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Submission Title: Determination of Aggregate Morphological Properties Using Laser and their Effects on Rutting of Asphalt Mixes

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ABSTRACT

A new and innovative three-dimensional (3-D) laser based technique was employed to accurately determine the morphological (shape) properties of aggregates used in asphalt mixes. The objective of this paper is to investigate the influence of shape properties (i.e., form, angularity and surface texture) of coarse size fractions of three aggregates on rutting performance of asphalt mixes. The asphalt mixes were manufactured using designed (blended) aggregates, and tested with the Hamburg wheel tracking test. It was established that the 3-D laser scanning technique could clearly differentiate between the form, angularity and surface texture characteristics of the three aggregates studied. The results obtained from the study indicate that a more angular and textured aggregates provide better resistance to rutting, thereby improving the performance of asphalt mixes.

INTRODUCTION

Aggregates constitute more than 90% by mass of asphalt mixes. The morphological or shape characteristics of aggregate particles, i.e., form (sphericity, roundness, flatness and elongation), angularity, and surface texture are critical determinants of the asphalt performance in pavements. Inadequate characterization of these properties could lead to poor mix designs of asphalt in the pavement resulting in unforeseen spending on infrastructure and even fatal road accidents. Generally, angular aggregate particles rather than rounded are preferred for good interlock. Also, textured aggregate particles are preferred to smooth particles in road pavements.

The shape and surface characteristics of aggregates are important in asphalt mix design. Since 1942 the standard method used worldwide for measuring the surface area of coarse aggregate particles (larger than 4.75 mm in size) for asphalt mix design, is based on the assumption that all aggregate particles are spherical in shape (*1*) in contrast to the highly irregular and non-ideal shapes of aggregates. This is possibly the main reason why the current standard methods used to quantify shape properties of aggregates are perceived to have inherent errors. The use of imaging techniques attempts to address some of the limitations of the standard methods (*2, 3*). However, most of these methods capture a two-dimensional (2-D) image of the aggregates and provide only 2-D information about the geometry and shape characteristics of the aggregate particles as opposed to the true three-dimensional (3-D) shape of aggregate particles.

The Council for Scientific and Industrial Research (CSIR) in South Africa is undertaking an extensive research programme using a 3-D laser scanning and numerical modelling techniques to effectively characterize the shape properties of natural, recycled, and non-conventional (e.g., industrial slag) aggregate materials, and quantify their influence on the performance of pavements. Coarse aggregate structure (skeleton) is very influential to pavement performance. This paper relates the shape properties of coarse aggregate particles sampled from three different types of aggregates to rutting behaviour of asphalt mixes manufactured from those aggregates. The selected aggregates are commonly used for road construction in South Africa.

INNOVATION

CSIR recently introduce the use of a portable 3-D laser scanning system in South Africa to effectively quantify and model aggregate shape properties affecting pavement performance. The 3-D laser technology has been used in medical healthcare for many years to visualise shapes and surface characteristics of dental and orthopaedic structures. The laser device has been calibrated by the CSIR research team to determine the shape properties of conventional aggregates (e.g., crushed stones) and ballast, as well as non-conventional aggregates (e.g. reclaimed asphalt, industrial slags, etc.) used for construction of roads, airfields and railways. The device can potentially be used in the following areas:

- Reference device to accurately determine the form, angularity, surface texture, surface area, and volume properties of aggregates used as unbound or bound pavement materials.
- Validation tool for the conventional test methods such as index of aggregate particle shape and texture, flakiness, grading, angularity and other physical tests related to aggregates.
- Analysis tool for establishing an aggregate database to efficiently rank and utilise the sources/quarries of aggregate stockpiles and rank different aggregate crushers.

- Appropriate device to overcome and improve the limitations associated with the conventional aggregate test methods.
- Tool for providing data that can be numerically analysed and modelled to simulate the properties of aggregates used in pavements.
- Tool to aid the investigation of performance of aggregates used in in-service pavements.

