LABORATORY INVESTIGATION OF THE PERFORMANCE PROPERTIES OF HOT MIX ASPHALT CONTAINING WASTE GLASS

JK ANOCHIE-BOATENG[1], TB GEORGE[2]

[1]CSIR Built Environment, P O Box 395, Pretoria, 0001./ Department of Civil Engineering, Tshwane University of Technology, Pretoria, 0001, South Africa
Tel: +27 12 841-2947, Email: JAnochieBoateng@csir.co.za
[2]CSIR Built Environment, P O Box 395, Pretoria, 0001 South Africa
Tel: +27 12 841-2924, Email: TGeorge@csir.co.za

ABSTRACT

CSIR is currently undertaking a study on the potential utilization of crushed glass as a substitute material to natural aggregate in asphalt mixes. As part of the study, a laboratory investigation is needed to determine the performance characteristics of hot-mix-asphalt produced with the crushed glass material. In this paper, the glass asphalt mix is evaluated for its stiffness characteristics, rutting potential and fatigue performance and compared with a dense- graded asphalt surfacing mix. The results indicate that the asphalt mix with crushed glass could outperform the conventional dense-graded mix in terms of rutting. The fatigue performance was comparable although the conventional mix performed marginally better than the glass asphalt mix. This fatigue behaviour is attributed to the fact that the glass asphalt mix was stiffer than the conventional mix at typical field conditions, i.e. temperature of 20°C and a loading frequency of 10Hz. It can be concluded that waste glass materials can be reclaimed and re-processed into asphalt mixes that are cost-effective and at the same time exhibit good performance.

1 INTRODUCTION

South Africa is currently in the process of adopting a new asphalt mix design manual that will use dynamic modulus, permanent deformation and fatigue properties to characterise the performance of asphalt mixes. The design philosophy in this manual is to move from a more empirical-based mix design approach towards the implementation of a performance-related approach to set specifications for asphalt mixes, thus allowing for a direct linkage between asphalt mix design and structural design of the pavement. In addition, the manual uses a design methodology that is applicable to both conventional hot-mix-asphalt (HMA) and unconventional mixes such as warm mix asphalt, Enrobé à Module Élevé (EME) asphalt, cold mix asphalt, mixes with reclaimed asphalt and waste materials. An important aspect of the new manual is the introduction of performance related asphalt mix design procedures to select the optimum mix (Anochie-Boateng et al. 2015).

South Africa faces a potential shortage of virgin aggregates used to produce asphalt mixes. Future availability and sustainability of these virgin aggregates is, therefore, a major concern. Substituting the use of virgin aggregates with alternative materials can contribute significantly towards minimizing the utilisation of non-renewable aggregate resources as well as reducing large amounts of energy and generation of greenhouse gas (GHG) emissions associated with pavement applications.

Currently, there is a steady supply of waste glass being generated from a major glass manufacturing company in Gauteng. A significant amount (approximately 3 000 tons per month) of processed fine glass in (i.e. < 5 mm size) that cannot be used as re-cycled material during glass production accumulates as stockpiles at the company's processing plant. According to the glass manufacturer, approximately $100,000 per month is accounted for the disposal and transportation of the waste glass to landfill sites. An alternative application can be proposed whereby the waste glass can be used as an "aggregate" substitute in pavement applications which will provide a more cost effective and environmentally friendly solution to disposal.

To date, there have been few investigations on the application of waste glass in the field of pavement. Glass was initially implemented in asphalt pavements in the early 1960's and 1970's in the United States and Canada [RMRC, Madison, WI, USA]. Recent studies have demonstrated that optimum performance can best be achieved when 10 to 15 percent crushed glass is used as a fine aggregate substitute in asphalt mixes for road pavements (Flynn, 1993). The major concern is the lack of absorption of bitumen by glass and the hydrophilic properties of glass that contribute to the moisture damage (i.e. stripping and ravelling) of glass-asphalt pavements. Hughes (1990) revealed that the addition of hydrated lime (~ 1% to 3% by mass of aggregate) acts as an antistripping agent and reduces the potential stripping problems.

An economic impact analysis conducted on waste glass and virgin aggregates (George and Anochie-Boateng, 2016) demonstrated both sustainable and economic benefits as long as the transportation distance is within the same range as the virgin aggregates. An initial study conducted by Anochie-Boateng and George (2016) focused on developing a mix design for glass asphalt. The mix design results indicated that the optimum binder content of the medium continuously graded asphalt mix with crushed glass is 5.1% compared with 5.0% for a standard medium continuously grade asphalt mix that was used as a reference mix in this paper.

