FILLER: IS IT 'FIXING' YOUR BINDER?

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ABSTRACT

The workability of an asphalt mix is dependent on factors including mix nominal size, particle size distribution, binder content, binder properties, mastic properties and temperature. An investigation was undertaken into the properties of the mastic component, which is the combination of filler (material passing the 0.075 mm sieve) and binder, of Stone Mastic Asphalt (SMA).

For some time, the filler-binder ratio has been used as an indicator of the workability of an asphalt mix. This investigation found that the filler-binder ratio has some influence on workability, but on its own is misleading.

In this investigation, various mastics were manufactured using a combination of filler and binder types, mixed at different proportions. The viscosities of the produced mastics were measured at temperatures covering the range typically utilised for plant mixing and field compaction.

It was demonstrated that a proportion of the binder becomes 'fixed' to the filler, and is therefore no longer available, or 'free' to coat the coarse and fine aggregates in the mix, nor provide adequate adhesion to the underlying substrate.

The proportion of binder fixed by the various fillers used was shown to be a function of the following parameters: voids in the dry compacted filler (Rigden Voids); apparent particle density of the filler, proportion of filler in the combined aggregates; proportion of binder in the mix; and, binder density.

The viscosities of the mastics were found to be dependent on the proportion of binder fixed by the filler, binder viscosity, and temperature.

This investigation showed that the influence of filler type on workability could be significantly different to past experiences.

1 INTRODUCTION

In recent years in Queensland the workability of Stone Mastic Asphalt (SMA) has been variable. Cases of poor workability have been reported, resulting in difficulties in achieving adequate compaction, and associated permeability issues.

The purpose of this project was to improve the workability of SMA. The workability of any asphalt mix is a function of factors such as mix nominal size, particle size distribution, binder properties, binder content, mastic properties and temperature. An investigation was undertaken into the mastic component of SMA, in relation to mix workability.

SMA is a processed mixture of:

- Coarse aggregate (4.75 mm or larger in size);
- Fine aggregate (natural sand particles and/or crushed rock or crushed gravel particles of size smaller than 4.75 mm but larger than 0.075 mm);

- Filler (natural sand particles and/or crushed rock or crushed gravel particles and/or added filler, with particle size smaller than 0.075 mm);
- Bituminous binder; and,
- Fibre.

The term 'mastic' has been used historically in various ways. One such definition has been to describe all the material which fills the void space in the coarse aggregates (i.e. it includes sand, filler, binder and fibre). However, for the purposes of this investigation the term mastic has been used to refer to the combination of filler and binder only.

For some time, the filler-binder ratio has been used as an indicator of the workability of an asphalt mix. The filler-binder ratio is calculated by dividing the percentage by mass of filler in the combined aggregates by the percentage by mass of binder in the mix. This investigation found that the filler-binder ratio has some influence on workability, but on its own is misleading. Other characteristics of the mastic were identified as being significant in relation to mix workability.

In this investigation, various mastics were manufactured in the laboratory using a combination of filler and binder types, mixed at different proportions. Typical proportions for SMA were adopted. However, the observed relationships may also be relevant for other asphalt mix types.

The viscosities of the produced mastics were measured at various temperatures, covering the range typically adopted for plant mixing and field compaction. The existence of a relationship between the mastic component properties and viscosity was investigated.

2 MATERIALS

The components of the mastic (filler and binder) were analysed individually as well as in their mastic form. Materials that were commonly included in Queensland SMA mixes were studied.

BINDERS

Size 14 mm SMA mixes (SM14) in Queensland typically incorporate between 5.8 and 6.2 % (by mass) of binder. The typical binder used is A5S polymer (SBS) modified binder (PMB) in accordance with Queensland Department of Main Roads (QDMR) specification MRS11.18, which A15E binder is nearest to in the Austroads classification system in APT-04. Some mixes have been manufactured with C320, multigrade and other PMB binders.

The two most common binders, A5S PMB and Class 320 bitumen were selected for this study. The viscosities of the binders at various temperatures were measured using the Brookfield Viscometer. Results are summarised in Table 2.1.

Table 2.1 Binder Properties

Binder	**Viscosity (Pa.s) at given temperature**			
	135 ^{o}C	**150 ^{o}C**	**165 ^{o}C**	**180 ^{o}C**
A5S	3.0	1.3	0.88	0.54
Class 320	0.45	0.23	0.14	0.09

FILLERS

SMA mixes typically include added filler and filler generated from the coarse and/or fine aggregates due to crushing and abrasion during handling/mixing. The added filler may be one or a combination of materials including quarry dust, rock flour, flyash, hydrated lime, agricultural lime or baghouse fines (which is typically a mixture of various filler types, depending on what was used in manufacture at the time).

At the time of this project, the QDMR specification (MRS11.33A) for SM14 required 8 to 10 % (by mass) of the combined aggregates passing the 0.075 mm sieve (i.e. 8 to 10 % filler). The specification also required a minimum of 2 % (by mass) hydrated lime and a minimum of 4 % (by mass) total added filler. A minimum limit of 38 % was specified for voids in the dry compacted combined filler. This minimum limit (originally minimum 40 %) had been historically adopted as it conveniently excluded fillers which had been problematic (Spies, 1996).

The fillers were tested for apparent particle density, voids in the dry compacted filler and particle size distribution. Results are summarised in Table 2.2. In addition to the Queensland fillers tested, results from testing of some USA fillers using Queensland test methods are included for comparison. Shaded rows indicate fillers which were the most commonly used fillers in South-East Queensland at the time and which were further analysed and used for mastic manufacture.