The use of laser scanning and imaging techniques have been widely accepted internationally, in principle as the most effective way to determine shape and surface properties of natural rock aggregates and ballast (*4-6*). Although these techniques add benefits of automation and provide accurate measurements of aggregate shape properties, evaluation of fine aggregates could be very time consuming and problematic. In comparison to imaging techniques, the laser technique captures a 3-D images of the aggregate particles and processed them to determine shape properties. The current research at the CSIR extends laser techniques to evaluate unconventional materials (recycled, cementitious stabilised, industrial slags, marginal materials, etc.) and railway ballast. Figure 1 shows the roughness (texture) and irregularity of aggregate shape at micro level in contrast with angularity at macro level as illustrated by (*7*).

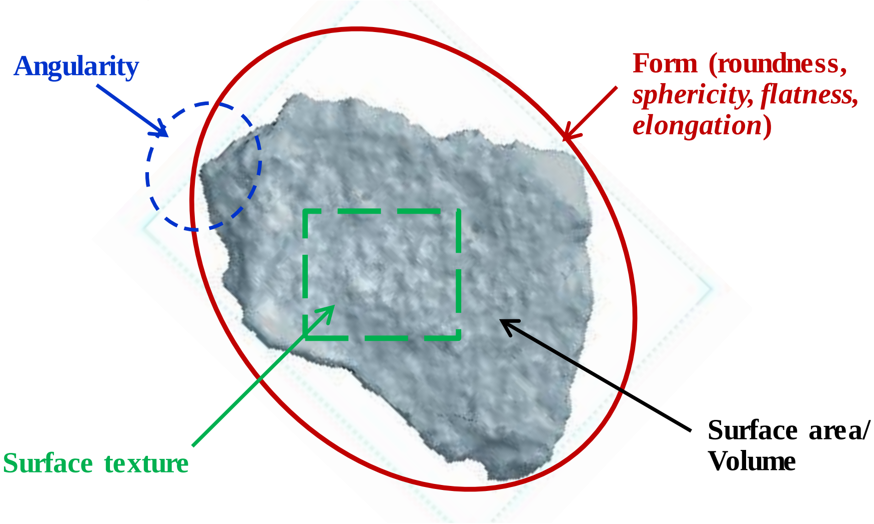


FIGURE 1 Fundamental aggregate shape properties (*7*).

MATERIALS AND SAMPLING

Aggregate Materials

Two crushed aggregates and one non-conventional aggregate materials were sampled from South African quarries for this study. The selection of these materials was in line with the on-going laser research at the CSIR on aggregates. The crushed aggregates are andesite and dolerite, and the non-conventional aggregate material is industrial chrome slag.

In order to characterize the effect of coarse aggregate shape properties on the performance of asphalt mixes, the fine components (passing sieve size 4.75 mm) of all the three aggregate samples were designed to be similar to each other. Moreover, to eliminate the effect of the shape characteristics of fine components in the crushed aggregates, andesite crusher dust was used to substitute fines in the dolerite aggregate. This would allow a direct comparison of the effect of the coarse aggregate shape properties on the performance of the mixes produced from the two crushed aggregates. To date, no thorough studies has been done with imaging and laser techniques to accurately evaluate the effect of fine aggregate shape characteristics on the performance of asphalt mixes.

Table 1 shows the design aggregate grading used for this study, and Figure 2 shows representation of 13.2 mm size aggregate particles of the design (blended) aggregate materials. These gradings were used to produce three asphalt mixes.

TABLE 1 Design Aggregate Structure (Grading)

Sieve size (mm)	[1]Design Aggregate 1	[2]Design Aggregate 2	[3]Design Aggregate 3
26.5	100	100	100
19	93	94	92
13.2	82	83	83
9.5	71	72	72
6.7	58	66	60
4.75	51	51	54
2.36	35	36	37
1.18	25	28	25
0.6	18	24	19
0.3	13	19	14
0.15	8	8	8
0.075	4.9	4.6	4.6

[1]Andesite grading with andesite fines; [2]Dolerite grading with andesite fines
[3]Chrome slag grading with slag fines

FIGURE 2 Example of aggregate particles scanned for this study.

