Article

Effects of Ground-Granulated Blast-Furnace Slag Used as Filler in Dense Graded Asphalt

Amin Chegenizadeh *, Scott W. Hanson [ID], Hamid Nikraz and Calvin Scott Kress

School of Civil and Mechanical Engineering, Curtin University, Kent Street, Bentley, WA 6102, Australia;
scott.hanson@outlook.com.au (S.W.H.); h.nikraz@curtin.edu.au (H.N.); c.kress@student.curtin.edu.au (C.S.K.)
* Correspondence: amin.chegenizadeh@curtin.edu.au

Abstract: Industrial waste materials are increasingly being used in asphalt to improve pavement quality and reduce environmental impacts. The aim of this research was to test the pavement distress-related effects of using ground-granulated blast-furnace slag (GGBFS) as a filler in hot mix asphalt. There is potential for GGBFS to be integrated into Western Australian (WA) asphalt pavements. GGBFS was used as a replacement for the conventional hydrated lime (HL) filler used in mix designs of the Main Roads WA specifications. A control mixture (1.5% HL) was compared with three prototype mixtures containing 1.5%, 3% or 5% GGBFS instead of HL. To investigate their characteristics, we conducted wheel tracking tests, four-point bending tests, and assessments with an asphalt mixture performance tester (AMPT). The findings support the use of GGBFS in asphalt pavements. The mixture with 3% GGBFS had the best fatigue life, rutting resistance and AMPT results.

Keywords: ground-granulated blast-furnace slag (GGBFS); filler; dense asphalt; fatigue; rutting

1. Introduction

The inclusion of waste in materials for pavements and geotechnical engineering projects has become a focus of research. The complex influences of aggregate on soil mechanics [1–5] and excessive waste production create a challenge in investigating waste issues in different scenarios. Researchers across the world have used various waste materials [6–8], such as fibre and plastic, in geotechnical and pavement applications and investigated their performance.

The filler used in asphalt mixes makes up a maximum of 5% of the total aggregate mass and can have a large impact on the asphalt's properties in accordance with Western Australian standards. Filler materials are defined as being finer than what would pass through a 0.075 mm sieve and play an important role in the performance of asphalt mixtures. The fillers affect the air voids in an asphalt mixture and the physical and chemical properties of bitumen.

The addition of filler materials can greatly increase the efficiency of asphalt. Waste materials can be recycled or repurposed into an asphalt mix and maintain or improve its performance while also reducing landfill. The filler material used in an asphalt mixture affects the resulting pavement's performance. This is due to the high surface area of fine filler particles, which enhances absorption by the asphalt binder [9].

The performance of asphalt mixes is significantly affected by the particle size distribution, shape, surface area, surface texture, void material and mineral composition of the aggregate and fillers used [10]. A portion of filler is absorbed by the bitumen while the rest reduces air voids. [11] According to Anderson et al. [10], when filler enters voids, it serves as additional contact points between aggregate particles, which provides a better stress distribution, and as micro-rollers, which allow greater aggregate packing. A rolling surface of contact is created when filler particles surround aggregates, resulting in increased compaction, density and pressure. An increased filler content improves the mixture's hardness;

however, unnecessary filler degrades an asphalt mixture because more bitumen is required to bind the aggregate and filler [9,12].

Bitumen expansion occurs as a result of filler particles being absorbed, resulting in a thicker coating around the aggregates. Increased flexural stress dissipation and fatigue efficiency are possible with a thicker coating [9,13]. Owing to the increased viscosity of the asphalt mastic, the stiffness of the bitumen is also increased by the adsorbed filler. Coarse and fine aggregates bind together more strongly as finer particles fill the voids in the asphalt mix matrix and enhance resistance to movement within it [12,14]. Behiry [15] found that adding filler to a pavement improves its resistance to permanent deformation at the cost of stability and fatigue resistance. Additional filler, as discovered by Pell [16], improves fatigue efficiency by extending the bitumen and reducing air voids. Furthermore, Aragao [17] found that although filler stiffens the mix, it also makes it more resistant to micro-cracking, which delays the onset of fatigue distress.

The majority of previous research has concentrated on either improving the efficiency of asphalt pavements or the use of alternative filler materials. The aim of this study was to see how filler substitutes like GGBFS affect the rutting and fatigue efficiency of asphalt pavements. Mix designs with various percentages of GGBFS were employed to examine its effects on the rutting and fatigue efficiency of mixes compliant with the *Main Roads WA Specification 504 for Asphalt Wearing Course*. The aims of the study were to (1) assess the relationship between GGBFS proportion and the fatigue cracking and permanent deformation characteristics of hot mix asphalt pavement, and (2) determine the optimal GGBFS proportion.

Significance of the Research

It is critical to continue investigating the application of waste materials in the pavement industry as the amount of waste generated is growing due to population and industrial growth. Hence, the need to repurpose waste is increasing. The reuse of recycled or waste products can reduce landfill, abiotic degradation and resource extraction. This study aimed to advance research in this area by using GGBFS, a recycled industrial by-product, in asphalt pavement. The findings of this study will be helpful in deciding whether GGBFS is a suitable substitute for the traditional mineral fillers used in WA mixes; specifically, hydrated lime (HL).

Figure 1 depicts the strategy used to achieve the research goals and objectives.

