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High modulus asphalt mix (EME) for heavy duty applications and preliminary laboratory test results in Australia

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Abstract

With the ever increasing traffic intensity and axle loadings, the state road authorities and the road construction industry face the challenge of designing and delivering high performance asphalt materials to meet the increasing demands. As part of Austroads project TT1353, 'Asphalt properties and mix design procedures' ARRB conducted a study in 2012/2013 to investigate the potential introduction of the French high modulus hot mix asphalt technology, called enrobés à module élevé (EME) to Australia. The EME mix technology provides a high performing asphalt material for use in heavy duty pavements, specifically suitable to carry large volumes of heavy vehicles, where there is a need for increased resistance to permanent deformation. Also, the technology can be utilised successfully in pavement strengthening, especially in areas with clearance constrains.

By using locally available aggregates and hard penetration grade bitumen, a laboratory based demonstration project, strictly based on performance related testing, was performed to provide insight and guidance for EME mix design. The laboratory program carried out in the work included the comprehensive characterisation of the EME mix on performance related testing, such as workability, durability, rutting resistance, stiffness and fatigue resistance.

In France, EME is designed and tested according to the European test series EN 12697, and specification requirements are set according to these test methods. The need for identifying specification limits based on locally available test methods is highlighted in the work, which needs to be completed in future research for a successful introduction of the technology to Australia.

1 INTRODUCTION

With the ever increasing traffic intensity and axle loadings, the state road agencies and the road construction industry face the challenge of designing and delivering high performance asphalt materials to meet these increasing demands. In Australia, several jurisdictions have specifications for heavy duty asphalt; however, currently, none of the jurisdictions have a specification for high modulus asphalt. As part of Austroads project TT1353 *Asphalt properties and mix design procedures* a demonstration study was conducted by ARRB in 2012-13 to investigate the potential transfer of French high modulus hot mix asphalt technology, known as enrobés à module élevé (EME) to Australia.

EME was developed in the mid-seventies in France and provides a high performance asphalt material for use in heavy duty pavements, specifically suitable in the following situations:

- pavements carrying large volumes of heavy vehicles and requiring strengthening to protect underlying layers

- where there are constraints to the allowable pavement thickness, especially in urban areas or motorways, where geometric constraints persist
- heavily trafficked areas, such as slow lanes, climbing lanes, bus lanes and airport pavements, where there is a need for increased resistance to permanent deformation.

The EME technology is predominantly used for structural asphalt layers, i.e. base and intermediate layers, which are referred to as foundation and base layer in the French terminology.

This work is an initial explorative study, and the main objective is to provide insight to and guidance on the EME mix design process, which is different to mix design approaches widely used in Australia. The full report is published in *EME Technology Transfer to Australia: An Explorative Study* (Austroads forthcoming) and this conference paper provides a summary of the work and the philosophy behind it. The objectives of this study can be summarised as follows:

- investigate the design methodology of EME asphalt mix, based on available international literature
- investigate requirements and availability of aggregate type, aggregate grading, and hard penetration grade binder
- provide input for implementation of the EME technology in Australia
- provide a comprehensive characterisation of EME mix using Australian test methods, including workability, moisture sensitivity, rutting resistance, stiffness and fatigue resistance.

The information collected and provided in this study will form the basis of the complete technology transfer which goes beyond the scope of this study and will be conducted in subsequent years.

This paper will summarised the design properties of EME and the experimental program carried out in 2012/13.

2 DESIGN PROPERTIES OF EME IN FRANCE

The French guidelines and specifications determine two types of EME, which are referred to as AC-EME in line with the European specifications. The two types of EME are AC-EME class 1 and AC-EME class 2 (National foreword, NF EN 13108-1-2007). Before the introduction of NF EN 13108-1-2007, EME was specified in NFP 98-140-1992, *Enrobés hydrocarbons, Couches d`assises: Enrobés à Module Élevé*, October 1992 (Asphalt – Road basecourses: road base high modulus asphalt concrete).

2.1 Binder Content and Richness Modulus

In the former EME standard NFP 98-140, the binder content was based on the concept of richness modulus, which is a bitumen film type approach and the binder content heavily depends on the combined aggregate grading curve of the mixture. In order to conform to the EN 13108 series which does not acknowledge this concept, the requirements for richness modulus were transformed to binder content requirements. In the new system, a minimum of 3.0% is determined as the empirical requirement for both AC-EME class 1 and AC-EME class 2. The requirements for richness modulus are summarised in Table 2.1.

Table 2.1: Requirements for richness modulus for AC-EME

Asphalt mix	Minimum richness modulus K (-)
AC-EME class 1	2.5
AC-EME class 2	3.4

Source: Delorme, Roche and Wendling (2007).

The richness modulus should be calculated according to Equation 1:

$$K = \frac{\left(\frac{100B}{100-B}\right)}{\alpha\sqrt[5]{\Sigma}} \tag{1}$$

where

B = ratio of the binder mass to the total asphalt mix mass, according to Equation 2 (mass %); in the French terminology B is also referred to as internal percentage of binder content. It is usually referred to as tl_{int}

α = correction coefficient relative to the density of the aggregates, according to Equation 3 (-)

Σ = the specific surface area, according to Equation 4 (m^2/kg)

$$B = 100\frac{bitumen\ mass}{dry\ aggregate\ mass + bitumen\ mass} \tag{2}$$

$$\alpha = \frac{2.65}{\rho_G} \tag{3}$$

where

ρ_G = the maximum density of aggregate (g/cm^3)

$$100\Sigma = 0.25G + 2.3S + 12s + 150f \tag{4}$$

where

G = the proportion of aggregate particles greater than 6.3 mm

S = the proportion of aggregate particles between 6.3 mm and 0.250 mm

s = the proportion of aggregate particles between 0.250 mm and 0.063 mm

f = the proportion of aggregate particles less than 0.063 mm.

The French mix design approach utilises various steps in general asphalt mix design. For AC-EME it requires the utilisation of all four steps, where the next following step should always be conducted, once the previous step has been met or finished. Testing levels and associated requirements are listed in Table 2.2.

Table 2.2: Testing levels and requirements for AC-EME

Step	Test method	Test type	Reference standard	Requirement
0	Grading and binder content (only for non-trafficked areas)	General + empirical	En 12697-2 EN 12697-1 or EN 12697-39	
1	Gyratory compaction	General + empirical	EN 12697-31	Gyratory compactor, % void at different gyrations
	Void content	General + empirical	EN 12697-6	Specifications on the percentage of voids based on the gyratory compactor test (direct height-based measurement) For cores EN 12697-6, C method (bulk density - sealed specimen)
	Water resistance	General + empirical	EN 12697-12	
2	Wheel tracking	General + empirical	EN 12697-22	Wheel tracking, large device (for asphalt mixes designed for axle loads greater than 13 tonnes), 30000 cycles, 60 °C
3	Stiffness modulus	General + fundamental	EN 12697-26	Two-point bending test, complex modulus, 15 °C, 10 Hz
4	Fatigue	General + fundamental	EN 12697-24	Two-point bending test, 10 °C, 25 Hz

Source: Delorme, Roche and Wendling (2007) and the cited EN standards.