Table 2.2 Filler Properties

Filler Type	Apparent Particle Density (t/m^3)	Voids in the dry compacted filler (%)	% passing dry 0.075 mm sieve(1)
Hydrated Lime (DML)	2.23	52	75
Flyash (Swanbank) Samp1e 1a	2.19	54	97
Flyash (Swanbank) Sample 1b (2)	2.26	57	97
Flyash (Swanbank) Sample 2 (2)	2.04	54	84
Ultra-fine quarry dust (Petrie)	2.90	52	99
Baghouse fines (BCW)	2.72	41	89
Agricultural lime	2.69	39	75
Flyash (Yabula)	2.18	50	70
Hydrated Lime (Woodstock)	2.24	57	75
Limestone (Maryland, USA)	2.81	37	43
Granite quarry dust from washing (Virginia, USA)	2.90	44	64
Granite quarry dust from vacuum collection (Virginia, USA)	2.79	35	36

Notes

(1) source material contains particles of size 0.075 mm or larger, however, only the portion passing the 0.075 mm sieve is defined as filler;

(2) due to higher than expected voids in Flyash Sample 1a, the sample was re-tested (Sample 1b) and a second independent sample was sourced and tested (Sample 2). Sample 1a was used for all subsequent testing and analysis.

The particle size distribution of the commonly used fillers, as measured by Cement Australia Limited, are shown in Figure 2.1. The fillers were also analysed under a scanning electron microscope (SEM). The resulting images are shown in Figures 2.2a to 2.2d.

Some of the significant observations from the grading curves and SEM images are:

- Flyash was more single sized than the other fillers with a much lower proportion of mid-sized particles around 5 to 25 microns;
- Ultra-fine dust was much finer in size than the other fillers;
- Flyash particles had rounded edges and a porous structure;
- Baghouse dust includes a mixture of material types which would be dependent on the materials being used in the asphalt plant at the time of production.