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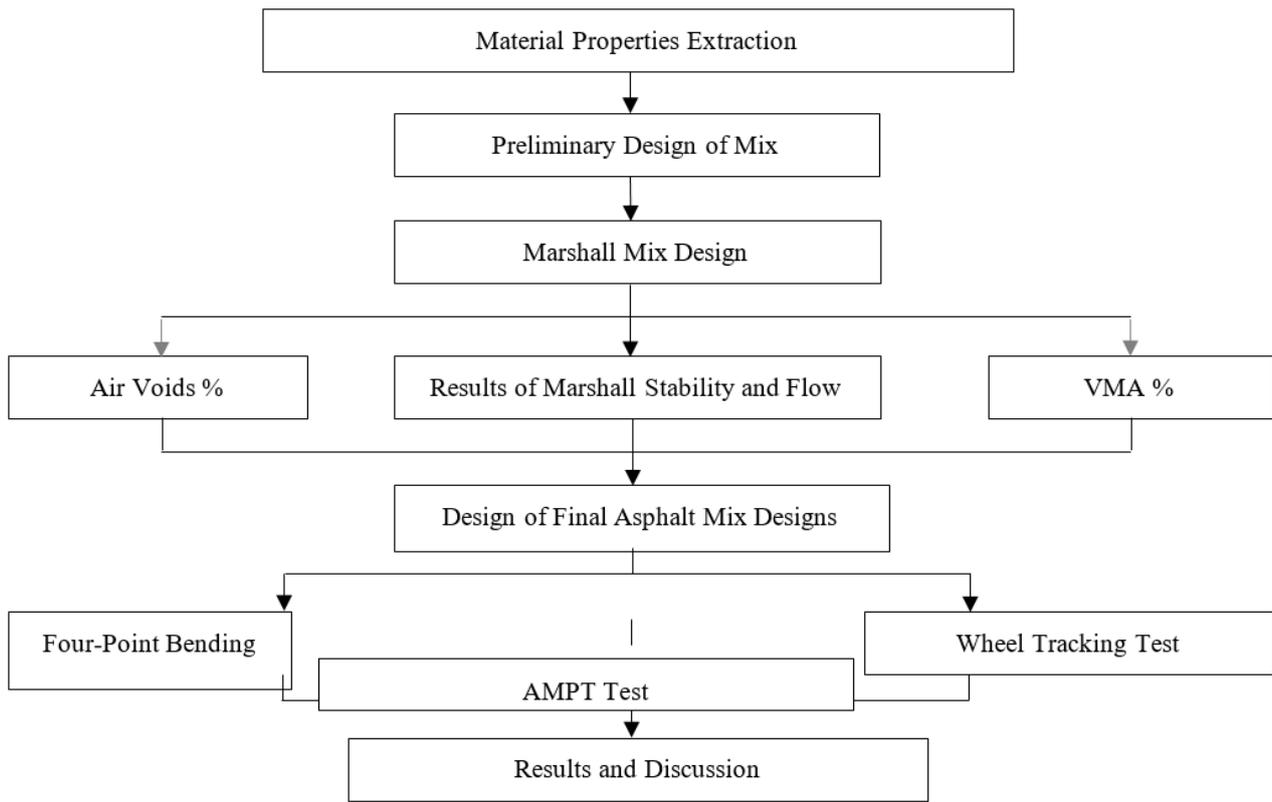
Figure 1. Outline of the research.

2. Materials

2.1. Aggregate

This study used crushed granite aggregate from a local BGC asphalt plant, which is typical of the materials used in WA asphalt production. To produce asphalt mixtures that conformed to the necessary particle size distribution of a 14 mm DG mix, 14 mm, 10 mm, 7 mm, and 5 mm aggregate sizes were used. The particle size distribution (PSD) of each aggregate is shown in Table 1.

Table 1. PSD of the materials.

	Fines (%)				
Sieve (mm)	**5 mm**	**10/7 mm**	**14 mm**	**GGBFS**	**HL**
26.5	100.0	100.0	100.0	100.0	100.0
19.0	100.0	100.0	100.0	100.0	100.0
13.2	100.0	100.0	96.9	100.0	100.0
9.50	100.0	91.4	36.5	100.0	100.0
6.70	99.9	44.4	9.1	100.0	100.0
4.75	94.0	18.6	5.1	100.0	100.0
2.36	10.2	5.5	3.4	100.0	100.0
1.18	6.1	3.6	2.8	100.0	100.0
0.600	4.5	2.9	2.5	100.0	100.0
0.300	3.4	2.4	2.1	100.0	100.0
0.150	2.8	2.0	1.7	100.0	100.0
0.075	2.2	1.5	1.2	95.0	95.0

2.2. Fillers

In most asphalt blends, stone dust, cement and HL are generally used as mineral fillers. HL is a popular choice of filler additive used in hot mix asphalt in WA. One way

to reduce the need for HL is to substitute it with a more sustainable alternative, such as ground-granulated blast-furnace slag.

2.2.1. HL

Hydrated lime is used as an active filler in WA pavement systems. The manufacturer provided the particle size distribution for the HL used in this study (Table 1). A control mix was made with 1.5% HL, as per the WA standard (*MRWA Specification 504 Asphalt Wearing Course* [18]).