Sampling for Scanning

Wet sieve analysis tests were conducted on the designed aggregates using the standard South African sieve sizes shown in Table 1. As seen in the table, all three aggregate types have the nominal maximum aggregate sizes of 19 mm. Each aggregate grading was divided into its respective size fractions by screening with the aid of a sieve stack. Some 15 particles were randomly sampled to represent each coarse aggregate fraction (19.0 mm, 13.2 mm, 9.5 mm, 6.7 mm and 4.75 mm) resulting in 75 (= 5 ×15) particles for each aggregate type or a total of 225 particles for the three aggregate samples for this study. It is believed that this number of particles was enough to provide indication of the effect of the shape properties on the performance of the asphalt mixes manufactured from the aggregates. Each aggregated particle was given a sample number and marked for easy identification and referencing during scanning, modelling, data processing and evaluation.

LASER SCANNING

Figure 3 shows a photograph of the laser scanning device available at the CSIR for aggregate shape characterization. The laser device offers a direct 3-D measurements of the longest, intermediate and shortest dimensions, as well as the surface area and volume properties of the aggregate particles. The device consists of laser beam moving vertically and horizontally, and a rotary table on which the aggregate particles are placed for scanning. The whole system is integrated with commercially available software for data acquisition and processing. The capability of the laser scanning device to measure aggregate shape properties as well as detailed process of scanning and modelling of aggregate particles were presented by (*8–10*). The maximum resolution of the scanner is 0.1 mm (100µm).

All 225 coarse aggregate particles for the andesite, dolerite and chrome slag aggregates were scanned individually to collect data for analysis. A final scanned and processed aggregate particle is a mesh consisting of vertices with 3-D *x*, *y* and *z* Cartesian coordinates and triangular surfaces known as poly-faces. Also, the coordinates of the mass centre to the surface of aggregate particles are obtained from scanning for numerical analyses of the aggregate shape properties. Figure 4 shows the photos of the original aggregate particles in comparison with the corresponding laser modelled particles to demonstrate the high level of accuracy and reliability of the 3-D laser scanning method.

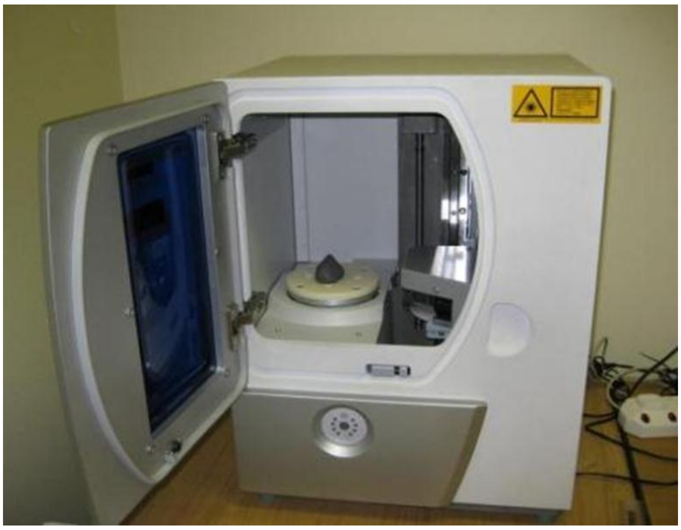
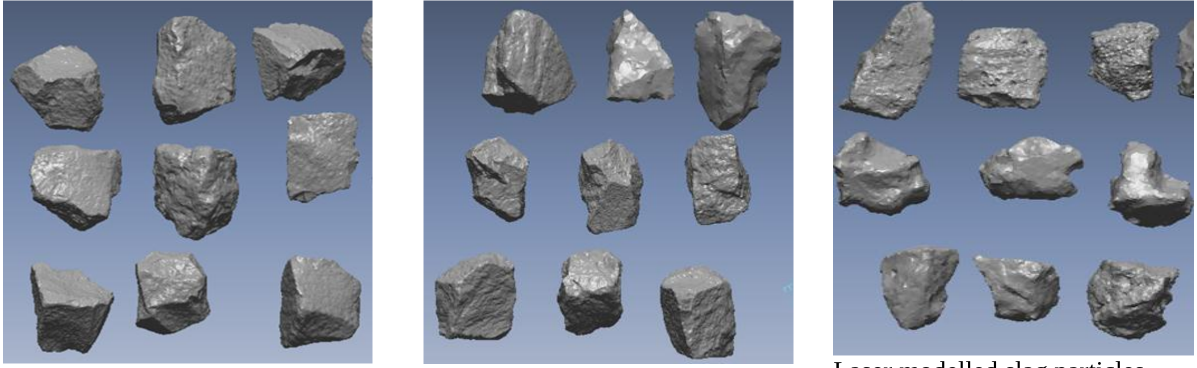


