Building Local Government Road Network Asset Management and Maintenance Capability

Portable Assessment Devices

ARRB Project No.: 014801

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SUMMARY

A key factor in the performance of bituminous seals, prior to needing maintenance or replacement, is the aging characteristics of the seal itself. The ability to assess the age of in situ binders through a swift and simple technique is therefore advantageous in supporting maintenance and rehabilitation strategies across Australia's sealed road network.

Good quality asset management records may not always be available, and therefore the budgeting and planning of future works can be challenging. It is crucial that appropriate maintenance and rehabilitation programs are supported and that the correct tools and methodologies are used to help prevent serious failures of roads or erratic reallocation of resources.

The binders in a pavement surface are subjected to various environmental factors (oxygen, UV light, high temperatures and rainfall) that can contribute to its deterioration. To assist in the provision of an easy and rapid in situ test to assess the deterioration (or aging) of binders, the Department of Infrastructure, Transport, Cities and Regional Development (DITCRD) sponsored a project to assess the suitability of a portable Fourier Transform Infrared Spectroscopy (FTIR) device as a possible candidate for adoption in practice.

FTIR devices are often used to characterise the chemical composition of samples for comparison against other samples, and for the monitoring of any changes that may occur to the initial composition. In this project, the portable FTIR device was used to determine the variation in oxidation levels (i.e. aging) between samples of different ages.

Field samples of seals from local government authorities across various climatic regions around the country were collected for testing and the results used to develop oxidation-age reference curves .The infrared spectroscopy parameters and bituminous binder ageing characteristics for the different climatic zones were uniquely linked. The resultant reference curves enabled the rapid assessment of seal age in each of the studied climatic regions across Australia's widespread road network.

The ability to quickly determine seal age in the field using the portable FTIR device and the resultant reference curves, can assist road managers to manage their networks, including the development of long-term maintenance plans, the selection and prioritisation of road sections for resurfacing and resealing operations, and the budgeting of the required future work within their networks.

This report documents the development of a testing methodology for the use of the portable FTIR in the field and the determination of in situ binder ages using samples provided by governing authorities across the country. Recommendations for future work are also provided.

ACKNOWLEDGEMENTS

Thank you to Murrindindi Shire Council, Snowy Monaro Regional Council, Yorke Peninsula Council, Dorset Council, Shire of Bruce Rock, Narrandera Shire Council, Golden Plains Shire Council, Shire of Cranbrook, District Council of Coober Pedy, Access Canberra, NACOE and the Northern Territory Department of Infrastructure, Planning and Logistics for their generous provisions of sample binders from across Australia, which were instrumental in this research.

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1 INTRODUCTION

1.1 PROJECT BACKGROUND

A key factor in the performance of bituminous seals, prior to needing maintenance or replacement, is the aging characteristics of the seal itself. The ability to assess the age of in situ binders through a swift and simple technique is therefore advantageous in supporting maintenance and rehabilitation strategies across Australia's sealed road network.

Good-quality asset management records of previous construction or maintenance occurrences are not always available, and therefore budgeting and planning of future works is a challenge for road agencies and local government. It is crucial that appropriate maintenance and rehabilitation programs are supported, with the correct tools and methodologies, to ensure serious failures of roads or erratic reallocation of resources does not occur.

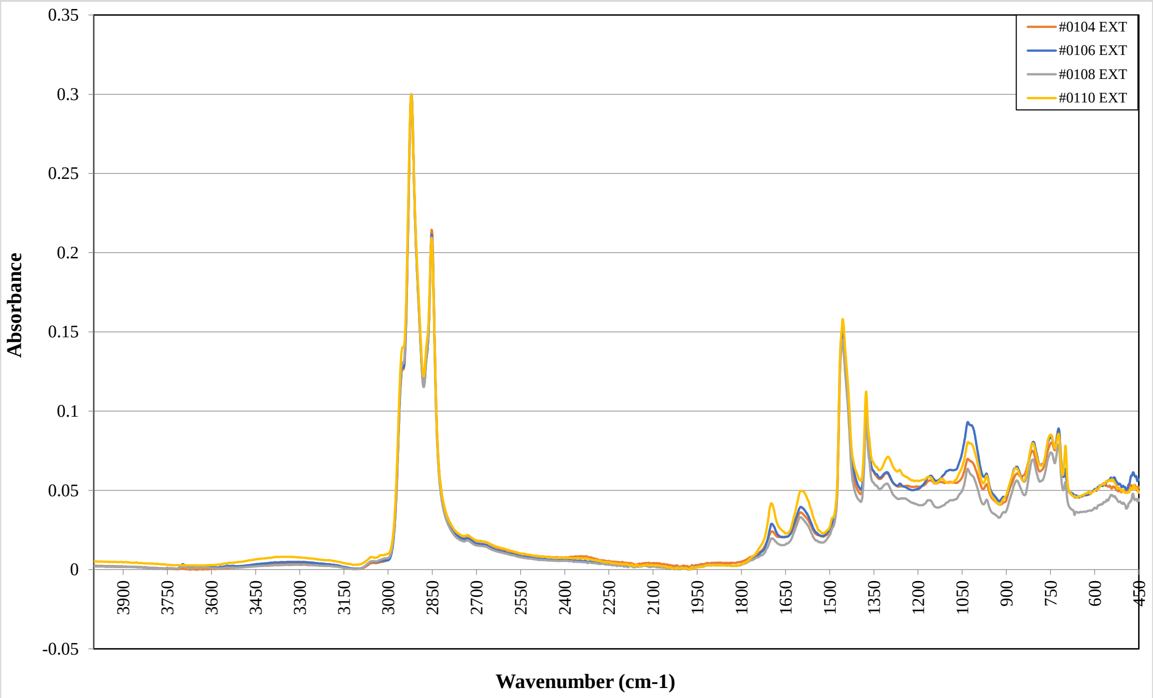
The binders used in a pavement surfacing are subjected to various environmental factors, such as oxygen, UV light, high temperatures and rain; all can contribute to the deterioration of the binder. To assist in the provision of an easy and rapid in situ test to assess the deterioration (or aging) of binders, the Department of Infrastructure, Transport, Cities and Regional Development (DITCRD) sponsored a project to assess the suitability of a portable Fourier Transform Infrared Spectroscopy (FTIR) device as a possible candidate for adoption in practice.

FTIR devices are often used to characterise the chemical composition of bituminous samples for comparison against other samples, and the monitoring of any changes that may occur to the initial composition. For this project, the characterisation of binder samples was undertaken using the portable FTIR device to determine the variation in chemical composition due to oxidation (i.e. aging), between samples of different ages, from various climatic regions across Australia.

1.2 UNDERSTANDING FTIR

FTIR is a technique used to obtain a spectrum (Figure 1.1) of the infrared absorption (or emission) of a compound, either solid, liquid or gas. Each peak shown on the spectra corresponds to a different chemical bond within the sample compound, as different bond types absorb infrared light at different frequencies. In Figure 1.1, the vertical axis shows infrared absorbance, while the horizontal axis depicts the different frequencies (as a wavelength or wavenumber) of the infrared light.

Figure 1.1 Fourier-transform infrared spectrum



2 METHODOLOGY

2.1 EXPERIMENTAL DESIGN

The modelling of the binder oxidation-to-seal age relationship was the focus of the experimental design in this project. As binders are exposed to environmental factors over time, they begin to experience aging via oxidation. This oxidation of the binder is identifiable in the FTIR spectrum, using the carbonyl peak that occurs at a wavenumber of approximately 1,700 cm^{-1}. The more oxidised a binder is, the larger this peak will be. It therefore makes it possible to correlate the age (in years) of a binder to the area beneath this peak.

For this project, samples of known[1] ages were collected from across Australia and their level of oxidation was analysed using a portable FTIR device. This device is portable and allows for quick, field analysis of samples, and has limited, if any, laboratory-condition requirements for operation. The development and validation of the testing methodology and subsequent results were conducted in the laboratory, however the testing procedure was conducted to mimic that expected in the field. The results were then validated using alternative laboratory testing (e.g. viscosity and stress ratio assessment using the Dynamic Shear Rheometer (DSR)).

The results obtained from the FTIR testing were used to develop reference curves relating binder age to carbonyl peak area for each supplier (covering various climatic regions). Using this information, the age of unknown samples could be calculated. The ease of device use, along with the reference curves, will ensure access to useful and robust seal age data is available for local government authorities (LGAs) without demanding extensive resources.

2.2 SAMPLE COLLECTION

As environmental factors (oxidation, UV exposure, air temperature and rainfall) play a part in the ageing process, samples were collected from multiple climatic regions across Australia so that reference curves applicable to the different regions could be developed.

To assess the relationship between carbonyl peak area and age, samples were collected for three-to-four age groups, for each of the 14 participating regions across Australia (shown in Figure 2.1[2]).

Seal samples were provided as either core samples or A4-sized slabs, covering the following age brackets:

a. Fresh binder (up to three years old)
b. Intermediate I (between three to ten years old)
c. Intermediate II (between ten to 15 years old)
d. End of life (15+ years old).

For a robust reference curve to be developed, at least three values from three different age groups that have the same type of binder and location were required.

Upon receipt, samples were photographed, numbered and assigned a sample reference ID. Binder extraction, in line with Austroads Test Method AGPT/T191-15, was then carried out to isolate the binder from the provided cores/slabs. Some sample duplicates were retained as is (i.e. not extracted), in order to take subsamples for testing directly from the sample pavement surface (mimicking field sampling).

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1 Received samples were accompanied by information from the suppliers, including the seal age. In some cases, the ages were noted by the supplier as "best estimates", whilst in others it was determined that the provided age was inaccurate. To help inform whether the provided/estimated ages were reliable or not, other laboratory processes for binder age determination were used, such as the Dynamic Shear Rheometer (DSR), and visual/tactile physical assessment (e.g. noting how brittle or soft the binder was).

2 For Queensland three general regions were represented in the project. However, as samples were initially collected for a NACOE project, they were not necessarily obtained from specific LGAs; as such Figure 2.1 therefore shows the variety of locations within Queensland where samples were obtained.

Figure 2.1 Sample locations

Source: Google Maps, 2020.

In addition to the samples received from government agencies, stored bitumen samples from ARRB with different ages were tested. These ARRB samples, with recorded storage years from 1972 until 2019, are presented in Table A.1, where changes in oxidation of these stored samples over time can be seen.

2.3 INSTRUMENT CALIBRATION

As a new portable FTIR device was to be used for most of the sample analysis, the results were compared to a currently used, desktop (laboratory-based) FTIR device to determine if a calibration factor was required.

Extracted binders (both PMB and C170) from Queensland samples were selected and analysed for this calibration process. The correlation, reported in Table A.2, was over 0.99 for all samples. As such, it was determined that no calibration factor was required for the portable device.

2.4 KNOWN AGE VALIDATION

To validate the age information accompanying each of the provided samples, two tests were carried out. All field samples provided had the binder extracted in accordance with Austroads Test Method AGPT/T191-15. This process provided enough binder so that FTIR testing could be done in conjunction with determining the complex viscosity at 45°C and the stress ratio at 15°C in line with Austroads Test Method AGPT/T125-18 using a DSR. The DSR validation tests provided an opportunity to determine if the stated age of each sample was accurate to ensure accuracy in further analysis. Comparison of complex viscosity, stress ratio and the FTIR results are discussed in Section 3.

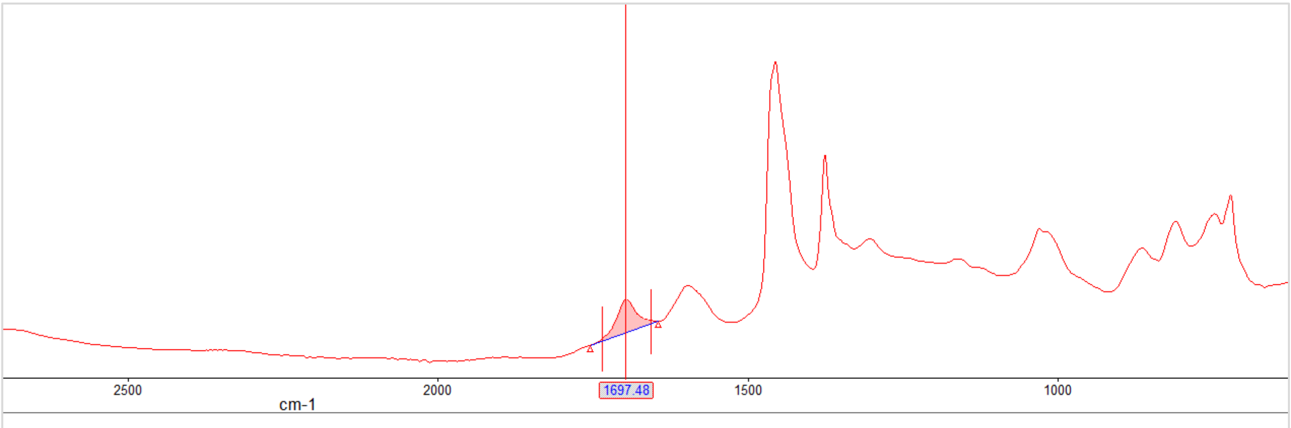
2.5 REFERENCE CURVE DEVELOPMENT

For each climatic region, three samples from at least three age groups were required. If, for some locations, insufficient samples were available, a reference curve was not developed. The results are discussed in Sections 3 and 4.

The following procedure for the development of the reference curves was followed:

1. Two FTIR readings were obtained for each sample, including a 'field' reading from binder samples taken directly from the core or slab, and a 'lab' reading using the extracted binder.
2. The field and lab FTIR outputs were normalised for the lowest ordinate value for each set of samples using the device's infrared (IR) software.
3. The area under the peak of interest on the spectra for each sample was calculated, which in this case is the carbonyl peak area. The area was calculated using the IR software by selecting the highest and lowest limits of the carbonyl peak (1754.4 cm^{-1} and 1645.4 cm^{-1}), and the start and the end of the selected area (1737.9 cm^{-1} and 1656.5 cm^{-1}), as shown in Figure 2.2.

Figure 2.2 Calculation of carbonyl peak area



4. The Beer's Law function (provided in the IR software) was used to fit the regression model. This calculates the quantities of each property or component in a multi-component sample to generate a regression equation that links the height or the peak area with the property value of a set of standard spectra. The software was used to develop relationships linking the FTIR absorbance (area under the carbonyl peak at wavenumber 1697 cm^{-1}) to the known ages (in years) of the binder samples.
5. Different curves were developed depending on the samples and the information provided, including:
   a. different analysis types:
      i. laboratory (extracted binder)
      ii. field (directly taken from core/slab)
   b. different binder types:
      i. modified (PMB)
      ii. unmodified (C170)
   c. sample locations[3]:
      d. WP – within wheelpath (some samples are then separated as inner WP (right), or outer WP (left))
      e. OWP – outside of/not within either wheelpath
      f. All – combination of inside and outside the wheelpath.

The IR software was used to normalise the outputs, calculate the carbonyl area and develop the reference curves. Excel software was then used to plot all outputs and results. In addition, Excel and SPSS software were used to develop the models and test the correlation of the reference curves to ensure the IR software results were reliable; this analysis is provided in Appendix B.

[3] It is highlighted here for the sample locations that the commonly used acronyms of IWP and OWP were not used in relation to inner and outer wheelpaths, due to the use of OWP referring to "Outside the Wheelpath" for this document.

2.6 REFERENCE LIBRARY DEVELOPMENT FOR STORED BITUMENS

A similar approach was adopted for obtaining a library of FTIR reference spectra for a range of stored Australian bitumens. The same steps, with a few exceptions, as outlined in Section 2.5, were applied to 26 stored binder samples, covering three binder classes (Figure 2.3).

In this study, samples were unused binders (i.e. no field samples, or need for lab-based extraction, and no sample location in reference to the wheelpath), which had been obtained between 1981 and 2019, and kept in air-tight tins. Details of the library of the stored binder samples are provided in Table A.1and Table 2.1.

Table 2.1 Library of stored binder samples

Sample #	Year	Age	Binder class	Sample #	Year	Age	Binder class
1	1981	38	C160	**14**	2006	13	C170
2	1983	36	C170	**15**	2014	5	C600
3	1983	36	C170	**16**	2006	13	C320
4	1986	33	C170	**17**	2007	12	C170
5	1992	27	C320	**18**	2007	12	C320
6	1992	27	C170	**19**	2008	11	C170
7	1995	24	C170	**20**	2018	1	C170
8	1996	23	C170	**21**	2018	1	C600
9	1997	22	C600	**22**	1992	27	C170
10	1998	21	C320	**23**	2007	12	C320
11	1981	38	C170	**24**	2017	3	C320
12	1985	34	C170	**25**	2019	1	C320
13	1998	21	C170	**26**	2019	1	C170

2.6.1 BITUMEN LIBRARY RESULTS[4]

The analysis of the FTIR results for the stored samples provided the reference curve models listed in Table 2.2. The trends of the three binder types are shown in Figure 2.3, where the reference curves and FTIR data is plotted.

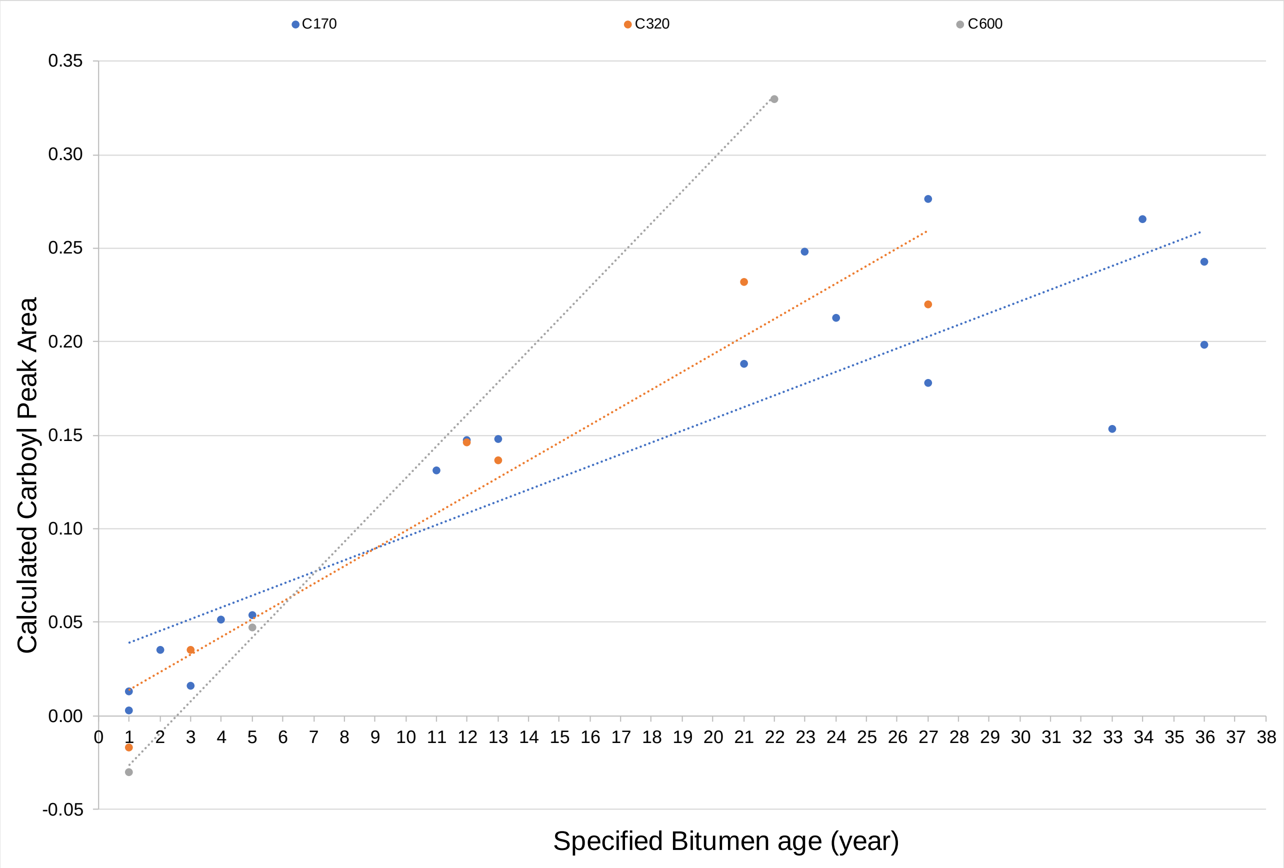
Table 2.2 Details of reference curves for different binder types from stored samples

Binder Class	Reference curve	Comments		
C170	Y = 0.0063 * AGE + 0.0330	R^2=0.89	SE=7.04	18 SAMPLES
C320	Y = 0.0095 * AGE + 0.0037	R^2= 0.96	SE=5.44	6 SAMPLES
C600	Y = 0.0170 * AGE – 0.0430	R^2= 0.99	SE=0.38	3 SAMPLES

Y = Carbonyl area. *AGE = Binder age.* *R^2 = Correlation coefficient.* *SE = Standard Error.*

4 It is important to note that, as these binders were kept in air-tight tins, the level of oxidation is minimal. As such, the carbonyl peak areas will be much lower than those calculated for seal samples obtained from around the country, even for the same age (i.e. a stored sample 33 years old will show an carbonyl peak area of a similar size to that of a ~0-3 years old seal sample).

Figure 2.3 Developed FTIR reference curves for different binder types from stored samples



3 RESULTS

Figure 3.1 and Figure 3.2 show reference curves for each region for the laboratory and field samples respectively. Further details are provided in Table B.1.

