Potential for carbon capture and reduced GHG emissions through innovative asphalt pavement design: Use of biochar waste

Milestone 4 Report

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About PATREC

The Planning and Transport Research Centre (PATREC) is a collaboration between the Government of Western Australia and local universities, constituted to conduct collaborative, applied research and teaching in support of policy in the connected spaces of transport and land use planning. The collaborating parties are: The University of Western Australia, Curtin University, Edith Cowan University, Department of Transport, Main Roads Western Australia, Western Australian Planning Commission and the Western Australian Local Government Association.

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Executive Summary

The findings from Milestone Reports 1, 2 and 3 are re-capped first. Then the findings from this final report on the entire laboratory testings are summarised.

This final milestone report presents a comprehensive evaluation of hot mix asphalt (HMA) modified with three types of biochar, **BC-1**, **BC-2**, and **BC-5**, used as partial replacements for fine aggregates (i.e. **2.5%** and **5%** of total mass). The study assesses the mechanical performance, moisture susceptibility, deformation resistance, fatigue behaviour, and carbon sequestration potential of biochar-modified asphalt relative to an unmodified control mix. The aim is to determine whether biochar can improve pavement performance while enabling net reductions in greenhouse gas emissions.

Key Findings

1. Asphalt Performance

Marshall Stability and Flow

- Most biochar mixes showed **minor reductions in Marshall Stability (<10%)**, except **BC-5 at 5% replacement**, which **increased stability by 11%**, outperforming the control mix.
- Marshall Flow increased slightly in most mixes but remained within acceptable ranges.
- Density reductions were small (<3%), reflecting lower biochar particle density.

Resilient Modulus (Stiffness)

- All biochar mixes achieved **substantial increases in resilient modulus**, ranging **from 164% to 211%** relative to the control.
- The highest increase was observed in **BC-5 2.5%**.
- Increased stiffness is attributed to higher binder viscosity and reduced effective binder content due to biochar absorption.

Stripping Potential (Tensile Strength Ratio)

- All mixes met the minimum TSR requirement (≥80%).
- Biochar mixes achieved **TSR improvements of 3–12%** over the control, indicating **better moisture resistance**.
- Visual assessments confirmed no increased stripping tendency.

Fatigue Performance (Four-Point Bending)

- Fatigue results were **highly variable**, both within and between mixes.
- Due to inconsistency and limited sample numbers, **no conclusive statements** about fatigue performance can be made.
- Future testing with more specimens (e.g. minimum of 12 beams of each mix) and statistical treatment is recommended, before large-scale production trials.

Wheel Tracking (Rutting Resistance)

- Most biochar mixes performed similarly to the control.
- **BC-2 2.5%** showed **8% reduction** in rut depth (improved rut resistance).
- **BC-5 mixes** showed increased rutting:
  - **BC-5 2.5%**: 27% increase
  - **BC-5 5%**: 61% increase, suggesting sensitivity to biochar type and pore structure.

2. Carbon Sequestration Potential

Carbon balance calculations per tonne of asphalt show:

- Net positive mixes:

  - **BC-2 2.5%**: +7.52 kg CO_2 equivalent
  - **BC-2 5%**: +52.65 kg CO_2 equivalent
  - **BC-5 5%**: +22.56 kg CO_2 equivalent

- Net negative (emitting) mixes:
  - BC-1 2.5%
  - BC-5 2.5%
  - Control mix (baseline, −36.47 kg CO_2 equivalent)

Biochar effectiveness is strongly correlated with **carbon content**, with **BC-2** (85.2% carbon) showing the best sequestration outcomes.

Overall Conclusions

1. Performance

Biochar can be incorporated into HMA without compromising essential performance requirements. However fatigue results remain inconclusive; more extensive testing is required. In some cases (e.g., BC-5 5% stability, BC-2 2.5% rutting, multiple mixes' stiffness), it offers notable improvements.

2. Moisture Resistance

Biochar **improves TSR** and reduces stripping potential—an important advantage in pavement durability.

3. Carbon Benefits

When biochar has a high carbon content and is used at appropriate replacement levels, the modified asphalt can achieve net-positive carbon sequestration, supporting climate-positive construction practices.

4. Practical Considerations

Differences between biochars matter—density, pore volume, and surface area influence binder absorption, compaction effort, and performance. Biochar types must be carefully selected and mix designs tailored to prevent excessive air voids or stiffness.

Overall Recommendation

Biochar-modified HMA shows strong potential as a **sustainable**, **lower-carbon pavement material**. With proper selection of biochar type, especially high-carbon variants like BC-2, and optimized mix designs, biochar can enhance certain mechanical properties while enabling net carbon sequestration. Further work on fatigue performance and large-scale production trials is recommended before field implementation. In full depth asphalt pavements, at higher levels in the pavement, fatigue performance is not likely to be a detractor for the use of biochar in asphalt, for thin wearing courses, application should be limited at this stage to low traffic volume situations until further testing determines the fatigue properties.

Where biochar has shown to be a positive additive for mix performance, further research would be required to optimise the quantity, particle sizes, component specifications, and sources.

1. Biochar in Hot Mix Asphalt (re-cap from M1 report)

Biochar is produced by pyrolysis process from biowaste. It is stable, carbon-rich and capable of long-term caron sequestration. WA generates ~10 million tonnes of biowaste annually, much of which is underutilised. The current disposal methods like burning or landfill release significant GHGs.

Pyrolysis can convert up to 50% biomass into biochar. Studies show that biochar in asphalt can improve rutting resistance, temperature susceptibility and binding aging resistance. Carbon-based additives in asphalt can also offset emissions from pavement construction.

Hot Mix Asphalt (HMA) production emits CO_2, CH_4 and N_2O. Bitumen and mixing are the largest contributors. Average emissions are 60 kg CO_2 per tonne of asphalt. However, 1 kg of biochar has the potential carbon sequestration of 2.46 kg CO_2 equivalent. With 5% biochar replacement in HMA, the net sequestration of Co2 can be 197 kg (i.e. carbon-negative asphalt).

2. Biochar Selection from Market in WA (re-cap from M2 report)

Our market research has revealed a limited number of biochar producers in WA, this can be attributed to the low uptake of such products. This seems to create a situation of mutual dependency, where the lack of demand may be hindering the growth of biochar production.

Seven biochar products were sourced from suppliers specialised agricultural biochar, located in WA and Victoria. They were produced from a variety of feedstocks, predominantly biomass waste, that includes native hardwoods such as jarrah and wandoo, and other woody and green waste.

The long-term availability of woody feedstock of pyrolysis might be jeopardised when the forestry of these timbers is being stopped. However, there will be more green waste collected due to the more categorised waste collections. Biochar can also be produced by other bio-waste, such as coffee grounds and agriculture wastes. Consequently, biochar's feedstocks are expected to be of abundant availability.

2.1. Selection of biochar samples for asphalt testing

The carbon contents of all biochar samples are listed in the Table 2.1 (i.e. Table 3.1 in M2 report). To test a range of biochar performance in asphalt mix, the highest, lowest and average carbon contents are selected. Thus, BC-1 (lowest carbon content), BC-2 (highest carbon content) and BC-5 (average carbon content) are selected for asphalt testing, which are highlighted in GREEN.

Table 2.1 Elemental Analysis Results

Source	Sample ID	Al	Ca	Fe	K	Mg	S	C	N
		mg/kg	%	mg/kg	%	%	%	%	%
Wundowie	**BC-1**	**5008**	**2.687**	**15128**	**0.03**	**0.068**	**0.013**	**48.7**	**0.151**
Simcoa	**BC-2**	**2184**	**0.973**	**1633**	**0.12**	**0.101**	**0.028**	**85.2**	**0.308**
Manjimup	BC-3	2668	2.932	2278	0.22	0.567	0.037	72.5	0.248
Renergy Pty LTD	BC-4	6835	2.253	23151	0.40	0.177	0.029	59.6	0.642
Greenlife Soil	**BC-5**	**2302**	**0.844**	**3926**	**0.05**	**0.058**	**0.018**	**65.1**	**0.149**

Hope Valley	BC-6	7438	1.094	11974	0.04	0.066	0.013	57.4	0.078
Green Man	BC-7	7665	1.818	4443	0.69	0.248	0.061	37.8	0.679

2.2. Biochar Characterisation

The BET analysis and SEM imaging of the three selected biochars (i.e .BC-1, BC2 and BC-5 in Table 2.1) were conducted. The BET analysis revealed the selected bicochars possess ultra-microporous structures with very high specific surface areas. This confirms their ability to adsorb small molecules such as CO_2 and water. However, due to the large molecular size of bitumen hydrocarbons, significant absorption of binder into biochar pores is considered unlikely.

The SEM imaging showed that all three selected biochars had fine particles. However, BC-1 and BC-5 involved larger particles, and BC-2 has mostly finer particles. Larger particles had the potential to include larger pores, which were likely to absorb bitumen molecules when mixed in HMA.

3. HMA Laboratory Mix Design (re-cap from M3 report)

The use of biochar as a partial replacement of dust in HMA was investigated, with the aim of carbon sequestration and GHG reduction while maintaining acceptable pavement performance. Laboratory mix design and Marshall testing were conducted on control mix and asphalt modified with different biochar type (i.e. BC-1, BC2 and BC-5) at replacement levels of 2.5% and 5% by mass.

Overall, the testing results showed that biochar can be incorporated into HMA. However, its effectiveness is highly dependent on biochar properties, particularly particle size and micro-porosity, which strongly influence bitumen absorption, air voids and mechanical performance.

Problem identified: biochar replacement by mass of dust is not suitable, as the specific gravity of biochar is ~50% of that of the dust. Thus, in the following laboratory tests, biochar replacement by volume will be used.

4. Introduction of Laboratory Tests

Hot mix asphalt (HMA) production and road construction contribute significantly to carbon emissions through aggregate quarrying, bitumen production, material transport, and energy-intensive mixing processes. As road authorities and industry partners seek pathways toward net-zero construction materials, biochar has emerged as a promising additive with the potential to both improve pavement performance and sequester carbon. Produced through pyrolysis of organic waste streams, biochar contains stable carbon structures that can be incorporated into asphalt mixes, potentially offering mechanical, durability, and environmental benefits.

This final milestone report presents the outcomes of an experimental program evaluating HMA modified with three types of biochar, BC-1, BC-2, and BC-5, used as partial replacements for fine aggregates. The work builds on earlier milestones that examined biochar sourcing and carbon sequestration estimation (M001), biochar characterisation and test planning (M002), and HMA mix design with preliminary Marshall stability testing (M003).