FIGURE 3 A photo of a laser scanning device at the CSIR.

Andesite particles Dolerite particles Chrome slag particles



Laser modelled andesite particles Laser modelled dolerite particles Laser modelled slag particles

FIGURE 4 Actual and modelled aggregate particles.

Analyses and Discussion of Laser Scanning Results

The spherical harmonic analysis methods proposed by (*11*) was used to determine the form, angularity and surface texture of the aggregates. This method generally defines the shape of an aggregate particle as a function of radius distance from the mass centre to the surface points of the particle in three-dimensions using Equation 1. Thus, this mathematical function was applicable to the 3-D scanning data of aggregates established by this study.

$$R(\beta,\alpha)=\sum_{1=m}^{1_{\max}}\sum_{m=-1}^{1}a_{1m}Y_1^m(\beta,\alpha) \qquad (1)$$

$$0\le\beta\le\pi\,,\ 0\le\alpha\le2\,\pi$$

where,

$R(\beta,\alpha)$ = radius from the aggregate mass centre to the surface
β = angle measured from the positive z-axis
α = angle measured from the positive x-axis
a_{1m} = scalar coefficient, and
$Y_1^m(\beta,\alpha)$ = harmonic function of degree *l* and order *m*

The scalar coefficients in Equation 1 can be written in matrix form as presented in Equation 2.

$$R=a_{lm}\times Y_l^m \qquad (2)$$

where,

R = Column vector representing radii at each corresponding β and α
a_{lm} = Vector representing the coefficients to be determined, and
Y_l^m = Spherical harmonics.

Masad et al (*12*) used the scalar coefficient (a_{lm}) to propose three descriptors to quantify aggregate form, angularity and surface texture of aggregate particles (Equations 3–5). Komba (*13*) found that the form index could be computed using a degree (*l*) value of 5, and angularity and surface texture indices could be computed with a maximum *l* values of 20, and 25, respectively. Based on these equations, a perfectly spherical or rounded shaped particles should have form index approximately equal to one (1), whereas a more flat and elongated particles will have form index far greater than 1. On the other hand, rounded shape or smooth aggregate particles are expected to have close to zero (0) angularity and surface texture, respectively.

$$Form=\sum_{l=0}^{5}\sum_{m=-l}^{l}\left|a_{lm}\right| \qquad (3)$$

$$Angularity=\sum_{l=6}^{25}\sum_{m=-l}^{l}\left|a_{lm}\right| \qquad (4)$$

$$Surface\ texture=\sum_{l=25}^{l_{max}}\sum_{m=-l}^{l}\left|a_{lm}\right| \qquad (5)$$

In this study, a MATLAB$^{\text{TM}}$ code developed by the CSIR laser scanning of aggregates research team was used to compute the form, angularity and surface texture indices of all scanned particles of the three types of aggregates. For each aggregate particle scanned, the 3-D *x, y* and *z* Cartesian coordinates of the surface points, and the coordinates of the mass centre of individual aggregate particles were exported to MATLAB$^{\text{TM}}$ software for the shape analyses. The mathematical details of the use of spherical harmonic analysis techniques to analyse laser scanning of aggregates are presented by (*14*).

