NACOE
NATIONAL ASSET CENTRE OF EXCELLENCE

ANNUAL SUMMARY REPORT

Project Title: P57: Implementing the use of Reclaimed Asphalt Pavement (RAP) in TMR registered dense grade asphalt mixes - Background analysis report

Project No: PRP16112

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arrb Queensland Government

SUMMARY

Austroads published the results of a multiyear project in 2016 which provided guidance on the design and specification of asphalt mixes containing reclaimed/recycled asphalt pavement (RAP) to reduce uncertainty regarding the performance of these mixes. As part of the Austroads project, the application of the binder blend characterisation in accordance with test method AGPT/T193-2015 was validated to be used for designing the binder blend in mixes containing RAP without compromising the performance of the mix.

A NACoE project was conducted around the core findings of the Austroads project which aimed at facilitating the application of higher percentages of RAP in dense graded asphalt mixes by providing approval requirements for contactors if they wished to progress from RAP approval level 1S to a higher approval level. This was provided in the form of a technical note detailing the binder blend viscosity requirements for high RAP dense graded asphalt mixes. This report documents the technical analyses and the background information that led to the development of the technical note.

The project included extensive laboratory testing to characterise the supplied RAP materials. The testing included the viscosity of the binders recovered from 12 monthly RAP samples from three major RAP manufacturers in the South East Queensland (SEQ) area. Supplementary information such as the RAP binder content and historical viscosity records of the virgin binders supplied in SEQ were also collected as part of the project. The collected information was then analysed and used in assessing the risks associated with incorporating high percentages (15%) of RAP material in dense graded asphalt mixes in TMR projects.

The analysis included identifying the probability distributions of the binder blend equation input parameters, e.g. RAP binder content, RAP binder viscosity and virgin binder viscosity. Once the probability distributions were characterised, Monte Carlo simulations were used to evaluate the sensitivity of the resulting binder blend viscosity to variations in the input variables/parameters.

Based on the results from the simulations, variations in the resulting binder blend viscosity were translated into equivalent binder classes. This classification was conducted based on the current TMR approach to accept up to 15% RAP in hot asphalt mixes with no proven performance requirement. Therefore, the upper limit of the binder blend viscosity of virgin binders with 15% RAP and the lower limit of the virgin binder's viscosity were considered as the ranges of the new equivalent binder classes.

The specified ranges for each equivalent binder class band were used in the development of a technical note to control and regulate the blend viscosity of contractors' high RAP asphalt mixes.

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1 INTRODUCTION

Reclaimed/recycled asphalt pavement (RAP) has both economic and environmental benefits when reused in new asphalt material. RAP is the most recycled construction and demolition waste material in many countries including Australia (Austroads 2016).

Austroads has published the findings of a recent multiyear research project (*TT1817 Maximising the Use of Reclaimed Asphalt Pavement in Asphalt Mix Design*) which investigated the mix design requirements to ensure asphalt mixes with high RAP contents will provide adequate performance (Austroads 2013, 2015, 2016). The performance implications of including higher percentages of RAP in asphalt mixes were also evaluated. In addition, mix design procedures to mitigate negative impacts associated with the inclusion of higher percentages of RAP were developed and validated. As part of the Austroads project, it was concluded that the binder blend characterisation can be used for the design of asphalt mixes with high RAP content without risking the performance of the asphalt mix.

In line with the Austroads study, a research program was initiated by TMR and ARRB to transfer the results and implement the findings into the TMR asphalt and RAP specifications – MRTS30 and MRTS102 (Department of Transport and Main Roads 2017a, 2017b). TMR allows contractors under the current dense grade asphalt mix specification (MRTS30) to use up to 15% RAP material in the surfacing and other pavement courses with no ‘proven performance’ requirements. However, for high RAP contents, contractors need to demonstrate a history of proven performance (of up to 5 years, depending on the RAP percentage and the pavement course). The incorporation of the findings from the Austroads project could enable a relaxation in the ‘history of proven performance’ requirement that currently exists in TMR specifications for asphalt mixes containing RAP contents above 15%.

Findings of the NACoE study resulted in the development of a technical note that outlines/specifies the TMR requirements on how contractors should manage the viscosity of their asphalt mixes binder blends that contain high percentages (> 15%) of RAP. The supporting information and the background analyses that led to the development of the technical note are presented in this report.

The report provides the following background information:

- the RAP test results
- statistical analyses on the binder blend equation input parameters
- sensitivity analysis of the binder blend equation to variation in the input variables
- matrix tables of the resulting binder classes for given virgin binder classes and added RAP percentages.

It should be noted that this technical background only considers provisions required to satisfy the binder blend properties. Designing an asphalt mix which contains RAP material involves a range of other considerations (e.g. meeting/complying with the aggregate gradation tolerances, practical limitations, etc.) which are not looked at in this report and should be addressed separately. It is worth noting that during production, the contractor’s RAP management practice plays an important role in the performance of asphalt mix with high RAP contents.

2 REVIEW OF THE BINDER BLEND EQUATION

The Austroads test method *Design of Bituminous Binder Blends to a Specified Viscosity Value* (AGPT/T192-2015) specifies the procedure for designing a bituminous binder blend. This process has the following steps:

1. Calculate the viscosity blending index (VBI_i) of all the blend components (i.e. RAP binder(s), virgin binder and rejuvenator) using Equation 1.
2. Calculate the volume fraction of each binder blend component.
3. Calculate the viscosity blending index of the blend (VBI_β) using Equation 2.
4. Once the viscosity blending index of the binder blend is known, calculate the viscosity of the blend using Equation 3.

$$VBI_i = \frac{3 + \log\vartheta_i}{6 + \log\vartheta_i} \quad (1)$$

$$VBI_\beta = \sum_{i=1}^{n} x_i . VBI_i \quad (2)$$

$$\mu = 10^{\left(\frac{3VBI_\beta}{1 - VBI_\beta} - 3\right)} \quad (3)$$

where

ϑ = viscosity of the i^{th} component (Pa.s)

VBI_i = viscosity blending index of i^{th} component

VBI_β = viscosity blending index of the blend

x_i = volume fraction of the i^{th} component

μ = viscosity of the blend (Pa.s)

Note I: In the blend equation, the differences between the densities of the blend components are ignored/neglected i.e. it is assumed that the RAP binder(s), virgin binder and the rejuvenator oil/agent (if used) have the same densities.

Note II: Equation 1 and Equation 3 are mathematically the same equation just rearranged differently. Equation 1 is to calculate the viscosity blending index and Equation 3 is rearranged to calculate the viscosity when the viscosity blend index is known.

Note III: AGPT/T193 requires the estimated binder blend viscosity to be reported to **three** significant figures.

The flowchart of the binder blend viscosity calculations is shown in Figure 2.1.

Figure 2.1: Binder blend viscosity process flowchart

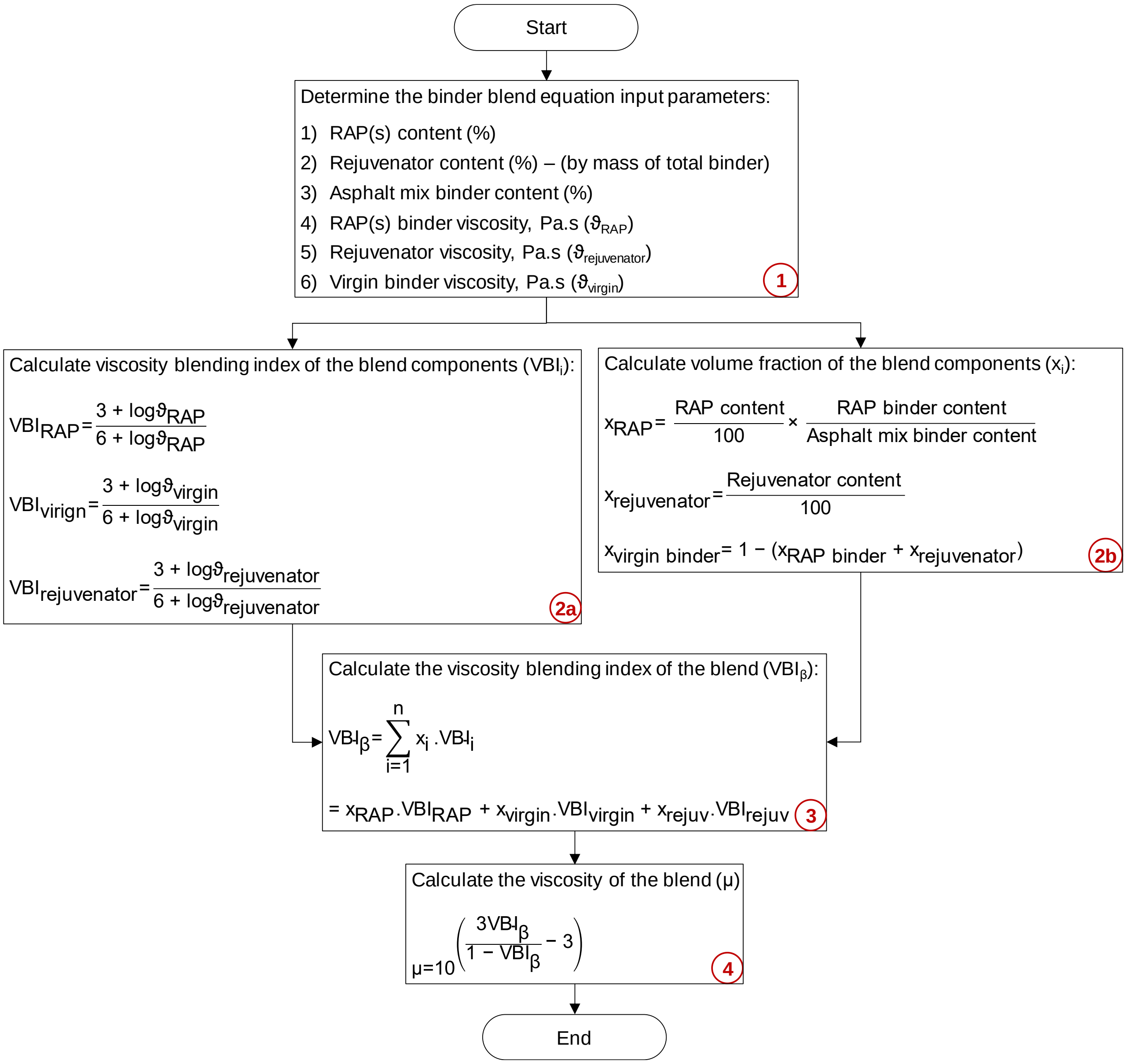
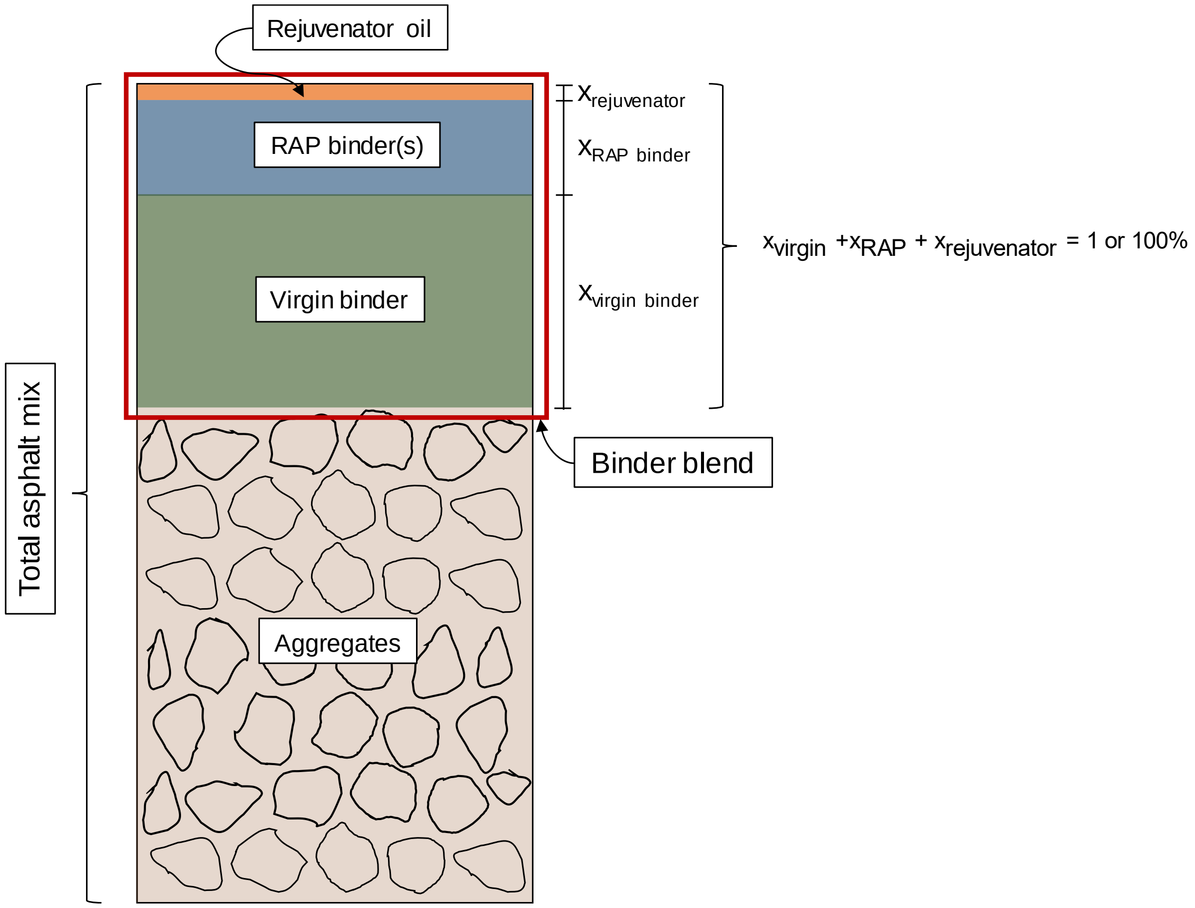


Figure 2.2 shows a schematic diagram of an asphalt mix containing RAP and rejuvenator oil. It helps with defining the binder blend equation parameters such as the volume fraction of the blend components. Volume fractions are the contribution of each blend component to the total binder blend as illustrated in Figure 2.2.

Figure 2.2: Binder blend components schematic diagram



3 SUMMARY OF THE QUEENSLAND RAP DATA

This section presents the laboratory test results of the RAP samples collected from three manufacturers in SEQ (Figure 3.1). For simplicity, they are referred to as contractors A, B and C in this report. Contractor A produces two sizes of RAP; as a result, 48 RAP samples were prepared for sampling and testing. Aggregate gradings of the RAP material provided by the suppliers are presented in Section 3.3.

The RAP binder was extracted according to the Austroads test method *Extractions of Bituminous Binder from Asphalt* (AGPT/T191-2015). In this method, samples are soaked in toluene to dissolve the binder. The binders are then extracted from the solution by evaporating the toluene in a rolling thin film oven (RTFO). Once the binders were extracted, they were tested for viscosity. Details and the results of the viscosity testing are presented next.

Figure 3.1: Photos of collected RAP samples, (a) contractor A coarse RAP, (b) contractor A fine RAP, (c) contractor B RAP, (d) contractor C RAP

(a) (b) (c) (d)

3.1 RAP binder viscosity

Once the monthly RAP supplies were collected, they were sent to the laboratory for their binders to get extracted and the viscosity of the binders measured in a dynamic shear rheometer (DSR) testing instrument.

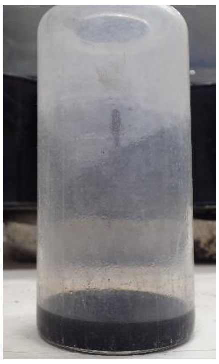
The binder extraction was carried out in accordance with Austroads test method AGPT/T191. The binder extraction procedure involves the following steps:

1. RAP samples are heated to 100 °C for 10 minutes to soften them.
2. Samples are broken up and quartered until 50 grams of representative material is obtained.
3. Samples are initially soaked with toluene for about one hour and washed with toluene repeatedly to dissolve the binder completely.
4. The binder solution (binder and toluene) is centrifuged for 15 minutes at 3000 RPM to remove the fine particles in the binder solution.
5. The binder is separated from the centrifuged solution by evaporating the solvent (toluene) in an RTFO purged with carbon dioxide and heated to 100 °C for 45 minutes.

6. The residual binders are then scraped off the RTFO bottles and the collected samples are tested in the DSR.

Photographs of the binder extraction process are shown in Figure 3.2.

Figure 3.2: RAP binder extraction process



(a) Binder solution in RTFO bottle

(b) Centrifuge

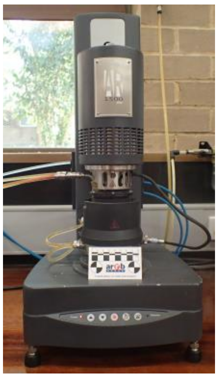
(c) RTFO oven

(d) Residual binder after heating

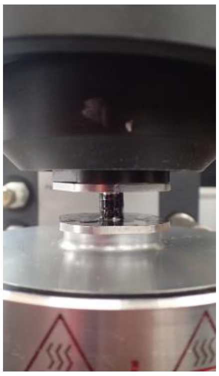
(e) Scraping tool

(f) Binder layer scraped out

(g) Binder after extraction



(h) DSR testing equipment



(i) Binder under testing in DSR

Two approaches were used to measure the binder viscosity of the RAP materials:

- Contractor A samples (coarse and fine fractions) for August, October, November and December 2016 and contractor B and contractor C samples for August, September, October and November 2016 were tested for full temperature/frequency sweep in the DSR (ASTM D7175-2015). This is referred to as method A in this report.

- Due to time/budget constraints, the rest of the samples were tested according to the Austroads test method Characterisation of the Viscosity of Reclaimed Asphalt Pavement Binder Using the Dynamic Shear Rheometer (AGPT/T192-2015). This is referred to as method B in this report.

Testing was conducted using the TA Instruments Ltd. DSR (model AR1500ex). The machine is equipped with an upper heated plate (UHP) asphalt environment system (model AS2000ex). The temperature during testing is controlled through the use of a combined UHP and Peltier plate manifold and a water-cooling system which includes a Julabo refrigerated/heating circulator (model FP35-HE).

The full temperature/frequency sweep test method (method A) has the following key test set-up parameters:

- test temperature: 70 to 30 °C (at 5 °C increments i.e. 70, 65, 60, 55, 50, 45, 40, 35 and 30 °C)
- oscillation frequency: 0.1 to 62.83 rad/s (5 points per decade on the log scale i.e. 0.1, 0.1585, 0.2512, 0.3981, 0.631, 1, 1.585, 2.512, 3.981, 6.31, 10, 15.85, 25.12, 39.81 and 62.83 rad/s)
- strain: 5%
- binder sample diameter: 8 mm and 25 mm (70 to 50 °C tested in 25 mm spindles and 50 to 30 °C in 8 mm spindles)
- binder film thickness: 1 and 2 mm (1 mm for 25 mm diameter samples and 2 mm thickness for 8 mm diameter samples)
- number of test points at each temperature/frequency: 1.

The Austroads test method (method B) has the following key set-up parameters:

- test temperature: 60 °C
- strain: 10%
- angular frequency: 1 rad/s
- binder film thickness: 1 mm
- binder sample diameter: 25 mm
- number of test points: 20 points (10 pre-conditioning points followed by 10 test points). The average of the last 10 points is reported as the DSR viscosity. An example of the DSR viscosity calculation is illustrated in Figure 3.3.

The main difference between the two DSR measurements at 60 °C (methods A and B) is in the applied strain level i.e. 5% in method A vs 10% in method B. Within the linear viscoelastic (LVE) range, the recorded complex viscosity is independent of the shear strain. The applied stain levels of 5% and 10% are normally expected to be well within the LVE region unless the binder in heavily modified. Therefore, it is believed that the difference between the measured viscosities is minimal. Full results of the viscosity testing are tabulated in Appendix A.1.

Carrying out a full temperature/frequency sweep test on a binder can give a broader assessment of the rheology of the binder, however since the focus of this study was primarily on the viscosity of the RAP binders, except for 12 samples in the beginning of the testing program, the rest of the testing (36 samples) was limited to the measurement of the complex viscosity of the samples.

Figure 3.4 shows an extract of the DSR complex viscosity range over a spectrum of angular frequency at 60 °C for the contractor A coarse RAP supply of October 2016 (test #2).

A summary of the complex viscosity results of contractor A (fine and coarse RAP), contractor B and contractor C RAP supply over a period of 12 months is depicted in Figure 3.5, Figure 3.6 and Figure 3.7 respectively.

Testing was carried out on duplicate samples. When sampling was missed for a particular month, the testing period was extended for an extra month to make sure the full cycle of 12 samples was collected for each RAP supply.

In Figure 3.5, Figure 3.6 and Figure 3.7, results of the duplicate testing are shown in bar charts, and the average values are shown in the form of points labelled with the values rounded to three significant figures, as per AGPT/T192 test method requirements.

The average complex viscosity values were then further analysed to characterise the probability distribution of the viscosities over the sampling period. The identified probability distribution parameters were then used to study the variation of the blend viscosity. This is discussed in more detail in Section 4 and Section 5.

Figure 3.3: DSR viscosity calculation example – method A (sample #45288, contractor A coarse RAP, June 2017 test #1)

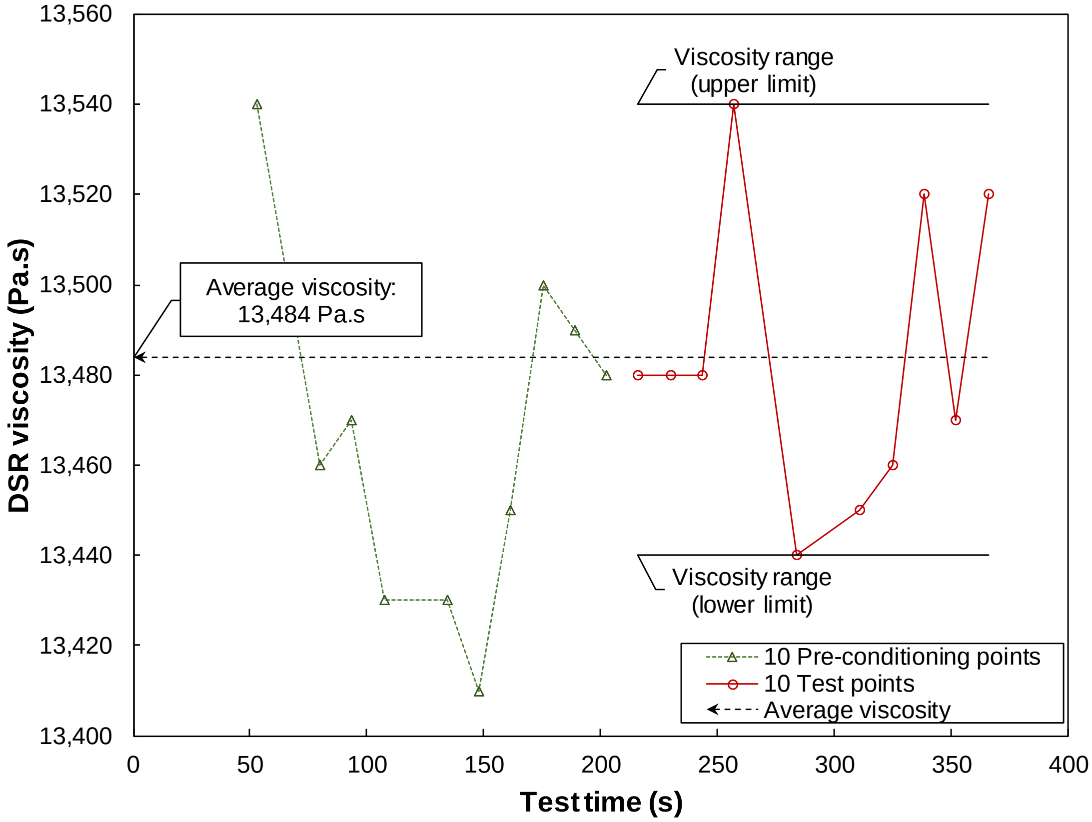


Figure 3.4: DSR viscosity calculation example – method B (sample #4794, contractor A coarse RAP, October 2016 test #2)

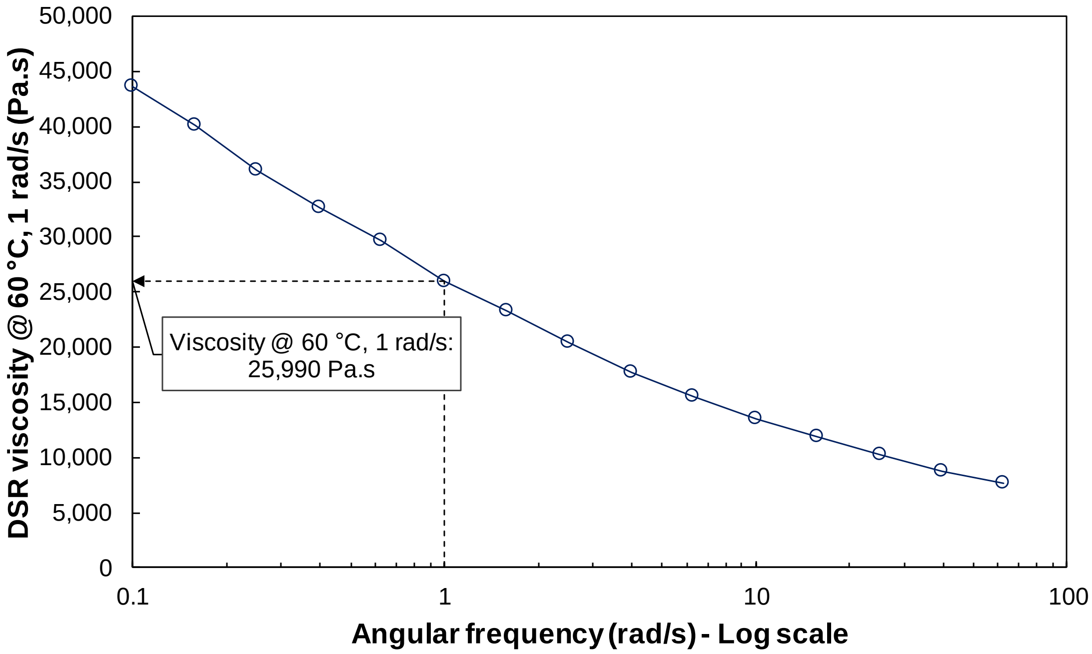


Figure 3.5: Contractor A fine RAP binder viscosity test results

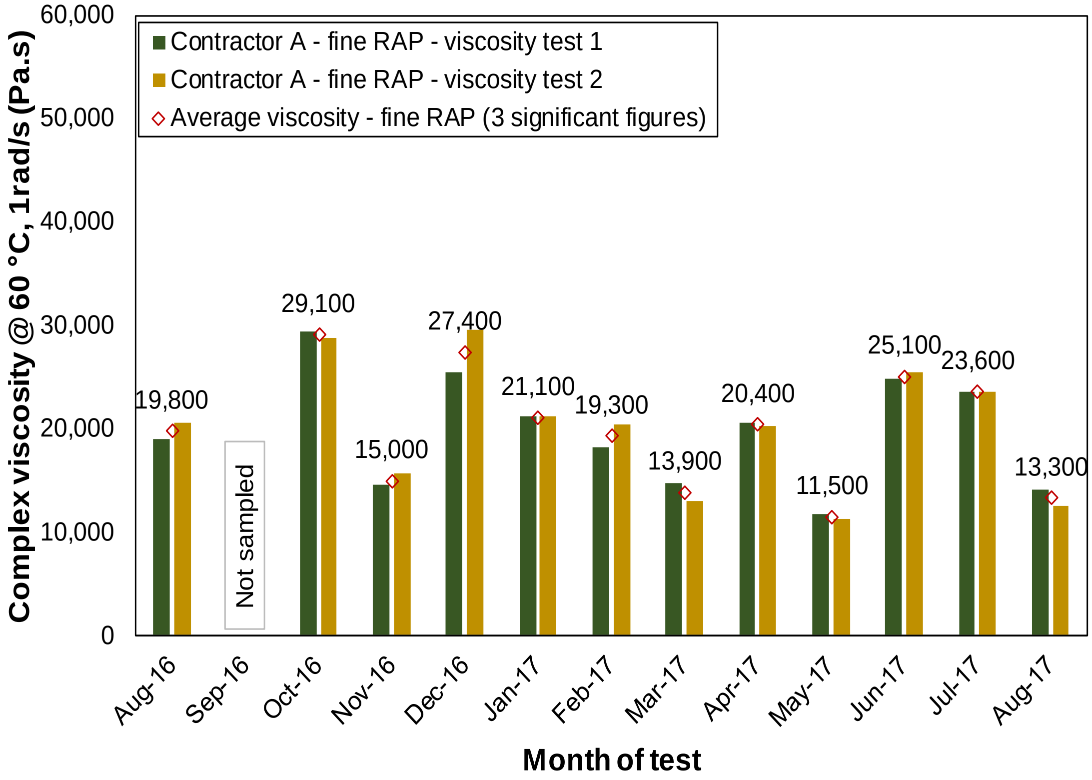


Figure 3.6: Contractor A coarse RAP binder viscosity test results

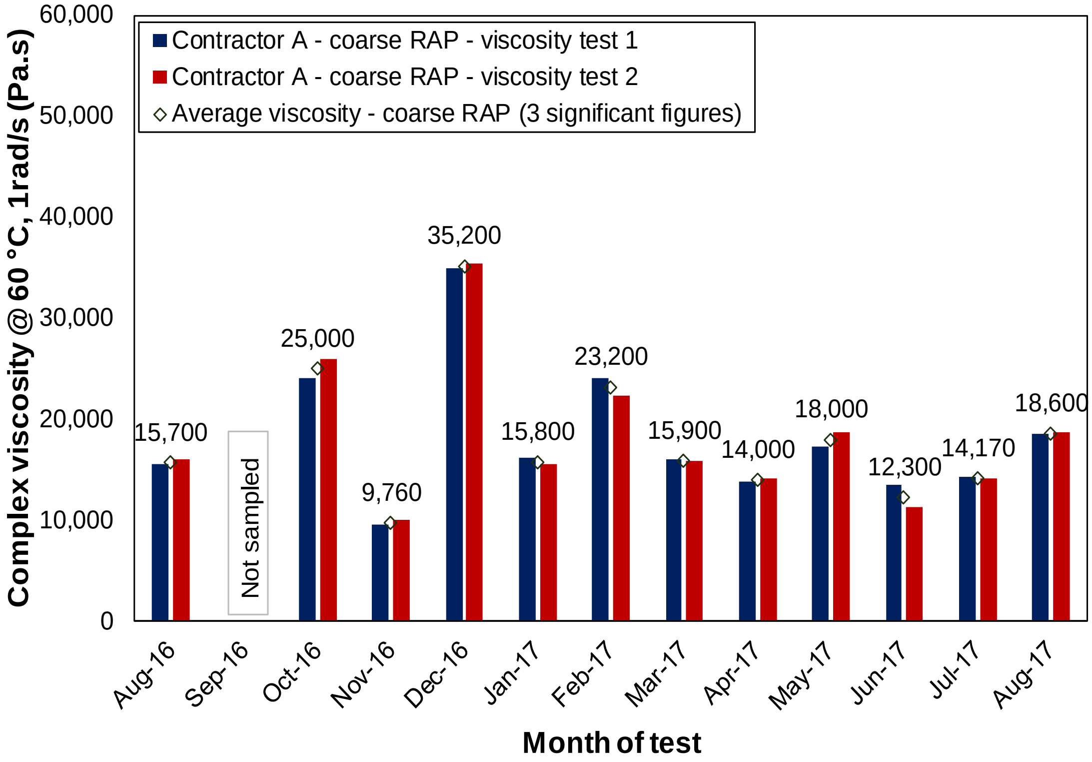


Figure 3.7: Contractor B RAP binder viscosity test results

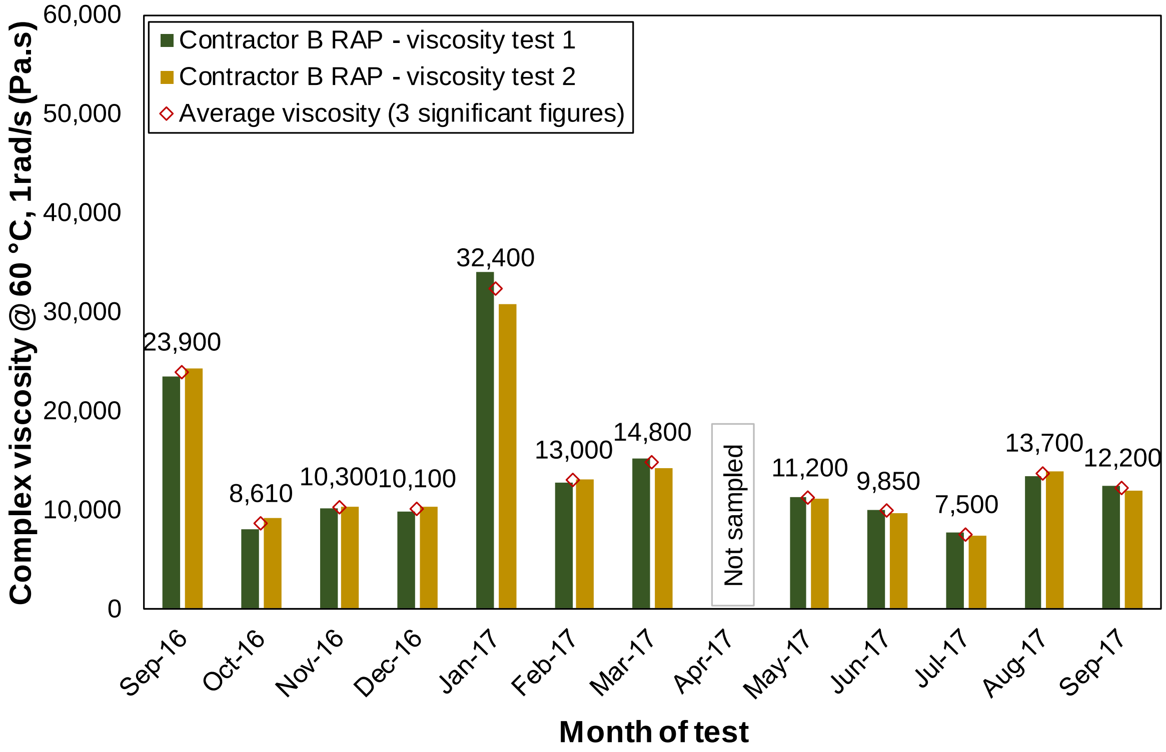
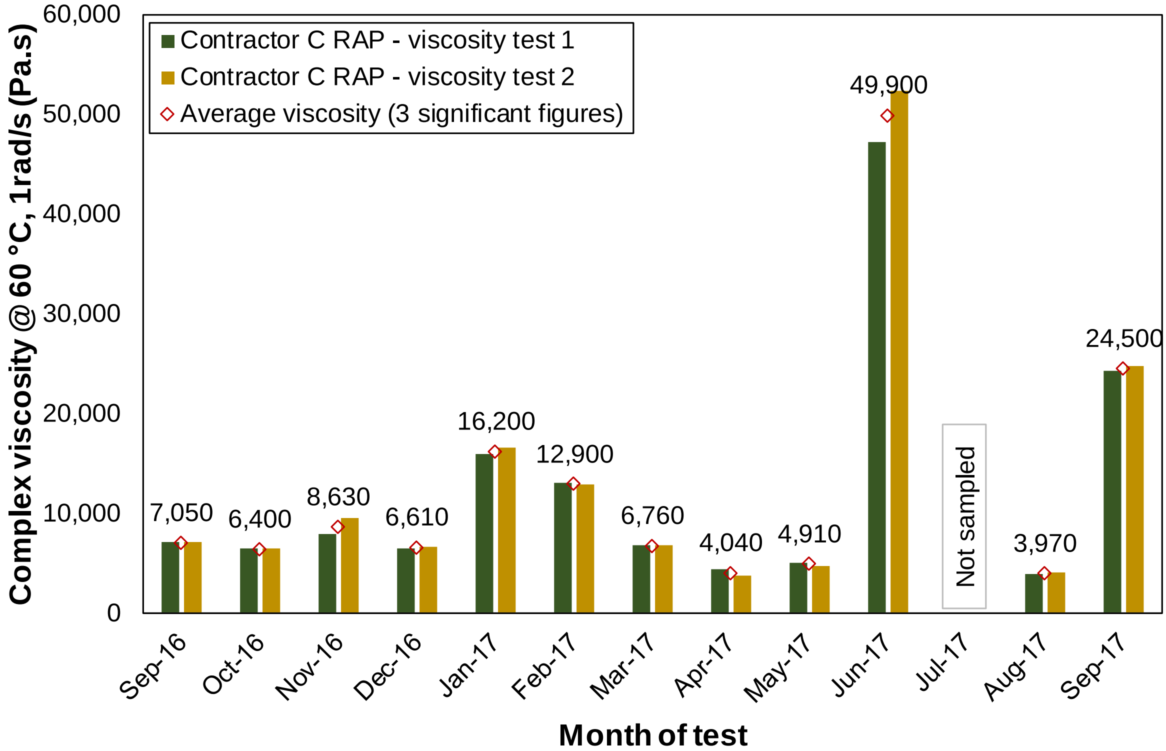


Figure 3.8: Contractor C RAP binder viscosity test results



3.2 Virgin binder viscosity

Similar to RAP binders, the viscosity of the fresh/virgin binders supplied in SEQ was also investigated. Raw data were collected from TMR as well as the three main binder suppliers in Queensland. Once data were collected they were analysed and their probability distributions characterised.

The complete record of the collected information on virgin binders is tabulated in Appendix B.

Two sets of data were used for the sensitivity analysis of the blend equation:

1. The parameters of the probability distribution fit to the actual/historical virgin binder supply to SEQ
2. The parameters of the probability distribution fit to the binder properties as defined in *Bitumen for Pavements* (AS2008-2013).

3.3 RAP aggregate grading

RAP suppliers were requested to provide the aggregate grading of their samples. The grading was carried out in accordance with the TMR test method (Q308A-2016). This method is broadly set up around the procedure in the standard AS/NZS 2891.3.1-2013.

The particle size distributions of the studied RAP samples are illustrated in Figure 3.9, Figure 3.10, Figure 3.11 and Figure 3.12. The data is also presented in Appendix A.2.

The figures show that the particle size distributions of the RAP samples are reasonably consistent. The aggregate grading envelopes are consistently narrow which indicates limited variation within the monthly productions. It was noted that all of the participating contractors have their in-house RAP management plans in place. The Australian Asphalt Pavement Association (AAPA) has also drafted a unified RAP management plan to address the necessities for quality and consistency in the winning of RAP and the delivery of the processed RAP for its re-use in asphalt mixes.