2.2.2. GGBFS

The GGBFS used in this research was sourced from Cement Australia. Table 2 presents its properties, and its particle size distribution is in Table 1. The major chemical components were CaO (around 45%), SiO_2 (around 29%) and Al_2O_3 (approximately 14%), Fe_2O_3 (approximately 5.5%) and MgO (approximately 6.2%). Figure 2 shows a scanning electron microscope (SEM) image of the GGBFS particles.

Table 2. GGBFS characteristics (Australia Cement [19]).

Characteristic	Value
Specific gravity	3.0–3.2
Odour	No distinctive odour
Appearance (dry)	Grey to off-white
Melting point	>1200 °C
Vapour pressure	Not applicable
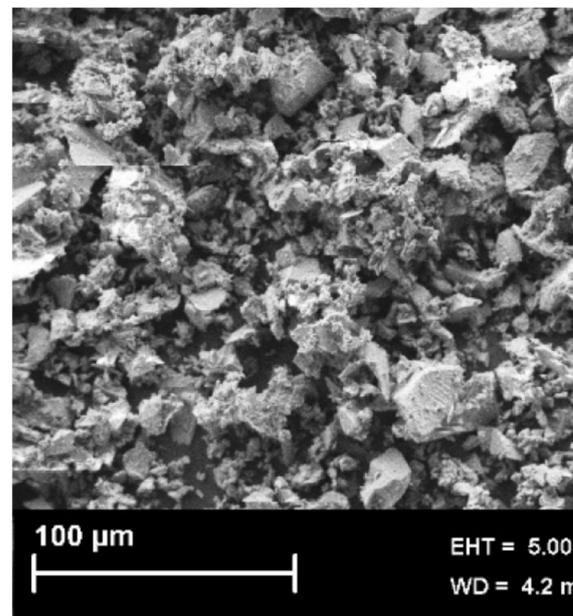
Figure 2. SEM image of the GGBFS used in the study.

2.3. Bitumen

Class 320 bitumen was used (SAMI Bitumen Technologies) and Table 3 presents its characteristics.

Table 3. Bitumen characteristics [18].

Characteristic	Value
Specific gravity @ 25 °C	1.04
Auto-ignition temperature	>250 °C
Viscosity	320 Pa·s @ 60 °C

3. Asphalt Mix Design Criteria

Asphalt mixtures were constructed in compliance with the *Main Roads WA (MRWA) Specification 504 for Asphalt* [20]. As per the specification [20–22], Marshall tests of the mix design were conducted. Marshall tests are used to assess the density and stability of mixes to determine their performance. Table 4 shows the Marshall mix design requirements that must be met under *Main Roads WA Specification 504*.

Table 4. Marshal test accepted limits for 14 mm DG asphalt (MRWA [14]).

Item	Minimum	Maximum
Marshall flow	2.00 mm	4.00 mm
Marshall stability	8.0 kN	-
Voids in mineral aggregate (VMA)	14.0%	-
Air voids	4.0%	7.0%

The *MRWA Specification 504* [20] was used in the creation of a control mix for this investigation. The upper and lower limits of the PSD are shown in Table 5. The mix design can be seen in Table 6 and Figure 3.

Table 5. 14 mm DG mix parameters conforming to *MRWA Specification 504* [20].

Sieve (mm)	PSD											Binder	HL
	19.00	13.20	9.50	6.70	4.75	2.36	1.18	0.600	0.300	0.150	0.075		
Upper limit (%)	100	100	89	73	59	41	32	23	18	11	5	4.7 ± 0.3%	1.5%
Lower limit (%)	100	93	79	63	49	33	22	15	10	6	2		

Table 6. Asphalt mixes.

Mix	HL (%)	GGBFS (%)
Control	1.5	-
1	-	1.5
2	-	3
3	-	5
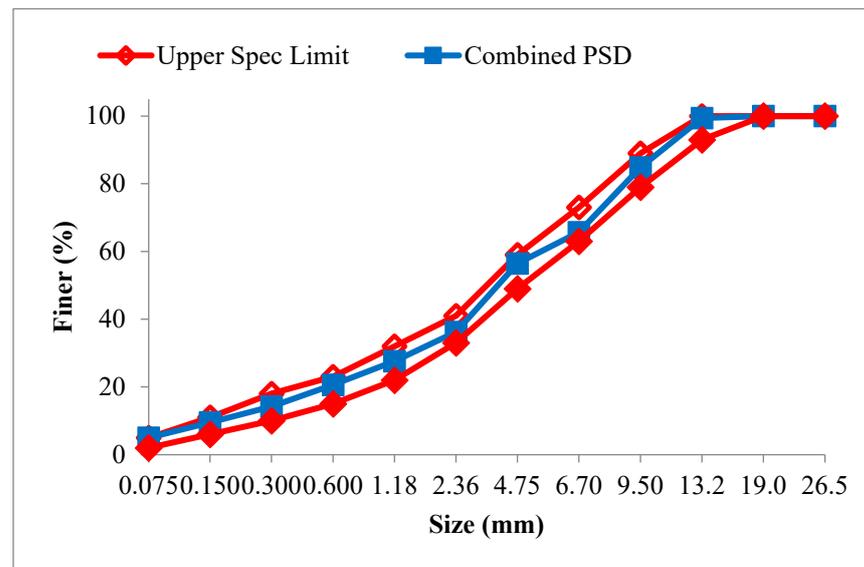
Figure 3. PSD of Mix 2.