2.2 Performance-based Mix Design of EME

2.2.1 Level 1 Testing

In the European product standards over specification is not allowed, i.e. to set multiple requirements for the same property. Therefore, for rut resistance, it is only the wheel-tracking test which should be conducted, and there is no requirement for void content at 10 gyrations.

Level 1 testing requirements for void content control are listed in Table 2.3. The maximum void content after a specified number of gyrations is required to ensure workability of the material. In this case the air void content should be determined according to EN 12697-31; this test standard includes a determination of the void percentage based on measurement of the specimen height.

For all AC-EME, the water sensitivity is required to be at least $ITSR_{70}$, tested according to EN 12697-12.

Table 2.3: Level 1 requirements for AC-EME

Asphalt mix	Gyratory compactor specifications after n gyrations		
	Number of gyrations (n)	Void percentage (%), EN 12697-31	
AC10-EME class 1	80	<10	V_{max10}
AC10-EME class 2	80	<6	V_{max6}
AC14-EME class 1	100	<10	V_{max10}
AC14-EME class 2	100	<6	V_{max6}
AC20-EME class 1	120	<10	V_{max10}

Asphalt mix	Gyratory compactor specifications after n gyrations		
AC20-EME class 2	120	<6	V_{max6}

Source: Delorme, Roche and Wendling (2007) and NF EN 13108-1.

2.2.2 Level 2 Testing

Level 2 testing requires the wheel-tracking test according to EN 12697-22, using the large device, which is related to asphalt mixes designed for axle loads greater than 13 tonnes. The test should be carried out at 60°C and terminated at 30 000 cycles. Percentage in rutting should be less than 7.5%, where the result should be calculated as the rut depth divided by the slab thickness. This means the standard requires relative and not absolute rut depth.

2.2.3 Level 3 and Level 4 Testing

Level 3 testing requires testing of the stiffness modulus at 15 °C and 10 Hz according to EN 12697-26, method A, which refers to the two-point bending test on trapezoidal specimens.

Level 4 testing requires testing of the fatigue resistance at 10 °C and 25 Hz according to EN 12697-24, method A, which refers to the two-point bending test on trapezoidal specimens (Delorme, Roche & Wendling 2007 and NF EN 13108-1). Testing requirements are summarised in Table 2.4.

Table 2.4: Level 3 and level 4 requirements for AC-EME

Asphalt mix	Minimum stiffness modulus at 15 °C and 10 Hz (MPa)	Fatigue resistance at 10 °C, 25 Hz (microstrain)
AC-EME class 1	14 000	100
AC-EME class 2	14 000	130

Source: Delorme, Roche and Wendling (2007) and NF EN 13108-1.

2.3 Requirements for Constituent Materials

2.3.1 Binder Types Used in EME

Although NF EN 13108-1 does not provide guidance about the binder type in EME mixes, useful information can be found in Delorme, Roche and Wendling (2007). It is suggested that the binder should be 15/25 or 10/20 hard penetration grade binder according to EN 13924-2006, *Bitumen and bituminous binders, specifications for hard paving grade bitumens*. The requirements of the above binder types are summarised in Table 2.5.

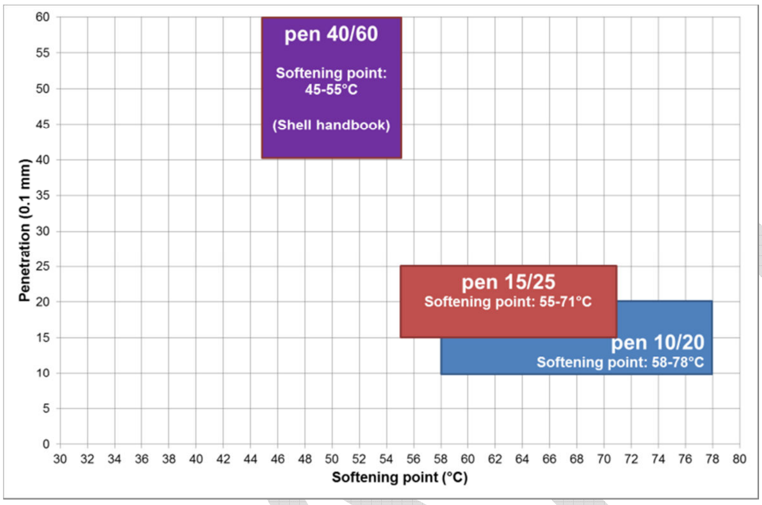
Table 2.5: The requirements of hard penetration grade binders

Requirement	Property	Standard	Unit	Penetration grade	
				15/25	10/20
Consistency at mid-temperatures	Penetration at 25 °C	EN 1426	0.1 mm	15 to 25	10 to 20
Consistency at high temperatures	Softening point	EN 1427	°C	55 to 71	58 to 78
	Dynamic viscosity at 60 °C	EN 12596	Pa.s	≥ 550	≥ 700
Long-term performance (resistance to hardening)	Mass change	EN 12607-1 or -3	%	≤ 0.5	
	Retained penetration	EN 1426	%	≥ 55	
	Softening point after hardening	EN 1427	°C	≥ original minimum + 2	
	Increase in softening point	EN 1427	°C	≤ 8	≤ 10

Requirement	Property	Standard	Unit	Penetration grade	
Other properties	Kinematic viscosity at 135 °C	EN 12595	mm2/s	≥ 600	≥ 700

Source: EN 13924.

Figure 2.1 visualises the requirements of 10/20 and 15/25 hard penetration grade binders. For comparison, the requirements of a Pen 40/60 bitumen are also provided, based on the data taken from the Shell handbook (Read & Whiteoak 2003).



Source: Based on Read and Whiteoak (2003) and EN 13924.

Figure 2.1: Visualisation of hard penetration grade binder requirements

2.3.2 Aggregate Grading of the EME

Particle size distributions are considered to be continuous for AC-EME mixes; however, utilisation of discontinuities into the grading curve is allowed. According to EN 130108-1 *Bituminous mixtures, Material specifications, Part 1: Asphalt concrete* the requirements for the grading shall be expressed in terms of maximum and minimum values by selection for the percentages passing the sieves of:

- 1.4 D (where D is the nominal size of the aggregate in the mixture, in millimetres)
- D (where D is the nominal size of the aggregate in the mixture, in millimetres)
- a characteristic coarse sieve
- 2 mm
- 0.063 mm.