Figure 2.1 Particle size distribution of portion passing 0.075 mm sieve

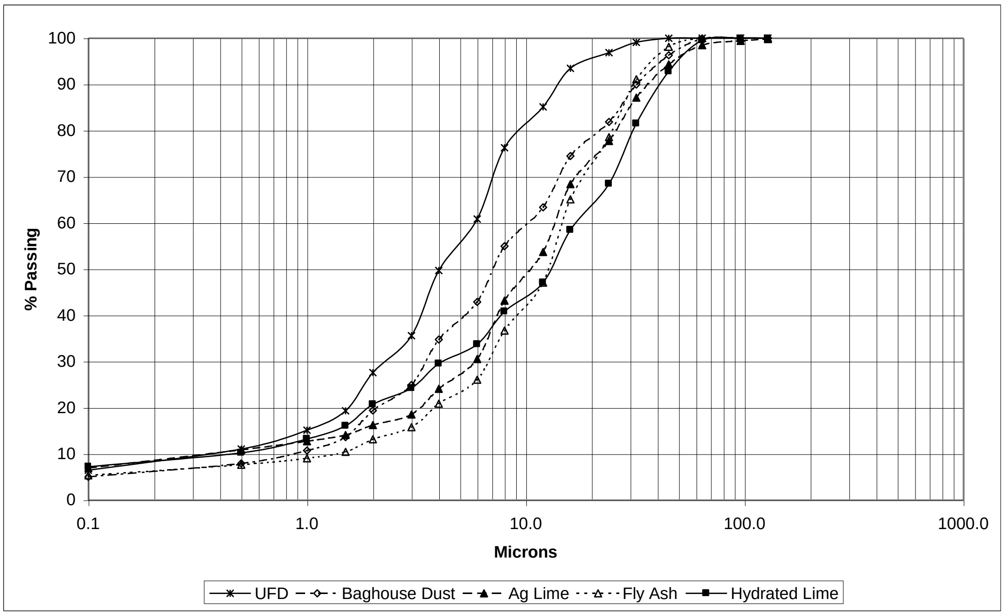


Figure 2.2a SEM Image of Hydrated Lime

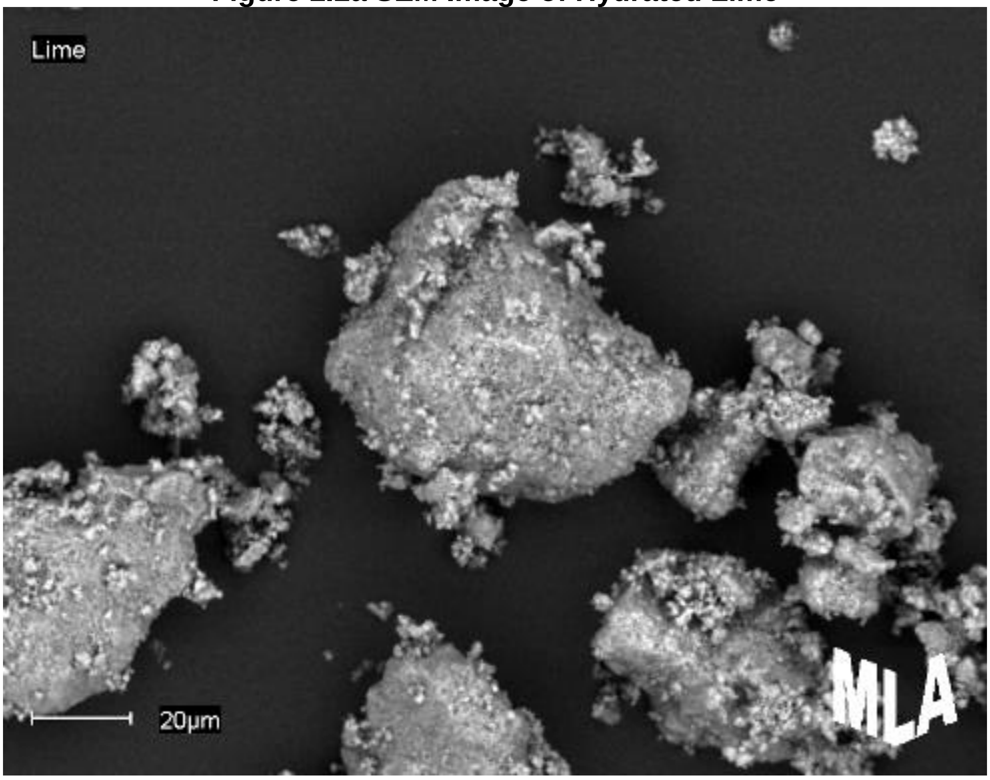


Figure 2.2b SEM Image of Flyash

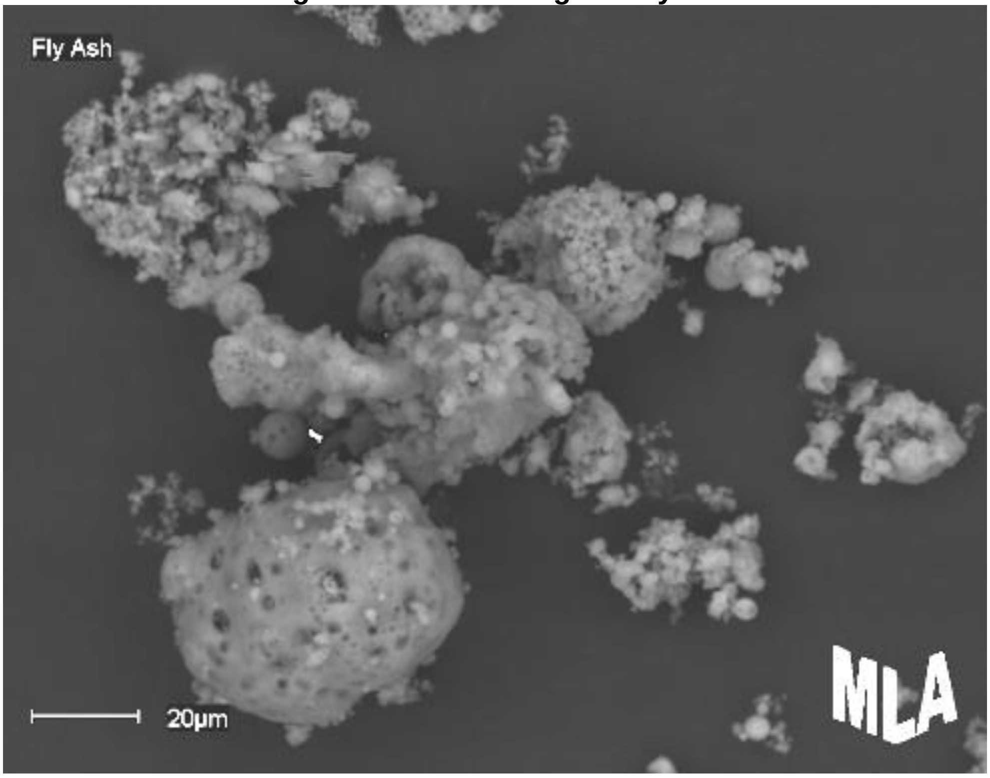


Figure 2.2c SEM Image of Ultra-fine Dust

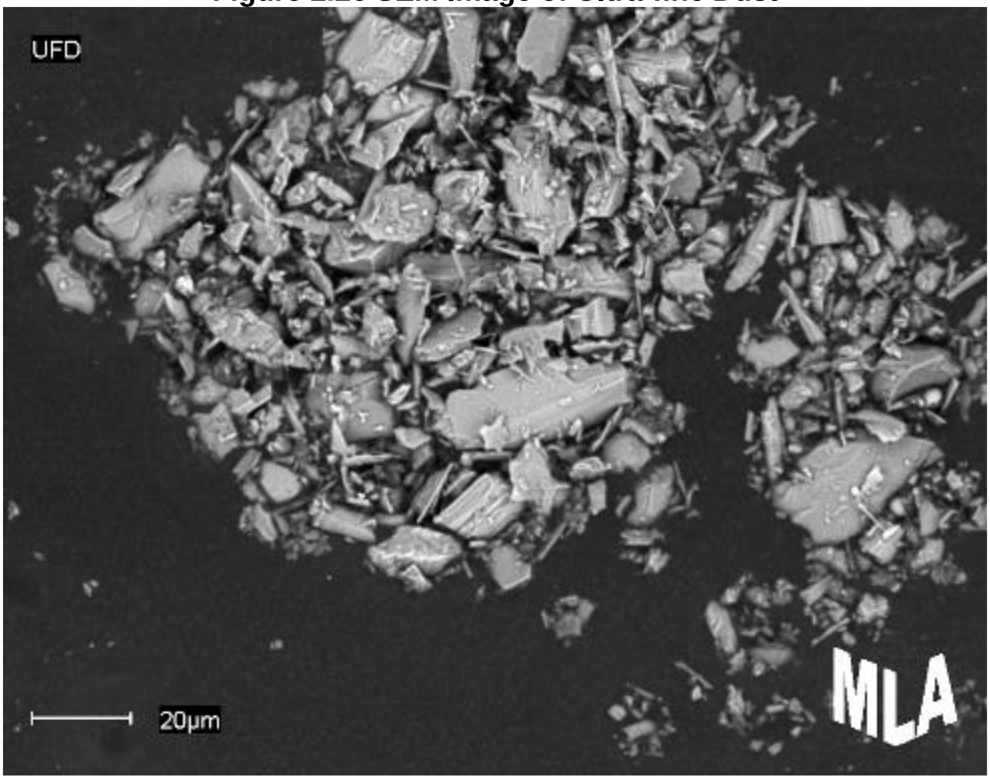
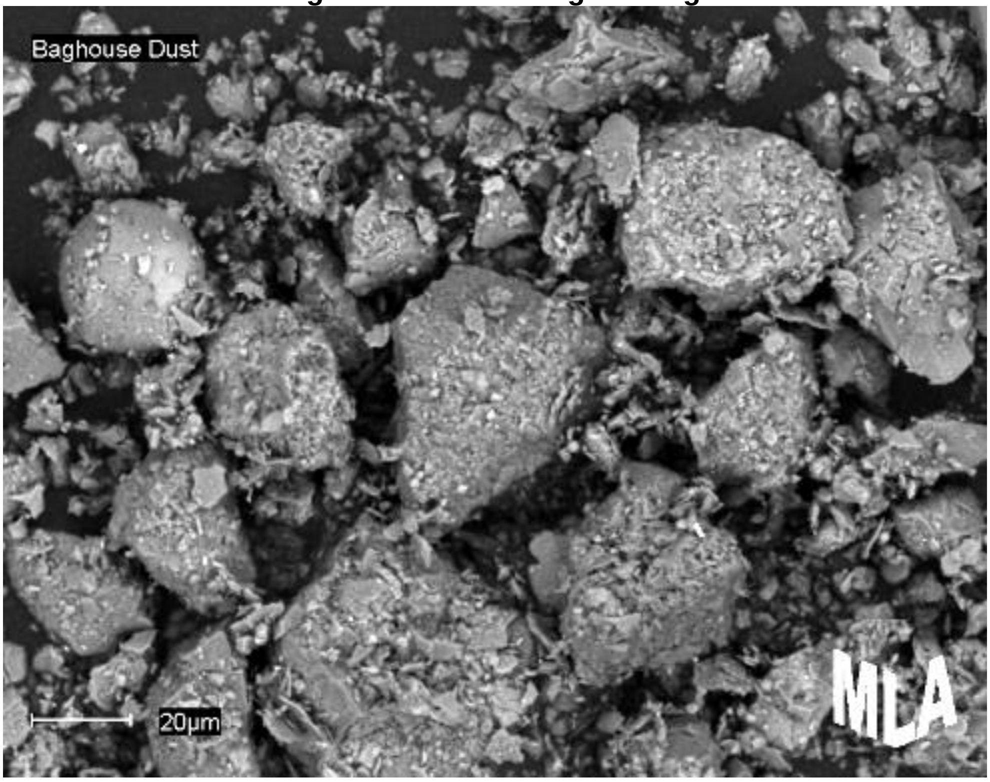


Figure 2.2d SEM Image of Baghouse Dust



MASTICS

Sixteen mastics were manufactured in the laboratory for each of the two binder types (i.e. 32 total). The sixteen combinations consisted of four fillers at four different filler-binder ratios (by mass) as summarised in Table 2.3. Only the filler portions passing the 0.075 mm sieve (dry sieving) were used in the manufacture of the mastics.

The mastics listed in Table 2.3 were selected to cover the range of filler and binder types, and proportions, adopted in typical Queensland SMA mixes. It was recognised that asphalt mixes typically contain more than one filler type (i.e. at least one added filler plus the filler produced as part of the manufacturing process). However, for this study, the fillers were investigated separately so that the performance of each could be analysed individually.

Table 2.3 Laboratory Manufactured Mastics

Mastic Number	Binder Type	Filler Type	Filler-Binder Ratio (by mass)
1	Class 320	Hydrated Lime (DML)	1.00
2			1.25
3			1.50
4			1.75
5		Flyash (Swanbank)	1.00
6			1.25
7			1.50
8			1.75
9		Ultra-fine quarry dust (Petrie)	1.00
10			1.25
11			1.50
12			1.75
13		Baghouse fines (BCW)	1.00
14			1.25
15			1.50
16			1.75
17	A5S	Hydrated Lime (DML)	1.00
18			1.25
19			1.50
20			1.75
21		Flyash (Swanbank)	1.00
22			1.25
23			1.50
24			1.75
25		Ultra-fine quarry dust (Petrie)	1.00
26			1.25
27			1.50
28			1.75
29		Baghouse fines (BCW)	1.00
30			1.25
31			1.50
32			1.75

The mastics were manufactured by weighing out a given mass of binder at an elevated temperature, and then adding the necessary mass of filler to achieve the required filler-binder ratio.