Figure 3.1 Relationship between specified age and carbonyl peak area for all lab samples

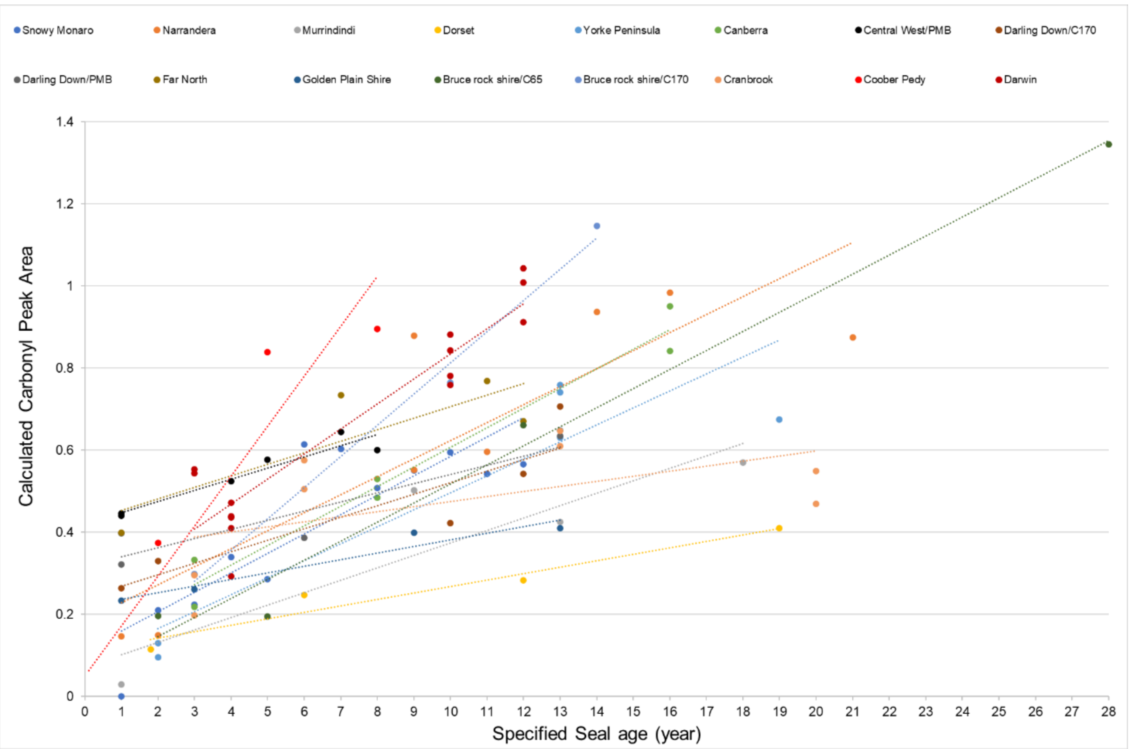
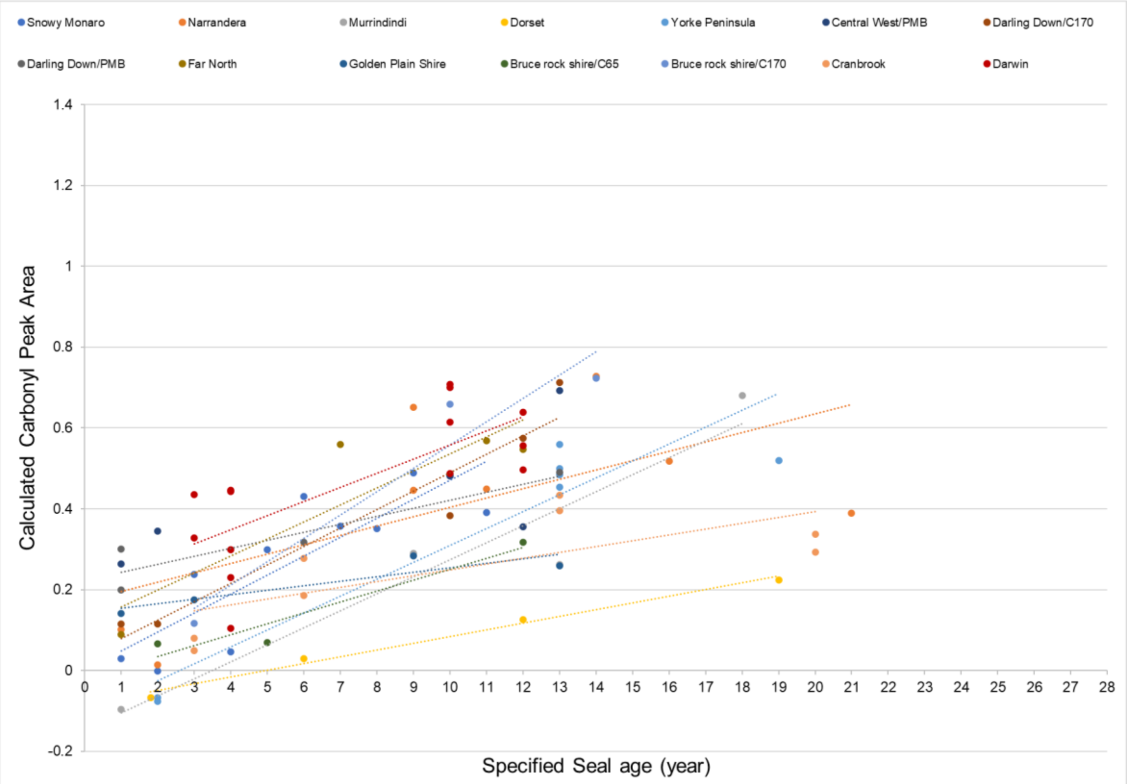


Figure 3.2 Relationship between specified age and carbonyl peak area for all field samples



Section 3.1 to Section 3.14 discuss the laboratory and field analysis of the samples collected from all 14 regions. The analysis includes the age validation tests, complex viscosity and stress ratio, as well as the calculated area under the carbonyl peak. Some of the results were consistent with an age or binder type notably different to those specified by the supplier; each occurrence of such a discrepancy is discussed. Highly-aged samples occasionally failed the stress ratio test or were unable to be sampled as field samples for FTIR testing. This is due to the hard and brittle nature of such aged binders. In such cases, the samples are recorded as having "Failed" the test.

Further details for each region's reference curves, and the FTIR spectra, are presented in Appendix B.

For the sample locations given in sections 3.1 to 3.14, OWP refers to samples taken outside of either wheelpath, while WP refers to those taken within a wheelpath (either inner or outer). Regarding the latter, the inner or outer wheelpath is only specified where such information was provided with received samples.

3.1 SNOWY MONARO (ALPINE), NSW

The sample information and test results for Snowy Monaro are shown in Table 3.1, while the sample analysis and calculated age for the lab and field samples are shown in Table 3.2 and Table 3.3 respectively.

Sample #0121 was excluded from further analysis as validation analysis using the DSR estimated the sample as between eight and 16 years of age, which was notably different from the specified age of four years.

Samples #006 to #0010 were identified in the FTIR spectra as polymer modified binders (PMBs) due to the presence of additional peaks at 966 cm^{-1} and 699 cm^{-1}; known to be present in PMBs) as opposed to the stated Class 170 (C170). They were therefore excluded from the analysis of the C170 sample results.

Table 3.1: Sample information and test results – Snowy Monaro

ARRB ID	Sample location	Specified age (years)	Log complex viscosity at 45°C	Stress ratio at 15°C	Area under the carbonyl peak – lab	Area under the carbonyl peak – field
#001	Inner WP	~3	4.4113	0.9039	0.2101	0.0299
#002	OWP	~3	4.3634	0.8850	extra sample	
#003	OWP	~3	4.4363	0.8848	0.2236	–0.0012
#004	Inner WP	~3	4.4890	0.8671	0.3399	0.2375
#005	WP	~3	4.5216	0.8975	0.2858	0.0468
#006	WP	~5	4.6946	1.0548	Excluded (found to be PMB)	
#007	OWP	~5	4.5477	1.1987		
#008	OWP	~5	4.5505	1.2968		
#009	WP	~5	4.6779	1.1657		
#0010	WP	~5	4.6490	1.2436		
#0011	WP	~12	5.4293	0.8809	0.6025	0.4302
#0012	OWP	~12	5.3575	0.8757	0.5081	0.3566
#0013	OWP	~12	5.3425	0.8590	0.5509	0.3509
#0016	OWP	~15	5.2344	0.8569	0.5943	0.4883
#0017	WP	~15	5.1894	0.8620	0.5417	0.4821
#0018	WP	~15	5.1486	0.8392	0.5652	0.3906
#0121	Unknown	4	5.0528	0.8683	0.6142	0.2982

Table 3.2: Sample analysis and calculated age – Snowy Monaro – lab

ARRB ID	Sample location	Specified age (years)	Calculated age (years) – OWP/WP	Residual	Calculated age (years) – all	Residual
#001	Inner WP	3	-0.0018	3.0018	0.7024	2.2976
#003	OWP	3	2.8143	0.1857	1.2049	1.7951
#004	Inner WP	3	5.1120	–2.1120	5.5095	–2.5095
#005	WP	3	2.9872	0.0128	3.5076	–0.5076
#0011	WP	12	15.6101	–3.6101	15.2350	–3.2350
#0012	OWP	12	11.7072	0.2928	11.7404	0.2597
#0013	OWP	12	13.0355	–1.0355	13.3274	–1.3274
#0016	OWP	15	14.4430	0.5570	14.9333	0.0667
#0017	WP	15	13.2128	1.7872	12.9841	2.0159
#0018	WP	15	14.0796	0.9204	13.8556	1.1444

Table 3.3: Sample analysis and calculated age – Snowy Monaro – field

ARRB ID	Sample location	Specified age (years)	Calculated age (years) – OWP/WP	Residual	Calculated age (years) – all	Residual
#001	Inner WP	3	0.2723	2.7277	1.4113	1.5887
#003	OWP	3	3.0674	–0.0674	0.4334	2.5666
#004	Inner WP	3	7.3642	–4.3642	7.9292	–4.9292
#005	WP	3	0.8595	2.1405	1.9423	1.0577
#0011	WP	12	14.0162	–2.0162	13.9776	–1.9776
#0012	OWP	12	11.9351	0.0649	11.6670	0.3330
#0013	OWP	12	11.7952	0.2048	11.4904	0.5096
#0016	OWP	15	15.2023	–0.2023	15.8029	–0.8030
#0017	WP	15	15.8576	–0.8576	15.6099	–0.6099
#0018	WP	15	12.6303	2.3697	12.7359	2.2641

3.2 NARRANDERA, NSW

The sample information and test results for Narrandera are shown in Table 3.4, while the sample analysis and calculated ages are shown in Table 3.5.

The DSR values (complex viscosity and stress ratio) for the lab samples were obtained from Roberts *et al.* (2018).

Table 3.4: Sample information and test results – Narrandera

ARRB ID	Sample location	Specified age (years)	Log complex viscosity at 45°C	Stress ratio at 15°C	Area under the carbonyl peak – lab	Area under the carbonyl peak – field
#0073	OWP	1	3.9374	0.9080	0.1463	0.1011
#0074	OWP	2	4.1809	0.8679	0.1491	0.0146
#0075	OWP	9	5.4837	0.8423	0.8786	0.6512
#0076	OWP	9	4.6905	0.8442	0.5518	0.4465
#0077	OWP	11	5.1579	0.8167	0.5966	0.4494
#0078	OWP	14	5.2391	0.8365	0.9374	0.7277
#0079	OWP	16	5.0394	0.7779	0.9842	0.518
#0080	OWP	21	5.5064	0.8404	0.8747	0.39

Table 3.5: Sample analysis and calculated age – Narrandera

ARRB ID	Sample location	Specified age (years)	Calculated age (years) – field	Residual	Calculated age (years) – lab	Residual
#0073	OWP	1	0.4269	0.5731	–0.7311	1.7311
#0074	OWP	2	0.4892	1.5108	–4.2539	6.2539
#0076	OWP	9	9.3809	–0.3809	13.3394	–4.3394
#0077	OWP	11	10.3690	0.6310	13.4550	–2.4550
#0078	OWP	14	17.8953	–3.8953	24.7958	–10.7958
#0079	OWP	16	18.9277	–2.9277	16.2505	–0.2505
#0080	OWP	21	16.5109	4.4891	11.1443	9.8557

3.3 GOLDEN PLAINS, VIC

The sample information and test results for Golden Plains are shown in Table 3.6, while the sample analysis and calculated ages are shown in Table 3.7.

Table 3.6: Sample information and test results – Golden Plains

ARRB ID	Sample location	Specified age (years)	Log complex viscosity at 45°C	Stress ratio at 15°C	Area under the carbonyl peak – lab	Area under the carbonyl peak – field
#0022	WP	1	4.121	1.0861	0.2334	0.1408
#0037	WP	3	3.8807	1.0267	0.2612	0.1749
#0027	WP	9	4.6949	0.9257	0.3983	0.2837
#0032	WP	13	4.5311	0.8848	0.4100	0.2597

Table 3.7: Sample analysis and calculated age – Golden Plains

ARRB ID	Sample location	Specified age (years)	Calculated age (years) – field	Residual	Calculated age (years) – lab	Residual
#0022	WP	1	–0.1626	1.1626	0.8945	0.1055
#0037	WP	3	2.9147	0.0853	2.5163	0.4837
#0027	WP	9	12.7009	–3.7009	10.5257	–1.5257
#0032	WP	13	10.5469	2.4531	12.0635	0.9365

3.4 MURRINDINDI (ALPINE), VIC

The sample information and test results for Murrindindi (Alpine) are shown in Table 3.8, while the sample analysis and calculated ages are shown in Table 3.9. Despite being reported as older, sample #0069 required less stress to be sheared than samples in the Intermediate I and II age groups (Table 3.8). The exact reason for this is as yet unknown.

Table 3.8: Sample information and test results – Murrindindi

ARRB ID	Sample location	Specified age (years)	Log complex viscosity at 45°C	Stress ratio at 15°C	Area under the carbonyl peak – lab	Area under the carbonyl peak – field
#0072	WP	1	3.4253	1.0130	0.0288	–0.0954
#0070	WP	9	4.7707	0.9078	0.5029	0.2900
#0071	WP	13	4.8101	0.8513	0.4246	0.2617
#0069	WP	18	4.7332	0.7994	0.5700	0.6800

Table 3.9: Sample analysis and calculated age – Murrindindi

ARRB ID	Sample location	Specified age (years)	Calculated age (years) – field	Residual	Calculated age (years) – lab	Residual
#0072	WP	1	1.2452	–0.2452	–1.3992	2.3992
#0070	WP	9	10.3707	–1.3707	14.2657	–5.2657
#0071	WP	13	9.6992	3.3008	11.6789	1.3211
#0069	WP	18	19.6849	–1.6849	16.4545	1.5455

3.5 DORSET, TAS

The sample information and test results for Murrindindi (Alpine) are shown in Table 3.10, while the sample analysis and calculated ages are shown in Table 3.11.

Table 3.10: Sample information and test results – Dorset

ARRB ID	Specified age (years)	Log complex viscosity at 45°C	Stress ratio at 15°C	Area under the carbonyl peak – lab	Area under the carbonyl peak – field
#0043	1.8	3.9835	0.9781	0.1145	–0.0669
#0042	6	4.4103	1.0245	0.2475	0.0298
#0041	12	4.5776	0.8998	0.2834	0.1265
#0044	19	4.7326	0.8702	0.4093	0.2242

Table 3.11: Sample analysis and calculated age – Dorset

ARRB ID	Specified age (years)	Calculated age (years) – field	Residual	Calculated age (years) – lab	Residual
#0041	12	12.5927	–0.5927	10.9562	1.0439
#0042	6	6.7807	–0.7807	8.6728	–2.6728
#0043	1.8	0.9687	0.8313	0.2047	1.5954
#0044	19	18.4579	0.5422	18.9664	0.0336

3.6 YORKE PENINSULA, SA

The sample information and test results for the Yorke Peninsula are shown in Table 3.12, while the sample analysis and calculated ages for the lab and field are shown in Table 3.13 and Table 3.14 respectively. Samples of the Intermediate I age group (#0047 and #0118) were found to be PMBs so they were excluded from the analysis of the remaining C170 samples. As such, they are not reported.

Table 3.12: Sample information and test results – Yorke Peninsula

ARRB ID	Sample location	Specified age (years)	Log complex viscosity at 45°C	Stress ratio at 15°C	Area under the carbonyl peak – lab	Area under the carbonyl peak – field
#0119	Inner WP	2	4.2380	0.9253	0.0955	–0.0663
#0120	OWP	2	4.5191	0.9038	0.1297	–0.0755
#0116	Inner WP	13	5.7087	Failed	0.7588	0.4991
#0045	OWP	13	5.4786	Failed	0.7414	0.5593
#0117	Inner WP	13	5.4372	Failed	0.6307	0.4542
#0046	OWP	13	5.4558	Failed	0.6481	0.4842
#0048	Inner WP	19	5.0564	0.8423	0.4869	0.2354
#0049	OWP	19	5.3999	0.9032	0.6746	0.5201

Table 3.13: Sample analysis and calculated age – Yorke Peninsula – lab

ARRB ID	Sample location	Specified age (years)	Calculated age (years) – OWP/WP	Residual	Calculated age (years) – all	Residual
#0120	OWP	2	–0.0174	2.0174	–1.4680	3.4680
#0045	OWP	13	17.1726	–4.1726	–0.4048	2.4048
#0046	OWP	13	14.5433	–1.5433	15.1694	–2.1694
#0049	OWP	19	15.3015	3.6985	15.7086	–2.7086
#0119	Inner WP	2	–2.0712	4.0712	19.1500	–6.1500
#0116	Inner WP	13	20.9921	–7.9921	18.6115	–5.6115
#0117	Inner WP	13	16.5430	–3.5430	10.6987	8.3013
#0048	Inner WP	19	11.5361	7.4639	16.5346	2.4654

Table 3.14: Sample analysis and calculated age – Yorke Peninsula – field

ARRB ID	Sample location	Specified age (years)	Calculated age (years) – OWP/WP	Residual	Calculated age (years) – all	Residual
#0120	OWP	2	0.1466	1.8534	–0.9034	2.9034
#0045	OWP	13	16.6074	–3.6074	–1.1984	3.1984
#0046	OWP	13	14.6439	–1.6439	15.8731	–2.8731
#0049	OWP	19	15.6021	3.3979	16.8389	–3.8389
#0119	Inner WP	2	–3.0033	5.0033	17.3185	–4.3185
#0116	Inner WP	13	21.0395	–8.0395	19.2579	–6.2579
#0117	Inner WP	13	19.1364	–6.1364	8.81945	10.1806
#0048	Inner WP	19	9.8273	9.1727	17.9940	1.0060

3.7 COOBER PEDY, SA

The sample information and test results for Coober Pedy are shown in Table 3.15, while the sample analysis and calculated ages are shown in Table 3.16. The DSR values (stress ratio) for the lab samples were obtained from Austroads (2019).

Table 3.15: Sample information and test results – Coober Pedy

ARRB ID	Sample location	Specified age (years)	Log complex viscosity at 45°C	Stress ratio at 15°C	Area under the carbonyl peak – lab
#0125	OWP	0	Samples unable to be assessed	0.92	–0.0643
#0126	OWP	2		0.88	0.3739
#0127	OWP	5		0.82	0.8384
#0128	OWP	8		Failed	0.8949

Table 3.16: Sample analysis and calculated age – Coober Pedy

ARRB ID	Specified age (years)	Calculated age (years) – lab	Residual
#0125	0	–1.0115	1.0115
#0126	2	2.6171	–0.6171
#0127	5	6.4631	–1.4631
#0128	8	6.9313	1.0687

3.8 BRUCE ROCK, WA

The sample information and test results for Bruce Rock are shown in Table 3.17, while the sample analysis and calculated ages are shown in Table 3.18. As the use of C65 emulsion is common practice in this region, in addition to C170, samples of C65 emulsion were provided and they were included in the analysis.

For the provided samples, it was noted that samples #0113, #0114 and #0115 failed the stress ratio analysis, likely due to being highly aged. With sample #0115 also being unable to be sampled for field analysis due to being highly aged and therefore too hard and brittle.

Table 3.17: Sample information and test results – Bruce Rock

ARRB ID	Binder class	Specified age (years)	Log complex viscosity at 45°C	Stress ratio at 15°C	Area under the carbonyl peak – lab	Area under the carbonyl peak – field
#0112	C65	2	4.3015	0.9586	0.1956	0.0668
#0113	C170	10	5.3825	Failed	0.7640	0.6589
#0114	C170	14	5.9052	Failed	1.1470	0.7227
#0115	C65	28	6.4572	Failed	1.3453	Failed
#0122	C65	12	5.3149	0.8961	0.6615	0.3177
#0123	C65	5	4.1855	0.9383	0.1946	0.0697
#0124	C170	3	4.3155	0.9601	0.2980	0.1166

Table 3.18: Sample analysis and calculated age – Bruce Rock

ARRB ID	Specified age (years)	Calculated age (years) – field	Residual	Calculated age (years) – lab	Residual
#0112	2	3.1902	–1.1902	3.0624	–1.0624
#0124	3	2.3573	0.6427	3.2313	–0.2313
#0123	5	3.2997	1.7003	3.0409	1.9591
#0113	10	11.7675	–1.7676	9.3639	0.6361
#0122	12	12.5101	–0.5101	13.0899	–1.0899
#0114	14	12.8752	1.1248	14.4048	–0.4048
#0115	28	Failed	Failed	27.8069	0.1931

3.9 CRANBROOK, WA

The sample information and test results for Cranbrook are shown in Table 3.19, while the sample analysis and calculated ages for the lab and field are shown in Table 3.20 and Table 3.21 respectively.

For this region, the R^2 values reported for the reference curves (Table B.1) were very low. This indicates that the results are unreliable at this stage. Further sampling and investigation will be needed to develop more reliable reference curves.

Additionally, sample #0053 was removed from the analysis (Table 3.19) due to not being C170, and also exhibiting results inconsistent with the reported age.

Table 3.19: Sample information and test results – Cranbrook

ARRB ID	Sample location	Specified age (years)	Log complex viscosity at 45°C	Stress ratio at 15°C	Area under the carbonyl peak – lab	Area under the carbonyl peak – field
#0050A	Outer WP	3	4.3970	0.8946	0.1968	0.0806
#0050B	OWP	3	4.6315	0.9003	0.2948	0.0492
#0051A	Outer WP	6	4.6574	0.9142	0.5046	0.1849
#0051B	OWP	6	4.8663	0.8740	0.5755	0.2770
#0052A	Outer WP	20	5.0845	0.8802	0.4686	0.3371
#0052B	OWP	20	5.1117	0.8963	0.5498	0.2927
#0053	Outer WP	1	Removed from analysis			
#0054A	Inner WP	13	5.2345	0.8243	0.6471	0.4338
#0054B	OWP	13	5.1464	0.9095	0.6095	0.3950

Table 3.20: Sample analysis and calculated age – Cranbrook – lab

ARRB ID	Sample location	Specified age (years)	Calculated age (years) – OWP/WP	Residual	Calculated age (years) – all	Residual
#0050A	Outer WP	3	–8.7085	11.7085	–12.5212	15.5212
#0050B	OWP	3	–8.4083	11.4083	–4.5798	7.5798
#0051A	Outer WP	6	14.2681	–8.2681	12.4242	–6.4242
#0051B	OWP	6	16.5611	–10.5611	18.1738	–12.1738
#0052A	Outer WP	20	24.8986	–11.8986	23.9784	–10.9784
#0052B	OWP	20	19.5836	-6.5836	20.9280	–7.9280
#0054A	Inner WP	13	11.5417	8.4583	9.5056	10.4944
#0054B	OWP	13	14.2636	5.7365	16.0910	3.9091

Table 3.21: Sample analysis and calculated age – Cranbrook – field

ARRB ID	Sample location	Specified age (years)	Calculated age (years) – OWP/WP	Residual	Calculated age (years) – all	Residual
#0050A	Outer WP	3	–0.3343	3.3343	–1.6489	4.6489
#0050B	OWP	3	–5.9011	8.9011	–3.8179	6.8179
#0051A	Outer WP	6	5.9960	0.0040	5.5607	0.4393
#0051B	OWP	6	12.3699	–6.3699	11.9307	–5.9307
#0052A	Outer WP	20	21.1055	–8.1055	22.7752	–9.7752
#0052B	OWP	20	21.8772	–8.8772	20.0900	–7.0900
#0054A	Inner WP	13	15.2328	4.7672	16.0894	3.9106
#0054B	OWP	13	13.6540	6.3460	13.0209	6.9792

3.10 DARLING DOWNS, QLD

The sample information and test results for Bruce Rock are shown in Table 3.22, while the sample analysis and calculated ages are shown in Table 3.23.

Table 3.22: Sample information and test results – Darling Downs

ARRB ID	Binder class	Sample location	Specified age (years)	Log complex viscosity at 45°C	Stress ratio at 15°C	Area under the carbonyl peak – lab	Area under the carbonyl peak – field
#0057	PMB	OWP	1	4.3899	1.2249	0.3976	0.3001
#0061	PMB	OWP	1	4.5615	1.1243	0.3221	0.1993
#0062	C170	OWP	1	3.8801	1.0359	0.2640	0.1146
#0063	C170	OWP	2	4.4049	0.9698	0.3305	0.1148
#0059	PMB	OWP	6	4.4599	1.0667	0.3861	0.3173
#0066	C170	OWP	10	5.3275	0.8367	0.4219	0.3826
#0065	C170	OWP	12	4.9452	0.7904	0.5422	0.5751
#0055	C170	OWP	13	5.6267	0.8452	0.7069	0.7125
#0060	PMB	OWP	13	5.1136	0.8548	0.6347	0.4900

Table 3.23: Sample analysis and calculated age – Darling Downs

ARRB ID	Specified age (years)	Calculated age (years) – field	Residual	Calculated age (years) – lab	Residual
#0057	1	3.9286	–2.9286	3.5623	–2.5623
#0061	1	–1.2323	2.2323	0.1630	0.8370
#0062	1	1.7862	–0.7862	0.8551	0.1449
#0063	2	1.7923	0.2077	3.2269	–1.2269
#0059	6	4.8062	1.1938	3.0423	2.9577
#0066	10	7.6583	2.3418	6.4886	3.5114
#0065	12	11.8757	0.1243	10.7780	1.2220
#0055	13	14.8876	–1.8876	16.6514	–3.6515
#0060	13	13.4974	–0.4974	14.2324	–1.2324

3.11 FAR NORTH, QLD

The sample information and test results for Far North are shown in Table 3.24, while the sample analysis and calculated ages are shown in Table 3.25. For this region, samples #0089 and #0082 failed the stress ratio test (Table 3.24), likely due to being highly aged.