Figure 3.9: Contractor A fine RAP particle size distribution

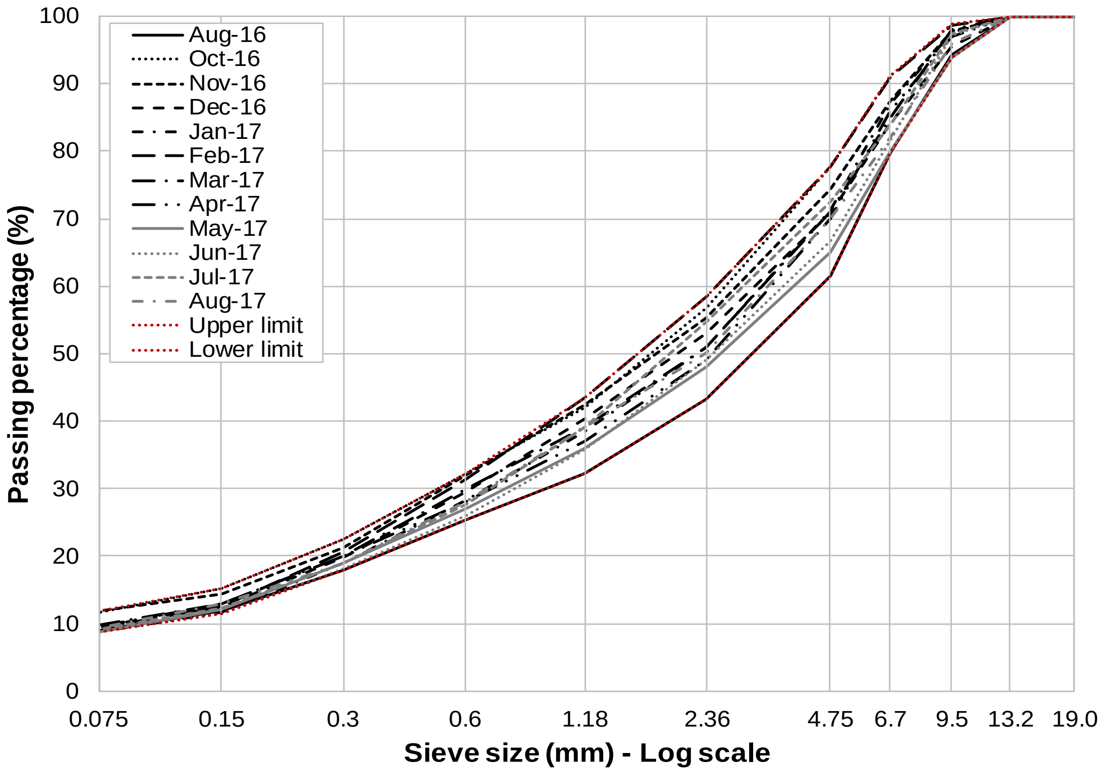


Figure 3.10: Contractor A coarse RAP particle size distributions

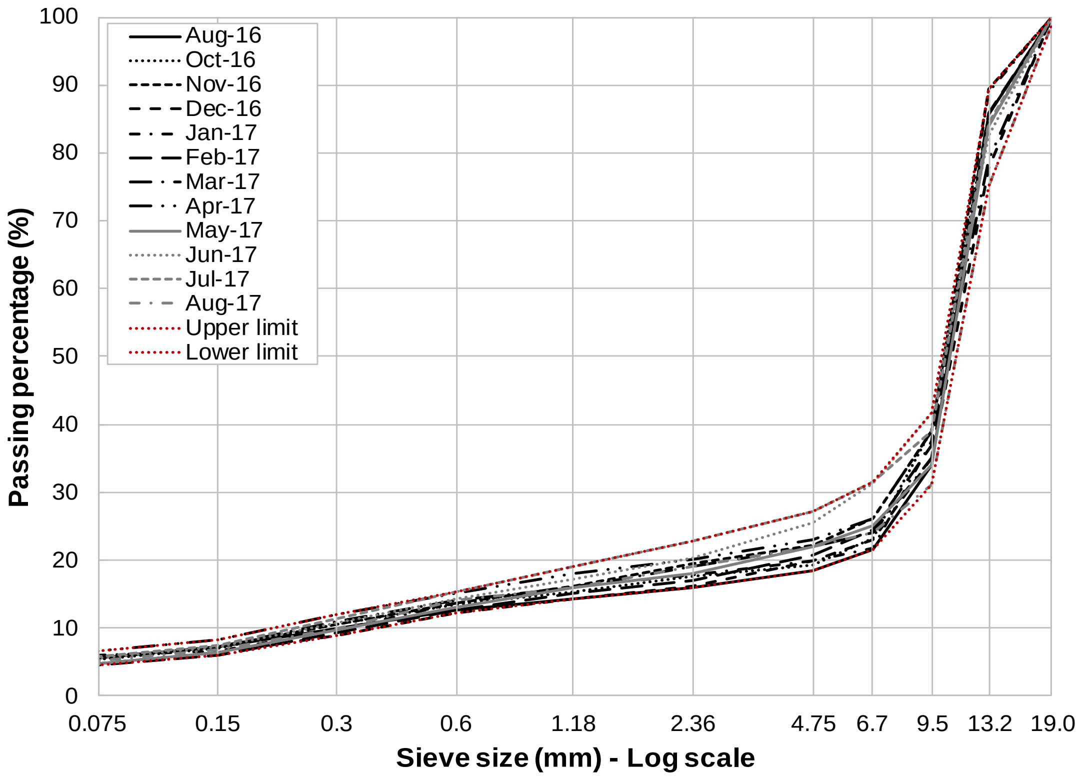


Figure 3.11: Contractor B RAP particle size distributions

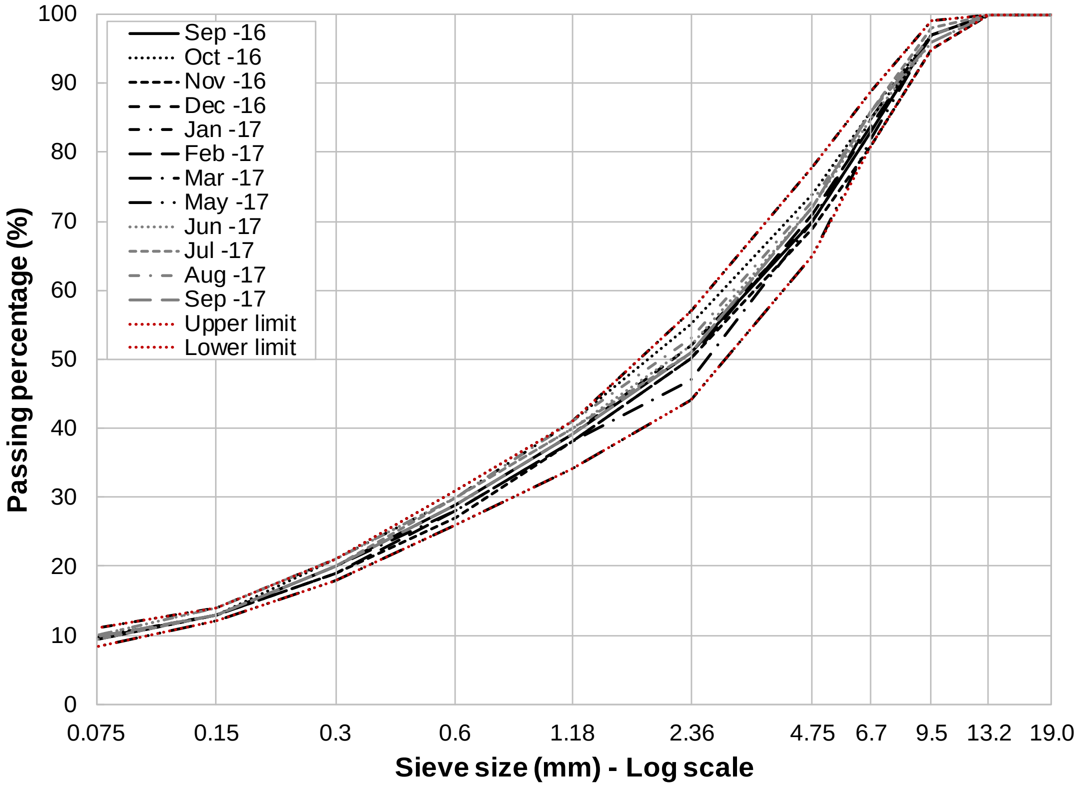
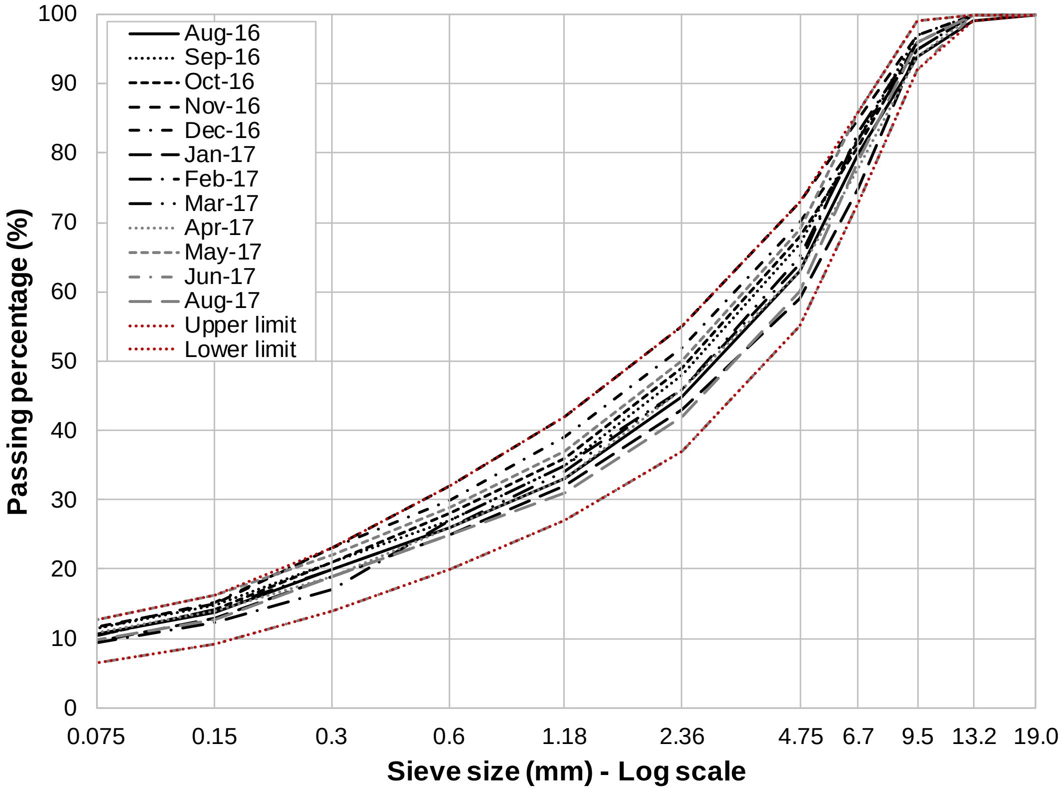


Figure 3.12: Contractor C RAP particle size distributions



3.4 RAP binder content

The studied RAP binder contents as reported by the contactors are shown in Figure 3.13, Figure 3.14 and Figure 3.15. Since contractor A produces two fractions of RAP (nominally 10 and 14 m), Figure 3.13 contains two sets of data to show the binder content of both the fine and coarse RAP fractions.

The figures show that the RAP binder contents collected from all three suppliers are fairly consistent with minimal variation in the production of contractors A and B. However, there were two low binder contents identified with the contractor C RAP supply which were flagged as potential outliers. This was confirmed later during statistical analysis. Contractor C was contacted to discuss any potential reasons for this inconsistency (e.g. change in the source, processing methods etc.), but the inconsistency remained unexplained.

Figure 3.13: Contractor A fine and coarse RAP binder content test results

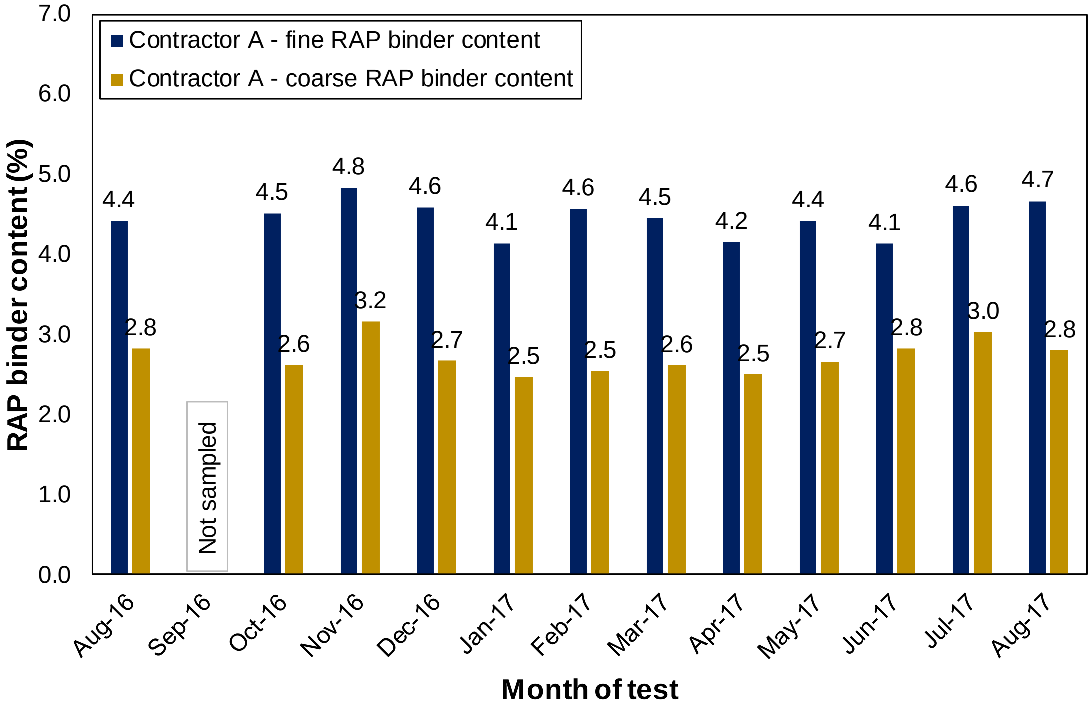


Figure 3.14: Contractor B RAP binder content test results

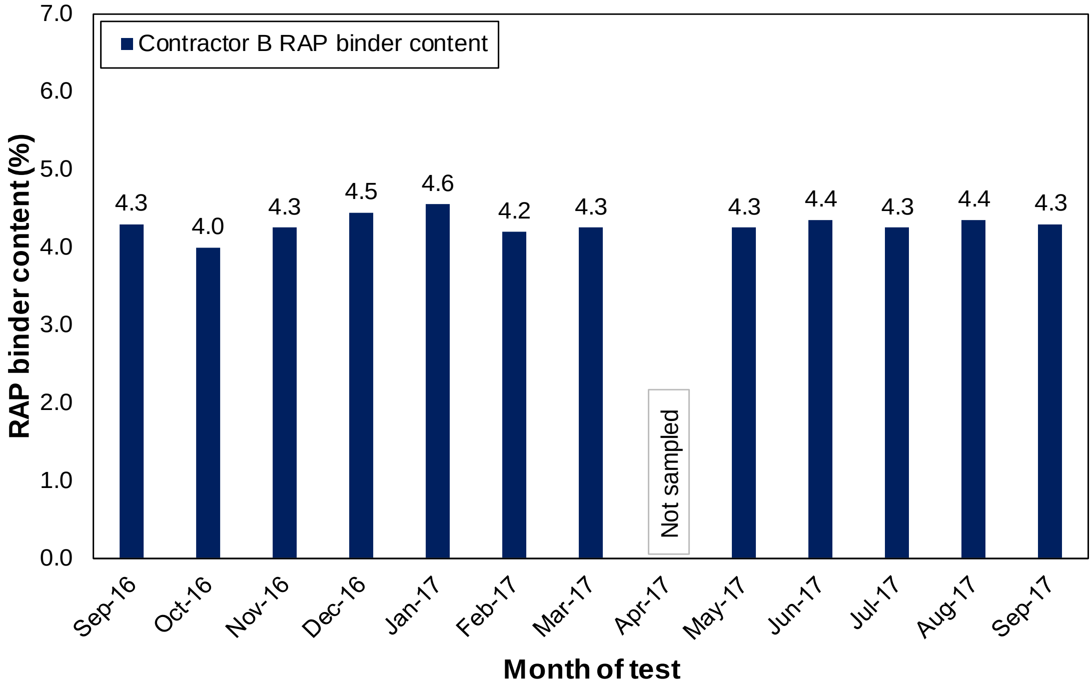
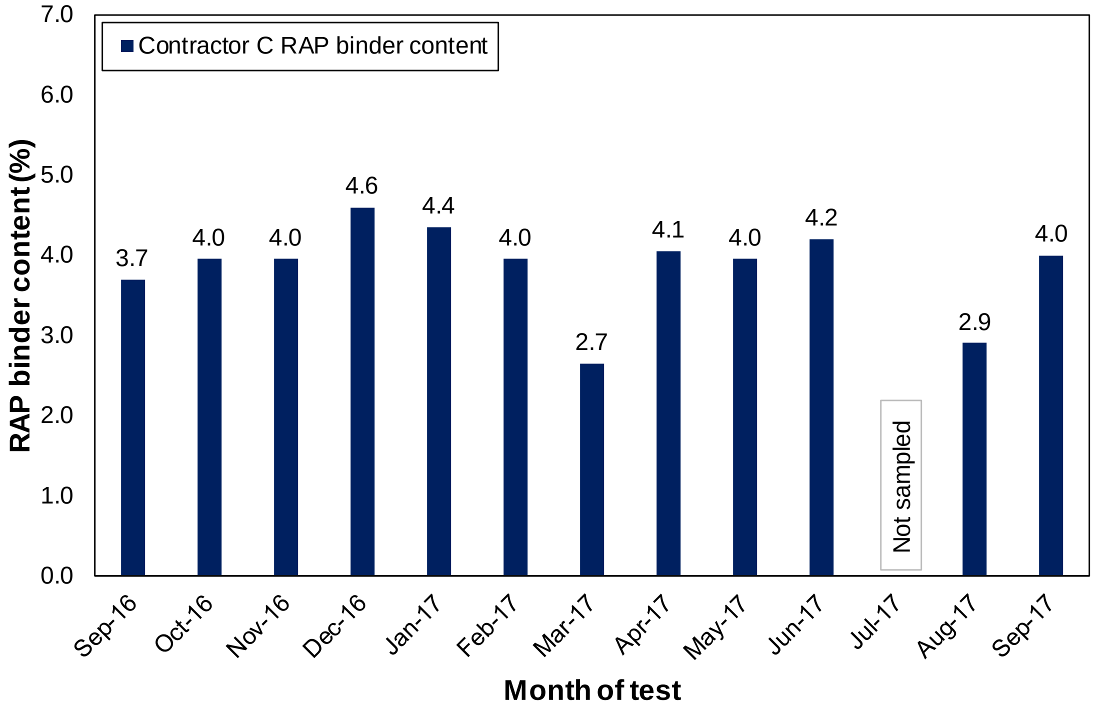


Figure 3.15: Contractor C RAP binder content test results



4 STATISTICAL ANALYSIS

4.1 Methodology

The binder blend equation as outlined in the Austroads test method comprises a number of input parameters including virgin binder viscosity, RAP binder viscosity, RAP binder content, asphalt mix design binder content (asphalt mix total binder content) (AGPT/T193-2015). To understand the sensitivity of the resulting binder blend equation to its input variables, it was necessary for the probability distribution of the blend equation input variables to be identified.

The RAP binder viscosities of the three participating contractors were tested in the ARRB laboratory; the RAP binder contents were provided by the contractors. The virgin binder viscosities were retrieved from TMR's historical data; also, additional virgin binder viscosities were collected by contacting three major binder suppliers to the SEQ. The asphalt mix design binder content was assumed to be variable between 4 and 5% based on uniform probability distribution.

To identify the probability distribution of the binder blend input variables, Anderson-Darling (AD) statistics were used to calculate the p-value for each distribution. The p-value provides a criterion to find the best probability distribution fit to the data set. In the AD test the null hypothesis assumes that the data follow the nominated distribution. Therefore, a lower p-value indicates a stronger likelihood that the data do not follow the distribution. Minitab software (version 18.1) was used to identify the distribution parameters. The assumed null and the alternative hypotheses were defined as follows:

- null hypothesis (H_0): data follow the nominated distribution
- alternative hypothesis (H_1): data do **not** follow the nominated distribution.

Normally a significance level (α or alpha) of 0.05 is assumed. A significance level of 0.05 means that there is 5% risk of concluding that the data do not follow the nominated distribution while they actually follow the distribution. The calculated p-value will fit into one of the following categories in relation to the assumed significance level:

1. The calculated p-value is less than or equal to the assumed significance level (p-value < 0.05).

   This means that the null hypothesis is rejected, and it can be concluded that the data do not follow the distribution.

2. The calculated p-value is greater than the assumed significance level (p-value ≥ 0.05).

   This means that the null hypothesis is not rejected. In other words, there is not enough evidence to conclude that the data do not follow the distribution. Therefore, it can be assumed that the data follow the distribution.

The strategy to select a fit to the data was to satisfy both simplicity and accuracy. Therefore, it was decided to avoid overly complicated distributions while a reasonably accurate fit could be found with simpler and more common/familiar distributions such as normal or lognormal distributions.

The following 18 distributions were examined to determine the best fit to the data:

- normal
- normal after Box-Cox transformation
- normal after Johnson transformation
- lognormal

- 3-parameter lognormal
- exponential
- 2-parameter exponential
- Weibull
- 3-parameter Weibull
- smallest extreme value
- largest extreme value
- gamma
- 3-parameter gamma
- logistic
- loglogistic
- 3-parameter loglogistic.

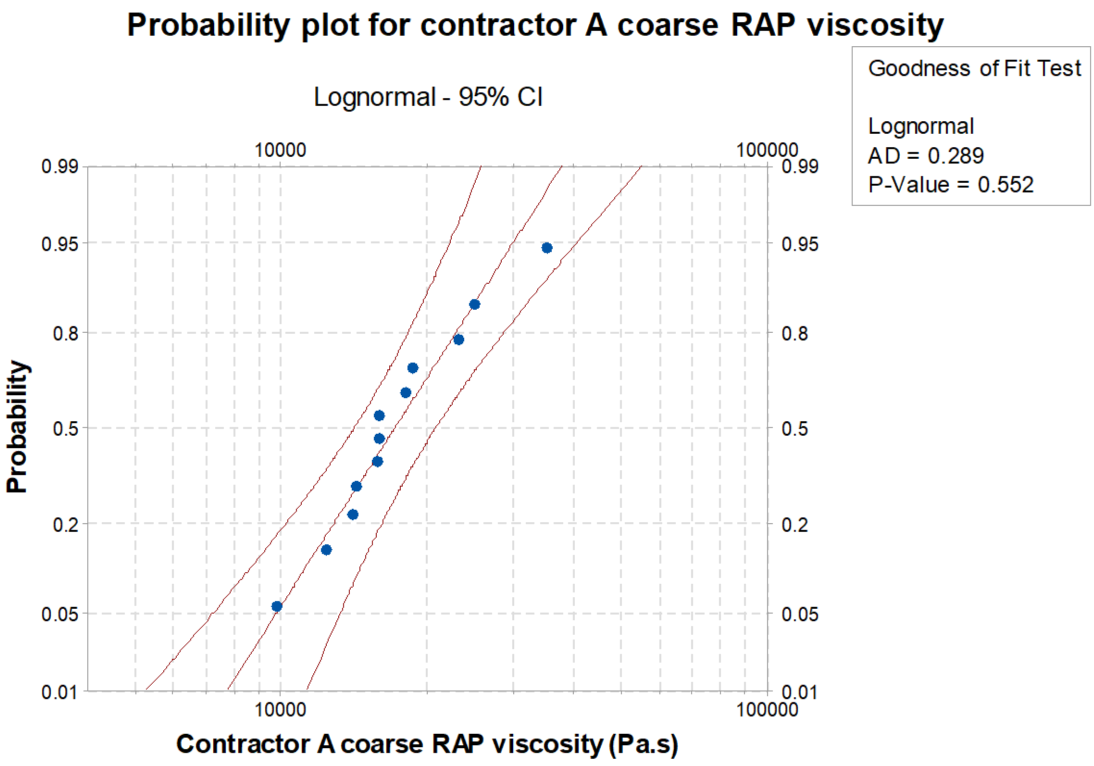
As mentioned earlier, priority was given to the simpler and the most commonly used distributions i.e. if the calculated p-value for a number of distributions was satisfactorily above the assumed 0.05 significance level, the more common distribution was selected for the given dataset.

4.2 RAP binder viscosity probability distribution

The RAP binder viscosity data of each contractor (A fine and coarse, B and C) was analysed, and a probability distribution was fit to each dataset.

It was found that all tested RAP binder viscosities followed lognormal distribution. Figure 4.1 shows an example probability plot with 5% confidence intervals for the percentiles (CI) for contractor A coarse RAP binder viscosity. The resulting p-value for lognormal distribution was well above the 0.05 significance level providing strong evidence that the data follow the lognormal distribution.

Figure 4.1: Example of lognormal probability distribution – contractor A coarse RAP binder viscosity



When the logarithm of the random variable is normally distributed, the distribution of the data is identified as lognormal. The generalised lognormal distribution (3-parameter lognormal distribution) can be identified with three parameters: mean, standard deviation and location. The lognormal probability distribution function (PDF) formulation and the definition of the terms both in logarithmic and arithmetic spaces are expressed in Equation 4 to Equation 8 following (Singh, Jain and Tyagi 2007).

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma_{log}(x - L)} \exp\left[-\frac{\left[\ln(x - L) - \mu_{log}\right]^2}{2\sigma_{log}^2}\right] \qquad 4$$

$$\mu_{log} = \ln\left(\frac{\mu_{ar} - L}{\exp\left(\frac{(\sigma_{log})^2}{2}\right)}\right) \qquad 5$$

$$\sigma_{log} = \sqrt{\ln\left(\exp\left(2 . \ln\frac{\sigma_{ar}}{\mu_{ar} - L}\right) + 1\right)} \qquad 6$$

$$\mu_{ar} = L + \exp\left[\left(\frac{\sigma_{log}^2}{2}\right) + \mu_{log}\right] \qquad 7$$

$$\sigma_{ar}=\sqrt{\exp\left(2\mu_{log}+\sigma_{log}{}^{2}\right)\times\left(\exp\left(\sigma_{log}{}^{2}\right)-1\right)} \quad (8)$$

where

μ_{log} = mean (in logarithmic space)

μ_{ar} = mean (in arithmetic space)

σ_{log} = standard deviation (in logarithmic space)

σ_{ar} = standard deviation (in arithmetic space)

L = location parameter, also known as the threshold parameter, the lower bound of the distribution (always in arithmetic space)

Table 4.1 summarises the probability distribution parameters for contractor A (fine and coarse), B and C RAP binder viscosity in arithmetic space. Probability distribution plots of all the tested RAP binders are presented in Appendix C.1.

Table 4.1: Lognormal probability distribution parameters of the RAP binder viscosity

RAP source	RAP size (mm)	RAP binder viscosity lognormal distribution parameters				
		Location	Mean (arithmetic)	Standard deviation (arithmetic)	Min.	Max.
Contractor A	10	0	20 055	6159	11 519	29 095
Contractor A	14	0	18 174	6390	9764	35 200
Contractor B	10	0	13 892	6061	7498	32 436
Contractor C	10	0	12 284	10 959	3968	49 854

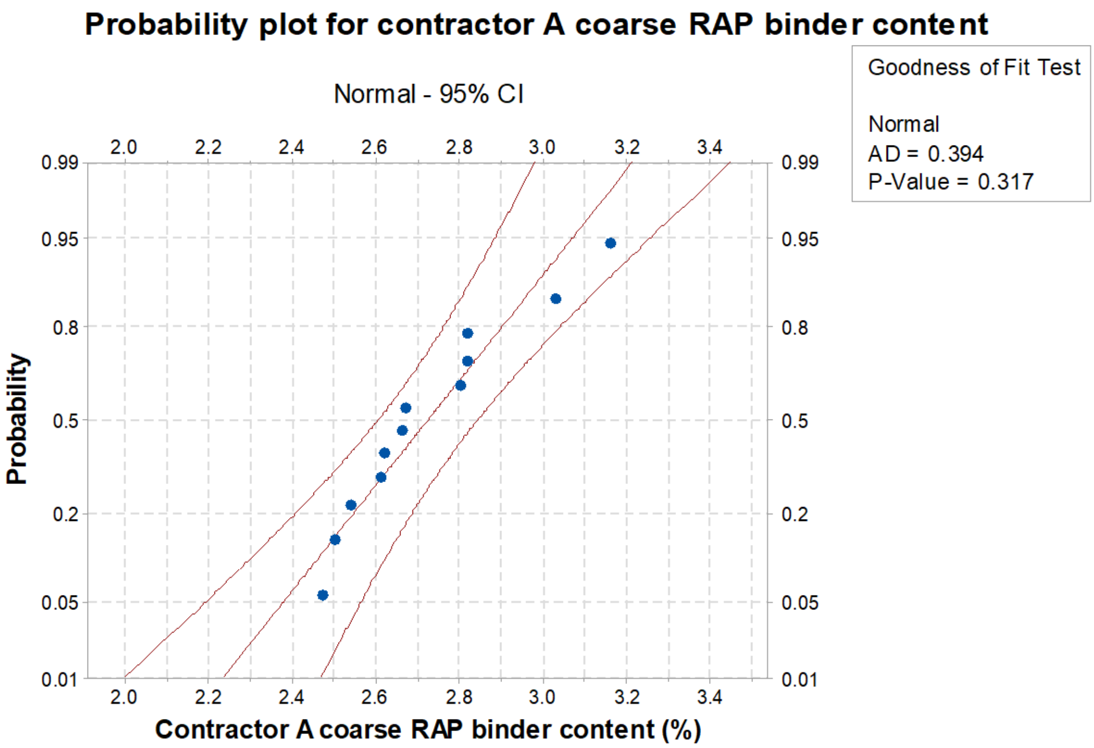
In a study published by Austroads on the sensitivity of the binder blend equation to the input parameters, the distribution of the RAP binder viscosity was assumed to be triangular (Austroads 2016). This difference was due to the fact that in the Austroads study there has no historical RAP binder viscosity data available and triangular distribution for viscosity was assumed as an approximation to the actual data. In the current NACoE study, the lognormal distribution was identified based on the existing actual monthly test results.

4.3 RAP binder content probability distribution

The binder contents of the RAP supplied by contractors A, B and C were also collected as part of the agreement between the participating contractors and TMR. Similar to the RAP binder viscosity distributions identification process, the binder content of the studied RAP material was also analysed, and the probability distributions identified.

It was found that normal distribution best fit the data. This was similar to the findings of the study in Austroads (2016). Figure 4.2 shows an example probability plot with a 5% confidence interval (CI) for percentiles for contractor A coarse RAP binder content.

Figure 4.2: Example of normal probability distribution – contractor A coarse RAP binder content



The normal distribution can be identified with two parameters: mean and standard deviation. The normal probability distribution formulation and the definition of the terms are expressed in Equation 9 following (Singh, Jain and Tyagi 2007).

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right) \quad 9$$

where

μ = mean

σ = standard deviation

Table 4.2 summarises the probability distribution parameters for contractor A (fine and coarse), B and C RAP binder contents. Probability distribution plots of all the tested RAP binders are presented in Appendix C.2.

Table 4.2: Normal probability distribution parameters of the RAP binder content

RAP source	RAP size (mm)	RAP binder content normal distribution parameters			
		Mean	Standard deviation	Min.	Max.
Contractor A	10	4.5	0.22	4.1	4.8
Contractor A	14	2.7	0.21	2.5	3.2
Contractor B	10	4.3	0.13	4.0	4.6
Contractor C	10	4.1 (1)	0.25 (1)	3.7 (1)	4.6 (1)

1 After removal of two outliers.

4.3.1 *Identification of outliers*

Two samples of the contractor C RAP (March and August 2017) production showed excessively low binder contents which were found to be unusual hence flagged as potential outliers. In this section, an outlier analysis is conducted to confirm whether or not the flagged samples with low binder contents could statistically be justified/proved as outliers.

The RAP binder content of contractor A (both fine and coarse) and contractor B followed normal probability distribution; Also, in the Austroads RAP study, the RAP binder content was considered to be normally distributed. Therefore, it was assumed that contractor C RAP binder content should also be normally distributed. On the basis of this assumption, the Dixon ratio test was used to identify the outliers in the contractor C RAP binder content dataset. More technical details of the test including the formulation can be found in several sources (Dixon 1951; King 1953; McBane 2006; Rorabacher 1991). Minitab software was used to run the outlier analysis.

In outlier analysis, the null hypothesis (H_0) and the alternative hypothesis (H_1) were assumed as follows:

- null hypothesis: all the binder contents are from the same, normally distributed population
- alternative hypothesis: one of the values in the sample is not from the same normally distributed population.

The calculated p-values and the significance level (0.05 in this study) were then compared to decide to accept or reject the null hypothesis. The p-value may fit into one of the following scenarios when it is compared with the assumed significance level:

- p-value ≤ 0.05 (reject H_0)

  If the calculated p-value is less than or equal to the assumed significance level, the decision is to reject the null hypothesis and conclude that an outlier exists.
- p-value > 0.05 (fail to reject H_0)
- If the calculated p-value is greater than the assumed significance level, then there is not enough evidence to reject the null hypothesis and it cannot be concluded that an outlier does not exist.

The contractor C RAP binder content dataset consists of 12 data points (representing the RAP binder contents of 12 monthly samples over the sampling period). Given the number of data points, the Dixon r21 ratio test was used to identify any potential outliers. Only one outlier can be identified each time the analysis is conducted. So theoretically, once an outlier is identified it should be removed from the dataset and the analysis re-run on the remaining data points. This should be continued until no outliers are found.

The first run of the outlier analysis showed that 2.65% binder content (the binder content of the RAP sample collected in March 2017) is statistically an outlier (p-value of 0.032 which was less than the significant level of 0.05). The second round of the outlier analysis was conducted once the first outlier was removed from the dataset. The second run identified the 2.90% binder content (the binder content of the RAP sample collected in August 2017) as the other outlier (p-value of 0.007 which was less than the significance level of 0.05). The summary of the two outlier analysis runs is illustrated in Figure 4.3 and Figure 4.4.

The third run of the outlier analysis did not identify any other outliers. Therefore, the two identified outliers were excluded from the dataset and the probability distribution was fit to the 10 remaining data points of the contractor C RAP binder content dataset (Table 4.2 and Figure C 7).

Figure 4.3: Dixon r21 outlier test results plot (first run)

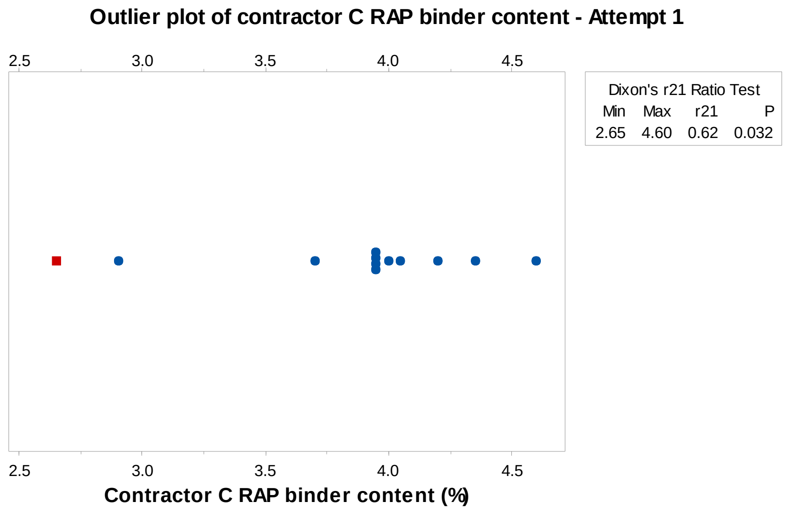
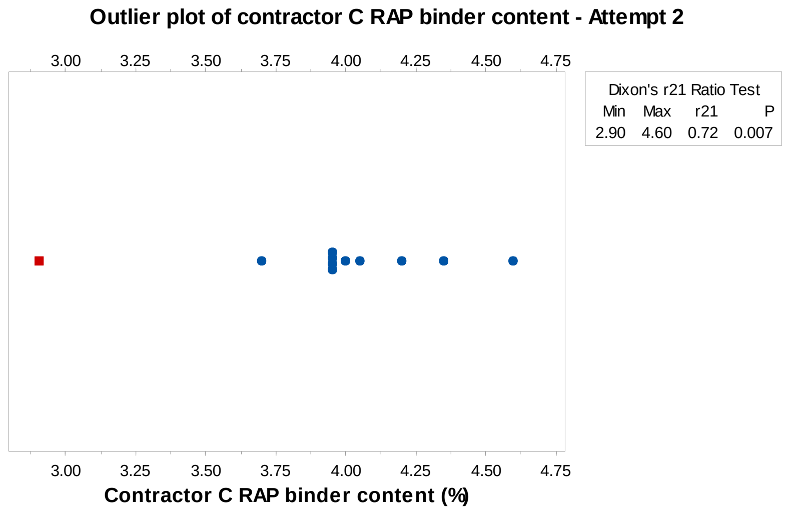


Figure 4.4: Dixon r21 outlier test results plot (second run)



4.4 Virgin binder probability distribution

The other input parameter of the binder blend equation is the viscosity of the virgin binder in the asphalt mix. Therefore, the variability in the viscosity of the supplied virgin binders needed to be identified as well. Historical data of different virgin binder classes (C170, C240, C320, C450 and C600) supplied in SEQ were retrieved from TMR records. Three major binder suppliers (referred to as supplier no. 1, 2 and 3 in this report) were also contacted and requested to provide historical data on their binder production supplied in SEQ. A summary of the collected data is presented in Appendix B.

It was found that normal probability distribution best described the variation of the virgin binder viscosities. As discussed before, normal distribution can be characterised by two parameters namely mean and standard deviation. Table 4.3 summarises the distribution parameters of the surveyed virgin binder classes.

Table 4.3: Normal probability distribution parameters of the Qld virgin binder viscosity

Binder class	Mean (Pa.s)	Standard deviation	Min.	Max.	Range
Qld C170	183	9.2	149	207	58
Qld C240	221	13.5	202	238	36
Qld C320	326	20.4	269	388	119
Qld C450	402	29.3	339	474	135
Qld C600	584	36.5	445	745	300

Standards Australia (AS2008-2013) also specifies the compliance viscosity range of different virgin binder classes. The variation in the viscosity of the virgin binders as specified by the standard were also investigated as a separate scenario and the results of the final binder blend viscosities were compared to the scenario with the actual virgin binders supplied in Queensland. This is discussed in Section 5. The historical virgin binder viscosity data are denoted as ‘Qld’ and the AS2008 viscosity ranges are denoted as ‘AS’ binder in this report.

The mean and standard deviation of the AS2008 virgin binder viscosities are listed in Table 4.4. The standard deviation of each binder class viscosity is calculated based on the fact that in normal distribution, 99.7% of the observations fit in the area of mean ± 3 standard deviations. The mean and the range of the viscosities of each binder class are specified in the standard; the standard deviation was calculated by dividing the viscosity range by six. As an example, for the C170 virgin binder class, with the given compliance range of 140 to 200 Pa.s, the range is 60 (200-140=60) and 10 which is one-sixth of 60 assumed for the standard deviation of the C170 virgin binder class.

Table 4.4: Normal probability distribution parameters of the AS virgin binder viscosity

Binder class	Mean (Pa.s)	Standard deviation	Min.	Max.	Range
AS C170	170	10.0	140	200	60
AS C240	240	15.0	190	280	90
AS C320	320	20.0	260	380	120
AS C450	450	26.7 (1)	300 (1)	600 (1)	160
AS C600	600	33.3	500	700	200

[1] Estimated values.

It should be noted that in AS2008, the viscosity range of class C450 binder is only specified at the post-RTFO treatment condition. The pre-RTFO range was calculated based on assuming a viscosity range of 160 Pa.s for this class of binder. The assumed range was calculated based on an approximate nonlinear interpolation on the viscosity range of the other specified binder classes in AS2008.

Generally, it was found that the Qld C170 and C320 virgin binder classes were slightly on the more viscous side of the compliance range. This was the opposite for the C450 and C600, i.e. the binders were found slightly softer than the specified range in AS2008. It should be noted that the data for the C240 virgin binder are based on a relatively limited number of historical data. Therefore, the results of the statistical analysis on this particular binder should be treated with more care/caution.

5 SENSITIVITY ANALYSIS OF THE BINDER BLEND EQUATION

5.1 Monte Carlo simulation

In a simplified case when a model is a function of only one or two independent variables, the effect of variation in the input variables on the output of the function can be easily plotted and assessed visually. It is also feasible to assess the sensitivity of the equation to the input parameters mathematically especially for those with closed-form equations. However, when the modelled system contains nonlinear models with various (more than two) input variables such as the binder blend viscosity model, the assessment of the variability will become complex and cumbersome.

Monte Carlo simulation (MCS) is a computational risk analysis method commonly used in probabilistic modelling. It is mainly used in analysing the effect of multiple inputs that contain inherent uncertainty. MCS uses the probability distribution of input parameters of a model/equation and transforms a deterministic model to a probabilistic model. It allows for hundreds or thousands of calculations taking into account the variability in the input parameters of a model (Singh, Jain and Tyagi 2007).

In this study, MCS was used to simulate the resulting binder bled viscosity under a number of scenarios given the properties of the RAP materials supplied in SEQ. In the MCS, random values are generated for each input variable based on the respective probability distribution (identified previously), for each combination of randomly generated input variables, and the binder blend viscosity is calculated and recorded for analysis. The schematic outline of the MCS process is shown in Figure 5.1. Oracle Crystal Ball (Version 11.2.4.600) was used for the simulations.

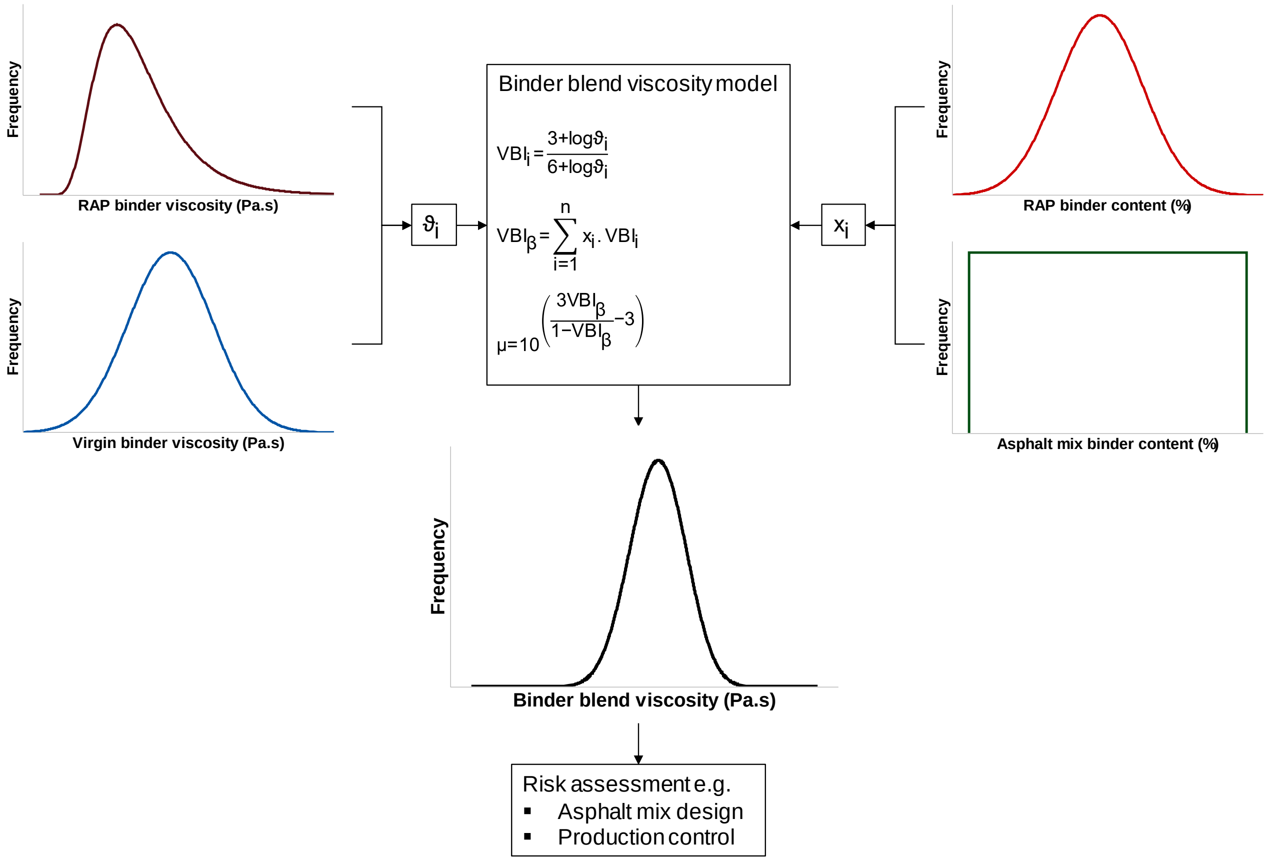
The parameters investigated include the following:

- virgin binder class (C170, C240, C320, C450 and C600) based on:
  - historical data of the virgin binders supplied to SEQ obtained from TMR, and three major bitumen suppliers across the state
  - the compliance viscosity ranges specified in AS2008
- asphalt mix design binder content (ranging from 4 to 5%)
- asphalt mix RAP content (0, 10, 15, 20, 25, 30, 35 and 40%)
- RAP binder viscosity (based on the results from the laboratory testing – Section 3)
- RAP binder content (based on the QA reports provided by the participating contractors).

