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The impact of different shapes of aggregate and crumb rubber on the deformation properties of asphalt concrete

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Abstract. Bitumen and high-quality subangular aggregates, the two principal materials used for asphalt concrete construction, are finite and expensive materials. The general availability of crumb rubber and naturally occurring aggregates of different shapes, especially flat and elongated shapes, indicates that they are feasible alternative materials for expanding the volume of bitumen and utilizing a wider range of aggregate shapes for the development of asphalt concrete, with an associated environmental benefit. The study investigated the effect of adding up to 15% crumb rubber and aggregates sorted into different groups, i.e., rounded, elongated, flat, and their combinations, on the rheological and mechanical properties and durability of 50/70 of hot-mix asphalt pavement. The addition of crumb rubber decreased ductility and penetration but increased the softening point. For a 5.5% bitumen content, asphalt concrete briquettes consisting of 7% crumb rubber and three types of aggregate shapes, i.e., 100% rounded, a mix of 75% rounded and 25% elongated, and a mix of 75% rounded, 15% elongated and 10% flat, were associated with high Marshall stability and indirect tensile strength as well as low lateral deformation due to their high solidity and moderate angularity ratio. Also, the addition of 7% crumb rubber resulted in a significant improvement in the tensile strength ratio and rebound strain of briquettes consisting of 75% rounded and 25% elongated aggregates and those with 75% rounded, 15% elongated and 10% flat aggregates. In relation to the parameters investigated, the three groups of briquettes met some of the local (South Africa) requirements for the surface course and base course of low traffic volume roads.

Keywords: aggregate shape; angularity ratio; asphalt concrete; crumb rubber; indirect tensile strength

1. Introduction

The effects of plastomers and elastomers on the rheological and mechanical properties of bitumen and asphalt concrete are well documented in the literature. In one of studies in literature (Wulandari and Tjandra 2017) the use of 1% and 2% rubber crumbs as an additive in asphalt concrete was investigated and reported a decrease in penetration value and ductility value and an increase in softening point for an increase of up to 2% rubber crumb. Additionally, a Marshall stability of 1 418.50 kN and a flow of 3.30 mm were reported. The effects of warm-mix asphalt (WMA) additives on the compaction temperature and properties of a crumb rubber modified (CRM) asphalt binder and mixture were investigated and two different WMA additives (named Sas and Evm) used to prepare a warm-mix CRM asphalt binder and mixture (Ma *et al.* 2017). It was found that both WMA additives could lower the compaction temperatures of CRM asphalt mixtures by 10–20°C. However, they affected the rheological properties of the CRM binder and the performance of the CRM mixture differently. The effect of carbon black (CB) as an additive on the resistance of bitumen to delay or prevent rutting was investigated in the study of Geckil *et al.* (2018).

Low-temperature cracking was also investigated. For this purpose, different amounts of CB (0, 5, 10, and 15 wt%) were added to bitumen with a performance grade of 58–28. The results indicated that the addition of CB increased both the stiffness and resistance of bitumen to rutting at high temperatures and its resistance to thermal cracking at low temperatures. Another study by Jiao *et al.* (2019) examined the influence of 8%–12% crumb rubber and tafpack super on the performance of SBS-modified porous asphalt mixtures. The study reported that the ductility values decreased from 106 cm to 70 cm. The softening point increased from 78°C to 85°C and the penetration values decreased from 56 dmm to 43 dmm. The study further concluded that for 5.2% optimum bitumen content, 10% optimum rubber crumbs with a stability of 6.21 kN and a flow of 2.9 mm as well as an indirect tensile strength (ITS) of 2.38 MPa enhanced moisture damage resistance, rutting resistance, and overall durability. The use of crumb rubber in flexible pavements developed from 80/100 mm bitumen is another research avenue in the literature. When 10% crumb rubber is included, a decrease in penetration values, an increase in softening point and a decrease in ductility values has been reported (Sharma and Singh 2018). Also, for asphalt concrete developed from coarse and fine aggregates and stone dust filler, and an

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optimum binder content of 5.2% of crumb rubber, an improved Marshall stability of 16.80 kN and a flow of 1.5mm is reported, as well as an improvement of tensile strength ratio (TSR) of 0.906 over 0.813 for a conventional mix.

Qadir (2014) concluded that a crumb rubber mixture could carry a greater traffic load, be resistant to stability loss due to waterlogging of flexible pavements, and thus be resistant to moisture damage due to a higher TSR. The performance of polypropylene fiber-modified asphalt concrete mix against rutting has been investigated. Two types of asphalt concrete samples were prepared, namely control samples (those without polypropylene addition) and modified samples (with polypropylene modification). The samples were tested at four temperatures, i.e. 40°C, 50°C, 55°C, and 60°C, under the application of 10000 load passes of 700 N of axle load. The polypropylene fibers were found to increase the Marshall stability by almost 25%. The fibers were also determined to be effective against rutting at elevated temperatures, while the modification was found to increase the ITS by stiffening the mix at high temperatures. However, at low temperatures, the modification failed to perform effectively.

In another study by Soleimani *et al.* (2020), the effect of rubber crumb modified binder in asphalt pavement material was investigated. For 15%–22% crumb rubber in 5.3% bitumen, an optimum crumb content of 17% and associated Marshall stability, flow, and quotient and ITS of 9.5 kN, 3.5 mm, 2.71 kN/mm, and 2.71 MPa respectively was reported. The composite reflected higher resistance to temperature susceptibility and lower deformation, as well as a high axle load capacity due to higher stability relative to conventional asphalt. Many authors have also investigated the effect of crumb rubber on the mechanical properties of asphalt concrete. One study explored the influence of crumb rubber size particles on moisture damage and strength of hot-mix asphalt that was constituted from coarse aggregates, 5.8% 60/70 optimum bitumen and filler sand (Bilema *et al.* 2021). The results showed that 15% crumb rubber was the optimum amount with regard to moisture damage resistance; moreover, a TSR of 83.5% was reported. Moisture damage in rubberized asphalt mixtures containing reclaimed asphalt pavement (RAP) was tested (Xiao and Amirkhanian 2009) and the results showed that 15% of rubber crumbs exhibited the highest moisture damage at 0% of RAP, with the lowest TSR and wet ITS value. Digital image processing has been utilized to quantify the fracture area of epoxy asphalt concrete composed of rounded, elongated, and flat aggregates.