The visual appearance of the resulting mastics using the A5S polymer modified binder is shown in Figure 2.3. The appearance of each mastic proved to be a good initial indicator of its viscosity, with viscosity increasing with decreasing lustre. The mastic incorporating baghouse dust at a filler-binder ratio of 1.0 was visually observed to be the shiniest, indicating it would have the lowest viscosity. The mastics incorporating flyash at filler-binder ratios of 1.5 and 1.75 formed dry powdery materials, indicating the highest viscosities and that the filler had sucked up, or ‘fixed’ all the binder.

Figure 2.3 Mastics with A5S Binder

Filler	Filler-Binder Ratio (by mass)			
	1/1	1.25/1	1.5/1	1.75/1
Baghouse Dust				
Ultra-fine Dust				
Hydrated Lime				
Flyash				

The viscosity of each mastic was measured using the Brookfield viscometer. It was recognised from the outset that this approach would be somewhat affected by the non-Newtonian nature of the mastics being tested. However, Brookfield testing was considered appropriate for this study for the following reasons:

- Brookfield testing can be undertaken at elevated and controlled temperatures - a key aim of this project was to test the materials at actual mixing and compaction temperatures;
- preliminary testing trials indicated that realistic results could be achieved, which agreed with the visual observations;
- lack of other suitable and readily available testing equipment; and,
- the accuracy of results required was considered to be achievable with the Brookfield apparatus.

3 MASTIC TEST RESULTS AND ANALYSIS

The viscosities of the mastics measured using the Brookfield Viscometer are presented in Table 3.1. Also included are the viscosities of the raw binders. The existence of a relationship between filler-binder ratio (by mass) and mastic viscosity was first investigated to determine the suitability of the common belief that mix workability was directly related to the filler-binder ratio. The viscosity versus filler-binder ratio was plotted independently of filler type and is shown in Figure 3.1 for the A5S binder.