Figure 5 shows shape indices results plotted against the aggregate sieve sizes for the three aggregates. In these graphs, form, angularity and surface texture indices of the andesite, dolerite and chrome aggregates are compared with each other. On the average, the chrome aggregates appear to have higher texture and angularity values than the andesite and dolerite aggregate particles. The andesite particles had the highest form index values for most aggregate particles when compared to the dolerite and chrome slag aggregates. This means that the andesite particles probably have more flat and elongated particles than the other two aggregate types. Figure 5 shows that significantly more flat and elongated can be attributed to the 13.2 mm size particles in the andesite sample. In comparison with the chrome slag, the dolerite aggregates generally had high form index values. The andesite particles were found to be more angular than dolerite particles. It should be mentioned that the results presented in this study is limited, and general conclusions could be premature since additional aggregates are needed to expand the discussions on the shape properties of the aggregate tested. However, it can be seen that the shape parameters of aggregate can be differentiated in a more scientific way using the 3-D laser scanning technique.

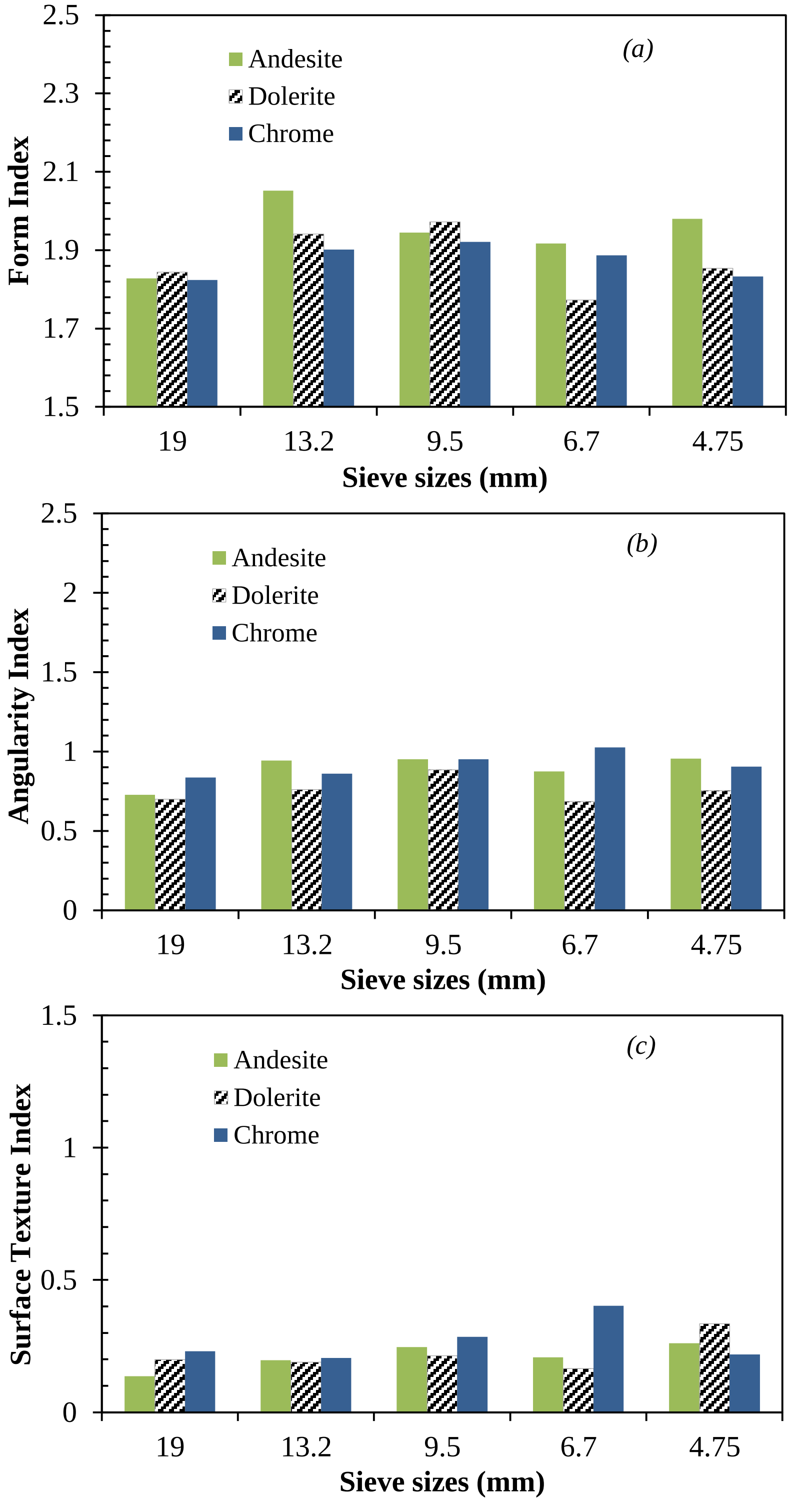


FIGURE 5 Aggregate shape properties quantified for the three mixes.

ASPHALT MIXES AND LABORATORY TESTING

Asphalt manufacturing

In South Africa, hot-mix asphalt samples are produced in accordance with the methods in the South African National Standard (SANS) method SANS 3001-AS1 (*15*). A conventional 35/50 penetration grade bituminous binder was mixed with the three aggregate gradings (Table 1) to manufacture three different mixes for the study. It should be mentioned that details of the asphalt mix design (binder selection, aggregate selection, design of aggregate structure and determination of optimum binder content) is not part of the scope of this paper.

Following mixing, the loose asphalt samples were placed in an oven for 4 hours at compaction temperature of 140°C to simulate short-term ageing before compaction. The prepared loose asphalt mixes were used to produce compacted slab samples with 7% air voids. All slabs were compacted using a commercially available slab compactor, and in accordance with the CSIR in-house test protocol. From the slabs, samples were cored to the size of 150 mm in diameter x 60 mm in height for Hamburg wheel tracking testing.

Laboratory Testing and Results