4. Asphalt Mixing and Conditioning

The MRWA and Australian Standards were followed to prepare the asphalt specimens. The aggregates, HL and GGBFS preparation procedures remained consistent and in compliance with AS/NZS 2891. [23–25]. All excess moisture was removed by oven-drying. Prior to mixing, the aggregates and fillers were heated to 180 °C to achieve a homogeneous blend.

To ensure thorough cohesion and coating of aggregates with bitumen, the temperature of the asphalt must remain above 140 °C during mixing. All equipment and materials were preheated to the specified mixing temperature prior to use. As defined by AS/NZS 2891 [23–25], mixing was conducted using a Hobart mixer until a homogeneous consistency was visually observed. Prior to conditioning, the mixtures were immediately quartered into acceptable sample sizes for the Marshall tests. Prior to compaction, the asphalt was conditioned in an oven at 150 °C for 1 h in compliance with AS/NZS 2891 [23–25].

Prior to the experiments, the wheel tracking slabs were allowed to reach 60 °C and the fatigue beams were allowed to reach 20 °C. For wheel tracking tests, Austroads Standard AG:PT/T231 [26] was used, while for four-point bending tests, Austroads Standard AG:PT/T233 [27] was used.

4.1. Marshall Stability and Flow

The Marshall properties must adhere to the limits set in the local specifications when using the Marshall method of mix design. These limits differ depending on the mix type, with the Marshall properties conforming to DG hot mix asphalt under *MRWA Specification 504* [20], shown in Table 4. The Marshall testing system was used to determine peak load and flow values in two specimens of each mix configuration.

4.2. Four-Point Flexural Bending

The built slabs were cut into dimensions of 390 mm × 50 mm × 63.5 mm 5 mm in each axis.

After that, the beams were checked for air voids (5.5%) before being dried to a constant mass as per Austroads Standard AG:PT/T233 [27] and the test conditions mentioned in Table 7. The beam samples were put in a temperature-controlled chamber prior to testing until their temperature stabilised at the testing temperature of 20 °C. Each sample was clamped in the testing rig for 30 min before the four-point bending tests to allow induced clamping stresses to dissipate.

Table 7. Four-point bending testing condition as per AG:PT/T233 [27].

Test Item	Conditions
Peak tensile strain	$400 \pm 10 \ \mu\varepsilon$
Frequency	10 ± 0.1 Hz
Loading mode	Continuous haversine
Air void content	$5 \pm 0.5\%$

The failure condition was defined as the sample's flexural stiffness decreasing by 50%, as defined in the standards.

4.3. Wheel Tracking

A Cooper wheel tracking device was used to run wheel tracking tests after the air voids (5.5%) were confirmed and the asphalt slabs were conditioned at 60 °C. The experiments were carried out in accordance with the Austroads standard for wheel tracking testing, AG:PT/T231 [25]. The test terminated at either 10,000 passes or when a rut depth of 15 mm was reached.

4.4. Dynamic Modulus

Asphalt mixture performance tester (AMPT) tests were conducted in accordance with AASHTO TP 79 [28]. The aim was to determine the dynamic modulus and phase angle of the mixture at different temperatures (4 °C, 20 °C, 40 °C) and at four frequencies (10, 1 Hz, 0.1 Hz, 0.01 Hz). Australian standard AS2891.2.2 [21] was followed in conducting the tests and the samples were cut to 150 mm $\times$ 100 mm diameter [29].

5. Results and Discussion

The initial analysis validates the chosen mix designs by comparing them to Marshall mix design specifications, with subsequent results displaying the efficiency of each mix.

The efficiencies of the GGBFS and HL fillers are compared next.

5.1. Mixture Design Verification

To comply with *MRWA Specification 504* [20], the Marshall properties of each mix were determined prior to performance testing. Table 8 shows the mix conformance parameters, while Table 8 shows the study's findings.

Table 8. Marshall properties of the asphalt mixtures.

Mix	Air Voids (%)	VMA (%)	Flow (mm)	Stability (kN)	Conformance
Control (1.5% HL)	4.79	15.49	2.44	16.16	√
1 (1.5% GGBFS)	4.44	15.21	2.80	16.96	√
2 (3% GGBFS)	4.15	14.98	2.82	19.16	√
3 (5% GGBFS)	4.02	14.87	2.79	17.04	√

5.2. Volumetric Properties

The volumetric properties of each mix configuration are presented in Table 9, as per MRWA [23–25].

Marshall stability is an indicator of the resistance of bituminous materials to rutting and shearing stresses, whereas *flow* is defined as the vertical deformation occurring under the maximum load applied by an apparatus. An ideal asphalt mixture has low flow and high Marshall stability, making it resistant to permanent deformation.

According to Figure 4 and Table 9, the Marshall stability of the asphalt mixtures improved with the addition of GGBFS because this filler reduces air voids. It should be noted that the effect of voids is crucial to the Marshall results.

Table 9. Volumetric characteristics of the mixtures.