Table 3.24: Sample information and test results – Far North

ARRB ID	Specified age (years)	Log complex viscosity at 45°C	Stress ratio at 15°C	Area under the carbonyl peak – lab	Area under the carbonyl peak – field
#0092	1	4.9104	0.8825	0.3988	0.0892
#0090	7	5.5537	0.8620	0.7347	0.5594
#0089	11	5.8508	Failed	0.7684	0.5688
#0082	12	5.7469	Failed	0.6700	0.5464

Table 3.25: Sample analysis and calculated age – Far North

ARRB ID	Specified age (years)	Calculated age (years) – field	Residual	Calculated age (years) – lab	Residual
#0092	1	–0.5993	1.5993	-0.9668	1.9668
#0090	7	10.5616	–3.5616	11.0708	–4.0708
#0089	11	10.7843	0.2157	12.2805	–1.2806
#0082	12	10.2534	1.7466	8.6154	3.3846

3.12 CENTRAL WEST, QLD

The sample information and test results for Central West are shown in Table 3.26, while the sample analysis and calculated ages are shown in Table 3.27.

Table 3.26: Sample information and test results – Central West

ARRB ID	Specified age (years)	Log complex viscosity at 45°C	Stress ratio at 15°C	Area under the carbonyl peak – lab	Area under the carbonyl peak – field
#0093	1	4.6353	1.1738	0.2870	0.0826
#0094	8	5.4273	0.9665	0.4263	0.3872
#0095	8	5.4917	0.8672	0.6000	0.3900
#0096	8	5.1383	0.8897	0.4274	0.0262
#0097	7	5.8657	failed	0.6443	0.6929
#0098	4	5.1293	0.8729	0.5249	0.4814
#0099	4	5.6584	failed	0.9372	0.5830
#0100	5	5.1975	0.9902	0.5774	0.3554
#0101	1	4.8692	0.9753	0.4455	0.2638
#0102	1	4.5790	1.1396	0.2592	0.2411
#0103	1	4.9930	0.9057	0.4406	0.3452

Table 3.27: Sample analysis and calculated age – Central West

ARRB ID	Specified age (years)	Calculated age (years) – field	Residual	Calculated age (years) – lab	Residual
#0101	1	–0.0786	1.0786	0.8902	0.1098
#0103	1	1.9606	–0.9606	0.7123	0.2877
#0098	4	5.3754	–1.3754	3.8203	0.1797
#0100	5	2.2170	2.7830	5.7581	–0.7581
#0097	7	10.6730	–3.6730	8.2275	–1.2275
#0095	8	5.8526	2.1474	6.5917	1.4083

3.13 CANBERRA, ACT

The sample information and test results for Canberra are shown in Table 3.28, while the sample analysis and calculated ages are shown in Table 3.29.

Table 3.28 shows that sample #0110 was very aged and brittle and thus field samples were unable to be taken directly from the sample surface; the stress ratio test failed. Due to a similar issue, field testing was also unable to be performed on sample #0111. As such, insufficient samples were available to produce the field reference curve.

As can be seen in Table 3.28, samples #0108 and #0109 appeared to behave as fresh samples, exhibiting similar results to samples #0104 and #0105, rather than Intermediate II aged samples. These samples were therefore removed from the analysis due to the discrepancy between the calculated and ‘known’ ages.

Table 3.28: Sample information and test results – Canberra

ARRB ID	Sample location	Specified age (years)	Log complex viscosity at 45°C	Stress ratio at 15°C	Area under the carbonyl peak – lab	Area under the carbonyl peak – field
#0104	WP	3	3.9736	1.2558	0.3325	0.0096
#0105	OWP	3	4.0408	1.3030	0.2187	0.0259
#0106	WP	8	4.9001	1.0125	0.4839	0.1550
#0107	OWP	8	4.8932	1.0333	0.5294	0.4634
#0108	WP	10-15	4.1846	1.1212	0.2477	–0.0352
#0109	OWP	10-15	4.1687	1.1329	0.1979	–0.0156
#0110	WP	15+	5.7862	Failed	0.9500	Failed
#0111	OWP	15+	5.1110	0.9891	0.8410	Failed

Table 3.29: Sample analysis and calculated age – Canberra

ARRB ID	Sample location	Specified age (years)	Calculated age (years) – WP/OWP	Residual	Calculated age (years) – all	Residual
#0104	WP	3	3.7071	–0.7071	4.2511	–1.2511
#0105	OWP	3	2.3847	0.6153	1.8598	1.1402
#0106	WP	8	6.8510	1.1490	7.4317	0.5683
#0107	OWP	8	8.9998	–0.9998	8.3881	–0.3881
#0110	WP	16	16.4419	–0.4419	17.1355	–1.1355
#0111	OWP	16	15.6155	0.3846	14.9339	1.0661

The specified age of each sample was very similar to the calculated age using the reference curve.

3.14 DARWIN, NT

The sample information and test results for Darwin are shown in Table 3.30, while the sample analysis and calculated ages are shown in Table 3.31 and Table 3.32.

Table 3.30 Sample information and test results – Darwin

ARRB ID	Sample location	Specified age (years)	Log complex viscosity at 45°C	Stress ratio at 15°C	Area under the carbonyl peak – lab	Area under the carbonyl peak – field
#0129C	Between WP	12	5.960091	Failed	1.0085	0.5556
#0129R	Inner WP	12	5.866825	Failed	1.0426	0.4971
#0129L	Outer WP	12	5.878002	Failed	0.9126	0.6388
#0131C	OWP	3	5.129783	1.3307	0.5435	0.3278
#0131R	Inner WP	3	5.192643	1.3302	0.5528	0.4346
#0132C	OWP	10	5.528744	Failed	0.8434	0.7072
#0132L	Outer WP	10	5.634709	Failed	0.8819	0.6996
#0133C	OWP	4	4.916289	1.1025	0.4724	0.4425
#0133L	Outer WP	4	4.588371	1.296	0.2929	0.1043
#0134C	OWP	10	5.385181	1.0671	0.7811	0.4873
#0134R	Inner WP	10	5.400326	1.1	0.7593	0.614
#0135C	OWP	4	4.822505	1.1683	0.4096	0.2991
#0135R	Inner WP	4	4.923989	1.193	0.4388	0.2296
#0135L	Outer WP	4	4.978049	1.184	0.4359	0.4463

Table 3.31 Sample analysis and calculated age – Darwin – lab

ARRB ID	Sample location	Specified age (years)	Calculated age (years) – OWP/WP	Residual	Calculated age (years) – all	Residual
#0129C	OWP	12	12.9393	-0.9393	12.8437	-0.8437
#0129L	Outer WP	12	11.3244	0.6756	11.2681	0.7319
#0129R	Inner WP	12	13.4440	-1.4440	13.4029	-1.4029
#0131C	OWP	3	4.8563	-1.8563	5.1863	-2.1863
#0131R	Inner WP	3	4.6312	-1.6312	5.3368	-2.3368
#0132C	OWP	10	10.0700	-0.0700	10.1248	-0.1248
#0132L	Outer WP	10	10.9008	-0.9008	10.7733	-0.7733
#0133C	OWP	4	3.6193	0.3807	4.0143	-0.0143
#0133L	Outer WP	4	2.7771	1.2229	1.0607	2.9393
#0134C	OWP	10	8.9870	1.0130	9.0993	0.9007
#0134R	Inner WP	10	8.3465	1.6535	8.7368	1.2632
#0135C	OWP	4	2.5281	1.4720	2.9806	1.0194
#0135L	Outer WP	4	4.9977	-0.9977	3.7129	0.2871
#0135R	Inner WP	4	2.5783	1.4217	3.4595	0.5405

Table 3.32 Sample analysis and calculated age – Darwin – field

ARRB ID	Sample location	Specified age (years)	Calculated age (years) – OWP/WP	Residual	Calculated age (years) – all	Residual
#0129C	OWP	12	9.9612	2.0388	9.9329	2.0671
#0129L	Outer WP	12	10.6506	1.3494	12.3321	-0.3321
#0129R	Inner WP	12	9.3996	2.6004	8.2610	3.7390
#0131C	OWP	3	2.5300	0.4700	3.4004	-0.4004
#0131R	Inner WP	3	6.8765	-3.8765	6.4663	-3.4663
#0132C	OWP	10	14.9067	-4.9068	14.2822	-4.2822
#0132L	Outer WP	10	11.7993	-1.7993	14.0730	-4.0730
#0133C	OWP	4	6.2733	-2.2733	6.6868	-2.6868
#0133L	Outer WP	4	0.5417	3.4583	-2.9961	6.9961
#0134C	OWP	10	7.7333	2.2667	7.9789	2.0211
#0134R	Inner WP	10	14.1132	-4.1132	11.6090	-1.6090
#0135C	OWP	4	1.5955	2.4045	2.5820	1.4180
#0135L	Outer WP	4	7.0085	-3.0085	6.8058	-2.8058
#0135R	Inner WP	4	-1.3894	5.3894	0.5857	3.4143

4 DISCUSSION

Upon completion of the laboratory testing and sample analysis, some overall trends were identified and explored for the sample binders. Figure 3.1 and Figure 3.2 display all reference curves for the participating regions. For all regions, the oxidation was minimal within the first year, and then increased significantly at the early stage of ageing, between four to six years. Beyond this time, oxidation continued to occur but the rate gradually slowed. Table B.1 shows further details for the reference curve models for both lab and field samples, for each studied region.

In general, the reference curves demonstrate that regions with higher average temperatures show greater levels of absorbance at the carbonyl peak than those with low average temperatures; this demonstrates the greater impact of higher temperatures on ageing characteristics.

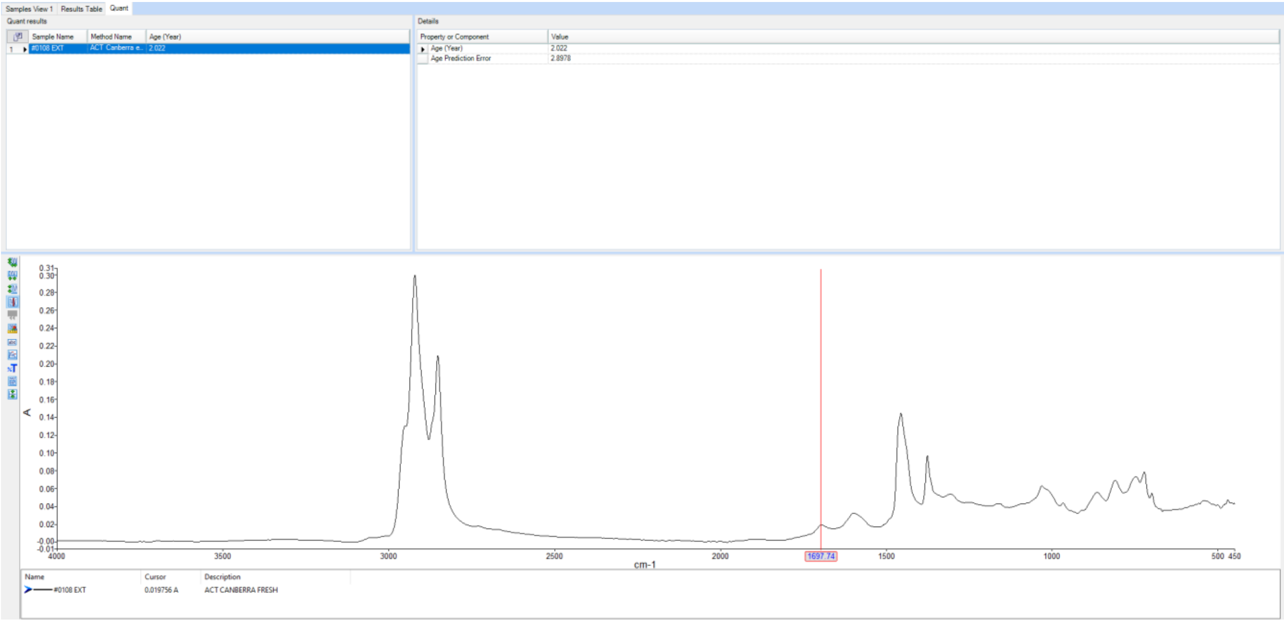
For all samples discussed in Section 3.1 to Section 3.14 there is variation between field and lab results, albeit within an acceptably low range of difference. The variation in the field samples may be related to the existence of fine materials (different sulphur -containing compounds) that were taken directly from the core/slab .While they remain in the field samples, these fine materials were removed from the lab samples during the extraction process, indicating this as a potential reason for the difference between the field and lab results.

For most participating regions in this project, the IR system software successfully developed relationships linking FTIR absorbance values (area under the carbonyl peak) to the ages of the binder samples. Binder type and sample location were taken into consideration, as different binder types and different locations (relative to the wheelpath) were found to exhibit different ageing characteristics and needed to be evaluated separately.

Reference curves were developed for all 14 regions with the exception of the Cranbrook region, where there was a clear difference between the lab and field results. More investigation would be required from this region, including the provision of more samples from different age groups to redevelop a relationship. Excluding Cranbrook, for which the reference curve needs further analysis, the data in Table B.1 shows that the R^2 values overall showed reliable correlations, indicating useful relationships can be developed using this methodology.

Upon development of each reference curve, the calculated age of each known sample was determined. This was carried out to establish a ‘proof of concept’ and to ensure that the calculated ages were within close proximity of the known age. Generally, the calculated age was within ± 3 years. An example of this process is shown in Figure 4.1, where the sample is calculated as being two years old.

Figure 4.1 Sample age calculated from a reference curve



For the local government regions that participated, the reference curve models from this work can be used, in conjunction with the portable FTIR assessment device, to indicate the apparent seal ages of other roads in their networks. This will help plan for future budget and maintenance programs as required.

5 CONCLUSIONS AND RECOMMENDATIONS

The testing methodology and reference curves developed in this project demonstrate the ability to use the portable FTIR system in supporting the asset management of Australia's sealed road network, through quick and simple characterisation of in situ binder age.

During the project, as the portable FTIR device was used for most of the sample analyses, the results were compared to a currently used, desktop (laboratory-based) FTIR device to determine if a calibration factor was required. It was determined that no calibration factor was required for the portable device when comparing it back to the desktop device.

It was demonstrated that FTIR testing can be conducted on samples taken directly from the road surface, with the exception of samples that are highly aged. This provides a promising future for this research methodology, indicating that field analysis can be conducted swiftly and simply, providing immediate results. For highly-aged samples, the results can be obtained from laboratory extracted binders, extending the process slightly but still demonstrating great possibility.

To further improve the accuracy of these reference curves, it would be necessary to obtain a wider sample base for analysis. For long-term, accurate reference curves, recommendations are as follows:

- For the development of new reference curves, a minimum of four samples from each age group in each region should be collected. More samples would improve the accuracy of each reference curve.
- In terms of further research, the selection of the sample collection process should be based on careful consideration of the context and requirements of the project, to ensure that the samples are collected with a suitable foundation of experience and that all required information is collected with rigour. It is also recommended that trained and well-informed operators conduct the sub-sampling (sampling binder from provided seal specimens), testing and reference curve development to ensure improved accuracy.
- Further research could consider the crude bitumen source, to study the variation in the results between samples of the same age within the same climatic region.
- Explore another type of regression analysis could be used to develop reference curves and the results compared to those obtained using the IT method.

In terms of the implementation of this work in the field, it is recommended that an operator with experience, or appropriate training in utilising the FTIR device, carry out the seal sampling and analysis across any given jurisdiction. This will help to identify the age of seals where the date of construction information is not easily accessible, and improve the accuracy of obtained results and minimising invested resources.

As the research methodology is applicable to both modified and unmodified binders, for a wide age range, this research model could be also applied to different aspects of the road asset aside from binder age (potentially the determination of type, and quantity of additives or modifiers within the binder), by identifying and studying different peaks within the FTIR spectra.

The appropriate application of this model could help road owners to manage their networks and provide for long-term maintenance plans, select and prioritise road sections for resurfacing and resealing operations, and to budget for the required future work in their networks.

REFERENCES

Austroads 2019, *Accelerated long-term aging methods for sprayed sealing binders: a field validation study*, AP-T349-19, prepared by Y Choi & J Trochez, Austroads, Sydney, NSW.

Roberts, J, Foster, E, Choi, Y & Trochez, J 2018, 'Investigation of seal life in South West Riverina, NSW', contract report PRA17054, ARRB Group, Vermont South, Vic.

Austroads Test Methods

AGPT/T191-15, *Extractions of bituminous binder from asphalt.*

AGPT/T125-18, *Stress ratio of bituminous binders using the Dynamic Shear Rheometer.*

Appendix A ARRB SAMPLE DETAILS AND INSTRUMENTATION CALIBRATION

Table A.1: Age analysis of ARRB samples

Sample ID	Year	Age (Years)	Binder Type
275	1981	38	C160
345	1983	36	C170
361	1983	36	C170
394	1986	33	C170
545	1992	27	C320
559	1992	27	C170
B144	1995	24	C170
B041	1996	23	C170
B093	1997	22	C600
B136	1998	21	C320
273	1981	38	C170
389	1985	34	C170
129	1998	21	C170
728	2006	13	C170
#3237	2014	5	C600
729	2006	13	C320
808	2007	12	C170
809	2007	12	C320
814	2008	11	C170
FRESHC170	2018	1	C170
FRESHC600	2018	1	C600
541	1992	27	C170
809	2007	12	C320
#5365	2017	3	C320
#6240	2019	1	C320

Table A.2: FTIR instrument calibration

Region	Binder Class	Sample Name	Correlation	Pass/Fail
Darling Downs Shire	C170	#6079 site37.sp	0.997964	Pass
	C170	#6080 site38.sp	0.997303	Pass
	C170	#6081 site39.sp	0.997171	Pass
	PMB	#6082 site42.sp	0.998326	Pass
	PMB	#6083 site 40.sp	0.997954	Pass
	C170	#6084 site63.sp	0.99737	Pass
	C170	#6085 site64.sp	0.997759	Pass
	C170	#6072 site6.sp	0.998229	Pass
	C170	#6073 site7.sp	0.997127	Pass
	C170	#6074 site23.sp	0.99574	Pass
	PMB	#6075 site24.sp	0.997886	Pass
	C170	#6076 site25.sp	0.995218	Pass
	PMB	#6077 site33.sp	0.996849	Pass
	PMB	#6078 site34.sp	0.997422	Pass
Far North	PMB	#6066 site26.sp	0.998443	Pass
	PMB	#6067 site8.sp	0.998043	Pass
	PMB	#6068 site12.sp	0.997938	Pass
	C170	#6069 site11.sp	0.996996	Pass
	C170	#6070 site10.sp	0.994711	Pass
	C170	#6071 site43.sp	0.996077	Pass
	C170	#6086 site45.sp	0.995893	Pass
	C170	#6087 site66.sp	0.995785	Pass
	C170	#6088 site57.sp	0.99417	Pass
	C170	#6089 site56.sp	0.997457	Pass
	C170	#6090 site40.sp	0.994283	Pass
	C170	#6065 site9.sp	0.998232	Pass
Central West	PMB	#6189 site1.sp	0.997485	Pass
	PMB	#6190 site2.sp	0.994051	Pass
	PMB	#6191 site3.sp	0.996566	Pass
	PMB	#6192 site4.sp	0.995281	Pass
	PMB	#6193 site5.sp	0.993828	Pass
	PMB	#6194 site20.sp	0.994963	Pass
	PMB	#6195 site21.sp	0.995023	Pass
	PMB	#6196 site22.sp	0.998231	Pass
	PMB	#6197 site30.sp	0.998122	Pass
	PMB	#6198 site31.sp	0.995743	Pass
	PMB	#6199 site32.sp	0.997727	Pass

Appendix B FTIR RESULTS

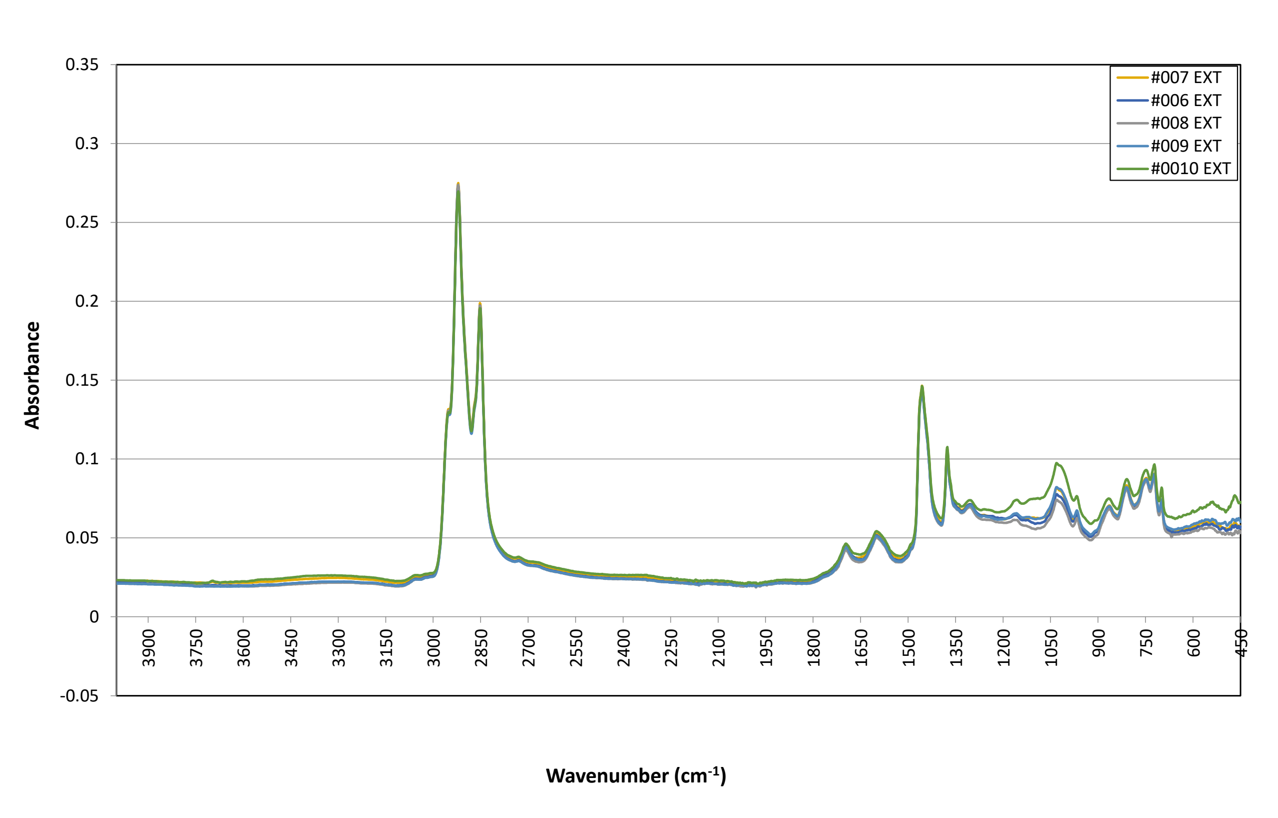
B.1 REFERENCE CURVE MODELLING

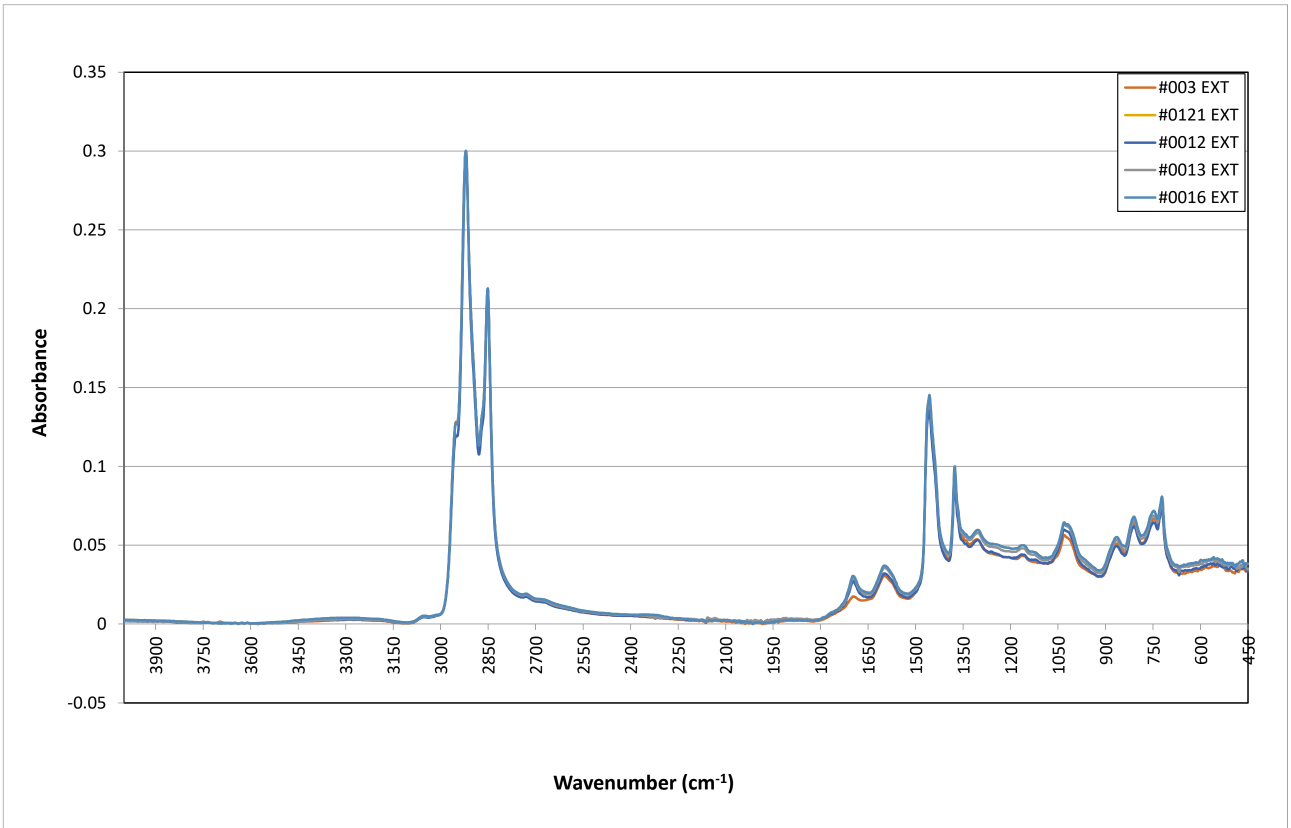
Table B.1: Reference curve models for field and lab results