The objective of this paper is to present and discuss the performance (stiffness, permanent deformation and fatigue characteristics) evaluation of a glass asphalt mix for road construction. The results are analysed and compared to the South African national Roads Agency Limited (SANRAL) medium continuously graded asphalt (dense graded wearing course) mix with 50/70 penetration grade binder. In order to carry out a comparative study on the two mixes, the 50/70 binder used in the reference asphalt mix was used to prepare the glass asphalt mix. The aggregate grading of the glass asphalt mix was made the same as the reference mix.

2 MATERIALS AND PROPERTIES

2.1 Bituminous binder

The 50-70 penetration grade binder was sourced from a petroleum refinery in South Africa and was supplied by an asphalt manufacturing plant. Table 1 presents the summary of the binder properties as tested by the petroleum refinery company. All criteria were met by the selected binder for an asphalt mix design.

Table 1: Properties of the 50-70 Penetration Grade Bitumen

Property	Units	Results	Limits	Test Method
Penetration @ 25°C/100g/5sec	0.1 mm	66	50-70	ASTM D5
Softening Point (Ring &Ball)	°C	50	46-56	ASTM D36
Viscosity @ 60°C	Pa.s	261	120 min	ASTM D4402
Viscosity @ 135°C	mPa.s	469	220-500	ASTM D4402
Flash Point (Open Cup) @101.3 kPa	°C	340	230 min	ASTM D92
Spot Test	% Xylene	25	30 max	AASHTO T102

2.2 Aggregates and Design Grading

Aggregates materials for the glass asphalt mix were sourced from the same sources (local stone quarries) as the reference asphalt mix and the crushed glass was sourced from a major glass manufacturing company in South Africa. Hydrated lime was used as filler for the mix design. Standard aggregate property tests were conducted on the individual aggregates and the crushed glass in accordance with the South African National Standard (SANS) test methods described in SANS 3001, and the American Standards for Testing and Materials (ASTM).

The grading analysis conducted on the individual aggregate fractions formed the basis for selecting the substitute material in the reference mix for the crushed glass. The goal was to use the same aggregate type from the same sources as the reference mix. This was achieved by an optimization process using the least square analysis method in Microsoft Excel™.

Table 2 indicates the percentage blends of each aggregate type and the filler required to achieve the design grading for the reference and crushed glass mixes and Table 3 indicates their design grading. The intension was to make grading for the crushed glass mix similar to the reference mix in terms of particle size distribution. Note that during the optimization, the granite crusher sand was partially substituted by 15% of the crushed glass. It is known that 1 to 3 per cent of hydrated lime could act as an antistripping agent to reduce potential stripping problems in asphalt mixes with glass. Accordingly, to achieve the desired bonding effect between the crushed glass and the binder, 3% hydrated lime was chosen to replace 1% of the plant lime in the reference mix. Figure 1 shows photographs of crushed glass and granite crusher sand samples used in the two mixes.

(a) Crushed Glass

(b) Granite crusher sand

Figure 1: Photograph of crushed glass and crushed sand samples

Table 2: Aggregate Properties and Proportions for the Mixes

Nominal size (mm)	Aggregate Type	Bulk Relative Density	App. Relative Density	Absorp tion	Fine Aggregate Angularity	Aggregate Proportions	
						Reference Mix	Glass Asphalt Mix
9.5	Andesite	2.884	2.919	0.4	N/A	21%	31%
6.7	Andesite	2.887	2.928	0.5	N/A	24%	16%
Crusher dust	Andesite	2.816	2.956	1.7	39.7	25%	18%
Crusher Sand	Granite	2.628	2.676	0.7	38.3	26%	10%
Mine Sand	Mine Sand	2.600	2.634	0.5	48.3	3%	7%
Crushed Glass	Glass	2.489	2.519	0.5	51.3	--	15%
Mineral Filler	Hydrated Lime	2.861	--	N/A	N/A	1%	3%

Table 3: Design Aggregates for the Mixes

Sieve Size (mm)	Equivalent SANS 3001-AG1 sieve sizes (mm)	Design Grading (% Passing)		Grading Specification	
		Reference Mix	Glass Asphalt Mix	Min (%)	Max (%)
19	20	100	100	100	100
13.2	14	100	100	100	100
9.5	10	97	97	82	100
6.7	7.1	75	75	66	87
4.75	5	59	59	54	75
2.36	2	42	42	35	50
1.18	1	30	29	27	42
0.6	0.6	21	21	18	32
0.3	0.3	14	15	11	23
0.15	0.15	9	9	7	16
0.075	0.075	5.8	6.0	4	10