The following 16 scenarios were considered in the simulations for each contractor (A, B and C) RAP asphalt mixes (48 scenarios altogether):

- varying RAP percentage – 8 scenarios: 0, 10, 15, 20, 25, 30, 35 and 40%
- varying asphalt mix total binder content (asphalt mix design binder content) for each RAP percentage – 2 scenarios:
  - fixed total binder content of the asphalt mix (4.5%)
  - variable total binder content of the asphalt mix, ranging from 4 to 5% based on a uniform probability distribution.

Figure 5.1: Schematic outline of the Monte Carlo simulations



Uniform probability distribution can be characterised by two parameters: the lower and the upper endpoints (minimum and maximum). The uniform probability distribution function formulation and the definition of the terms are expressed in Equation 10 to Equation 12 following (Singh, Jain and Tyagi 2007).

$$f(x) = \frac{1}{(Max - Min)}, \ Min < x < Max, \ Min < Max \qquad 10$$

$$mean = \frac{Min + Max}{2} \qquad 11$$

$$variance = \frac{(Max - Min)^2}{12} \qquad 12$$

where

Min = minimum value (lower endpoint)

Max = maximum value (upper endpoint)

For contractor A, with two RAP fractions, a 2:1 ratio of fine and coarse fractions was assumed. This was based on the current practice of the RAP production of contractor A (personal communication with contractor A).

A total of 200 000 binder blend viscosity calculation simulations were performed for each contractor (A, B and C) and each of the16 abovementioned scenarios (total 48 scenarios). A probability distribution was then fit to each of the 48 scenarios of the binder blend viscosity.

Oracle Crystal Ball can check 14 different distribution to find the best fit to the data. In identifying the best fit to the data, both the simplicity and accuracy criteria were considered. The priority was given to the more common and less complex distributions as long as it resulted in a satisfactory/robust/accurate fit to the dataset. Below is the list of the Oracle Crystal Ball probability distributions available in its distributions library that were checked against each dataset:

- beta
- beta-PERT
- exponential
- gamma
- logistic
- lognormal
- max extreme
- min extreme
- normal
- Preto
- Student's t
- triangular
- Weibull.

The best fit is normally ranked based on either Anderson-Darling, Kolmogorov-Smirnov, or chi-square goodness of fit statistics. It was found that beta probability distribution best fit each of the blend viscosity scenarios (48 scenarios).

Beta probability distribution can be characterised by four parameters: alpha, beta, minimum and maximum. The beta probability distribution function formulation and the definition of the terms are expressed in Equation 13 to Equation 15 following (Singh, Jain and Tyagi 2007).

$$f(x) = \frac{z^{(\alpha - 1)}(1 - z)^{(\beta - 1)}}{\beta(\alpha , \beta)} \qquad 13$$

$$z = \frac{x - Min}{Max - Min} \qquad 14$$

$$\beta(\alpha , \beta) = \frac{\Gamma(\alpha)\,\Gamma(\beta)}{\Gamma(\alpha + \beta)} \qquad 15$$

where

α = alpha (shape parameter 1)

β = beta (shape parameter 2)

Γ: = gamma function

Min = lower limit

Max = upper limit

A full list of the beta distribution parameters for each of the analysed 48 scenarios is tabulated in Appendix D and Appendix E for binder blends made with both Qld virgin binders and AS virgin binders. Figure 5.2 and Figure 5.3 show example beta distribution curves fitted to the binder blend viscosity for asphalt mixes consisting of various percentages of contractor A RAP (combined by 2:1 ratio) and variable asphalt mix total binder content (TBC) (4–5% uniformly distributed). In general, as one would expect, introducing higher percentages of RAP to the asphalt mix will result in a greater variability in the binder blend viscosity as shown in Figure 5.2 and Figure 5.3. However, it should be highlighted that the effect of this variation can be kept minimal by carefully implementing a RAP management plan. With an effective plan in place, the variability within the RAP binder viscosity can be minimised, hence the effect of increasing the RAP percentage on the resulting binder blend viscosity may be limited/negligible. The complete series of the MCS plots are presented in Appendix F.

Figure 5.2: Example binder blend viscosity variation of contractor A combined RAP, Qld C170 virgin binder

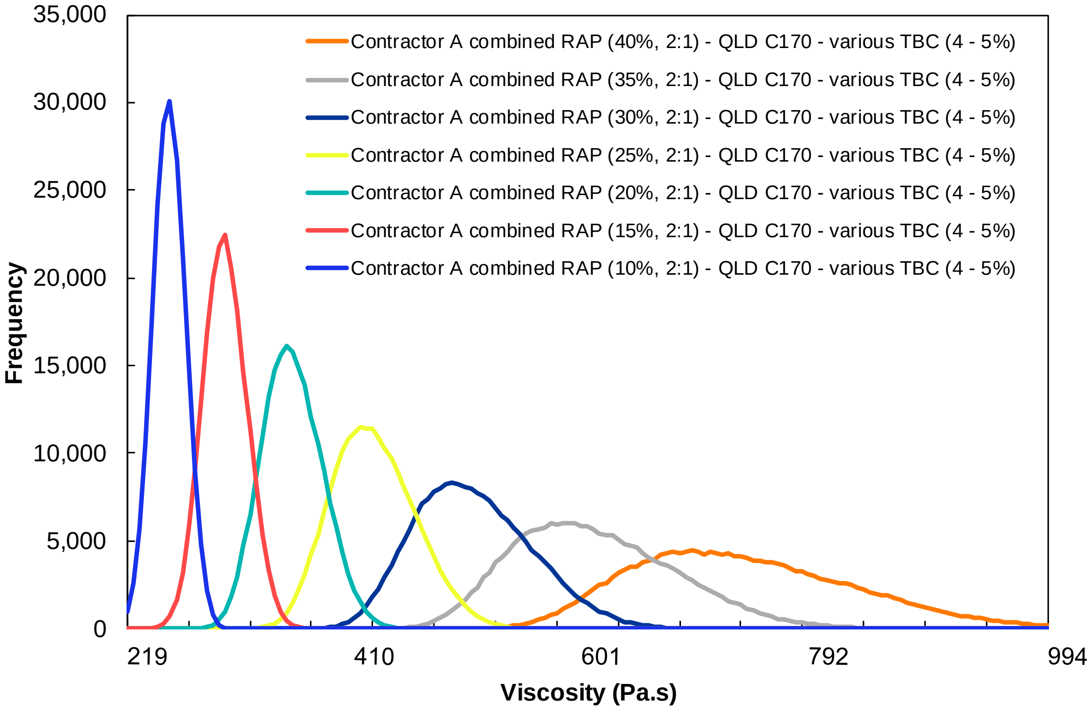
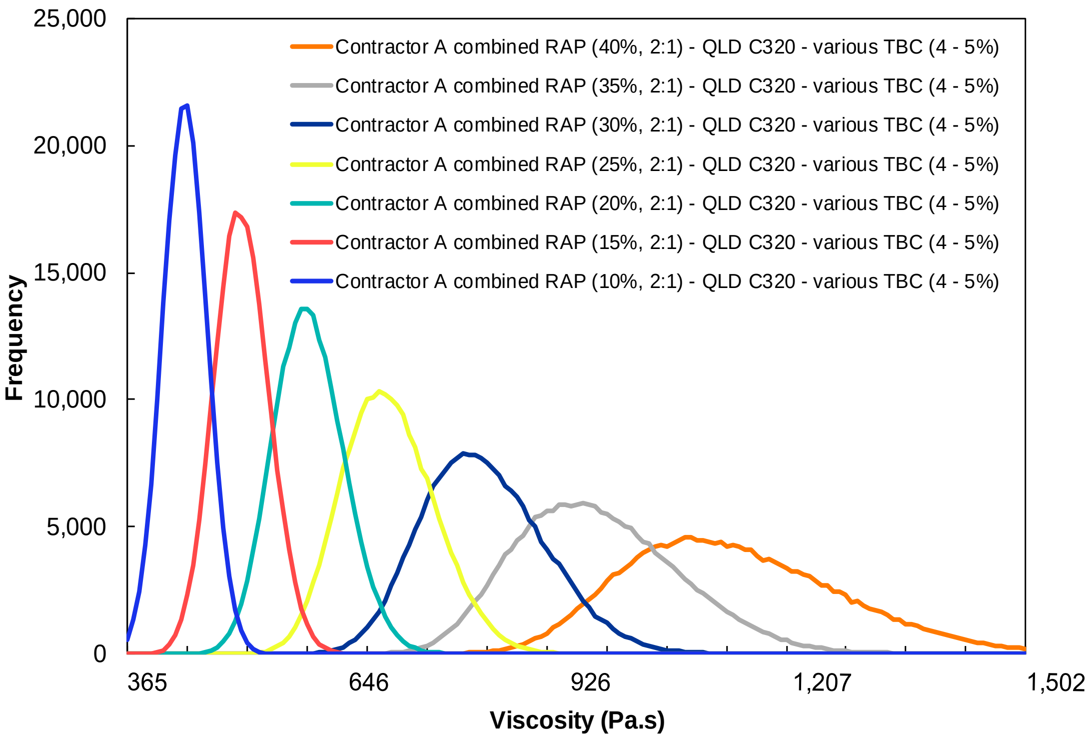


Figure 5.3: Example binder blend viscosity variation of contractor A combined RAP, Qld C320 virgin binder



Once the probability distribution of each of the 48 scenarios was characterised (i.e. the alpha, beta, minimum and maximum values identified), then the following steps were taken to combine the results for all the contractors' data to come up with a general probability distribution for all RAP data combined at each RAP percentage and for each virgin binder class:

1. For each of the 48 scenarios, 200 000 data points were reproduced based on the already characterised beta probability distribution parameters.
2. At each RAP percentage and for each virgin binder class, the generated 200 000 binder blend viscosity data points for each contractor's production (i.e. A, B and C) were combined (3 × 200 000 data points) and a new distribution was then fit to the accumulated dataset.
3. The 10, 50 and 90th percentile values of the fit curves were extracted and used for RAP mix viscosity matrix tables (presented in Section 5.2).

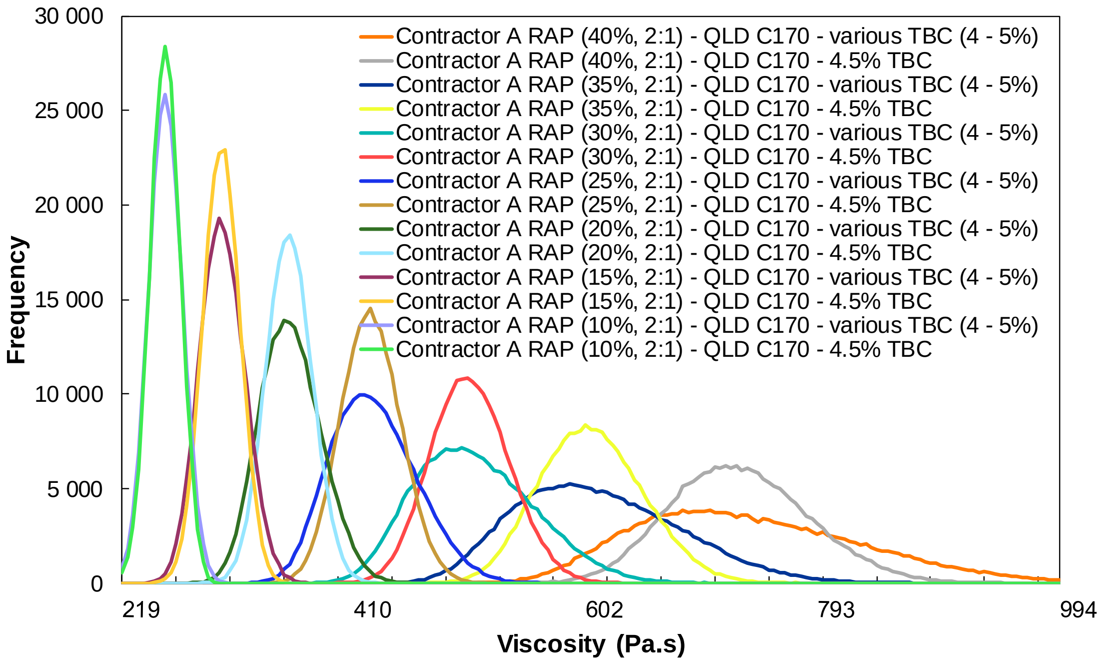
It was found that for the combined RAP data at each RAP percentage, lognormal probability distribution best fit the data. The formulation of the lognormal distribution function is provided in Section 4.2. A summary of the lognormal probability distribution parameters and the 10, 50 and 90th percentiles for the combined RAP scenarios and Qld virgin binder are presented in Table 5.1.

The same steps were considered for the mixes with the assumed compliance viscosity ranges as specified in AS2008 and the results were compared with the mixes containing Qld virgin binder. The summary of the lognormal probability distribution parameters and the 10, 50 and 90th percentiles for the combined RAP scenarios and the AS virgin binders are presented in Table 5.2.

Figure 5.4 shows an example comparison of the binder blend viscosity distributions for contractor A RAP and Qld C170 virgin binder when the asphalt mix total binder content is variable. It shows that at low RAP percentages, the binder blend viscosity does not change significantly when the total binder content changes i.e. there is not much difference between the scenario of the fixed total binder content of 4.5% and the variable total binder content of 4 to 5%. However, as the RAP percentages increase, the contribution of the RAP binder in the total asphalt mix binder increases. This results in greater variability in the blend viscosity at higher RAP percentages.

Therefore, to capture a more realistic image of the variation in the RAP asphalt mixes blend viscosities, the total binder content of the asphalt mix (TBC) was also considered variable ranging from 4 to 5% based on a uniform probability distribution.

Figure 5.4: Example comparison between the variability in the binder blend viscosity for fixed and variable total asphalt mix binder content scenarios (contractor A combined RAP, Qld C170 virgin binder)



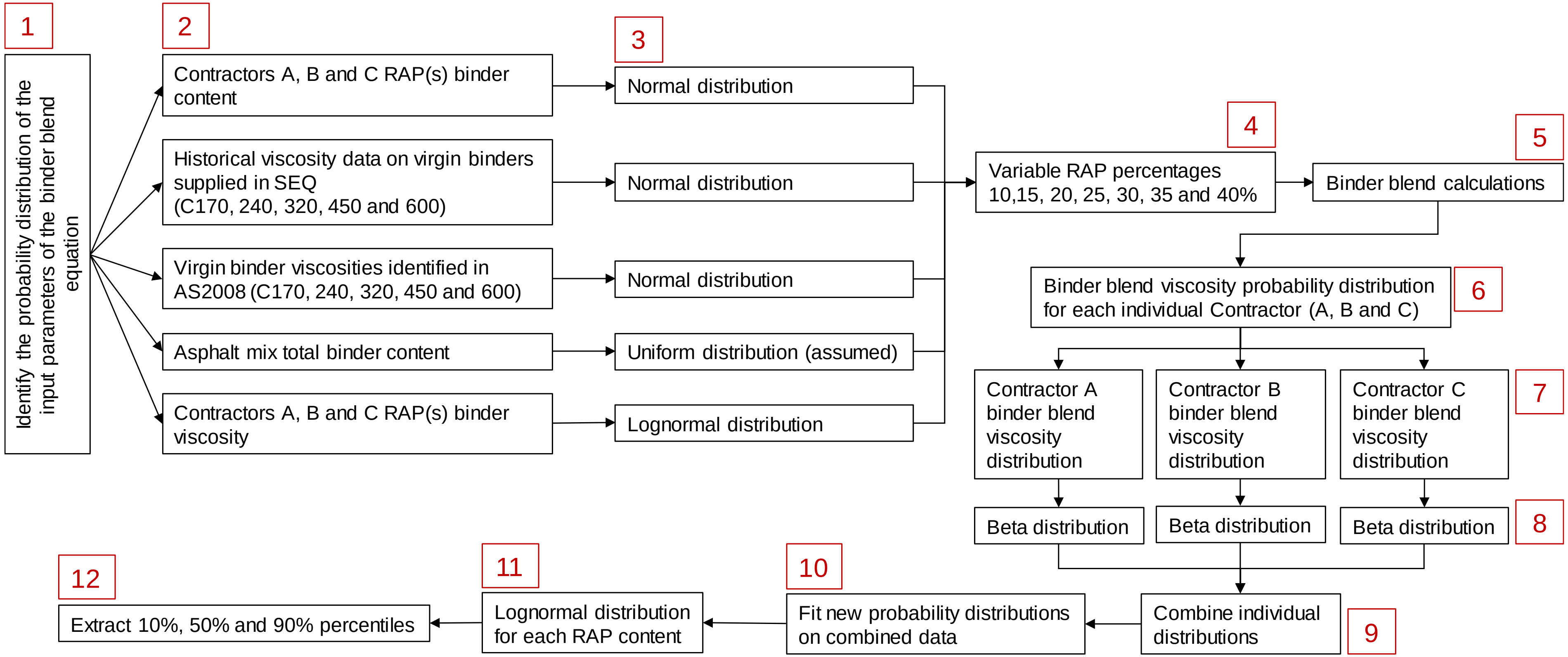
5.2 Results

Figure 5.5 shows a summary flowchart of the variability study of the RAP data. It also includes the findings of the probability distribution fitting exercise. The flowchart is based on the following procedure:

1. The binder blend equation input parameters include RAP binder content, asphalt mix total binder content, RAP binder viscosity and virgin binder viscosity. So, the first requirement was to identify the probability distribution of the input parameters (Steps 1 and 2 Figure 5.5).
2. It was found that the RAP binder contents and the virgin binder viscosities were normally distributed, and the RAP binder content distribution was lognormal. The asphalt total binder content was also assumed uniformly distributed varying between 4 and 5%. (Step 3).
3. Then 200 000 iterations of the binder blend viscosity calculations were attempted for various RAP percentages (10, 15, 20, 25, 30, 35 and 40%) and for each contractor's production. The blend equation input parameters were randomly varied for each based on their relevant probability distributions which were identified previously (Steps 4 and 5).
4. For each RAP percentage and each contractor's RAP production, a probability distribution was fit to the simulated blend calculations (200 000 iterations). It was found that beta distribution best fit the data (Steps 6,7 and 8).

5. The simulated blend calculations of all the contractors were then combined at each RAP percentage; a new probability distribution was then fit to the combined data. This resulted in identifying the probability distribution of all the production at any assumed RAP percentage. It was found that lognormal distribution best fit the combined dataset (Step 9, 10 and 11).
6. The 10, 50 and 90th percentiles data were extracted from each fitted curve. This information was then used to produce the matrix tables for the resulting equivalent binder class of the various RAP percentages and virgin binder classes.

Figure 5.5: Flowchart of the binder blend equation variability study



Based on the 10, 50 and 90th percentile data extracted from the MCS on the combined RAP data, a summary was prepared and is presented in Table 5.1 (for Qld virgin binders) and Table 5.2 (for AS virgin binders). The percentiles are presented in the form of a matrix table; the intersection of the RAP percentage and the virgin binder class is the resulting binder blend viscosity for the given percentile. Table 5.1 and Table 5.2 data are also graphically illustrated in Appendix G.

Table 5.1: Resulting binder blend viscosity percentiles for different percentages of RAP and Qld virgin binder classes

		RAP percentage							
Virgin binder class	Percentile	0%	10%	15%	20%	25%	30%	35%	40%
Qld C170	10%	172	235	273	317	369	429	501	583
	50%	183	254	300	356	424	506	606	728
	90%	195	274	330	399	487	597	735	909
Qld C240	10%	207	281	325	375	433	499	578	670
	50%	221	302	355	419	495	587	699	833
	90%	233	323	388	467	566	689	843	1034
Qld C320	10%	300	399	457	522	596	681	778	889
	50%	326	436	507	589	687	803	941	1106
	90%	352	475	560	663	790	944	1137	1371
Qld C450	10%	401	520	589	665	750	847	958	1082
	50%	427	561	645	744	860	995	1153	1341
	90%	452	603	705	829	979	1160	1381	1648
Qld C600	10%	538	686	771	864	966	1079	1207	1350
	50%	584	753	856	975	1113	1273	1460	1675
	90%	632	819	944	1094	1274	1489	1747	2057

Table 5.2: Resulting binder blend viscosity percentiles for different percentages of RAP and AS virgin binder classes

		RAP percentage							
Virgin binder class	Percentile	0%	10%	15%	20%	25%	30%	35%	40%
AS C170	10%	157	217	253	295	343	399	465	541
	50%	170	237	281	335	400	480	579	700
	90%	183	257	310	375	458	562	693	858
AS C240	10%	221	299	345	398	458	527	606	699
	50%	240	328	384	453	535	633	753	898
	90%	259	357	424	507	611	740	900	1098
AS C320	10%	295	391	448	511	584	665	758	865
	50%	320	429	499	581	680	797	937	1106
	90%	346	467	550	651	776	929	1116	1347
AS C450	10%	416	540	611	689	777	875	985	1108
	50%	450	590	678	781	902	1043	1210	1409
	90%	484	641	745	872	1026	1211	1435	1709
AS C600	10%	557	710	794	886	988	1102	1226	1366
	50%	600	772	878	1000	1142	1308	1500	1725
	90%	642	834	961	1114	1296	1515	1774	2085

5.2.1 Classification of the binder blend results

TMR in its current asphalt pavement specification (MRTS30), permits contractors to use RAP of up to 15% in the surfacing and other pavement courses with no required history of proven performance. The only testing requirements for RAP containing asphalt mixes are the binder content and the RAP aggregate grading. In other words, the current TMR specification treats mixes with up to 15% RAP as normal mixes with no additional performance requirements.

Based on this assumption, a new viscosity range was considered for the resulting binder blend viscosities. This viscosity range was used to classify the binder blends into equivalent C170, C240, C320, C450 and C600 binder blend classes. The viscosity range for each virgin binder class was defined as follows:

- lower limit: defined as the 10^{th} percentile of the relevant base virgin binder viscosity (containing no RAP)
- upper limit: defined as the 90^{th} percentile of the binder blend viscosity containing 15% RAP.

Table 5.3 and Table 5.4 are extracts from Table 5.1 and Table 5.2, and summarise the viscosity ranges of the equivalent binder classes. It should be noted that since these limits were defined based on statistical simulations on binder blend viscosities, they are not definite, and some tolerance level could be introduced. However, the extent of the flexibility in the ranges requires more testing and further analysis which at this stage is out of the scope of this project.

Table 5.3: Binder blend viscosity ranges of the equivalent Qld virgin binder classes

Equivalent binder class	10^{th} percentile	90^{th} percentile
Qld C170	172	330
Qld C240	207	388
Qld C320	300	560
Qld C450	401	705
Qld C600	538	944

Table 5.4: Binder blend viscosity ranges of the equivalent AS virgin binder classes

Equivalent binder class	10^{th} percentile	90^{th} percentile
AS C170	157	310
AS C240	221	424
AS C320	295	550
AS C450	416	745
AS C600	558	962

As an example, the resulting binder blend could be classified as an equivalent Qld C320 if its viscosity ranges from 300 to 560 Pa.s (as shown in Table 5.3). The viscosity of 300 Pa.s (the lower limit) is the 10^{th} percentile of the base Qld C320 virgin binder with no RAP, and the viscosity of 560 Pa.s (the upper limit) is the 90^{th} percentile of a binder blend with a base Qld C320 virgin binder with 15% RAP.

The resulting binder blend viscosities and the introduced lower and upper limits were plotted for each virgin binder class. The ranges of the blend viscosities for various virgin binders at different RAP percentages are plotted and presented in Appendix H. To make the presented data distinguishable, the virgin binder classes are colour coded. Each line represents the 10^{th}, 50^{th} and 90^{th} percentile of a virgin binder class at any given RAP percentage. An offset along the x-axis

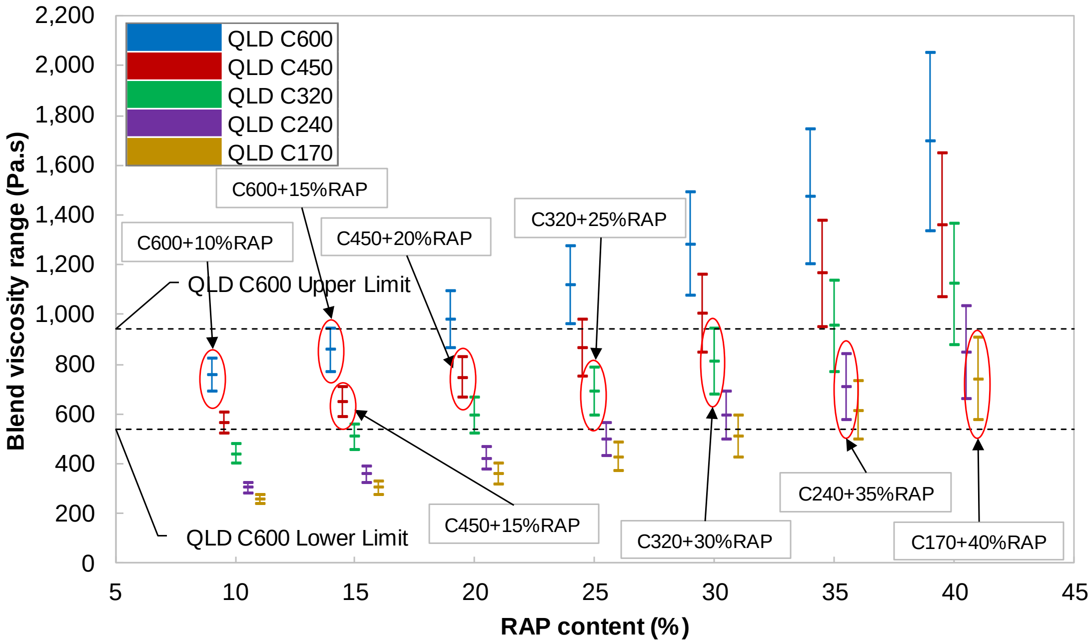
(RAP percentage) was considered between the lines at each RAP percentage so that the data could be read and differentiated.

As an example, the lower and the upper viscosity limits of the equivalent Qld C600 binder blend viscosity are shown in Figure 5.6. It shows for this example that the following combinations of Qld virgin binders and RAP percentages will fit within the lower and upper limits of an equivalent Qld C600 binder blend classification:

- Qld C600 virgin binder + 10% RAP
- Qld C600 virgin binder + 15% RAP
- Qld C450 virgin binder + 15% RAP
- Qld C450 virgin binder + 20% RAP
- Qld C320 virgin binder + 25% RAP
- Qld C320 virgin binder + 30% RAP
- Qld C240 virgin binder + 35% RAP
- Qld C170 virgin binder + 40% RAP.

The summary of all the binder blend equivalent classes for mixes with both Qld virgin and AS virgin binders is presented in Table 5.5 and Table 5.6 respectively. There are some subtle differences between the equivalent binder blend classes listed in Table 5.5 and Table 5.6 (highlighted in red). This difference is due to the different virgin binder viscosity ranges considered for the Qld and the AS virgin binders.

Figure 5.6: Resulting binder blend viscosities equivalent to Qld C600 classification



Once the classification of the equivalent binder blends was complete, a binder blend classification matrix was developed both for Qld virgin binders and AS virgin binders (Table 5.5 and Table 5.6). As mentioned previously, since the calculated ranges are not definite, the binder classes that were marginally out of the specified limits are also listed in Table 5.5 and Table 5.6. The differences in the binder blend classification based on Qld virgin and AS virgin binders are highlighted in red. These differences are due to the different viscosity ranges considered for each. The viscosity ranges of the Qld virgin binders were tested in the laboratory; the viscosities assumed for the AS virgin binders are the compliance ranges specified in AS2008.

Table 5.5: Resulting binder blend viscosity classifications for binder blends containing Qld virgin binders

	RAP percentage						
Virgin binder class	**10%**	**15%**	**20%**	**25%**	**30%**	**35%**	**40%**
Qld C170	C170/C240	C170/C240	C240(1)/C320	C320	C450	-	C600
Qld C240	C170/C240	C240/C320	C320	C320(2)/C450	C450	C600	-
Qld C320	C320/C450(3)	C320/C450	C450/C600(4)	C600	C600(5)	-	-
Qld C450	C450	C450/C600	C600	-	-	-	-
Qld C600	C600	C600	-	-	-	-	-

(1) Upper limit out by 11.64 Pa.s, 3.00 %.

(2) Upper limit out by 6.34 Pa.s, 1.13 %.

(3) Lower limit out by 2.48 Pa.s, 0.62 %.

(4) Lower limit out by 16.43 Pa.s, 3.05 %.

(5) Upper limit out by 0.31 Pa.s, 0.03 %.

Table 5.6: Resulting binder blend viscosity classifications for binder blends containing AS virgin binders

	RAP percentage						
Virgin binder class	**10%**	**15%**	**20%**	**25%**	**30%**	**35%**	**40%**
AS C170	C170/C240(1)	C170/C240	C240/C320	C320	C320(2)/C450(3)	C450	C600(4)
AS C240	C240/C320	C240/C320	C320/C450(5)	C450	C450	C600	-
AS C320	C320	C320/C450	C450	C600	C600	-	-
AS C450	C450	C450/C600	C600	-	-	-	-
AS C600	C600	C600	-	-	-	-	-

(1) Lower limit out by 4.05 Pa.s, 1.83 %.

(2) Lower limit out by 14.08 Pa.s, 3.38 %.

(3) Upper limit out by 13.80 Pa.s, 2.51 %.

(4) Lower limit out by 6.68 Pa.s, 1.20 %.

(5) Lower limit out by 17.27 Pa.s, 4.15 %.

6 CONCLUSION AND RECOMMENDATIONS

This study was conducted under a NACoE program to facilitate implementation of the application of higher percentages of RAP in TMR's dense graded asphalt mixes. The study was based on the core findings of a previous multiyear Austroads project to maximise the re-use of RAP in asphalt mixes. The outcome of the NACoE project was modifications to the MRTS30 specification and development of a technical note on binder blend calculations and the requirements of the binder blend viscosities for TMR projects. This report provides background information and supplementary details of the statistical analyses from which the TMR technical note was developed.

The statistical analyses were conducted on the results of a 12-month testing program on three participating contractors' RAP production. One of the contractors (A) produces two fractions of RAP (10 and 14 mm). The other contractors (B and C) only produce 10 mm (fine) RAP. The testing program included collection of 12 monthly RAP samples from each contractor. The binder component of the collected RAP samples was then extracted and put into DSR testing in the laboratory. Supplementary information such as the RAP aggregate grading and the RAP binder content were also provided by the contactors.

The probability distribution of the binder blend equation input parameters i.e. RAP binder content, RAP binder viscosity and the virgin binder viscosity were identified. Also, a uniform probability distribution was assumed for the total binder content of the asphalt mix. Details of the fit distributions are presented in Section 4.

The primary focus of the study was to investigate the effect of variation in the binder blend equation input parameters on the resulting binder blend viscosity to evaluate the associated risk with variation in RAP binder properties supplied in SEQ. Monte Carlo simulations were used to evaluate the sensitivity of the binder blend viscosity to variation in the input parameters. The flowchart of the variability analysis is presented in Section 5.2. Based on the statistical analysis, matrix tables of equivalent binder blend classes were developed both for binder blends made with Qld virgin binder and AS virgin binder viscosity ranges (Table 5.5 and Table 5.6).

Findings of the statistical analyses were used to develop the TMR technical note (use of high percentages of asphalt pavement material in dense graded asphalt), which at the time of preparation of this report is undergoing industry consultation.

6.1 Recommendations

The reliability of statistical analysis is dependent on the available volume of data in the dataset, as the larger the dataset, potentially the more reliable/accurate the results. Therefore, it is recommended that, if possible, the monitoring of the RAP binder viscosities continues under future research programs to expand the database of the RAP characteristics to improve the robustness of the analysis and reduce the risk. Contractors are testing and collecting RAP binder content, grading, etc. on an ongoing basis. An agreement can be made with the contractors to collect this information over a longer period. This will impose no additional testing cost and can enrich/expand the RAP material information database, hence improve the reliability of the statistical analyses.

Also, further testing and analysis is required to introduce tolerance levels on the specified blend viscosity ranges for each equivalent binder blend classification. This could be expressed in terms of suggested significant figures for the calculated binder blend viscosity and/or equivalent binder blend viscosity range for each specific binder classification. The other alternative could be to introduce tolerance percentage for each specified classification viscosity range.

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APPENDIX A LABORATORY TEST RESULTS

A.1 RAP binder viscosity test results

A.1.1 Contractor A

Table A 1: Contractor A RAP binder viscosity test results

Contractor A - RAP binder complex viscosity (AGPT/T192-15) - (60 °C, 1 rad/s) - Pa.s					
Fine RAP (10 mm)					
Sampled month	Test 1	Test 2	Average	Reported (1)	Binder content (%)
Aug-16	19 040	20 470	19 755	19 800	4.42
Oct-16	29 410	28 780	29 095	29 100	4.51
Nov-16	14 470	15 580	15 025	15 000	4.83
Dec-16	25 430	29 470	27 450	27 400	4.59
Jan-17	21 118	21 100	21 109	21 100	4.14
Feb-17	18 169	20 342	19 256	19 300	4.57
Mar-17	14 745	12 966	13 856	13 900	4.45
Apr-17	20 533	20 303	20 418	20 400	4.15
May-17	11 744	11 293	11 519	11 500	4.42
Jun-17	24 805	25 399	25 102	25 100	4.13
Jul-17	23 546	23 563	23 555	23 600	4.61
Aug-17	14 066	12 494	13 280	13 300	4.67
Coarse RAP (14 mm)					
Sampled month	Test 1	Test 2	Average	Reported (1)	Binder content (%)
Aug-16	15 530	15 940	15 735	15 700	2.82
Oct-16	24 030	25 990	25 010	25 000	2.62
Nov-16	9468	10 060	9764	9760	3.16
Dec-16	34 960	35 440	35 200	35 200	2.67
Jan-17	16 107	15 593	15 850	15 800	2.47
Feb-17	24 111	22 240	23 176	23 200	2.54
Mar-17	16 041	15 771	15 906	15 900	2.61
Apr-17	13 859	14 096	13 978	14 000	2.50
May-17	17 240	18 659	17 950	18 000	2.66
Jun-17	13 484	11 184	12 334	12 300	2.82
Jul-17	14 285	14 054	14 170	14 170	3.03
Aug-17	18 479	18 746	18 613	18 600	2.80

[1] Three significant figures.