Mix	Average Maximum Density (t/m³)	Average VMA (%)	Average Air Voids (%)
Control (1.5% HL)	2.464	15.49	4.79
1 (1.5% GGBFS)	2.470	15.21	4.44
2 (3% GGBFS)	2.476	14.98	4.15
3 (5% GGBFS)	2.476	14.87	4.02

(**a**)   (**b**)
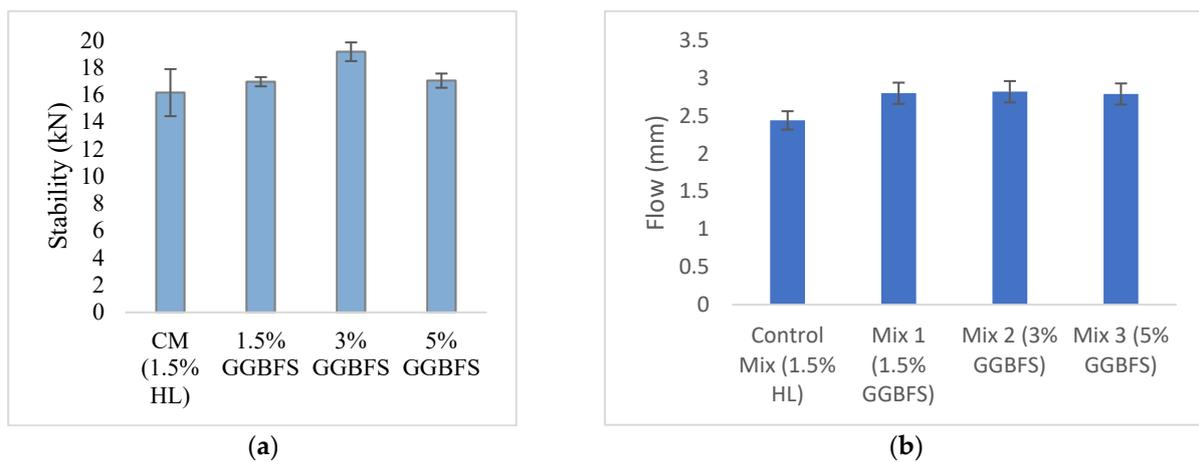
Figure 4. (**a**) Marshall stability and (**b**) flow values of the mixtures.

More bitumen will be required to coat these particles and allow them to adhere to the aggregates [4]. A higher amount of bitumen, on the other hand, results in pavement with significantly less stiffness and a greater tendency to bend at higher temperatures, making it more prone to rutting [30]. Accordingly, an optimal concentration of GGBFS should be added to a mixture to improve its Marshall properties.

When 1.5% GGBFS was added to the asphalt mixture, the Marshall stability was 16.96 kN, while the control mixture with 1.5% HL had a Marshall stability of 16.16 kN. It increased by 4.95%. Figure 4 shows that there was an increase in flow, although it was not significant. The flow of Mixture 1 with 1.5% GGBFS was 2.80 mm.

The Marshall stability of the mixture with 3% GGBFS addition was 19.16 kN. This is 18.56% higher than that of the control mixture containing 1.5% HL. The flow of Mixture 2 with 3% GGBFS was 2.82 mm, which is similar to that of Mixture 1 (1.5% GGBFS).

Finally, the Marshall stability of the mixture with 5% GGBFS was 17.04 kN, which is 11.06% lower than that of Mixture 2 (3% GGBFS). The flow of Mixture 3 (5% GGBFS) was 2.79 mm, which is roughly equivalent to those of Mixtures 1 and 2.

Despite having a higher flow than Mixtures 1 and 3, the peak values in these datasets reflect the ability of each mix to prevent rutting and fatigue distress. Mixture 2 had a peak stability of 19.16 kN, indicating that this configuration may have the best wheel tracking performance.

5.3. Fatigue Life

Four-point bending fatigue tests were performed for each mix. These experiments were carried out in accordance with Austroads standard AG:PT/T233 [27]. The results are shown in Table 10.

Table 10. Fatigue test results.

Mix	Average Initial Flexural Stiffness (MPa)	Average Number of Cycles to Failure, $N_{f\,50}$ (Cycles)
Control 1.5% HL	6650	73,393
1.5% GGBFS	6687	72,348
3% GGBFS	6718	92,524
5% GGBFS	6702	78,940