3 SAMPLE PREPARATION

The mix designs of the glass asphalt and the reference mix were followed by preparation of asphalt samples for testing. Mixing and compaction of specimens was done in accordance with the CSIR test protocol development for SANRAL (Anochie-Boateng et al., 2010). The binder was added to the blended aggregates and then poured into a heated mixer and the filler was added to the mixture. The mixture was mixed for 10 minutes and then discharged back into the pans, placed back into the oven set at compaction temperature for four hours to induce short-term ageing described by Von Quintus et al (1991). The aim was to simulate the ageing that takes place during the production process in an asphalt plant and transported to site.

The loose asphalt mixes were compacted to slabs and gyratory specimens to a density of between 93 and 95 percent of maximum theoretical relative density (MTRD). The slabs were compacted to obtain beam specimens, whereas the gyratory samples were compacted to obtain cylindrical specimens. The slabs were compacted to 60 mm height, whereas gyratory samples were compacted to 170mm height. The gyratory test specimens were compacted to the dimensions of 150 mm diameter by 170 mm high following the AASHTO PP 60 procedures. The specimens were cored and cut to a final nominal dimension of 100 mm diameter by 150 mm high to achieve the recommended voids of approximately 7% (typical field voids for continuously graded mixes at the time of construction). The beam specimens are of dimensions 400 mm long by 65 mm wide by 50 mm high cut from slabs. Before compaction, the various moulds were placed in the oven at the compaction temperature. At the end of the ageing period, the gyratory specimens were compacted to the target voids content of 7% and the slabs were compacted to design voids of 4.9%. The gyratory compacted specimens were used for the rutting and dynamic modulus testing, and the compacted slabs were cut into beams for fatigue testing. All the samples were compacted to the voids necessary to obtain the target design voids for testing. A trial and error method is usually used to obtain the target voids content of all specimens.

4 PEFORMANCE TESTING OF THE MIX

4.1 Evaluation of stiffness

Dynamic modulus property is used to evaluate the stiffness properties of hot mix asphalt mixes for pavement design. The dynamic modulus testing was conducted in a Universal Testing Machine (UTM-25) device at the CSIR Built Environment Unit pavement materials laboratory. During testing, a haversine load pulse with no rest period was applied to the prepared gyratory compacted samples at five test temperatures of -5, 5, 20, 40, and 55°C, and six loading frequencies of 25, 10, 5, 1, 0.5, and 0.1Hz. That is, a total of 30 tests were conducted on each mix to complete a full factorial dynamic modulus test matrix.

Three duplicate specimens were tested for each mix in accordance with the CSIR protocol (Anochie-Boateng et al. 2010). The specimen’s vertical deformation was determined by averaging the readings of three axial linear variable displacement transducers. The axial stresses and the corresponding axial strains recorded for the last 10 load cycles for each test are normally used to compute the dynamic modulus of the sample. The dynamic modulus is an absolute value, and is computed as the ratio of the compressive axial stress to the corresponding axial resilient strain.

4.2 Evaluation of permanent deformation

The resistance to permanent (plastic) deformation (rutting indicator) of asphalt mixes in the field can be evaluated in the laboratory by using a repeated load test. Rutting is depressions in the wheel paths as a result of traffic loads. In this study, permanent deformation of the mixes was evaluated using the flow number test. The flow number is a property related to the resistance of the asphalt mix to permanent deformation.

The asphalt mixture performance tester (AMPT) test procedure stipulated in AASHTO TP79 was used to determine and compare the flow number of the mixes for the glass asphalt mix and the reference mix. Three duplicate specimens per mix were tested at the temperature of 50°C, two deviatoric stress levels of 483 kPa and 276 kPa and one confining pressure of 69 kPa using a repeated compressive haversine loading (1 cycle with 0.1 s loading time and 0.9 s resting time). During testing, cumulative permanent axial deformations were measured and used to calculate the flow number. The flow number is the number of repetitions corresponding to the minimum rate of change of permanent deformation under the repeated loading conditions.