A.1.2 Contractor B

Table A 2: Contractor B RAP binder viscosity test results

Contract B RAP binder complex viscosity (AGPT/T192-15) - (60 °C, 1 rad/s) - Pa.s					
Sampled month	Test 1	Test 2	Average	Reported (1)	Binder content (%)
Sep-16	23 530	24 260	23 895	23 900	4.30
Oct-16	8021	9202	8612	8610	4.00
Nov-16	10 160	10 360	10 260	10 300	4.25
Dec-16	9887	10 274	10 081	10 100	4.45
Jan-17	34 064	30 807	32 436	32 400	4.55
Feb-17	12 811	13 114	12 963	13 000	4.20
Mar-17	15 236	14 285	14 761	14 800	4.25
May-17	11 351	11 064	11 208	11 200	4.25
Jun-17	10 024	9681	9853	9850	4.35
Jul-17	7632	7364	7498	7500	4.25
Aug-17	13 482	13 833	13 658	13 700	4.35
Sep-17	12 349	11 984	12 167	12 200	4.30

1 Three significant figures.

A.1.3 Contractor C

Table A 3: Contractor C RAP binder viscosity test results

Contract C RAP binder complex viscosity (AGPT/T192-15) - (60 °C, 1 rad/s) - Pa.s					
Sampled month	Test 1	Test 2	Average	Reported (1)	Binder content (%)
Sep-16	7060	7047	7054	7050	3.70
Oct-16	6433	6377	6405	6400	3.95
Nov-16	7830	9438	8634	8630	3.95
Dec-16	6526	6689	6608	6610	4.60
Jan-17	15 904	16 532	16 218	16 200	4.35
Feb-17	13 001	12 837	12919	12 900	3.95
Mar-17	6818	6711	6765	6760	2.65
Apr-17	4288	3792	4040	4040	4.05
May-17	5071	4755	4913	4910	3.95
Jun-17	47 325	52 382	49 854	49 900	4.20
Aug-17	3885	4050	3968	3970	2.90
Sep-17	24 274	24 765	24 520	24 500	4.00

1 Three significant figures.

A.2 RAP particle size distributions

Table A 4: Contractor A RAP particle size distribution

Contractor A RAP particle size distribution (%)												
Fine RAP (10 mm)												
Sieve size (mm)	Aug-16	Oct-16	Nov-16	Dec-16	Jan-17	Feb-17	Mar-17	Apr-17	May-17	Jun-17	Jul-17	Aug-17
26.50	100	100	100	100	100	100	100	100	100	100	100	100
19.00	100	100	100	100	100	100	100	100	100	100	100	100
13.20	100	100	100	100	100	100	100	100	100	100	100	100
9.50	94	99	98	96	98	99	98	97	94	97	98	96
6.70	80	91	87	84	87	91	85	86	80	82	84	82
4.75	62	78	74	71	71	78	71	70	65	67	73	70
2.36	43	57	55	53	51	58	51	49	48	49	55	50
1.18	32	42	43	40	38	44	39	37	36	36	39	39
0.60	25	32	32	30	28	32	30	28	27	26	28	28
0.30	18	22	21	20	19	21	20	20	19	18	19	19
0.15	12	15	14	13	12	13	13	13	12	12	12	13
0.075	9.0	11.7	11.8	9.6	8.8	9.4	9.9	9.7	8.8	8.7	9.2	9.5
Coarse RAP (14 mm)												
Sieve size (mm)	Aug-16	Oct-16	Nov-16	Dec-16	Jan-17	Feb-17	Mar-17	Apr-17	May-17	Jun-17	Jul-17	Aug-17
26.50	100	100	100	100	100	100	100	100	100	100	100	100
19.00	100	100	100	100	100	100	100	100	100	100	100	99
13.20	86	86	89	78	89	86	84	79	84	83	85	75
9.50	34	39	39	35	38	37	35	39	34	42	39	31
6.70	22	23	26	23	22	24	24	26	25	31	32	24
4.75	18	19	22	20	20	21	22	23	22	25	27	22
2.36	16	18	19	16	18	17	19	20	18	20	23	19
1.18	14	15	16	14	16	15	16	18	16	17	19	16
0.60	13	14	14	12	14	13	14	15	13	14	15	14
0.30	10	11	11	9	10	9	11	12	10	11	11	10
0.15	7	7	7	6	7	6	7	8	6	7	8	7
0.075	5.5	5.3	5.6	4.8	5.9	4.4	5.5	6.6	4.8	5.5	5.8	5.2

Table A 5: Contractor B RAP particle size distribution

Sieve size (mm)	Contractor B RAP particle size distribution (%)											
	Sep-16	Oct-16	Nov-16	Dec-16	Jan-17	Feb-17	Mar-17	May-17	Jun-17	Jul-17	Aug-17	Sep -17
26.50	100	100	100	100	100	100	100	100	100	100	100	100
19.00	100	100	100	100	100	100	100	100	100	100	100	100
13.20	100	100	100	100	100	100	100	100	100	100	100	100
9.50	97	97	95	97	99	97	97	97	96	98	97	96
6.70	83	86	81	83	89	84	85	82	85	86	86	86
4.75	70	74	69	70	78	71	70	65	72	72	73	72
2.36	51	55	50	52	57	50	47	44	52	51	53	51
1.18	39	41	38	39	41	38	38	34	40	40	41	39
0.60	29	31	27	29	30	28	28	26	30	30	30	29
0.30	20	21	19	20	21	19	20	18	21	20	21	20
0.15	13	13	13	13	14	13	13	12	14	13	14	13
0.075	9.6	9.9	9.5	9.8	11.0	9.3	9.6	8.4	10.0	9.4	10.0	9.8

Table A 6: Contractor C RAP particle size distribution

Sieve size (mm)	Contractor C RAP particle size distribution (%)											
	Aug-16	Sep-16	Oct-16	Nov-16	Dec-16	Jan-17	Feb-17	Mar-17	Apr-17	May-17	Jun-17	Aug-17
26.50	100	100	100	100	100	100	100	100	100	100	100	100
19.00	100	100	100	100	100	100	100	100	100	100	100	100
13.20	99	100	100	100	100	100	100	100	100	100	100	100
9.50	94	97	96	97	96	95	96	95	94	99	92	96
6.70	80	82	81	85	82	75	83	82	78	86	73	79
4.75	63	67	68	73	70	59	64	65	63	69	55	60
2.36	45	48	49	55	52	43	46	46	46	50	37	42
1.18	33	35	36	42	39	32	35	34	33	37	27	31
0.60	26	27	28	32	30	25	27	26	26	29	20	25
0.30	20	21	21	23	23	19	17	20	19	22	14	19
0.15	14	15	14	15	15	13	12	14	14	16	9	13
0.075	10.7	11.4	10.4	11.7	11.4	9.6	9.3	10.5	10.9	12.8	6.4	9.8

APPENDIX B HISTORICAL VIRGIN BINDER VISCOSITY DATA

B.1 TMR records

Table B 7: TMR historical records of C170, C320 and C600 virgin binder viscosities

Binder class	Period	No. samples	Ave. visc. (Pa.s)	Std. dev.	Visc. range (Pa.s)
C170	2015/16	98	180.0	8.0	149 -207
	201617	103	185.0	9.9	154 - 207
	2017/18	46	188.2	9.7	141 - 203
C320	2015/16	89	328.2	21.6	274 - 388
	201617	120	322.3	19.0	269 - 380
	2017/18	47	327.3	45.2	293 - 372
C600	2015/16	17	595.8	67.2	445 - 745
	201617	40	580.5	29.5	527 - 682
	2017/18	26	579.2	23.0	512 - 678

B.2 Supplier no.1

Table B 8: Historical C450 virgin binder viscosity records obtained from supplier no.1 (plants A and B)

Plant A		Plant B		
Date	Viscosity (Pa.s)	Period (years)	Ave. visc. (Pa.s)	Range (Pa.s)
N/A	479	2015 - 2018 (4 years)	428 (500 production runs)	372 - 481
N/A	427			

B.3 Supplier no. 2

Table B 9: Historical C240 virgin binder viscosity records obtained from supplier no.2

Binder class	Date	Viscosity (Pa.s)
C240	28/03/2017	225
	30/05/2017	230
	27/06/2017	220
	27/09/2017	202
	14/11/2017	208
	13/12/2017	238

Table B 10: Historical C450 virgin binder viscosity records obtained from supplier no.2

Binder class	Date	Viscosity (Pa.s)	Date	Viscosity (Pa.s)	Date	Viscosity (Pa.s)
C450	19/07/2016	473	12/09/2017	452	15/05/2017	455
C450	20/07/2016	436	20/09/2017	421	18/05/2017	457
C450	25/07/2016	412	4/10/2017	415	22/05/2017	452
C450	17/08/2016	462	16/10/2017	400	23/05/2017	428
C450	6/09/2016	483	1/11/2017	388	24/05/2017	411
C450	15/09/2016	432	10/11/2017	430	25/05/2017	439
C450	19/09/2016	398	16/11/2017	413	30/05/2017	434
C450	26/09/2016	423	24/11/2017	424	31/05/2017	434
C450	3/01/2017	414	9/01/2017	394	5/06/2017	420
C450	10/01/2017	406	17/02/2017	409	15/06/2017	383
C450	11/01/2017	420	20/02/2017	396	17/06/2017	422
C450	23/01/2017	444	13/03/2017	429	6/07/2017	410
C450	14/03/*2017	406	20/03/2017	429	3/08/2017	439
C450	28/03/2017	433	29/03/2017	450	3/08/2017	393
C450	29/03/2017	430	30/03/2017	405	7/08/2017	465
C450	30/04/2017	413	3/04/2017	425	8/08/2017	434
C450	9/05/2017	415	10/04/2017	448	10/08/2017	389
C450	25/05/2017	425	12/04/2017	433	10/08/2017	437
C450	5/06/2017	447	21/04/2017	415	29/08/2017	399
C450	27/06/2017	417	24/04/2017	428	5/09/2017	475
C450	4/07/2017	427	2/05/2017	471	7/09/2017	465
C450	13/07/2017	399	4/05/2017	471	27/09/2017	438
C450	27/07/2017	421	8/05/2017	449	21/11/2017	407
C450	9/08/2017	415	10/05/2017	447	8/12/2017	414
C450	29/08/2017	399	15/05/2017	455	14/12/2017	458
C450	8/09/2017	440				

B.4 Supplier no. 3

Table B 11: Historical C450 virgin binder viscosity records obtained from supplier no.3

Binder class	Date	Viscosity (Pa.s)	Date	Viscosity (Pa.s)
C450	6/04/2017	339	18/09/2017	404
C450	30/06/2017	395	25/09/2017	474
C450	11/07/2017	402	23/10/2017	394
C450	17/07/2017	374	20/11/2017	427
C450	4/08/2017	399	27/11/2017	409
C450	11/08/2017	396	7/12/2017	393
C450	24/08/2017	406	7/02/2018	386
C450	1/09/2017	432		

APPENDIX C PROBABILITY DISTRIBUTION PLOTS

C.1 RAP binder viscosity probability distribution plots

Figure C 1: Probability distribution plot for contractor A fine RAP binder viscosity

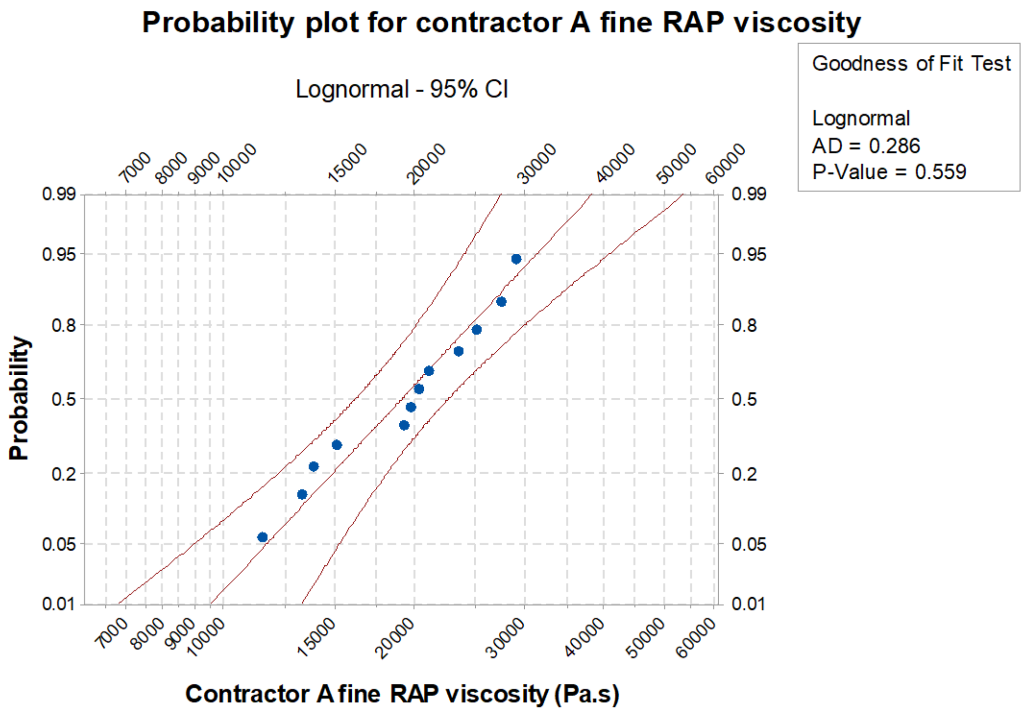


Figure C 2: Probability distribution plot for contractor B RAP binder viscosity

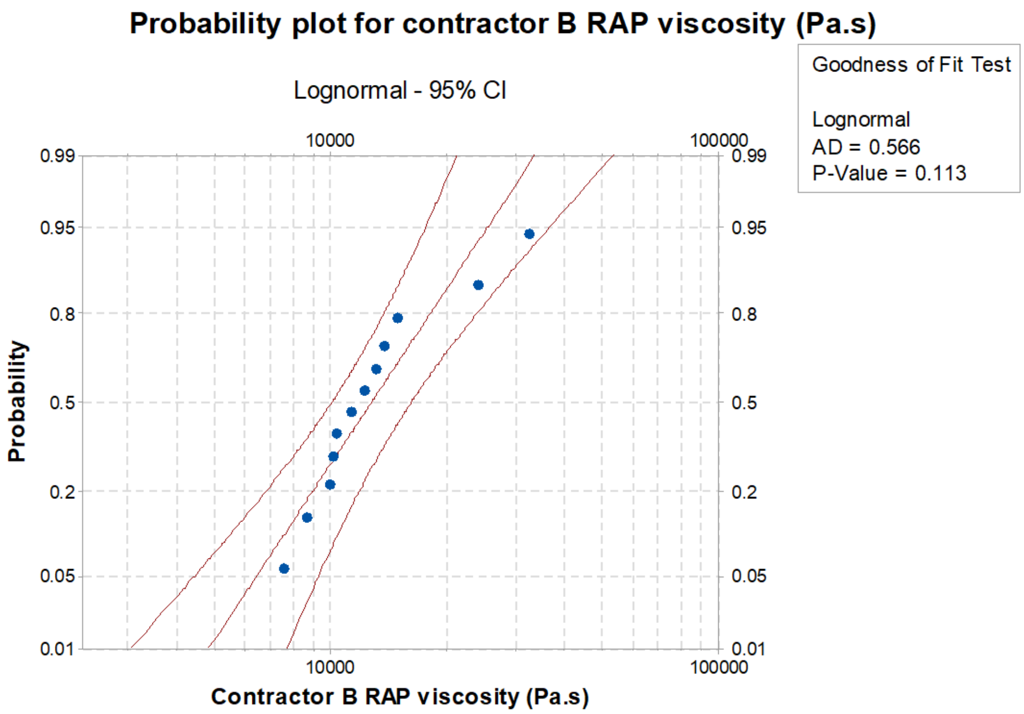
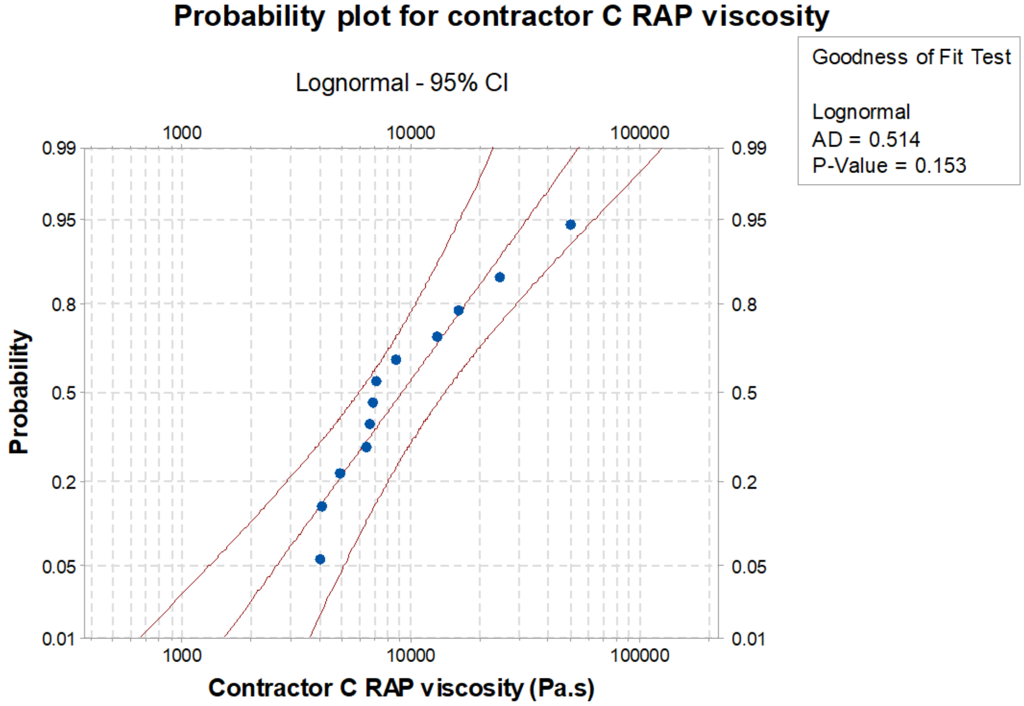


Figure C 3: Probability distribution plot for contractor C RAP binder viscosity



C.2 RAP binder content probability distribution plots

Figure C 4: Probability distribution plot for contractor A fine RAP binder content

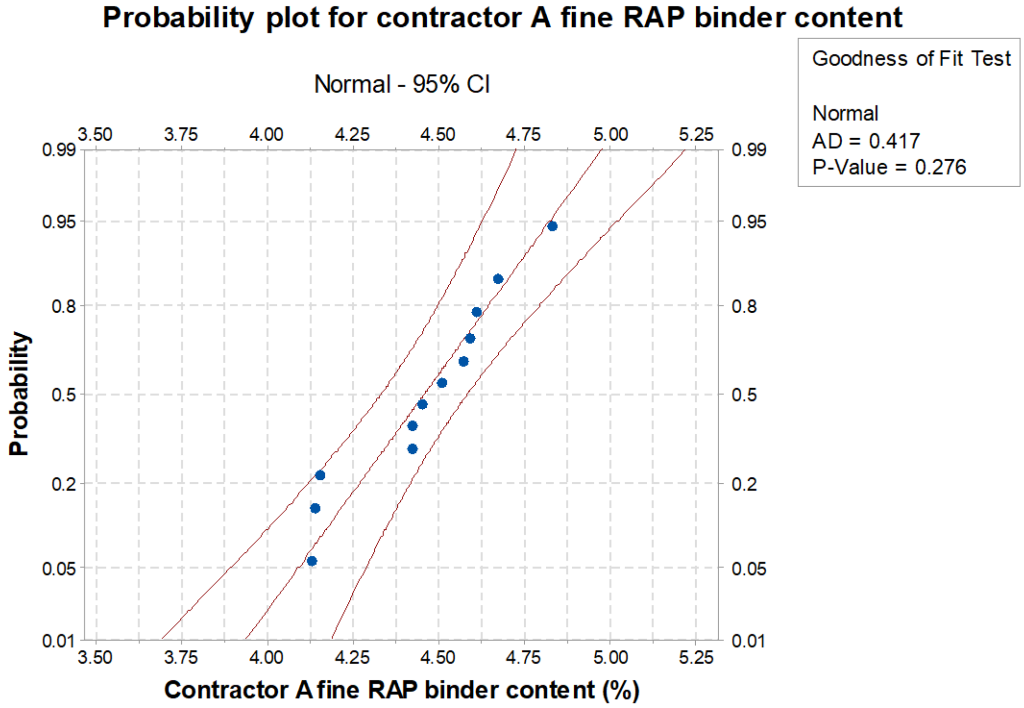


Figure C 5: Probability distribution plot for contractor B RAP binder content

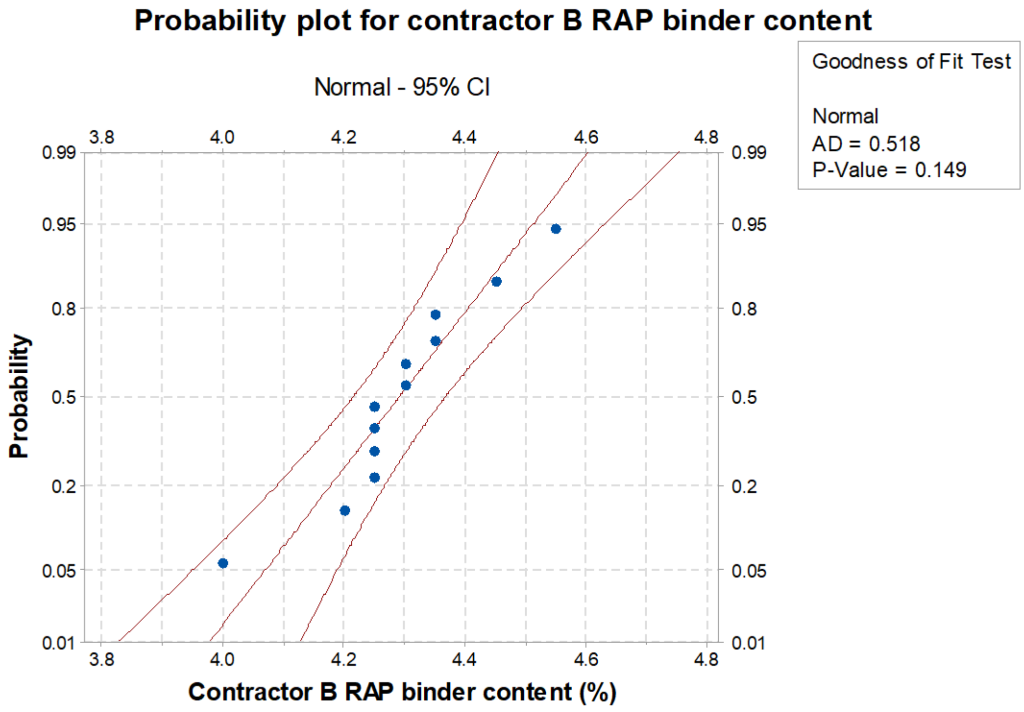


Figure C 6: Probability distribution plot for contractor C RAP binder content – original dataset

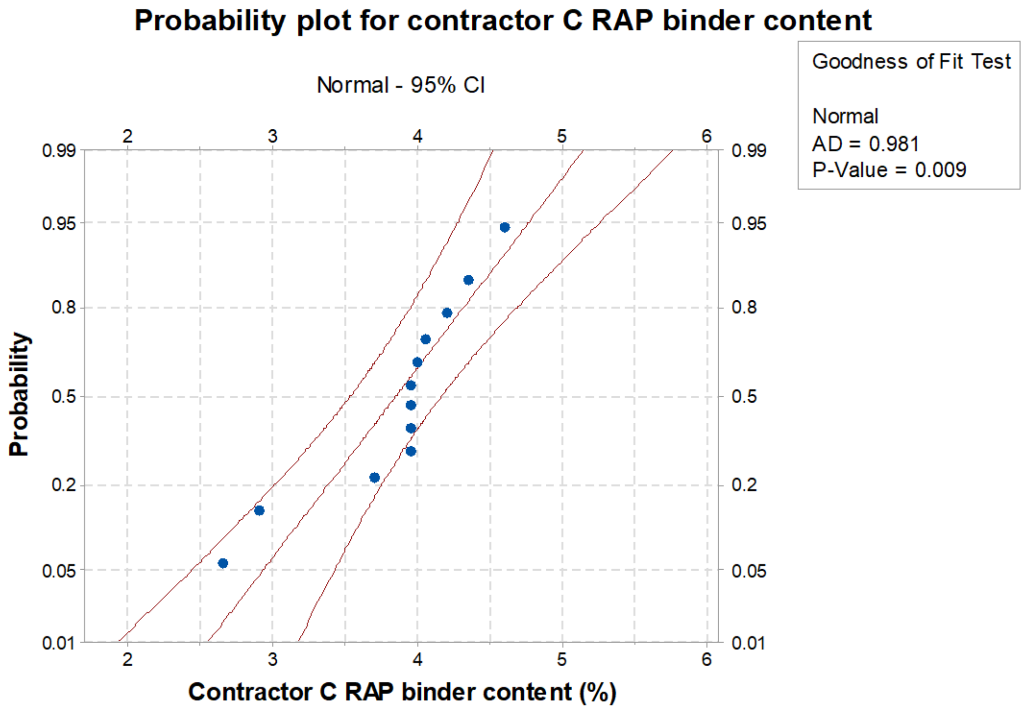
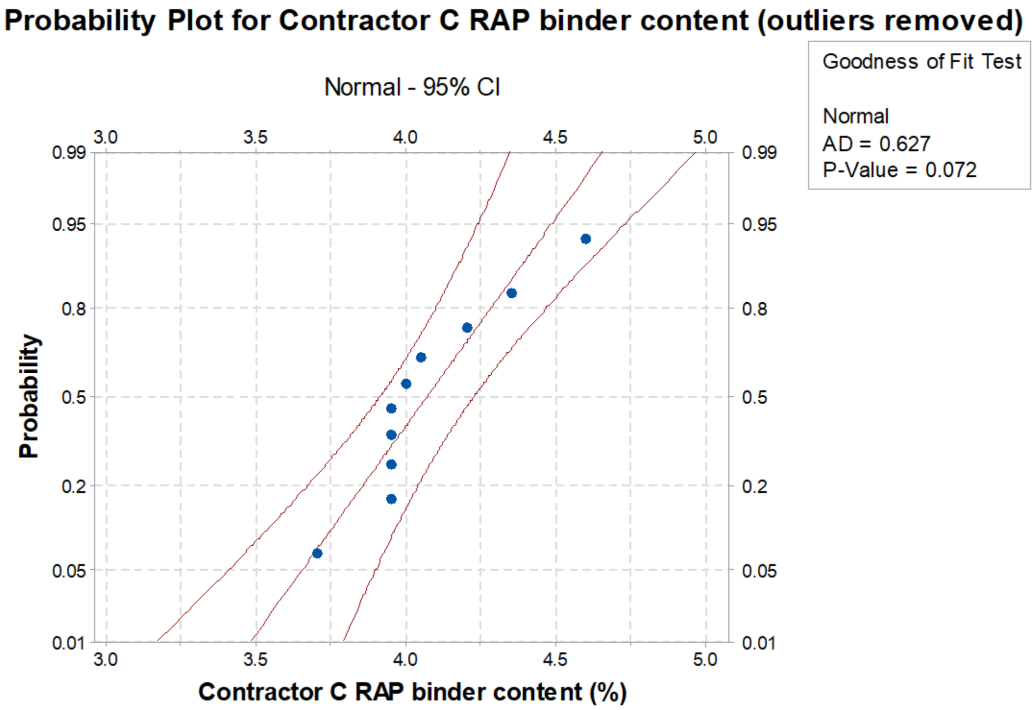


Figure C 7: Probability distribution plot for contractor C RAP binder content after outliers were removed



APPENDIX D PROBABILITY DISTRIBUTION PARAMETERS OF INDIVIDUAL BINDER BLEND SCENARIOS – QLD VIRGIN BINDER

D.1 Contractor A combined RAP binder blend viscosity

Table D 12: Probability distribution parameters of contractor A combined RAP binder blend viscosity scenarios containing Qld virgin binders

Scenario	Beta probability distribution parameters				Percentile	
	Minimum	Maximum	Alpha	Beta	10%	90%
Contractor A RAP (10%, 2:1) - Qld C170 - various TBC (4 - 5%)	159.98	360.39	25.23	28.32	237	272
Contractor A RAP (15%, 2:1) - Qld C170 - various TBC (4 - 5%)	205.12	447.40	16.38	24.90	278	325
Contractor A RAP (20%, 2:1) - Qld C170 - various TBC (4 - 5%)	260.94	533.55	9.21	16.66	326	392
Contractor A RAP (25%, 2:1) - Qld C170 - various TBC (4 - 5%)	316.56	646.63	6.27	12.55	383	474
Contractor A RAP (30%, 2:1) - Qld C170 - various TBC (4 - 5%)	380.94	781.02	4.48	9.38	450	576
Contractor A RAP (35%, 2:1) - Qld C170 - various TBC (4 - 5%)	450.16	973.26	3.72	8.29	530	704
Contractor A RAP (40%, 2:1) - Qld C170 - various TBC (4 - 5%)	530.12	1222.74	3.25	7.59	626	865
Contractor A RAP (10%, 2:1) - Qld C240 - various TBC (4 - 5%)	260.51	351.07	4.20	4.79	284	322
Contractor A RAP (15%, 2:1) - Qld C240 - various TBC (4 - 5%)	291.36	450.31	6.10	8.76	331	383
Contractor A RAP (20%, 2:1) - Qld C240 - various TBC (4 - 5%)	335.96	568.83	5.76	9.96	387	458
Contractor A RAP (25%, 2:1) - Qld C240 - various TBC (4 - 5%)	389.88	711.16	4.99	9.70	451	551
Contractor A RAP (30%, 2:1) - Qld C240 - various TBC (4 - 5%)	456.12	874.86	4.05	8.33	527	666
Contractor A RAP (35%, 2:1) - Qld C240 - various TBC (4 - 5%)	531.27	1094.60	3.56	7.85	616	809
Contractor A RAP (40%, 2:1) - Qld C240 - various TBC (4 - 5%)	619.06	1376.53	3.18	7.44	722	986
Contractor A RAP (10%, 2:1) - Qld C320 - various TBC (4 - 5%)	286.03	629.08	16.62	20.79	403	474
Contractor A RAP (15%, 2:1) - Qld C320 - various TBC (4 - 5%)	321.39	809.58	18.22	28.92	467	555
Contractor A RAP (20%, 2:1) - Qld C320 - various TBC (4 - 5%)	394.61	975.80	13.19	25.09	539	653
Contractor A RAP (25%, 2:1) - Qld C320 - various TBC (4 - 5%)	479.65	1151.82	9.19	19.39	624	773
Contractor A RAP (30%, 2:1) - Qld C320 - various TBC (4 - 5%)	572.25	1359.02	6.77	15.10	722	918
Contractor A RAP (35%, 2:1) - Qld C320 - various TBC (4 - 5%)	677.51	1621.49	5.18	12.17	835	1096
Contractor A RAP (40%, 2:1) - Qld C320 - various TBC (4 - 5%)	794.28	1966.49	4.24	10.50	968	1314
Contractor A RAP (10%, 2:1) - Qld C450 - various TBC (4 - 5%)	338.99	816.88	33.36	37.51	528	600
Contractor A RAP (15%, 2:1) - Qld C450 - various TBC (4 - 5%)	412.53	1039.86	26.43	43.18	605	698
Contractor A RAP (20%, 2:1) - Qld C450 - various TBC (4 - 5%)	546.36	1142.54	11.76	22.26	692	816
Contractor A RAP (25%, 2:1) - Qld C450 - various TBC (4 - 5%)	650.15	1329.62	7.72	15.89	792	958
Contractor A RAP (30%, 2:1) - Qld C450 - various TBC (4 - 5%)	749.25	1597.87	6.23	13.81	907	1128
Contractor A RAP (35%, 2:1) - Qld C450 - various TBC (4 - 5%)	876.31	1869.33	4.58	10.41	1039	1335
Contractor A RAP (40%, 2:1) - Qld C450 - various TBC (4 - 5%)	1004.88	2293.37	4.01	9.88	1191	1584
Contractor A RAP (10%, 2:1) - Qld C600 - various TBC (4 - 5%)	82.78	1432.58	100.00	100.00	697	819
Contractor A RAP (15%, 2:1) - Qld C600 - various TBC (4 - 5%)	53.73	1676.52	100.00	100.00	792	939
Contractor A RAP (20%, 2:1) - Qld C600 - various TBC (4 - 5%)	537.44	1990.09	27.73	61.33	900	1082
Contractor A RAP (25%, 2:1) - Qld C600 - various TBC (4 - 5%)	711.79	2131.26	15.41	36.37	1023	1252
Contractor A RAP (30%, 2:1) - Qld C600 - various TBC (4 - 5%)	854.56	2477.95	10.92	28.60	1162	1455
Contractor A RAP (35%, 2:1) - Qld C600 - various TBC (4 - 5%)	1033.35	2656.49	6.96	17.25	1319	1696
Contractor A RAP (40%, 2:1) - Qld C600 - various TBC (4 - 5%)	1193.80	3098.76	5.57	14.23	1499	1984

D.2 Contractor B RAP binder blend viscosity

Table D 13: Probability distribution parameters of contractor B RAP binder blend viscosity scenarios containing Qld virgin binders

Scenario	Beta probability distribution parameters				Percentile	
	Minimum	Maximum	Alpha	Beta	10%	90%
Contractor B RAP (10%) - Qld C170 - various TBC (4 - 5%)	151.30	423.53	31.99	49.67	239	277
Contractor B RAP (15%) - Qld C170 - various TBC (4 - 5%)	212.66	536.10	14.64	35.16	282	335
Contractor B RAP (20%) - Qld C170 - various TBC (4 - 5%)	262.27	689.67	9.21	27.91	331	408
Contractor B RAP (25%) - Qld C170 - various TBC (4 - 5%)	319.63	833.88	6.01	19.08	390	501
Contractor B RAP (30%) - Qld C170 - various TBC (4 - 5%)	376.51	1093.88	4.94	17.56	460	617
Contractor B RAP (35%) - Qld C170 - various TBC (4 - 5%)	446.83	1413.32	3.99	15.28	543	765
Contractor B RAP (40%) - Qld C170 - various TBC (4 - 5%)	526.80	1935.31	3.50	15.46	643	954
Contractor B RAP (10%) - Qld C240 - various TBC (4 - 5%)	255.36	376.76	5.78	7.91	286	327
Contractor B RAP (15%) - Qld C240 - various TBC (4 - 5%)	286.07	526.28	7.50	15.77	335	394
Contractor B RAP (20%) - Qld C240 - various TBC (4 - 5%)	331.52	706.69	6.43	17.51	391	477
Contractor B RAP (25%) - Qld C240 - various TBC (4 - 5%)	387.01	921.28	5.19	16.31	457	581
Contractor B RAP (30%) - Qld C240 - various TBC (4 - 5%)	450.00	1194.38	4.41	15.09	535	712
Contractor B RAP (35%) - Qld C240 - various TBC (4 - 5%)	524.70	1587.54	3.80	14.69	627	876
Contractor B RAP (40%) - Qld C240 - various TBC (4 - 5%)	604.99	2225.08	3.62	16.42	737	1083
Contractor B RAP (10%) - Qld C320 - various TBC (4 - 5%)	281.34	694.12	18.40	28.77	405	480
Contractor B RAP (15%) - Qld C320 - various TBC (4 - 5%)	320.13	1014.90	18.88	47.62	469	567
Contractor B RAP (20%) - Qld C320 - various TBC (4 - 5%)	405.77	1265.02	11.48	37.64	543	675
Contractor B RAP (25%) - Qld C320 - various TBC (4 - 5%)	487.91	1539.91	7.91	28.97	627	807
Contractor B RAP (30%) - Qld C320 - various TBC (4 - 5%)	580.40	1859.52	5.68	22.15	725	971
Contractor B RAP (35%) - Qld C320 - various TBC (4 - 5%)	680.06	2326.75	4.50	18.96	839	1174
Contractor B RAP (40%) - Qld C320 - various TBC (4 - 5%)	784.06	3094.15	3.98	19.08	972	1425
Contractor B RAP (10%) - Qld C450 - various TBC (4 - 5%)	342.79	956.21	34.15	58.84	529	608
Contractor B RAP (15%) - Qld C450 - various TBC (4 - 5%)	451.49	1249.89	17.73	50.87	606	713
Contractor B RAP (20%) - Qld C450 - various TBC (4 - 5%)	559.21	1396.29	9.01	27.83	692	842
Contractor B RAP (25%) - Qld C450 - various TBC (4 - 5%)	658.71	1645.20	5.94	19.50	790	999
Contractor B RAP (30%) - Qld C450 - various TBC (4 - 5%)	751.65	2079.32	4.91	17.93	902	1188
Contractor B RAP (35%) - Qld C450 - various TBC (4 - 5%)	863.17	2563.87	4.01	15.40	1032	1422
Contractor B RAP (40%) - Qld C450 - various TBC (4 - 5%)	982.10	3382.35	3.58	15.85	1181	1706
Contractor B RAP (10%) - Qld C600 - various TBC (4 - 5%)	50.46	1471.62	100.00	100.00	697	826
Contractor B RAP (15%) - Qld C600 - various TBC (4 - 5%)	-30.06	1772.17	100.00	100.00	791	954
Contractor B RAP (20%) - Qld C600 - various TBC (4 - 5%)	629.25	2492.69	15.57	62.81	896	1110
Contractor B RAP (25%) - Qld C600 - various TBC (4 - 5%)	779.44	2572.30	8.71	33.60	1014	1295
Contractor B RAP (30%) - Qld C600 - various TBC (4 - 5%)	915.37	2996.81	6.06	24.84	1147	1521
Contractor B RAP (35%) - Qld C600 - various TBC (4 - 5%)	1052.55	3525.59	4.68	19.64	1297	1791
Contractor B RAP (40%) - Qld C600 - various TBC (4 - 5%)	1201.31	4447.08	3.93	18.51	1469	2116

D.3 Contractor C binder blend viscosity

Table D 14: Probability distribution parameters of contractor C RAP binder blend viscosity scenarios containing Qld virgin binders

Scenario	Beta probability distribution parameters				Percentile	
	Minimum	Maximum	Alpha	Beta	10%	90%
Contractor C RAP (10%) - Qld C170 - various TBC (4 - 5%)	161.02	527.39	22.50	69.91	230	272
Contractor C RAP (15%) - Qld C170 - various TBC (4 - 5%)	210.64	654.13	9.21	39.86	264	327
Contractor C RAP (20%) - Qld C170 - various TBC (4 - 5%)	251.14	777.28	5.40	24.44	303	395
Contractor C RAP (25%) - Qld C170 - various TBC (4 - 5%)	289.71	1002.28	4.10	20.29	347	482
Contractor C RAP (30%) - Qld C170 - various TBC (4 - 5%)	331.55	1370.90	3.40	19.46	398	590
Contractor C RAP (35%) - Qld C170 - various TBC (4 - 5%)	374.47	2240.29	3.18	25.75	458	725
Contractor C RAP (40%) - Qld C170 - various TBC (4 - 5%)	427.26	3406.40	2.81	28.72	526	896
Contractor C RAP (10%) - Qld C240 - various TBC (4 - 5%)	238.25	418.55	7.00	14.31	275	321
Contractor C RAP (15%) - Qld C240 - various TBC (4 - 5%)	268.82	617.25	6.01	20.65	314	385
Contractor C RAP (20%) - Qld C240 - various TBC (4 - 5%)	305.47	821.68	4.55	18.62	357	463
Contractor C RAP (25%) - Qld C240 - various TBC (4 - 5%)	345.29	1123.23	3.80	18.48	406	560
Contractor C RAP (30%) - Qld C240 - various TBC (4 - 5%)	389.69	1545.17	3.26	18.44	463	682
Contractor C RAP (35%) - Qld C240 - various TBC (4 - 5%)	438.90	2337.42	2.96	21.71	528	832
Contractor C RAP (40%) - Qld C240 - various TBC (4 - 5%)	494.82	3529.57	2.70	24.86	603	1022
Contractor C RAP (10%) - Qld C320 - various TBC (4 - 5%)	265.06	872.12	19.44	52.32	390	471
Contractor C RAP (15%) - Qld C320 - various TBC (4 - 5%)	337.29	1099.99	9.87	37.86	441	554
Contractor C RAP (20%) - Qld C320 - various TBC (4 - 5%)	403.35	1294.46	5.68	24.36	497	656
Contractor C RAP (25%) - Qld C320 - various TBC (4 - 5%)	462.25	1645.55	4.19	20.58	559	781
Contractor C RAP (30%) - Qld C320 - various TBC (4 - 5%)	522.68	2104.74	3.36	18.18	629	935
Contractor C RAP (35%) - Qld C320 - various TBC (4 - 5%)	583.19	2963.21	2.99	19.72	707	1122
Contractor C RAP (40%) - Qld C320 - various TBC (4 - 5%)	655.15	4183.44	2.62	20.89	797	1354
Contractor C RAP (10%) - Qld C450 - various TBC (4 - 5%)	387.72	1016.74	15.91	45.08	508	598
Contractor C RAP (15%) - Qld C450 - various TBC (4 - 5%)	473.76	1159.83	6.83	23.19	567	699
Contractor C RAP (20%) - Qld C450 - various TBC (4 - 5%)	540.07	1386.60	4.39	16.18	631	822
Contractor C RAP (25%) - Qld C450 - various TBC (4 - 5%)	602.33	1731.07	3.40	13.71	701	972
Contractor C RAP (30%) - Qld C450 - various TBC (4 - 5%)	665.90	2272.42	2.93	13.62	780	1151
Contractor C RAP (35%) - Qld C450 - various TBC (4 - 5%)	736.41	3033.66	2.60	14.03	868	1367
Contractor C RAP (40%) - Qld C450 - various TBC (4 - 5%)	814.99	4127.33	2.34	14.81	966	1634
Contractor C RAP (10%) - QLDC600 - various TBC (4 - 5%)	-39.02	1518.35	100.00	100.00	671	812
Contractor C RAP (15%) - QLDC600 - various TBC (4 - 5%)	558.59	1925.31	10.54	41.63	743	935
Contractor C RAP (20%) - QLDC600 - various TBC (4 - 5%)	667.75	2080.51	5.49	22.61	820	1084
Contractor C RAP (25%) - QLDC600 - various TBC (4 - 5%)	759.33	2320.32	3.66	14.74	903	1264
Contractor C RAP (30%) - QLDC600 - various TBC (4 - 5%)	835.54	2982.49	3.08	14.38	994	1478
Contractor C RAP (35%) - QLDC600 - various TBC (4 - 5%)	916.53	3880.26	2.70	14.41	1093	1734
Contractor C RAP (40%) - QLDC600 - various TBC (4 - 5%)	998.51	5334.13	2.47	15.95	1201	2040

APPENDIX E PROBABILITY DISTRIBUTION PARAMETERS OF INDIVIDUAL BINDER BLEND SCENARIOS – AS VIRGIN BINDER

E.1 Contractor A combined RAP binder blend viscosity

Table E 15: Probability distribution parameters of contractor A combined RAP binder blend viscosity scenarios containing AS virgin binders

Scenario	Beta probability distribution parameters				Percentile	
	Minimum	Maximum	Alpha	Beta	10%	90%
Contractor A RAP (10%, 2:1) - AS C170 - various TBC (4 - 5%)	148.64	349.08	20.43	25.82	219	256
Contractor A RAP (15%, 2:1) - AS C170 - various TBC (4 - 5%)	181.82	439.02	16.69	26.42	257	306
Contractor A RAP (20%, 2:1) - AS C170 - various TBC (4 - 5%)	226.69	556.35	11.93	24.36	303	369
Contractor A RAP (25%, 2:1) - AS C170 - various TBC (4 - 5%)	284.06	638.90	7.20	14.81	357	447
Contractor A RAP (30%, 2:1) - AS C170 - various TBC (4 - 5%)	345.71	780.53	5.18	11.62	421	544
Contractor A RAP (35%, 2:1) - AS C170 - various TBC (4 - 5%)	412.13	959.06	4.15	9.58	497	667
Contractor A RAP (40%, 2:1) - AS C170 - various TBC (4 - 5%)	489.44	1199.63	3.51	8.48	588	820
Contractor A RAP (10%, 2:1) - AS C240 - various TBC (4 - 5%)	192.10	472.03	21.54	22.78	301	355
Contractor A RAP (15%, 2:1) - AS C240 - various TBC (4 - 5%)	235.00	586.13	18.10	24.13	352	420
Contractor A RAP (20%, 2:1) - AS C240 - various TBC (4 - 5%)	294.67	730.34	13.22	22.91	411	499
Contractor A RAP (25%, 2:1) - AS C240 - various TBC (4 - 5%)	364.94	892.21	9.15	18.97	479	598
Contractor A RAP (30%, 2:1) - AS C240 - various TBC (4 - 5%)	441.35	1060.00	6.55	14.30	559	718
Contractor A RAP (35%, 2:1) - AS C240 - various TBC (4 - 5%)	531.54	1290.36	4.87	11.60	654	868
Contractor A RAP (40%, 2:1) - AS C240 - various TBC (4 - 5%)	627.17	1590.86	4.06	10.23	766	1053
Contractor A RAP (10%, 2:1) - AS C320 - various TBC (4 - 5%)	251.39	640.60	23.05	27.04	396	466
Contractor A RAP (15%, 2:1) - AS C320 - various TBC (4 - 5%)	297.67	820.93	21.58	33.87	458	545
Contractor A RAP (20%, 2:1) - AS C320 - various TBC (4 - 5%)	373.35	988.69	15.15	28.87	530	642
Contractor A RAP (25%, 2:1) - AS C320 - various TBC (4 - 5%)	463.26	1148.35	9.86	20.68	613	760
Contractor A RAP (30%, 2:1) - AS C320 - various TBC (4 - 5%)	561.28	1338.75	6.82	15.09	710	904
Contractor A RAP (35%, 2:1) - AS C320 - various TBC (4 - 5%)	665.58	1606.15	5.22	12.33	823	1080
Contractor A RAP (40%, 2:1) - AS C320 - various TBC (4 - 5%)	780.06	1951.63	4.29	10.71	954	1296
Contractor A RAP (10%, 2:1) - AS C450 - various TBC (4 - 5%)	85.57	1100.55	100.00	100.00	547	639
Contractor A RAP (15%, 2:1) - AS C450 - various TBC (4 - 5%)	249.56	1402.26	60.26	100.00	627	740
Contractor A RAP (20%, 2:1) - AS C450 - various TBC (4 - 5%)	435.93	1604.14	27.57	63.81	718	861
Contractor A RAP (25%, 2:1) - AS C450 - various TBC (4 - 5%)	616.18	1557.85	11.23	24.53	822	1007
Contractor A RAP (30%, 2:1) - AS C450 - various TBC (4 - 5%)	742.32	1765.28	7.44	16.72	940	1183
Contractor A RAP (35%, 2:1) - AS C450 - various TBC (4 - 5%)	868.95	2091.62	5.77	13.83	1077	1395
Contractor A RAP (40%, 2:1) - AS C450 - various TBC (4 - 5%)	1010.64	2478.83	4.62	11.53	1234	1648
Contractor A RAP (10%, 2:1) - AS C600 - various TBC (4 - 5%)	495.56	1105.12	22.09	25.80	721	833
Contractor A RAP (15%, 2:1) - AS C600 - various TBC (4 - 5%)	565.36	1372.47	21.36	32.39	818	956
Contractor A RAP (20%, 2:1) - AS C600 - various TBC (4 - 5%)	692.03	1615.53	14.53	27.30	928	1101
Contractor A RAP (25%, 2:1) - AS C600 - various TBC (4 - 5%)	821.56	1869.07	10.07	21.12	1052	1274
Contractor A RAP (30%, 2:1) - AS C600 - various TBC (4 - 5%)	948.23	2220.24	7.94	18.45	1192	1480
Contractor A RAP (35%, 2:1) - AS C600 - various TBC (4 - 5%)	1097.83	2597.47	6.08	15.01	1352	1725
Contractor A RAP (40%, 2:1) - AS C600 - various TBC (4 - 5%)	1251.00	3075.53	5.12	13.11	1534	2017