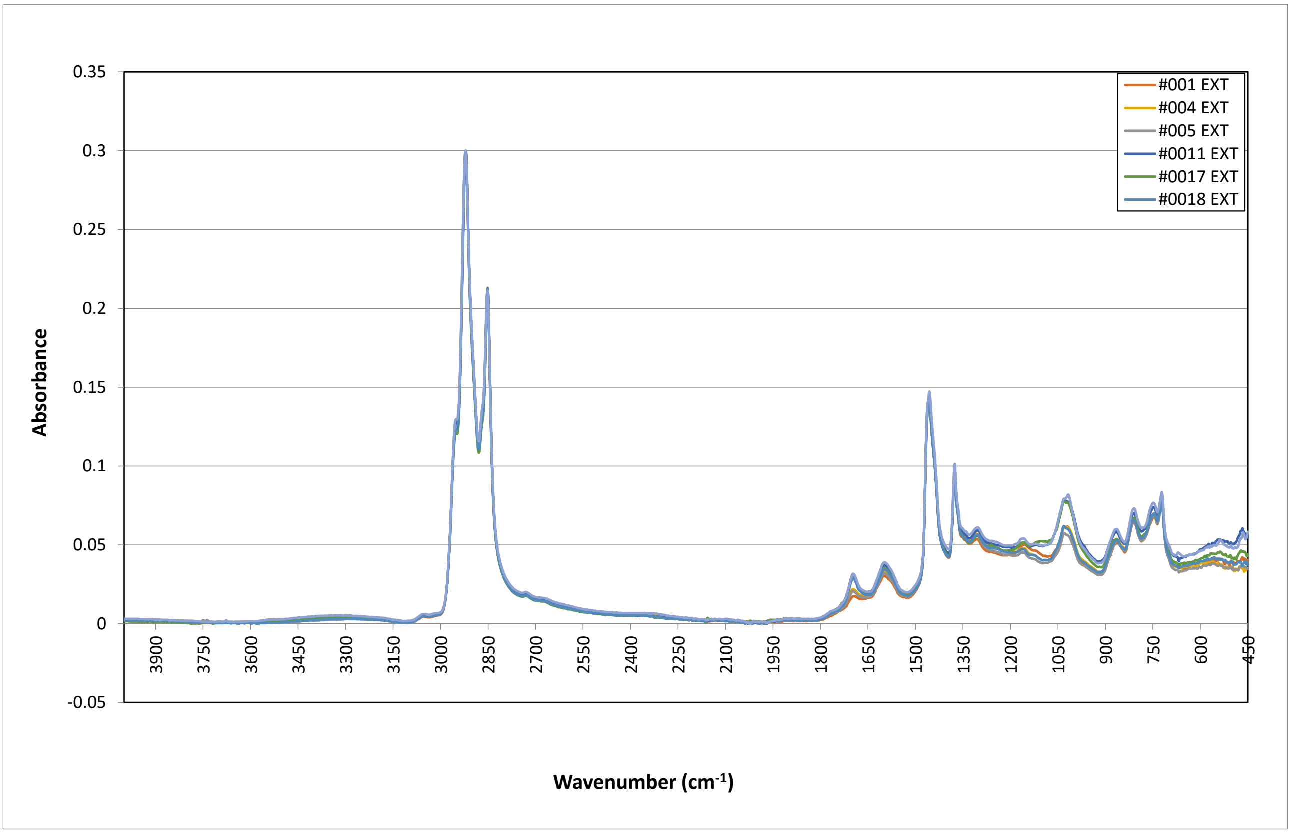
State	Council/Region	Sample Location	Binder Class	Field reference curve, R^2	Lab reference curve, R^2
NSW	Snowy Monaro Regional Council (NSW Alpine)	OWP	C170	Y = 0.040 * AGE - 0.125, 0.99	Y = 0.032 * AGE + 0.135, 0.99
		WP	C170	Y = 0.029 * AGE + 0.021, 0.90	Y = 0.025 * AGE + 0.211, 0.93
		All	C170	Y = 0.032 * AGE - 0.015, 0.93	Y = 0.027 * AGE + 0.191, 0.96
	Narrandera Shire Council	OWP	C170	Y = 0.046 * AGE + 0.033, 0.96	Y = 0.028 * AGE + 0.240, 0.90
VIC	Golden Plains Shire Council	WP	C170	Y = 0.011 * AGE + 0.017, 0.90	Y = 0.017 * AGE + 0.218, 0.98
	Murrindindi Shire Council (VIC Alpine)	WP	C170	Y = 0.042 * AGE – 0.148, 0.95	Y = 0.030 * AGE + 0.071, 0.90
TAS	Dorset Council	OWP	C170	Y = 0.017 * AGE – 0.083, 0.99	Y = 0.016 * AGE + 0.111, 0.97
SA	Yorke Peninsula Council	Outer WP	C170	Y = 0.039 * AGE – 0.081, 0.89	Y = 0.036 * AGE + 0.131, 0.91
		Inner WP	C170	Y = 0.034 * AGE + 0.005, 0.65	Y = 0.029 * AGE + 0.155, 0.71
		All	C170	Y = 0.031 * AGE – 0.038, 0.77	Y = 0.032 * AGE + 0.143, 0.80
	District Council of Coober Pedy	OWP	C170	N/A	Y = 0.121 * AGE +0.058, 0.94
WA	Shire of Bruce Rock	WP	Emulsion C65	Y = 0.027* AGE – 0.019, 0.96	Y = 0.046 * AGE + 0.053, 0.99
		WP	C170	Y = 0.058 * AGE – 0.019, 0.96	Y = 0.076 * AGE + 0.052, 0.99
	Shire of Cranbrook	Inner WP	C170	Y = 0.016 * AGE + 0.086, 0.80	Y = 0.013 * AGE + 0.314, 0.54
		Outer WP	C170	Y = 0.012 * AGE + 0.123, 0.65	Y = 0.011 * AGE + 0.390, 0.59
		All	C170	Y = 0.014 * AGE + 0.104, 0.72	Y = 0.012 * AGE + 0.351, 0.55
QLD	Darling Downs	OWP	C170	Y = 0.046 * AGE + 0.033, 0.96	Y = 0.028 * AGE + 0.240, 0.90
		OWP	PMB	Y = 0.020 * AGE + 0.223, 0.93	Y = 0.022 * AGE + 0.318, 0.92
	Far North	OWP	C170	Y = 0.042 * AGE + 0.114, 0.90	Y = 0.028 * AGE + 0.426, 0.83
	Central West	OWP	PMB	Y = 0.040 * AGE + 0.267, 0.77	Y = 0.027 * AGE + 0.421, 0.95
ACT	Canberra	OWP	PMB	Not enough field samples	Y = 0.047 * AGE + 0.107, 0.99
		WP	PMB	Not enough field samples	Y = 0.048 * AGE + 0.154, 0.99
		All	PMB	Not enough field samples	Y = 0.046 * AGE + 0.156, 0.99
NT	Darwin	OWP	S10E	Y = 0.031 * AGE + 0.250, 0.80	Y = 0.058 * AGE + 0.264, 0.95
		Inner WP	S10E	Y = 0.038 * AGE + 0.179, 0.73	Y = 0.063 * AGE + 0.201, 0.93
		Outer WP	S10E	Y = 0.025 * AGE + 0.264, 0.68	Y = 0.056 * AGE + 0.295, 0.93
		WP (All)	S10E	Y = 0.053 * AGE + 0.076, 0.81	Y = 0.073* AGE + 0.092, 0.97
		All	S10E	Y = 0.035 * AGE + 0.209, 0.75	Y = 0.061 * AGE + 0.229, 0.94

B.2 SNOWY MONARO (ALPINE), NSW

Figure B.1 Normalised spectra – Snowy Monaro







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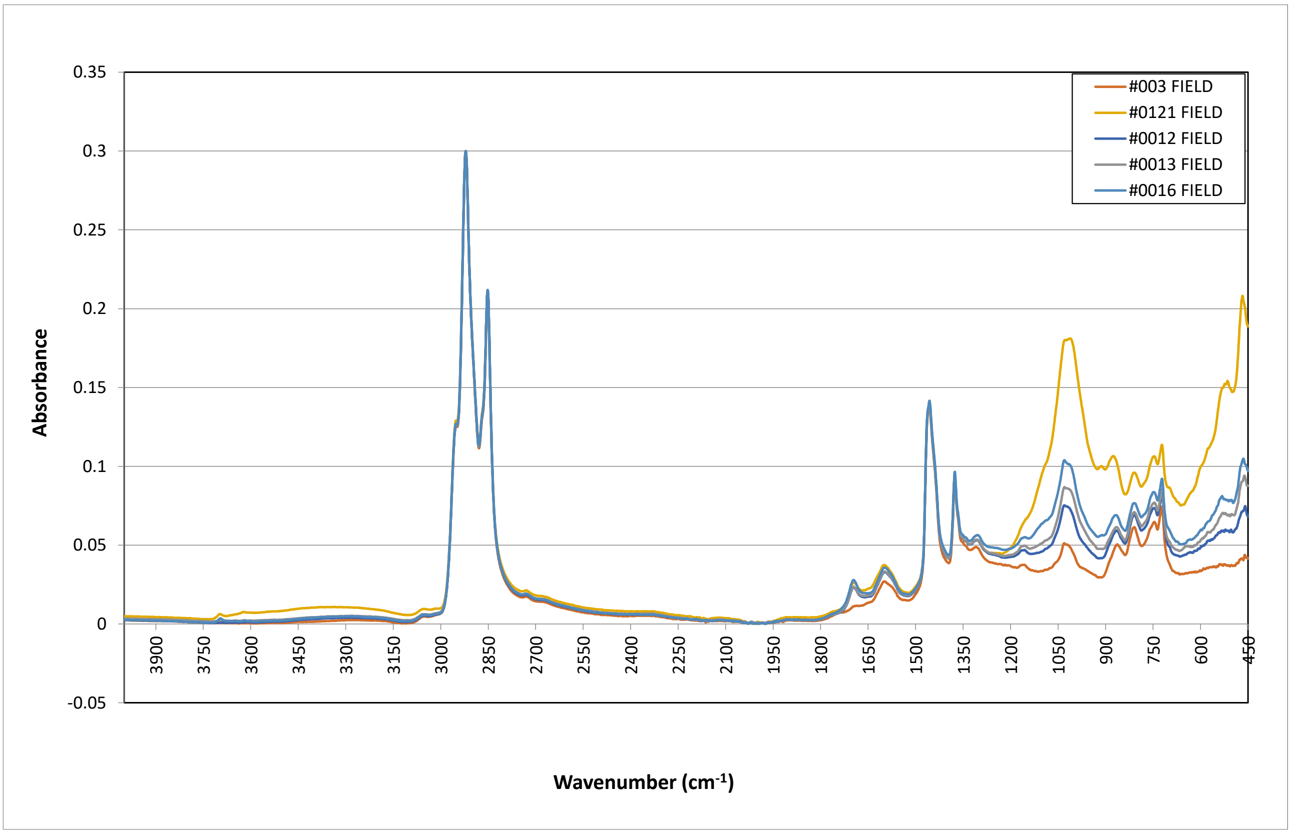
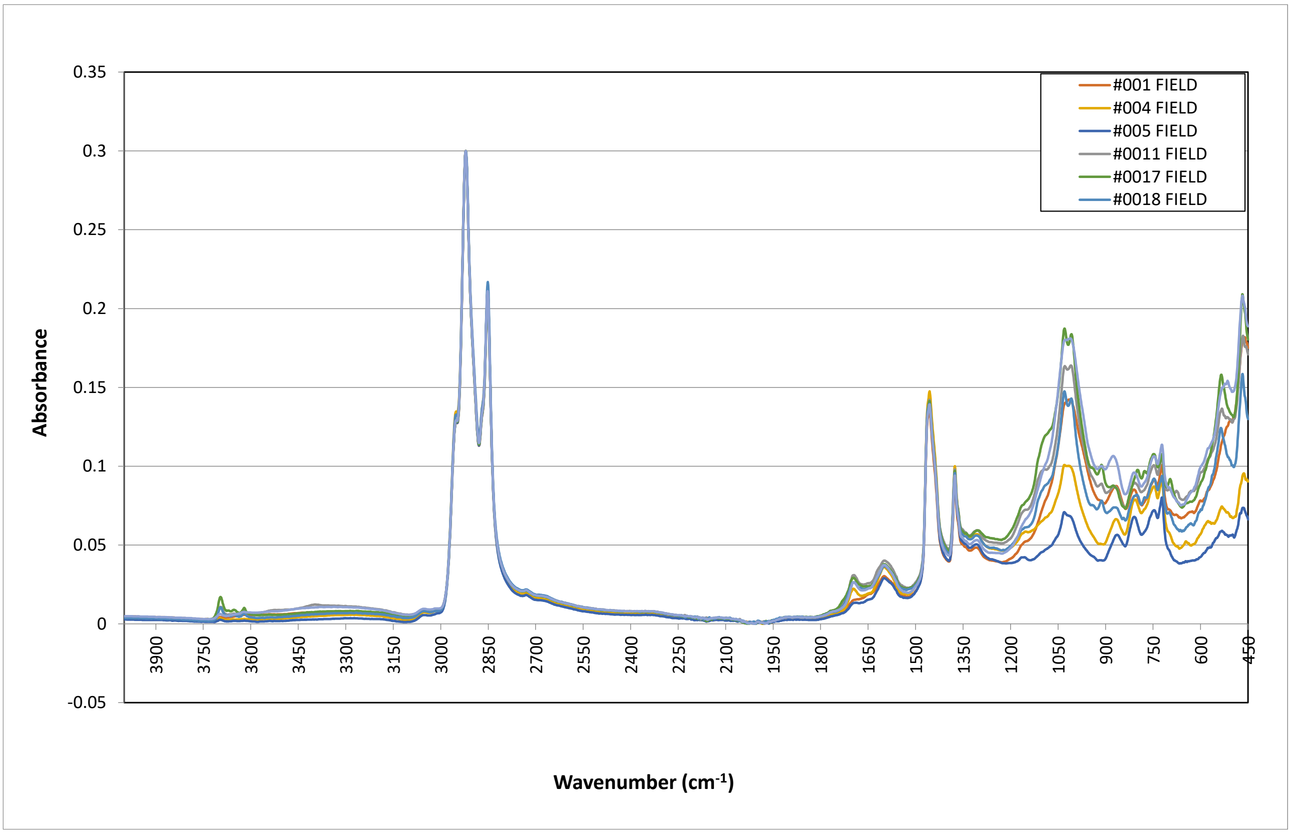
#004 EXT
#005 EXT
#0011 EXT
#0017 EXT
#0018 EXT
Absorbance
Wavenumber (cm-1)

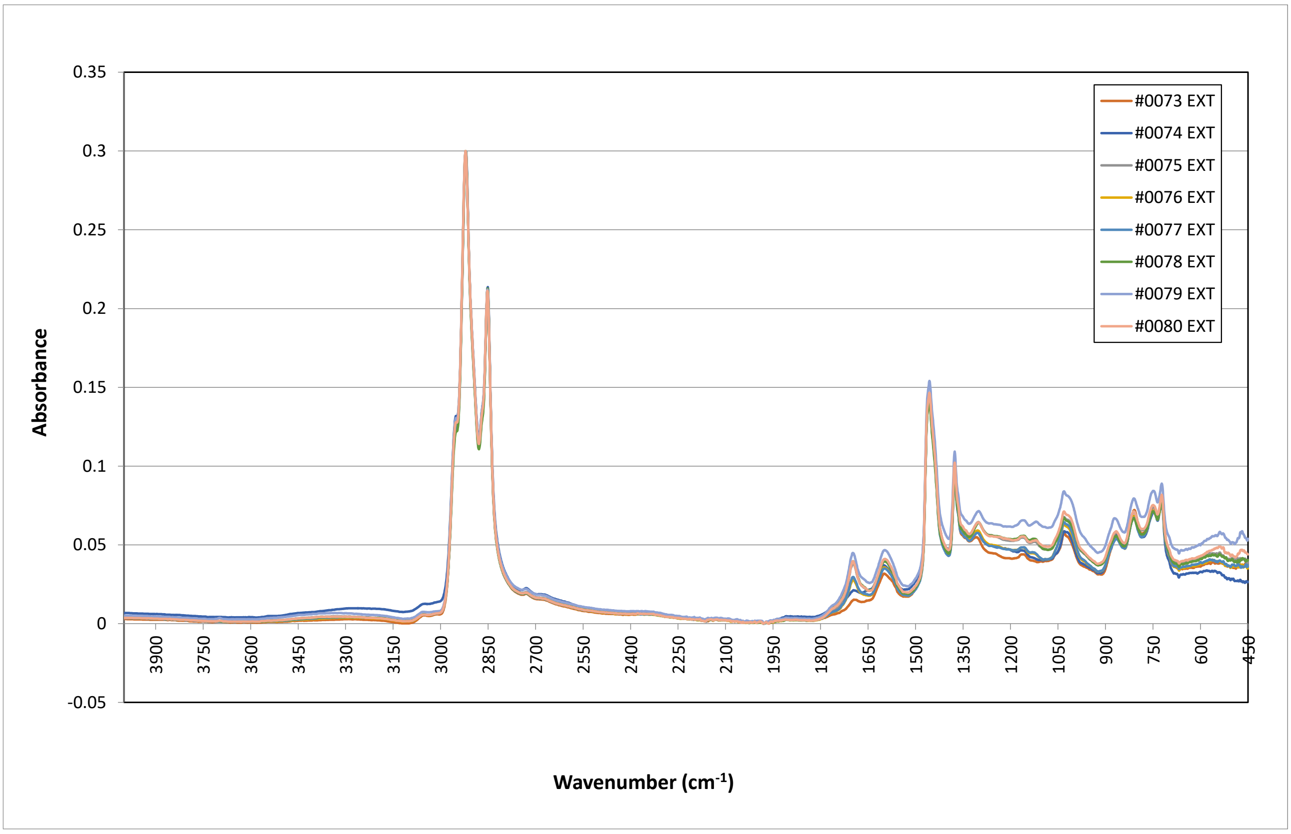


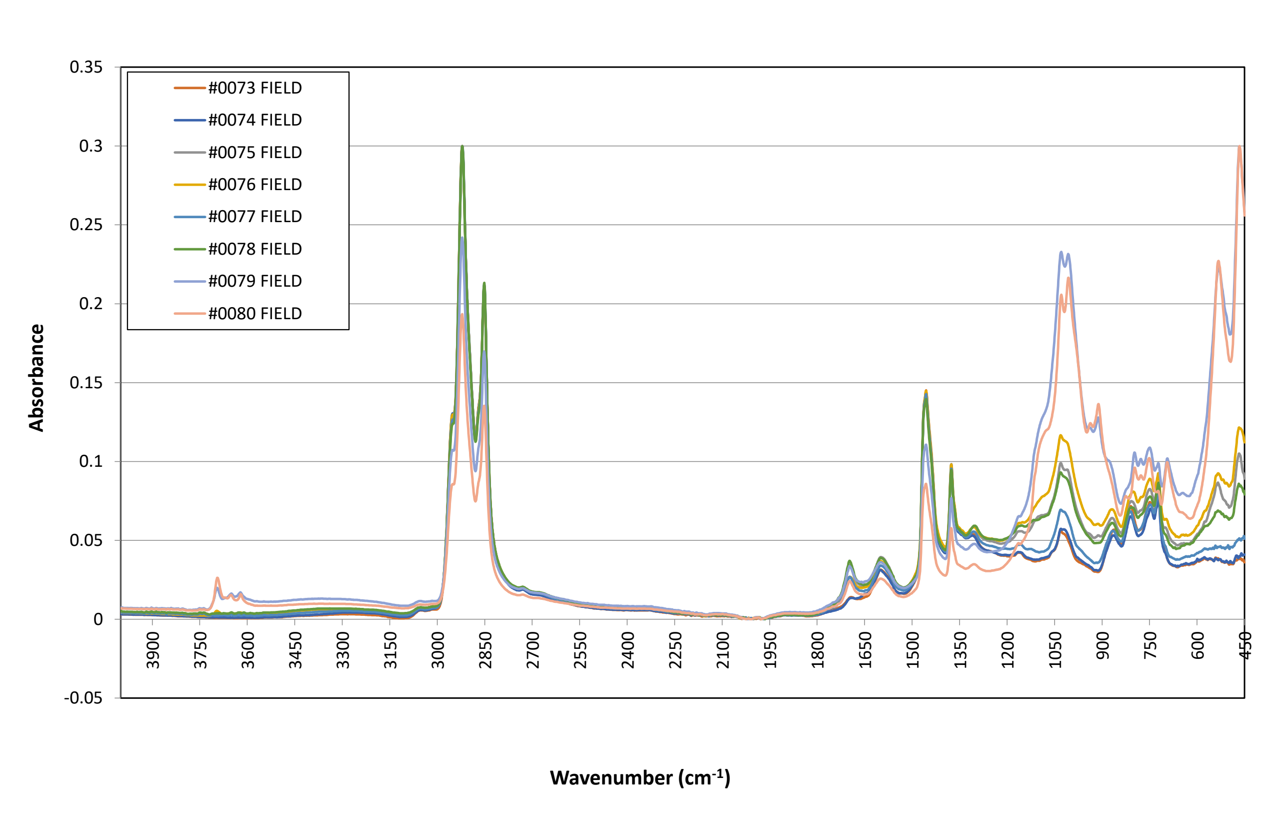
#003 FIELD
#0121 FIELD
#0012 FIELD
#0013 FIELD
#0016 FIELD
Absorbance
Wavenumber (cm-1)