It should be mentioned that investigations by the CSIR are currently underway to determine whether or not modifications such as sample confinement, reduced deviatoric stress levels can be made to overcome any identified deficiency in the AMPT permanent deformation test. The current investigation is focused on determining the effect of three deviatoric stresses, i.e. 138, 276 kPa, and 483 kPa, and confining pressure of 69 kPa on flow number, permanent strain at flow, and rate of permanent deformation. The aim is to standardise the test for future use in South Africa.

4.3 Evaluation of fatigue performance

Fatigue is a phenomenon in which a road pavement is subjected to repeated stress levels until ultimate failure. Load associated fatigue cracking is one of the major distress types occurring in asphalt pavements due to the action of repeated loading caused by traffic induced tensile and shear stresses in the pavement. Fatigue cracks are initiated at points where critical tensile strains and stresses occur.

The four-point beam fatigue test procedure is recommended in South Africa to evaluate fatigue cracking in the laboratory. The test is conducted in accordance with AASHTO T321 with modifications by CSIR based on South Africa pavement conditions (Anochie-Boateng et al, 2015).

In this study, the fatigue tests were conducted on beam specimens under controlled-strain loading conditions at three strain amplitude levels of 200, 400 and 600 macrostrains at a frequency of 10 Hz and a temperature of 20°C to compare fatigue life of the two mixes. The test was run to 50% reduction in stiffness, which is defined as the failure criteria. Three duplicate specimens were tested under a continuous sinusoidal load at the design voids and design binder content for the glass asphalt mix and the reference mix. The fatigue life of the mix, i.e. number of repetitions to failure, was defined as the load cycle at which the specimen reaches 50% reduction in flexural stiffness relative to the initial stiffness i.e. the stiffness at the first 50 repetitions.

5 DISCUSSION OF TEST RESULTS

5.1 Dynamic Modulus Test Results

The dynamic modulus is a performance-related property, which is currently the accepted property used for the evaluation and for characterizing the stiffness of asphalt for pavement design. Stiffness relates to the structural performance of the asphalt mix in the pavement, i.e. the stiffness of an asphalt mix determines its ability to carry and spread traffic loads to underlying layers. Relatively stiff asphalt is generally required for asphalt bases. A stiffer mixes are normally preferred in hotter regions compared with less stiffer mixes in relatively colder regions.

Table 4 presents the dynamic modulus results for the two mixes, and indicates the variation of the dynamic modulus values at varying frequencies and temperatures, Figure 3 compares the results of the two mixes at 10 Hz and 20°C. It is believed that these two conditions better simulate field pavement conditions. At these conditions, the dynamic modulus of the glass-asphalt mix increase by 25% from the reference mix.

As previously mentioned, the glass-asphalt mix contains 3% hydrated lime which acts as an anti-stripping agent. The anti-stripping characteristics of hydrated lime result in stronger cohesion between the aggregates and glass particles with the bitumen. Furthermore, the higher angularity of the glass particles, in comparison with the conventional aggregates, plays an important role in the increased dynamic modulus behaviour of the glass-asphalt mix. It is suspected that the higher internal friction, which is due to the increased angularity of the glass particles, in turn increases the interlock between the particles which contributes to the increased dynamic modulus of the glass-asphalt mix. It can be further observed that at temperatures of 20°C and 40°C the stiffness of the glass-asphalt was marginally higher than the reference mix, whereas the stiffness was comparable at temperatures of -5°C and 55°C.

Table 4: Dynamic modulus results for the two asphalt mixes

Temp (°C)	Frequency (Hz)					
	0.1	0.5	1	5	10	25
Glass Asphalt Mix (MPa)						
-5	16 171	18 751	19 774	22 070	22,977	24 085
5	9 745	13 101	14,384	17 376	18,651	20 387
20	3 103	5 540	6 633	9 517	10 733	12 356
40	453	737	913	1 441	1 895	2 686
55	203	279	343	680	983	1 201
Reference Mix (MPa)						
-5	15 238	18 214	19 472	22 270	23 492	25 159
5	9 357	12 108	13 301	16 174	17 336	18 966
20	2 809	4 414	5 385	7 836	9 014	10 638
40	432	650	782	1 540	2 009	2 803
55	265	350	363	790	1 108	1 577