Based on Delorme, Roche and Wendling (2007) and NF EN 13108-1 the overall control points for AC14-EME is visualised in Figure 2.2.

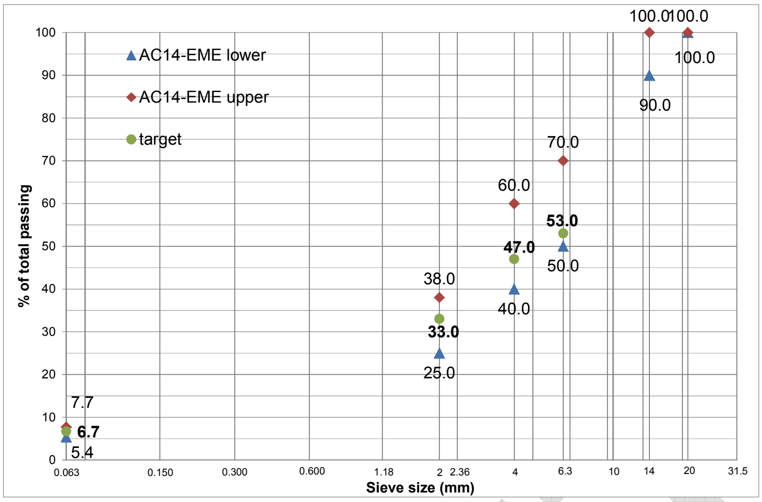


Figure 2.2: Grading control points for AC-EME

Source: Based on Delorme, Roche and Wendling (2007) and NF EN 13108-1

2.3.3 Aggregate Requirements

Requirements for fillers and aggregates of the EME mix are outlined in the French specifications, which is discussed in the Austroads report (Austroads forthcoming). The relevant AS test methods are also summarised in the report; due to limited space it is not discussed here.

3 EXPERIMENTAL PROGRAM – EME MIX DESIGN

3.1 Binder Test Results

A number of major Australian bitumen suppliers were approached during September and October 2012, to find out whether they would be able to supply hard paving grade binder (10/20 Pen or 15/25 Pen), with properties within or close to the requirements of EN 13924:2006. Two suppliers responded that their product would be able to fulfil the above requirements and binder samples were supplied for laboratory testing and subsequent EME mix design; the test results of the binders are summarised in Table 3.1.

3.1.1 Brookfield Test

Brookfield tests were performed according to *AGPT/T111 Handling viscosity of polymer modified binders, Brookfield thermosel* (Austroads 2006a). In this study a Brookfield DV–II+PRO viscometer was used. In order to determine mixing and compaction temperature ranges, the Brookfield test was conducted at 135 – 150 – 165 – 180 °C. In this test series spindle S31 was used throughout the test series. The test results are summarised in Figure 3.1. For comparison, a conforming C320 binder and an A15E binder are also presented on the graph.

Table 3.1: Specifications for hard paving grade bitumens according to EN 13924-2006

Specifications	Surrogate characteristic	Test methods	Unit	Classes [3]		Australian test method		ARRB material register	
				2	3			B1973	B2316
Consistency at intermediate service temperature	Penetration at 25 °C	EN 1426	0.1 mm	15 to 25	10 to 20	Penetration at 25 °C (pu)	AS 2341.12	19.7	20.1
Consistency at elevated service temperature	Softening point	EN 1427	°C	55 to 71	58 to 78	Softening point (°C)	AGPT/T131	64.5 63.0 [2]	70.8 69.3 [2]
	Dynamic viscosity at 60 °C	EN 12596	Pa.s	≥ 550	≥ 700	Viscosity at 60 °C (Pa.s)	AS 2341.2	2776	10200
						Viscosity at 60 °C (shear rate)		0.60	0.16
Durability, resistance to hardening at 163 °C (EN 12607-1)	Change of mass	EN 12607-1 or -3	%	≤ 0.5	N/A	Loss of heating (%)	AGPT/T103	0.02	0.02
	Retained penetration	EN 1426	%	≥ 55	N/A	Penetration at 25 °C after RTFO (pu)	AGPT/T103 AS 2341.12	13.7 (retained penetration 70%)	16.2 (retained penetration 74%)
	Softening point after hardening	EN 1427	°C	≥ orig. min. +2	N/A	Softening point after RTFO (°C)	AGPT/T103 AGPT/T131	70.4 68.9 [2]	81.0 79.5 [2]
	Increase in softening point	EN 1427	°C	≤ 8	≤ 10			Increase in softening point 5.9 °C	Increase in softening point 10.2 °C
	Increase in softening point & penetration index before test	EN 1427 Ip[1]	°C	≤ 10 from -1.5 to +0.7	≤ 10 ≤ -1.5			PI on original bitumen -0.1; -0.4 considering shift factor [2]	PI on original bitumen +1.1; +0.8 considering shift factor [2]
Other properties	Kinematic viscosity at 135 °C	EN 12595	mm²/s	≥ 600	≥ 700	Brookfield viscosity at 135 °C (Pa.s)	AGPT/T111	1.329 (1290 mm²/s)	2.264 Pa.s (2198 mm²/s)
	Fraas breaking point	EN 12593	°C	≤ 0	≤ 3	Not tested	Not tested	Not tested	Not tested
	Flash point	EN ISO 2592	°C	≥ 235	≥ 245	Not tested	Not tested	Not tested	Not tested
	Solubility	EN 12592	% mass fraction	≥ 99.0	N/A	Matter insoluble in toluene (% mass)	AS 2341.8	0.03	0.11
Tested for Australian specification (not required in EN standard)	N/A					Viscosity at 60 °C after RTFO (Pa.s)	AGPT/T103 AS 2341.2	6992	54428
	N/A					Viscosity at 60 °C after RTFO (shear rate)		0.40	0.18
	N/A					Precent increase in viscosity at 60 °C after RTFO test (%)	N/A	252	534

1: Ip calculation according to Annex A of EN 13924-2006.
2: Considering shift factor; the ASTM and AS results are generally 1.5 °C higher than for the EN method (Read & Whiteoak 2003).
3: Classes are defined according to EN 13924-2006.