B.3 NARRANDERA, NSW

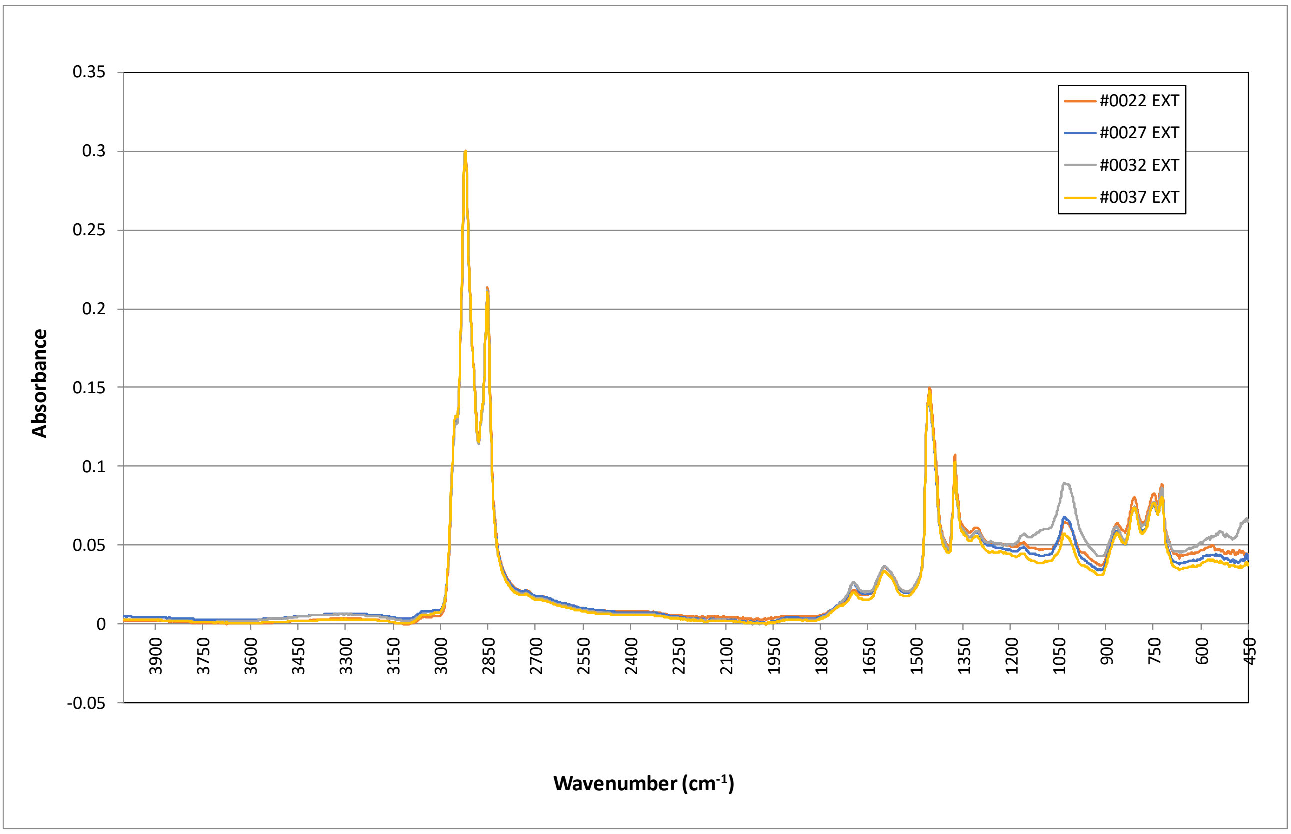
Figure B.2 Normalised spectra – Narrandera

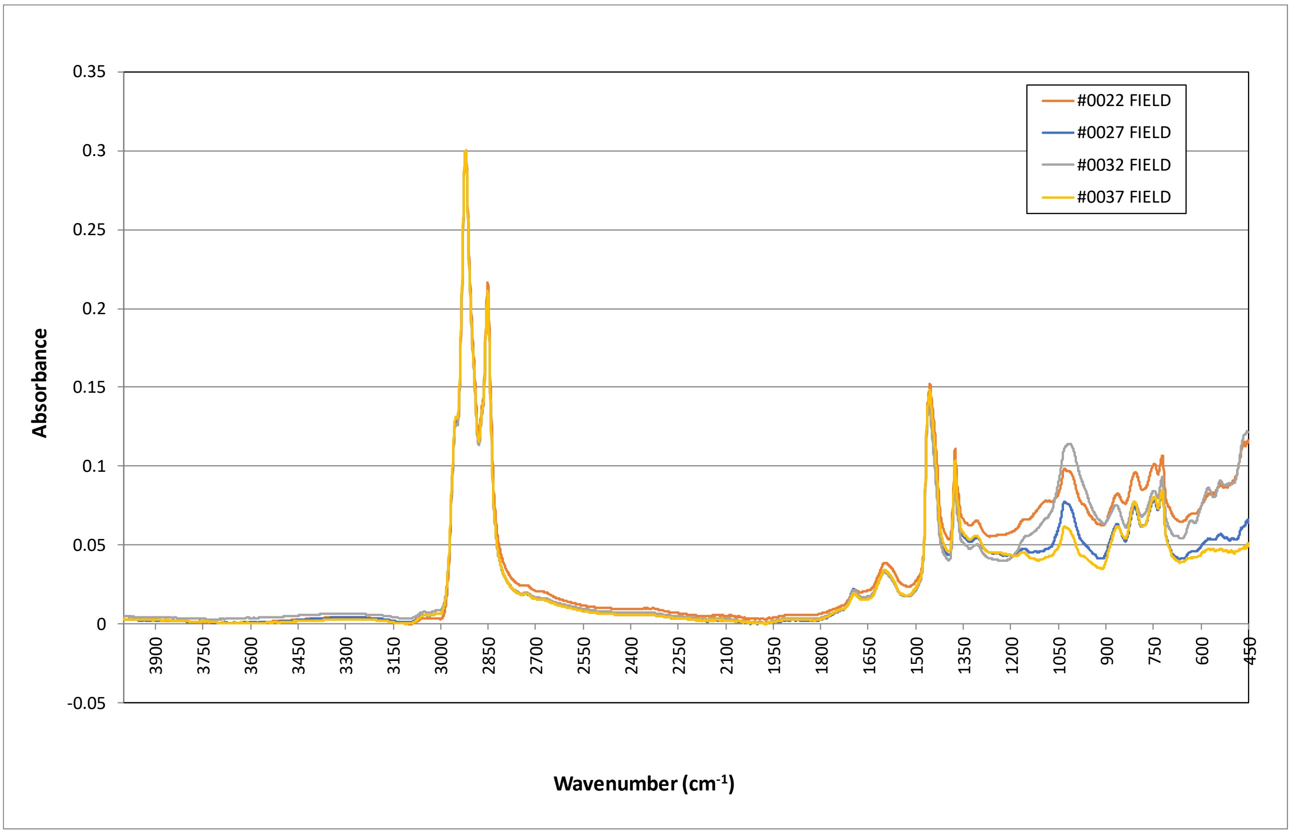




B.4 GOLDEN PLAINS, VIC

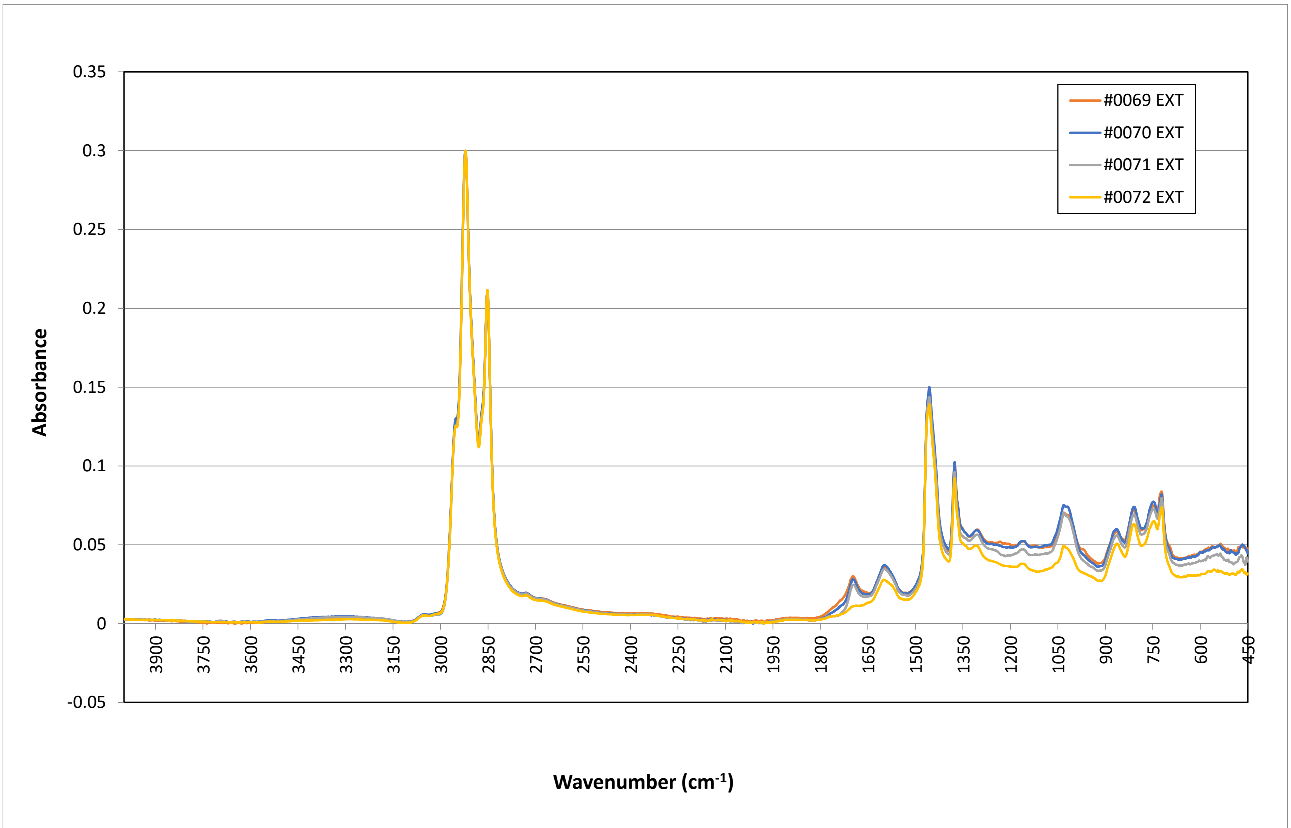
Figure B.3 Normalised spectra – Golden Plains

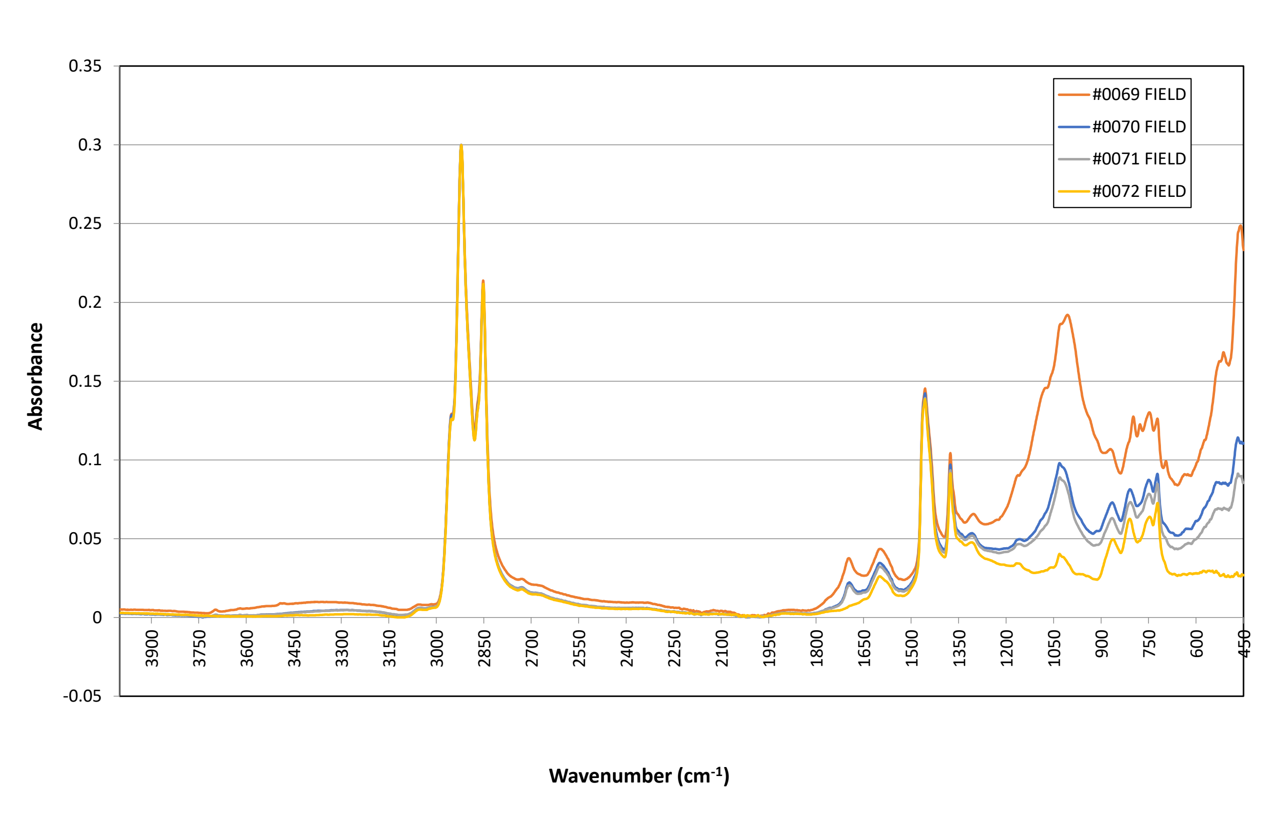




B.5 MURRINDINDI (ALPINE), VIC

Figure B.4 Normalised spectra – Murrindindi





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#0070 FIELD
#0071 FIELD
#0072 FIELD
Absorbance
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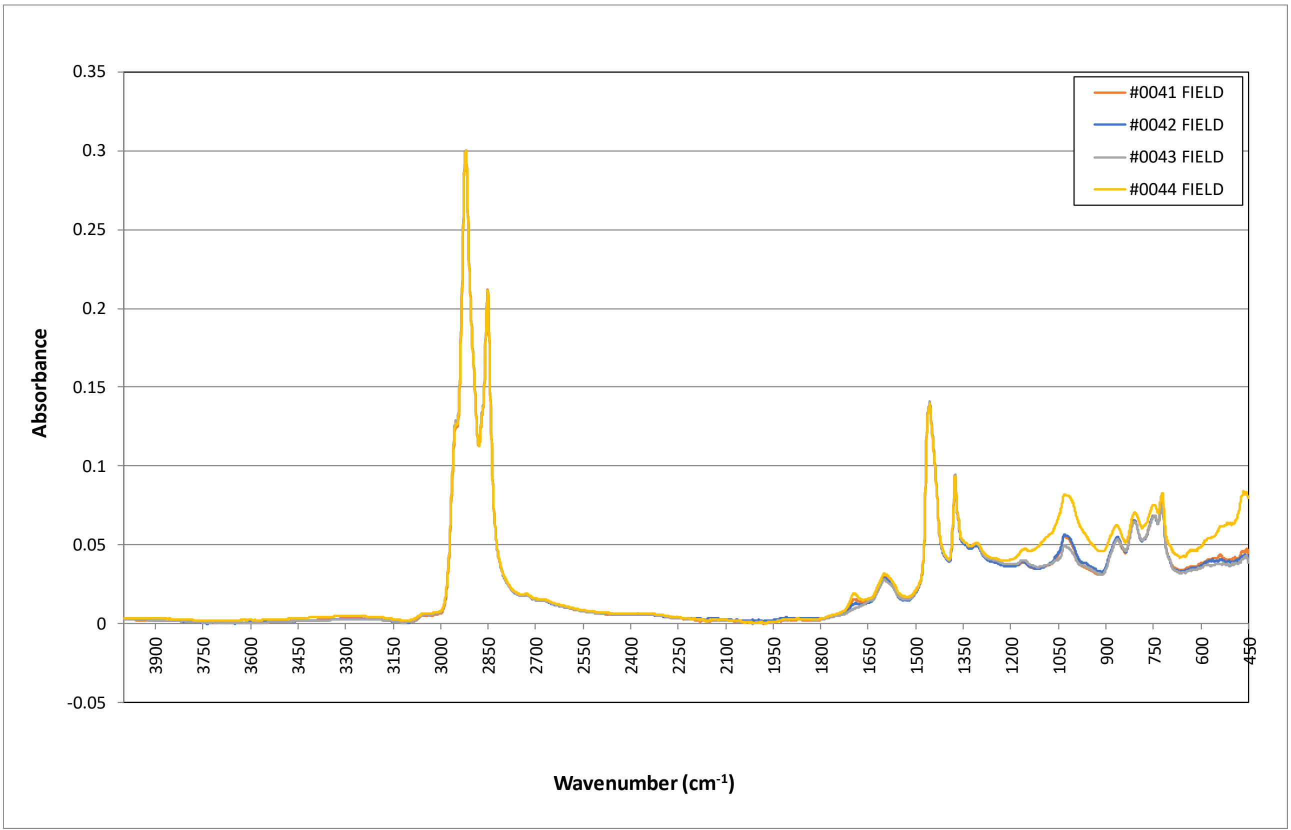
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
3900
3750
3600
3450
3300
3150
3000
2850
2700
2550
2400
2250
2100
1950
1800
1650
1500
1350
1200
1050
900
750
600
450
Wavenumber (cm-1)



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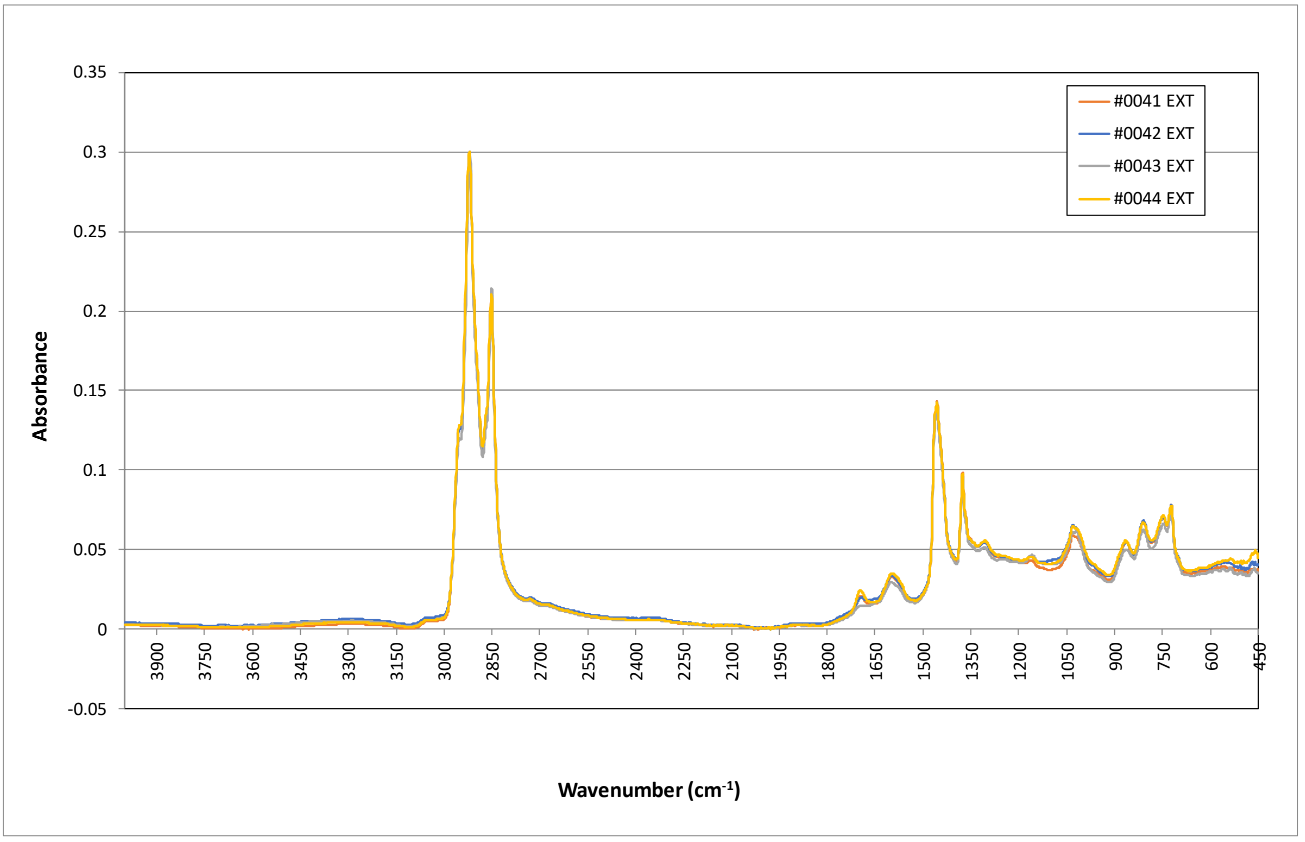
#0042 FIELD
#0043 FIELD
#0044 FIELD
Absorbance
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
3900
3750
3600
3450
3300
3150
3000
2850
2700
2550
2400
2250
2100
1950
1800
1650
1500
1350
1200
1050
900
750
600
450
Wavenumber (cm-1)