On study of Xu *et al.* (2020), they found that while rounded aggregate particles in an asphalt mixture move and rotate when compacted, flat and elongated aggregate particles are limited to horizontal movement and thus experience high torque from moving vehicles, which often results in particle breakage. To minimize aggregate fracturing and increase mixture crack resistance, the use of cubic high-strength aggregates and a minimum content of flat and elongated particles was recommended. According to a study by Little *et al.* (2018), some of the major factors influencing asphalt aggregate bonding are aggregate angularity, surface texture, and aggregate ageing. They noted that angular aggregates are more prone to stripping because angularity increases the chances of bond rupture of the asphalt binder or mastic. The effects of aggregate form and aggregate-binder adhesion of acidic phonolitic and granitic aggregates on the asphalt mixture were analyzed by the Aggregate Image Measurement System. In another study, which reported that aggregate acidity resulted in low adhesiveness to bitumen and that for 5% 50/70 bitumen, phonolitic aggregate with a 15% more moderate sphericity than the granitic aggregate but a similar angularity, mobilized better mechanical properties, having better interlocking properties than granitic aggregate (Lucas Júnior *et al.* 2020).

In a study by Mato *et al.* (2023), it was shown that the deformability of road pavements depends on different parameters, such as materials and the geometry of the pavement structure. Generally, different parameters such as particle shape, size, and soil additives have an effect on soil behavior (Gu *et al.* 2022, Karimi 2023).

Most aggregates derived from the weathering of rocks in the tropical and sub-tropical regions of Africa are predominantly naturally occurring and contain significant quantities of flat and elongated aggregates, which are often considered to be poor marginal materials because they cannot be easily compacted, tend to break down during field compaction and ruptures of the asphalt matrix. It is therefore important, and the purpose of this study is to investigate the effects of combinations of rounded, elongated, and flat aggregates on the behavior of asphalt concrete and, in particular, whether asphalt concrete mixes that were fabricated from aggregates of different shapes could be improved by the addition of crumb rubber through modification of their rheological, mechanical, deformation, and durability properties.

2. Materials and test methods

2.1 Aggregates and filler

The particle size distribution for the soil filler was 0 - 0.075 mm - 0.425 mm and the size range of aggregates 10 mm, 14 mm and 20 mm in accordance with Sabita (2019). The commercially available road construction aggregates used for the development of asphalt concrete are mostly rounded and subangular, with smaller percentages of flat and elongated particle.

Petroleum-derived and coal gasified bitumen accounts for nearly half of the cost of materials that are used in the development of asphalt concrete, yet is used in only 5% of road construction (Li *et al.* 2021). The 50/70 penetration grade of bitumen was used. The major properties of 50/70 bitumen according to Shell (Bitumen 2020) and crumb rubber were presented in Tables 1 and 2.

2.2 Test method

A series of tests were conducted to evaluate both the aggregate shape and form, the rheological properties of the

Table 1 Properties of 50/70 Bitumen

Standard Properties	Acceptable Range	ASTM
Penetration @ 25°C	50/70	D5
Softening point	46/64	D36
Ductility @ 25°C	100(min)	D113
Penetration post heating	20% (max)	D5
Relative density @ 25°C	1.01–1.06	D70
Flash point (min)	240 min	D92
Loss on heating (wt)%	0.2 (max)	D6
Solubility in trichloroethylene	99.5(min)	D2042

Table 2 Characteristics of Crumb Rubber

Standard Properties	Range
Density	1300–1330 kg/cm^3
Average thickness	0.075–0.425 mm
Melting point	200–210°C
Tensile strength	40–50 MPa
Young modulus	2600–2900 MPa

Table 3 List of Tests on Crumb Rubber Modified Bitumen and Asphalt Concrete

Standard Properties	Specification
Penetration	ASTM D 5
Ductility	ASTM D 113
Softening point	ASTM D 36
Marshall stability	ASTM D 6927
ITS	ASTM D 6931
Static creep	
Aggregate shape	Image J

bitumen and mechanical properties of the asphalt concrete. The tests are listed in Table 3.

2.3 Sample preparation

The experimental tests were conducted in the Johannesburg Road Agency laboratory. For the determination of the optimum bitumen content, a range of 4.0–6.0% bitumen was used to develop asphalt briquettes. Their bulk density, Marshall stability, and air void values were determined. The briquettes were 120 mm in diameter and 60 mm thick and an average of three samples was used for each parameter. Moreover, the effect of up to 15% crumb rubber on mechanical properties was investigated.

The particle size range of the crumb rubber used for the study is 0.0075 mm – 0.425 mm. Specifically, 0%, 3%, 5%, 7%, 10% and 15% crumb rubber were added as wet mix, in small fractions, to molten bitumen that was heated to 160°C and vigorously stirred for 30 minutes, before the addition of aggregates that were heated to 165°C. The wet, mixed materials were continuously stirred in a fully motorized asphalt mixing machine for 1 hour at a stirring velocity or mixing speed of 500 rpm and then compacted into briquettes with a bulk density range of 2.32–2.44 mg/m^3 (Kumar and Garg 2011). A typical failed briquette after the Marshall stability test is presented in Fig. 1.

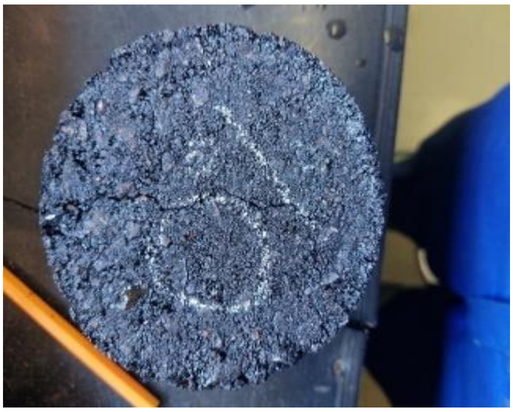

Fig. 1 Failed Briquette After Marshall Stability Test

TSR is a measure of the moisture susceptibility of asphalt concrete. It is the ratio of the ITS of wet sample (conditioned) in water at 60°C for 24 hours and stored at room temperature at 25°C for 2 hours to the ITS of dry sample (unconditioned), i.e., stored at room temperature at 25°C for 2 hours (Brown *et al.* 2001). The lateral deformation of the diametral loaded briquette disc was measured with the aid of two micro-digital gauges pointed to the centers of the briquettes on the left and right surfaces.

The static creep test estimates wheel path deformation. Briquettes with 0% and 7% crumb rubber were prepared in dry conditions, i.e., 25°C without moisture conditioning and subjected to static stress of 100 kPa in one cycle of one-hour loading and one-hour unloading. Both elastic and plastic permanent deformation were measured in the static creep loading apparatus. The axial deformation was measured throughout the creep test by the linear vertical displacement transducers (LVDT) to track the total deformation and the permanent deformation relative to the original height of the briquettes.

2.4 Aggregate shape by image analysis

Particle geometry can be fully expressed in terms of three independent properties: form, angularity or roundness, and surface texture. Form, the first-order property, reflects variations in the proportions of a particle. Angularity, the second-order property, reflects variations at the corners, that is, variations superimposed on the shape. Surface texture is used to describe the surface irregularity on a scale that is too small to affect the overall shape (Masad 2004). The aggregates in the current study were sorted by visual examination into three independent geometric aggregate groups of flat, elongated, and rounded, following the Zingg chart, and placed into three separate bags (Zingg 1935).