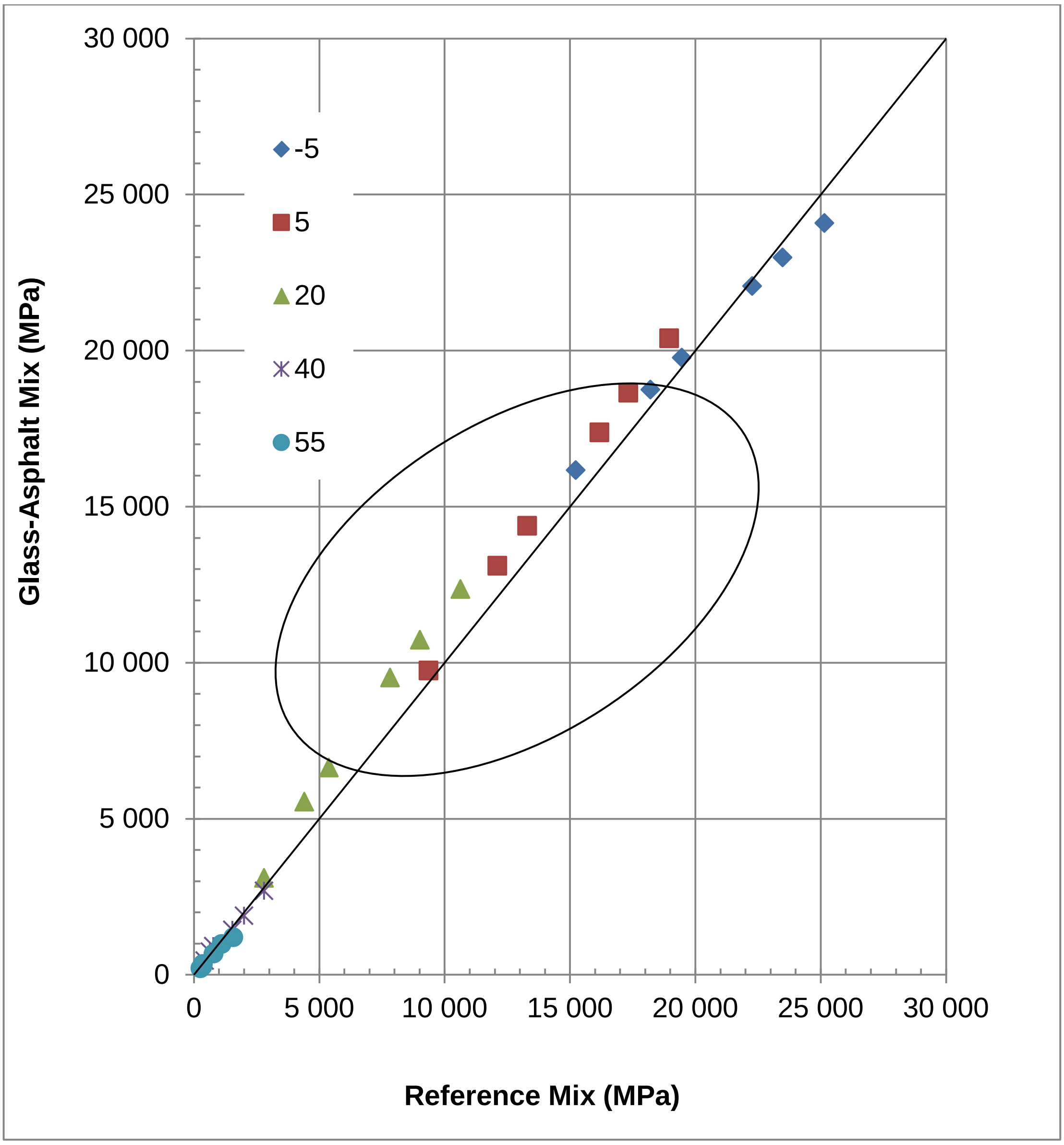

Figure 2: Stiffness comparisons the glass and reference mixes

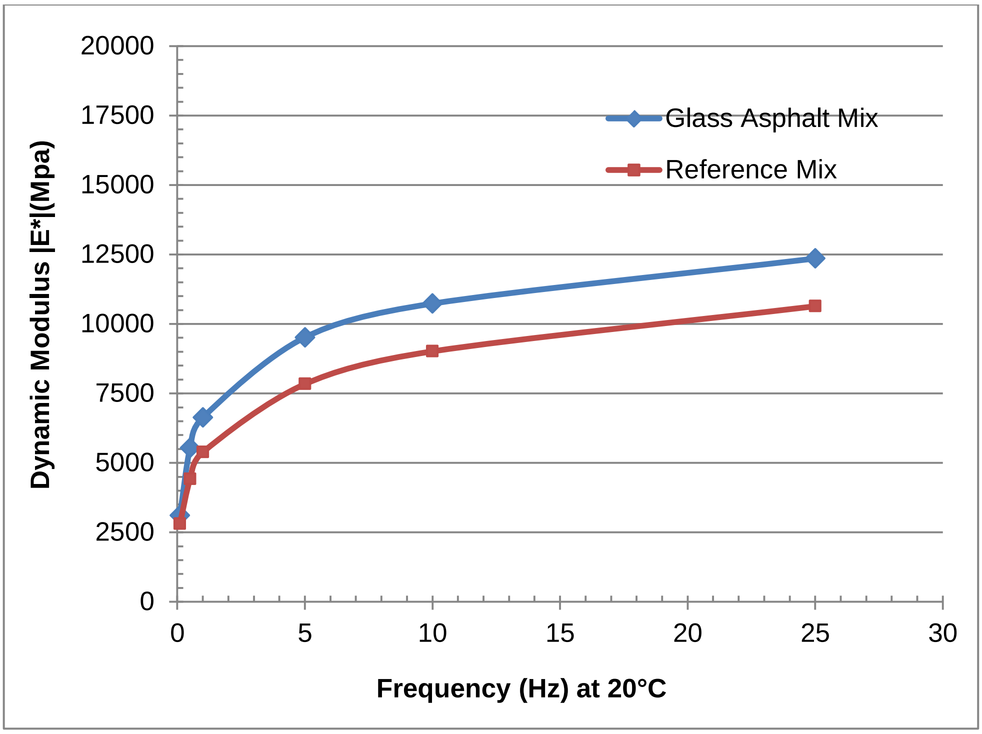

Figure 3: Dynamic modulus results for mixes at 10Hz and 20°C

5.2 Flow number test results

Permanent deformation properties determined from repeated load uniaxial or triaxial tests are key parameters to model rutting potential in advanced pavement design methods. High rut resistance asphalt mixes are normally preferred on high volume roads as well as at road intersections. Rutting can typically occur during the summer pavement temperatures in excess of 40°C which frequently occur in South Africa in summer. Under such conditions deformation is resisted by the frictional resistance in the aggregate and binder stiffness. Typically, asphalt mixes with high flow number can be expected to exhibit better rutting performance than a mix with low flow number under the same conditions.

The averaged flow number results of the glass-asphalt and reference mixes are presented in Table 5 and in Figure 4. The results indicate that the glass-asphalt mix has higher flow number than the reference mix implying that it has a lower susceptibility to rutting in comparison with the reference mix at 276 kPa and 483 kPa at the test temperature of 50°C. The ability of an asphalt mix to resist permanent deformation under the influence of traffic