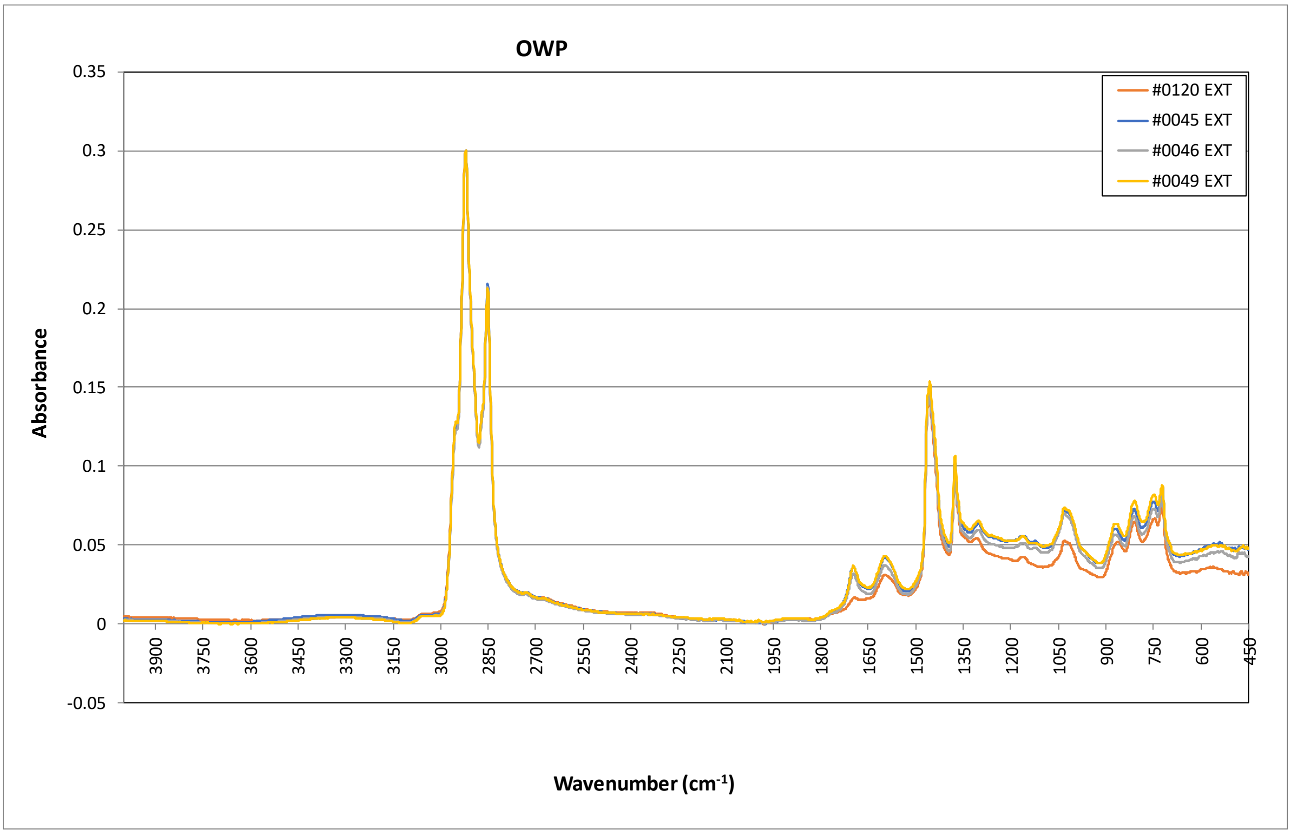
B.6 DORSET, TAS

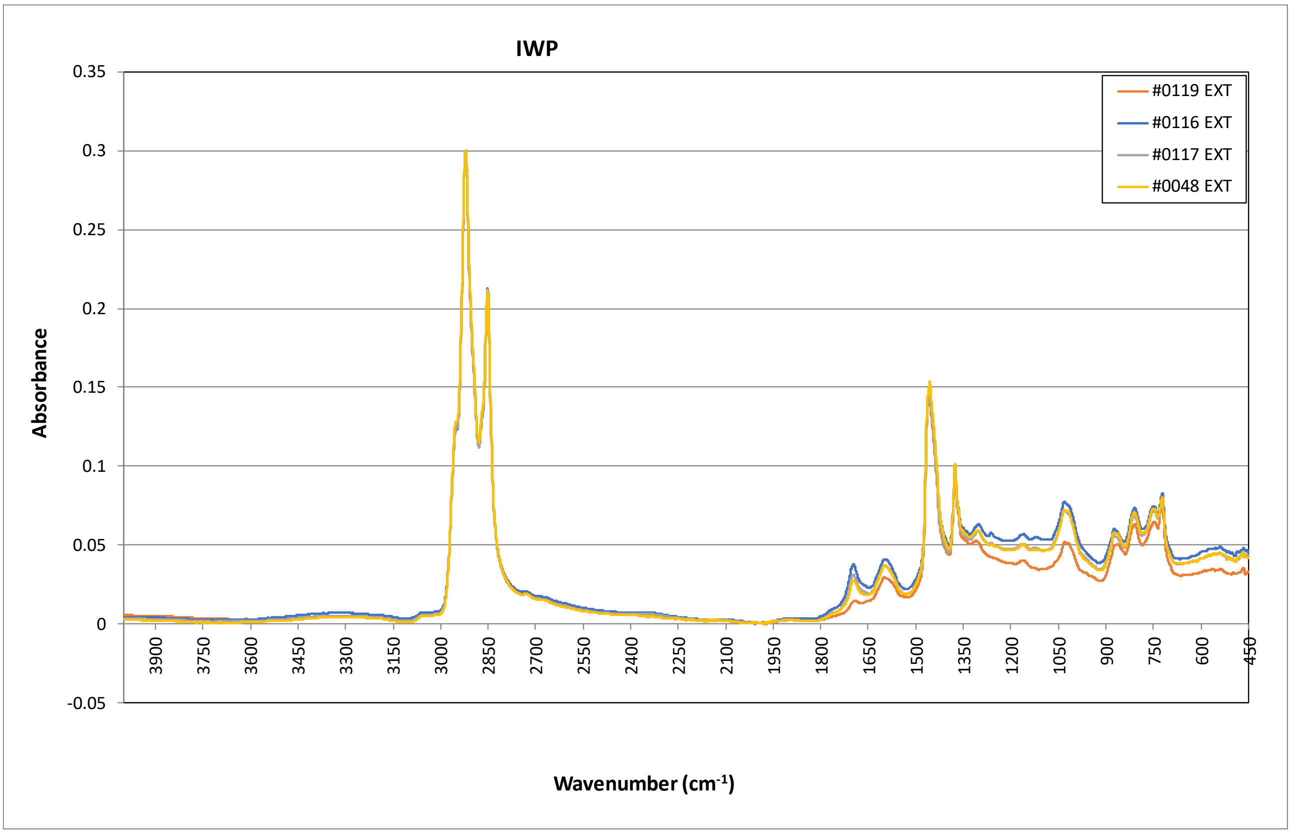
Figure B.5 Normalised spectra – Dorset

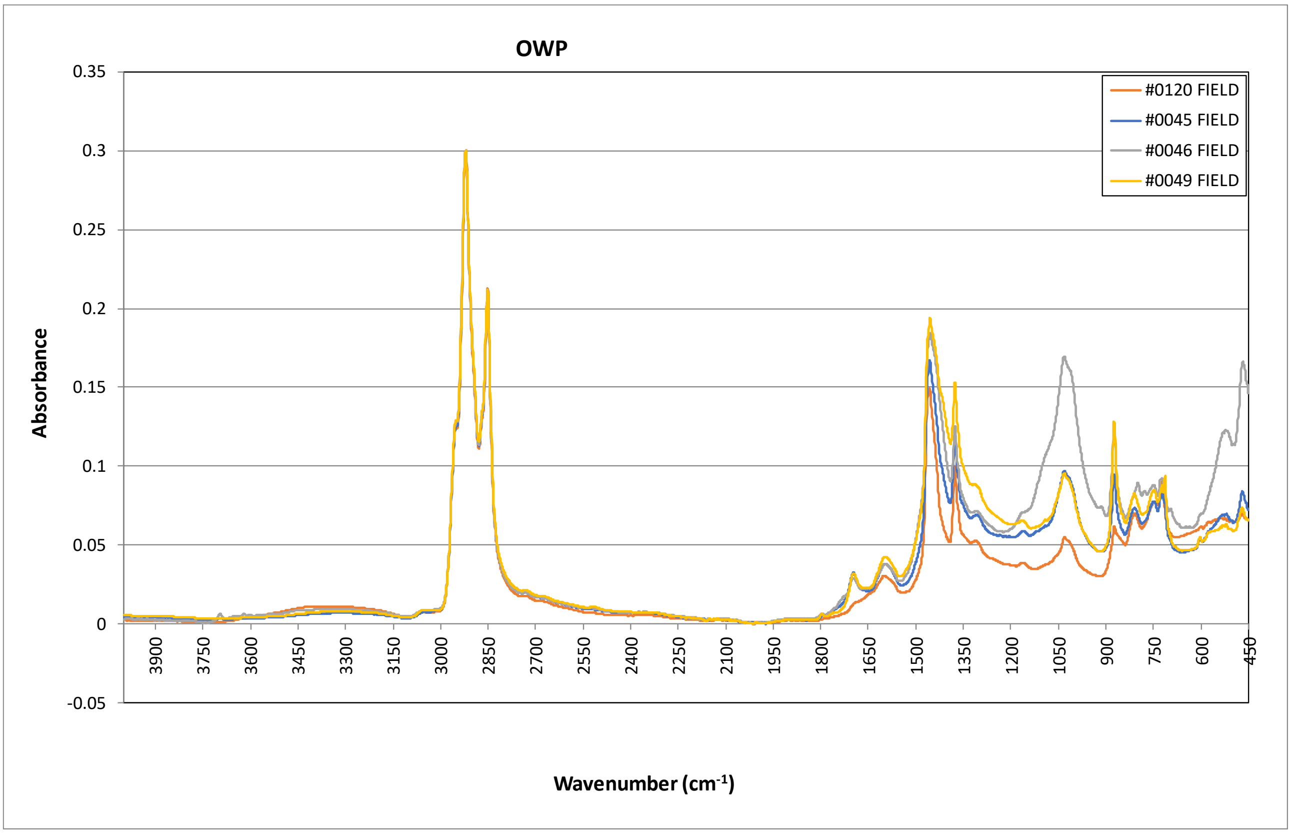


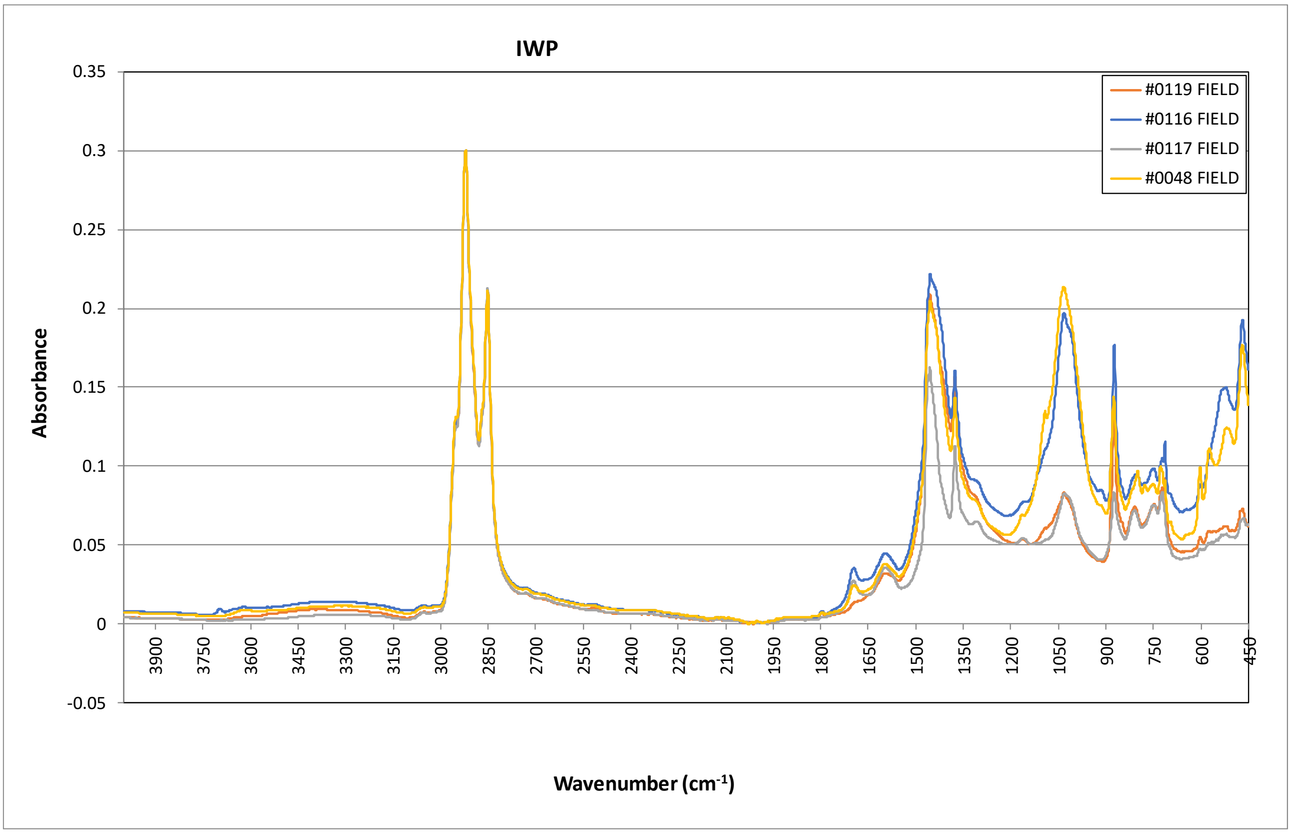
B.7 YORKE PENINSULA, SA

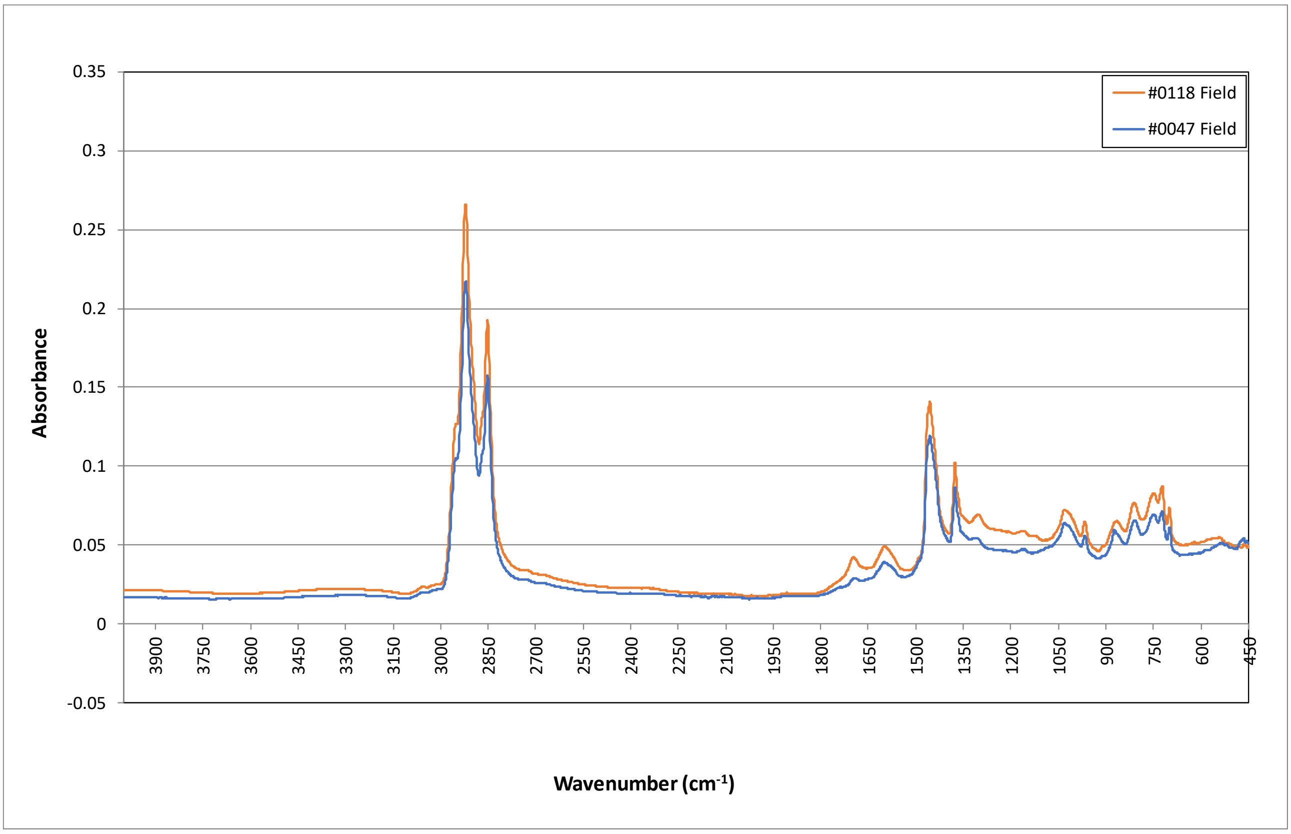
Figure B.6 Normalised spectra – Yorke Peninsula





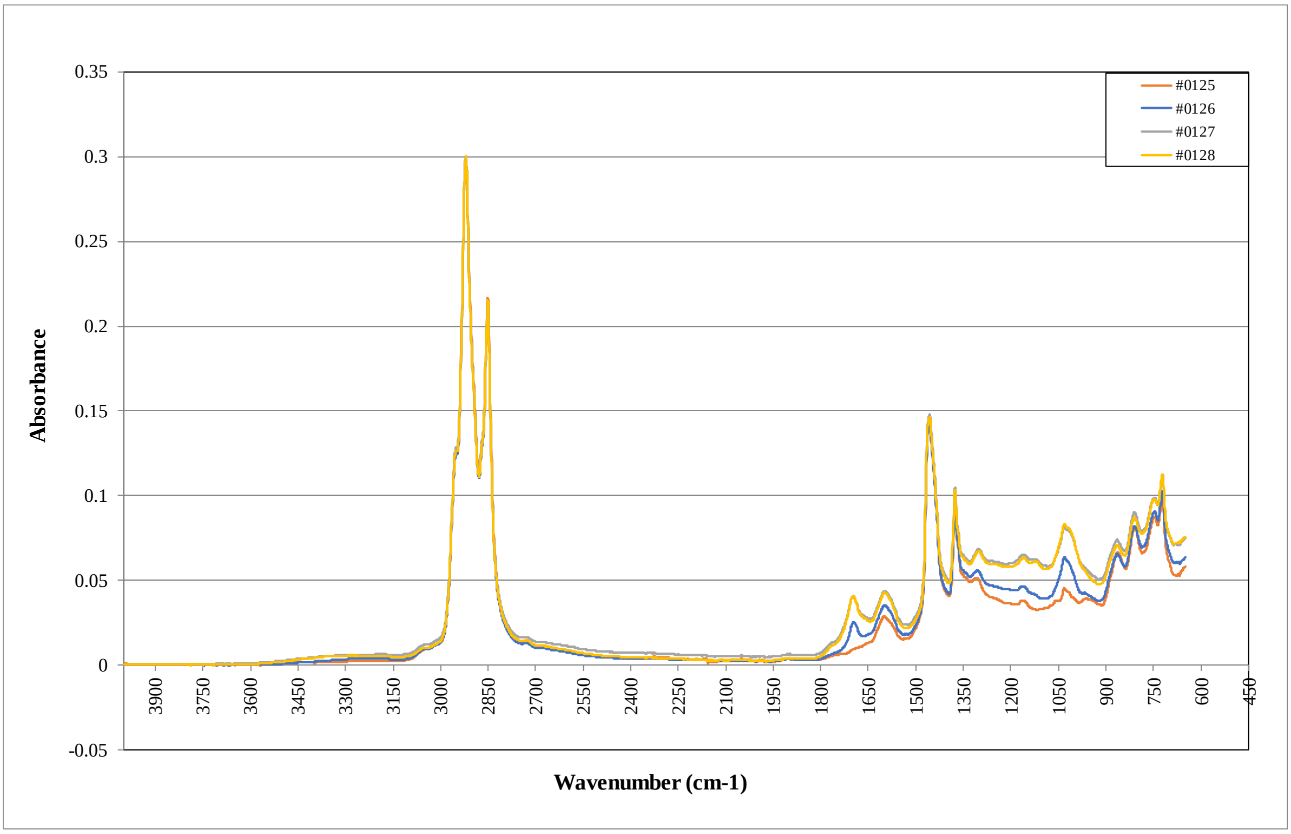

OWP
Absorbance
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
#0120 FIELD
#0045 FIELD
#0046 FIELD
#0049 FIELD
3900
3750
3600
3450
3300
3150
3000
2850
2700
2550
2400
2250
2100
1950
1800
1650
1500
1350
1200
1050
900
750
600
450
Wavenumber (cm-1)


IWP
Absorbance
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
#0119 FIELD
#0116 FIELD
#0117 FIELD
#0048 FIELD
3900
3750
3600
3450
3300
3150
3000
2850
2700
2550
2400
2250
2100
1950
1800
1650
1500
1350
1200
1050
900
750
600
450
Wavenumber (cm-1)



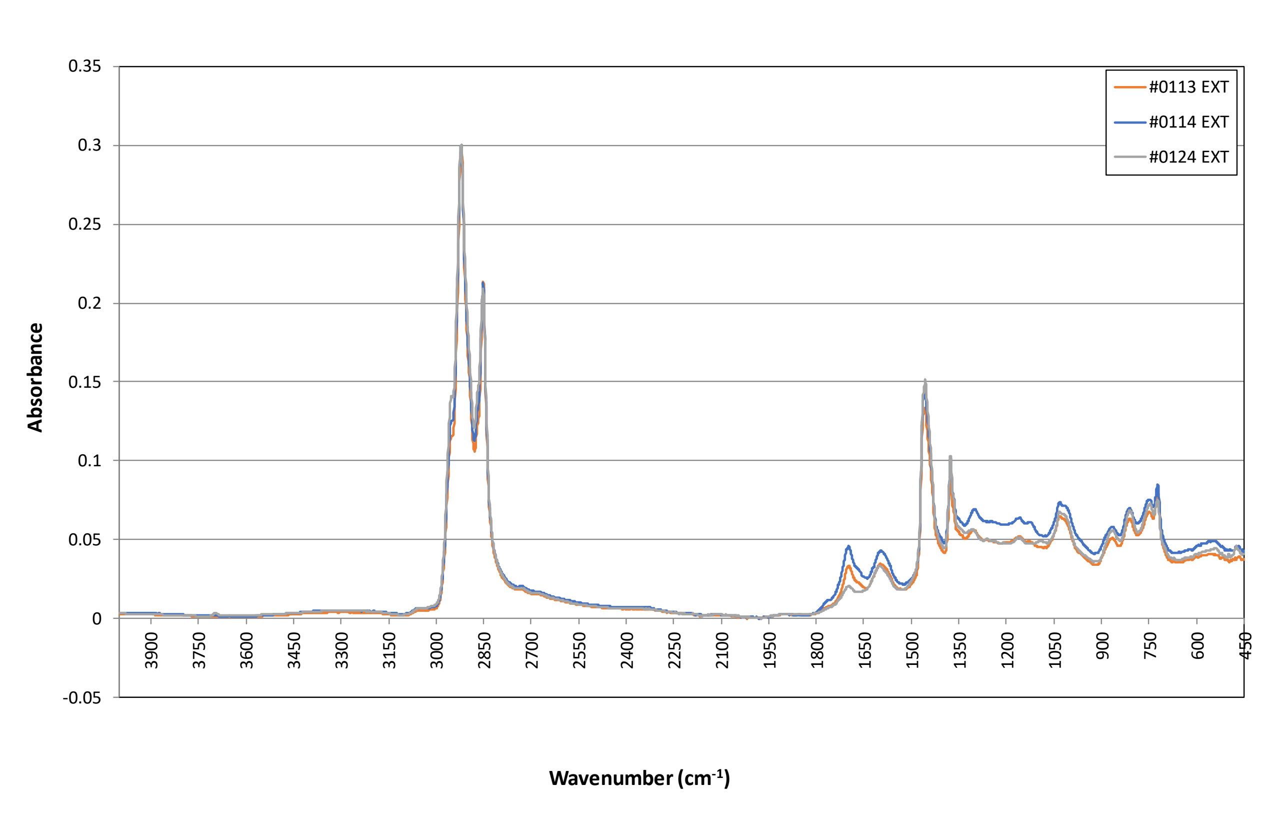
B.8 COOBER PEDY, SA

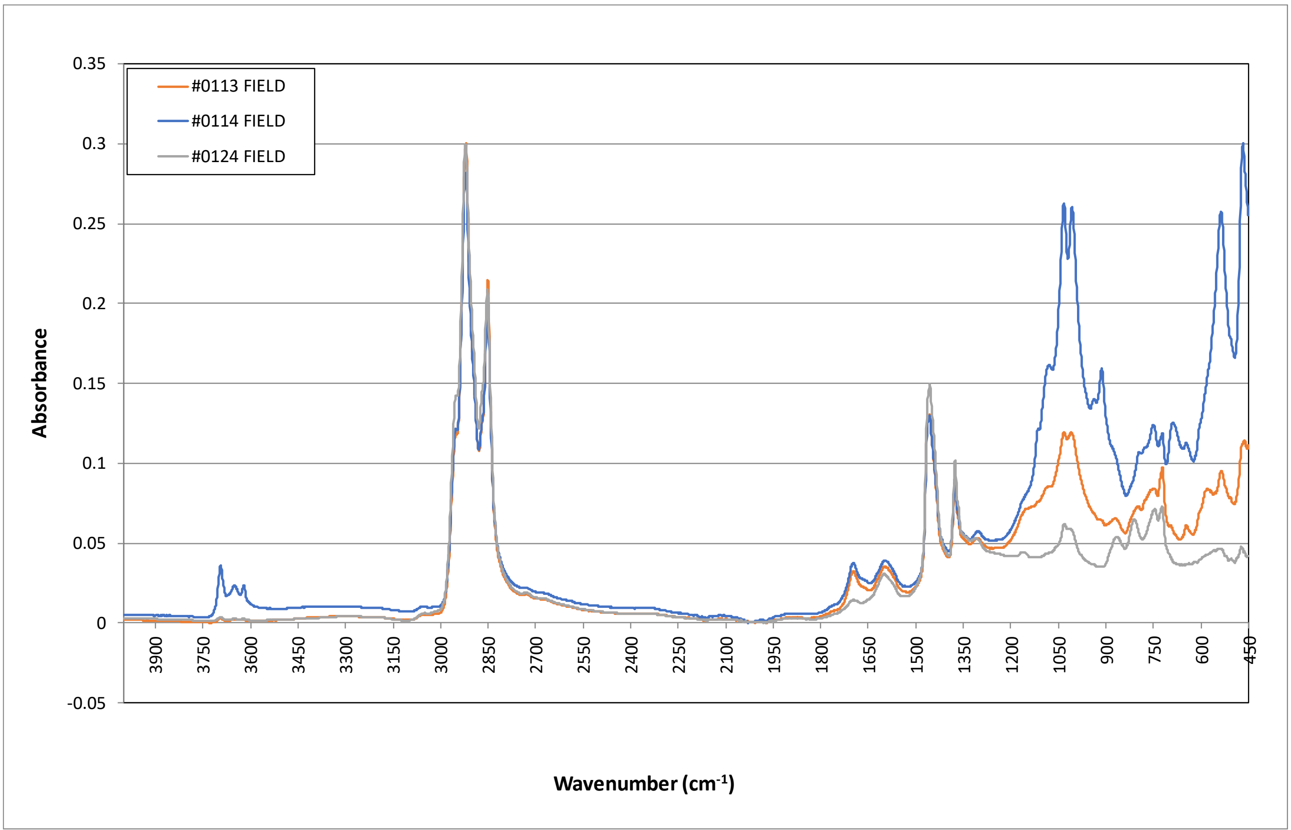
Figure B.7 Normalised spectra – Coober Pedy