They were then randomly checked by the digital veneer caliper (Arasan *et al.* 2011). Most naturally occurring aggregates and residual weathered rock-based backfill aggregates exist as mixtures of different shapes. Thus, two additional groups of aggregates were created by mixing rounded aggregates with small percentages of elongated and flat aggregates according to ASTM D6927 and ASTM 6931. The proportions of the five groups of aggregates are shown in Table 4. In the current study, rounded aggregates

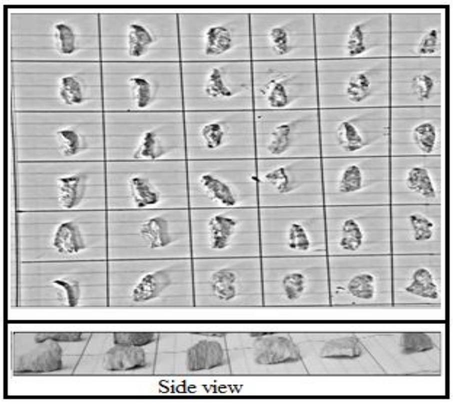

Fig. 2 Plan and Side Views of Processed Aggregates

Table 4 Aggregate Shape Groupings

Sample Number	%Flat Aggregates	%Rounded Aggregates	%Elongated Aggregates	ASTM Method	ASTM Method
1	100	0	0	D6927	D 6931
2	0	0	100	D6927	D 6931
3	0	100	0	D6927	D 6931
4	10	75	15	D6927	D 6931
5	0	75	25	D6927	D 6931

refer to spherical, near-spherical or cuboidal aggregates. Roundness using ImageJ software is defined as the ratio of 4 × (area) to π × (major axis)^2, where area is the area of the two-dimensional projection of the aggregate particle. The roundness varies between 0.1 and 0.9. A value greater than 0.6 indicates high roundness, between 0.4 and 0.6 indicates medium roundness, and less than 0.4, low roundness (Masad 2004, Arasan *et al*. 2011). The angularity ratio describes the variations at the particle boundary, with lower values indicating aggregate particles that are more angular.

A rough subangular aggregate has an angularity ratio close to 1.0. Circularity is a measure of the particle's shape relative to a perfect circle. A perfect circle has a circularity of 1, while an irregular object has a circularity value closer to 0 (Piotrowska *et al*. 2014). Solidity is the ratio of the area of the two-dimensional projection of the aggregate particle to the convex area (Janoo 1998). Solidity has values in the range of 0 to 1. A low solidity towards 0 indicates a rough particle edge. A high solidity of 1 indicates a smooth particle edge. The aggregate images were screened with a 64-megapixel camera from a constant height of 30 cm and the same lateral distance for the side view of seated aggregates in a 6×6 grid tray to ensure equidistance between aggregates. Two slide lamps were used to eliminate shadows. Three images were taken of each group of aggregates and uploaded in ImageJ software. The shape properties analyzed by ImageJ are circularity, angularity ratio, solidity and roundness. A minimum of 144 aggregates from scanned aggregates were used in grids of 6×6 from each sorted bag of aggregates to quantify the aggregate shapes and then to develop the asphalt briquettes to relate the aggregate shape properties to the mechanical properties of asphalt briquettes. A typical grid of unprocessed and processed aggregate is presented in Fig. 2.

Table 5 Effect of Crumb Rubber on Bitumen Rheology

% of Crumb Rubber	Ductility (cm)	Softening point (˚C)	Penetration value (dmm)
0	106	48.5	66.00
3	74	50.25	61.67
5	52.2	51.5	56.00
7	46.67	52.75	53.33
10	43.83	54.5	52.33
15	21.03	58.25	44.67

3. Results and analysis

3.1 Softening point, penetration value and ductility

The effect on some rheological properties of increasing the crumb rubber content incrementally from 0% to 15% is presented in Table 5. The ductility values decreased from 106 cm to 21.03 cm. The softening point increased from 48.5°C to 58.25°C, which is within the 46–64 °C range of the softening point of 50/70, ASTM D36. The penetration values decreased from 66.00 dmm to 44.67 dmm. The typical penetration value of 50/70 bitumen ranges between 50 and 70 dmm (ASTM D5). According to the literature, both the flow and the resistance to temperature susceptibility also increase (Chandh and Akhila 2016). Other authors have reported softening point increases of 13°C and 8°C for 2% and 4% increases in plastic, respectively, as well as increases of 3°C and 14°C for 10% and 22% increases in crumb rubber (Sharma and Singh 2018, Soleimani *et al.* 2020).

3.2 Effect of crumb rubber on marshall stability and flow

Briquettes with a bitumen content of 4%, 4.5%, 5.0%, 5.5%, and 6% were tested to determine the volumetric properties, i.e., bulk specific gravity, air voids, voids filled with binder, stability, and flow. The optimum bitumen content (OBC) was determined from the individual plots of bulk density, air void, voids filled with binder (VFB), stability, and flow versus percentage of binder content. The details are presented in Table 6, and the OBC is 5.5%.

The Marshall stability and flow for different percentages of crumb rubber are presented in Table 7. In the standard aggregates, the average Marshall stability increased non-linearly with the percentage of crumb rubber to a maximum value of 17.72 kN, associated with 10% crumb rubber. The

Table 6 Marshall Stability Properties of Asphalt Concrete

Standard Properties	Values	Sabita (2019) Specification
OBC (%)	5.5	-
Bulk SG	2.32	-
Air Voids (%)	4.82	3-5
VFB (%)	75	70 - 80
Marshall stability	11.22	>8
Flow (mm)	3.48	2-4

Table 7 Marshall Stability for Mixed Aggregates and Different Percentages of Crumb Rubber

Crumb Rubber (%)	**Average Bulk Density**	**Average Marshall Stability**	**Average Flow (mm)**	**Marshall Quotient (kN/mm)**
0	2.32	11.22	3.48	3.22
3	2.38	14.27	4.45	3.20
5	2.42	14.87	4.68	3.18
7	2.42	15.68	4.58	3.42
10	2.44	17.72	4.51	3.93
15	2.33	15.49	5.51	2.81

Table 8 Mean & Standard Deviation of Aggregate Groups

Shape	Sample Number	Circularity	Angularity Ratio	Roundness	Solidity
Flat	1	0.1365 (0.04)	4.319 (1.17)	0.594 (0.12)	0.666 (0.13)
Elongated	2	0.1225 (0.035)	5.48 (1.2)	0.761 (0.18)	0.892 (0.11)
Rounded	3	0.525 (0.12)	2.2765 (0.8)	0.738 (0.09)	0.874 (0.14)
Flat + Rounded+ Elongated	4	0.0595 (0.02)	3.3105 (0.8)	0.714 (0.21)	0.748 (0.16)
Elongated +Rounded	5	0.200 (0.085)	5.3865 (1.3)	0.769 (0.12)	0.879 (0.13)

addition of 10% crumb rubber represents a 50% increase in Marshall stability. The values in Table 7 show erratic but minimum changes in flow for an addition of up to 10% crumb rubber. However, the addition of 15% crumb rubber resulted in a significant increase of up to 1mm in flow, associated with a reduced Marshall stability. The asphalt stability at 10% crumb rubber indicates the highest rutting and deformation resistance.