and elevated temperatures depends, on the internal frictional resistance of the aggregates in the mix, the tensile strength resulting from the bonding ability of the binder in the mix, and cohesive strength, i.e. resistance to viscous flow of the binder at elevated temperatures. Recently, Anochie-Boateng and George (2016) reported on the microscopic morphology of the crushed glass by using scanning electron microscopy (SEM) to illustrate the angularity of the waste glass. The SEM examinations revealed that the crushed glass mainly consisted of angular flaky particles with a broad range of particle size.

In comparison, the crushed glass used in this mix has a higher fine aggregate angularity (51.3%) than the natural fine aggregates, i.e. crusher dust, crusher sand and mine sand (Table 2). Accordingly, it is expected that the crushed glass would have higher internal friction as a result of the increased angularity. This will in turn, increase the interlock between the particles and contribute to the increased resistance to permanent deformation of the glass-asphalt mix.

Table 5: Flow number results for the tow asphalt mixes

	Sample 1	Sample 2	Sample 3	Mean	Stdev	COV (%)
Glass-Asphalt						
σ_d= 276 kPa	586	401	481	**489**	93	19
σ_d= 483 kPa	372	295	292	320	45	14
Reference Asphalt						
σ_d= 276 kPa	359	326	461	382	70	18
σ_d= 483 kPa	219	285	271	258	35	13