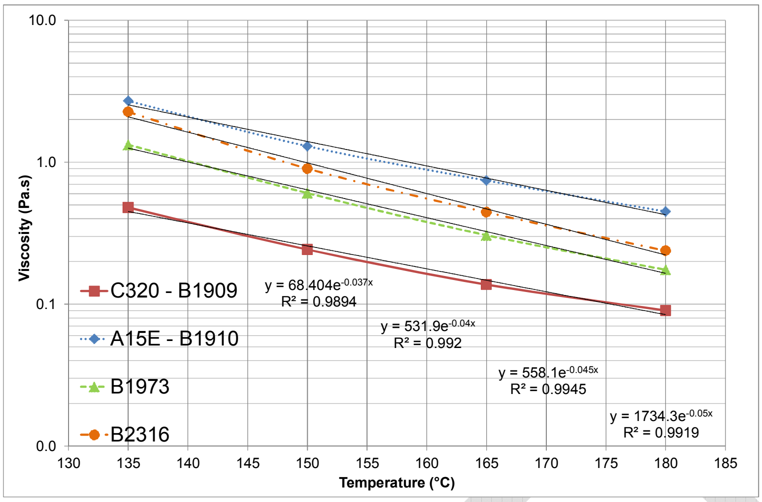


Figure 3.1: **Brookfield viscosity results for different binder types**

3.1.2 DSR Test – Temperature-Frequency Sweep Test

Temperature-frequency sweep was performed between 20 and 70 °C. Two sets of the frequency-temperature sweep were completed to be able to assess variability in the test data. It was found that there is no difference between the two set of test results. The master curve (visualised at 45 °C) of the two EME binders is presented in Figure 3.2; a conforming C320 binder and an A15E are also presented for comparison.

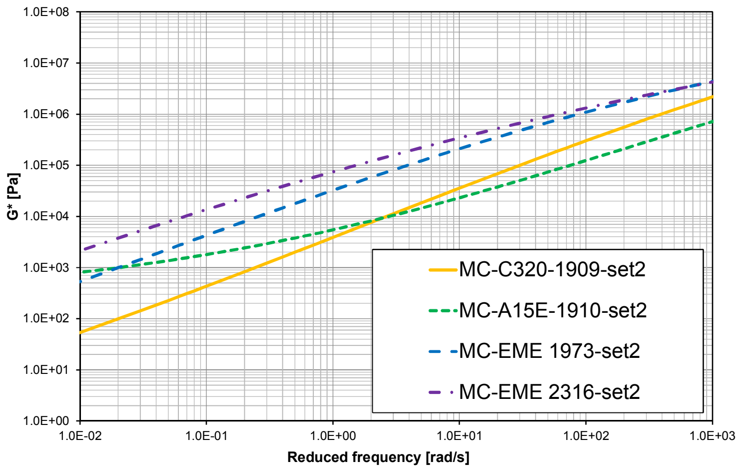


Figure 3.2: **Master curve of different binders at 45 °C**

3.2 Aggregate Test Results

It was envisaged during the project development that a road trial would be set up to evaluate in-place performance of the EME mix. Evaluation of the EME mix requires very heavy traffic loading and at the time of aggregate sourcing it was envisaged that a suitable construction site could be selected in the Sydney region. Therefore all aggregates were sourced for the mix design from Sydney.

3.2.1 Test Methods

The properties of the aggregate were characterised using the following tests:

- aggregate grading in accordance with AS 1141.11.1-2009
- particle density on a dry basis (ρ_{bd}) using AS 1141.5-2000 for fine aggregate and AS 1141.6.1 - 2000 for coarse aggregate
- compacted bulk density, or rodded unit weight (RUW) in accordance with AS 1141.4-2000
- uncompacted bulk density, or loose unit weight (LUW), also in accordance with AS 1141.4-2000.

3.2.2 Test Results

Table 3.2 shows the grading results for the aggregates. The 14 mm, 10 mm, 7 mm and 5 mm aggregates are basalts, the dust is a blend of natural sand and crusher dust, the sand is natural sand. Baghouse fines were used as filler for the mix designs; some mix designs also included one or two per cent of hydrated lime.

The results in Table 3.2 further show the particle density of the aggregates on a dry basis (ρ_{bd}). To be able to optimise the volumetrics of the mix design using the Bailey method (Vavrik et al. 2002), LUW and RUW parameters were determined. The mix design was to be created is an EME with a 14 mm nominal maximum aggregate size (NMAS). For a 14 mm NMAS mix, the Bailey method primary control sieve (PCS) is the 2.36 mm sieve. Any aggregate with more than 50% of particles retained above the PCS is a coarse aggregate according to the Bailey method principles, any aggregate with more than 50% passing the PCS is a fine aggregate. For a dense graded mix, LUW tests are performed on the coarse aggregates and RUW tests are performed on fine aggregates. LUW tests were therefore performed on the 14 mm, 10 mm, 7 mm and 5 mm aggregates. RUW tests were performed on the dust and the sand; on the fillers no tests are required. The LUW and RUW information can be used to assess the volume of coarse and fine aggregate in the mix and optimise the aggregate packing. The volume of voids in coarse aggregate in the LUW condition is 1–LUW / ρ_{bd}; voids left by the coarse aggregate are filled by the volume of fine aggregate which is equal to RUW / ρ_{bd}.

Table 3.2: Aggregate grading and density information

Sample ID	2134	2133	2131	2130	2135	2127	2136	1342
Product	14mm	10mm	7mm	5mm	Dust	Sand	Baghouse fines	Hydrated lime
26.50 mm	100	100	100	100	100	100	100	100
19.00 mm	100	100	100	100	100	100	100	100
13.20 mm	76	100	100	100	100	100	100	100
9.50 mm	12	83	100	100	100	100	100	100
6.70 mm	2	28	76	100	100	100	100	100
4.75 mm	2	10	27	87	100	100	100	100
2.36 mm	2	2	3	18	89	96	100	100
1.18 mm	1	1	1	3	67	88	100	100
600 µm	1	1	1	2	46	68	100	100
300 µm	1	1	1	2	26	24	100	100
150 µm	1	1	1	2	14	6	100	100
75 µm	0.8	0.8	1	1.5	8.4	2.1	94	100
ρ_{bd} (g/cm^3)	2.630	2.650	2.641	2.610	2.438	2.531	2.498	2.517
LUW (g/cm^3)	1.439	1.400	1.368	1.381	N/A	N/A	N/A	N/A