The Marshall quotient is a measure of asphalt concrete stiffness, and the values presented in Table 7 show that an increase in the percentage of crumbs rubber to 10% resulted in a maximum average Marshall quotient of 3.93 kN/mm, which represents a 45% increase in stiffness. Also, as the percentage of crumb rubber increased, the lateral deformation or bulge decreased, and the addition of 10% crumb rubber resulted in a 40% decrease in lateral deformation. The reduced lateral deformation offers greater resistance to deformation, rutting, shearing stresses, and distortions.

3.3 The forms of the different aggregate groups

The forms of the different aggregate groups are presented in Table 8. Sample 1 shows that flat aggregates have, relatively, a very low circularity, solidity and roundness, with a very high angularity ratio of 4.1005. Sample 2 shows that elongated aggregates have a relatively high angularity, roundness, and solidity. Sample 3 shows that rounded aggregates have very high circularity, roundness, solidity, and angularity ratios. Sample 4 shows that rounded, elongated, and flat aggregate groups have intermediate values of circularity and angularity ratio, roundness, and solidity. Sample 5 shows that a mixture of rounded and elongated aggregate groups has, relatively, a very high roundness and solidity and an intermediate circularity and angularity ratio. Table 8 shows the relationship between circularity and angularity of different aggregate groups and combinations. The addition of elongated and flat aggregates to rounded aggregates resulted in a stepwise decrease in average circularity. The angularity ratio of flat and elongated aggregate groups and Sample 5, with a combination of flat and elongated aggregates, is relatively high, while the angularity of rounded aggregates is relatively very low. The addition of flat and elongated aggregates to rounded aggregate groups increased the average angularity ratio stepwise.

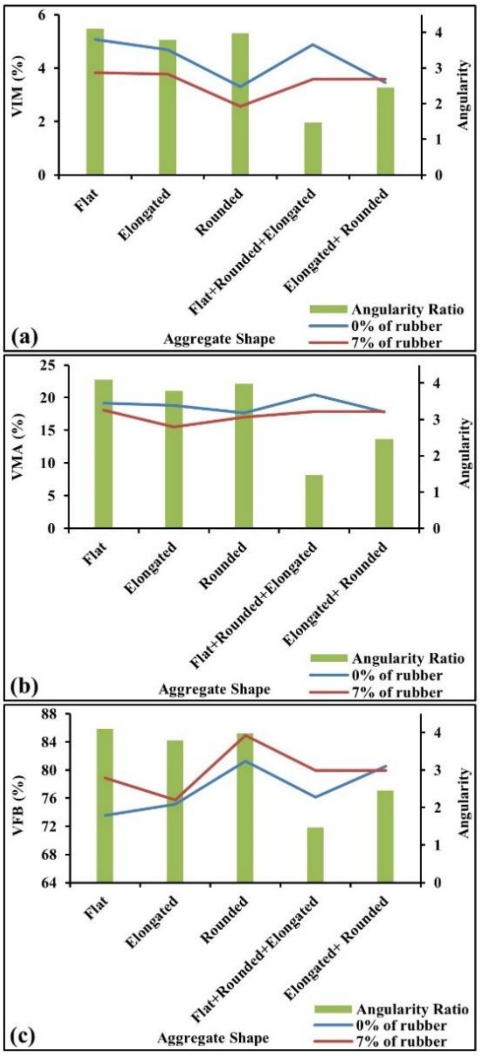

Fig. 3 (a) VIM vs Angularity, (b) VMA vs Angularity and (c) VFB vs Angularity Ratio

3.4 Effects of aggregate shape on voids in total mixture, mineral aggregate and filled bitumen

The effect of aggregate shape on voids in mixture (VIM) is presented in Fig. 3(a). The fraction of air spaces was lower for briquettes constituted with rounded aggregates because of better mechanical interlocking of aggregates in comparison with Sample 1 (flat aggregates) and Sample 2 (elongated aggregates). Sample 4, a combination of all three aggregate shapes, had the largest air voids, and Sample 5, which is a combination of rounded and elongated aggregates, had lower air voids than both flat aggregates and elongated aggregate groups. It was also observed that both the flat and elongated aggregates easily break during manufacture and compaction. The addition of 7% crumb rubber reduced the voids in the mix because of the fine particle and powdery size of the crumb rubber. Sabita M 35/TRH 8 specifies VIM in asphalt concrete mixtures of 3–5%. Only well-rounded aggregates fall slightly below the margin because of reduced aggregate voids. Fig. 3(b) shows the relationship between voids in the mineral aggregate (VMA) and aggregate shape. The VMA decreased for the five aggregate groups with the addition of 7% crumb rubber. However, for flat aggregates, rounded aggregates, and mixture of rounded, elongated and flat aggregates (REF), the reduction in VMA due to the addition of crumb rubber is marginal. However, for flat and elongated aggregate groups, the VMA for 0% of crumb rubber was greater than that of rounded aggregates. The mixture of rounded, elongated and flat aggregate had the highest VMA. It is noted that the rounded aggregates are considerably easier to compact than flat and elongated aggregates with a lower aggregate interlock.

VFB is a measure of the empty spaces between aggregate particles in a compacted asphalt mixture that are filled with bitumen. Fig. 3(c) depicts the relationship between VFB and bitumen content. The VFB of the rounded aggregate briquettes and briquettes of rounded and elongated particles were the highest, and the addition of fine crumb rubber increased the VFB of all the aggregate groups. It is noted that the elongated aggregates and the briquettes of the rounded and elongated aggregates group, which have very high angularity ratios, did not exhibit any increase in VFB when crumb rubber was added.

3.5 Marshall stability

The effect of aggregate angularity and solidity on the Marshall stability of briquettes is presented in Fig. 4. Briquettes with rounded aggregates mobilized the maximum Marshall stability of 12.2 kN, and a combination of rounded, elongated, and flat aggregates resulted in a decreased Marshall stability due to reduced angularity. Flat briquette aggregates mobilized the lowest Marshall stability due to their low solidity. The addition of 7% crumb rubber resulted in an almost 50% increase in Marshall stability for the five groups of aggregates. It is noted that the Marshall stability of Sample 5, which is the combination of rounded, flat and elongated aggregates most commonly encountered in situ, was only marginally less than the Marshall stability of rounded aggregate groups as in Sample 3. It is noted that rounded and cubical aggregates can maintain Marshall strength because of better interlocking, and that most flat and elongated aggregates promote bond rupture and prevent proper compaction, thus allowing the easy deterioration of pavements (Little *et al*. 2018, Kumbargeri *et al*. 2020).

