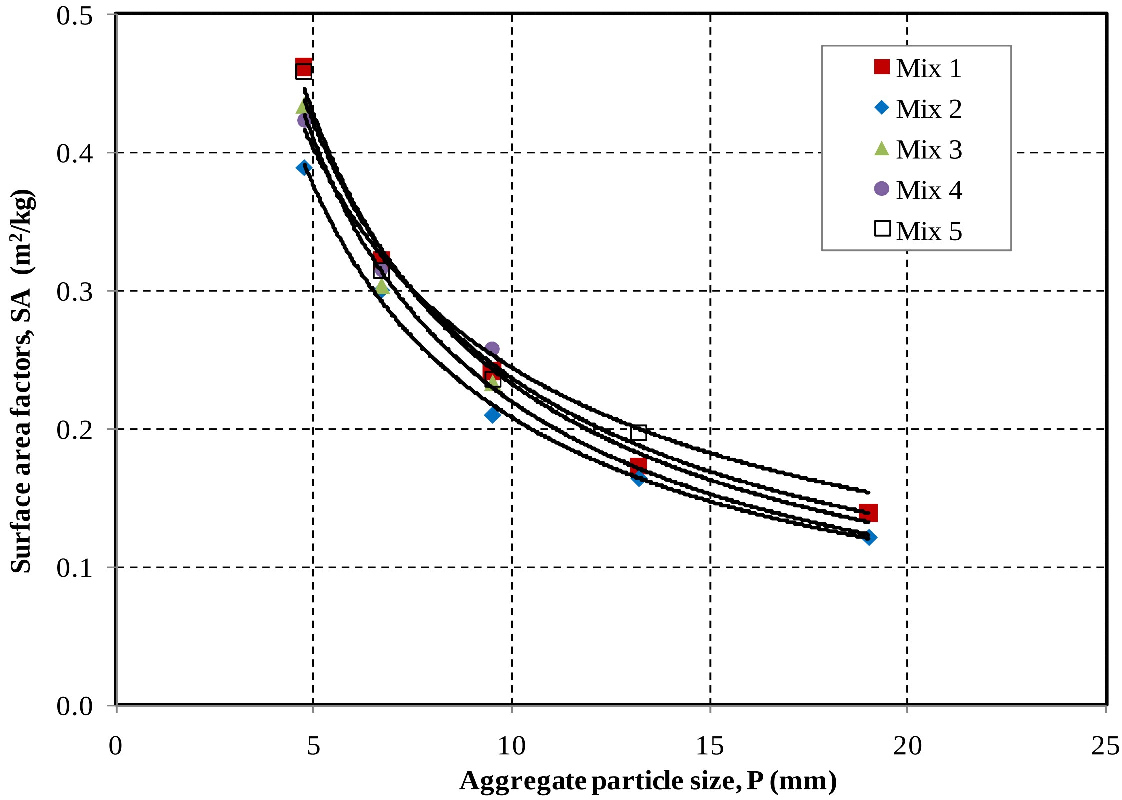


Fig. 6. Correlations between surface area factors and coarse aggregate particle sizes

$$\text{Mix 1}: SA = 1.747 \times P^{-0.876} \qquad : R^2 = 0.992 \tag{6}$$

$$\text{Mix 2}: SA = 1.471 \times P^{-0.850} \qquad : R^2 = 0.998 \tag{7}$$

$$\text{Mix 3}: SA = 1.726 \times P^{-0.896} \qquad : R^2 = 0.991 \tag{8}$$

$$\text{Mix 4}: SA = 1.277 \times P^{-0.719} \qquad : R^2 = 0.987 \tag{9}$$

$$\text{Mix 5}: SA = 1.594 \times P^{-0.829} \qquad : R^2 = 0.980 \tag{10}$$

where,

SA = Surface area of the aggregate (m^2/kg)

P = Aggregate particle size (mm)

Asphalt Film Thickness Based on Laser Scanning Method

The total surface area of the aggregate particles studied were calculated based on the coarse aggregate surface area factors presented in Table 4 (laser scanning method), and the specified surface area factors for fine aggregates presented in Table 1 (Hveem method). It should be mentioned that for the total aggregate surface area computation, the developed surface area factors for coarse aggregates were combined with specified surface area factors for fine aggregates. Eq. (1) was used to compute the total surface area of all aggregate particles included in the five mixtures. Based on the computed surface areas, Eq. (2) was used to calculate the asphalt film thicknesses of five mixtures studied. The following steps were followed to compute the film thicknesses for the asphalt mixtures studied:

i. The surface area of the coarse aggregates was obtained from the 3D laser scanning method.
ii. The surface area of the fine aggregates was obtained from the Hveem method.
iii. The total surface area was obtained by summing of the fine and coarse aggregates (i and ii).
iv. The effective asphalt binder by volume was calculated based on the asphalt binder content and absorption values presented in Table 6, and one kilogram of aggregates.
v. The asphalt film thickness was computed by dividing the volume of the effective asphalt binder by the total surface area.