Figures 5 and 6 and Table 10 display the initial flexural stiffness and fatigue life of the mixtures. Flexural stiffness is a measurement of deflection due to repetitive loading applied to the pavement surface. The fatigue life of an asphalt mixture is defined as the number of cycles at which stiffness is reduced by 50%.
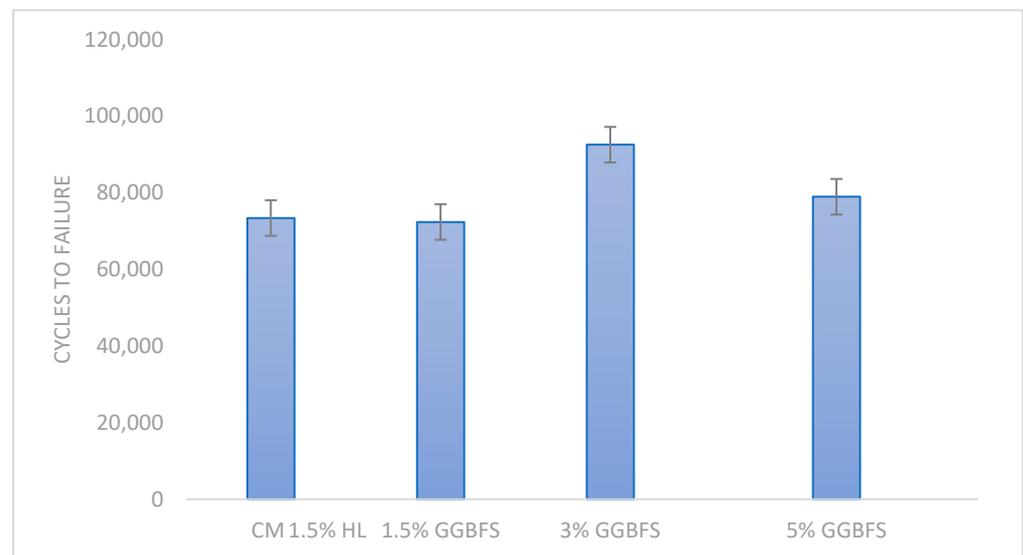
Figure 5. Fatigue life of different asphalt mixtures.
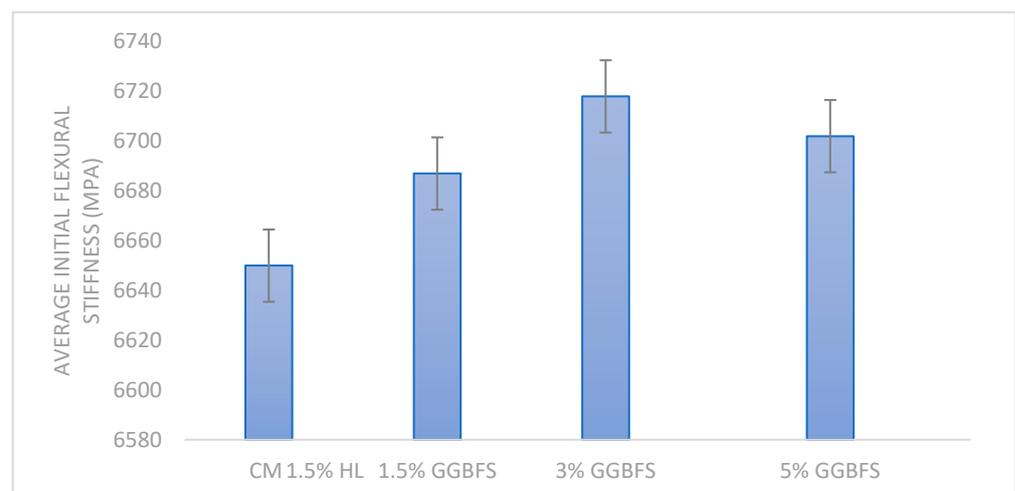
Figure 6. Comparison of the initial flexural stiffness of different asphalt mixtures.

A series of fatigue tests were conducted on all samples. The sample with 1.5% HL failed at cycle 73,393 which is close to that of the 1.5% GGBFS mixture, which failed at

72,348 cycles. The sample with 3% GGBFS failed at 92,524 cycles, which was the highest value. The sample with 5% GGBFS failed at 78,940 cycles. The initial flexural stiffnesses were recorded for all samples and were: 1.5% HL = 6650 MPa, 1.5% GGBFS = 6687 MPa. The highest value of initial flexural stiffness showed 6718 MPa. Once again, the sample with 5% GGBFS showed the initial flexural stiffness of 6702 MPa.

According to Table 10, when 1.5% GGBFS was added to the asphalt mixture, the average number of cycles to failure was 1.42% lower than that of the control mixture with 1.5% HL. The average initial flexural remained relatively constant.

With 3% GGBFS addition, the average number of cycles to failure increased by 26%, while the average initial flexural remained relatively constant.

However, when the concentration of GGBFS was increased to 5%, the average number of cycles to failure decreased significantly, by 14.68%, compared to that of Mixture 2 (3% GGBFS).

These results support the Marshall stability and flow test results. The addition of GGBFS to the asphalt mixture improves fatigue life because it reduces air voids. When the concentration of GGBFS was 3%, the fatigue life decreased due to an excess of filler in the asphalt mixture, which compromises its strength and durability. As a result, there is an optimal concentration of GGBFS for asphalt mixtures. Mixture 2 (3% GGBFS) had the best fatigue behaviour of all the tested mixtures.

5.4. Rutting Results

Wheel tracking studies were performed to accurately characterise the effect of GGBFS addition on permanent deformation resistance in DG hot mix asphalt. As a result, this study offers a useful comparison and review of rutting and fatigue efficiency with filler inclusion. The tests were carried out in accordance with Austroads standard AG:PT/T231 [26] and the results are presented in Tables 11 and 12.

Table 11. Wheel tracking test results.

Mix	Average Rut Depth (mm)	Standard Deviation
Control (1.5% HL)	3.73	0.55
1.5% GGBFS	3.70	0.36
3% GGBFS	2.70	0.10
5% GGBFS	3.13	0.25

Table 12. Rutting Test Results.