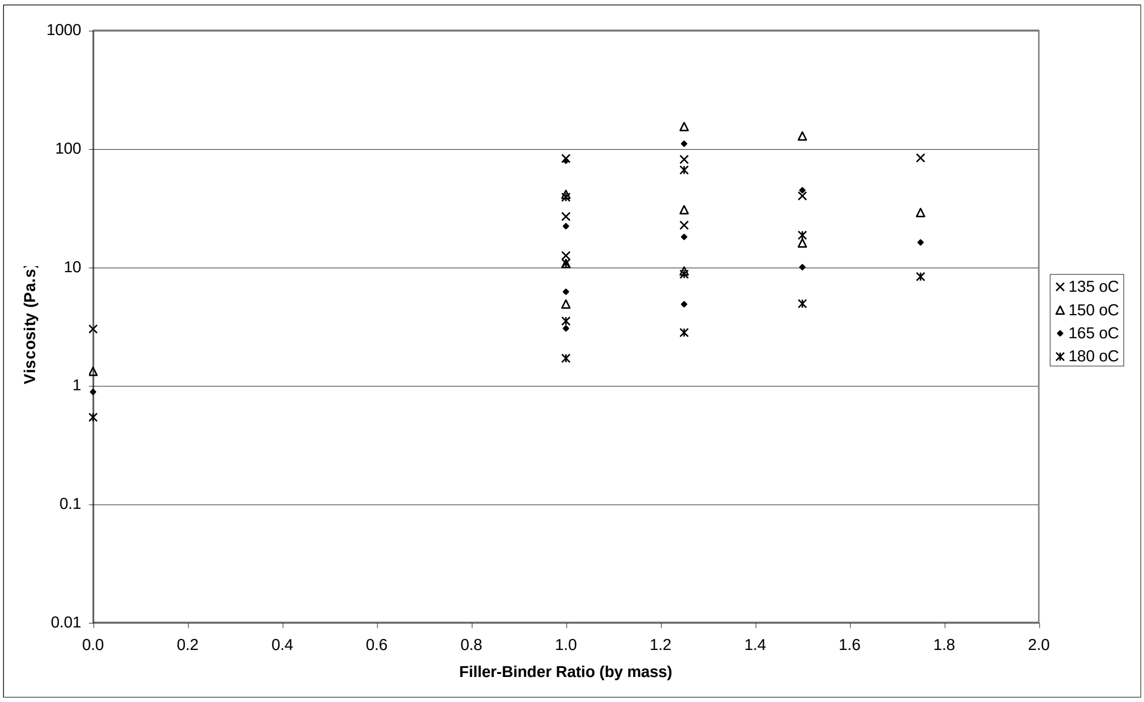
Table 3.1 Summary of Mastic Viscosities

Mastic Number	Binder Type	Filler Type	Filler-Binder Ratio (by mass)	Viscosity &/or Observation at Test Temperature Pa.s			
				135°C	150°C	165°C	180°C
-	Class 320	No filler	0	0.452	0.230	0.140	0.088
1		Hydrated Lime (DML)	1.00	11.4	5.19	3.06	1.68
2			1.25	64.2	45.5	28.0	12.1
3			1.50	Note 2	Note 2	Note 2	Note 2
4			1.75	Note 1	Note 1	Note 1	Note 1
5		Flyash (Swanbank)	1.00	Note 2	83.3	44.6	20.7
6			1.25	Note 2	Note 2	Note 2	Note 2
7			1.50	Note 1	Note 1	Note 1	Note 1
8			1.75	Note 1	Note 1	Note 1	Note 1
9		Ultra-fine quarry dust (Petrie)	1.00	4.95	2.33	1.50	0.849
10			1.25	24.6	11.1	5.58	2.81
11			1.50	Note 2	56.5	28.0	7.62
12			1.75	Note 2	Note 2	Note 2	Note 2
13		Baghouse fines (BCW)	1.00	2.04	1.02	0.478	0.290
14			1.25	3.74	1.95	0.824	0.504
15			1.50	6.76	3.21	1.70	0.929
16			1.75	20.2	8.27	4.26	2.20
-	A5S	No filler	0	3.00	1.32	0.882	0.539
17		Hydrated Lime (DML)	1.00	82.8	41.2	22.2	10.8
18			1.25	Note 2	154	110	66.0
19			1.50	Note 2	Note 2	Note 2	Note 2
20			1.75	Note 1	Note 1	Note 1	Note 1
21		Flyash (Swanbank)	1.00	Note 2	Note 2	79.2	38.9
22			1.25	Note 2	Note 2	Note 2	Note 2
23			1.50	Note 1	Note 1	Note 1	Note 1
24			1.75	Note 1	Note 1	Note 1	Note 1
25		Ultra-fine quarry dust (Petrie)	1.00	26.8	10.7	6.19	3.50
26			1.25	81.1	30.6	18.0	8.72
27			1.50	Note 2	128	44.6	18.6
28			1.75	Note 2	Note 2	Note 2	Note 2
29		Baghouse fines (BCW)	1.00	12.5	4.88	3.04	1.70
30			1.25	22.6	9.28	4.86	2.80
31			1.50	40.0	16.0	10.0	4.91
32			1.75	83.5	28.9	16.2	8.32

Notes
(1) Filler absorbed all binder. Could not form an homogenous sample;
(2) Formed an homogenous paste but too viscous to test.

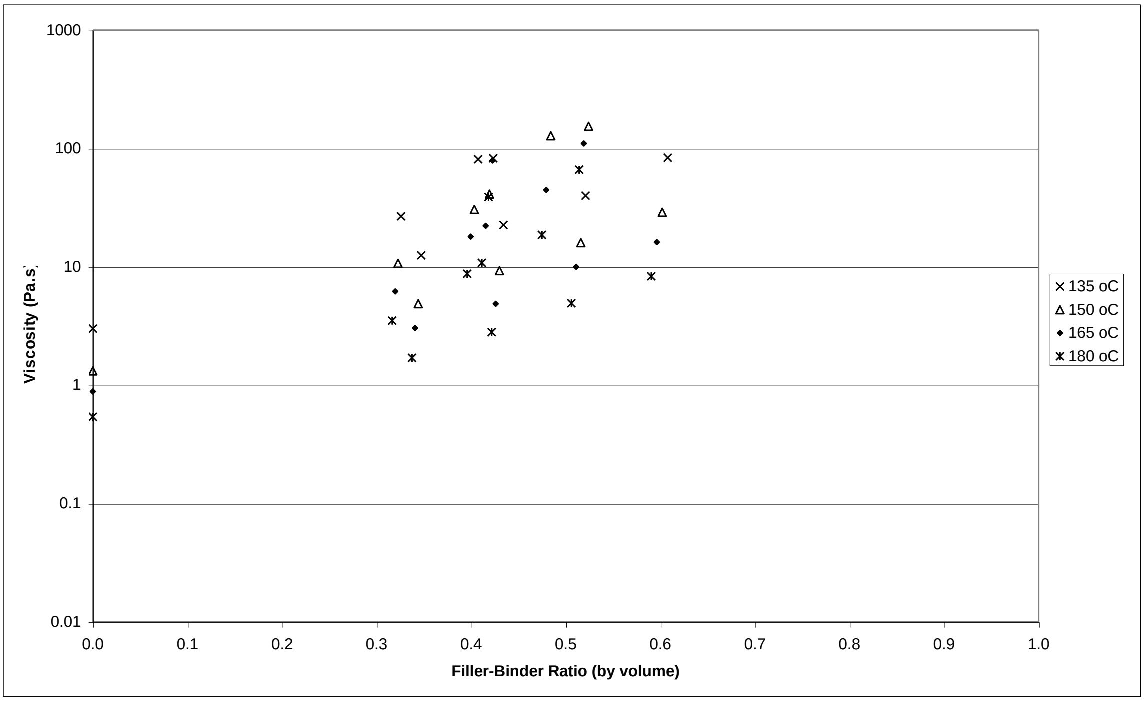
It can be seen from Figure 3.1 that there is only a very loose increasing trend in results, but no definitive relationship. The best attempt to define a relationship gave an R-squared value of 0.3 (R-squared is defined as the coefficient of determination which may range in value from 0 to 1 and which indicates how close actual values are to a defined relationship, with 1 being a perfect correlation). A value of 0.3 indicates a poor correlation. For example, at a temperature of 180 °C and filler-binder ratio of 1.0, the measured viscosities for A5S binder ranged between 1.7 Pa.s (BCW baghouse) and 38.9 Pa.s (Swanbank flyash). Thus, it was confirmed that using the filler-binder ratio on its own as an indicator of workability is misleading and may give unpredictable results.

Figure 3.1 Viscosity vs Filler-Binder Ratio (by mass) for A5S binder



The filler-binder ratio (by volume), rather than by mass, was then investigated as the volume of filler in each mastic could vary significantly depending on the filler density. For the fillers considered in this investigation, the volume of filler in mastics with the same filler-binder ratio (by mass) could vary by up to 30 %. Viscosity results versus filler-binder ratio (by volume) for mastics using the A5S binder are plotted in Figure 3.2. Again, a loose increasing trend in results was evident, but a definitive relationship had still not been identified. The R-squared value increased to 0.5, indicating a better relationship than with filler-binder ratio (by mass) but there was still an unacceptably low level of reliability.