The research focuses on whether biochar-modified asphalt can meet or exceed conventional performance requirements while reducing the net carbon footprint of asphalt production. Laboratory testing was carried out on control and biochar-modified mixes to evaluate:

- **Volumetric and mechanical performance**, including Marshall Stability and Flow
- **Stiffness characteristics**, through resilient modulus testing
- **Moisture susceptibility**, using the Tensile Strength Ratio method
- **Fatigue behaviour**, assessed via four-point bending beam tests
- **Deformation resistance**, using wheel-tracking rutting tests
- **Carbon sequestration potential**, quantifying emissions offsets based on biochar carbon content and mix proportions

By consolidating material sources, mix design methodology, and performance results, this report provides an integrated understanding of how biochar influences HMA behaviour and whether it presents a viable option for sustainable pavement construction in Western Australia and beyond. The findings are intended to support future field trials, specification development, and continued investigation into low-carbon road materials.

5. Aggregates and Biochar in Mix Design

5.1. Materials

All materials were sourced from local suppliers and are identified in this report by the material IDs listed in Table 5-1.

Table 5-1: Materials Sources

Material	Source/Supplier	ID
Biochar	Wundowie Carbon	BC-1
Biochar	Simcoa Operations	BC-2
Biochar	Greenlife Soil Co	BC-5
Bitumen Class 320	SAMI Bitumen Technologies PTY LTD	C320
Aggregate (**10mm**, 7mm, 5mm, Dust)	BGC Quarries	-

5.2. Control Mix Design

As a reference, this research aims to compare the performance of a control mix and modified mix with addition of biochar by direct replacement of fine aggregates by biochar from different sources to evaluate the performance and potential carbon sequestration. The base for the control mix selection started with the selection of the nominal size of the mix, number of Marshall compaction blows and bitumen type and mass content, as outlined in Table 5-2.

Table 5-2: Control Mix Design

Component	Percentage of mix
10mm	24%
7mm	17%
5mm	16%
Dust	42%
Hydrated Lime	1%

The HMA mix design most suitable for this research is shown in the Table 5-3. This mix was selected when the combined aggregates met the midpoint of gradings limits of the AS 2150:2020 and tested for air voids at three different bitumen content, such as 5%, 5.75% and 6.5% resulting with 5.75% bitumen content mix meeting Main Roads' minimum requirements for Air Voids and Marshall Stability and Flow. The DGA 10/75 (Dense graded asphalt mix/number of blows each side) tests were undertaken following the guidelines of the AS 2891.2.1-2014, AS/NZS 2891.5-2015, Test method WA 733.1-2022, Test method WA 732.2-2022 and Test method WA 731.1-2018. With bitumen content of 5.75% of C320 bitumen and minimum 1% hydrated lime added to all mixes.

Table 5-3: Combined Grading

Sieve Size	Nominal 10mm	Nominal 7mm	Nominal 5mm	Dust	Hydrated Lime	Combined
(mm)	Passing (%)	Passing (%)	Passing (%)	Passing (%)	Passing (%)	Passing (%)
16	24.00	17.00	16.00	42.00	1.00	100.00
13.2	24.00	17.00	16.00	42.00	1.00	100.00
9.5	19.72	17.00	16.00	42.00	1.00	95.72
6.7	2.78	14.90	16.00	42.00	1.00	76.68
4.75	0.70	4.20	13.78	41.95	1.00	61.63
2.36	0.45	0.62	1.42	37.46	1.00	40.94
1.18	0.39	0.39	0.75	28.52	1.00	31.06
0.6	0.33	0.32	0.60	20.94	1.00	23.18
0.3	0.26	0.25	0.49	13.78	1.00	15.77
0.15	0.11	0.08	0.12	7.98	1.00	9.29
0.075	0.05	0.02	0.02	5.39	1.00	6.48

Figure 5-1 illustrates the grading limits, the midpoint target and combined PSD of this mix design.

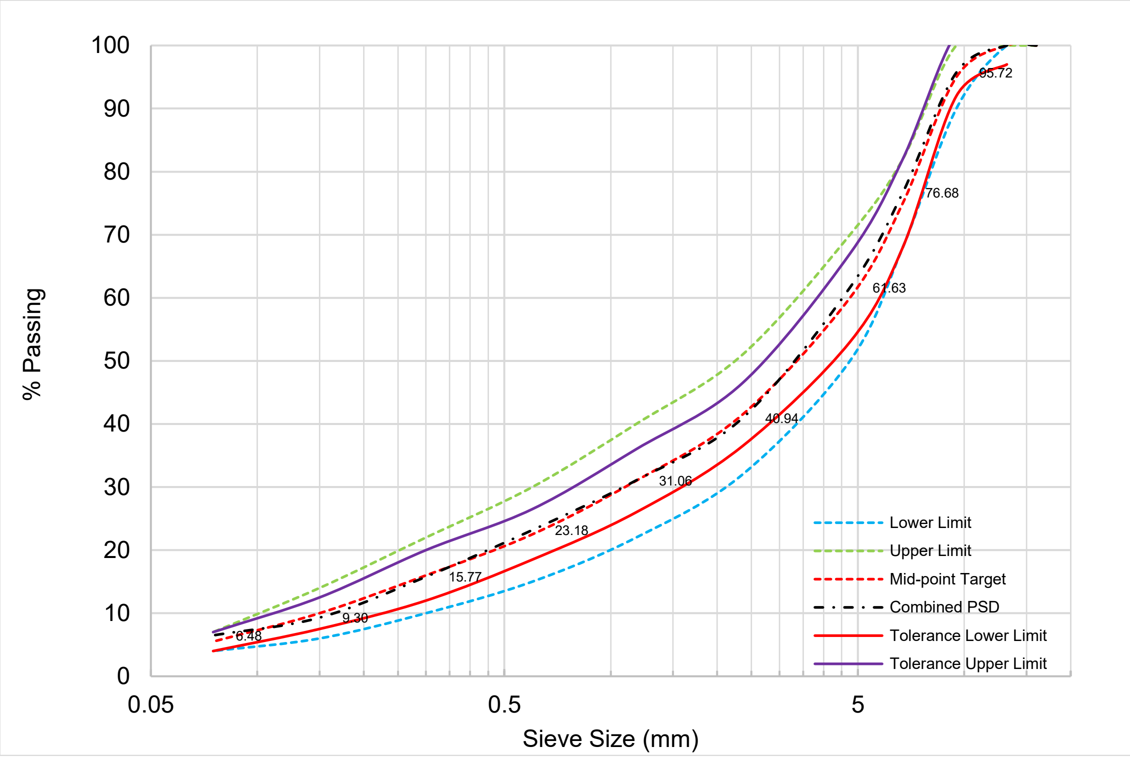

Figure 5-1: Combined PSD and grading limits control mix Biochar HMA design

Initial observations and data from milestone report M003 indicate that adding biochar to asphalt mix increases bitumen loss, resulting in a drier mixture. This effect is likely due to the larger surface area and pore volume of the biochar, which absorb more bitumen from the mix.

It is worth noting that HMA with biochar with more than 5% fines aggregates replacement was unfeasible due to the high air voids content (higher than 6%). For this reason, only mixes with achievable air voids within the range of 5±1% were further tested for performance in this report.

Biochar exhibits particle densities that differ substantially from those of conventional granite aggregates. Preliminary testing indicated that biochar is unsuitable for particle density and water absorption determination using AS/NZS 1141.5-2000, primarily due to difficulties in achieving a saturated surface dry (SSD) condition and the tendency of biochar particles to float during immersion. Accordingly, particle density was determined using the apparent particle density method specified in AS/NZS 1141.7-2014. These apparent particle density values were subsequently used to enable volume-equivalent replacement of fine aggregates with biochar in the mix design. The results are presented in Table 5-4.

Table 5-4: Biochar and filler apparent particle density

Material	Apparent particle density (t/m^3)
BC-1	1.630
BC-2	1.748
BC-5	1.456
Dust-filler	2.647

5.3. Biochar and Aggregate Particle Density Analysis

Biochar exhibits a variable particle size distribution (PSD), with larger particles—those above 2.36 mm—being easily crushed during compaction. In this study, biochar was sieved and sorted to replace the fine aggregate fraction at either 2.5% or 5% of the total aggregate mass. Importantly, only biochar particles that passed completely through the 0.6 mm sieve were used for replacement. This approach was taken to minimise further segregation of biochar during compaction and to reduce potential bitumen loss from the mix.

The apparent particle density of biochar varies among samples. Therefore, the replacement of fines was set at 2.5% and 5% by mass. For instance, “BC-1 2.5%” refers to a mix where BC-1 biochar replaces 2.5% of fine aggregates by mass, but equivalent volume of BC-1 is added to the mix. This means the added BC-1 is 1.67% BC-1 of the total mass. A detailed breakdown of the mix composition for each blend is shown in Table 5-5.

Table 5-5: Biochar Mixes properties

Mix	Aggregate	Percentage of Mix by mass (%)
BC-1 2.5%	10mm	24.21
	7mm	17.15
	5mm	16.14
	Dust	39.84
	Biochar	1.67
	Hydrated Lime	1.01
BC-2 2.5%	10mm	24.23
	7mm	17.16
	5mm	16.16
	Dust	39.88
	Biochar	1.55
	Hydrated Lime	1.01
BC-2 5%	10mm	24.47
	7mm	17.33
	5mm	16.31
	Dust	37.73
	Biochar	3.14
	Hydrated Lime	1.02
BC-5 2.5%	10mm	24.27
	7mm	17.19
	5mm	16.18
	Dust	39.95
	Biochar	1.39
	Hydrated Lime	1.01
BC-5 5%	10mm	24.55
	7mm	17.39
	5mm	16.37
	Dust	37.85
	Biochar	2.81
	Hydrated Lime	1.02

6. Marshall Stability and Flow

All Marshall specimens were prepared following the same mixing, compaction, and conditioning procedures described in Section 3.1. Biochar-modified mixes followed the aggregate replacement proportions defined in Table 5-5, with grading curves shown in the corresponding figures. Mixing temperature, compaction effort, and testing standards were kept constant across all mixes to allow direct comparison of Marshall Stability and Flow results. Unless otherwise noted, specimens were visually uniform and showed no evidence of segregation.

6.1. Control mix

The mixes were designed for Marshall Compaction and tested for Stability and Flow. Four specimens were made per mix: three for testing and one spare in case of air voids, height issues, or sample damage during preparation Figure 6-1.