E.2 Contractor B RAP binder blend viscosity

Table E 16: Probability distribution parameters of contractor B RAP binder blend viscosity scenarios containing AS virgin binders

Scenario	Beta probability distribution parameters				Percentile	
	Minimum	Maximum	Alpha	Beta	10%	90%
Contractor B RAP (10%) - AS C170 - various TBC (4 - 5%)	143.64	395.46	24.14	38.63	221	260
Contractor B RAP (15%) - AS C170 - various TBC (4 - 5%)	182.87	546.50	17.42	43.04	261	315
Contractor B RAP (20%) - AS C170 - various TBC (4 - 5%)	230.30	713.40	11.23	36.00	309	384
Contractor B RAP (25%) - AS C170 - various TBC (4 - 5%)	288.01	843.90	6.91	23.03	365	473
Contractor B RAP (30%) - AS C170 - various TBC (4 - 5%)	346.16	1074.73	5.26	19.17	431	583
Contractor B RAP (35%) - AS C170 - various TBC (4 - 5%)	412.89	1448.44	4.34	18.27	512	726
Contractor B RAP (40%) - AS C170 - various TBC (4 - 5%)	492.48	1865.14	3.60	15.92	607	906
Contractor B RAP (10%) - AS C240 - various TBC (4 - 5%)	188.26	516.90	23.74	30.53	304	361
Contractor B RAP (15%) - AS C240 - various TBC (4 - 5%)	235.59	731.54	19.45	42.07	356	431
Contractor B RAP (20%) - AS C240 - various TBC (4 - 5%)	297.17	993.85	13.21	41.43	416	519
Contractor B RAP (25%) - AS C240 - various TBC (4 - 5%)	375.98	1200.22	7.84	28.44	486	628
Contractor B RAP (30%) - AS C240 - various TBC (4 - 5%)	448.12	1525.83	5.90	23.97	568	765
Contractor B RAP (35%) - AS C240 - various TBC (4 - 5%)	535.64	1864.98	4.50	18.79	665	937
Contractor B RAP (40%) - AS C240 - various TBC (4 - 5%)	627.38	2475.46	3.89	18.24	780	1151
Contractor B RAP (10%) - AS C320 - various TBC (4 - 5%)	254.98	699.02	23.05	33.94	398	472
Contractor B RAP (15%) - AS C320 - various TBC (4 - 5%)	303.81	1008.19	20.81	50.82	461	558
Contractor B RAP (20%) - AS C320 - various TBC (4 - 5%)	390.00	1287.88	12.62	42.19	534	664
Contractor B RAP (25%) - AS C320 - various TBC (4 - 5%)	480.09	1486.29	7.76	27.34	618	796
Contractor B RAP (30%) - AS C320 - various TBC (4 - 5%)	567.27	1921.55	5.97	24.93	714	956
Contractor B RAP (35%) - AS C320 - various TBC (4 - 5%)	663.36	2397.18	4.78	21.22	828	1157
Contractor B RAP (40%) - AS C320 - various TBC (4 - 5%)	774.41	3000.52	3.93	18.40	959	1405
Contractor B RAP (10%) - AS C450 - various TBC (4 - 5%)	61.10	1133.03	100.00	100.00	549	646
Contractor B RAP (15%) - AS C450 - various TBC (4 - 5%)	-9.04	1389.26	100.00	100.00	628	755
Contractor B RAP (20%) - AS C450 - various TBC (4 - 5%)	513.72	1872.15	14.59	54.76	718	887
Contractor B RAP (25%) - AS C450 - various TBC (4 - 5%)	641.66	2034.26	8.05	31.02	820	1048
Contractor B RAP (30%) - AS C450 - various TBC (4 - 5%)	752.82	2360.54	5.75	22.41	936	1243
Contractor B RAP (35%) - AS C450 - various TBC (4 - 5%)	879.97	2820.71	4.30	17.49	1070	1483
Contractor B RAP (40%) - AS C450 - various TBC (4 - 5%)	1000.66	3638.35	3.80	17.19	1222	1773
Contractor B RAP (10%) - AS C600 - various TBC (4 - 5%)	476.94	1247.49	25.46	39.30	721	840
Contractor B RAP (15%) - AS C600 - various TBC (4 - 5%)	587.96	1651.00	17.73	44.31	816	971
Contractor B RAP (20%) - AS C600 - various TBC (4 - 5%)	715.37	2072.50	10.83	37.09	922	1130
Contractor B RAP (25%) - AS C600 - various TBC (4 - 5%)	837.46	2416.31	7.31	27.03	1041	1319
Contractor B RAP (30%) - AS C600 - various TBC (4 - 5%)	973.95	2690.77	5.00	17.77	1175	1549
Contractor B RAP (35%) - AS C600 - various TBC (4 - 5%)	1099.10	3458.67	4.34	17.98	1327	1821
Contractor B RAP (40%) - AS C600 - various TBC (4 - 5%)	1240.62	4389.42	3.76	17.35	1498	2149

E.3 Contractor C RAP binder blend viscosity

Table E 17: Probability distribution parameters of contractor A combined RAP binder blend viscosity scenarios containing Qld virgin binders

Scenario	Beta probability distribution parameters				Percentile	
	Minimum	Maximum	Alpha	Beta	10%	90%
Contractor C RAP (10%) - AS C170 - various TBC (4 - 5%)	145.69	453.97	19.68	49.52	212	255
Contractor C RAP (15%) - AS C170 - various TBC (4 - 5%)	186.61	656.03	10.71	46.35	245	307
Contractor C RAP (20%) - AS C170 - various TBC (4 - 5%)	227.02	793.40	6.17	29.68	282	372
Contractor C RAP (25%) - AS C170 - various TBC (4 - 5%)	265.16	1088.55	4.56	26.83	325	454
Contractor C RAP (30%) - AS C170 - various TBC (4 - 5%)	305.75	1436.43	3.68	23.62	374	557
Contractor C RAP (35%) - AS C170 - various TBC (4 - 5%)	349.67	2107.89	3.23	25.45	431	687
Contractor C RAP (40%) - AS C170 - various TBC (4 - 5%)	401.23	3082.19	2.84	26.96	497	849
Contractor C RAP (10%) - AS C240 - various TBC (4 - 5%)	184.94	648.63	23.23	55.25	292	353
Contractor C RAP (15%) - AS C240 - various TBC (4 - 5%)	244.51	932.87	12.05	51.38	334	420
Contractor C RAP (20%) - AS C240 - various TBC (4 - 5%)	302.57	1019.51	6.29	27.00	380	503
Contractor C RAP (25%) - AS C240 - various TBC (4 - 5%)	351.85	1328.38	4.52	22.87	433	605
Contractor C RAP (30%) - AS C240 - various TBC (4 - 5%)	399.82	1961.64	3.80	25.42	492	733
Contractor C RAP (35%) - AS C240 - various TBC (4 - 5%)	458.87	2543.90	3.08	22.45	560	890
Contractor C RAP (40%) - AS C240 - various TBC (4 - 5%)	519.14	3883.02	2.77	26.12	639	1087
Contractor C RAP (10%) - AS C320 - various TBC (4 - 5%)	235.33	993.36	26.97	82.55	383	463
Contractor C RAP (15%) - AS C320 - various TBC (4 - 5%)	322.15	1146.24	11.22	44.98	433	545
Contractor C RAP (20%) - AS C320 - various TBC (4 - 5%)	396.82	1284.06	5.66	24.71	488	646
Contractor C RAP (25%) - AS C320 - various TBC (4 - 5%)	449.47	1654.33	4.44	21.96	550	768
Contractor C RAP (30%) - AS C320 - various TBC (4 - 5%)	511.92	2170.49	3.47	19.95	620	920
Contractor C RAP (35%) - AS C320 - various TBC (4 - 5%)	574.74	2912.12	2.98	19.55	697	1106
Contractor C RAP (40%) - AS C320 - various TBC (4 - 5%)	645.11	4037.30	2.64	20.32	787	1336
Contractor C RAP (10%) - AS C450 - various TBC (4 - 5%)	269.99	1370.92	39.20	100.00	528	635
Contractor C RAP (15%) - AS C450 - various TBC (4 - 5%)	454.88	1439.09	9.60	36.27	589	739
Contractor C RAP (20%) - AS C450 - various TBC (4 - 5%)	538.80	1603.78	5.35	21.05	656	866
Contractor C RAP (25%) - AS C450 - various TBC (4 - 5%)	609.40	1995.53	3.94	17.54	731	1019
Contractor C RAP (30%) - AS C450 - various TBC (4 - 5%)	683.93	2424.66	3.06	14.28	811	1203
Contractor C RAP (35%) - AS C450 - various TBC (4 - 5%)	759.95	3171.16	2.62	14.02	901	1428
Contractor C RAP (40%) - AS C450 - various TBC (4 - 5%)	830.86	4725.78	2.53	17.83	1003	1695
Contractor C RAP (10%) - ASC600 - various TBC (4 - 5%)	503.04	1450.82	17.27	46.83	693	827
Contractor C RAP (15%) - ASC600 - various TBC (4 - 5%)	628.73	1555.46	6.88	21.33	765	954
Contractor C RAP (20%) - ASC600 - various TBC (4 - 5%)	710.56	1921.90	4.59	17.19	842	1106
Contractor C RAP (25%) - ASC600 - various TBC (4 - 5%)	793.27	2242.14	3.31	12.66	925	1289
Contractor C RAP (30%) - ASC600 - various TBC (4 - 5%)	867.46	2852.62	2.87	12.36	1017	1507
Contractor C RAP (35%) - ASC600 - various TBC (4 - 5%)	941.73	3881.15	2.64	13.95	1115	1761
Contractor C RAP (40%) - ASC600 - various TBC (4 - 5%)	1033.48	4942.57	2.33	13.48	1227	2076

APPENDIX F MONTE CARLO SIMULATION PLOTS

F.1 Binder blend viscosity variations for blends containing Qld virgin binders

Figure F 8: Binder blend viscosity variation of contractor A combined RAP, Qld C170 virgin binder

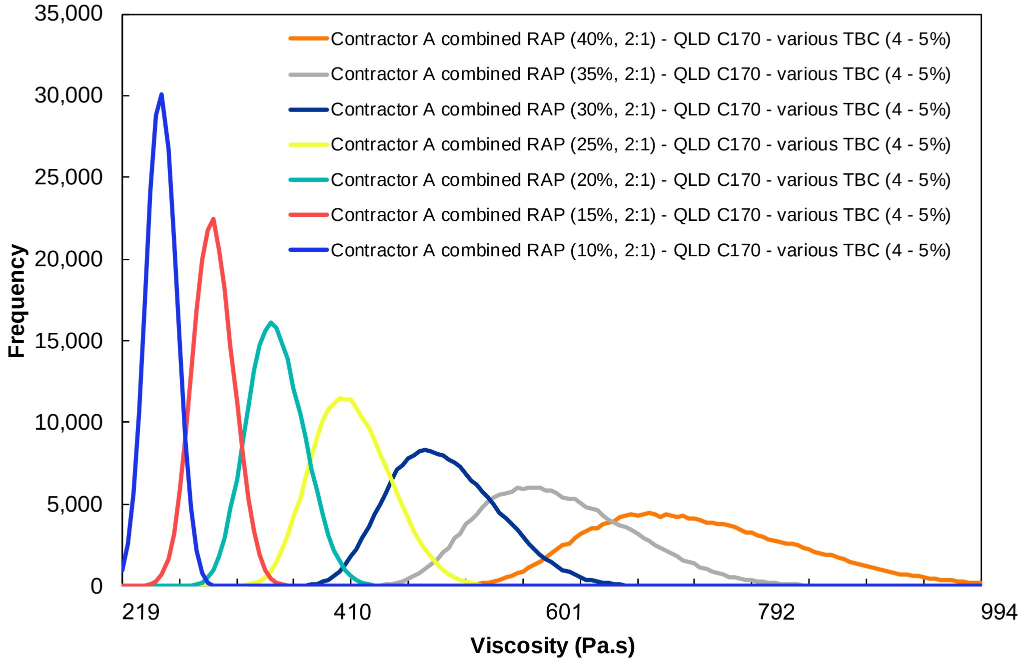


Figure F 9: Binder blend viscosity variation of contractor A combined RAP, Qld C240 virgin binder

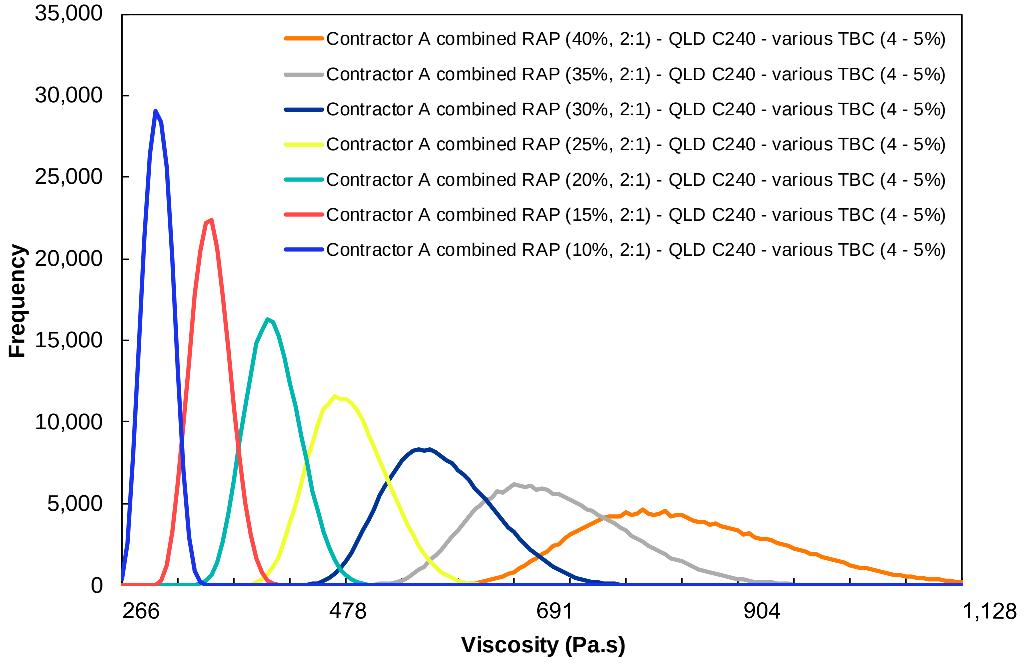


Figure F 10: Binder blend viscosity variation of contractor A combined RAP, Qld C320 virgin binder

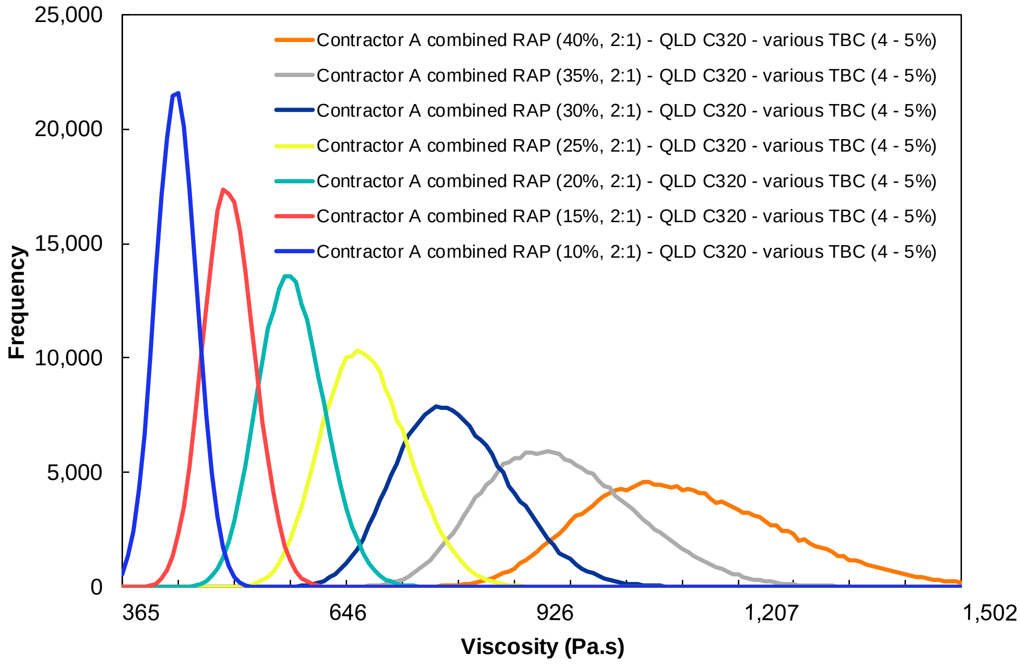


Figure F 11: Binder blend viscosity variation of contractor A combined RAP, Qld C450 virgin binder

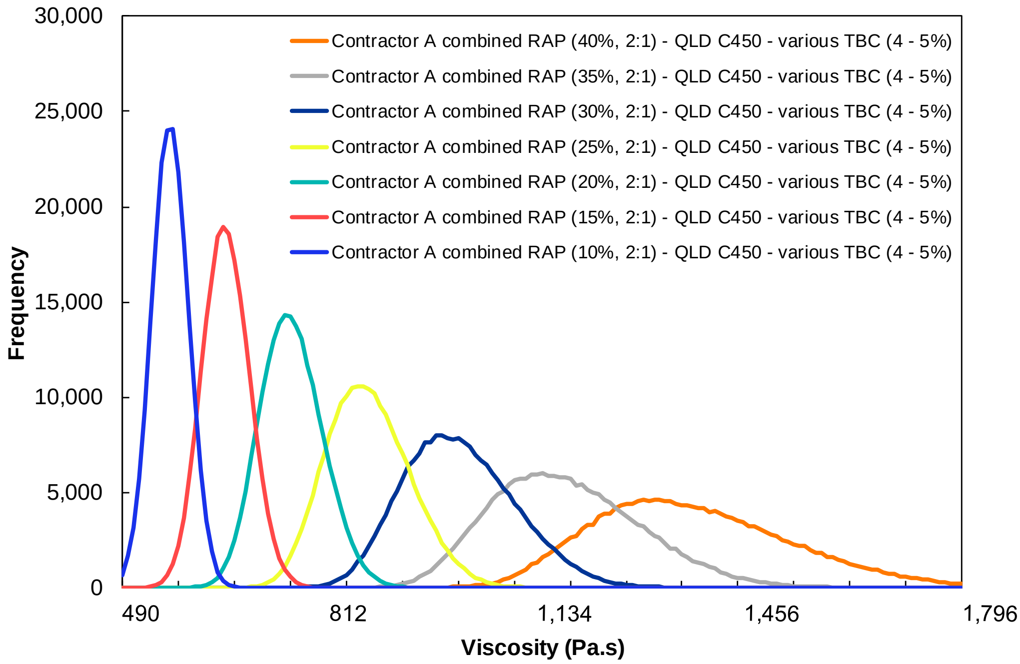


Figure F 12: Binder blend viscosity variation of contractor A combined RAP, Qld C600 virgin binder

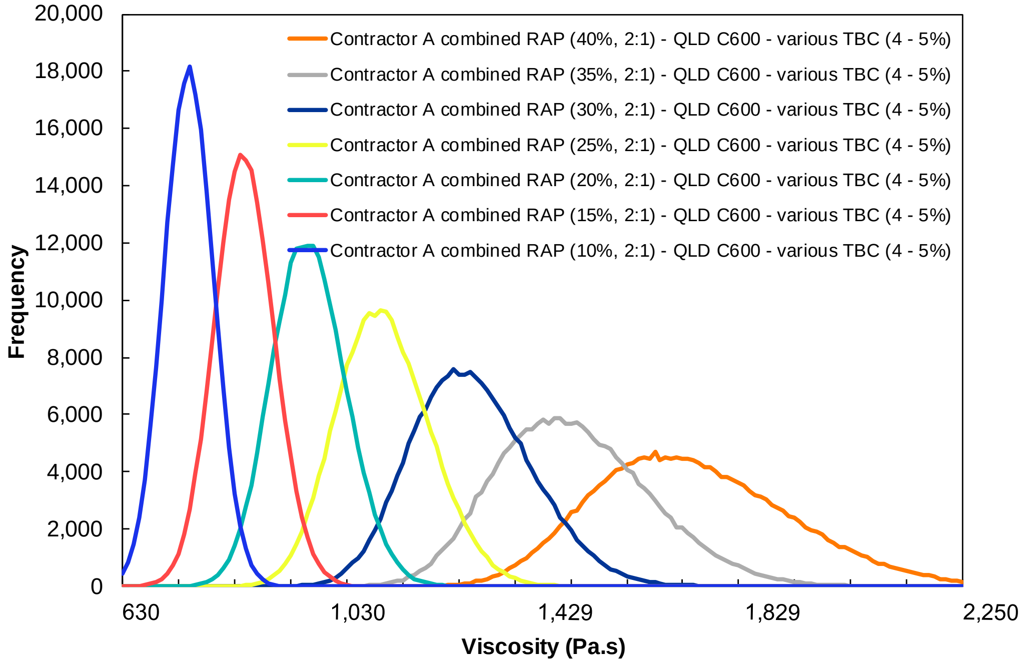


Figure F 13: Binder blend viscosity variation of contractor B combined RAP, Qld C170 virgin binder

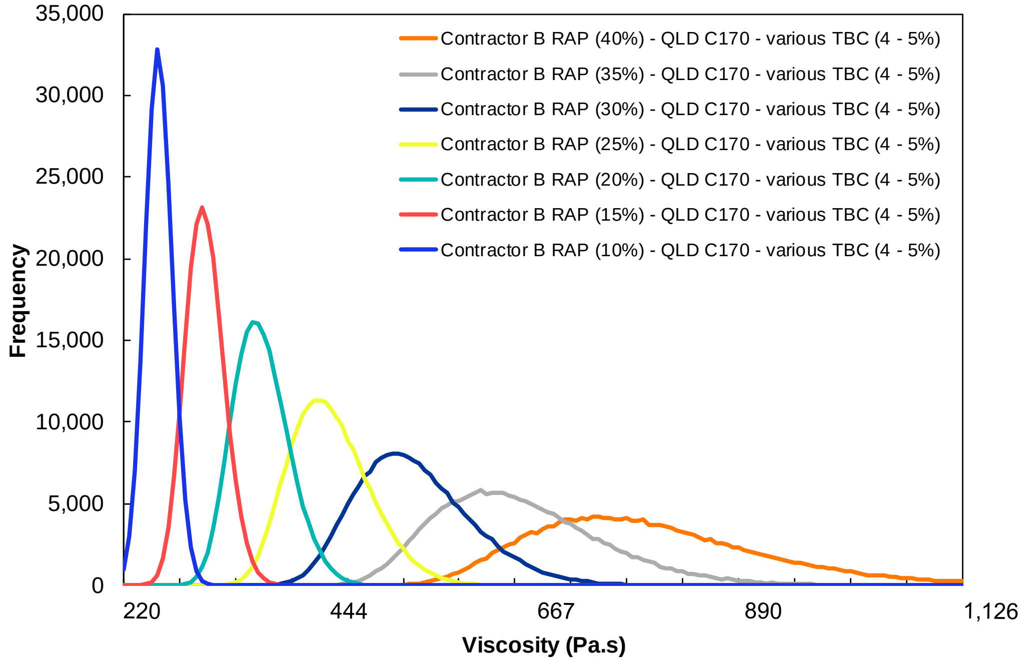


Figure F 14: Binder blend viscosity variation of contractor B combined RAP, Qld C240 virgin binder

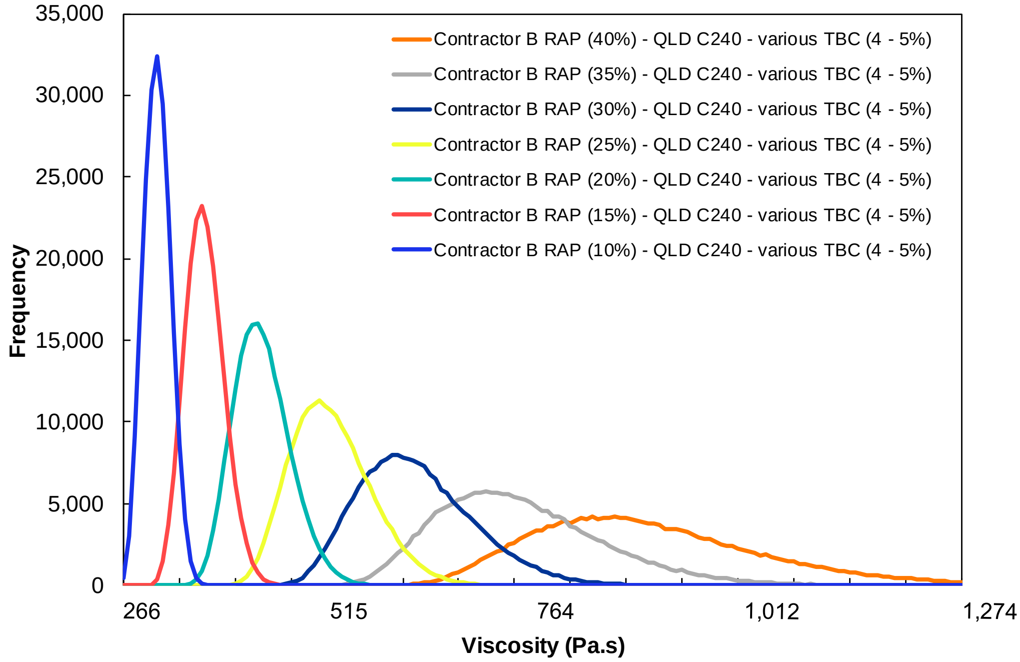


Figure F 15: Binder blend viscosity variation of contractor B combined RAP, Qld C320 virgin binder

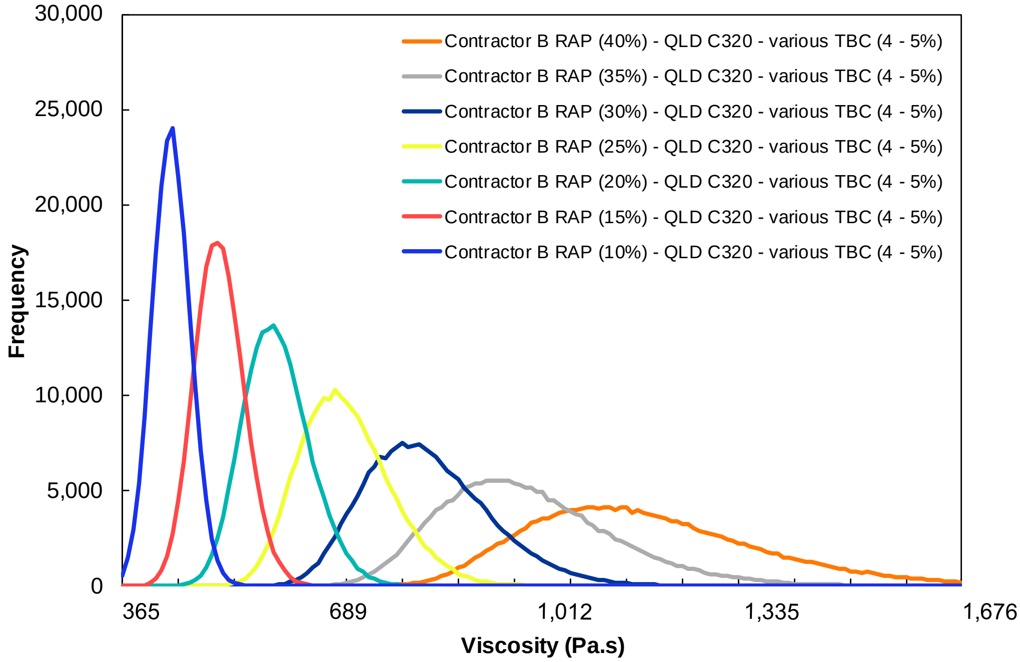


Figure F 16: Binder blend viscosity variation of contractor B combined RAP, Qld C450 virgin binder

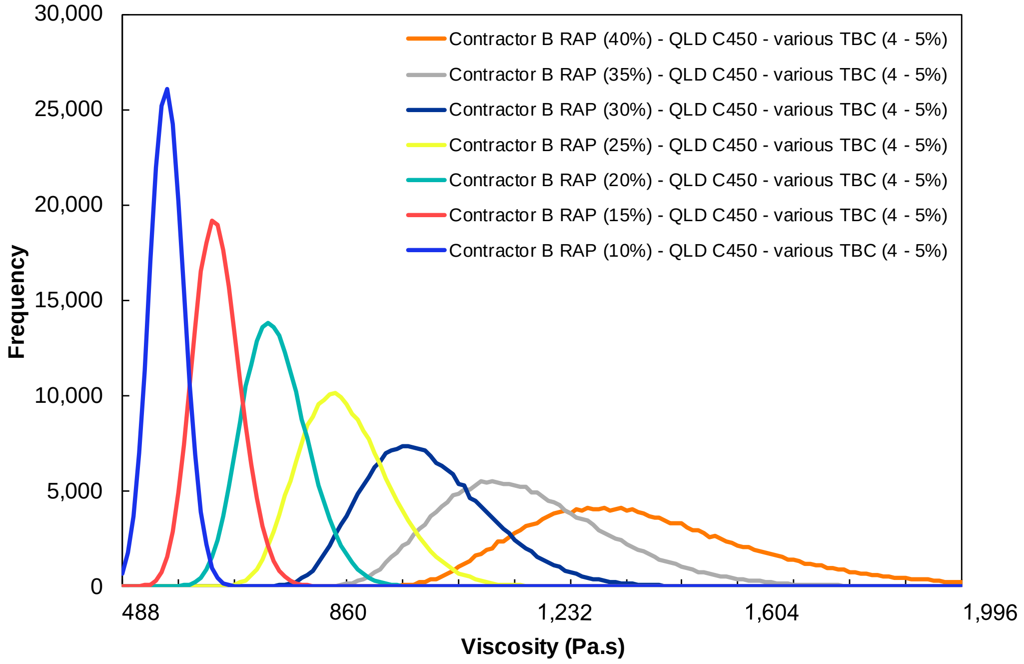


Figure F 17: Binder blend viscosity variation of contractor B combined RAP, Qld C600 virgin binder

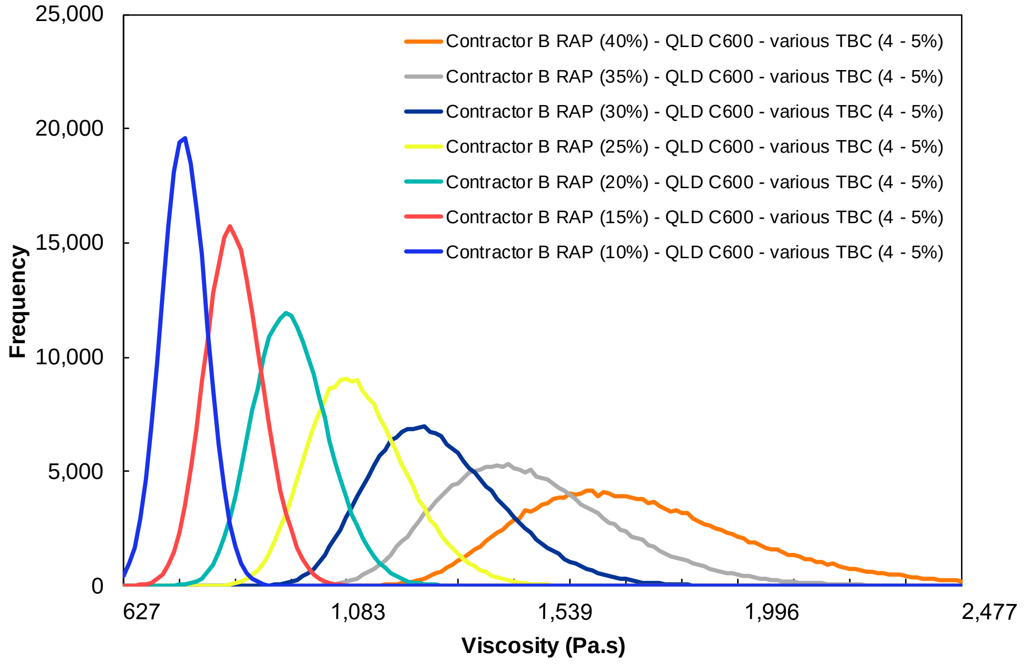


Figure F 18: Binder blend viscosity variation of contractor C combined RAP, Qld C170 virgin binder

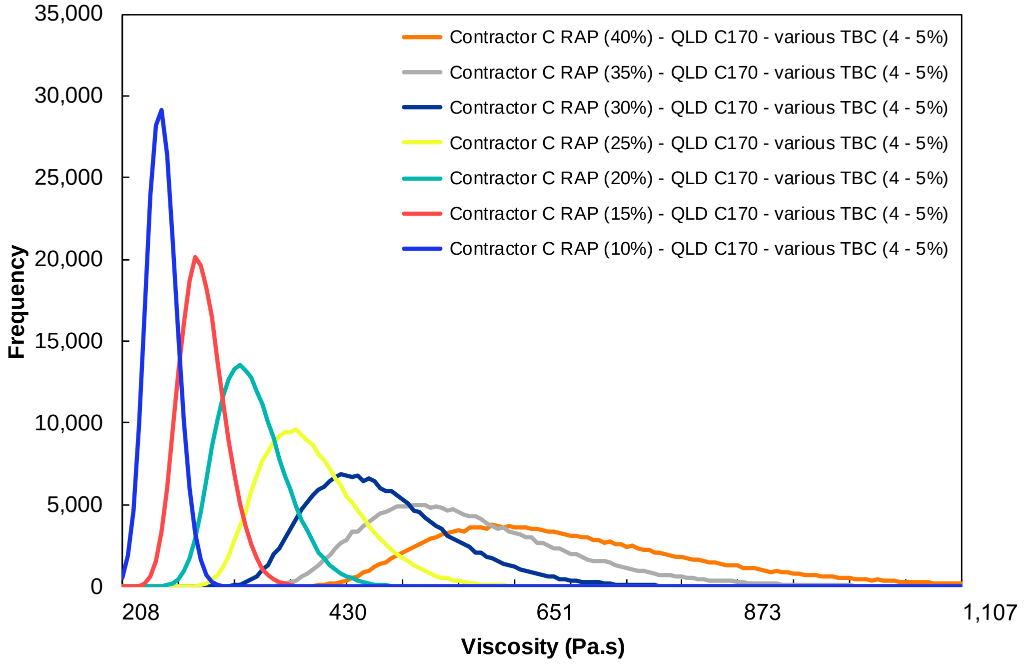


Figure F 19: Binder blend viscosity variation of contractor C combined RAP, Qld C240 virgin binder

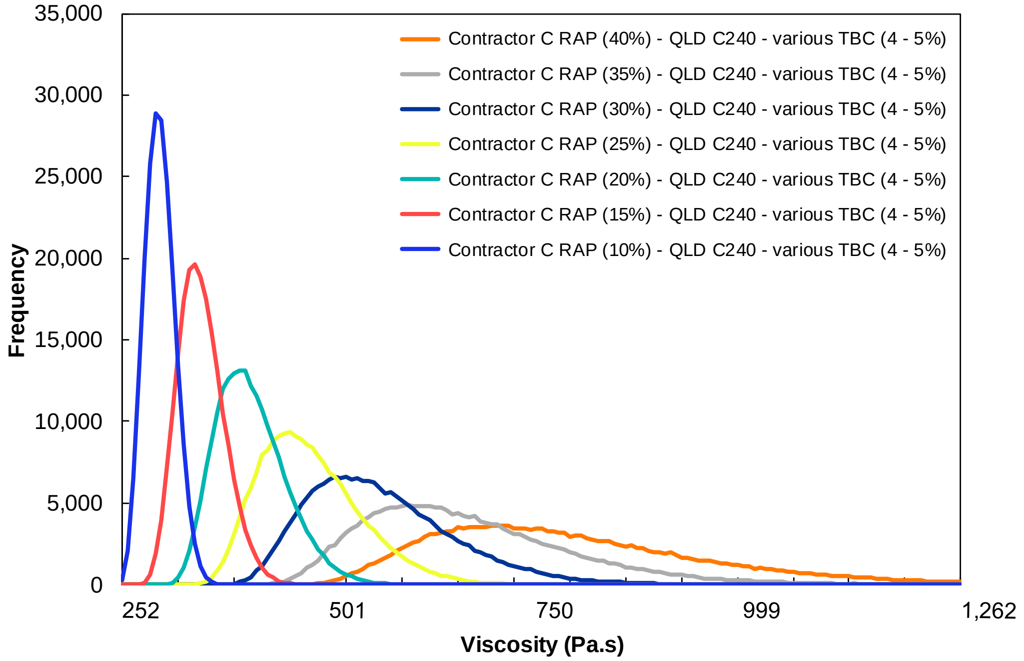


Figure F 20: Binder blend viscosity variation of contractor C combined RAP, Qld C320 virgin binder

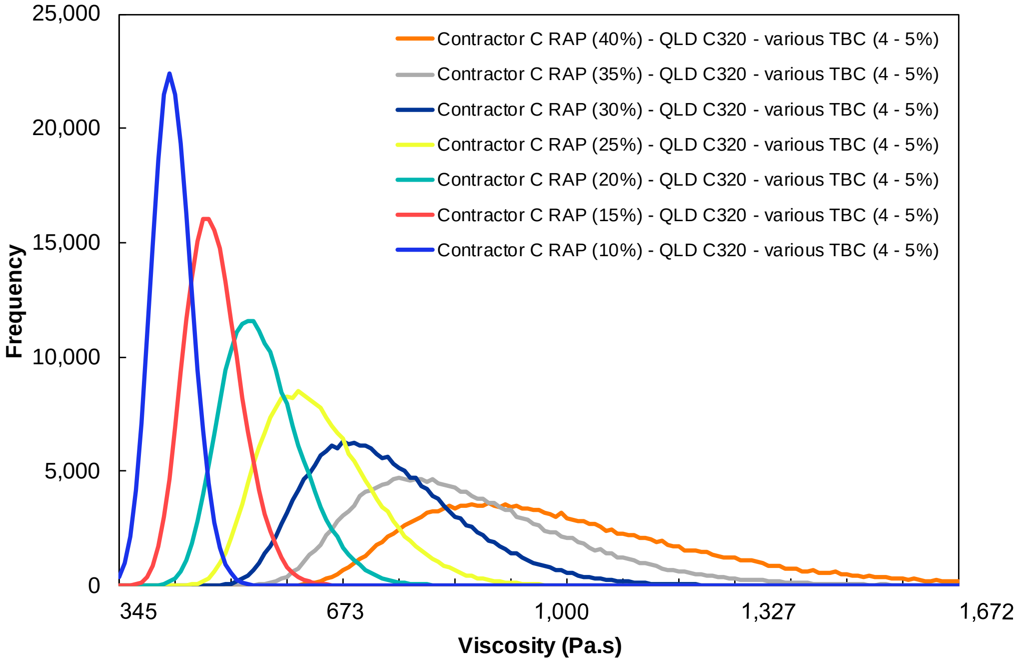


Figure F 21: Binder blend viscosity variation of contractor C combined RAP, Qld C450 virgin binder