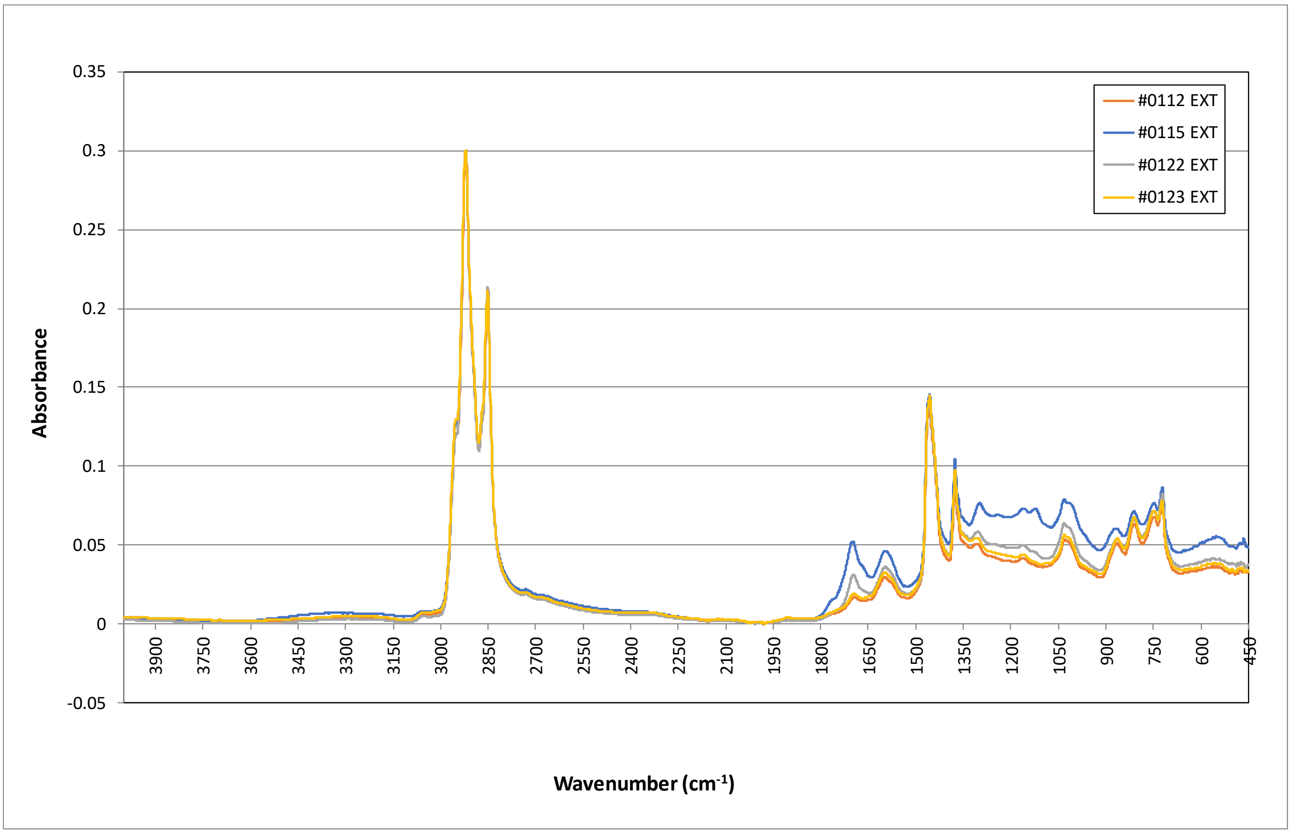


B.9 BRUCE ROCK, WA

Figure B.8 Normalised spectra – Bruce Rock






Absorbance
Wavenumber (cm-1)
#0112 EXT
#0115 EXT
#0122 EXT
#0123 EXT
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
3900
3750
3600
3450
3300
3150
3000
2850
2700
2550
2400
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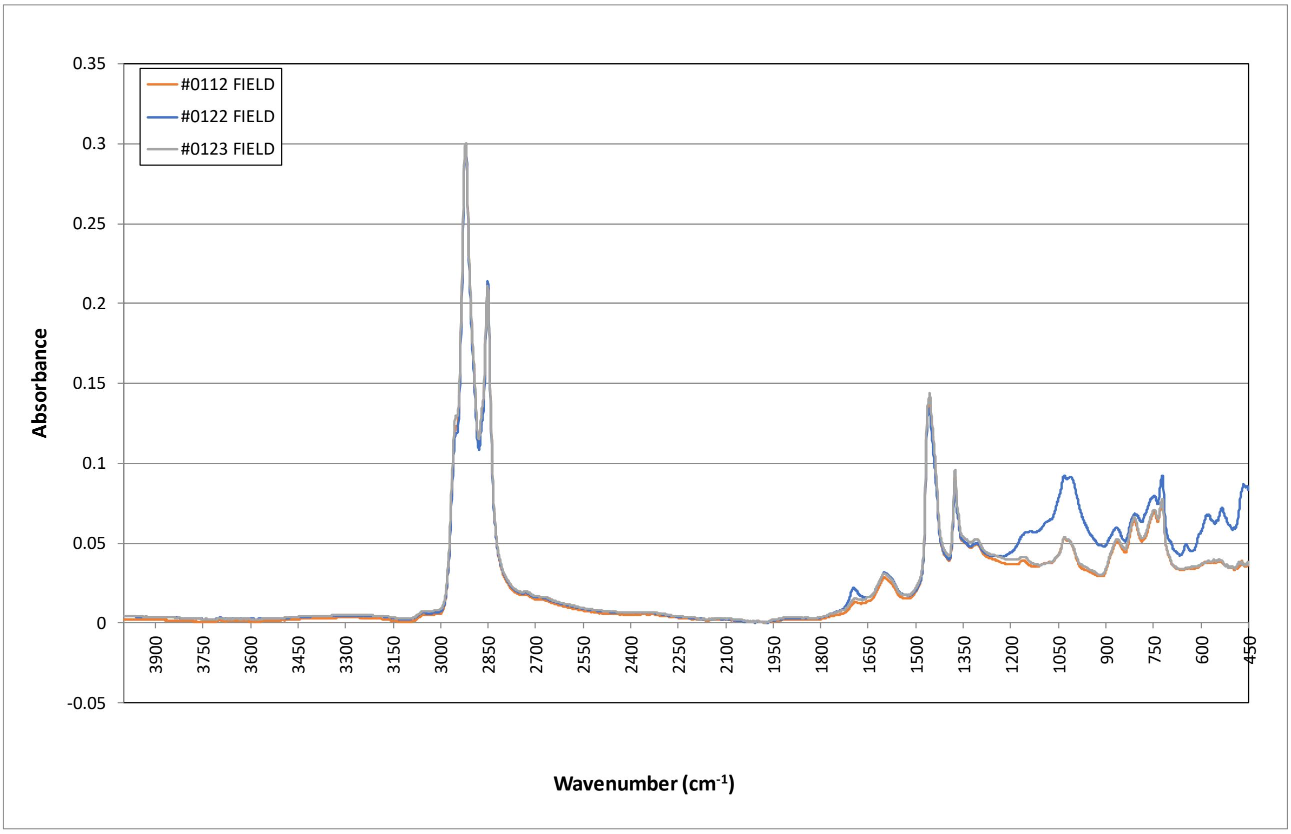
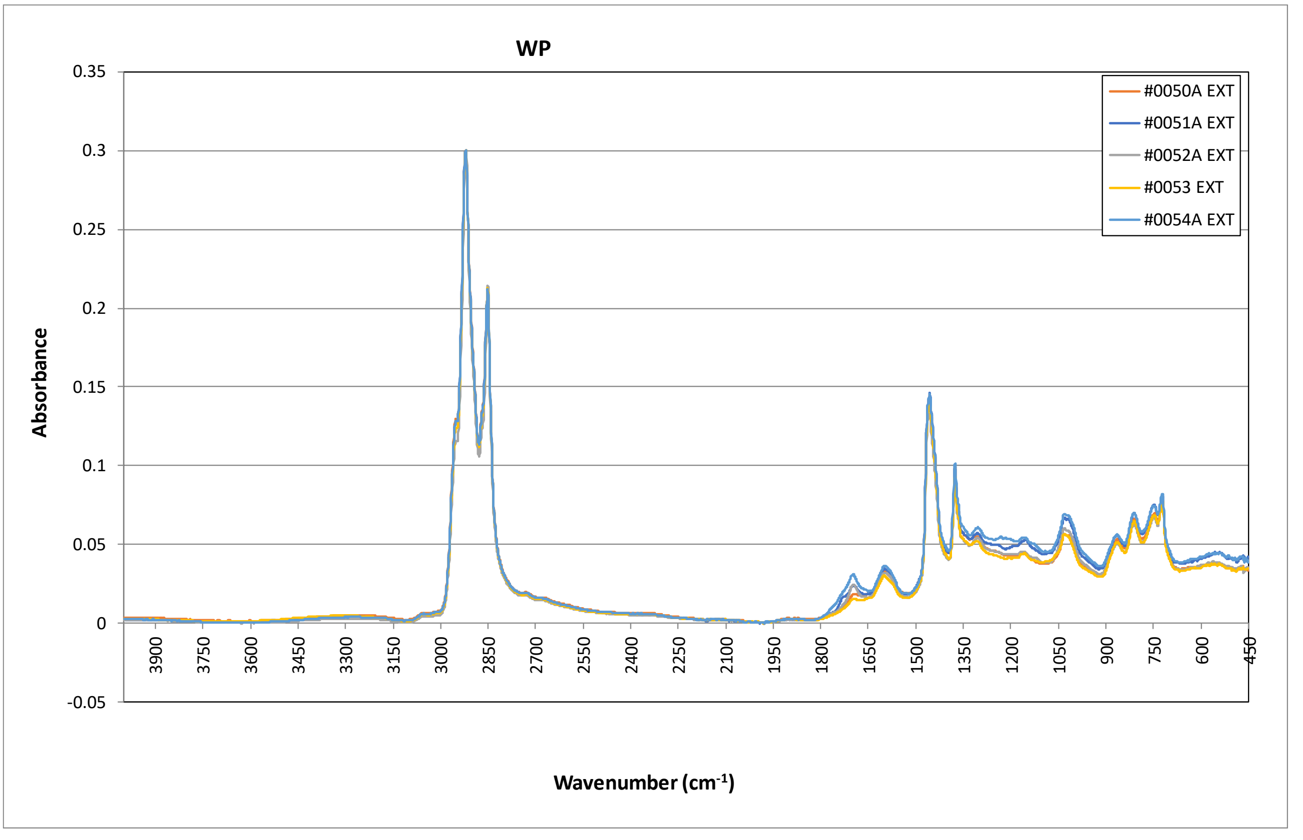
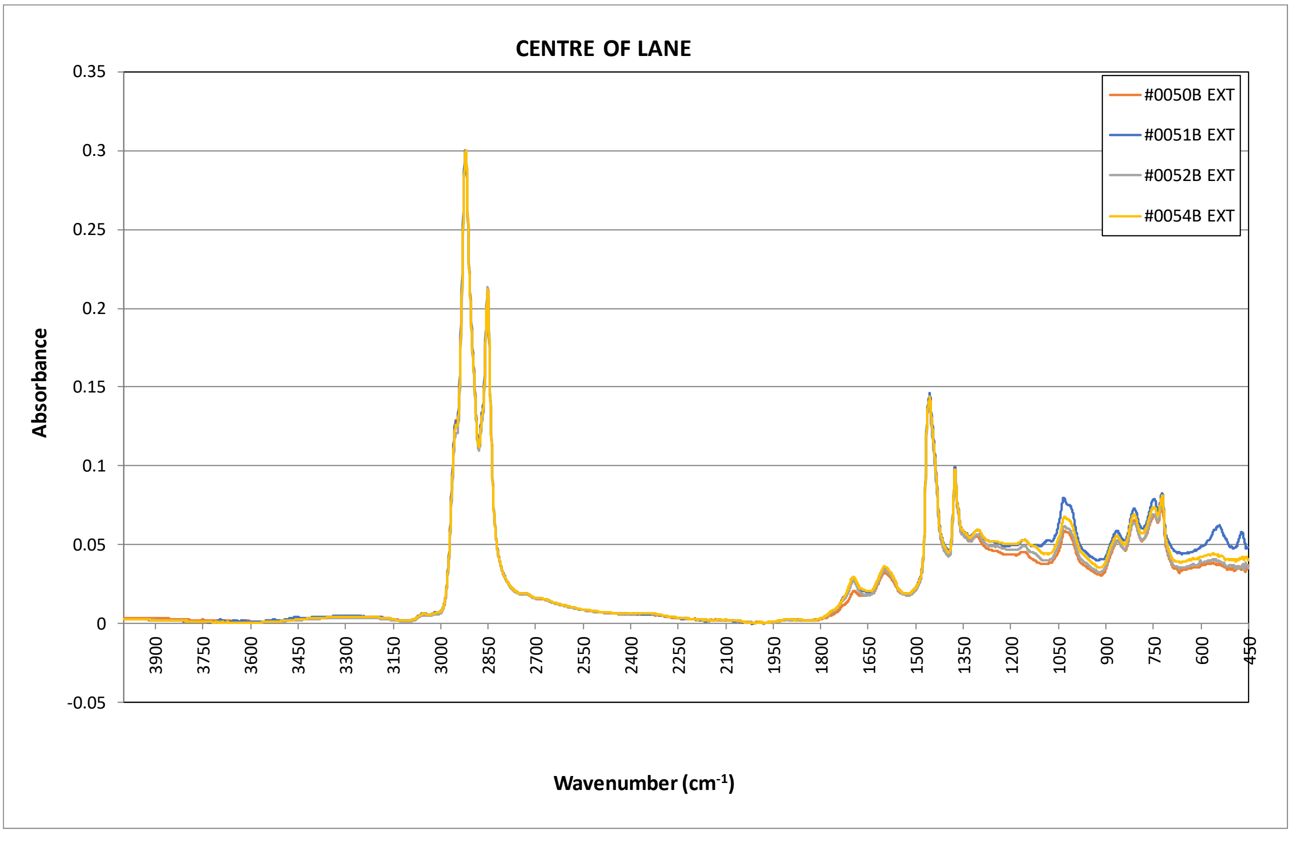
1050
900
750
600
450

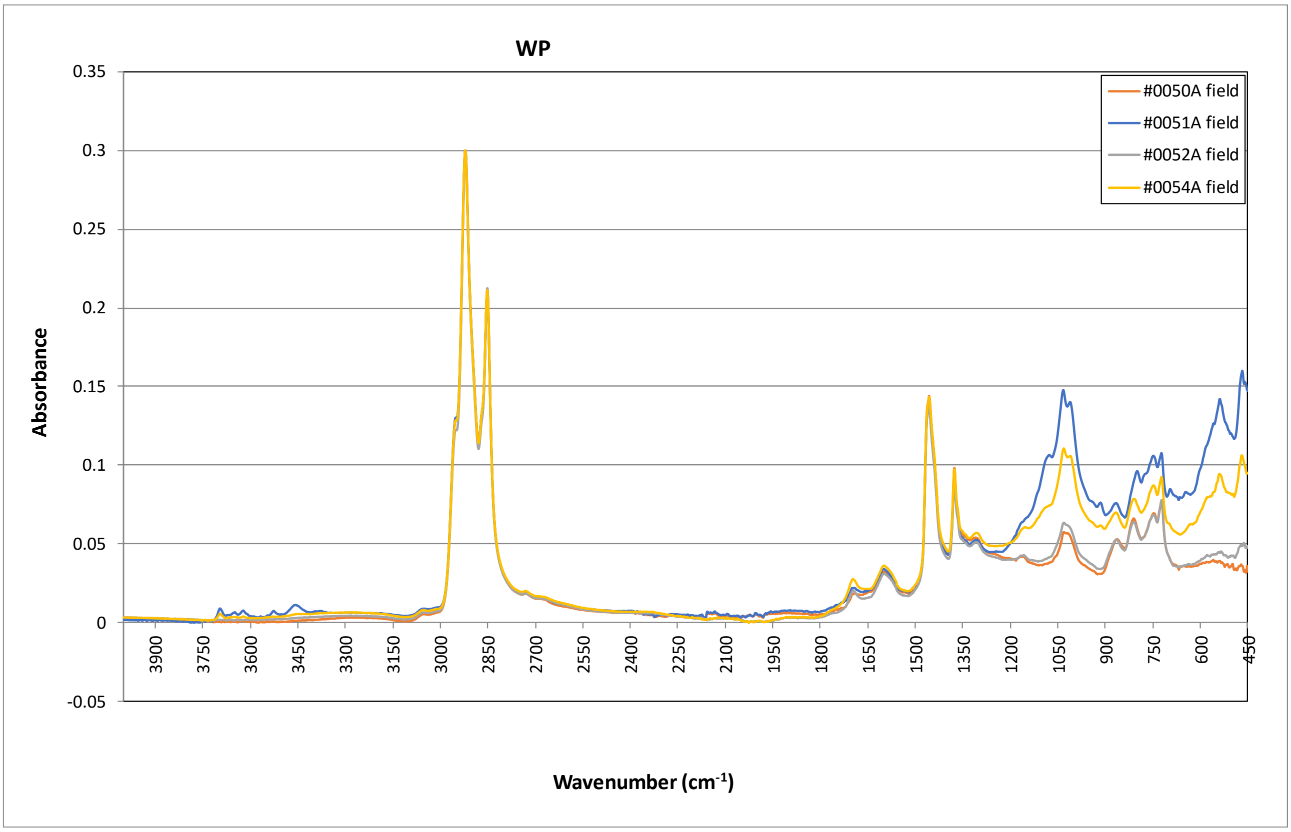

Absorbance
Wavenumber (cm-1)
#0112 FIELD
#0122 FIELD
#0123 FIELD
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
3900
3750
3600
3450
3300
3150
3000
2850
2700
2550
2400
2250
2100
1950
1800
1650
1500
1350
1200
1050
900
750
600
450