The control mix was prepared and tested according to AS/NZS 2891.2.1:2014, AS/NZS 2891.5:2015, Test method WA 733.1-2022, Test method WA 732.2-2022 and Test method WA 731.1-2018. The mix was prepared in small batches, ensuring that the temperature was kept at 150ºC during mixing, compaction and conditioning.

Figure 6-1: Marshall specimens - Control Mix

The control mix presented the typical properties as per Table 6-1 displays the average values of the sample properties and test results. This mix design meets the requirements set in the Main Roads specification 504 in terms of air voids (5±1%), stability (> 8 kN) and flow (2~4 mm).

Table 6-1: Control Mix properties

Property	Value
Average Bulk Density (t/m³)	2.342
Maximum density (t/m^3)	2.449
Average Air voids (%)	4.35
Bitumen content (%)	5.75
Blows	75
Average Marshall Stability (kN)	14.06
Average Flow (mm)	2.7

This mix design will be the baseline for all other mixes modified by partially (2.5% and 5%) replacing the dust (see Table 5-2). This will create a slight change of the PSD curve by mass, as the volume is kept constant between the addition of biochar and the replaced dust. The biochar include BC-1, BC-2 or BC-5.

6.2. Mix design BC-1 2.5%

Specimens prepared with BC-1 at 2.5% fine aggregate replacement were visually uniform, with no evidence of segregation (Figure 6-2). The combined particle size distribution remained within the specified grading envelope following biochar replacement, as shown in Figure 6-3. The addition of BC-1 resulted in a reduction in average Marshall Stability of approximately 10% relative to the control mix, while Marshall Flow remained unchanged. Bulk density and air void content remained within specification limits. Key mix properties are summarised in

Table 6-2.

Figure 6-2: Marshall specimens - BC-1 2.5%

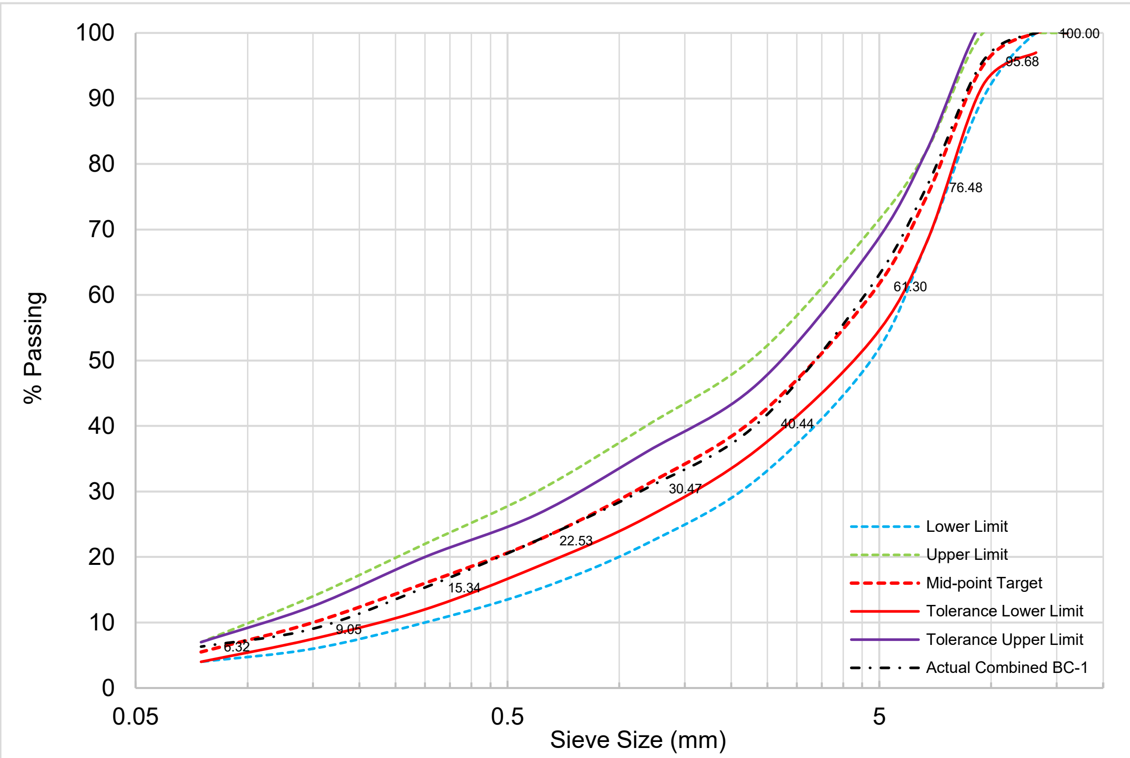

Figure 6-3: Combined PSD and grading limits BC-1 2.5%

Table 6-2: BC-1 2.5% mix properties

Property	**Value**
Average Bulk Density (t/m^3)	2.31
Maximum density (t/m^3)	2.42
Average Air voids (%)	4.57
Bitumen content (%)	5.75
Blows	75
Average Marshall Stability (kN)	12.66
Average Flow (mm)	2.7

6.3. Mix design BC-2 2.5%

Specimens prepared with BC-2 at 2.5% fine aggregate replacement were visually uniform, with no evidence of segregation (Figure 6-4). The combined particle size distribution remained within the specified grading envelope following biochar replacement, as shown in Figure 6-5. The BC-2 2.5% mix exhibited a minor reduction in Marshall Stability relative to the control mix, accompanied by a slight increase in Marshall Flow; however, all values remained within specification limits. Bulk density and air void content were maintained within the target range.

Figure 6-4: Marshall specimens - BC-2 2.5%

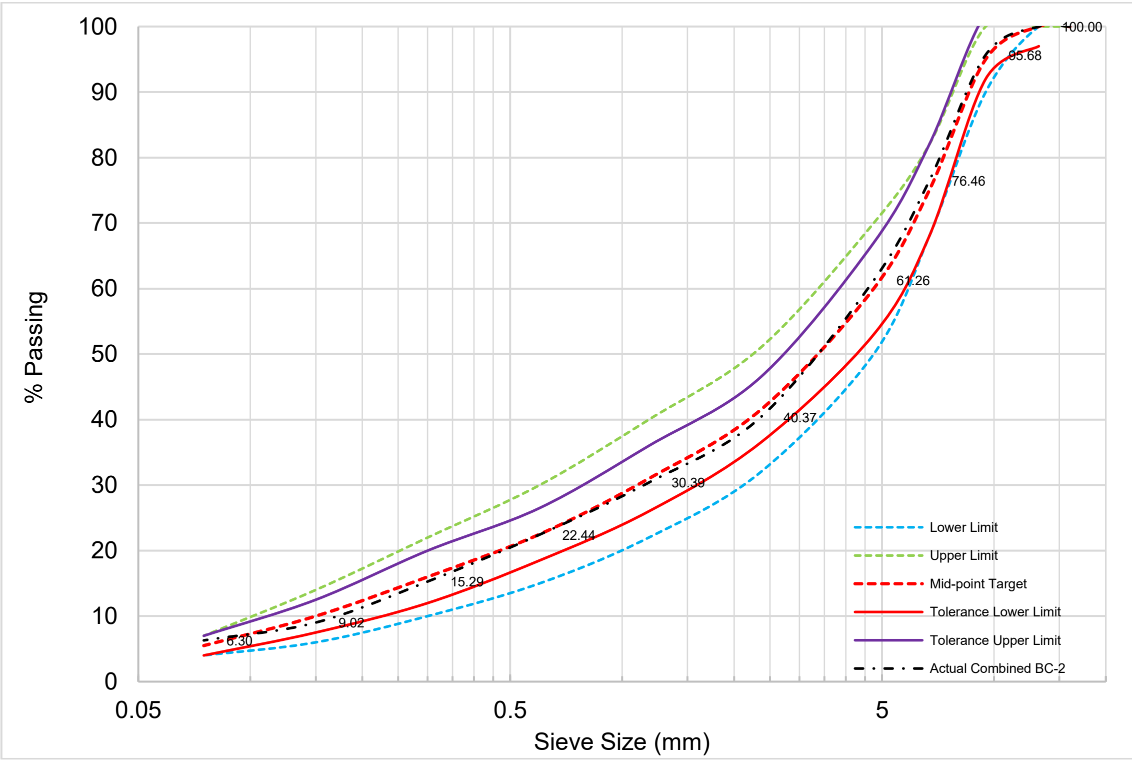

Figure 6-5: Combined PSD and grading limits BC-2 2.5%

Key mix properties are summarised in Table 6-3.

Table 6-3: BC-2 2.5% mix properties

Property	Value
Average Bulk Density (t/m^3)	2.312
Maximum density (t/m^3)	2.435
Average Air voids (%)	5.05
Bitumen content (%)	5.75
Blows	75
Average Marshall Stability (kN)	13.84
Average Flow (mm)	3.1

6.4. Mix design BC-2 5%

The BC-2 5% biochar appeared drier during mixing, but specimens were still successfully prepared, resulting in solid final samples (Figure 6-6). The same method was used to produce the

BC-2 5% biochar HMA batch. The mix design followed Table 5-5 and the grading curve shown in Figure 6-7.

Specimens prepared with BC-2 at 5% fine aggregate replacement were successfully compacted despite the mix appearing drier during mixing, producing solid and coherent samples (Figure 6-6). The combined particle size distribution remained within the specified grading limits following biochar replacement, as shown in Figure 6-7. The BC-2 5% mix exhibited Marshall Stability and Flow values comparable to those of the BC-2 2.5% mix, with no substantial change relative to the control. Bulk density was marginally lower, consistent with the higher proportion of biochar, while air void content remained within the target range.