Mixture	Rutting Depth at 10,000 (mm)	Rutting Depth at 4000 (mm)	Tangential Slope	SSTR
Control (1.5% HL)	3.76	2.76	1.67×10^{-4}	1.67×10^{-2}
1.5% GGBFS	3.68	2.65	1.72×10^{-4}	1.72×10^{-2}
3% GGBFS	2.71	1.94	1.27×10^{-4}	1.27×10^{-2}
5% GGBFS	3.15	2.26	1.47×10^{-4}	1.47×10^{-2}

The rut depths of the control mixture (1.5% HL) and Mixture 1 (1.5% GGBFS) are similar, as shown in Figure 7 and in the table. The rut depth in both mixtures is 3.70 mm.
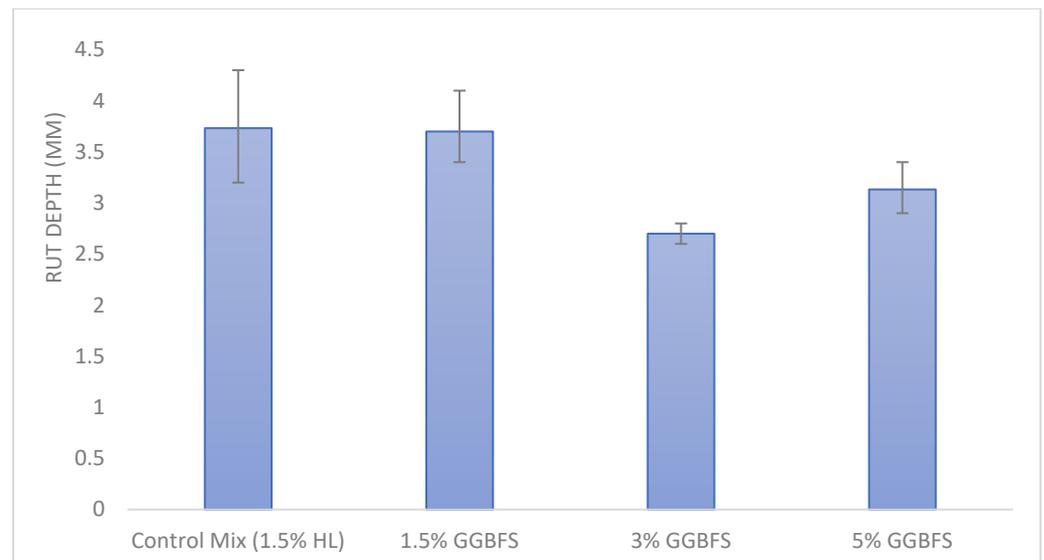
Figure 7. Rutting depths of different asphalt mixtures.

When 3% GGBFS was added to the asphalt mixture, the rutting depth decreased significantly. The rut depth of Mixture 2 (3% GGBFS) was 2.70 mm, a decrease of 27% compared to the control mixture (1.5% HL). This is because the fillers produce asphalt with greater packing and density as the fine filler particles act as micro-rollers to reduce air voids and increase compaction [9,11]. In addition, the hardness of the bitumen is improved because a higher filler content results in more particles being absorbed and a higher viscosity bitumen-filler mastic. This increased viscosity improves the mixture's stability and resistance to permanent deformation, but reduces its fatigue life.

This pattern, however, continued up to a filler concentration of 3%, after which the performance against permanent deformation began to regress. The rutting depth of Mixture 3 (5% GGBFS) was 3.15 mm, which is 16% higher compared to Mixture 2 (3% GGBFS). This is consistent with Zulkati, Diew, and Delai [8], who found that when the filler amount is too high, the bitumen cannot coat the filler and aggregates adequately.

This phenomenon is caused by two main factors. Increasing the amount of filler increases the total surface area, which must be coated with the same amount of bitumen as specified in the mix design. Secondly, as the amount of filler particles consumed increases, the bitumen's viscosity increases, making it more difficult for the bitumen to migrate through the mix and provide a dense and consistent coating.

These two factors result in a poorly performing mixture with reduced stability and resistance to permanent deformation. These findings are consistent with Likitlersuang and Chompoorat [31], who looked at the impact of fly ash as a filler at concentrations of 1–5%. The same patterns emerged; increasing the filler content up to 3% improved rutting efficiency before it deteriorated with further filler. The GGBFS was expected to perform similarly to fly ash. Figure 8 shows the highest rutting depth.

Figure 8. Photograph of a wheel track test sample made with the 1.5% GGBFS asphalt mixture.