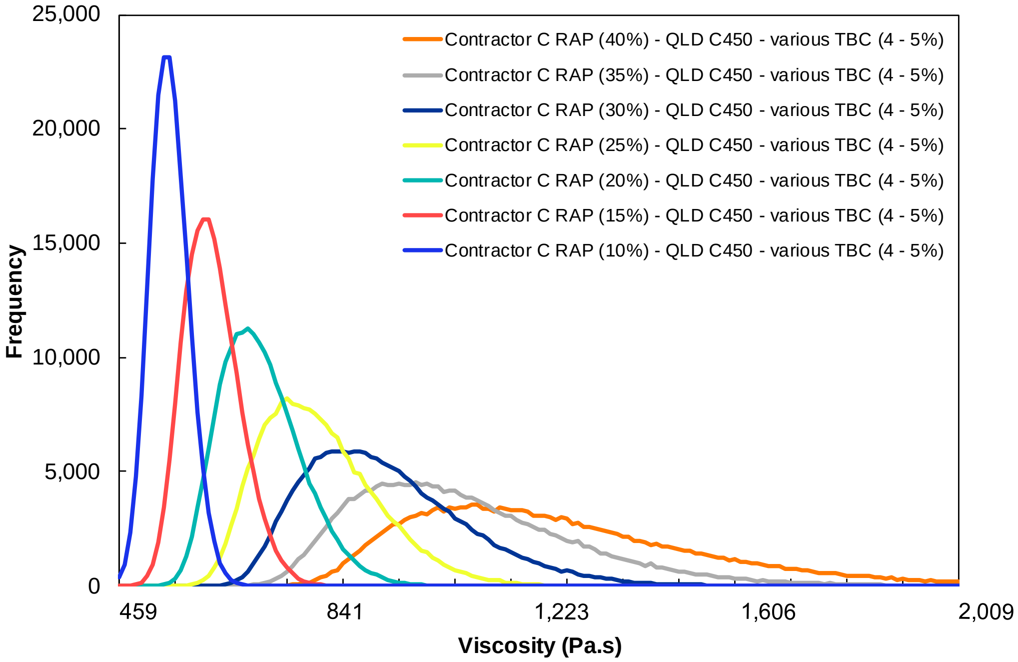
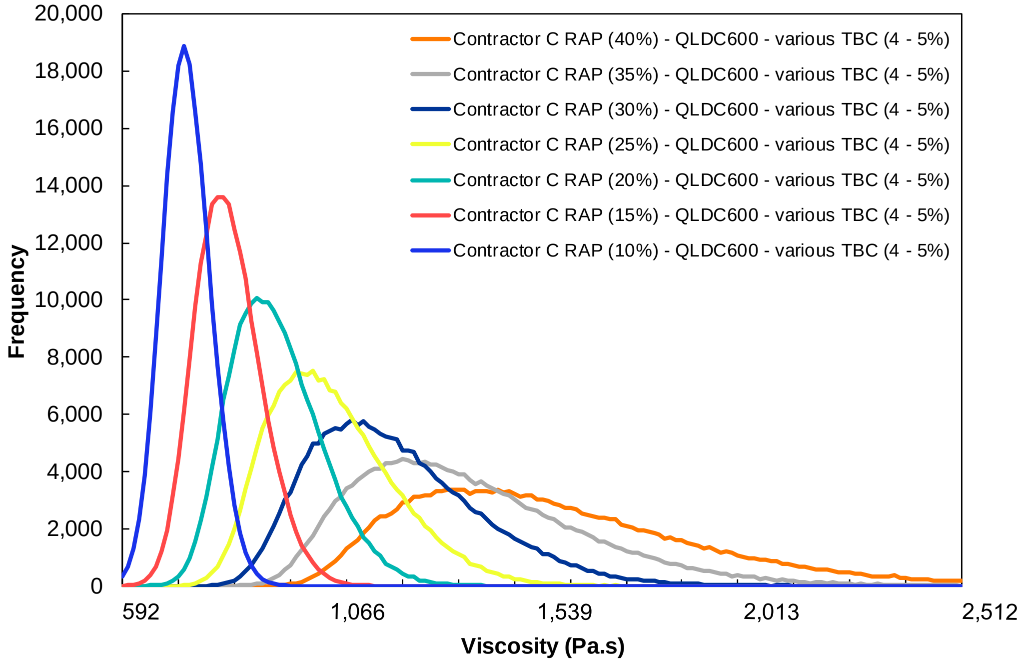


Figure F 22: Binder blend viscosity variation of contractor C combined RAP, Qld C600 virgin binder



F.2 Binder blend viscosity variations for blends containing AS virgin binders

Figure F 23: Binder blend viscosity variation of contractor A combined RAP, AS C170 virgin binder

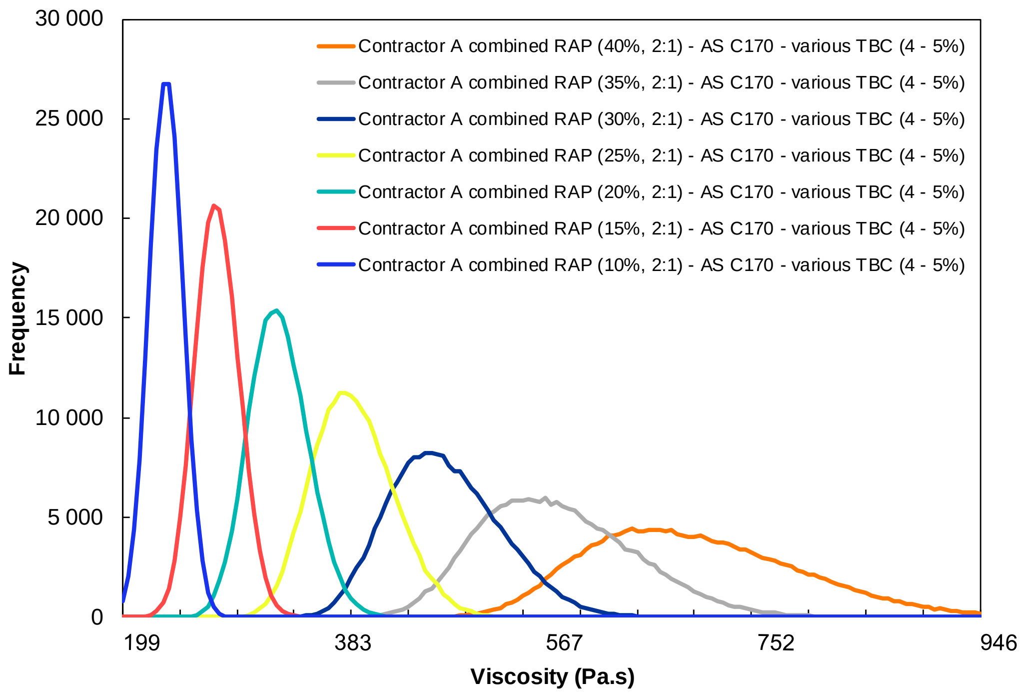


Figure F 24: Binder blend viscosity variation of contractor A combined RAP, AS C240 virgin binder

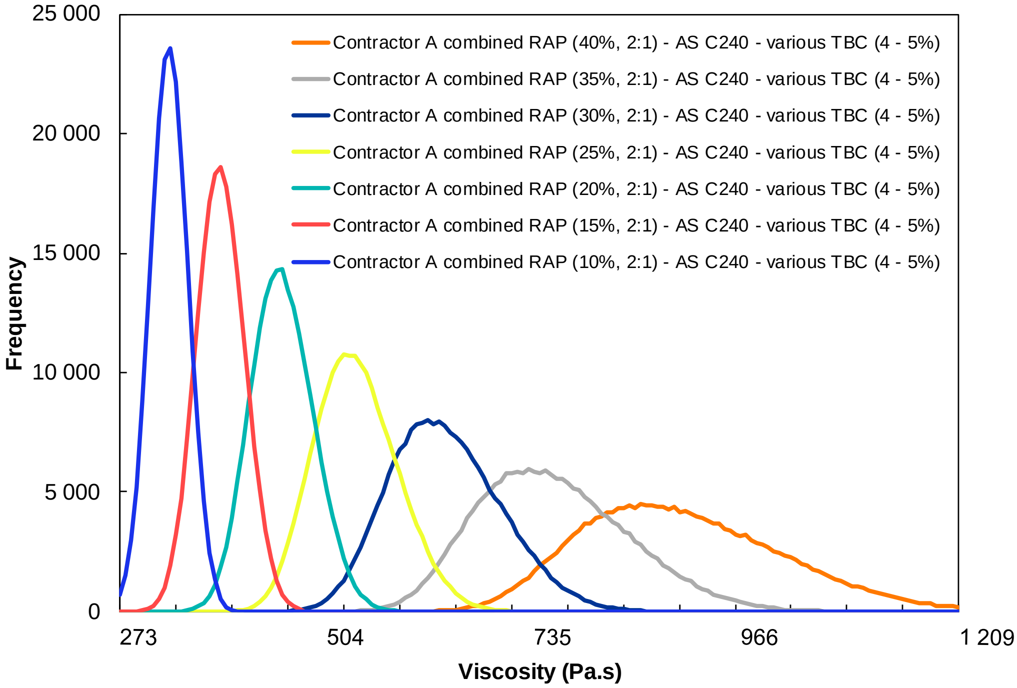


Figure F 25: Binder blend viscosity variation of contractor A combined RAP, AS C320 virgin binder

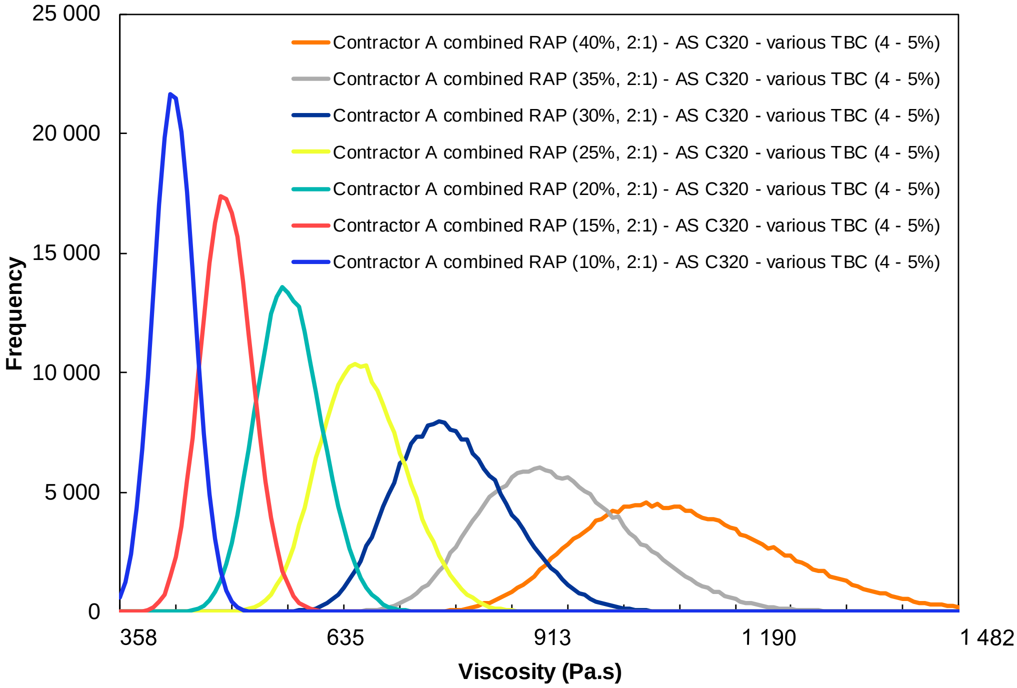


Figure F 26: Binder blend viscosity variation of contractor A combined RAP, AS C450 virgin binder

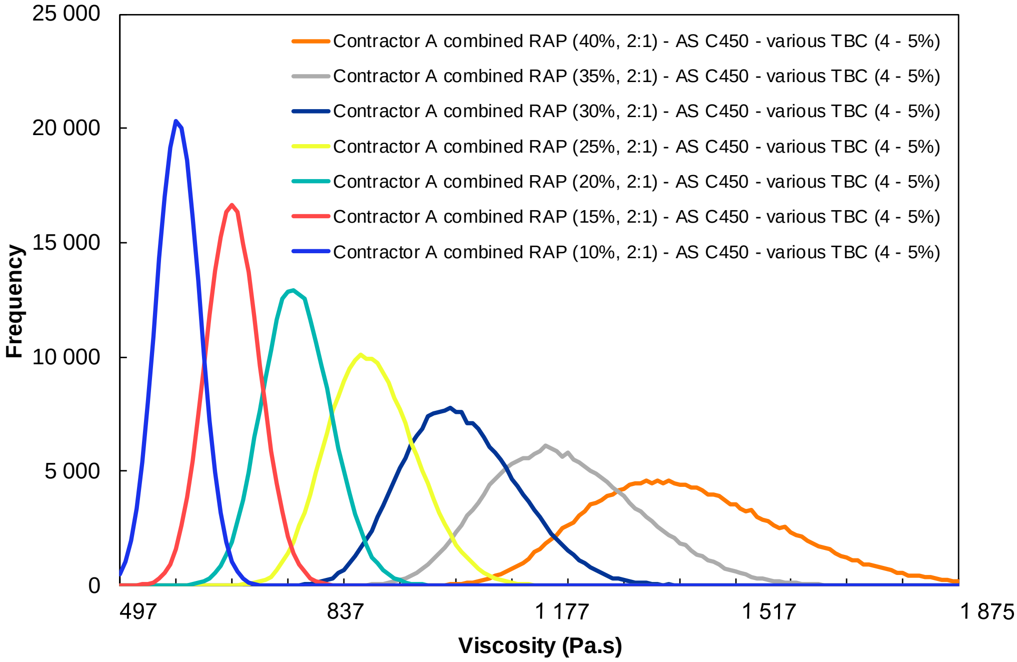


Figure F 27: Binder blend viscosity variation of contractor A combined RAP, AS C600 virgin binder

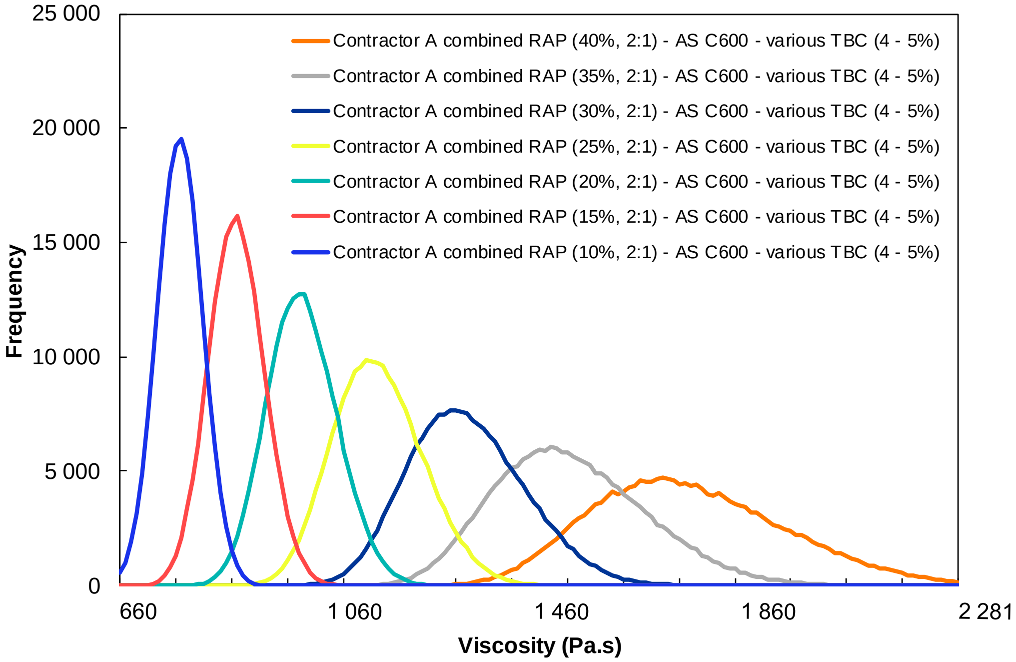


Figure F 28: Binder blend viscosity variation of contractor B combined RAP, AS C170 virgin binder

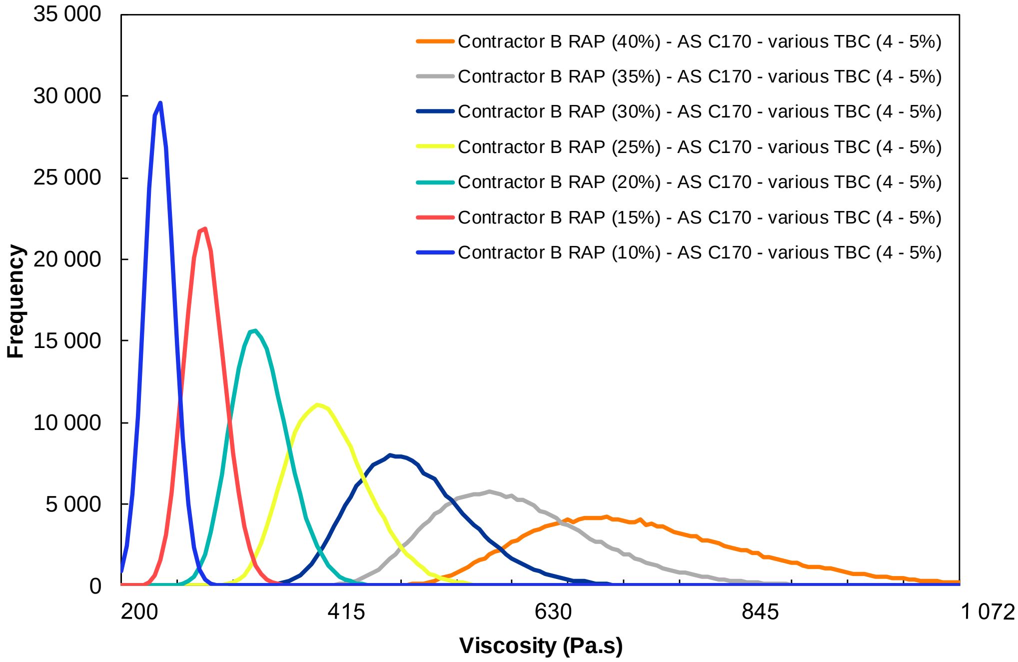


Figure F 29: Binder blend viscosity variation of contractor B combined RAP, AS C240 virgin binder

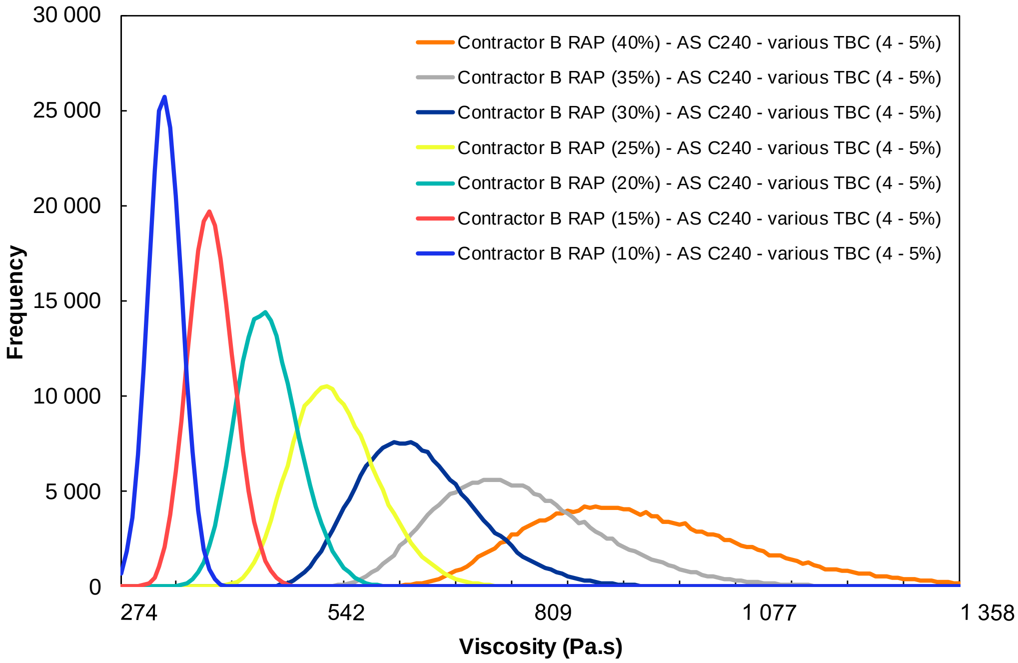


Figure F 30: Binder blend viscosity variation of contractor B combined RAP, AS C320 virgin binder

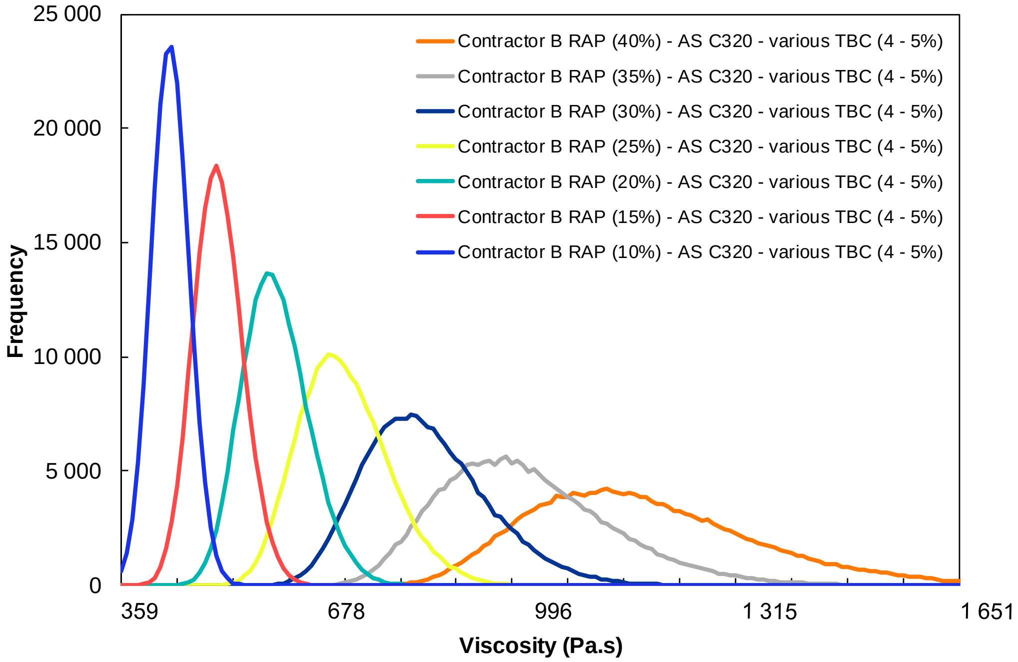


Figure F 31: Binder blend viscosity variation of contractor B combined RAP, AS C450 virgin binder

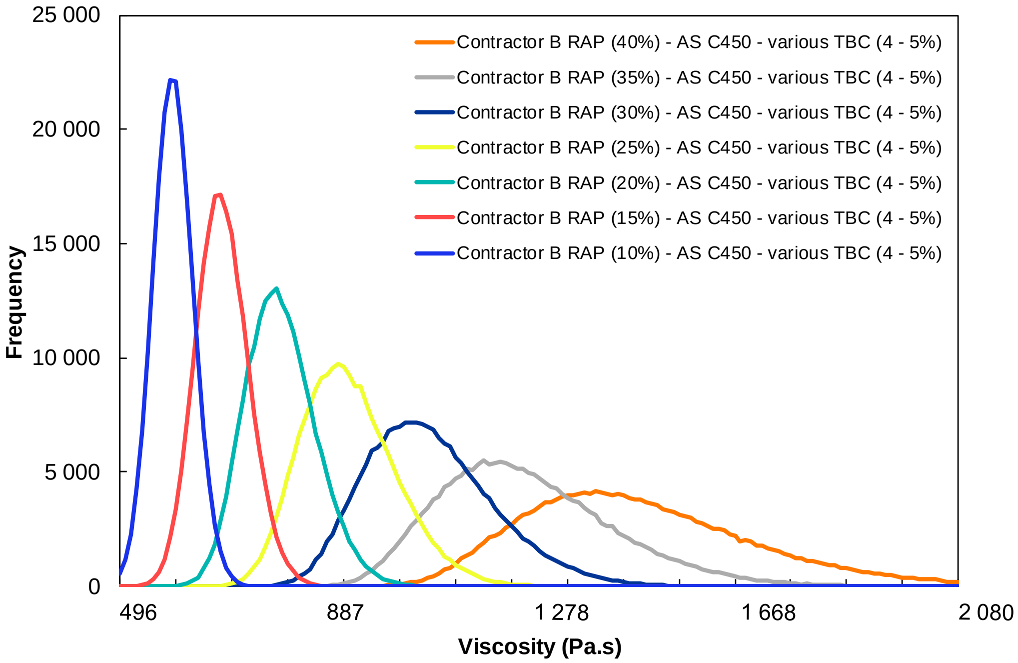


Figure F 32: Binder blend viscosity variation of contractor B combined RAP, AS C600 virgin binder

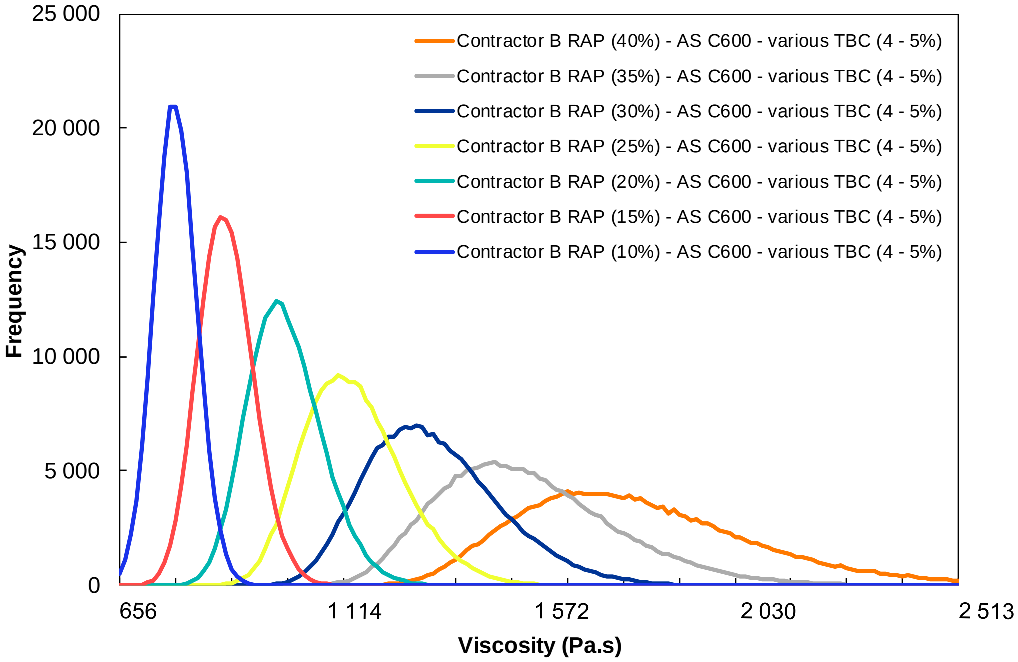


Figure F 33: Binder blend viscosity variation of contractor C combined RAP, AS C170 virgin binder

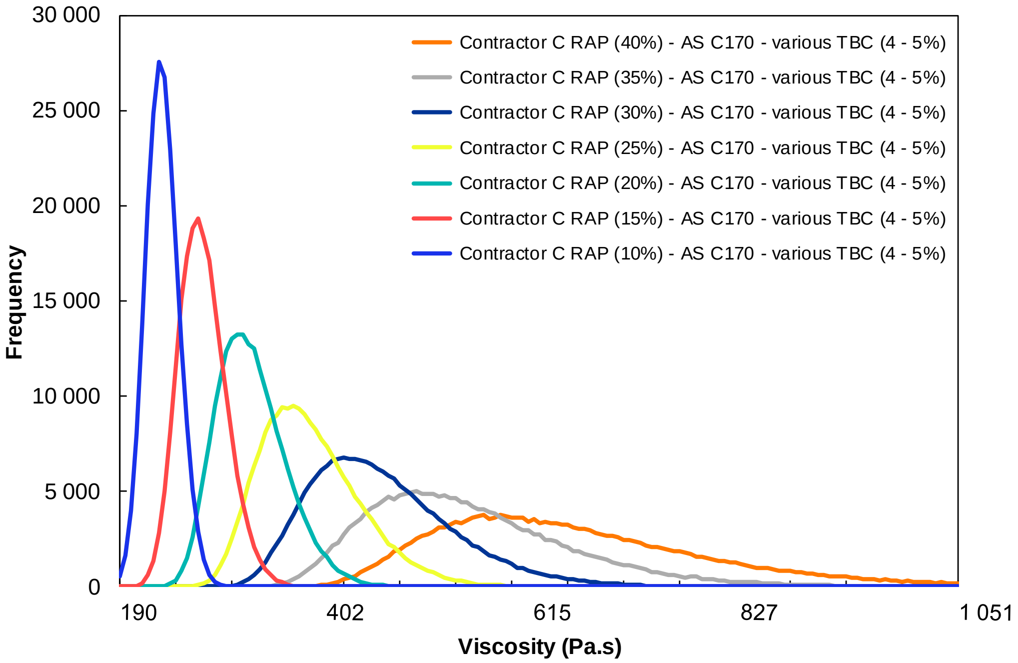


Figure F 34: Binder blend viscosity variation of contractor C combined RAP, AS C240 virgin binder

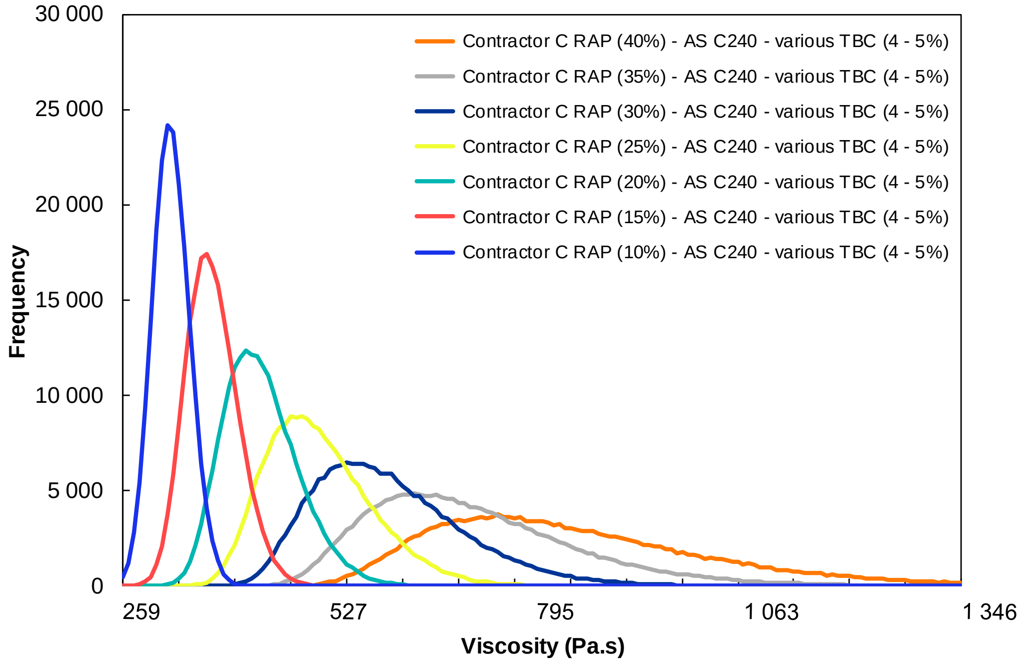


Figure F 35: Binder blend viscosity variation of contractor C combined RAP, AS C320 virgin binder

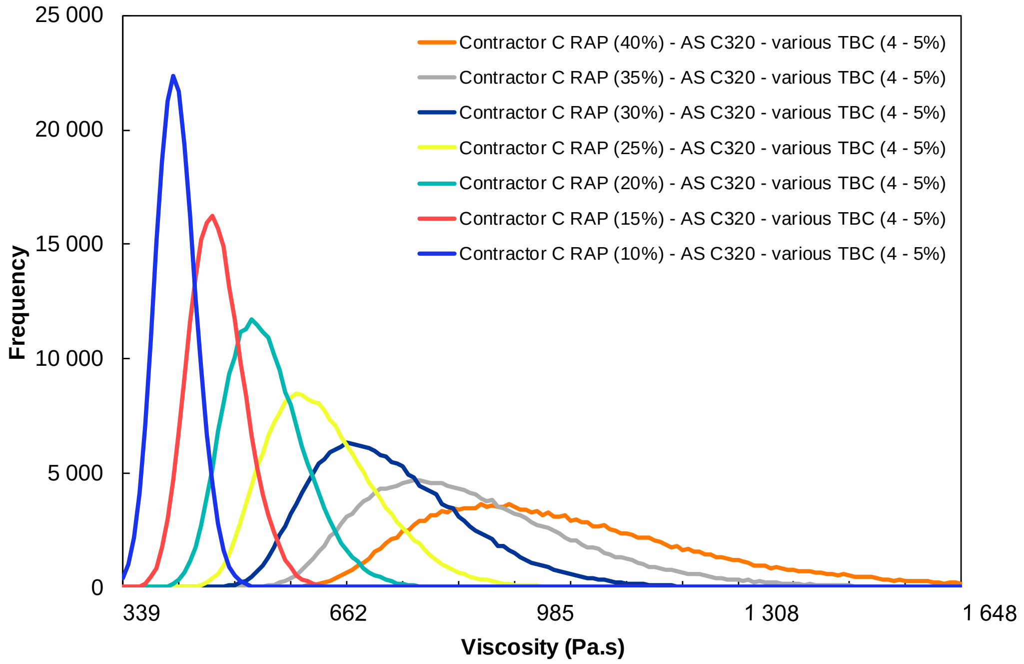


Figure F 36: Binder blend viscosity variation of contractor C combined RAP, AS C450 virgin binder

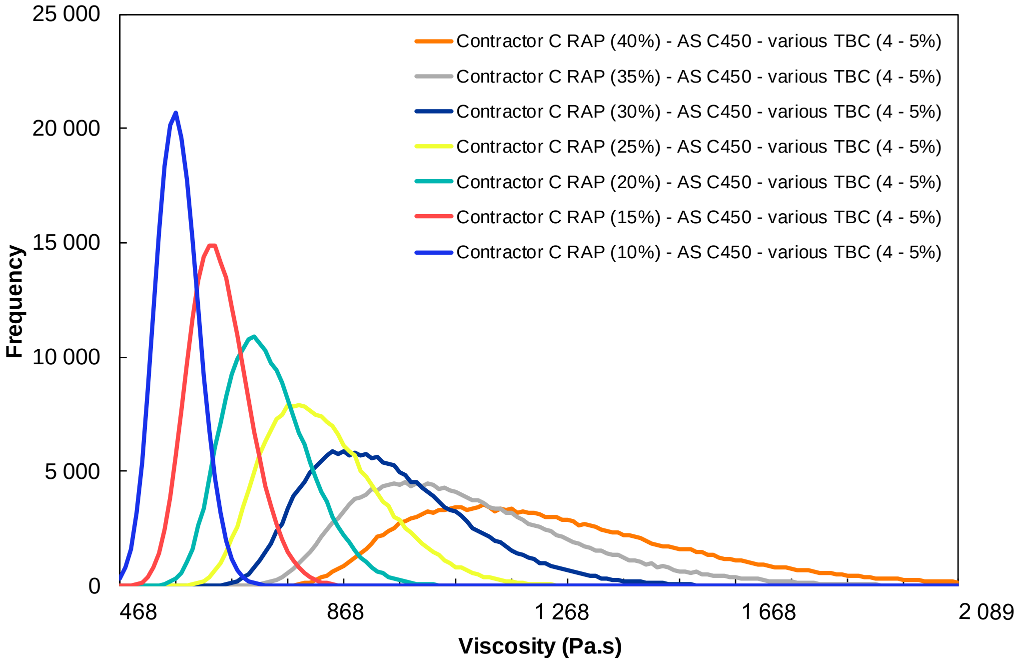
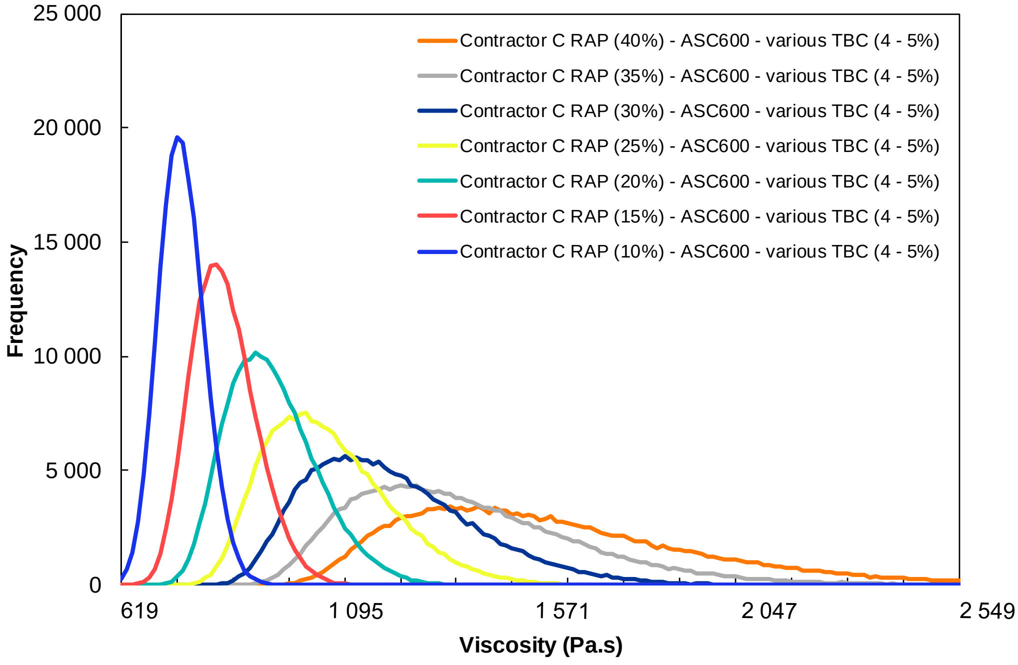


Figure F 37: Binder blend viscosity variation of contractor C combined RAP, AS C600 virgin binder



APPENDIX G BINDER BLEND VISCOSITY PLOTS (COMBINED RAP)

G.1 Binder blend viscosity variations for blends containing Qld virgin binders – combined RAP