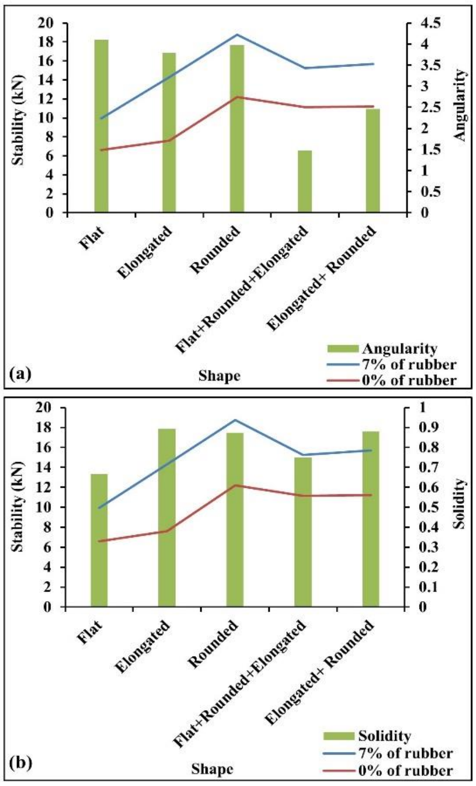

Fig. 4 Marshall Stability Versus (a) Angularity and (b) Solidity of Different Aggregate Groups

3.6 Flow

As shown in Fig. 5, the flow of 0% crumb rubber briquettes made from flat and elongated aggregate groups, i.e., samples 1 and 2, is less than that of the rounded aggregate group. Also, the addition of flat and elongated aggregates to rounded aggregates, i.e., samples 4 and 5, resulted in a further increase in the Marshall flow. Thus, the combined aggregate groups, mixture of rounded, elongated and flat, and RE, with their low angularity, mobilized the maximum flow for unmodified briquettes. The addition of 7% crumb rubber resulted in an increase in the flow of flat and elongated aggregate groups and a reduction in the flow of the mixture of rounded, elongated and flat aggregate (REF) and RE (Elongated + Rounded) aggregate groups. Thus, the interlocking of combined aggregate groups enhanced the briquette stiffness in CRM briquettes and the associated reduction in flow was caused by reduced angularity. Changes in the angularity ratio are moderately linearly aligned to changes in Marshall flow of 7% CRM briquettes with $R = 0.69$ and $R^2 = 0.48$, while the changes in solidity are moderately non-linearly aligned to the flow of 0%, i.e., unmodified asphalt concrete with $R = 0.735$ and R^2 of 0.54. The crumb rubber operates as a binder extender, stiffening the mastic and the mix and therefore enhancing stability. It acts as a void-filling substance, allowing for the adjustment of aggregate gradations and volumetric mix qualities typically associated with fine inert minerals.

As shown in Fig. 6(a), the bulging or lateral displacement of briquettes made from flat and elongated aggregate groups is greater than that of rounded aggregate groups, and the addition of flat and elongated aggregates to

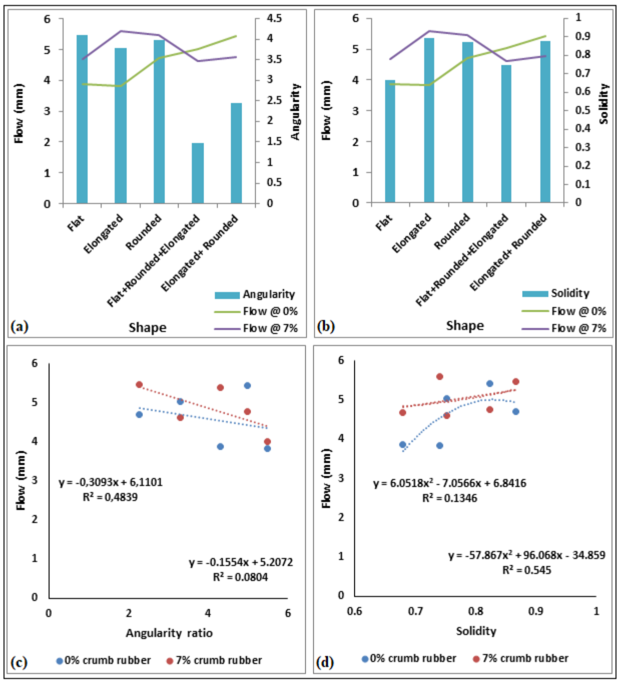

Fig. 5 Marshall Flow versus (a) Angularity Ratio (b) Solidity of Different Aggregate Groups (c) Angularity Ratio (d) Solidity of Different Aggregate Groups

rounded aggregates, as in samples 4 and 5, resulted in a slight increase in lateral displacement, resulting in combined aggregate groups 4 and 5, with their low angularity, exhibiting the minimum lateral displacement for unmodified briquettes. The addition of 7% crumb rubber resulted in an almost 50% reduction in lateral displacement of all aggregate groups. Figs. 4(a) and 4(b) show that rounded aggregates had the least lateral displacement because of their high angularity and solidity. Fig. 5(b) shows that changes in solidity are aligned to changes in a Marshall flow of 0% and 7% CRM briquettes. The crumb rubber operates as a binder extender, stiffening the mastic and the mix and therefore enhancing stability. It acts as a void-filling substance, allowing for the adjustment of aggregate gradations and volumetric mix qualities typically associated with fine inert minerals.

3.7 Indirect tensile strength for different aggregate shapes

The ITS and lateral bulging for different aggregate shapes and 0% and 7% crumb rubber briquettes is shown in Fig. 7. At 0% crumb rubber, the ITS of samples 3 and 5, which consisted of rounded aggregates and a combination of rounded and elongated aggregates, mobilized an ITS of 673 kPa and 613 kPa. The addition of 7% crumb rubber resulted in ITS increases of respectively 32%, 35%, 1%, 53%, and 8% to the five aggregate groups. Thus, the addition of 7% crumb rubber was most beneficial to three aggregate groups, namely the flat aggregates, elongated aggregates, and the REF aggregate groups. In comparison with the Marshall stability, the inclusion of crumb rubber resulted in a greater percentage increase in mobilized tensile resistance. It is also noted that the rounded aggregates in