Figure 6-6: Marshall specimens - BC-2 5%

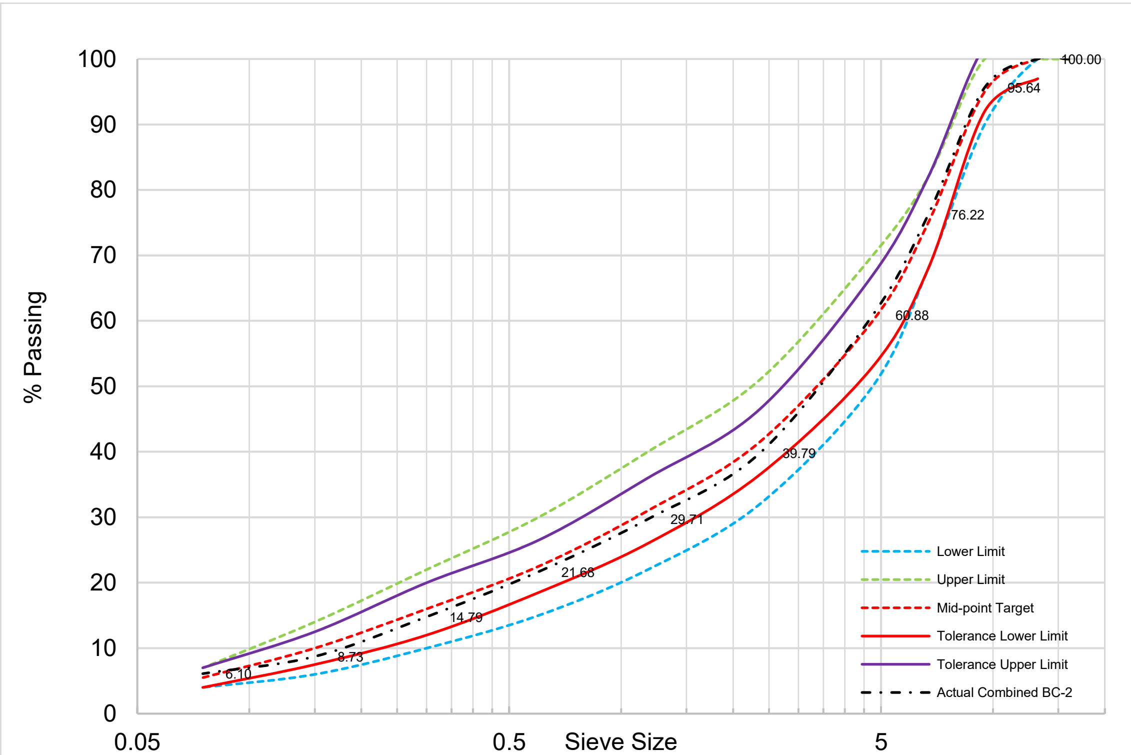

Figure 6-7: Combined PSD and grading limits BC-2 5%

Key mix properties are summarised in Table 6-4.

Table 6-4: BC-2 5% mix properties

Property	Value
Average Bulk Density (t/m^3)	2.277
Maximum density (t/m^3)	2.394
Average Air voids (%)	4.90
Bitumen content (%)	5.75
Blows	75
Average Marshall Stability (kN)	13.57
Average Flow (mm)	3.0

6.5. Mix design BC-5 2.5%

Specimens prepared with BC-5 at 2.5% fine aggregate replacement were visually uniform, with no evidence of segregation (Figure 6-8). The combined particle size distribution remained within the specified grading envelope following biochar replacement, as shown in Figure 6-9. The BC-5 2.5% mix exhibited Marshall Stability and Flow values broadly intermediate between those observed for the BC-1 2.5% and BC-2 2.5% mixes. Bulk density and air void content remained within specification limits.

Figure 6-8: Marshall specimens - BC-5 2.5%

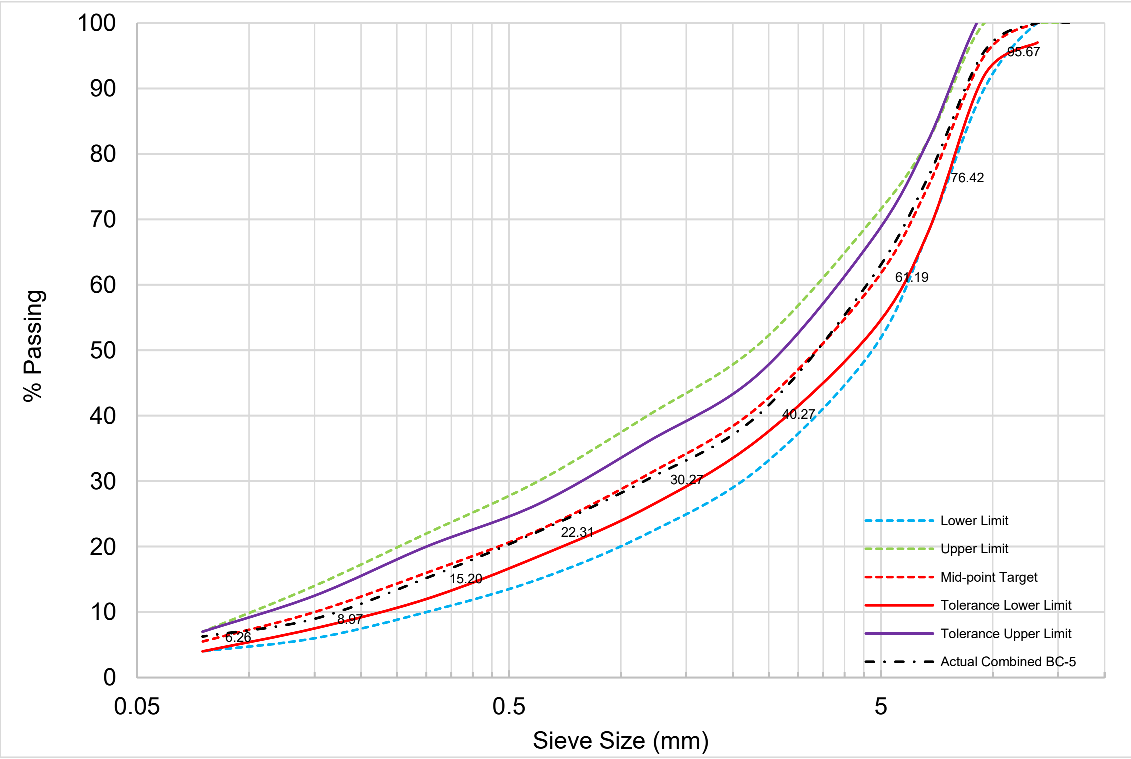

Figure 6-9: Combined PSD and grading limits BC-5 2.5%

Key mix properties are summarised in Table 6-5.

Table 6-5: BC-5 2.5% mix properties

Property	Value
Average Bulk Density (t/m^3)	2.319
Maximum density (t/m^3)	2.432
Average Air voids (%)	4.65
Bitumen content (%)	5.75
Blows	75
Average Marshall Stability (kN)	13.01
Average Flow (mm)	2.8

6.6. Mix design BC-5 5%

Specimens prepared with BC-5 at 5% fine aggregate replacement were successfully compacted, although the mix exhibited a drier appearance during mixing, consistent with observations from earlier milestones (Figure 6-10). The combined particle size distribution remained within the specified grading limits following biochar replacement, as shown in Figure 6-11. In contrast to other biochar-modified mixes, the BC-5 5% mix exhibited an increase in average Marshall Stability relative to the control mix, while Marshall Flow remained within acceptable limits. Bulk density was marginally reduced, reflecting the higher biochar content, and air void content remained within the target range.

Figure 6-10: Marshall specimens - BC-5 5%

As noted in Milestone Report M003, replacement levels exceeding approximately 2.8% biochar by mass of aggregates for BC-5, or 3.1% for BC-2, were found to be impractical due to the high surface area and pore volume of biochar, which adversely affect binder availability and compaction. Accordingly, **5% replacement represents the upper practical limit investigated in this study**.

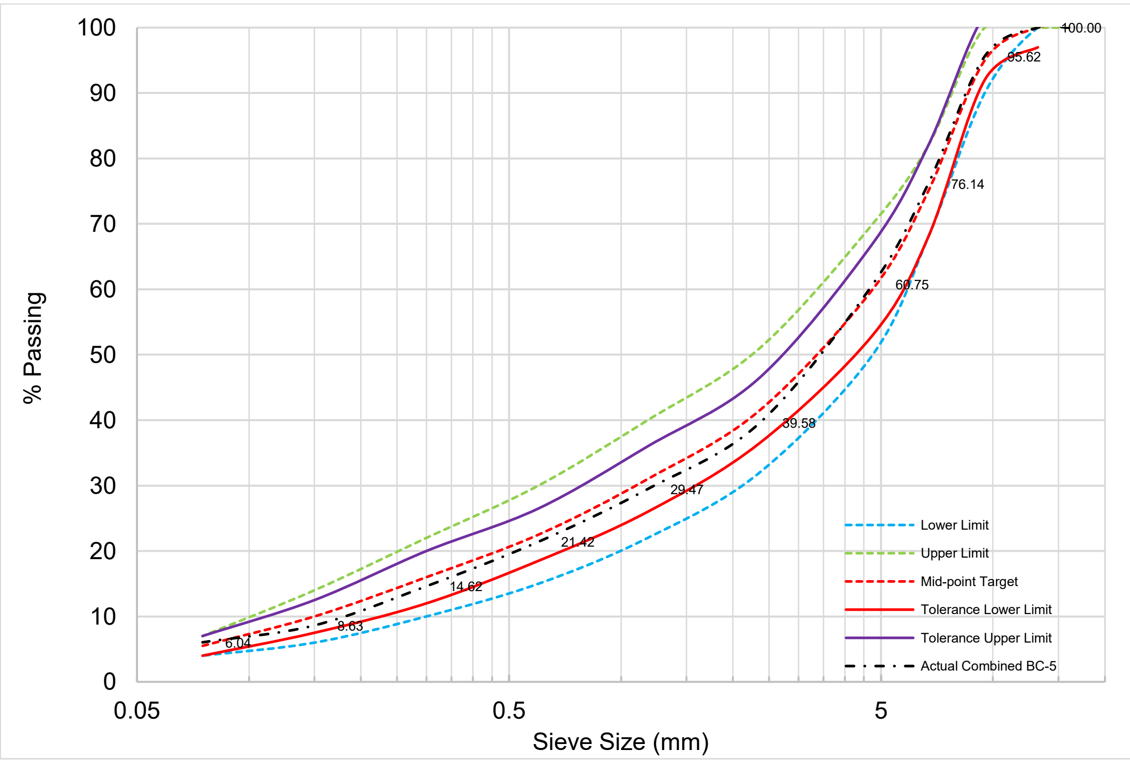

Figure 6-11: Combined PSD and grading limits BC-5 5%

Key mix properties are summarised in Table 6-6.