Figure G 1: Binder blend viscosity variation of all RAP, Qld C170 virgin binder

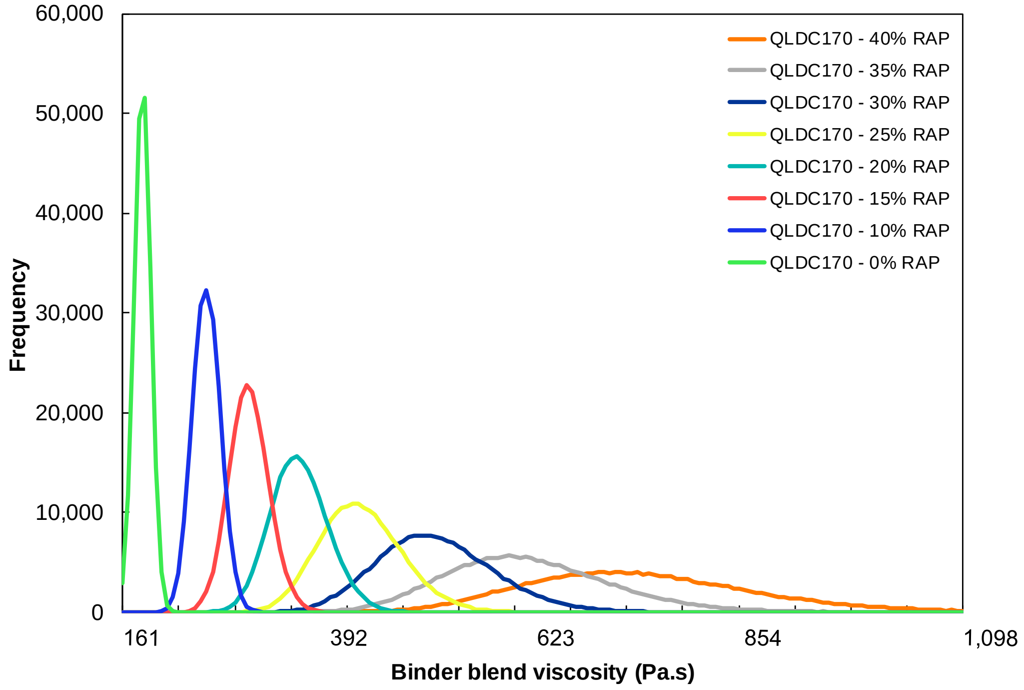


Figure G 2: Binder blend viscosity variation of all RAP, Qld C240 virgin binder

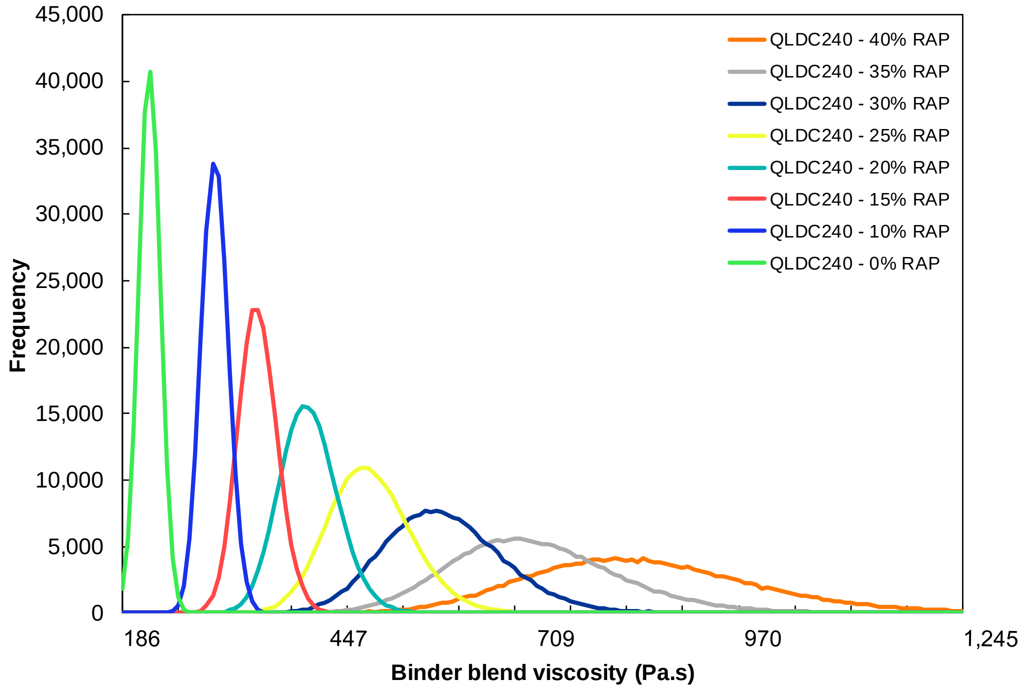


Figure G 3: Binder blend viscosity variation of all RAP, Qld C320 virgin binder

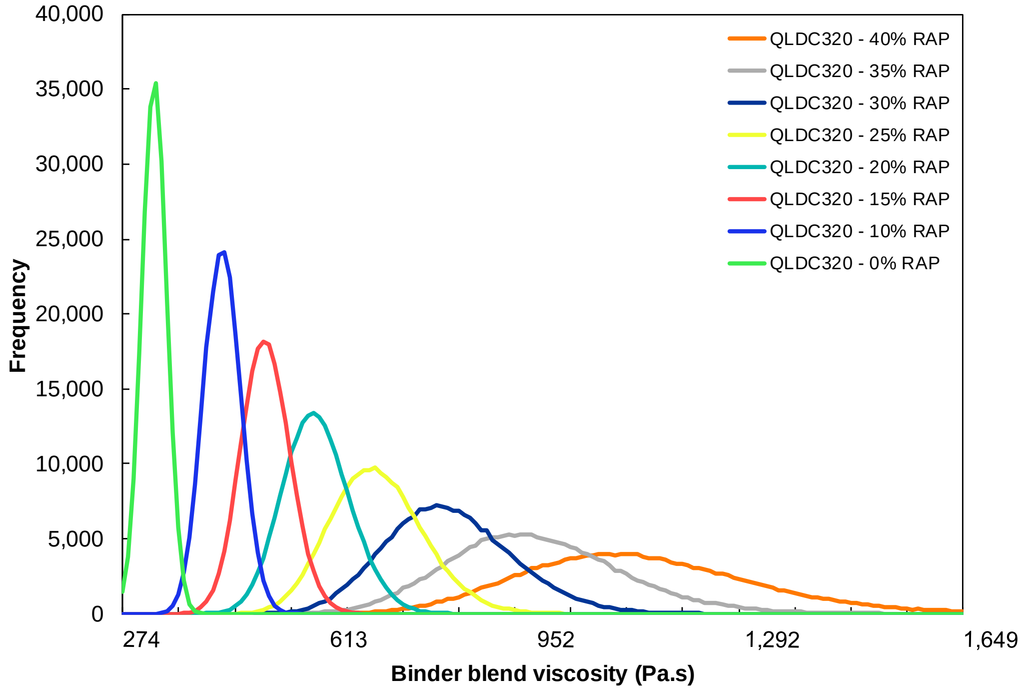


Figure G 4: Binder blend viscosity variation of all RAP, Qld C450 virgin binder

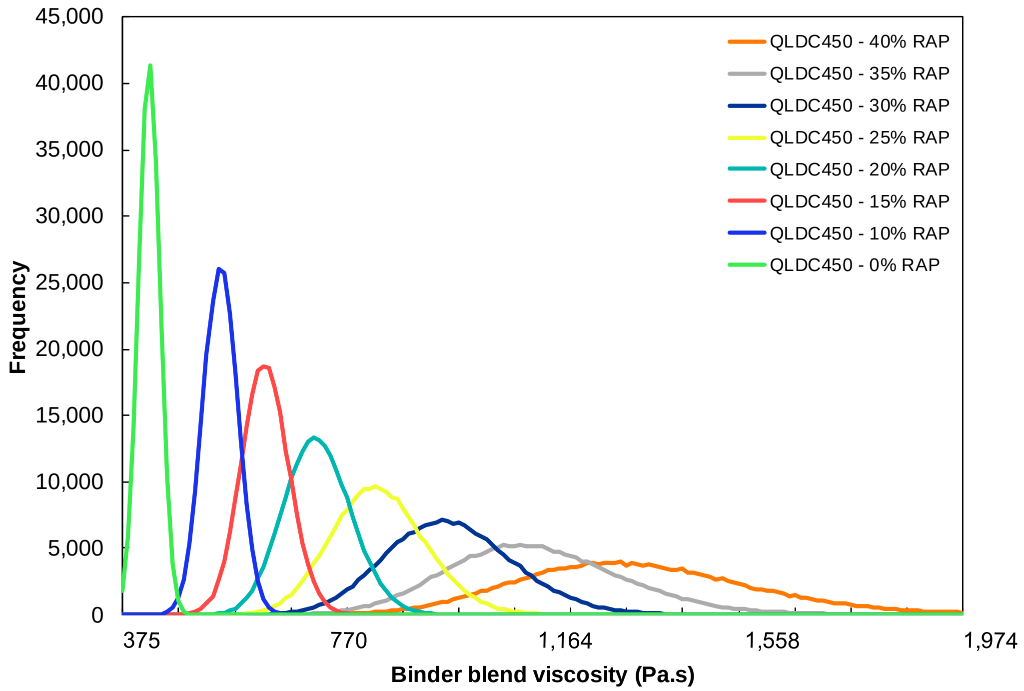


Figure G 5: Binder blend viscosity variation of all RAP, Qld C600 virgin binder

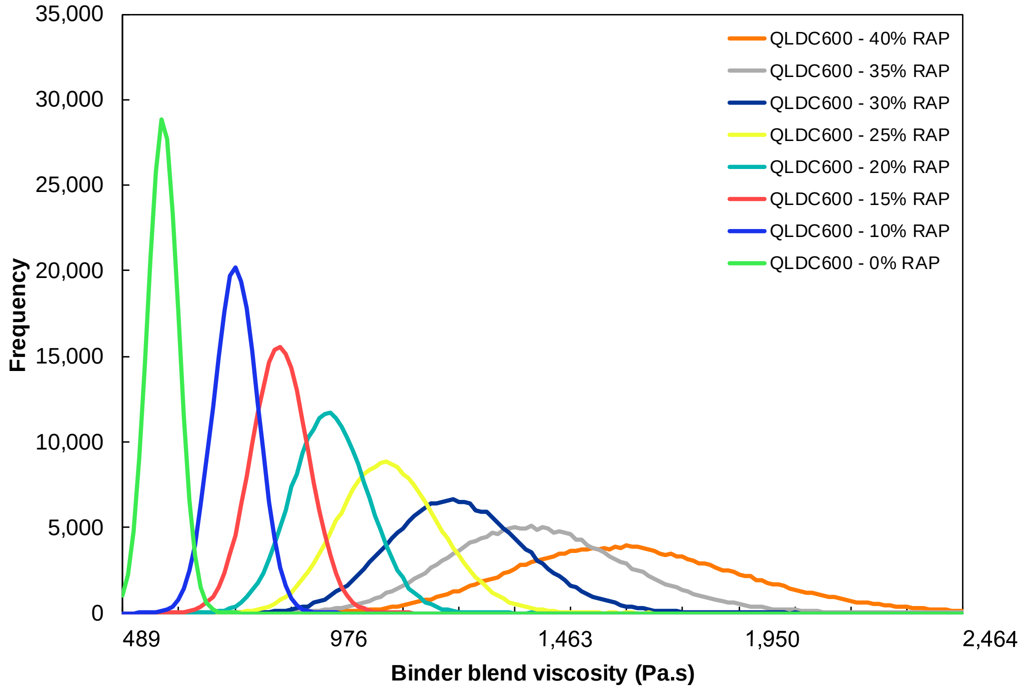


Figure G 6: Binder blend viscosity variation of all RAP, 10% RAP, Qld virgin binder

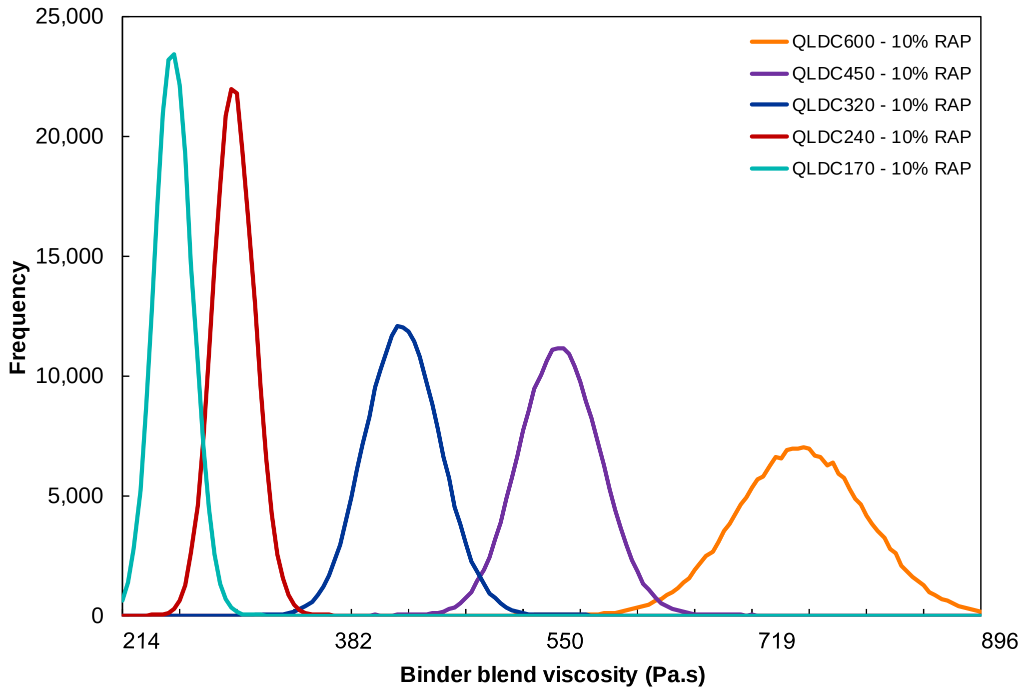


Figure G 7: Binder blend viscosity variation of all RAP, 15% RAP, Qld virgin binder

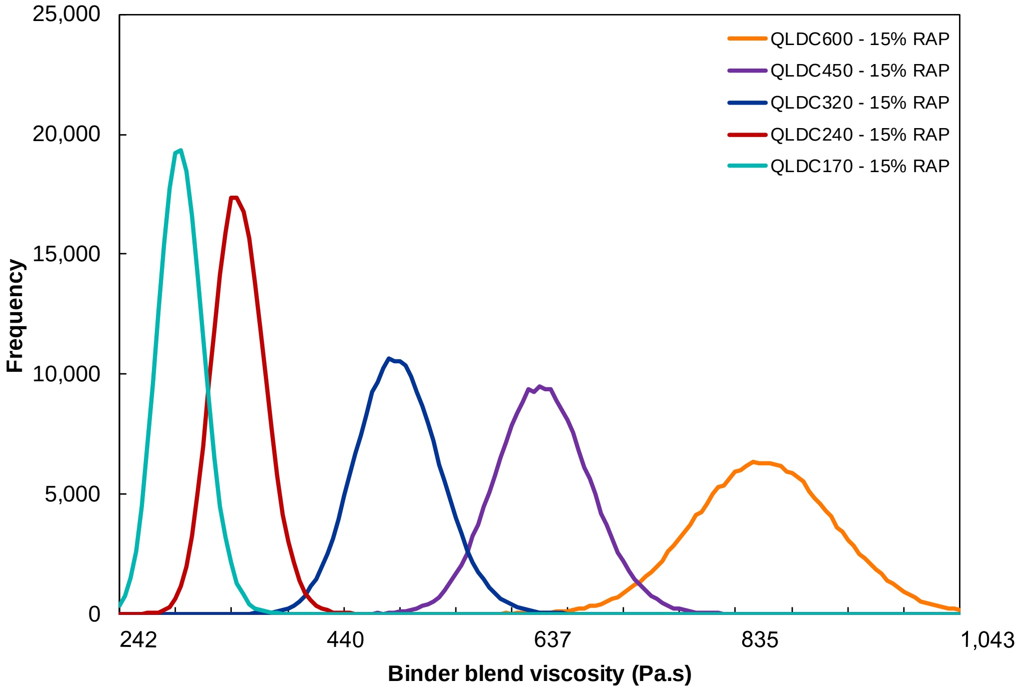


Figure G 8: Binder blend viscosity variation of all RAP, 20% RAP, Qld virgin binder

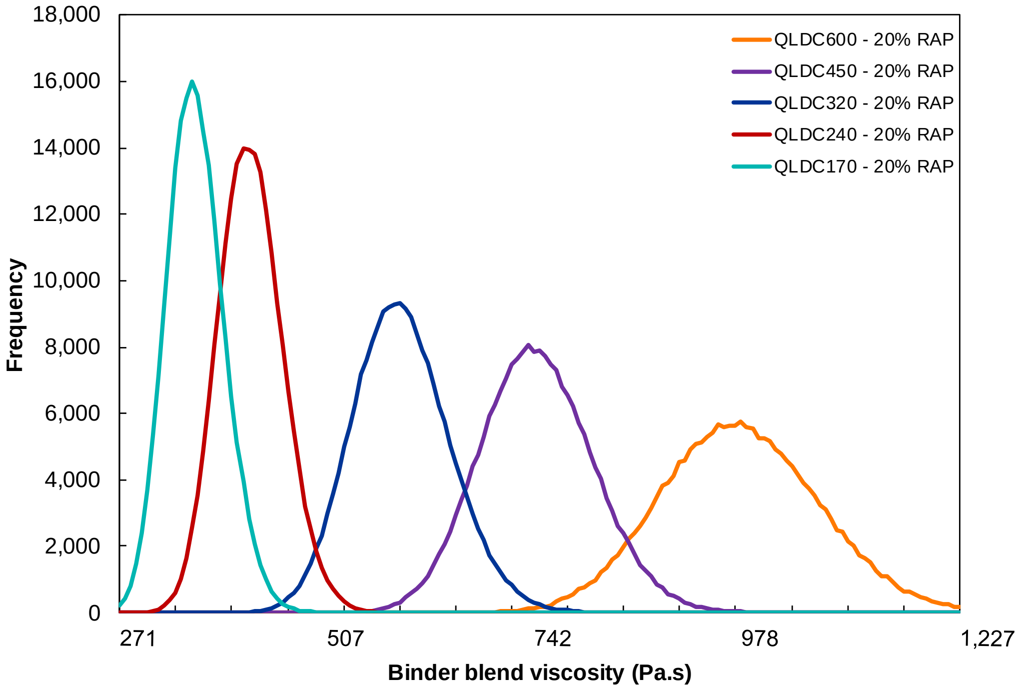


Figure G 9: Binder blend viscosity variation of all RAP, 25% RAP, Qld virgin binder

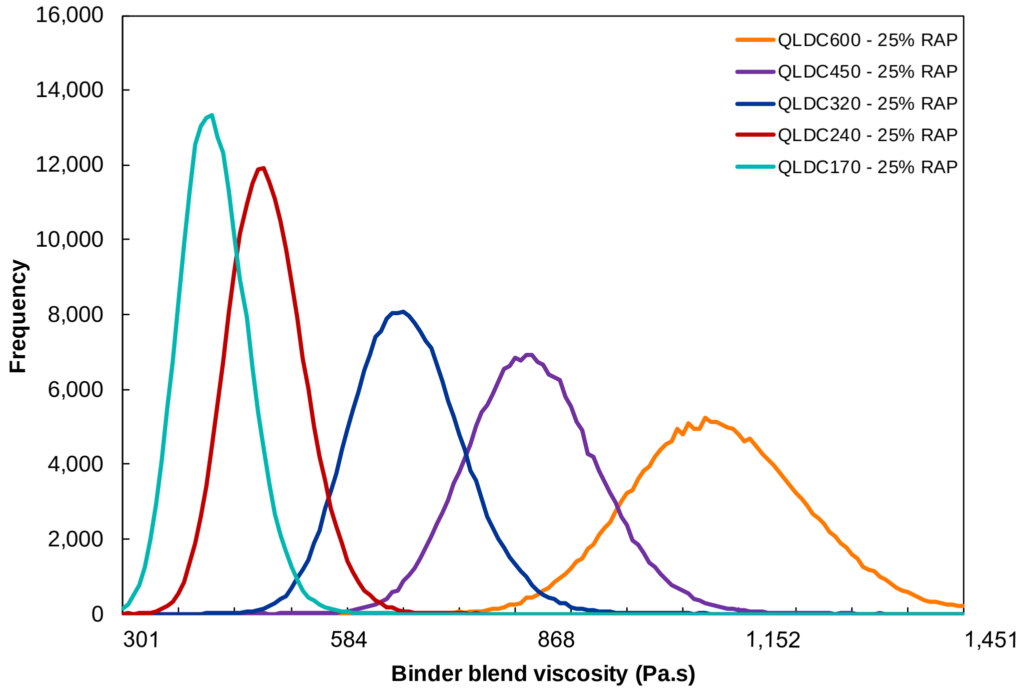


Figure G 10: Binder blend viscosity variation of all RAP, 30% RAP, Qld virgin binder

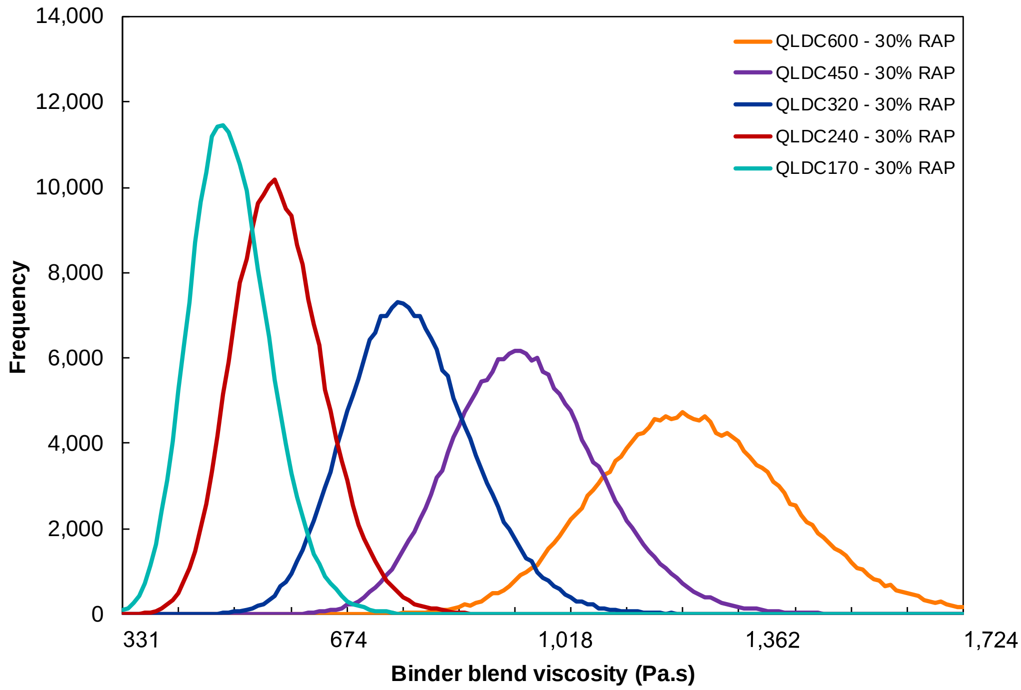


Figure G 11: Binder blend viscosity variation of all RAP, 35% RAP, Qld virgin binder

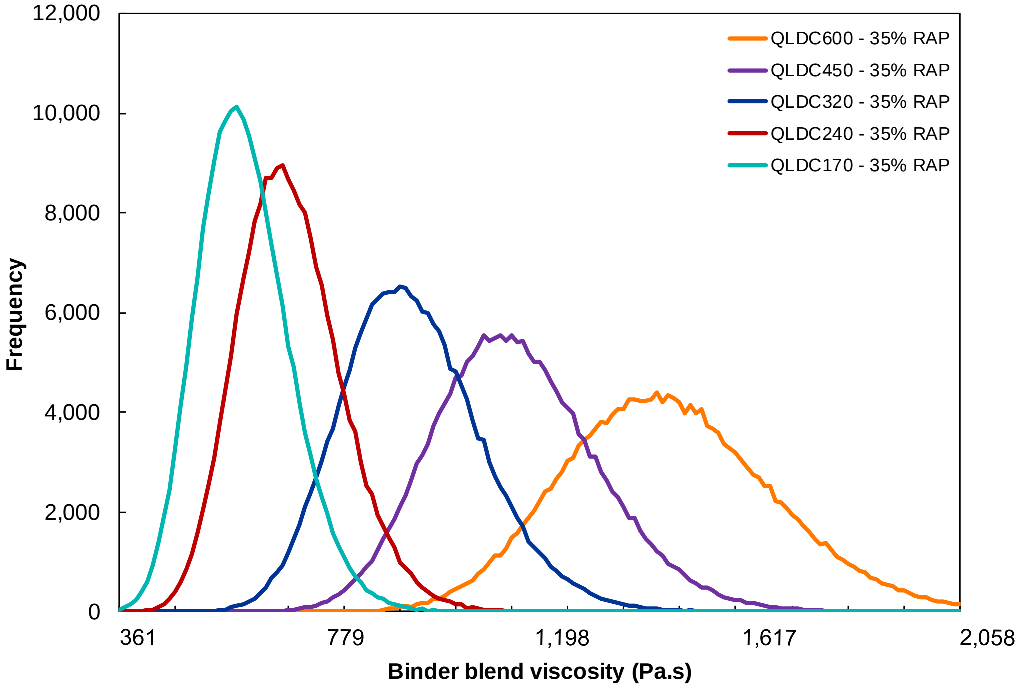
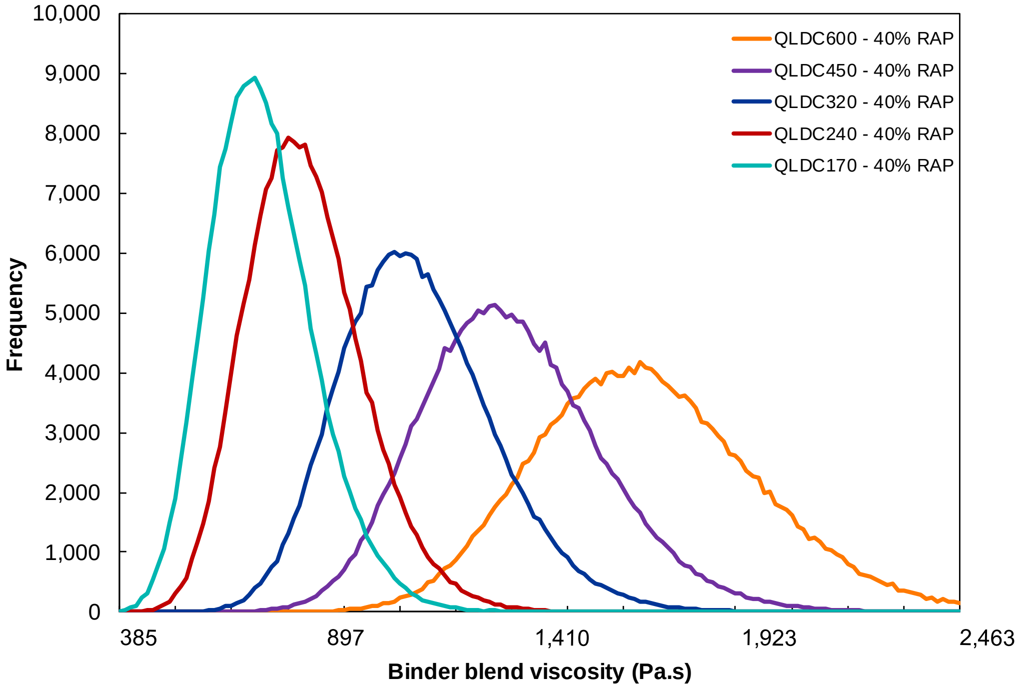


Figure G 12: Binder blend viscosity variation of all RAP, 40% RAP, Qld virgin binder



G.2 Binder blend viscosity variations for blends containing AS virgin binders – combined RAP

Figure G 13: Binder blend viscosity variation of all RAP, AS C170 virgin binder

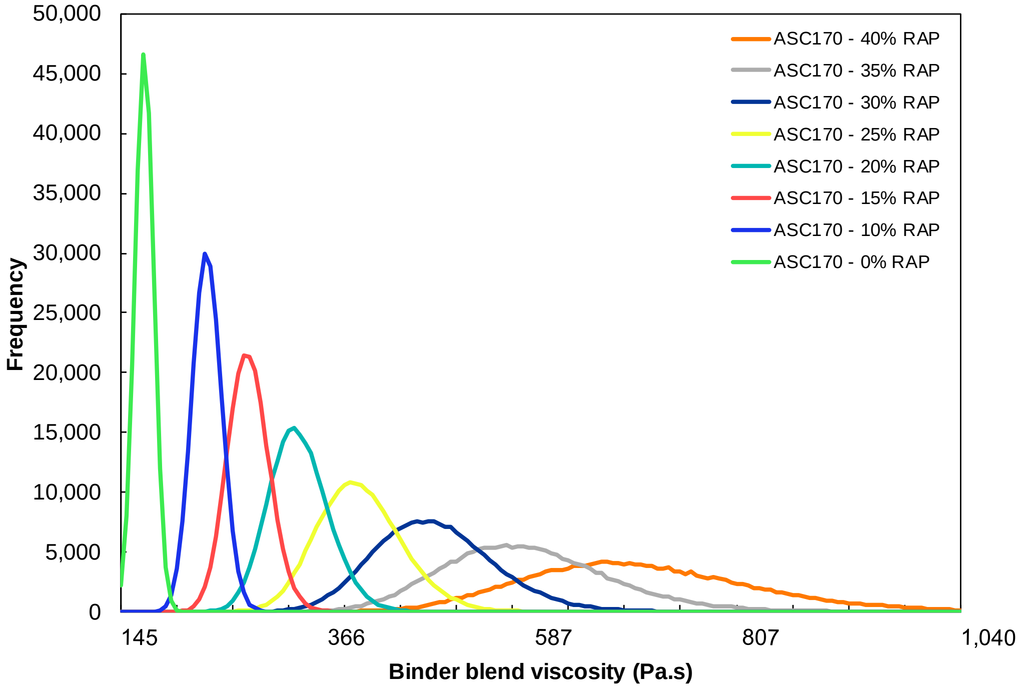


Figure G 14: Binder blend viscosity variation of all RAP, AS C240 virgin binder

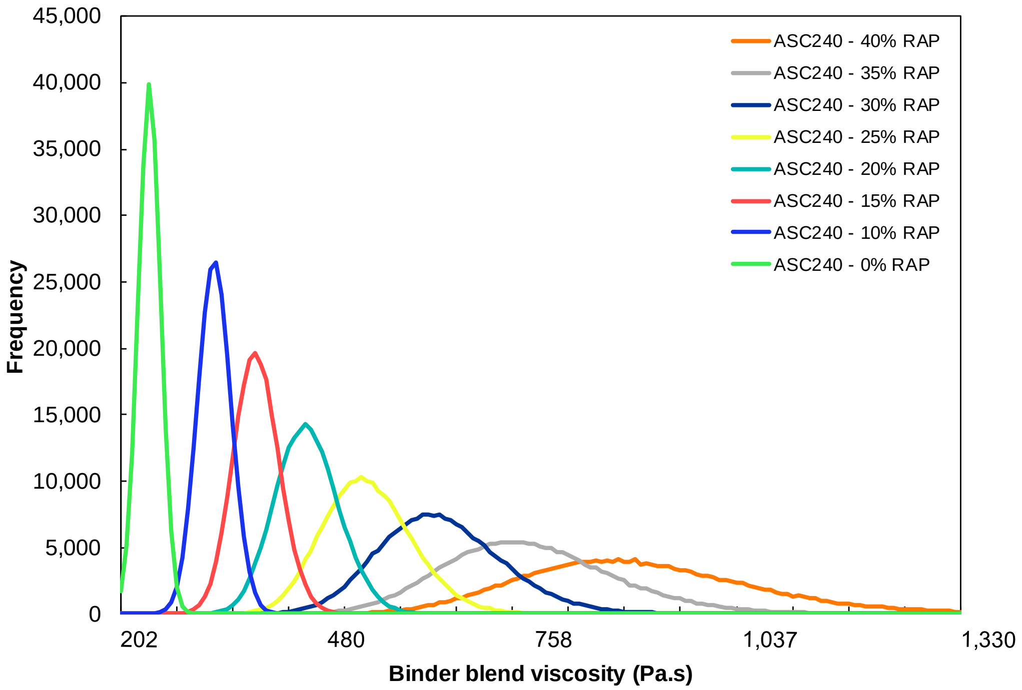


Figure G 15: Binder blend viscosity variation of all RAP, AS C320 virgin binder

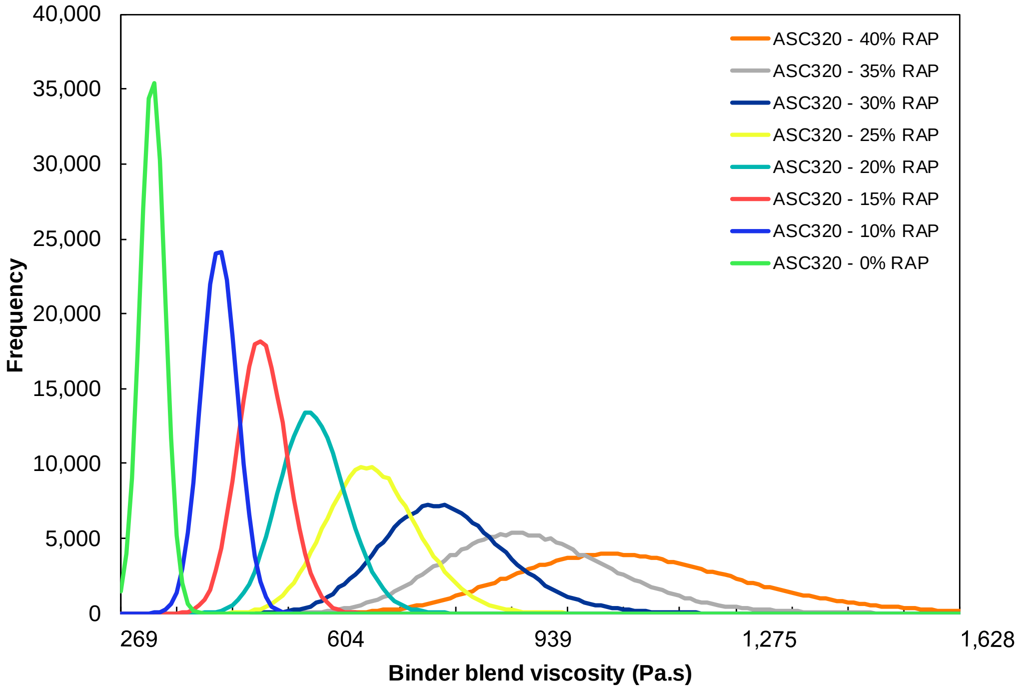


Figure G 16: Binder blend viscosity variation of all RAP, AS C450 virgin binder

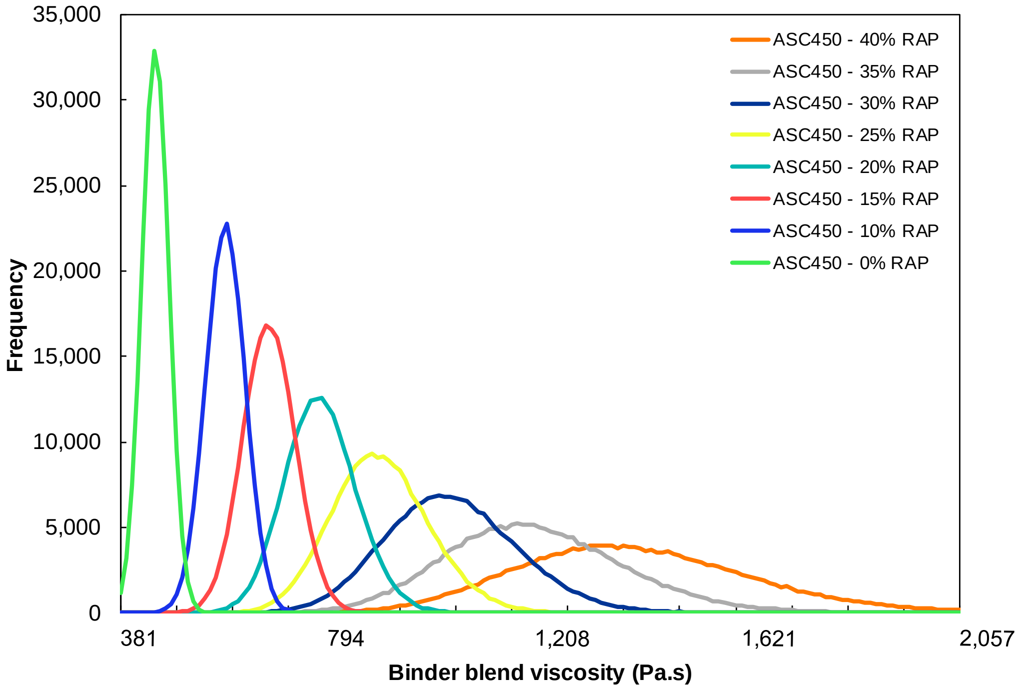


Figure G 17: Binder blend viscosity variation of all RAP, AS C600 virgin binder

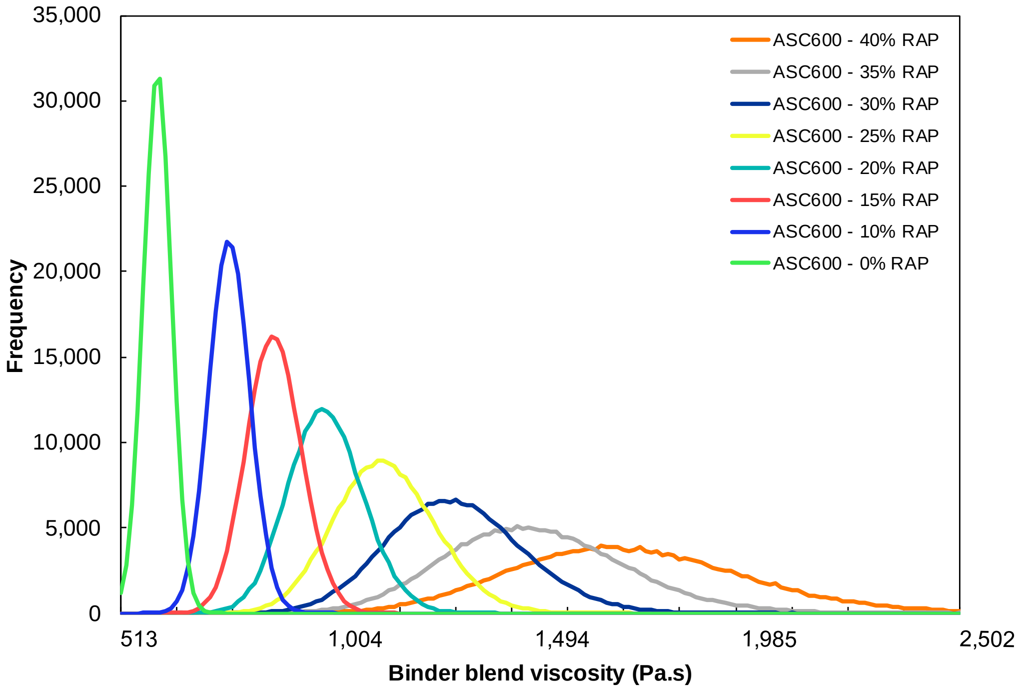


Figure G 18: Binder blend viscosity variation of all RAP, 10% RAP, AS virgin binder

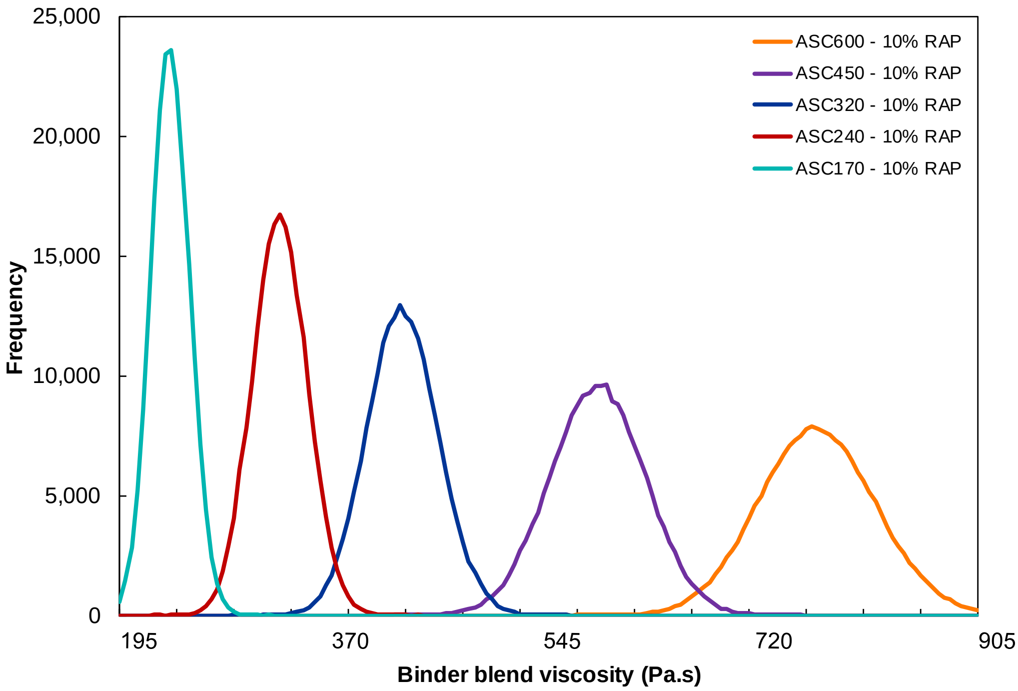


Figure G 19: Binder blend viscosity variation of all RAP, 15% RAP, AS virgin binder

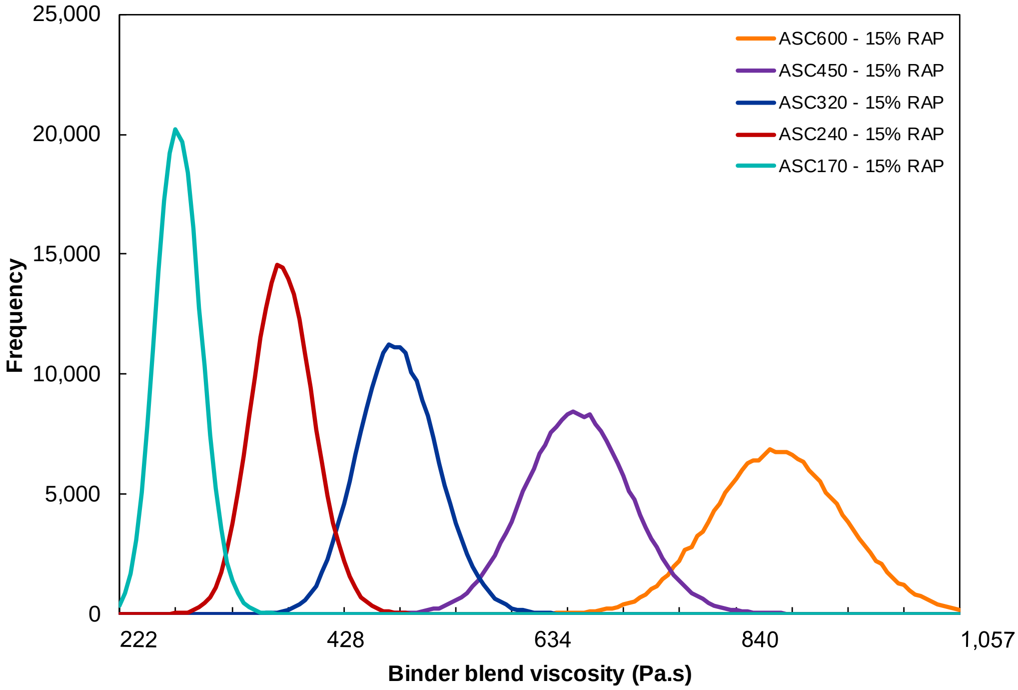


Figure G 20: Binder blend viscosity variation of all RAP, 20% RAP, AS virgin binder

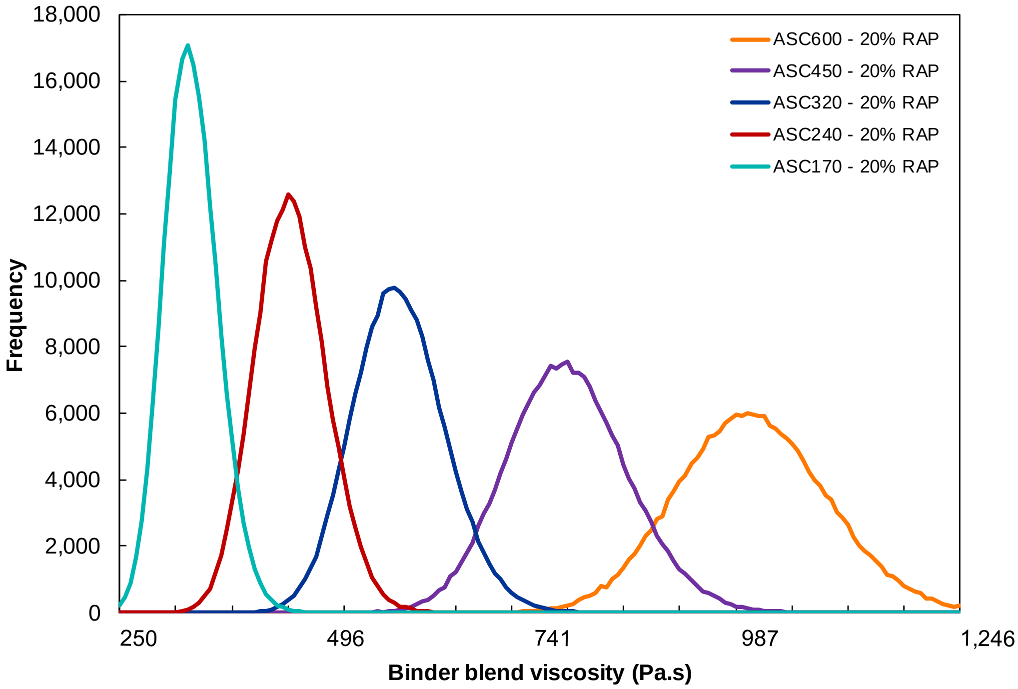


Figure G 21: Binder blend viscosity variation of all RAP, 25% RAP, AS virgin binder