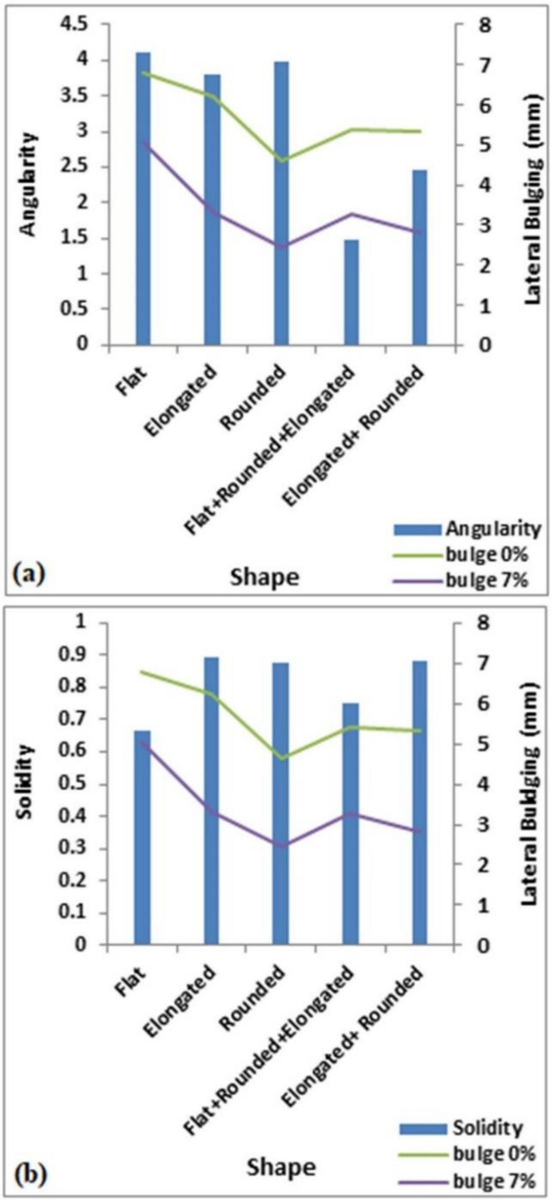

Fig. 6 Marshall Quotient and Lateral Bulging for Different Aggregate Shapes

Sample 3 exhibited the minimum lateral deformation on both the left and right sides of the briquettes of 0.285 mm and 0.33 mm and 0.4 mm and 0.425 mm for 0% and 7% crumb rubber respectively, and also reflected the highest rutting resistance and improved ductility. It is noted that the REF and RE aggregate groups also exhibited low lateral deformation and improved ductility with the addition of crumb rubber.

Sample 3 aggregates have a low angularity ratio and high solidity that support effective particle interlocking. Samples with a combination of aggregate shapes, namely REF and RE, also mobilize low lateral deformation due to low angularity and moderate solidity. The small percentage of elongated particles in REF and RE aggregate groups reduced the interlocking due to their extremely sharp edges. Flat aggregates easily break during compaction and have the lowest interlocking ability, and elongated aggregates

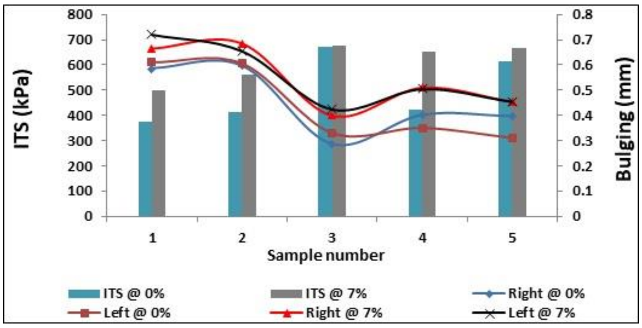

Fig. 7 ITS and Lateral Bulging for Different Aggregate Shapes and 0% and 7% Crumb Rubber Briquettes. Sample 1: Flat; Sample 2: Elongated; Sample 3: Rounded; Sample 4: Flat + Elongated + Rounded; Sample 5: Elongated + Rounded

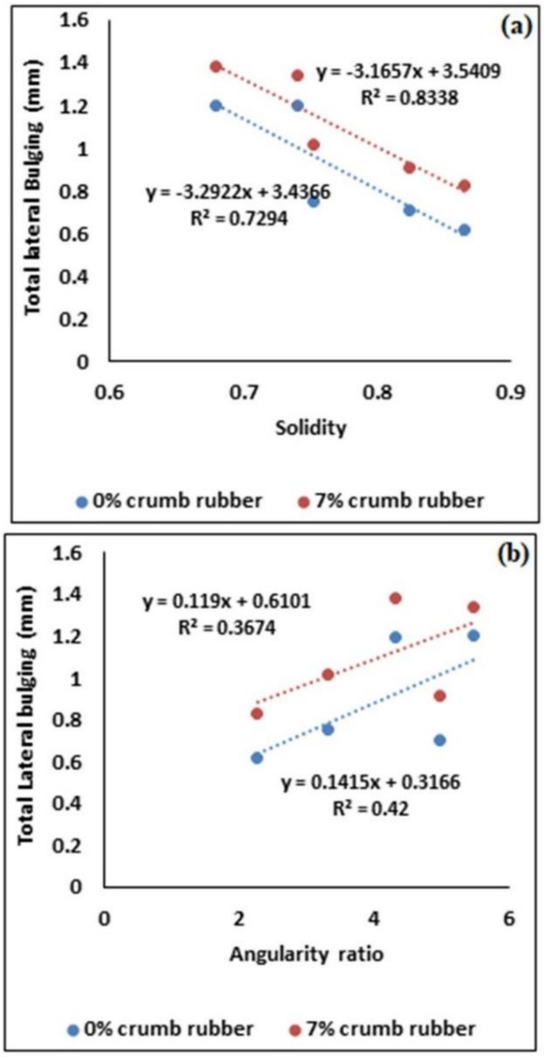

Fig. 8 Total Lateral Bulging of 0% and 7% Crumb Rubber Briquettes Related to (a) Solidity (b) Angularity Ratio