Table 6-6: BC-5 5% mix properties

Property	Value
Average Bulk Density (t/m^3)	2.295
Maximum density (t/m^3)	2.402
Average Air voids (%)	4.44
Bitumen content (%)	5.75
Blows	75
Average Marshall Stability (kN)	15.61
Average Flow (mm)	2.9

6.7. Summary of All Marshall Test Results and Comparisons

The Marshall test results for both the control mix and the five biochar mixes are presented in Table 6-7. The numbers brackets indicate the percentage change as compared to the control mix. All biochar mixes exhibit reductions in bulk density and maximum density, attributable to the lower specific gravity of biochar relative to the replaced dust; however, these density differences remain below 3%. Air void content was maintained within the specified range of 5±1% for all samples. Most biochar mixes demonstrated a reduction in Marshall stability of less than 10%, except BC-5 5%, which showed an 11% increase in Marshall stability. All samples fulfill the requirement of Marshall Stability > 8 kN. Furthermore, all biochar mixes displayed either comparable or enhanced Marshall flow, with increases not exceeding 15%, and all samples show the Marshall Flow within 2 ~ 4 mm (MainRoads WA 731.1).

Table 6-7: Summary of all mix Marshall test results

	Control	BC-1 (2.5%)	BC-2 (2.5%)	BC-2 (5%)	BC-5 (2.5%)	BC-5 (5%)
Average Bulk Density (t/m^3)	2.34	2.31 (-1.28%)	2.31 (-1.28%)	2.28 (-2.78%)	2.32 (-0.98%)	2.30 (-2.01%)
Maximum density (t/m^3)	2.45	2.42 (-1.06%)	2.44 (-0.57%)	2.40 (-2.25%)	2.43 (-0.69%)	2.40 (-1.92%)
Average Air voids (%)	4.35	4.57	5.05	4.9	4.65	4.44
Average Marshall Stability (kN)	14.06	12.66 (-9.96%)	13.84 (-1.56%)	13.57 (-3.49%)	13.01 (-7.47%)	15.61 (11.02%)
Average Flow (mm)	2.7	2.7 (0.00%)	3.1 (+14.81%)	3 (+11.11%)	2.8 (+3.70%)	2.9 (+7.41%)

Note: All mixes contain 5.75% bitumen by volume and are compacted with 75 blows.

7. Resilient Modulus Results

7.1. Specimen Preparation

The resilient modulus of all mixes was tested using indirect tensile method (ITM). The mixes included Control Mix, BC-1 2.5%, BC-2 2.5%, BC-2 5%, BC-5 2.5% and BC-5 5%. The samples were prepared according to AS/NZS 2891.2.1:2014 and compacted according to AS/NZS 2891.2.2:2014 using a gyratory compactor of fully electromechanical model. This procedure also involves heating the gyratory compactor mould assembly.

The compactor equipment revolves the mix in the 100 mm diameter mould at 60±5 rev/min, at 150°C applying a vertical loading stress of 240 kPa on a gyratory angle of 2±0.1 degrees. The compaction of the mixes was set to a target height, using the 95% of corresponding maximum density shown on Table 6-7. These results in a theoretical bulk density that contains 5±1% air voids. The bulk density of each block was then checked according to AS/NZS 2891.9.2:2014.

The initial compaction trial was carried out to determine the actual bulk density of the specimens. Results showed that the theoretical bulk density was approximately 3% lower for the control mix and 2.5% lower for the biochar mixes compared to the measured bulk density obtained using the water displacement (pre-saturation) method. This data helped ensure that each specimen was compacted to achieve the target air voids of 5±1%.

7.2. Test Results

Each specimen was conditioned in a temperature-controlled cabinet at 25 °C for approximately 4 hours, which is generally sufficient to reach equilibrium with the dummy specimens. The test was undertaken in line with AS/NZS 2891.13.1:2013 and the results are outlined in Table 7-1.

The average resilient modulus of each sample is based on the five loading pulses. The coefficient of variation of each sample indicates the reduction of resilient modulus during the five pulses. From Table 7-1, it can be seen that the control mix has higher coefficient of variation than those of the bicochar mixes. This demonstrates that the biochar mixes have more consistent over five loading pulses.

The resilient modulus was adjusted to a standard 5% air voids for all samples following AGPT Part 2 (Austroads, 2014), enabling more accurate comparisons. Table 7-1shows that all biochar mixes exhibit increased resilient modulus values, ranging **1.64 to 2.11** times that of the control mix, with BC-2 5% showing the smallest increase and BC-5 2.5% the largest. As noted in AGPT Part 4B (Austroads, 2014), this improvement may be due to higher binder viscosity from biochar or reduced binder content, which increases aggregate friction and thus the resilient modulus.

Increasing HMA stiffness improves load distribution (Austroads, 2014) and may serve as an alternative pavement structural layer. Proper mix design is essential to assess performance. Biochar mixes typically require more compaction due to reduced binder content and higher aggregate friction, so this should be considered when using biochar in HMA.

Table 7-1: Resilient Modulus Results Summary

Mix Design	Avg Max Density (t/m^3)	Avg Air Voids (%)	Gyro-compaction Number of Cycles	Avg Block Diameter (mm)	Avg Block Height (mm)	Avg Resilient Modulus (Mpa)	Coefficient of Variation (%)	Corrected Resilient Modulus to 5% Air Voids (AGPT PART 2)
CONTROL	2.449	4.55	73			2155.45		2095.62
A1		6.04	55	100	61.5	1949.0	39.4	2084.6
A2		4.00	80	100	61.5	2271.4	34.2	2138.2
A3		4.10	82	100	61.5	2282.9	38.7	2160.9
A4		4.04	75	100	61.5	2118.5	42.3	1998.8
BC-1 2.5%	2.423	4.68	102			3877.63		3804.38
A1		4.30	100	100	64.5	3663.3	11.3	3510.7
A2		4.70	108	100	64.4	4099.5	6.6	4025.1
A3		5.03	98	100	64.5	3870.1	7.7	3877.3
BC-2 2.5%	2.435	4.73	55.5			3487.90		3431.37
A1		5.05	51	100	62	3419.8	13.9	3431.3
A2		4.81	58	100	62	3578.8	8.9	3537.0
A3		4.37	55	100	62	3347.9	12.6	3220.8
A4		4.69	58	100	62	3605.1	14.2	3536.3
BC-5 2.5%	2.432	4.22	98.75			4768.03		4421.95
A1		4.13	95	100	63.6	4917.3	8.9	4663.7
A2		4.15	90	100	64.3	4770.8	6.4	4530.1
A3		4.46	100	100	63.4	4616	8.6	4466.1
A4		4.13	110	100	63.4	4247.8	7.5	4027.9
BC-2 5%	2.394	4.85	56.50			4036.23		3997.24
A1		5.14	56	100	63	3768.4	7.5	3801.1
A2		4.91	55	100	63	3705.2	6.8	3683.4
A3		4.35	60	100	63	4425.7	6.4	4252.1
A4		5.03	55	100	63	4245.6	8.2	4252.4
BC-5 5%	2.402	5.84	115.33			3888.67		4107.33
A1		5.71	115	100	65	3320.5	9.9	3474.3
A2		5.90	120	100	65	4345.7	11.7	4603.3
A3		5.92	111	100	65	3999.8	7.6	4244.4

8. Stripping Potential of Asphalt

To evaluate the stripping potential in all mixes for this project, the same procedures were followed for preparing and compacting specimens, as well as checking air voids, as detailed in Section 7.1. These steps ensure compliance with the requirements set out in ATM 232 (Austroads, 2022), which outlines methods for assessing asphalt stripping potential using the Tensile Strength Ratio.

All blocks were compacted to 8% ±1% air voids. Each batch produced ten specimens: three for dry testing, three for moisture-conditioned testing, two for partial saturation, and two as backups. Partial saturation followed ATM 232 clause 5.1, with all mixes reaching 71–79% saturation after five minutes in a vacuum desiccator (-80 kPa) at 50±5 °C. All moisture-conditioned specimens underwent this procedure prior to testing. No mix showed dimensional changes or swelling after moisture-conditioning.

The indirect tensile strength (ITS) test was performed on both dry and moisture-conditioned specimens, and the tensile strength ratio (TSR) is calculated as the ratio of tensile strength in wet to that in dry. Each group of dry and wet mixes contained three specimens, which produced consistent outcomes. Table 8-1 presents the average values from these specimens. The control mix achieved a TSR of **83%,** exceeding the required minimum of 80%.

Identical tests were performed for all biochar mixes, with detailed results provided in Appendix A. Table 8-2 summarises the test outcomes. All biochar mixes had lower average maximum densities than the control mix, with higher biochar content (5%) resulting in even lower densities due to dust replacement and the lower specific gravity of biochar. Air void content remained within the design specification (8±1%). TSR values for all mixes exceeded the 80% standard required by road and pavement authorities (Ur-Rehman, 2024), and biochar mixes showed **3–12%** higher TSR than the control, suggesting enhanced resistance to stripping.

After ITS completion, specimens were visually assessed for their broken faces. Figure 8-1 displays all control mix specimens, dry and wet. It can be observed that the dry mixes have more broken aggregates (white spots) than wet mixes, which appear darker. This means after soaking, the broke face shows more binder separation than aggregates breaking up. Figure 8-2 shows the images of biochar modified specimens with the high biochar content (BC-2 5%). The biochar addition yields a darker biochar mix appearance than the control mix. This could be due to the addition of biochar (dark colour) to form the matrix around the aggregates. The wet specimen of BC-2 5% shows lighter colour than that of dry specimen. With closer inspection, it displays the exposure of aggregates faces. This could mean that the biochar could absorb bitumen to its pores and leave less bitumen to bond all aggregates. Thus BC-2 5% has the lowest ITS. The images of all biochar mixes are in Appendix A, with similar results observed.

Table 8-1: TSR results of control mix

	Air Voids (%)	Gyro-Compaction (Number of Cycles)	Load (kN)	ITS (kPa)
Dry Specimen 1	8.74	14	38.85	38007.84
Dry Specimen 2	8.53	20	38.83	37988.27
Dry Specimen 3	8.72	20	42.30	41383.05
Dry Average	**8.66**	**18**	**39.99**	**39126.39**
Wet Specimen 1	8.76	15	36.09	35307.67
Wet Specimen 2	8.78	14	32.93	32216.17
Wet Specimen 3	8.81	17	31.08	30406.27
Wet Average	**8.78**	**15**	**33.37**	**32643.37**
TSR				**83%**

Note: all specimens have the height of 65mm and diameter of 100mm. The average maximum density is 2.45 t/m^3.