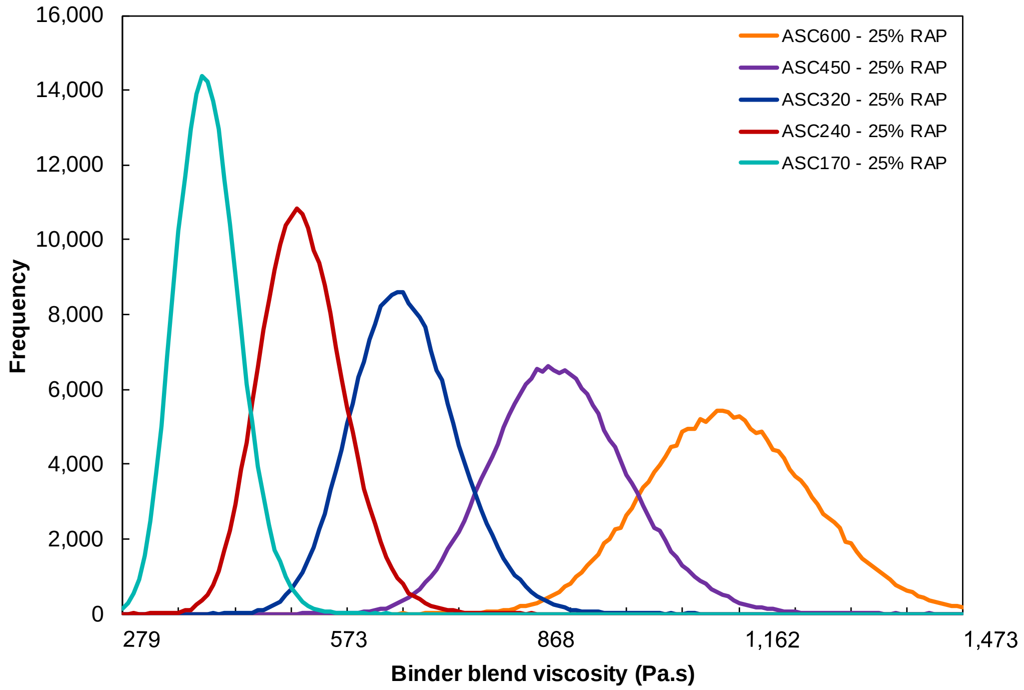


Figure G 22: Binder blend viscosity variation of all RAP, 30% RAP, AS virgin binder

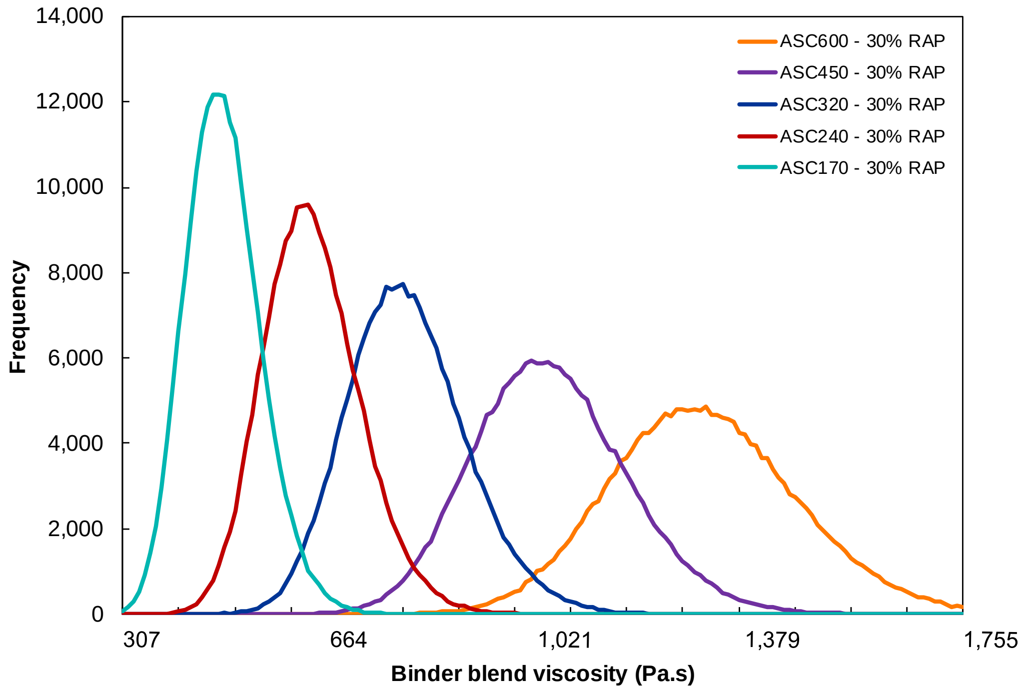


Figure G 23: Binder blend viscosity variation of all RAP, 35% RAP, AS virgin binder

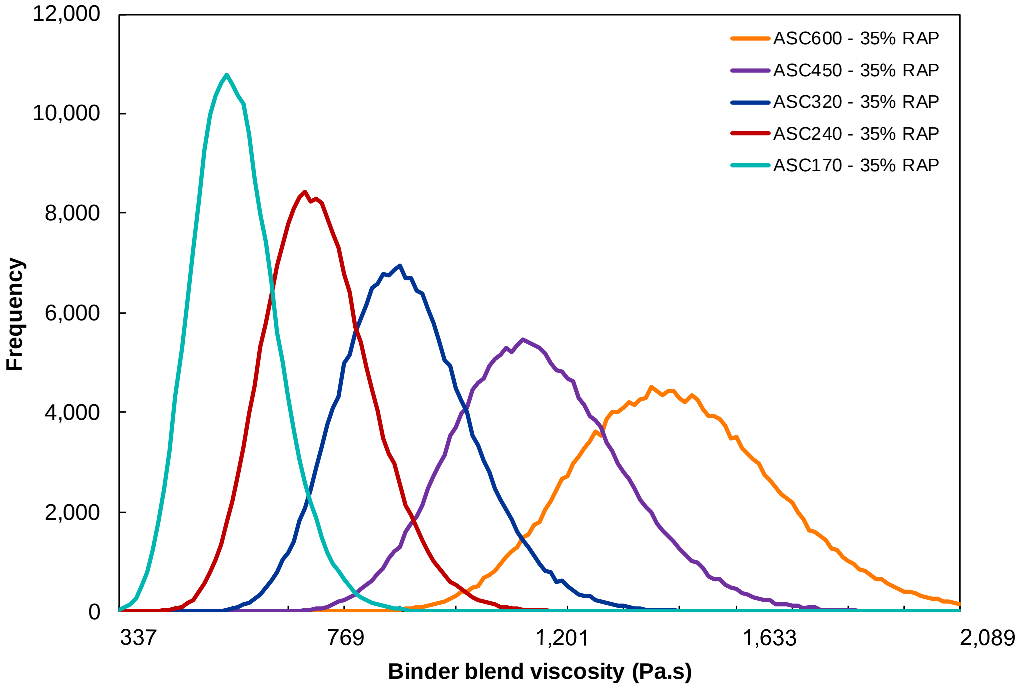
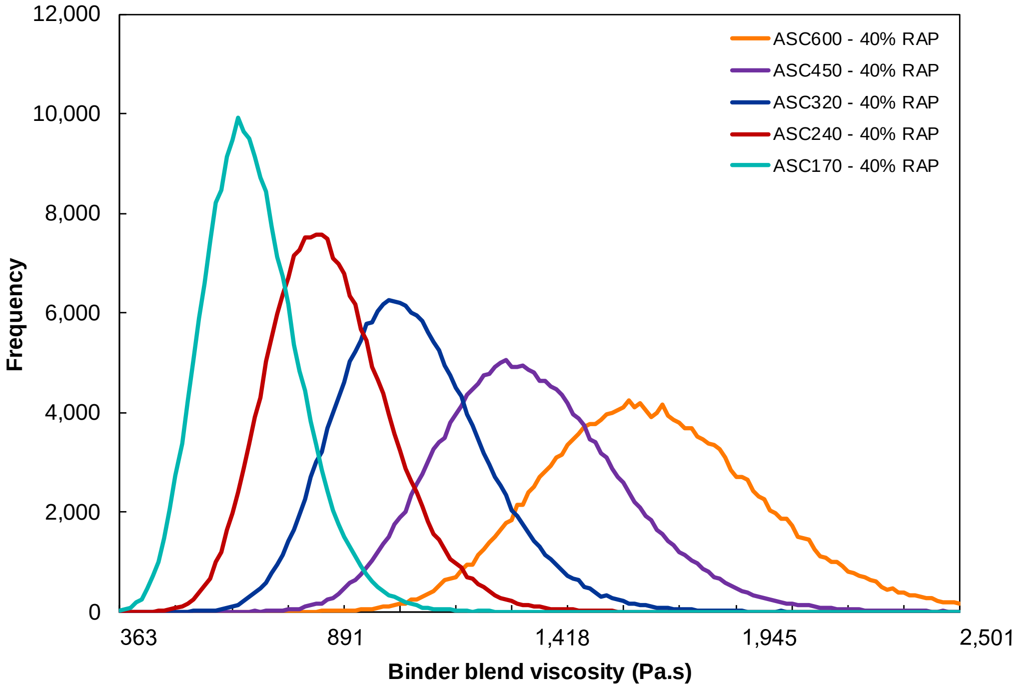


Figure G 24: Binder blend viscosity variation of all RAP, 40% RAP, AS virgin binder



APPENDIX H BINDER BLEND VISCOSITY RANGES

H.1 Equivalent Qld binder classes viscosity range

Figure H 25: Equivalent Qld C600 binder class viscosity range

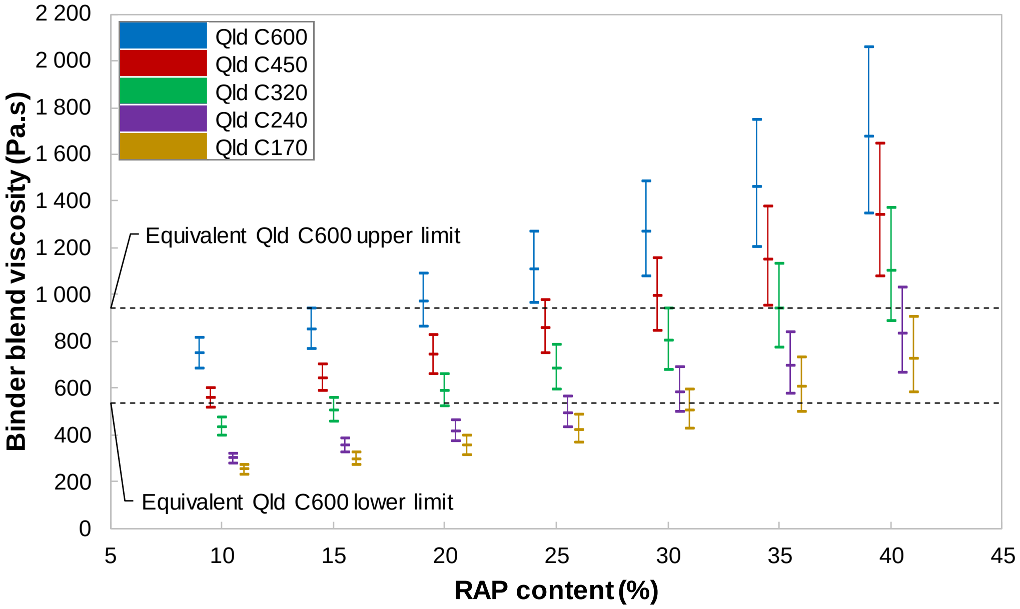


Figure H 26: Equivalent Qld C450 binder class viscosity range

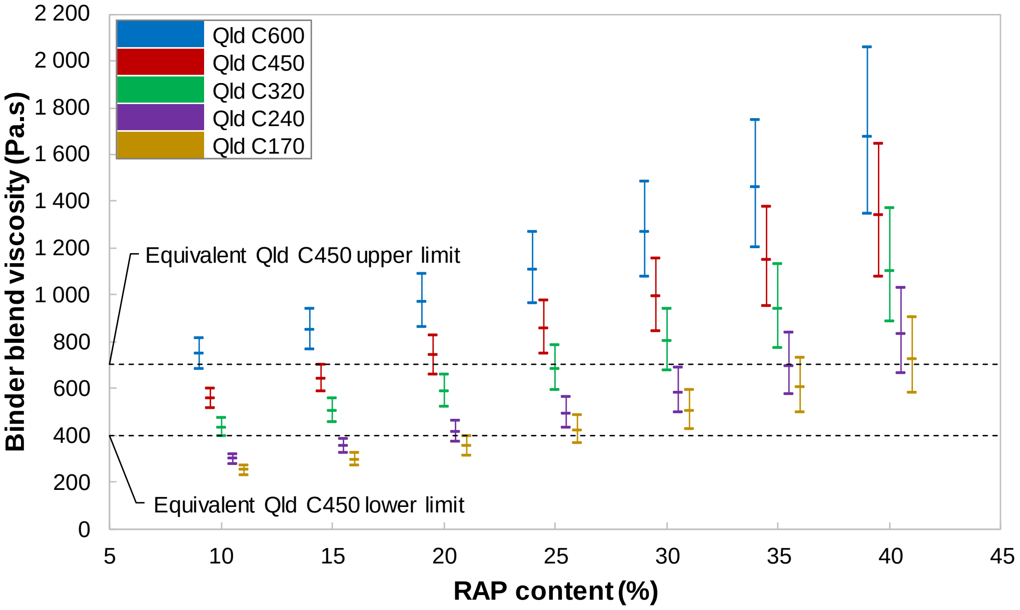


Figure H 27: Equivalent Qld C320 binder class viscosity range

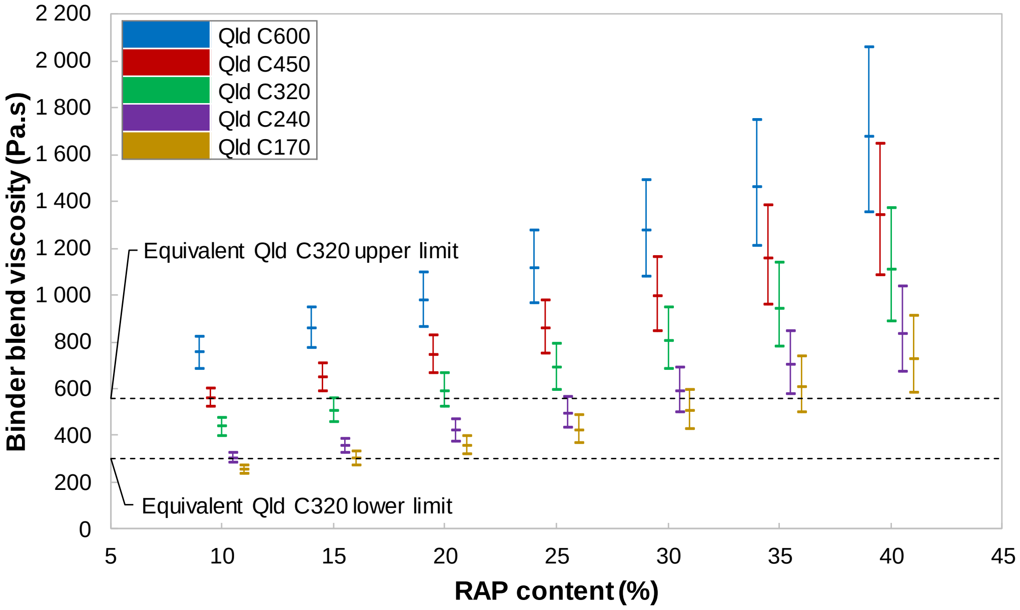


Figure H 28: Equivalent Qld C240 binder class viscosity range

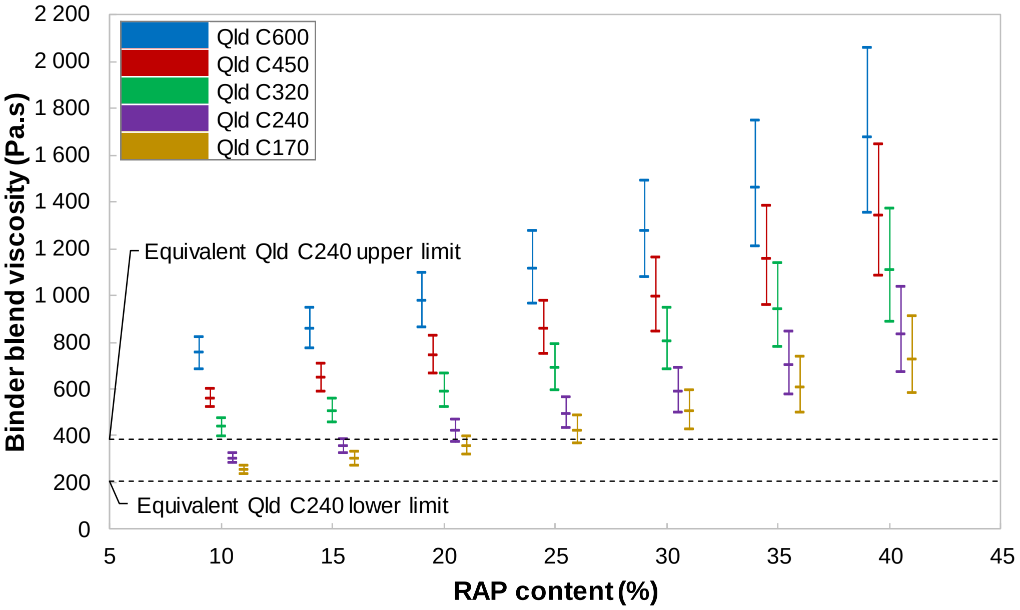


Figure H 29: Equivalent Qld C170 binder class viscosity range

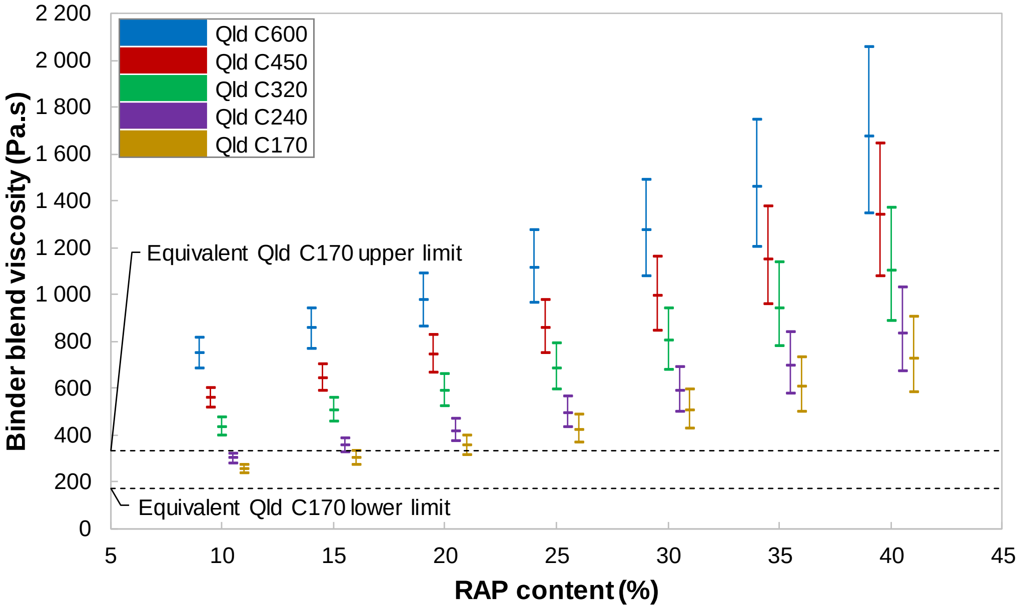
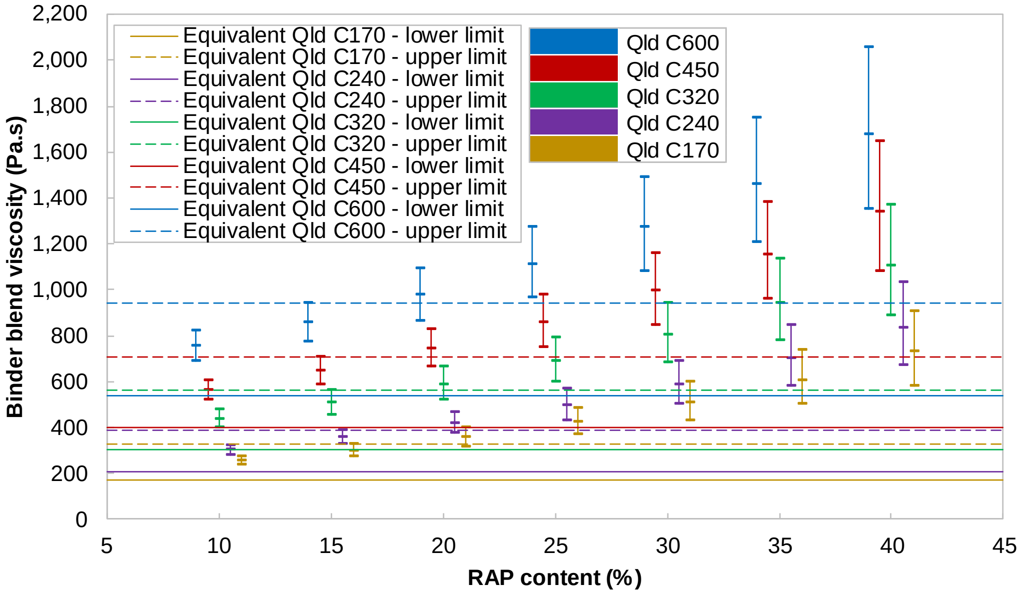


Figure H 30: Equivalent Qld binder class viscosity ranges – all classes



H.2 Equivalent AS binder classes viscosity range

Figure H 31: Equivalent AS C600 binder class viscosity range

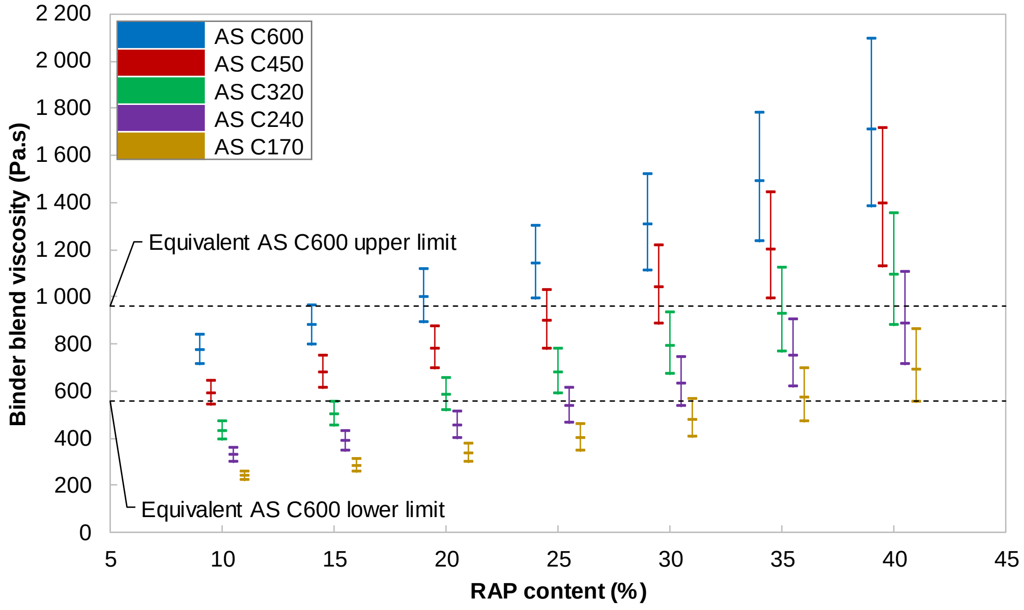


Figure H 32: Equivalent AS C450 binder class viscosity range

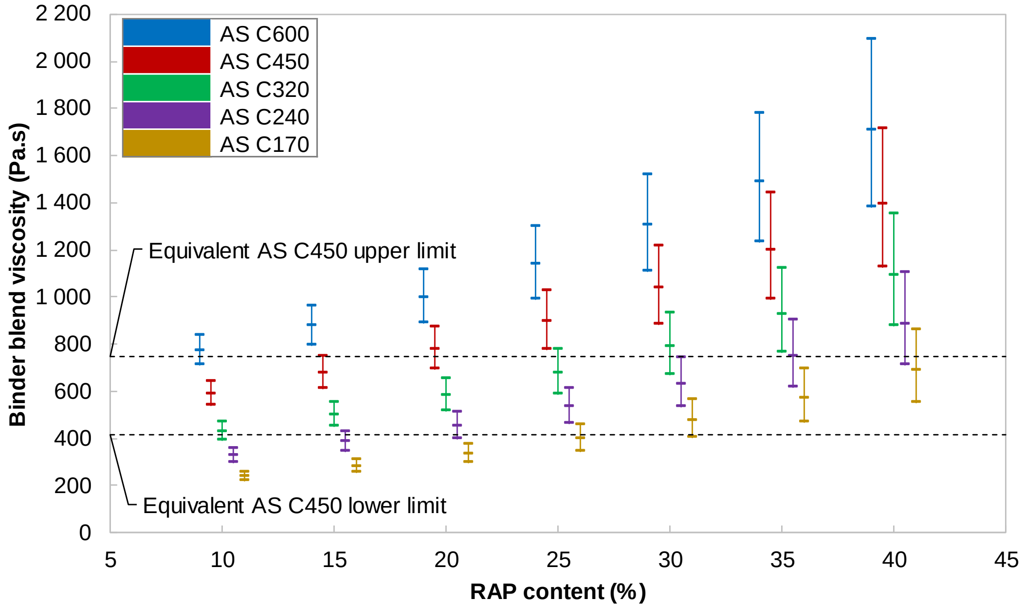


Figure H 33: Equivalent AS C320 binder class viscosity range

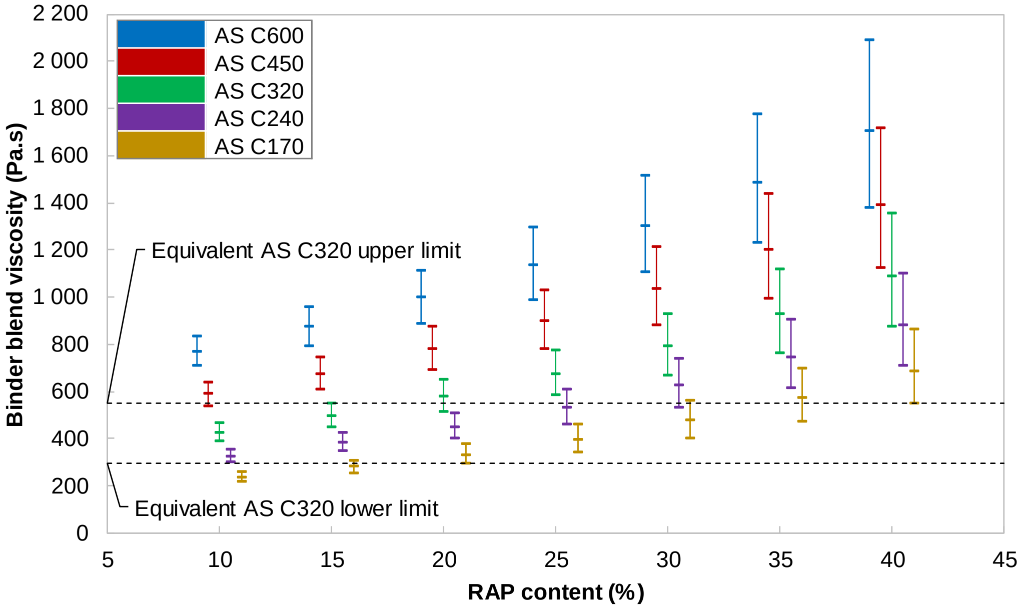


Figure H 34: Equivalent AS C240 binder class viscosity range

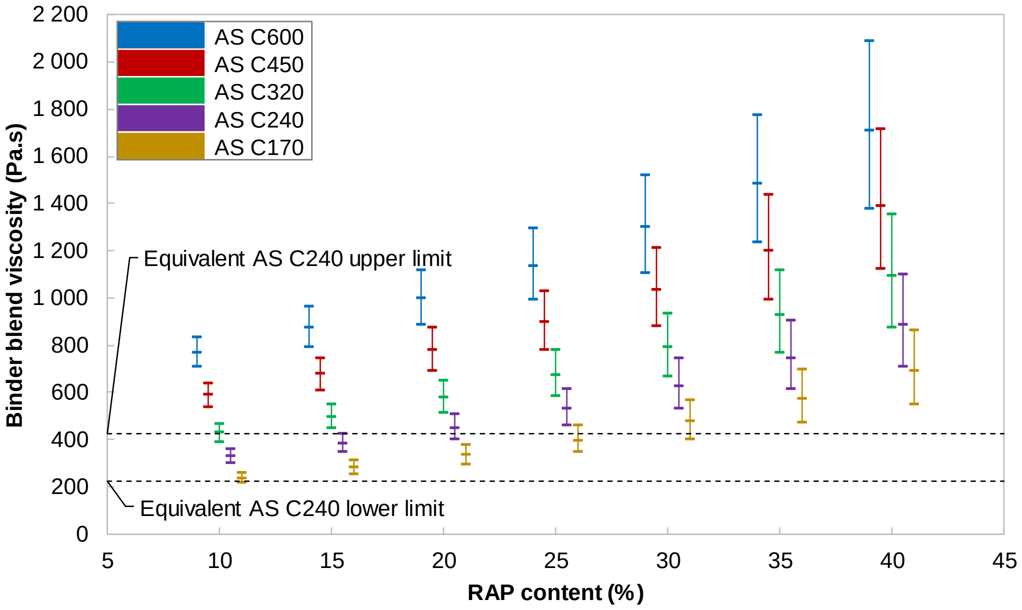


Figure H 35: Equivalent AS C170 binder class viscosity range

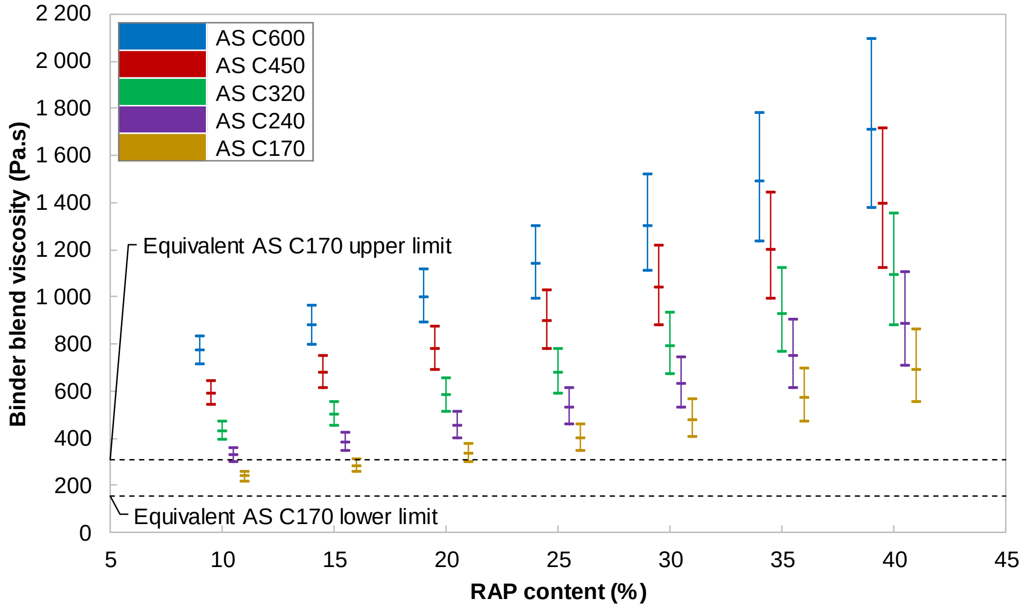
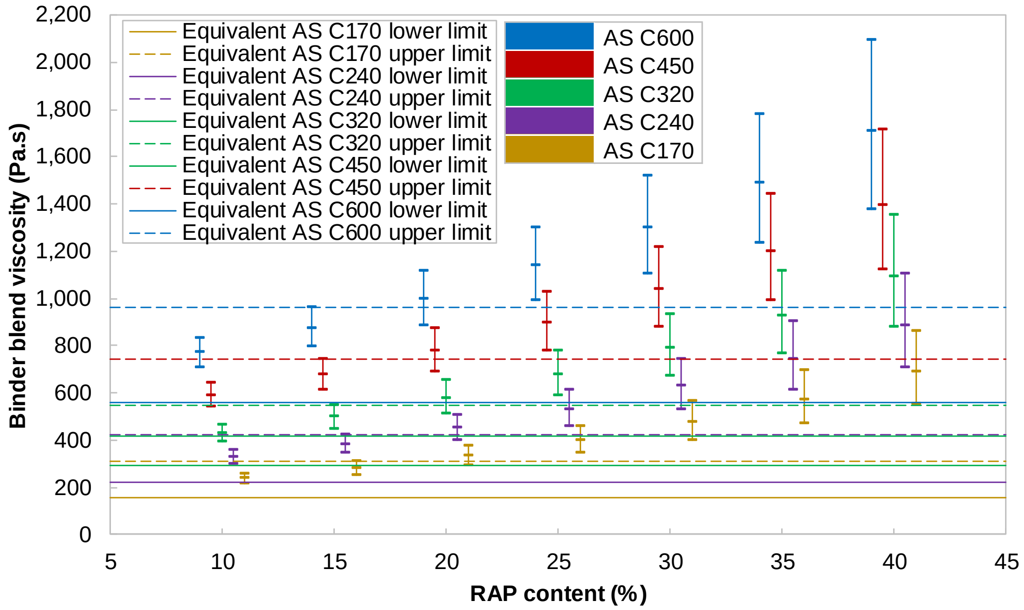


Figure H 36: Equivalent AS binder class viscosity range – all classes



APPENDIX I PROBABILITY DISTRIBUTION PARAMETERS OF ALL COMBINED RAP BINDER BLEND SCENARIOS

I.1 Binder blends containing Qld virgin binders

Table I 18: Probability distribution parameters of all RAP binder blend viscosity scenarios containing Qld virgin binders

Scenario	Lognormal probability distribution parameters			Percentile		
	Location	Mean	Std dev.	10%	50%	90%
10% RAP (all) - Qld C170 - lognormal	0.00	254.17	15.19	235	254	274
15% RAP (all) - Qld C170 - lognormal	0.00	300.96	22.05	273	300	330
20% RAP (all) - Qld C170 - lognormal	0.00	357.54	32.12	317	356	399
25% RAP (all) - Qld C170 - lognormal	5.11	426.17	46.18	369	424	487
30% RAP (all) - Qld C170 - lognormal	5.75	510.31	65.82	429	506	597
35% RAP (all) - Qld C170 - lognormal	3.34	613.07	92.28	501	606	735
40% RAP (all) - Qld C170 - lognormal	2.96	739.19	128.86	583	728	909
10% RAP (all) - Qld C240 - lognormal	0.00	302.28	16.40	281	302	323
15% RAP (all) - Qld C240 - lognormal	0.00	355.90	24.55	325	355	388
20% RAP (all) - Qld C240 - lognormal	0.00	420.02	36.23	375	419	467
25% RAP (all) - Qld C240 - lognormal	0.00	497.71	52.32	433	495	566
30% RAP (all) - Qld C240 - lognormal	0.00	591.42	74.68	499	587	689
35% RAP (all) - Qld C240 - lognormal	0.00	705.87	104.33	578	699	843
40% RAP (all) - Qld C240 - lognormal	0.00	845.00	144.22	670	833	1034
10% RAP (all) - Qld C320 - lognormal	0.00	436.71	29.92	399	436	475
15% RAP (all) - Qld C320 - lognormal	0.00	507.53	40.16	457	507	560
20% RAP (all) - Qld C320 - lognormal	0.00	591.02	55.07	522	589	663
25% RAP (all) - Qld C320 - lognormal	0.00	690.55	76.03	596	687	790
30% RAP (all) - Qld C320 - lognormal	0.00	808.64	103.73	681	803	944
35% RAP (all) - Qld C320 - lognormal	0.00	951.02	141.22	778	941	1137
40% RAP (all) - Qld C320 - lognormal	0.00	1120.42	190.08	889	1106	1371
10% RAP (all) - Qld C450 - lognormal	0.00	561.21	32.16	520	561	603
15% RAP (all) - Qld C450 - lognormal	0.00	646.13	45.08	589	645	705
20% RAP (all) - Qld C450 - lognormal	0.00	745.80	64.08	665	744	829
25% RAP (all) - Qld C450 - lognormal	0.00	862.70	89.56	750	860	979
30% RAP (all) - Qld C450 - lognormal	0.00	1000.34	122.55	847	995	1160
35% RAP (all) - Qld C450 - lognormal	0.00	1163.09	166.10	958	1153	1381
40% RAP (all) - Qld C450 - lognormal	0.00	1355.32	222.86	1082	1341	1648
10% RAP (all) - Qld C600 - lognormal	0.00	752.89	51.91	686	753	819
15% RAP (all) - Qld C600 - lognormal	0.00	856.88	67.67	771	856	944
20% RAP (all) - Qld C600 - lognormal	0.00	977.39	90.17	864	975	1094
25% RAP (all) - Qld C600 - lognormal	0.00	1117.34	120.62	966	1113	1274
30% RAP (all) - Qld C600 - lognormal	0.00	1280.29	160.63	1079	1273	1489
35% RAP (all) - Qld C600 - lognormal	0.00	1470.87	212.02	1207	1460	1747
40% RAP (all) - Qld C600 - lognormal	0.00	1692.55	278.17	1350	1675	2057

I.2 Binder blends containing AS virgin binders

Table I 19: Probability distribution parameters of all RAP binder blend viscosity scenarios containing AS virgin binders

Scenario	Lognormal probability distribution parameters			Percentile		
	Location	Mean	Std dev.	10%	50%	90%
10% RAP (all) - AS C170 - lognormal	0.00	237.04	15.76	217	237	257
15% RAP (all) - AS C170 - lognormal	0.00	281.23	22.02	254	281	310
20% RAP (all) - AS C170 - lognormal	3.67	334.92	31.45	296	333	376
25% RAP (all) - AS C170 - lognormal	0.00	400.31	44.88	345	398	459
30% RAP (all) - AS C170 - lognormal	5.65	480.41	63.58	402	476	564
35% RAP (all) - AS C170 - lognormal	11.25	578.71	88.59	471	572	696
40% RAP (all) - AS C170 - lognormal	0.00	699.57	122.62	551	689	861
10% RAP (all) - AS C240 - lognormal	0.00	327.47	22.59	299	327	357
15% RAP (all) - AS C240 - lognormal	0.00	384.42	30.71	346	384	424
20% RAP (all) - AS C240 - lognormal	0.00	452.69	42.62	399	451	508
25% RAP (all) - AS C240 - lognormal	0.00	534.34	59.57	460	532	612
30% RAP (all) - AS C240 - lognormal	0.00	633.12	82.87	531	628	742
35% RAP (all) - AS C240 - lognormal	0.00	753.32	113.86	614	745	903
40% RAP (all) - AS C240 - lognormal	0.00	897.73	155.20	709	885	1103
10% RAP (all) - AS C320 - lognormal	0.00	429.07	29.50	392	429	467
15% RAP (all) - AS C320 - lognormal	0.00	498.89	39.53	449	498	550
20% RAP (all) - AS C320 - lognormal	0.00	581.40	54.41	513	579	652
25% RAP (all) - AS C320 - lognormal	0.00	679.78	74.86	586	676	777
30% RAP (all) - AS C320 - lognormal	0.00	796.77	102.48	670	791	931
35% RAP (all) - AS C320 - lognormal	0.00	936.75	139.13	766	927	1119
40% RAP (all) - AS C320 - lognormal	0.00	1105.83	187.37	878	1091	1353
10% RAP (all) - AS C450 - lognormal	0.00	589.95	39.28	540	590	640
15% RAP (all) - AS C450 - lognormal	0.00	677.83	52.46	611	677	745
20% RAP (all) - AS C450 - lognormal	0.00	780.86	71.46	691	779	873
25% RAP (all) - AS C450 - lognormal	0.00	901.22	97.01	780	897	1028
30% RAP (all) - AS C450 - lognormal	0.00	1043.61	130.71	881	1037	1215
35% RAP (all) - AS C450 - lognormal	0.00	1209.87	175.80	993	1199	1440
40% RAP (all) - AS C450 - lognormal	0.00	1408.47	232.79	1123	1392	1715
10% RAP (all) - AS C600 - lognormal	0.00	771.54	48.33	710	771	834
15% RAP (all) - AS C600 - lognormal	0.00	877.47	65.09	795	876	962
20% RAP (all) - AS C600 - lognormal	0.00	1000.04	88.87	887	998	1115
25% RAP (all) - AS C600 - lognormal	0.00	1141.75	119.65	991	1138	1298
30% RAP (all) - AS C600 - lognormal	0.00	1308.49	160.87	1107	1302	1518
35% RAP (all) - AS C600 - lognormal	0.00	1498.31	212.82	1234	1487	1777
40% RAP (all) - AS C600 - lognormal	0.00	1724.60	279.87	1379	1708	2092