It is evident from this study that the 3D laser scanning method provides a more realistic coarse aggregate surface area measurement, and subsequently, a more accurate asphalt film thickness. However, careful examination of the scanned aggregates revealed that errors could be introduced in the results during post-processing of the scanned data, specifically when merging scanned surfaces of these irregularly shaped particles. The greatest errors in film thicknesses could be due to the fine aggregates, which are estimated, based on the specified surface areas obtained from the Hveem method. Note that the standard Hveem method of computing the asphalt film thickness is based on the assumption that the thickness of asphalt film around an aggregate particle is constant (i.e., the aggregate is spherical in shape). However, the aggregate particle has irregular and non-ideal shapes, which results in introducing errors in the asphalt film thickness estimation.

Table 6 lists the results of the total surface areas computed and the corresponding asphalt film thicknesses for all five asphalt mixtures. It can be seen that the calculated film thicknesses based on laser scanning method are lower than the film thicknesses based on the standard Hveem method for all five mixtures studied. Overall, there was an average percentage difference of about 6.7 % between the two methods. Note that the calculation of asphalt film thickness includes surface areas of both coarse and fine aggregates. The differences of calculated surface areas (10% ~ 30%) between the 3D laser scanning methods and the traditional Hveem method does not take into account the surface areas of fine aggregates while those for asphalt film thickness (6% ~ 7%) includes the contribution from the surface areas of fine aggregates. Although the percentage difference in the asphalt film thickness appears to be small, it does not guarantee acceptance of the Hveem method in its current state since the difference is contributed by coarse aggregate only. These results show that the contribution of individual coarse aggregate surface area could be significant, and should be taken into account in determining the aggregate surface areas used in asphalt mixtures.

In South Africa, typical asphalt film thicknesses have been reported to be in the range of 5.8 to 8.0 μm. A decisive conclusion can only be drawn with further studies on the additional coarse aggregate particles to verify the results presented in this study. In an exceptional case, the semi-open graded mixture (Mix 5) had higher asphalt film thickness, which can be attributed to higher amounts of coarse aggregates compared with fine aggregates. Kandhal et al. (1998) recommended a minimum asphalt film thickness of 11 μm to effectively prevent premature asphalt aging.

Table 6. Surface Areas and Film Thicknesses of South African Mixtures Studied

Mixture	Binder	G_b [a]	P_b [b] (%)	P_a [c] (%)	V_{asp} [d] x 10^{-5} (m^3)	SA [e] (m^2/kg)	SA [f] (m^2/kg)	F_{T1} [g] (µm)	F_{T2} [h] (µm)
1	40/50 Pen Grade	1.027	4.3	0.38	3.99	5.699	5.453	7.0	7.5
2	SBS Modified-1	1.027	4.8	0.20	4.70	5.648	5.470	8.3	8.8
3	SBS Modified-2	1.027	4.7	0.20	4.60	6.138	6.068	7.5	7.8
4	60/70 Pen Grade	1.027	5.0	0.10	5.02	6.301	5.957	8.0	8.7
5	Bitumen Rubber	1.031	7.5	0.40	7.44	2.671	2.569	27.9	29.9

[a] Specific gravity of asphalt binder

[b] Asphalt binder content

[c] Asphalt content absorbed

[d] Effective asphalt binder by volume

[e] Surface area of aggregate based on the 3D Laser scanning method

[f] Surface area of aggregate based on standard Hveem method

[g] Asphalt film thickness based on the 3D Laser scanning method

[h] Asphalt film thickness based on standard Hveem method

Conclusions

There is a general interest in employing laser-based techniques to characterize mineral aggregate surface/shape properties for asphalt mixtures in South Africa. The Council for Scientific and Industrial Research (CSIR) has recently acquired a modern 3D laser scanning device to accurately characterize aggregate and ballast shape/surface properties for road and airfield pavements and railroads in South Africa. This paper presented the 3D laser scanning method to directly quantify the surface area of aggregate particles of five commonly used hot-mix asphalt mixtures in South Africa. The aggregate surface areas were used to develop surface area factors, and to calculate asphalt film thicknesses for the mixtures studied. The following important conclusions can be drawn from this study:

- The 3D laser based scanning method is an improvement over the traditional Hveem method, and provides potentially a new test method to directly quantify the surface area of mineral aggregates.

- New surface area factors have been established for asphalt mixture coarse aggregates used in road pavements in South Africa. However, due to limited sample size, more scanning data may be needed to validate these factors.
- A more accurate computation of asphalt film thickness for mix design can be achieved through the use of 3D laser scanning method.

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