Table 8-2: Summary of TSR of all mixes

	Avg Max Density (t/m³)	***Moisture Condition***	***Avg Air Voids (%)***	***ITS (kPa)***	***TSR (%)***
Control Mix	2.45	Dry	8.66	39126	83
		Wet	8.79	32643	
BC-1 2.5%	2.42	Dry	7.82	41026	89
		Wet	7.89	36390	
BC-2 2.5%	2.44	Dry	7.40	45026	87
		Wet	7.89	39048	
BC-5 2.5%	2.43	Dry	8.27	33785	93
		Wet	8.66	31518	
BC-2 5%	2.40	Dry	8.28	45088	86
		Wet	8.55	38579	
BC-5 5%	2.40	Dry	8.34	33481	91
		Wet	8.52	30618	

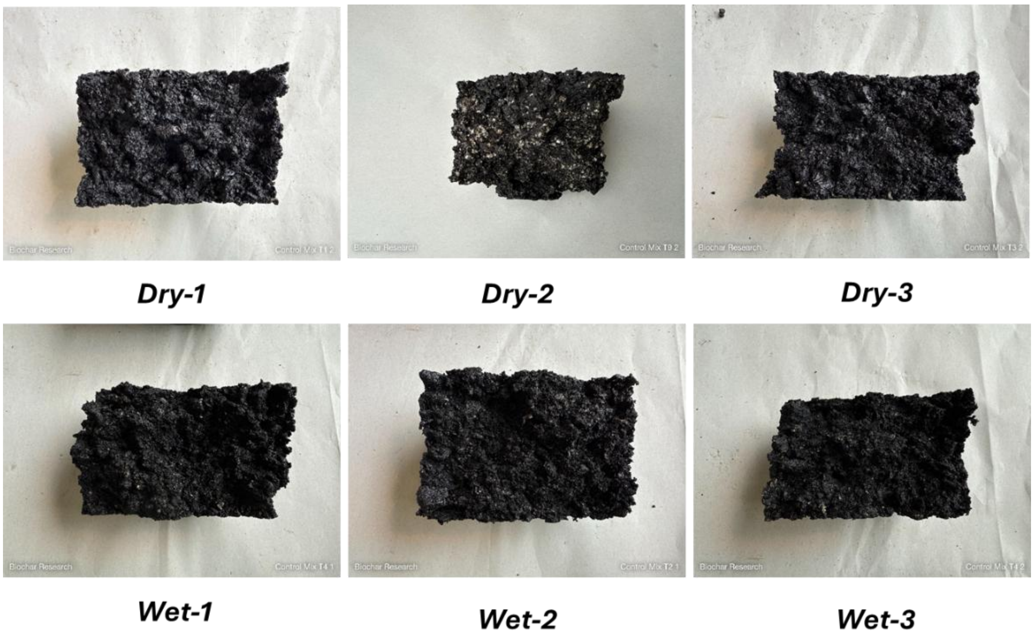

Figure 8-1: Images of broken faces of control mix post TSR tests

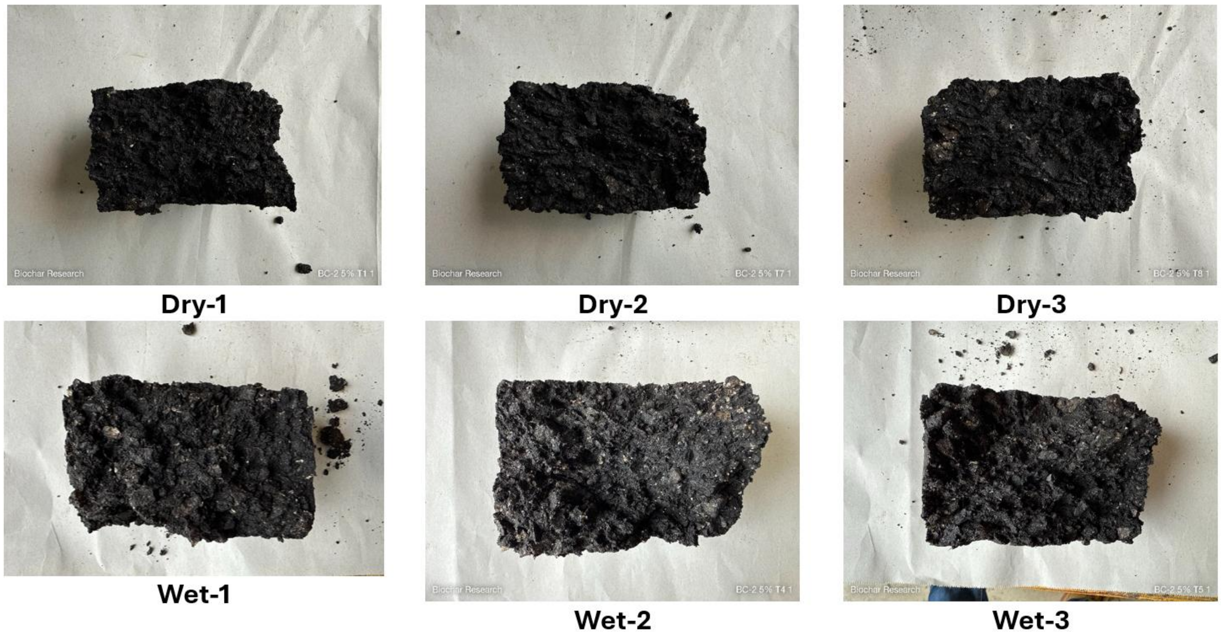

Figure 8-2: Images of broken faces of BC-2 5% Mix post TSR tests

9. Fatigue Performance Results

The fatigue performance of both the control and biochar mixes was assessed using four-point beam tests, in accordance with Austroads Test Method ATM 274 (AGPT/T274, 2023) and the European Standard EN 12697-24:2018 for Resistance to Fatigue. All mixtures were prepared and conditioned following AS/NZS 2891.2.1:2014, mixed according to ATM T220 (2005) using a Bitumix Automatic Laboratory Mixer with a 32L capacity, and compacted using a roller compactor fitted with a 305x400x100mm mould. Slabs were compacted to achieve target air voids of 5±0.5%. Each slab reached a height of 70mm and was allowed to cool at room temperature for a minimum of 24 hours prior to saw-cutting beams in the direction parallel to compaction (i.e., along the 400mm axis). The resulting beams exhibited smooth surfaces free from imperfections, measuring 50mm in height, approximately 63.5mm in width, and 395mm in length, as illustrated in Figure 9-1.

Figure 9-1: BC-2 2.5% Fatigue Beams B1 B2 and B3

Bulk densities and air voids were measured as per AS/NZS 2891.9.2:2014. After drying at room temperature for 24 hours, beams were conditioned at 20 °C for 4 hours. All beams underwent four-point bending at a strain amplitude of 200 με, with cabinet and test temperatures set to 20 °C. Fatigue tests ended at either 2×10^6 cycles at 10 Hz or when the modulus dropped to 50% of its initial value.

Table 9-1 presents four-point beam test results for six mixes (CB, B12, B22, B52, B25, B55). All meet the required air void content of 5±0.5%. While initial moduli for biochar mixes are generally higher than the control (except B55, which is 4.5% lower), their average fatigue life varies significantly and tends to be lower than the control. This may be due to increased binder viscosity from biochar, which, as noted in AGPT Part 4B (2014) and supported by findings from Ma et al. (2021), can reduce mix fatigue life.

Table 9-1: Fatigue performance results of all mixes at 200 με strain level

	Avg Air Voids (%)	Initial Modulus (Mpa)	Nf 50	Phase Angle (degrees)	Dissipated Energy (kJ/m³)	Cumulated Dissipated Energy (Mg/m³)
CONTROL	5.40	5898	215718			
C B1	5.38	5998	316279	22.7	0.146	64.870
C B2	5.35	5288	205732	21.1	0.120	34.840
C B3	5.46	6409	125144	23.6	0.164	29.000
BC-1 2.5%	5.35	6493	123465			
B12B1	5.25	6407	254969	21.0	0.146	49.470
B12B2	5.41	7087	64923	22.7	0.173	14.660
B12B3	5.38	5986	50503	19.5	0.131	13.720
BC-2 2.5%	5.20	6383	69620			
B22B1	4.85	6250	65396	19.5	0.131	13.720
B22B2	5.42	6574	63894	22.6	0.159	14.360
B22B3	5.34	6324	79570	22.6	0.153	17.050
BC-5 2.5%	5.13	7189	44401			
B52B1	4.85	7288	50820	24.6	0.191	13.760
B52B2	5.31	7538	32436	22.4	0.181	8.870
B52B3	5.32	6893	60154	22.6	0.168	14.180
B52B4	5.05	7036	34192	23.4	0.176	9.130
BC-2 5%	4.61	6194	110587			
B25B1	4.56	6583	289026	21.8	0.155	62.230
B25B2	4.35	6952	115003	22.4	0.168	26.280
B25B3	4.94	5727	13132	24.4	0.151	2.270
B25B4	5.45	5512	25187	23.0	0.135	4.590
BC-5 5%	5.03	5635	87506			
B55B1	4.74	6219	143605	22.4	0.150	32.630
B55B2	4.96	5445	46442	23.5	0.142	9.800
B55B3	5.34	5518	55455	22.9	0.136	10.890
B55B4	5.07	5359	104521	21.5	0.125	19.310

Fatigue life differs among beams cut from the same slab, with each slab divided into four beams. Beams that did not meet air void compliance were excluded. In the control mix, which included three beams, the beam with the highest fatigue life lasted more than twice as long as the one with the lowest. For the BC-5 5% mix, the two beams located at the ends of the slab (referred to as end beams: B55B1 and B55B4) exhibited significantly higher fatigue lives than those situated between them (middle beams: B55B2 and B55B3). Possible factors requiring further study include saw cutting consistency and uniformity of slab compaction.

Tseng et al. (2017) also reported variation in fatigue life results. Because four-point beam testing produces inconsistent fatigue life data, the impact of biochar on HMA remains unclear. Future research should increase specimen numbers and apply statistical analysis to clarify biochar’s effect on HMA fatigue life.

The fatigue life repeatability obtained from the Austroads four-point bending beam test is similar to that observed in EN 12697-24 fatigue methodologies. European round-robin studies have reported coefficients of variation for fatigue life generally ranging from 20% to 45%, with variations attributed to strain levels and specimen types. Accordingly, both Austroads and EN standards assess fatigue performance through regression-based relationships derived from multiple specimens, rather than relying on individual fatigue life measurements. It is recommended that a minimum of five beams be utilised for such evaluations.