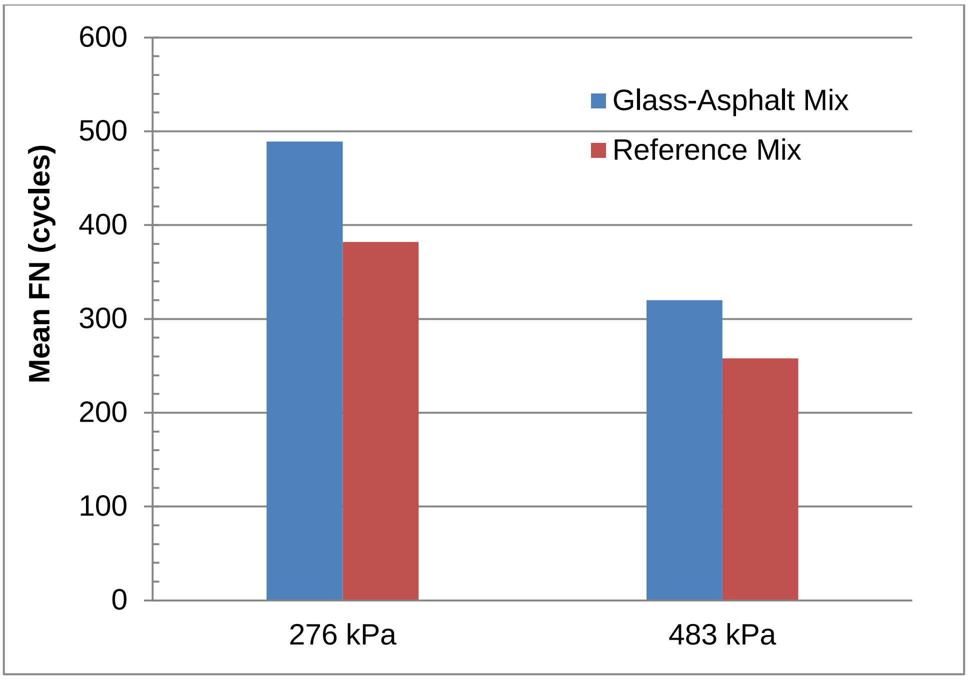

Figure 4: Comparison of flow number results at 276 kPa and 483 kPa @ 50°C.

5.3 Flexural beam fatigue test results

Resistance to fatigue cracking is the ability of the mix to withstand repeated tensile strains without fracture. Fatigue failure in asphalt layers occurs when the number of repetitions of applied loads exceeds the capacity of the asphalt to withstand the associated tensile strains. With relatively smooth asphalt surfacing, higher strain levels are usually associated with low speeds, whereas, low strain levels are associated with high speeds on highways.

The two mixes are compared against each other as illustrated in Figure 5. It can be seen that the two mixes have similar resistance to fatigue cracking at the higher strain levels. However, at low strain levels there is relatively large difference in terms of fatigue life of the two mixes. At a test temperature of 20°C and a frequency of 10 Hz, the fatigue life of the glass-asphalt mix reduces by 50% at 200 microstrains when compared to the reference mix. This is expected as the stiffness of the glass asphalt mix was higher than the reference mix by about 25%. For instance, this percentage increase in the stiffness of the glass-asphalt mix results in the fatigue life to be reduced by almost half at strain levels less than 300 microstrains.