5.5. AMPT Testing

The dynamic modulus (E*) and phase angle were derived from AMPT testing in accordance with AASHTO [28] (Figure 9). The phase angle of Mixture 2 (3% GGBFS) was the highest at 35, followed by 32 for the 1.5% GGBFS mix. The phase angle of the mixture with 5% GGBFS was 29, which is lower than those of the 3% and 1.5% GGBFS mixtures. This is consistent with the results indicating better fatigue and rutting performance in the 3% GGBFS mixture. Figure 10 shows a sample of AMPT test results. A higher phase angle supports the idea of the mixture being more elastic. Master curve construction is based on the fact that the dynamic modulus presents an S-shaped format. The tests were conducted in different reduced frequencies. Figure 11 presents the results at 20 °C. Figure 11 presents master curves for the tested specimens, which are plotted as E* versus reduced frequency. The curves show that Mixture 2 (3% GGBFS) had the best performance, showing that the majority of 3% GGBFS tests presented a higher E*.
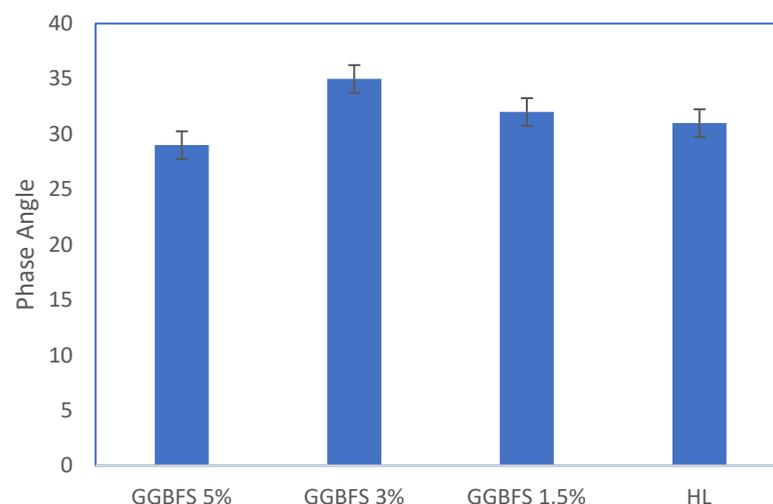
Figure 9. Phase angles of different asphalt mixtures.

Figure 10. AMPT test sample.
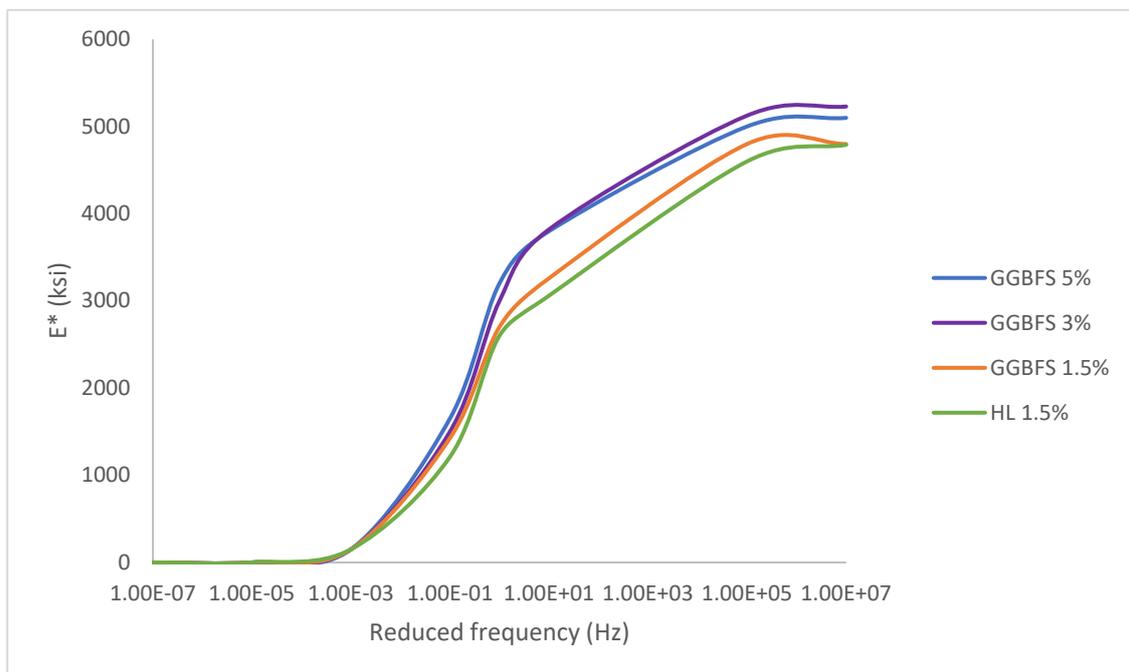
Figure 11. Master curves of different mixes.

6. Conclusions

This study explored the effects of replacing HL filler with GGBFS in asphalt mixtures. GGBFS was incorporated into three mixes at concentrations of 1.5%, 3% and 5%. The mixes were created to meet the requirements of *MRWA Specification 504* [20]

Four-point bending tests were used to assess fatigue life, while rutting resistance was also measured. According to research, optimal resistance to permanent deformation

often comes at the expense of stability and fatigue life [15]. The mix with 3% GGBFS filler had the longest fatigue life and best rutting resistance. GGBFS has been shown to be a more natural alternative to the more commonly used HL and its inclusion does not reduce asphalt performance. This is a positive outcome for improving fatigue, as cracking due to fatigue is the most common issue in WA asphalt pavements.

Mixture 2 (3% GGBFS filler) achieved excellent results, with a 27.7% improvement in rutting resistance. The introduction of GGBFS filler yielded promising results in terms of fatigue life and rutting resistance; however, further research and characterisation are needed before GGBFS can be commercially implemented.

The AMPT design also showed that the mixture with 3% GGBFS had the highest phase angle. The master curves of the mixtures also showed that the majority of Mix 2 (3% GGBFS) tests exhibited higher E*.

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