However, the findings indicate a significant likelihood that the incorporation of biochar adversely affects fatigue life. Due to the variability in the results, it is advisable that future research includes testing a minimum of twelve beams produced from three compacted slabs. This approach is necessary as outcomes may be influenced by:

- Air-void heterogeneity
- Specimen preparation
- Asphalt – being a mixture, will have variations in particle distribution with the slab
- Stress concentrations on the tensile face can develop due to aggregate orientation
- Slab compaction may not be entirely consistent across the slab (density and air void heterogeneity)
- Sawing/trimming damage
- Handling damage during multiple stages of beam production

10. Rutting Resistance

Specimen preparation procedures outlined in Section 6 were similarly applied to the wheel tracking test (rutting performance). Specimens were prepared in accordance with the minimum requirements specified by Austroads Test Method ATM 231 (AGPT/T231, 2023). For each mix design, two slabs measuring 305 mm x 400 mm x 50 mm were produced. Following mixing and compaction, slabs were allowed to cool at room temperature for at least 48 hours prior to removal from the roller compactor mould. Subsequent steps included bulk density assessment and sample drying at room temperature for an additional 48 hours before commencing testing. Each specimen was then conditioned within the wheel tracker enclosure at 60°C for a minimum of five hours, ensuring both the internal thermometer and specimen probes achieved and maintained the target test temperature.

Table 10-1 summarises the results of the wheel tracking test. The biochar mixes generally yielded comparable performance to the control mix. An exception was noted for the BC-5 5% mix, which exhibited an average rutting depth of 12.27 mm, compared to 7.62 mm for the control mix, reflecting a 61% increase in rutting depth. Conversely, the BC-2 2.5% mix demonstrated an 8% reduction in rutting deformation relative to the control. Additionally, the BC-5 2.5% mix showed a 27% increase in rutting depth. These findings indicate that the observed performance reduction cannot be attributed solely to the presence of biochar, as the BC-5 2.5% mix contained the lowest proportion of biochar among all tested mixes.

Table 10-1: Wheel tracking test results for all mixes

Mix Design	***Avg Max Density (t/m^3)***	***Avg Air Voids (%)***	***Rut Depth (mm)***	***Cycles at 42 passes/min***
CONTROL	2.449	5.11	7.62	
C S1		5.44	7.89	10000
C S2		4.78	7.35	10000
BC-2 2.5%	2.435	5.21	7.01	
B22S1		4.88	7.16	10000
B22S2		5.54	6.85	10000
BC-2 5%	2.394	4.57	7.46	
B25S1		4.36	7.66	10000
B25S2		4.78	7.26	10000
BC-1 2.5%	2.423	5.74	8.60	
B12S1		5.53	9.31	10000
B12S2		5.94	7.89	10000
BC-5 2.5%	2.432	5.05	9.71	
B52S1		5.21	9.85	10000
B52S2		4.90	9.56	10000
BC-5 5%	2.402	5.14	12.27	
B55S1		4.92	13.2	10000
B55S2		5.35	11.34	10000

11. Carbon Sequestration

As discussed in Milestone Report M001, the incorporation of biochar into hot mix asphalt (HMA) has the potential to reduce carbon emissions associated with asphalt production and may also enable net carbon sequestration. This benefit is contingent upon the carbon sequestration achieved through biochar production, accounting for feedstock processing and the pyrolysis process, exceeding the greenhouse gas emissions generated during conventional asphalt production, including aggregate quarrying, hydrated lime manufacture, bitumen production, and asphalt mixing.

The estimated carbon sequestration potential of the asphalt mixes investigated in this study is summarised in Table 11-1, with calculations normalised to the production of one tonne of asphalt. It should be noted, however, that this assessment does not include transport-related emissions, which can vary significantly depending on material source locations, asphalt plant proximity, and contractor operational practices.

Net carbon sequestration values indicate whether a mix achieves overall carbon removal (positive values, marked green) or produces net emissions (negative values, marked red). Three mixes achieved net sequestration: BC-2 at both 2.5% and 5%, and BC-5 5%. The remaining mixes, including the control, produced net emissions because production-related carbon outputs exceeded the sequestration capacity of the biochar.

Biochar mixes also exhibit slightly lower maximum densities than the control, resulting in greater volume per tonne. This characteristic may allow the same mass of material to cover a larger surfacing area.

It can be concluded that biochar with higher carbon content can sequester carbon more effectively and achieve net-positive carbon sequestration, as noted for BC-2 2.5% which is the only biochar mix at 1.39% by mass of the mix and containing 85.2% carbon content.

However, even smaller volumes of biochar have a positive effect on the reduction of the net carbon balance.

Table 11-1a: Mix Composition

Mix Type	Density (t/m^3)	Carbon (%)	Mix Composition (% by mass)			
			Aggregates	Hyd. Lime	Biochar	Bitumen
Control	2.449	0.0	99.00	1.00	0.00	5.75
BC-1 2.5%	2.423	48.7	97.32	1.01	1.67	5.75
BC-2 2.5%	2.435	85.2	97.44	1.01	1.55	5.75
BC-5 2.5%	2.432	65.1	97.60	1.01	1.39	5.75
BC-2 5%	2.394	85.2	95.84	1.02	3.14	5.75
BC-5 5%	2.402	65.1	96.17	1.02	2.81	5.75

Note: Density in t/m^3; Carbon content (%) refers to feedstock carbon content.

Table 11-1b: Carbon Balance

Mix Type	Biochar Mass	Carbon Balance (kg CO_2-eq per tonne)		
		Production	Sequestration	Net
Control	0	36.47	0.00	-36.47
BC-1 2.5%	16.7	36.52	25.11	-11.41
BC-2 2.5%	15.5	36.52	44.05	+7.52
BC-5 2.5%	13.9	36.53	29.25	-7.27
BC-2 5%	31.4	36.57	89.23	+52.65
BC-5 5%	28.1	36.58	59.14	+22.56

Notes: Biochar mass in kg per tonne of asphalt. For all biochar mixes, feedstock processing emissions = 5.3% and pyrolysis emissions = 2.4% (by mass). Production emissions include all processing stages. ***Positive net values (green, +) indicate net carbon sequestration; negative values (red, −) indicate net emissions.***

12. Conclusions

This report has presented findings for Marshall Stability and Flow, resilient modulus, tensile strength ratio, fatigue performance, wheel tracking, and carbon sequestration potential of biochar-modified hot mix asphalt compared against an unmodified control mix.

Performance

Biochar can be incorporated into HMA without compromising essential performance requirements. Most biochar mixes showed minor reductions in Marshall Stability (less than 10%), except for BC-5 at 5% replacement, which increased stability by 11% relative to the control. All biochar mixes achieved substantial increases in resilient modulus, ranging from 164% (BC-2 5%) to 211% (BC-5 2.5%), attributed to higher binder viscosity and reduced effective binder content. In some cases, notably BC-2 2.5% for rutting resistance (8% reduction in rut depth) and multiple mixes for stiffness, biochar offered measurable improvements over conventional HMA.

Moisture Resistance

Biochar improves tensile strength ratio (TSR) and reduces stripping potential. All mixes exceeded the minimum TSR requirement of 80%, with biochar mixes achieving TSR values between 86% and 93%, representing improvements of 3–12% over the control mix (83%). Visual assessments confirmed no increased stripping tendency, and no specimens exhibited swelling after moisture conditioning.

Fatigue Performance

Fatigue results remain inconclusive due to high variability in fatigue life between specimens of the same mix. Additionally, the limited number of specimens tested constrained full assessment of this performance criterion. The findings do, however, indicate a likelihood that biochar incorporation adversely affects fatigue life. Future research should include testing a minimum of twelve beams produced from three compacted slabs to clarify biochar's effect on HMA fatigue behaviour.

Rutting Resistance

Wheel tracking results varied by biochar type. BC-2 2.5% demonstrated an 8% reduction in rut depth compared to the control, indicating improved rutting resistance. Conversely, BC-5 mixes showed increased rutting susceptibility: BC-5 2.5% exhibited a 27% increase in rut depth, while BC-5 5% showed a 61% increase. These findings suggest sensitivity to biochar type and pore structure rather than biochar presence alone.

Carbon Sequestration

When biochar has a high carbon content and is used at appropriate replacement levels, the modified asphalt can achieve net-positive carbon sequestration. Three mixes achieved net carbon removal per tonne of asphalt produced: BC-2 2.5% (+7.52 kg CO_2-eq), BC-2 5% (+52.65 kg CO_2-eq), and BC-5 5% (+22.56 kg CO_2-eq). Biochar effectiveness correlates strongly with carbon content, with BC-2's 85.2% carbon content producing the best sequestration outcomes. Even where net sequestration was not achieved, all biochar mixes reduced the net carbon balance relative to the control (−36.47 kg CO_2-eq).

Practical Considerations

Differences between biochars matter. Density, pore volume, and surface area influence binder absorption, compaction effort, and performance. Biochar types must be carefully selected and mix designs tailored to prevent excessive air voids or stiffness. Biochar mixes typically require more compaction effort due to reduced effective binder content and higher aggregate friction.

Recommendation

Biochar-modified HMA shows strong potential as a sustainable, lower-carbon pavement material. With proper selection of biochar type, especially high-carbon variants like BC-2, and optimised mix designs, biochar can enhance certain mechanical properties while enabling net carbon sequestration. In full-depth asphalt pavements, at higher levels in the pavement structure, fatigue performance is not likely to be a detractor for the use of biochar in asphalt. For thin wearing courses, application should be limited at this stage to low-traffic-volume situations until further testing determines the fatigue properties. Further work on fatigue performance and large-scale production trials is recommended before field implementation.

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APPENDIX

All specimens were labelled after compaction to the following alphanumeric structure according to Figure 0-1 for all biochar mixes and labels ranging from T1 to T10 for control mixes. This is to allow accurate air voids check and sorting the specimens for dry and moisture conditioned specimens.