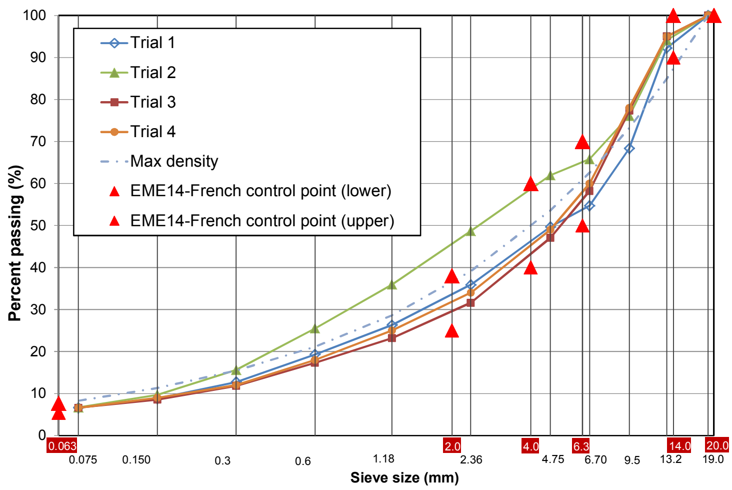
RUW (g/cm^3)	N/A	N/A	N/A	N/A	1.510	1.557	N/A	N/A
Loose voids (%)	45.3	47.2	48.2	47.1	N/A	N/A	N/A	N/A
Rodded voids (%)	N/A	N/A	N/A	N/A	38.1	38.5	N/A	N/A

3.3 Mix Design Procedure – Trial Mixes

The mix design of EME is an iterative process. Mixes are produced using trial aggregate grading curves and binder contents and submitted to the performance-based tests shown in Table 2.2. Based on the results of the tests, changes are made to optimise the design and improve the performance against one or more parameters in Table 2.2.

As part of the mix design process, the performance of four different trial gradings was assessed. The grading curves are shown in Figure 3.3. To provide an appreciation of the density of the gradation, the results are plotted using the so called 'Fuller' gradation with the sieve size raised to the power of 0.45. This allows the plotting of the maximum density line, i.e. the grading that theoretically would result in the highest possible density.

The first grading was designed to match the target grading for 14 mm EME; the subsequent trial gradings were created using Bailey method principles. The constituents of the different trial aggregate blends are shown in Table 3.3; the table also shows the Bailey method coarse chosen unit weight (CA CUW) condition. The CA CUW for the French EME target grading was back-calculated. It is 95% of the coarse aggregate LUW condition; this indicates that this is a coarse graded mix. Coarse graded mixes typically have a CA CUW of 95% to 105% of the CA LUW. Trial grading 2 was designed to be a fine graded mix with a CA CUW of 70% of the CA LUW condition. Trial grading 3 is a very coarse graded mix with a CA CUW of 105% of the CA LUW. Trial grading 4 is a design grading that was optimised using the Bailey method to have maximum voids in mineral aggregate (VMA). The aim was to create an aggregate skeleton that would allow the inclusion of a high binder content without compromising the air void content and permanent deformation performance. The CA CUW condition of Trial 4 is 100% of the CA LUW. The grading of the combined aggregate blends is shown in Figure 3.3. A variation on Trial grading 3, containing 2.0% of hydrated lime was tested as well.



Note: Sieve sizes indicated in red background are the French standard sieves.

Figure 3.3: Trial grading curves

Table 3.3: Components of aggregate blends

Trial	% of product added								CA CUW
	14 mm	10 mm	7 mm	5 mm	Dust	Sand	Baghouse fines	Hydrated lime	
1	32.6	19.6	0	11.4	32.6	0	3.8	0	95
2	24.4	14.3	0	9.7	49.4	0	2.2	0	70
3a	20.6	26.7	9.9	11.5	27.4	0	3.9	0	105
3b	20.6	26.7	9.9	11.5	27.4	0	1.9	2.0	105
4	19.8	25.6	9.5	11.1	30.4	0	2.6	1.0	100

The trial binder contents are shown in Table 3.4. As in any other asphalt mix design, the binder content is a key to meet fatigue performance and permanent deformation criteria in the mix design process. The initial binder content was set to 5.8% by mass of total mix. This results in a richness modulus K that is slightly higher than the minimum of 3.4 for 14 mm EME2 mixes. The intention of selecting this binder content was to assess the mixes at this initial binder content and then improving the fatigue or rutting performance of the mix where required by either increasing or decreasing the binder content. The aggregate packing of trial 4 was optimised to maximise VMA and as such, it was decided to initially test it at higher binder content (Trial 4a). A second set of tests was performed on Trial 4 for with the intention of maximising the rut resistance and therefore the binder content was reduced to the minimum K value of 3.4 (Trial 4b).

Table 3.4: Trial binder contents

Property	Trial 1	Trial 2	Trial 3a	Trial 3b	Trial 4a	Trial 4b
Binder content by mass of total mix (%)	5.8	5.8	5.8	5.8	6.3	5.5
Richness modulus K (-)	3.6	3.6	3.7	3.7	4.0	3.4

3.4 Mix Design Procedure – Performance of the Trial Mixes

The performance of the trial mixes was assessed against the performance parameters in Table 2.2. For each of the French performance tests, an Australian equivalent test method was selected; the test methods are shown in Table 3.5. The Servopac gyratory compactor equipment was used to provide a measure of the workability of the mix. To allow for an easier comparison of the results to the French EME specification, the settings of the Servopac equipment were changed to match the specifications of the French gyratory compactors. The compaction pressure was set to 600 kPa, the angle of gyration to 0.82 degrees and the speed of compaction to 30 cycles per minute (EN 12697-31).

3.4.1 Rut Resistance

The rut resistance of the mix was assessed using the wheel-tracking test in accordance with Austroads method AGPT/T231 (Austroads 2006b), instead of the large wheel-tracking device as required for EME in France. The test results are provided in Section 3.4.5.

3.4.2 Flexural Modulus

For the determination of the flexural modulus of the material, the four-point bending test on beam specimens was selected as an equivalent to the French two-point bending tests on trapezoidal specimens. The flexural modulus test was run in accordance with EN 12697-26. The modulus of the material was assessed at the same conditions as used in the French specifications i.e. at 10 Hz and 15 °C. The test results are discussed in Section 3.4.5.

3.4.3 Fatigue Resistance

The French specifications require performing the fatigue testing according to EN 12697-24, by using the two-point bending testing on trapezoidal specimens (method A). Due to the lack of equipment in Australia, fatigue testing was performed using the four-point bending test (Austroads 2006c) instead of the French two-point bending test. Tests were performed at 20 °C, initially at 400 microstrain, with the intention of running additional tests at three different strain levels to complete the full fatigue factorial on 18 specimens required in the European specification (EN 12697-24). Requirements for fatigue testing significantly differ from the Australian test method; the differences are outlined in the Austroads report (Austroads forthcoming).

Fatigue characterisation was performed according to AGPT/T233, with the following exceptions:

- three strain levels were applied, in line with EN 12697-24; strain levels were selected in such a way that the strain level to 1 000 000 load repetitions could be determined through interpolation
- at least one-third of the element tests provided results less than 10E+6 cycles and at least one-third of the element tests provided results greater than 10E+6 cycles
- at least 18 element tests were performed to determine the results.