The three asphalt mixes produced were assessed using the Hamburg wheel tracking test in accordance with AASHTO T 324 (*16*). This test method is being investigated for inclusion in the new Southern Africa asphalt mix design manual. The Hamburg test has been used with success for evaluating the rut resistance of asphalt mixes at elevated temperatures. The test method is used to determine premature failure susceptibility of asphalt mixes due to certain weaknesses such as aggregate structure, inadequate binder stiffness or moisture damage, and measures the rut depth and number of passes to failure. During testing, 204 mm diameter and 47 mm wide steel wheel is passed over submerged asphalt specimens in a heated water bath. The deformation of the specimen caused by the wheel loading is measured after 20,000 passes (i.e., 10,000 repetitions). The load on the wheel is 705 N.

The results for Hamburg tests performed at 55ºC on the three mixes are presented in Figure 6. For each asphalt mix three specimens were tested and the average of the repeatable test data were computed to represent rutting behaviour of the mix. In South Africa, asphalt mixes are classified as poor, medium and good in terms of load repetitions to a rut depth of 10 mm (failure). Mixes which attain less than 2,500 repetitions until failure are considered poor, between 2,500 and 5,000 repetitions, the mix is considered medium, and a mix with good rut resistance should attain more than 5,000 repetitions before failure.

For an acceptable level of rut depth (i.e., ≤ 10 mm) the test results presented in Figure 6 indicate that the asphalt mix manufactured with andesite aggregates has poor resistance to rutting (3,000 passes or 1,500 repetitions) when compared with the asphalt mix prepared with dolerite aggregates. Note that these two mixes contain similar crushed stones. Thus, the resistance to rutting behaviour can be attributed to the coarse aggregate components since the same fine components were used to manufacture the mixes. The rut resistance of the chrome asphalt mix is comparable to the dolerite mix as presented in the figure. However, up to 10,000 wheel passes (5,000 repetitions), the mix prepared with chrome slag perform relatively better in rutting than the mix manufactured with the dolerite aggregates. Repeated permanent deformation shear tests conducted on these mixes showed similar trend (*17*). Higher shear strains were accumulated in the asphalt mix produced from andesite aggregates when compared with mixes produced from dolerite and chrome slag aggregates. On the other hand, lower shear strains were accumulated in the asphalt mix manufactured from the chrome slag aggregates than the mixes prepared with dolerite aggregates.