Figure 3.2 Viscosity vs Filler-Binder Ratio (by volume) for A5S binder



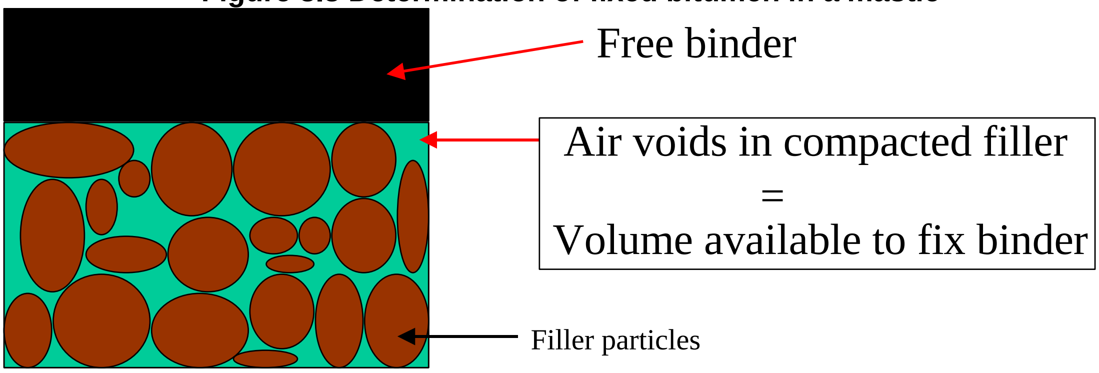
Hence, it was concluded that there must be other variables involved which are not recognised by the filler-binder ratio (by mass) or filler-binder ratio (by volume).

Previous research undertaken by QDMR (Spies, 1996) investigated the stiffening effect of fillers in relation to the fraction of binder which was absorbed by the filler. Binder absorbed by the filler was termed 'fixed' bitumen.

In this previous research it was presumed that the sole role of filler was to provide a sufficient volume of voids to absorb a portion of the binder (i.e. the filler acts totally as a bitumen filler rather than an aggregate filler). A relationship to determine the fraction of fixed binder was derived by assuming that the volume of fixed binder was equal to the voids in the dry compacted filler. This theory and resulting relationship are illustrated in Figure 3.3, where:

f_{binder} is the fraction of fixed bitumen;
$V_{airvoids}$ is the volume of airvoids in the dry compacted filler;
V_{binder} is the volume of binder in the mix;
F is the percentage by mass of filler in the combined aggregates;
B is the percentage by mass of binder in the mix;
G_b is the density of the binder;
G_f is the density of the filler; and,
V is the voids in the dry compacted filler (Rigden Voids).

Figure 3.3 Determination of fixed bitumen in a mastic

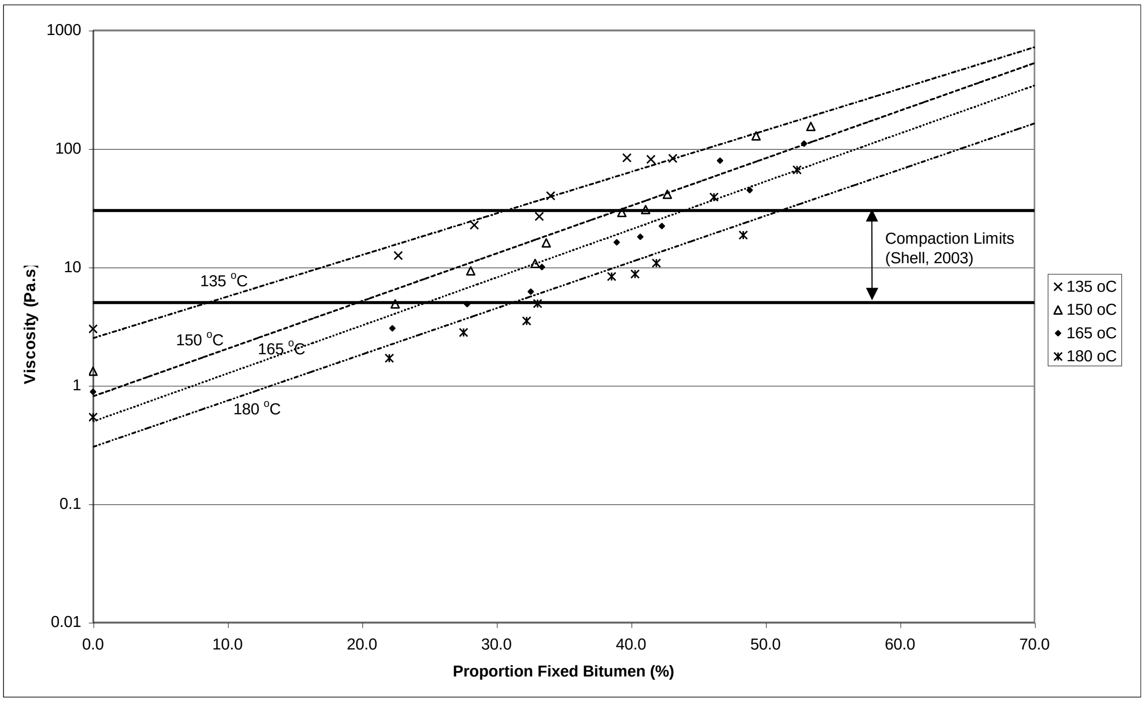


$$f_{binder} = \frac{V_{airvoids}}{V_{binder}} = \frac{F}{B} \frac{100 - B}{100} \frac{G_b}{G_f} \frac{V}{1 - V}$$

The original research involved the testing of mastics, with filler-binder ratios (by mass) between 0.8 and 1.4, for penetration and softening point. A significant relationship was found between penetration and the fraction of bitumen fixed by the filler as calculated using the equation in Figure 3.3.