The results of the complex fatigue characterisation of the EME mix are discussed in Section 3.4.5.

3.4.4 Moisture Sensitivity

For the moisture sensitivity, the standard AGPT/T232 (Austroads 2007b) modified Lotmann test and the standard European test method (EN 12697-12) were performed. Although the French methodology identifies moisture sensitivity as step two in the design process, in this study this test was performed at the final stage, in order to avoid extensive and unnecessary testing with failing trials.

The European standard includes different procedures to determine the moisture sensitivity (also referred to as water sensitivity), the indirect tensile test (method A) and direct compression test (method B) derived from the Duriez test. These two procedures give equivalent results, however, the repeatability and reproducibility of the direct compression test (Duriez test) is considered better (Delorme, Roche & Wendling 2007). Since equipment and experience are readily available in Australia with the indirect tensile test, this test method was performed according to the EN standard and the Austroads test methods respectively. A comparison of the EN and Australian test methods is provided in the Austroads report (Austroads forthcoming). The results of the moisture sensitivity tests are discussed in Section 3.4.5.

3.4.5 Test Results Summary

General discussion of the trialling phase

To set design criteria for EME1 and EME2, comparative testing would be required using French and Australian test equipment. This does not form part of the scope for the project for the current year. However, for the current project, indicative criteria were set, shown in the last column of Table 3.5. Since the Servopac settings were configured in accordance with the French test method, the indicative workability requirement is equal to the French specification for EME2. The flexural modulus requirement was also kept the same as the French criterion for EME2. The permanent deformation requirement was set based on the criterion for superior rutting performance in Part 4B of the *Austroads Guide to Pavement Technology* (Austroads 2007a). The indicative fatigue criteria were set based on the criterion for lightly modified PMB asphalt and superior conventional bitumen asphalt in Part 4B.

Table 3.5: Performance testing

Property	Test method	Settings	Indicative criteria (1)
Workability	Servopac compaction	100 gyrations, compaction pressure 600 kPa, angle of gyration 0.82 °, 30 gyrations/minute	Air voids < 6%
Modulus	Four-point bending (EN 12697-26)	10 Hz, 15 °C	> 14 GPa
Permanent deformation	Wheel tracker (AGPT T231)	60 °C to 10 000/30 000 load repetitions	< 3.5 mm
Fatigue	Four-point bending (AGPT/T233)	At 20 °C, initially at 400με and other two strain levels	Nf_{50} 1 x 10^{5}-10^{6}
Moisture sensitivity	AGPT/T232 – EN 12697-12	Standard	N/A

1: Indicative criteria are provided in order to assess performance based on existing Australian experiences. The criteria listed here are not considered as tentative specification limits; these limits should be developed in subsequent projects.

The results of the performance tests for the different trials are summarised in Table 3.6. Note that not all performance tests were run for each of the trial designs. During the mix design iterations, there is little benefit in performing all tests on each new trial design if that trial did not yield enough of an improved performance against the targeted parameter for that trial.

Table 3.6: Performance test results

Trial ID	1	CV(1)	2	CV(1)	3a	CV(1)	3b	CV(1)	4a	CV(1)	4b	CV(1)
Workability: air voids (%)	0.7	N/A	1.9	N/A					2.0	N/A	3.9	N/A
Modulus [MPa] (mean)	13 596	4.3%			12 020	3.8%	12 684	3.8%	11 092	4.3%	13 461	3.2%
Fatigue (mean) Nf_{50}	209 720	21.2%			260 420	33.1%	151 680	20.31%	243 950	31.0%	115 870	27.6%
Wheel tracking Rut depth 10k (mm)	3.8		3.2	N/A	3.7	N/A			3.1	N/A	2.7	N/A
Wheel tracking Rut depth 30k (mm)			4.1	N/A	4.7	N/A			4.3	N/A	3.1	

1: Coefficient of variation (CV) is the ratio of the standard deviation to the mean. It shows the extent of variability in the test results relative to the mean value.

The initial trial mixes–Trial 1, 2 and 3a–were designed at the same time. Wheel-tracker slabs were compacted for these mixes and it was found that only Trial 2 met the indicative criterion of < 3.5 mm. The wheel-tracker results are shown in Figure 3.5; tests were run up to 30 000 cycles as required for the large wheel-tracker according to the European specifications, but using the small wheel-tracker equipment. Rut depths at 10 000 and 30 000 cycles are reported in Table 3.6. Only one specimen was tested per trial, as the intention during the design process is to make significant improvements in each iteration. Only the final mix design is subjected to the full set of tests.

Slabs for modulus and fatigue testing were compacted for Trial 1 and 2. The average flexural modulus results for the different trials are shown in Figure 3.4; four beams were tested for each design. Frequency sweep tests were performed to characterise the modulus at different loading times. Note that the frequency at which the mixes are assessed against the 14 GPa criterion is 10 Hz. After it became clear that the trial mixes 1 and 3 did not meet the modulus criterion, it was decided not to compact a slab for fatigue beams for Trial 2. Instead, a mix was designed containing 2% hydrated lime in an attempt to increase the modulus–this is Trial 3b. Unfortunately, this did not have the desired effect on the modulus.

Another concern from the first design iterations was the low void content in the workability tests. Although there is only a maximum requirement for air voids, it was feared that very low void contents may be related to reduce permanent deformation resistance. An attempt was made to optimise the aggregate packing for VMA using the Bailey method. The results were Trial 4b, which has an increased VMA compared to the earlier iterations as shown in Table 3.7. Trial 4a does not have a higher void content in the workability test; this is because the binder content was also increased to optimise fatigue performance.

Table 3.7: Volumetric properties

Property	T1	T2	T4a	T4b
Max. density (t/m^3)	2.437	2.429	2.426	2.449
Bulk density (t/m^3)	2.419	2.383	2.377	2.353
Air voids (%)	0.7	1.9	2.0	3.9
VMA (%)	10.7	11.6	13.1	14.3

The results of the initial fatigue tests at 400 microstrain are shown in Figure 3.6. The results show considerable scatter, which is characteristic for fatigue test results. It is impossible to statistically rank the mix designs, even though four beams were tested per mix instead of the set of three specimens commonly tested in Australia.

With the intention to optimise rutting performance, specimens with the Trial 4 grading were also prepared at the minimum binder content that still yielded a satisfactory richness modulus K–this is Trial 4b.