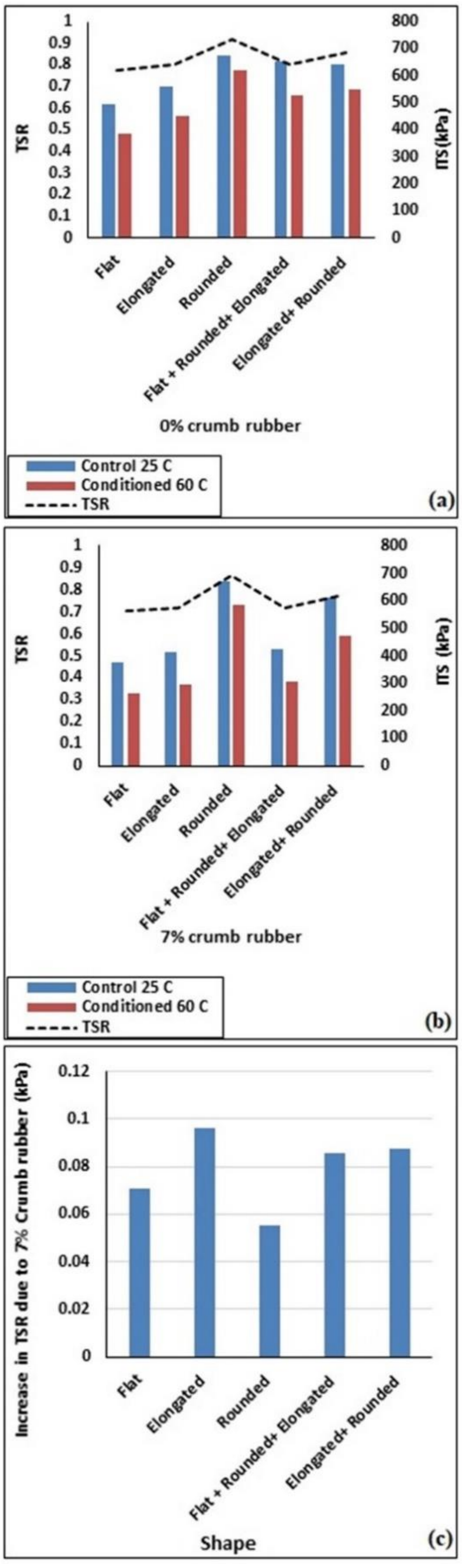

Fig. 9 The ITS and TSR of Normal and Conditioned Samples of (a) 0% and (b) 7% Samples; (c) Effect of 7% Crumb Rubber on TSR

have sharp corners with reduced circularity and solidity, and hence a reduced interlocking potential. Figs. 8(a) and 8(b) depicts the total lateral bulging of 0% and 7% crumb rubber briquettes in relation to two aggregate forms, namely solidity and angularity ratio. The total lateral bulging is strongly correlated with solidity with an R^2 of 0.73–0.83 and R = 0.83–0.91, and weakly correlated with the angularity ratio of 0.42 and 0.36 and R = 0.66–0.6. Table 8 shows that the average angularity ratio of the five aggregate groups is 3.5, i.e., medium angularity, while the average solidity ratio is 0.76, which is high solidity.

3.8 Moisture susceptibility of tensile strength

Fig. 9(a) shows the relationship between the TSR of normal and conditioned briquettes and ITS. The briquettes with rounded aggregates, namely samples 3 and 5, mobilized the greatest TSR, while those with flat aggregate groups mobilized the lowest TSR. The TSR range of 0.80 to 0.92 for all aggregate shapes and 0% crumb rubber was greater than the TSR of 0.70 to 0.86 for 0% crumb rubber briquettes. The effect of 7% crumb rubber on the TSR is presented in Fig. 9. The inclusion of crumb rubber was relatively most beneficial to the aggregate groups with flat and elongated shapes and least beneficial to the rounded aggregate groups. However, according to the ASTM D 4867/D 4867-M04 standard, the minimum permissible TSR should be 80% in order to have an asphalt mixture that sufficiently resists moisture and water-related damage, otherwise known as stripping. South African specification Sabita (2019) has recommended a minimum TSR of 0.70 for medium to wet climatic conditions, which was met by the CRM briquettes developed with three aggregate groups namely 100% rounded aggregates, 75% rounded and 25% elongated, as well as 75% rounded, 15% elongated and 10% flat aggregates (Li *et al.* 2021).

3.9 Effect of crumb rubber and aggregate shape on creep behavior

Figs. 10(a) and 10(b) shows total strain, which was calculated as the ratio of measured deformation to the original briquette height. For briquettes with 0% plastic waste, maximum and minimum deformations were exhibited by elongated and rounded aggregates respectively, although the elastic response of all the aggregate groups overlapped. The inclusion of 7% plastic resulted in a reduction in total and permanent deformations. The permeant strain is presented in Fig. 10, which reveals that the elongated and rounded aggregates also exhibited the maximum and minimum permanent deformation together with the minimum and maximum effect of 7% crumb rubber. The effects of 7% crumb rubber on the permanent strain and rebound strain of different aggregate groups are presented in Figs. 11(a) and 11(b).

The rebound strain of briquettes with 0% crumb rubber is not sensitive to aggregate shape, but the inclusion of 7% crumb rubber induced different viscosities that were beneficial to aggregate groups that contained rounded particles. Thus, crumb rubber inclusion can manage the failure of asphalt concrete composed of naturally occurring aggregates composed of particles of various shapes. It is attributed to the viscosity of the bitumen as increased resistance to rutting is offered by a stiffer or high viscosity or a low penetration binder (Roberts *et al.* 1996).

3.10 Preliminary Estimate of Permanent Deformation and Rutting Depth

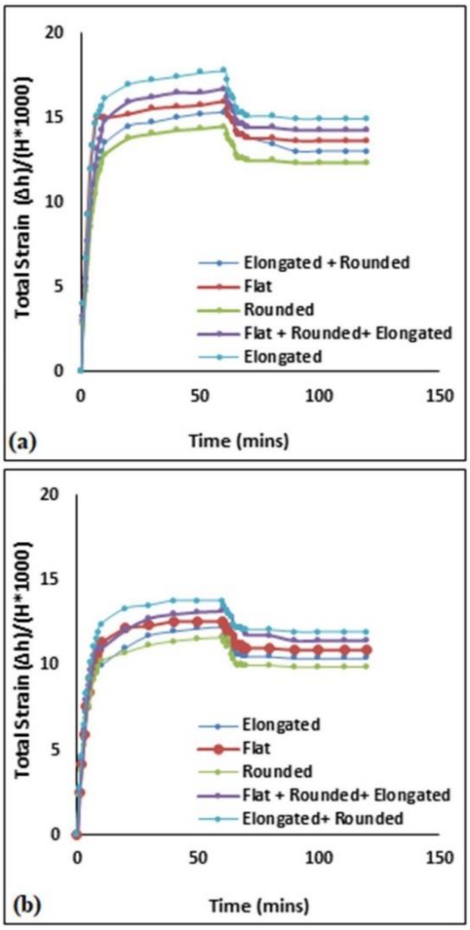

Fig. 10 Total Strain with Plastic Asphalt Concrete Briquettes with Different Aggregate Groups. (a) 0% Plastic Asphalt Concrete Briquettes and (b) 7% Plastic Asphalt Concrete Briquettes

Sabita (2019) reported on preliminary tests commissioned by the Johannesburg Road Agency to investigate the rutting resistance of a set of road construction asphalt briquettes, using the model mobile road simulator (DPI MMLS3). The DPI MMLS3 applies 7200 load repetitions per hour, with a tire pressure of 700 kPa and a 2.7 kN wheel load.

The major properties of the 30 briquettes that were developed with 50/70 grade bitumen and rounded and rough-textured aggregates in three sizes, namely 6,9 mm, 9.5 mm and 13.3 mm, are as follows: Density range 2446 kg/m^3–2466 kg/m^3; binder content = 5.3%; void content range 4.9–5.4; temperature range 30–34°C. The rut depth range for 100000 axle loads was 1.05–2.28 mm, with a mean of 1.66 mm. The extrapolated rutting depth for 1000000 axle loads is 2.2 mm.