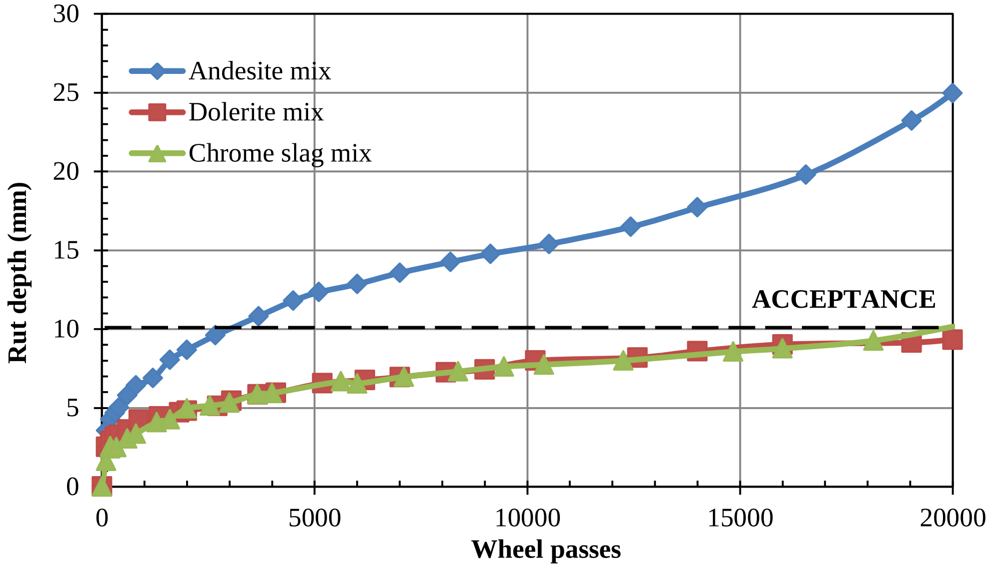


FIGURE 6 Hamburg test results for the three mixes.

EFFECT OF SHAPE PROPERTIES ON RUTTING

The resistance to rutting of aggregates in asphalt mixes could be enhanced by improved aggregate shape properties (form, angularity, roughness), as well as hardness of the parent material. The test results presented in Figure 6 showed that the asphalt mix with chrome slag aggregate provides better resistance to rutting than the two other mixes manufactured from andesite and dolerite crushed stones. This behaviour was found to be related to relatively high angularity and surface texture index values (on the average) exhibited by the chrome asphalt mix (Figure 5) when compared with the other two mixes. This is possibly the main reason why the asphalt mixes manufactured with the chrome slag aggregates provided better rutting resistance behaviour than the mix produced from the andesite and dolerite aggregates. Figure 5 also shows that the andesite aggregates were more flat and elongated (form parameter) than the dolerite and chrome slag aggregates resulting in poor rutting resistance with the andesite mix when compared with dolerite and chrome slag asphalt mixes. Flat and elongated aggregate particles have a tendency to lie flat in the asphalt mix, and tend to break easily under compaction and repeated loading leading to poor resistance to deformation.

CONCLUSIONS

This study investigated the influence of coarse aggregate shape properties on the rutting performance of asphalt mixes with an advance 3-D laser scanning technique, using a limited number of scanned aggregates particles. Therefore, the results and discussion presented are preliminary, and no valid conclusion can be made at this time. However, based on the results presented in this paper, the following conclusions can be made:

1. Applicability of 3-D laser scanning techniques to quantify aggregate shape properties and relating them to asphalt performance has been demonstrated.
2. Asphalt mixes manufactured with aggregates with different shape properties showed different resistance to rutting.
3. Aggregate particles with high surface texture and angularity appear to improve resistance to permanent deformation of the asphalt mixes.

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