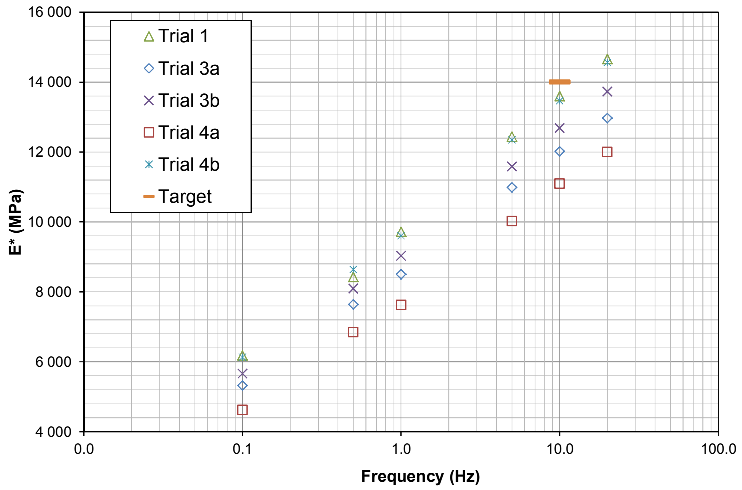


Figure 3.4: Flexural modulus frequency sweep results

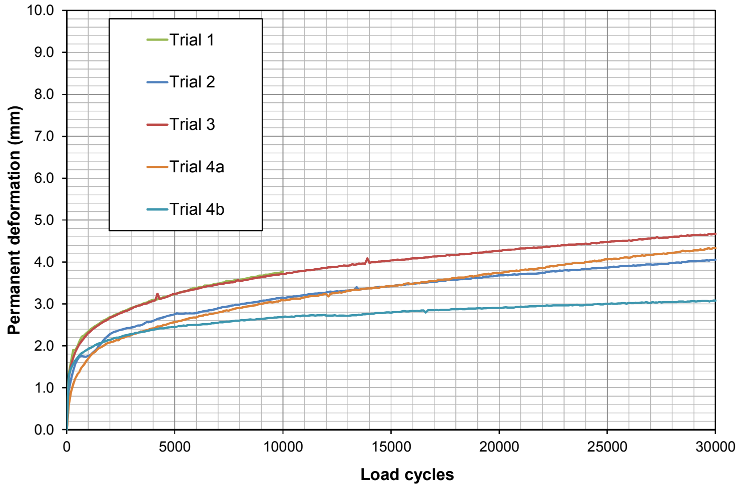


Figure 3.5: Wheel-tracker results

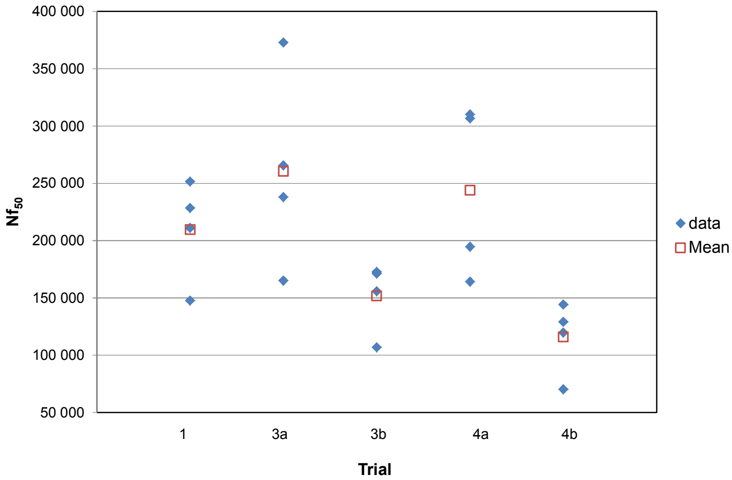


Figure 3.6: Preliminary fatigue results, mix design, trial phase

Fatigue characterisation

As discussed in Section 3.4.3, in order to determine the fatigue line and characterise the fatigue property of the EME mix in this way requires extensive laboratory testing. The results of the complete fatigue test, outlined in Table 3.8, required all together 247 hours to complete; given at 10 Hz frequency, 36 000 cycles can be applied in an hour. Although a full characterisation requires extensive and time consuming testing, it is considered the only feasible way to gain reliable results.

Table 3.8: Test results of fatigue testing (18 beams)

Strain level (microstrain)	Loading cycles						
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Specimen 6	Specimen 7
400	194 680	164 230	310 200	306 690	312 500	115 980	236 800
550	21 910	42 740	40 780	61 990	38 490	47 540	N/A
310	1 208 680	761 280	1 461 460	1 374 770	1 119 670	1 060 510	N/A

According to EN 12697-24, Appendix A, the general from of the fatigue line is provided in Equation 5. Based on the results in Table 3.8, the fatigue line is shown in Figure 3.7, which can be expressed as outlined in Equation 6:

$$\lg(N) = a + \left(\frac{1}{b}\right) * \lg(\varepsilon) \quad (5)$$

$$\lg(N) = 21.36 + \left(\frac{1}{-0.163}\right) * \lg(\varepsilon) \quad (6)$$

where

N = number of load cycles

a = constant

b = slope of fatigue line

ε = strain (microstrain)

The calculated strain is ε_6 = 319 μstrain (at 1 million cycles), and the slope of the fatigue line is b = -0.163.

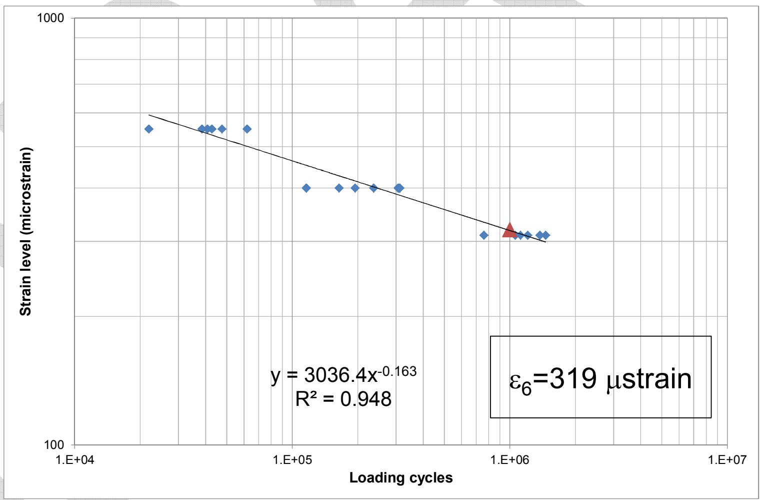


Figure 3.7: Fatigue line of the EME mix

The level 4 requirement for EME class 2 according to the French specification is 130 μstrain at 10 °C, 25 Hz, in accordance to EN 12697-24, method A (Delorme, Roche & Wendling 2007 and NF EN 13108-1). The test results of this study (Figure 3.7) cannot be directly related to the French specification limits as the test set-up and circumstances are different to the Australian test method. Establishing specification limits for confirming EME mixes under Australian test conditions will require extensive inter-laboratory testing and this work will be carried out in subsequent years and follow-up research projects.