The major property range of 7% CRM briquettes with the combination of rounded, elongated and flat aggregates was as follows: Average bulk density 2.42–2.44 kg/m^3; average flow 4.51–4.58; VIM = 3.7–3.9; aggregate size = 6.7 – 10.3 – 15.5 mm. Based on the close similarity in basic properties, it is anticipated that the rutting depth for 1000000 axle loads will be within the range of 2.2 mm. Moreover, since the rutting depth of unmodified asphalt concrete with a VIM of 3.5–4.9 is close to 2.2 mm, it is

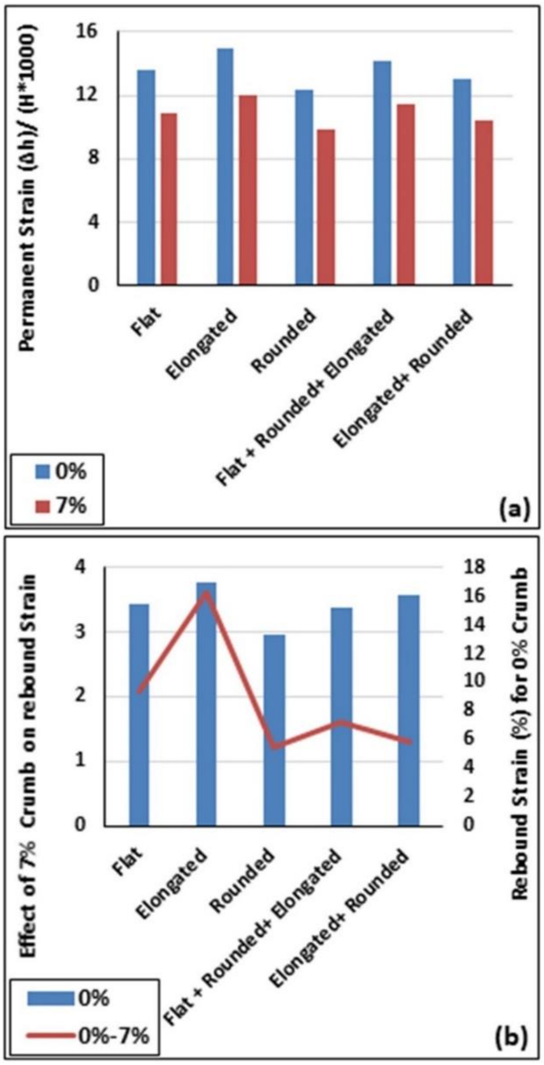

Fig. 11 Effect of 7% Crumb Rubber on Permanent Strain and Rebound Strain of Different Aggregate Groups

anticipated that the 7% crumb rubber briquettes with a VIM of 3.7–3.9 would exhibit a reduced rut depth of less than 2.2mm.

The performance-based design of 100% recycled hot-mix asphalt and validation using the traffic load simulator was detailed in a study by Zaumanis *et al*. (2019). An AC8-type mixture was designed by balancing performance in rutting using a French rutting tester and cracking using a semi-circular bend test. Five iterations of different grading and binder content combinations of a 100% reclaimed asphalt pavement (RAP) mixture were tested before achieving the same performance as with a traditional AC8 mixture. This optimum mixture design was then validated by producing asphalt slabs for testing using a model mobile load simulator (MMLS3). The digital image correlation results of the wheel loading demonstrated that performance-optimized 100% recycled asphalt can sustain 2.5 times more load applications compared to the traditional mixture before cracking. The cross-section of a flexible pavement structure consisting of a 0.04 m stone mastic asphalt layer (SMA), 0.08 m polymer-modified, high-modulus binder layer and 0.12 m conventional asphalt base layer. According to the previous experience, this optimum binder content derived from the performance-based triaxial cyclic compression test (TCCT) is about 0.3–0.1 m% lower than the binder content found by the traditional Marshall mix design method. The importance of performance-based criteria for the development of non-empirical pavement design specification with greater emphasis on local conditions has also been discussed (Denneman 2007, Prowell 2007).

4. Conclusions

The specific aim of the study was to evaluate the impact of crumb rubber and aggregates of different shapes i.e., rounded, elongated and flat aggregates on the rheological, strength and moisture resistance of 50/70 bitumen asphalt concrete. It is noted that most conventional roads are constructed with rounded aggregates, thus a major focus was the behavior of briquettes constituted of significant percentage of elongated and flat aggregates in combination with rounded aggregates.

Briquettes developed with 7% crumb rubber, and three aggregate groups, i.e., 100% rounded aggregates, 75% rounded and 25% elongated, and 75% rounded, 15% elongated and 10% flat aggregates, met the South African requirements for Sabita 2019 for the asphalt mix design for the surface and base asphalt layer of low traffic volume roads with E80 of < 300000 axle loads for an aggregate range of 10 mm, 14 mm and 20 mm.

The main characteristics of the aggregate groups discussed here are low VIM, high VFB, stability, low bulging, and ITS. The ITS of samples is due to their moderate aggregate angularity ratio and high solidity.

The addition of 7% crumb rubber resulted in an increase in the flow of the flat and elongated aggregate groups and a reduction in the flow of the REF and RE aggregate groups.

The addition of 7% crumb rubber resulted in ITS increases of 32%, 35%, 1%, 53%, and 8% respectively in the five aggregate groups. Thus, the addition of 7% crumb rubber was most beneficial to briquettes developed with the three aggregate groups.

It is also noted that the briquettes developed with the rounded aggregates exhibited the minimum lateral deformation on their respective left and right sides of 0.285 mm and 0.33 mm and 0.4 and 0.425 mm for 0% and 7% crumb rubber, which is a good indicator of rutting resistance and improved ductility. Briquettes developed with 75% rounded and 25% elongated as well as those with 75% rounded, 15% elongated and 10% flat aggregates also exhibited relatively low lateral deformation.

Furthermore, the addition of 7% crumb rubber was most beneficial to the durability of briquettes consisting of 75% rounded and 25% elongated aggregates and briquettes with 75% rounded, 15% elongated and 10% flat aggregates in relation to TSR and rebound strain. For South African conditions, Sabita 2019 has recommended a minimum TSR of 0.70 for medium to wet climatic conditions, which was met by CRM briquettes developed from three aggregate groups, namely 100% rounded aggregates, 75% rounded and 25% elongated, and 75% rounded, 15% elongated and 10% flat aggregates.

The rebound strain of briquettes with 0% crumb rubber is not very sensitive to aggregate shape, but the inclusion of 7% crumb rubber resulted in a rebound strain in the briquettes consisting of the three aggregate groups.

Acknowledgments

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