For the current research the viscosity approach was adopted so that observations could be more easily related to actual plant production and field compaction temperatures. The viscosities were plotted against the theoretical proportion of fixed bitumen, using the equation in Figure 3.3. The results are shown in Figure 3.4 for A5S binder.

Figure 3.4 Viscosity vs Proportion Fixed Bitumen for A5S binder



The results showed a significant relationship between mastic viscosity and the proportion of fixed bitumen. The R-squared values increased to around 0.9, indicating trend lines with good reliability for each temperature level. Thus this current research agrees with the outcomes of the previous study (Spies, 1996), that the theoretically calculated fraction of fixed bitumen provides a realistic means of assessing the stiffening effect of alternative fillers.

In Figure 3.4, lower and upper compaction limits of 5 Pa.s and 30 Pa.s respectively are shown (Shell, 2003). Results above the upper limit indicate viscosity may be too high to achieve adequate compaction in the field, while values below the lower limit may result in excessive movement under the rollers.

Within the equation in Figure 3.3, the component which relates purely to the filler characteristics (defined here as the Filler Fixing Factor, FFF) may be written as:

$$FFF = \frac{1}{G_f}\frac{V}{1-V}$$

The FFF indicates the fixing potential of a filler, where a higher FFF indicates a filler that will theoretically fix more binder, and therefore may result in a less workable mix. The FFF for the fillers used in this investigation are shown in Table 3.2, ranked in order of decreasing FFF. The measured viscosities in Table 3.1 for both Class 320 and A5S binders agree with the FFF theory in all cases. The results for hydrated lime support the anecdotal evidence that the inclusion of hydrated lime in SMA mixes has had an adverse affect on mix workability. The results for the Swanbank flyash were unexpected as there had previously been no association made between flyash and poor mix workability. A comparison was made between the current flyash results and available historic results (Spies, 1996 and 1999). It was evident from the results that the properties of the flyash had changed significantly during the past ten years. In particular, there has been a large increase in the dry compacted voids. The change may be related to factors such as changed coal properties and alternative procedures used in the filtering of ash from the exhaust gases upon burning of the coal.

Table 3.2 Filler Fixing Factors (FFF) for various Fillers

Filler Type	Apparent Particle Density (t/m^3)	Voids in the dry compacted filler (%)	Filler Fixing Factor (FFF)
Hydrated Lime (Woodstock)	2.24	57	0.59
Flyash (Swanbank) Sample 1b	2.26	57	0.59
Flyash (Swanbank) Sample 2	2.04	54	0.58
Flyash (Swanbank) Samp1e 1a	2.19	54	0.54
Hydrated Lime (DML)	2.23	52	0.49
Flyash (Yabula)	2.18	50	0.46
Ultra-fine quarry dust (Petrie)	2.90	52	0.37
Granite quarry dust from washing (Virginia, USA)	2.90	44	0.27
Baghouse fines (BCW)	2.72	41	0.26
Agricultural lime	2.69	39	0.24
Limestone (Maryland, USA)	2.81	37	0.21
Granite quarry dust from vacuum collection (Virginia, USA)	2.79	35	0.19

Note: Shading indicates fillers used for viscosity measurements

4 IMPLEMENTATION OF RESEARCH INTO PRACTICE

This research showed that the commonly used filler-binder ratio, as an indicator of mix workability, can be misleading and may result in unpredicted outcomes for some fillers. A significant relationship between the theoretical proportion of fixed bitumen and mastic viscosity was confirmed for various fillers. In particular, the stiffening effect of the flyash and hydrated lime samples used in this study were very high. In asphalt mix design, this stiffening effect should be recognised as it may have a significant influence on the workability of the mix.

As part of the recent QDMR/AAPA Strategic Alliance SMA trials, a free binder clause was introduced into the trial specification. The purpose of the clause was to ensure the stiffening effect of the fillers used in the mixes was recognised so that mixes with poor workability were less likely. The free binder volume (%) was calculated as the total binder volume (%) minus the binder volume absorbed by mix aggregates (%) minus the theoretical volume of binder fixed by the filler (%).

For the SMA trial specification (2005), free binder limits of 8.0 to 11.0 % were adopted for mix design, with extended limits of 7.5 to 11.0 % for production. These initial trial limits were based on calculated free binder volumes for mixes used in Virginia and Marylands in the USA, and a review of current Queensland mixes. Further use of the free binder requirement and monitoring of the future performance of the SMA trials are necessary to determine the suitability of its ongoing use.

5 CONCLUSIONS

The use of filler-binder ratio on its own to assess the workability of an asphalt mix should be discontinued. The Filler Fixing Factor (FFF) in combination with the filler-binder ratio can be used as an indicator of the workability of an asphalt mix. Alternatively, as elected by QDMR, the free binder volume can be used as an indicator of mix workability. The free binder volume accounts for the FFF, filler-binder ratio and binder absorption by the mix aggregates. Currently the limits for free binder volume set in the QDMR specification for SMA are 8.0 to 11.0 % for design. These limits may be refined after further trialling of various SMA specifications.

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