Moisture sensitivity

According to the test parameters outlined in Section 3.4.4, the moisture sensitivity test results are summarised in Table 3.9 and Table 3.10. The saturation requirements and conditioning framework are different in AGPT/T232 and EN 12697-12. Although the samples had a higher swell than 2% following the vacuum procedure, the test was performed on these samples. It is thought that the high swell value was a combined result of the low air void content, high negative pressure and long vacuum conditioning. More experience is needed with how to apply and build up the pressure since the EN standard sets out the requirements (timeframe and target) but does not provide practical guidelines for the procedure. Also, in the test series according to AGPT/T232 it is required that a vacuum is maintained for 10 minutes in the saturation procedure; this requirement was not fulfilled as the samples became saturated in a much shorter timeframe.

The minimum requirement of indirect tensile strain ratio (ITSR) is 70% according to the French specifications; the EME mix (Trial 4a) fulfilled this requirement with a TSR value of 94.0%, according to AGPT/T232 and an ITSR value of 94.6% according to EN 12697-12.

Table 3.9: Stripping potential according to AGPT/T232

Subset	Property	Series 1	Series 2	Series 3	Average
Wet	Number of gyratory cycles	10	10	10	N/A
	Air voids (%)	7.0	7.0	7.5	7.2
	Degree of saturation (Sp) (%)	57.1	58.0	62.7	59.3
	Swell (Vs nearest 0.1%)	0.6	0.3	0.1	0.3
	Force (P nearest 0.1 kN)	12.5	12.3	12.6	12.5
	Tensile strength (kPa)	1138.7	1127.0	1150.6	1138.8
	Type of failure (EN 12697-23)	C	C	C	N/A
Dry	Number of gyratory cycles	10	10	10	N/A
	Air voids (%)	7.0	7.0	7.6	7.2
	Force (P nearest 0.1 kN)	13.5	13.7	12.1	13.1
	Tensile strength (kPa)	1263.2	1274.3	1096.7	1211.4
	Type of failure (EN 12697-23)	A	A	A	N/A
Tensile strength ratio (TSR)					**94.0**

Table 3.10: Water sensitivity according to EN 12697-12 and EN 12697-23

Subset	Subset type	Series 1	Series 2	Series 3	Average
Wet	Number of gyratory cycles	50	50	50	N/A
	Air voids (%)	4.1	4.5	3.9	4.2
	AGPT/T232 degree of saturation (Sp) (%)	65.6	63.2	70.9	66.6
	EN 12697-6 (volume change after vacuum (%))	2.2	2.3	2.5	2.3
	EN 12697-6 (volume change after conditioning (%))	2.9	2.8	2.9	2.9
	AGPT/T232 degree of saturation (Sp) (%)	81.7	76.6	81.9	80.1
	Force (P nearest 0.01 kN)	17.5	17.7	16.8	17.3
	Tensile strength (GPa)	0.00158	0.00163	0.00157	0.00159
	Type of failure (EN 12697-23)	C	C	C	N/A
Dry	Number of Marshall blows or gyratory cycles	50	50	50	N/A
	Air voids (%)	3.5	3.3	3.5	3.4
	Force (P nearest 0.01 kN)	18.0	17.5	18.6	18.0

Subset	Subset type	Series 1	Series 2	Series 3	Average
	Tensile strength (GPa)	0.00166	0.00166	0.00173	0.00168
	Type of failure (EN 12697-23)	A	A	A	N/A
Indirect tensile strength ratio (ITSR)					**94.6**

4 SUMMARY AND CONCLUSIONS

The primary aim of this study was to investigate the potential introduction of the French high modulus asphalt technology, called enrobés à module élevé (EME) to Australia. The EME mix technology provides a high performing asphalt material for use in heavy duty pavements, specifically suitable in the following situations:

- the pavement carries large volumes of heavy vehicles and requires strengthening
- there are geometric constraints, such as height restrictions, to apply the required thickness of the overlay
- heavily trafficked areas, such as slow lanes, climbing lanes, bus lanes and airport pavements, where there is a need for increased resistance to permanent deformation.

Due to the elevated pavement temperatures in Australia, the EME application may provide a cost-effective solution for heavy duty pavements.

4.1 Summary

A comprehensive literature survey was conducted to provide information on the development of EME; this is considered important as the design approach of the EME mix differs from mix design approaches typically used in Australia in that it strictly applies performance-based and performance-related testing. Guidance on selecting appropriate aggregate grading and binder content for the trial mixes is discussed in detail. Also, case studies were referenced to provide insight into the mix design process and the achieved performance assessment.

The mix design procedure is summarised in Section 3. The iterative nature of the laboratory testing reported in the study also provides a good understanding for practitioners with respect to the complexity and requirements of an EME mix design. Aggregate grading was selected to meet the initial grading control points provided by the French guidelines and meet the minimum richness factor, which relates to the required binder content; the lowest selected binder content in the trials was 5.8%. The laboratory program carried out in the work includes the comprehensive characterisation of the EME mix on the performance-related parameters as summarised below.

4.2 Conclusions

The explorative study provides an insight into the complexity of the design of EME mixes. The trial mixes were tested in accordance with Australian test methods; at this stage it is not possible to benchmark the performance of the trial mixes against the French specification limits. However, the results are promising as the study showed that relatively high stiffness combined with superior fatigue resistance can be achieved, without compromising the rutting or stripping potential. It is believed that through further optimisation and/or the application of fully crushed sand and potentially harder bitumen would increase the design properties.

Also, this demonstration study highlighted that for a successful technology transfer it is important to select corresponding Australian standardised test methods to measure the performance of the design mix. This would also be the basis of setting correct performance limits in specifications; the complexity of this issue was discussed in the study. Test methods for the binder are readily available; however, test methods for fillers, aggregates and for the EME mix would require more work in subsequent projects.

Stiffness and fatigue properties are input values into the mechanistic pavement design. It is important to highlight that fatigue properties obtained from the mix design cannot be directly translated into transfer functions, which are used in the pavement design procedure. Transfer functions used in Australia today may not be suitable to use for EME mixes. The transfer functions currently used were developed for mixes which are different in composition to EME mixes. The utilisation of these functions would introduce a disconnection between mix performance in the laboratory and field. The correlation between fatigue properties obtained from the laboratory mix design procedure and transfer functions require long-term performance observations and performance monitoring. The work in this area will be continued in projects currently underway focusing on the following topics:

- develop specification limits and verify these under field conditions in future field trials
- provide a comprehensive pavement design method for EME; this work would require performance monitoring of trial sections.

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