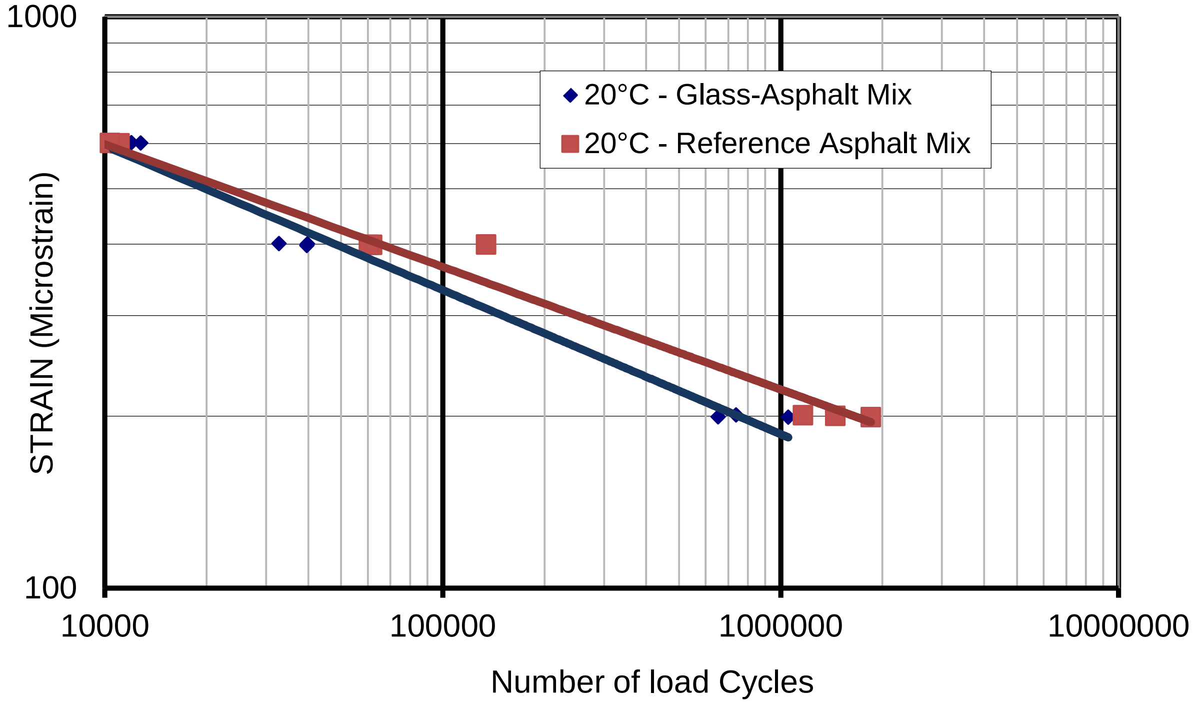

Figure 5: Fatigue life at the temperature of 20°C and frequency of 10Hz

6 CONCLUSIONS

The test results of the glass asphalt mix have been compared with the traditional medium continuously graded (dense graded) surfacing mix used for road construction in South Africa. The conclusions presented pertain to only the crushed glass evaluated in this study, and the specified design aggregate grading used to manufacture the glass asphalt mix. It should be noted that these conclusions cannot be transferred to any other crushed glass from different source, and the aggregates used in this study. Moreover, these conclusions are only based on the properties of the mixes as determined in the laboratory.

Based on the results presented in this study, the following conclusions are made;

- There is potential to substitute depleting natural aggregates with crushed glass in asphalt mixes. This is based on the finding that asphalt mixes with crushed glass could outperform a conventional dense graded mix in terms of rutting and has comparable fatigue resistance at low strains.
- The higher stiffness behaviour exhibited by the glass mix at 20°C and 40°C confirms that this mix is more likely to provide better resistance to permanent deformation than most conventional medium continuously asphalt mixes the reference mix.

ACKNOWLEDGEMENT

Funding for this study was provided through the Parliamentary Grant by the CSIR. The authors would also like to acknowledge the support provided by the glass manufacturing company in South Africa for providing the waste glass material.

REFERENCES

Anochie-Boateng, J., Denneman, E., O'Connell, J. and Ventura, D. 2010. Hot-mix asphalt testing for the South African pavement design method. Proceedings of 29th Southern Africa transportation conference, Pretoria, pp 111-128.

Anochie-Boateng, J., O'Connell, T., Verhaeghe, B., and Myburgh, P. Development of a new asphalt mix design manual for South Africa. In Proceedings, Conference on Asphalt Pavements for Southern Africa, Sun City, South Africa, August, 2015.

Flynn, Larry. "Glasphalt Utilization Dependent on Availability." Roads and Bridges, February 1993.

Hughes, C.S. ''Feasibility of using recycled glass in asphalt'', Report No.VTRC 90-R3, Charlottesville, Virginia Transportation Research Council (1990)

Rmrc.wisc.edu, (2015). UG-EG-Cost Issues | Recycled Materials Resource Center. [online] Available at: http://rmrc.wisc.edu/ug-cost-issues/ [Accessed 16 February. 2016].

Von Quintus, H.L., Scherocman, J.A., Hughes C.S., Kennedy, T.W., 1991. Asphalt aggregate mixture analysis sustem. NCHRP report 338. Prepared for Transportation Research Board, Brent Rauhut Engineering Inc, Austin, Texas.

AASHTO T321-03. Standard method of test for determining the fatigue life of compacted hot-mix asphalt subjected to repeated flexural bending, AASHTO, Washington DC. USA.

AASHTO TP 79-09. Standard method of test for determining the dynamic modulus and flow number for hot mix asphalt (HMA) using the asphalt mixture performance tester (AMPT), AASHTO, USA.

AASHTO PP 60-13. Standard Practice for Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor (SGC). AASHTO, Washington DC. USA.

Anochie-Boateng, JK and George. TB. Use of Waste Crushed Glass for the Manufacturing of Hot-Mix Asphalt. *Abstract Accepted*, 4th International Conference on Sustainable Construction Materials and Technologies, 7-11 August 2016, Las Vegas, Nevada, USA