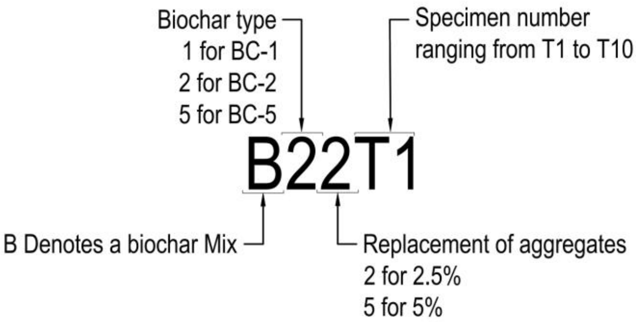

Figure 0-1: Specimen labelling structure

Table 0-1: Control Mix T1 Visual Assessment (Dry-1)

CONTROL MIX T1			
			
Aggregate size	**Property**	**Visual rating**	**Observations**
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Table 0-2: Control Mix T9 Visual Assessment (Dry-2)

CONTROL MIX T9

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Moderate	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Moderate	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-3: Control Mix T3 Visual Assessment (Dry-3)

CONTROL MIX T3

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Table 0-4: Control Mix T4 Visual Assessment (Wet-1)

CONTROL MIX T4

Aggregate size	**Property**	**Visual rating**	**Observations**
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-5: Control Mix T2 Visual Assessment (Wet-2)

CONTROL MIX T2

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-6: Control Mix T7 Visual Assessment (Wet-3)

CONTROL MIX T7

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-7: BC-1 2.5% TSR results summary

Mix Design / ID	Avg Max Density (t/m3)	Avg Air Voids (%)	Gyro-Compaction Number of Cycles	Specimen Set	H (mm)	D (mm)	L (kN)	ITS (dry) (Kpa)	ITS (wet) (Kpa)	TSR
BC-1 2.5%	**2.423**	**7.82**						**41025.97**	**36390.35**	**89%**
B12T6		7.77	26	DRY 1	65	100	41.89	40981.94		
B12T2		7.65	34	DRY 2	65	100	44.97	43995.18		
B12T10		7.78	31	DRY 3	65	100	38.9	38056.76		
	SUBSET AVERAGE AV (%)	**7.74**								
B12T1		7.93	50	MOISTURE 1	65	100	40.14		39269.88	
B12T4		7.85	29	MOISTURE 2	65	100	34.96		34202.17	
B12T9		7.97	30	MOISTURE 3	65	100	36.49		35699	
	SUBSET AVERAGE AV (%)	**7.89**								

Table 0-8: BC-1 2.5% T6 Mix Visual Assessment

_BC-1 2.5% T6_

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Table 0-9: BC-1 2.5% T2 Mix Visual Assessment

_BC-1 2.5% T2_

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Table 0-10: BC-1 2.5% T10 Mix Visual Assessment

BC-1 2.5% T10

Aggregate size	**Property**	**Visual rating**	**Observations**
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Table 0-11: BC-1 2.5% T1 Mix Visual Assessment

BC-1 2.5% T1

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Table 0-12: BC-1 2.5% T4 Mix Visual Assessment

BC-1 2.5% T4

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Table 0-13: BC-1 2.5% T9 Mix Visual Assessment

BC-1 2.5% T9

Aggregate size	**Property**	**Visual rating**	**Observations**
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Table 0-14: BC-2 2.5% TSR results summary

Mix Design / ID	***Avg Max Density (t/m3)***	***Avg Air Voids (%)***	***Gyro-Compaction Number of Cycles***	***Specimen Set***	***H (mm)***	***D(mm)***	***L (kN)***	***ITS (dry) KPa***	***ITS (wet) Kpa***	***TSR***
BC-2 2.5%	**2.435**	**7.61**						**45025.68**	**39048.12**	**87%**
B22T1		7.58	36	DRY 1	65	100	43.55	42605.96		
B22T6		7.28	44	DRY 2	65	100	49.13	48065		
B22T7		7.35	45	DRY 3	65	100	45.39	44406.07		
	SUBSET AVERAGE AV (%)	**7.40**								
B22T2		7.66	45	MOISTURE 1	65	100	41.28		40385.17	
B22T4		7.98	36	MOISTURE 2	65	100	40.34		39465.54	
B22T8		8.02	40	MOISTURE 3	65	100	38.12		37293.67	
	SUBSET AVERAGE AV (%)	**7.89**								

Table 0-15: BC-2 2.5% T1 Mix Visual Assessment

BC-2 2.5% T1

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-16: BC-2 2.5% T6 Mix Visual Assessment

BC-2 2.5% T6

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-17: BC-2 2.5% T7 Mix Visual Assessment

BC-2 2.5% T7

Aggregate size	**Property**	**Visual rating**	**Observations**
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-18: BC-2 2.5% T2 Mix Visual Assessment

BC-2 2.5% T2

Aggregate size	Property	Visual rating	Observations
Coarse	Coating of binder to aggregate	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	
Fine	Coating of binder to aggregate	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-19: BC-2 2.5% T4 Mix Visual Assessment

BC-2 2.5% T4

Aggregate size	Property	Visual rating	Observations
Coarse	Coating of binder to aggregate	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	
Fine	Coating of binder to aggregate	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-20: BC-2 2.5% T8 Mix Visual Assessment

BC-2 2.5% T8

Aggregate size	**Property**	**Visual rating**	**Observations**
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-21: BC-5 2.5% TSR results summary

Mix Design / ID	*Avg Max Density (t/m3)*	*Avg Air Voids (%)*	*Gyro-Compaction Number of Cycles*	*Specimen Set*	*H (mm)*	*D (mm)*	*L (kN)*	*ITS (dry) (Kpa)*	*ITS (wet) (Kpa)*	*TSR*
BC-5 2.5%	**2.432**	**8.44**						**33784.75**	**31518.3**	**93%**
B52T1		8.25	26	DRY 1	65	100	36.19	35405.5		
B52T3		8.57	22	DRY 2	65	100	31.99	31296.55		
B52T7		7.99	22	DRY 3	65	100	35.42	34652.19		
	SUBSET AVERAGE AV (%)	**8.27**								
B52T2		8.58	26	MOISTURE 1	65	100	29.24		28606.16	
B52T6		8.70	18	MOISTURE 2	65	100	32.26		31560.69	
B52T8		8.71	20	MOISTURE 3	65	100	35.15		34388.05	
	SUBSET AVERAGE AV (%)	**8.66**								

Table 0-22: BC-5 2.5% T1 Mix Visual Assessment

BC-5 2.5% T1

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Table 0-23: BC-5 2.5% T3 Mix Visual Assessment

BC-5 2.5% T3

3

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Table 0-24: BC-5 2.5% T7 Mix Visual Assessment

BC-5 2.5% T7

Aggregate size	**Property**	**Visual rating**	**Observations**
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Table 0-25: BC-5 2.5% T2 Mix Visual Assessment

BC-5 2.5% T2

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Table 0-26: BC-5 2.5% T6 Mix Visual Assessment

BC-5 2.5% T6

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Table 0-27: BC-5 2.5% T8 Mix Visual Assessment

BC-5 2.5% T8

Aggregate size	**Property**	**Visual rating**	**Observations**
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Table 0-28: BC-2 5% TSR results summary

Mix Design / ID	*Avg Max Density (t/m3)*	*Avg Air Voids (%)*	*Gyro-Compaction Number of Cycles*	*Specimen Set*	*H (mm)*	*D (mm)*	*L (kN)*	*ITS (dry) KPa*	*ITS (wet) Kpa*	*TSR*
BC-2 5%	**2.394**	**8.40**						**45087.64**	**38578.53**	**86%**
B25T1		8.15	44	DRY 1	65	100	45.65	44660.44		
B25T7		8.35	48	DRY 2	65	100	48.82	47761.72		
B25T8		8.35	54	DRY 3	65	100	43.79	42840.76		
	SUBSET AVERAGE AV (%)	**8.28**								
B25T2		8.51	41	MOISTURE 1	65	100	40.59		39710.12	
B25T4		8.48	51	MOISTURE 2	65	100	42.75		41823.3	
B25T5		8.66	45	MOISTURE 3	65	100	34.96		34202.17	
	SUBSET AVERAGE AV (%)	**8.55**								

Table 0-29: BC-2 5% T1 Mix Visual Assessment

BC-2 5% T1

Aggregate size	**Property**	**Visual rating**	**Observations**
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-30: BC-2 5% T7 Mix Visual Assessment

BC-2 5% T7

Aggregate size	**Property**	**Visual rating**	**Observations**
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-31: BC-2 5% T8 Mix Visual Assessment

BC-2 5% T8

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-32: BC-2 5% T2 Mix Visual Assessment

BC-2 5% T2

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	

	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-33: BC-2 5% T4 Mix Visual Assessment

BC-2 5% T4

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-34: BC-2 5% T5 Mix Visual Assessment

BC-2 5% T5

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-35: BC-5 5% TSR results summary

Mix Design / ID	***Avg Max Density (t/m3)***	***Avg Air Voids (%)***	***Gyro-Compaction Number of Cycles***	***Specimen Set***	***H (mm)***	***D (mm)***	***L (kN)***	***ITS (dry) (Kpa)***	***ITS (wet) (Kpa)***	***TSR***
BC-5 5%	**2.402**	**8.42**						**33481.47**	**30618.24**	**91%**
B55T1		8.68	18	DRY 1	65	100	33.20	32480.32		
B55T4		8.12	24	DRY 2	65	100	32.68	31971.59		
B55T10		8.22	23	DRY 3	65	100	36.79	35992.5		
	SUBSET AVERAGE AV (%)	**8.34**								
B55T2		8.58	19	MOISTURE 2	65	100	29.26		28625.73	
B55T3		8.26	21	MOISTURE 1	65	100	30.97		30298.66	
B55T5		8.71	21	MOISTURE 3	65	100	33.66		32930.35	
	SUBSET AVERAGE AV (%)	**8.52**								

Table 0-36: BC-5 5% T1 Mix Visual Assessment

BC-5 5% T1

Aggregate size	**Property**	**Visual rating**	**Observations**
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Table 0-37: BC-5 5% T4 Mix Visual Assessment

BC-5 5% T4

Aggregate size	**Property**	**Visual rating**	**Observations**
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Table 0-38: BC-5 5% T10 Mix Visual Assessment

BC-5 5% T10

Aggregate size	**Property**	**Visual rating**	**Observations**
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Semi-gloss	
	Cracked or broken aggregate	Minimal	

Table 0-39: BC-5 5% T2 Mix Visual Assessment

BC-5 5% T2

Aggregate size	**Property**	**Visual rating**	**Observations**
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-40: BC-5 5% T3 Mix Visual Assessment

BC-5 5% T3

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	
Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Table 0-41: BC-5 5% T5 Mix Visual Assessment

BC-5 5% T5

Aggregate size	Property	Visual rating	Observations
Coarse	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

Fine	**Coating of binder to aggregate**	Complete	
	Binder condition	Flat	
	Cracked or broken aggregate	Minimal	

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