B.10 CRANBROOK, WA

Figure B.9 Normalised spectra – Cranbrook



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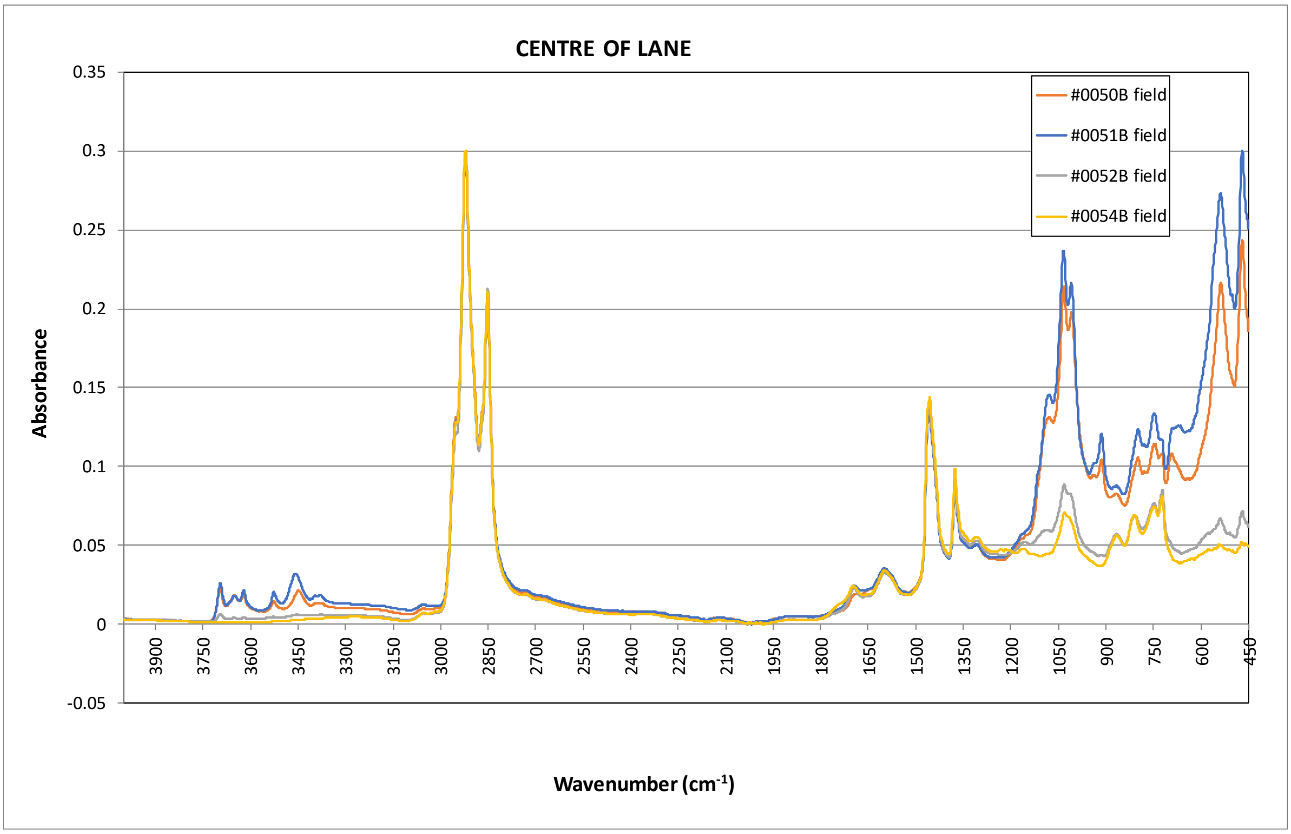
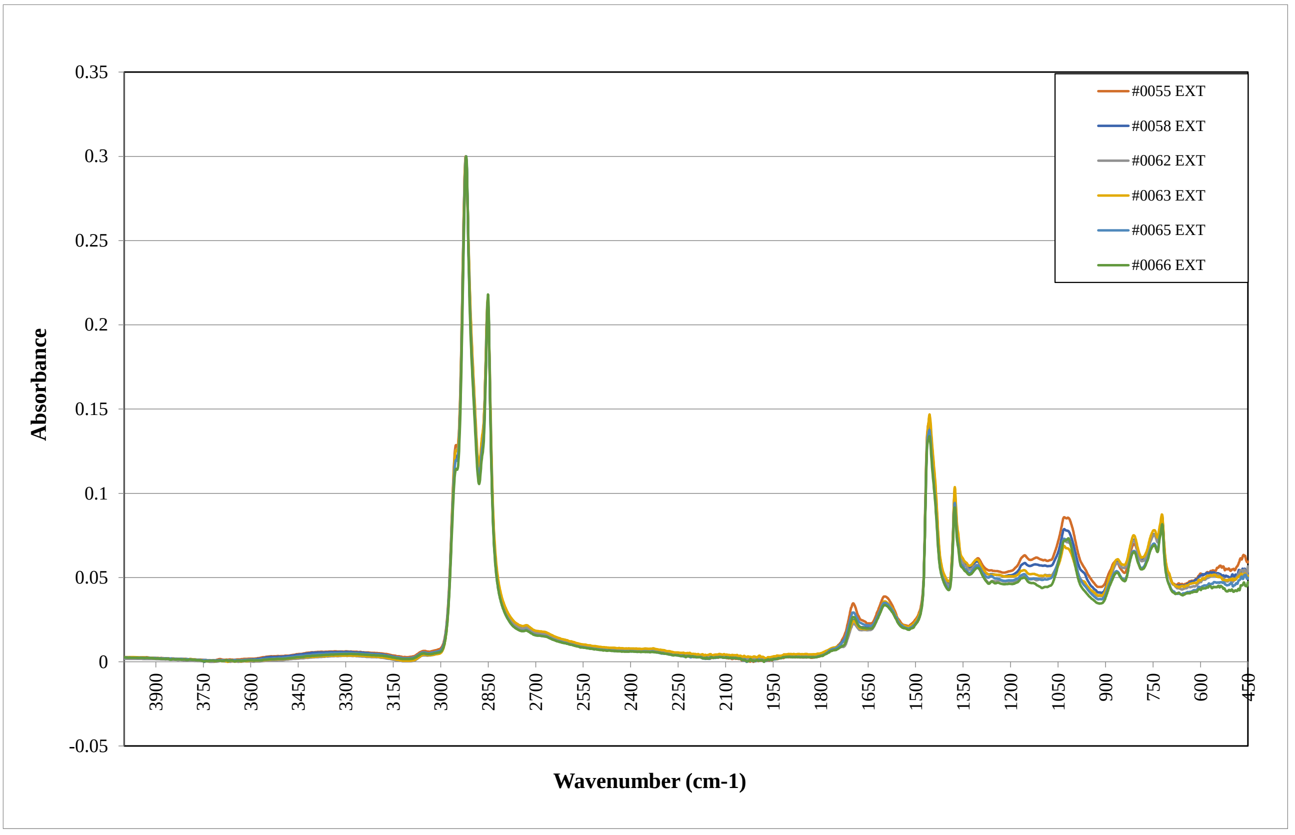
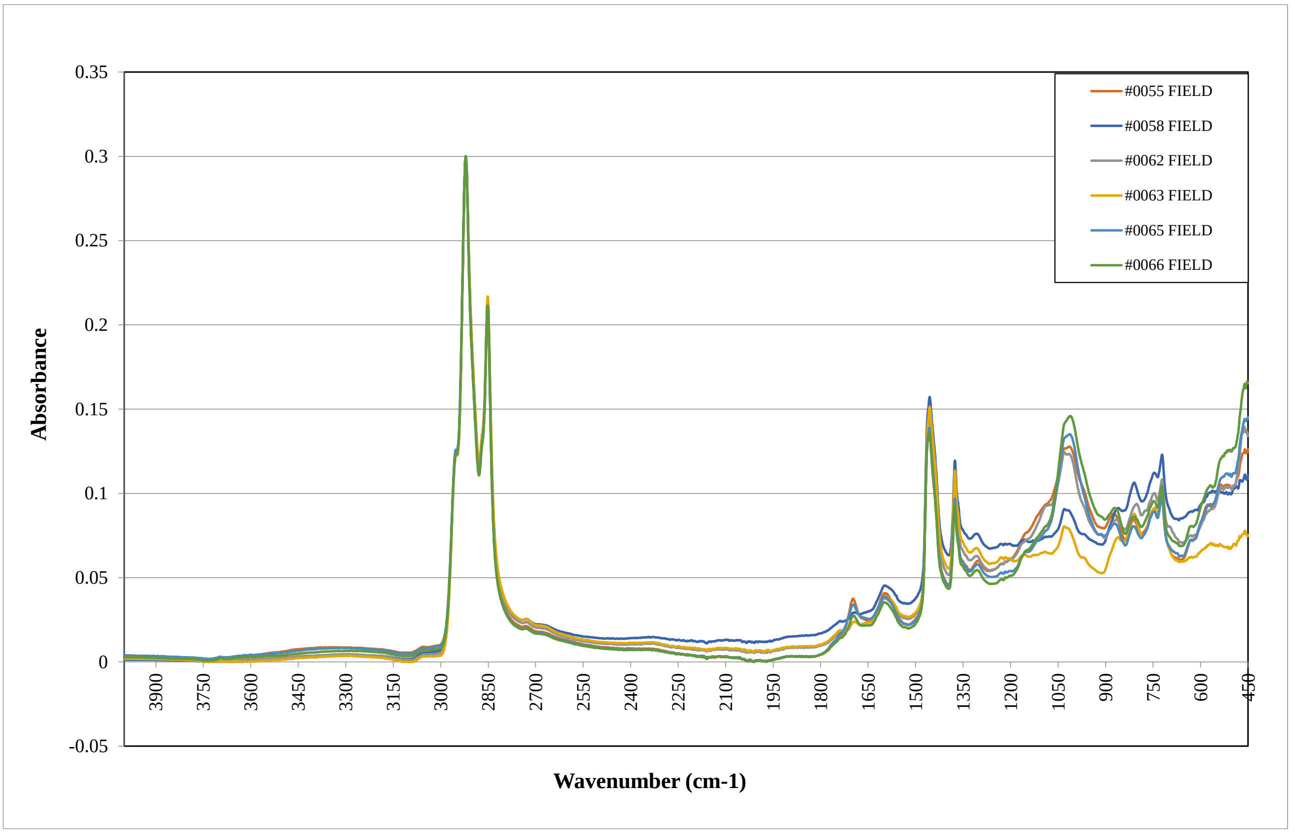
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
Absorbance
3900
3750
3600
3450
3300
3150
3000
2850
2700
2550
2400
2250
2100
1950
1800
1650
1500
1350
1200
1050
900
750
600
450
Wavenumber (cm-1)
#0050A field
#0051A field
#0052A field
#0054A field

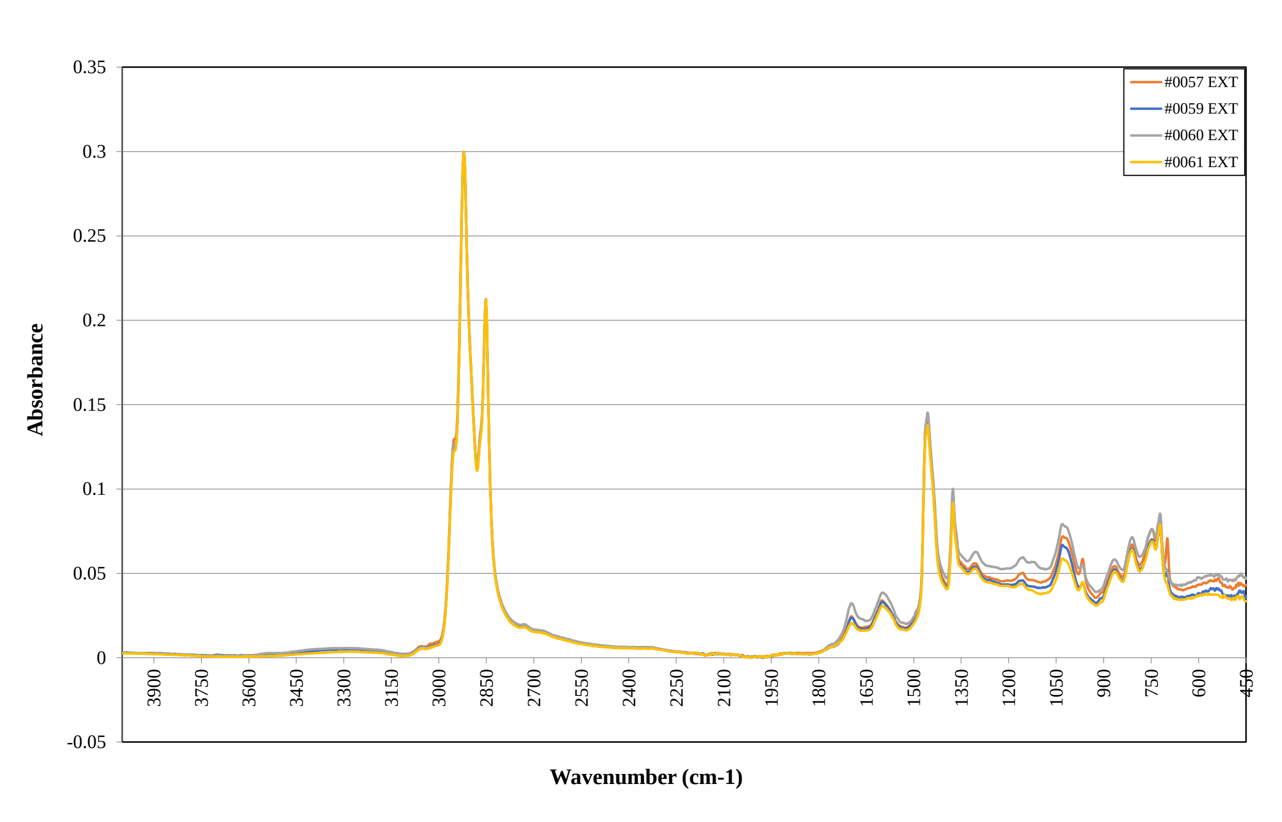

CENTRE OF LANE
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
Absorbance
3900
3750
3600
3450
3300
3150
3000
2850
2700
2550
2400
2250
2100
1950
1800
1650
1500
1350
1200
1050
900
750
600
450
Wavenumber (cm-1)
#0050B field
#0051B field
#0052B field
#0054B field

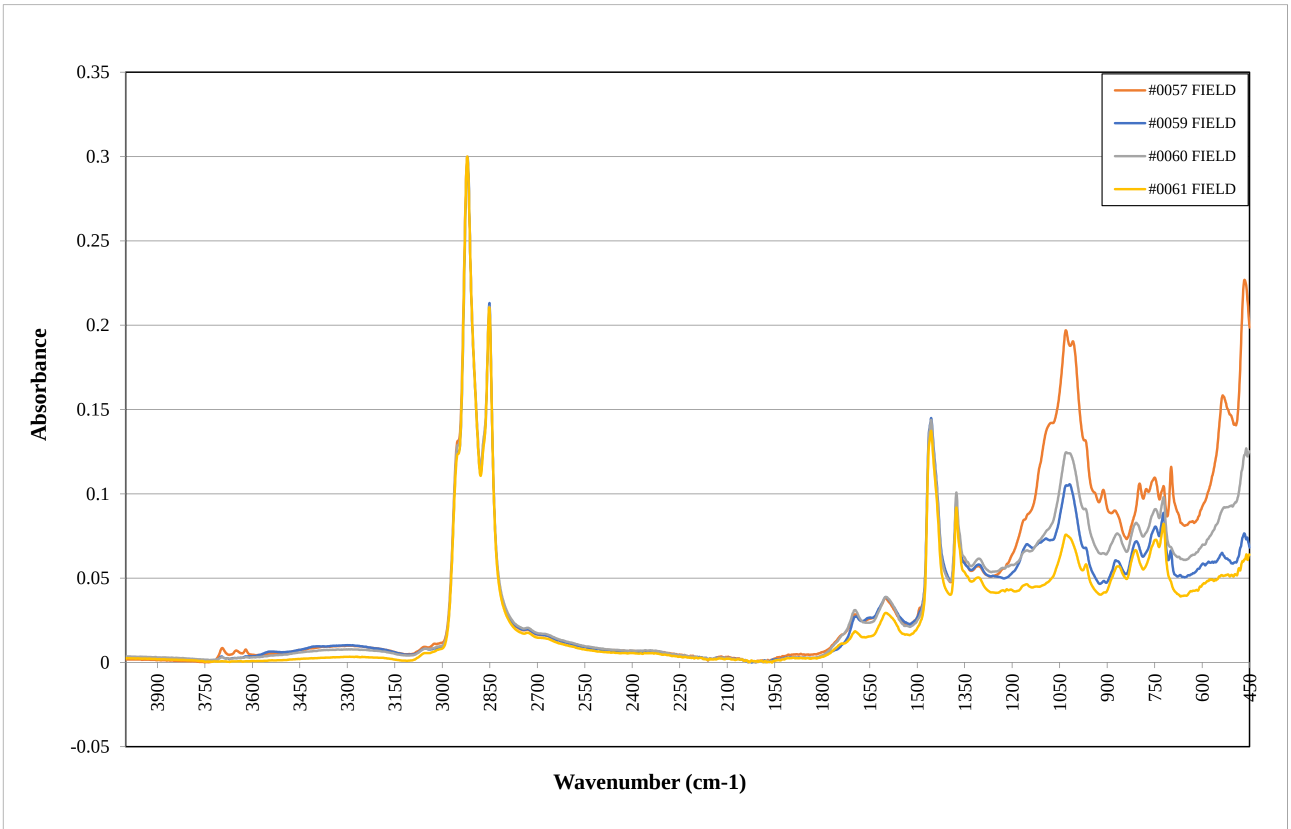
B.11 DARLING DOWNS, QLD

Figure B.10 Normalised spectra – Darling Downs



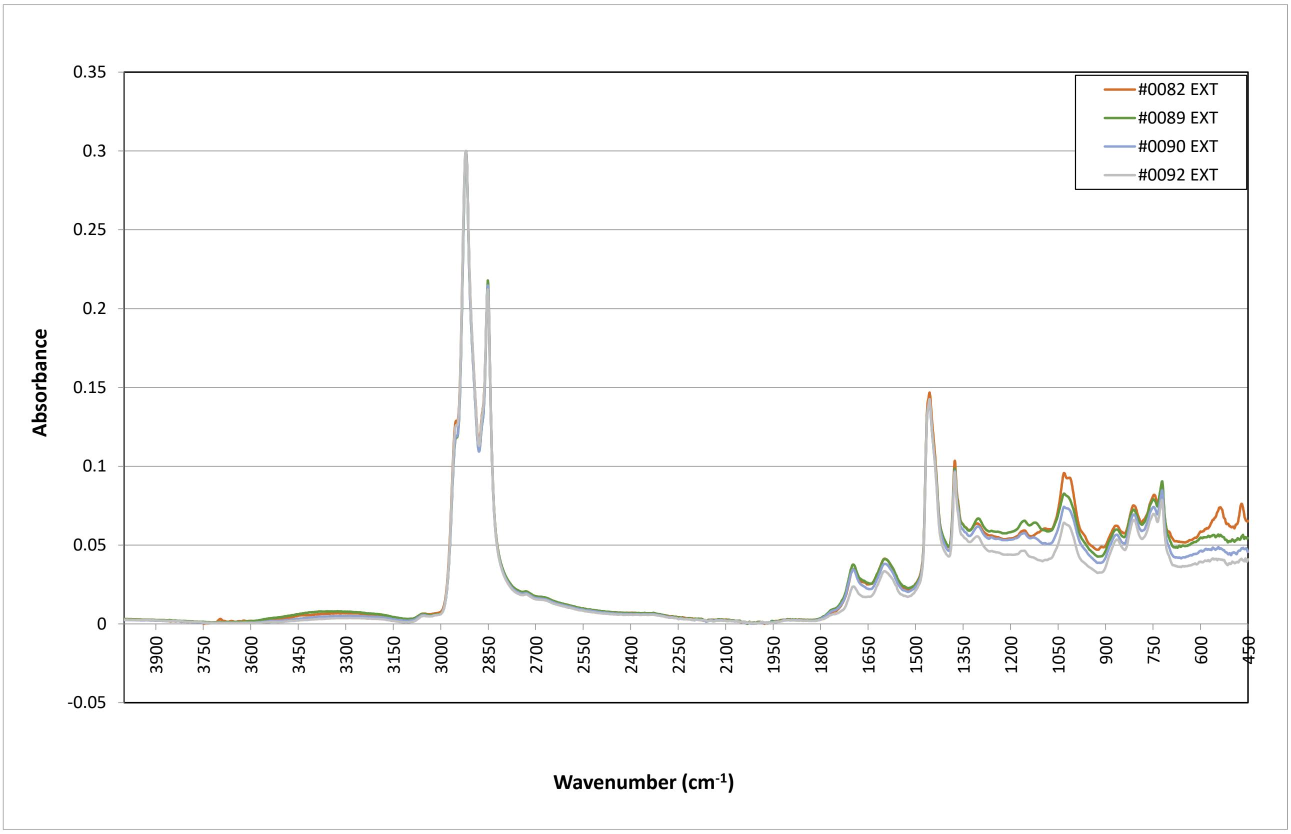


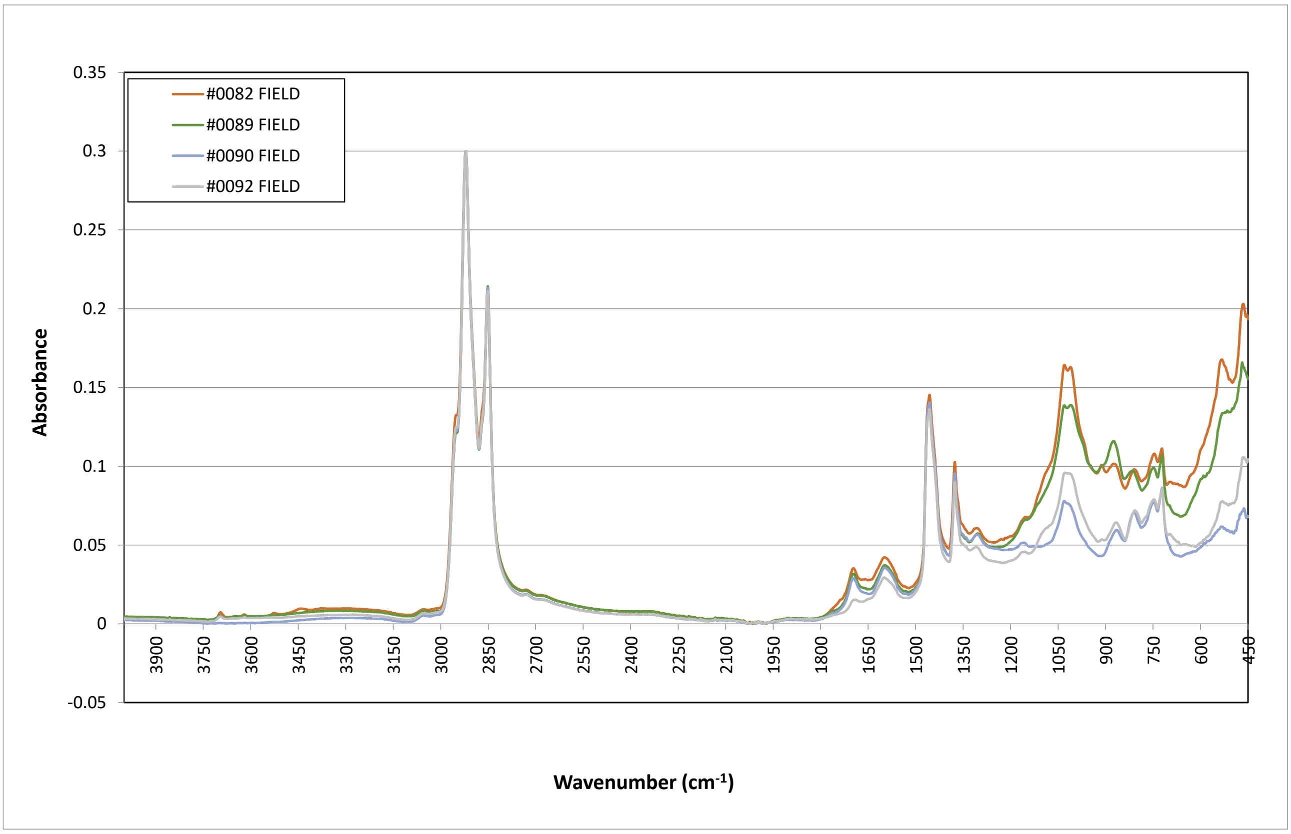

0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
Absorbance
3900
3750
3600
3450
3300
3150
3000
2850
2700
2550
2400
2250
2100
1950
1800
1650
1500
1350
1200
1050
900
750
600
450
Wavenumber (cm-1)
#0057 EXT
#0059 EXT
#0060 EXT
#0061 EXT


0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
Absorbance
3900
3750
3600
3450
3300
3150
3000
2850
2700
2550
2400
2250
2100
1950
1800
1650
1500
1350
1200
1050
900
750
600
450
Wavenumber (cm-1)
#0057 FIELD
#0059 FIELD
#0060 FIELD
#0061 FIELD

B.12 FAR NORTH, QLD

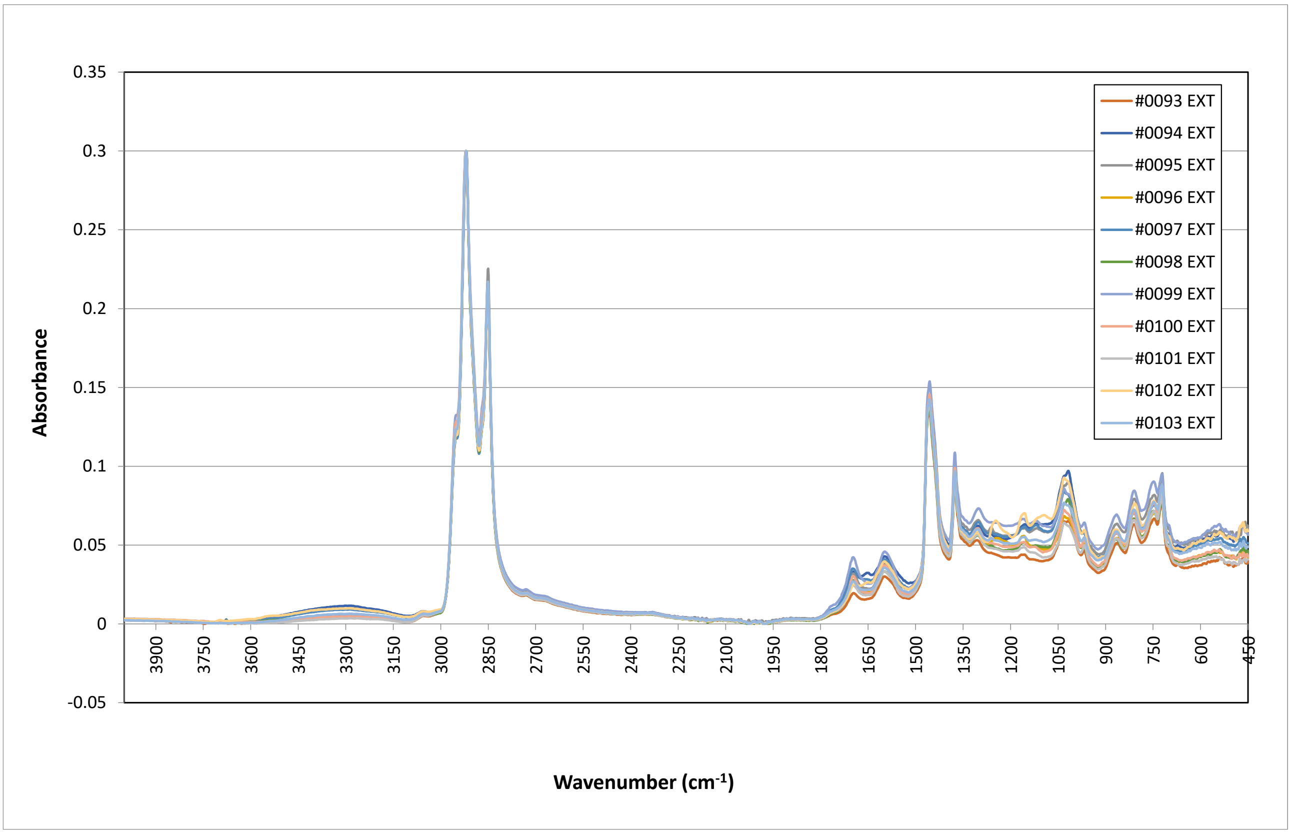
Figure B.11 Normalised spectra – Far North

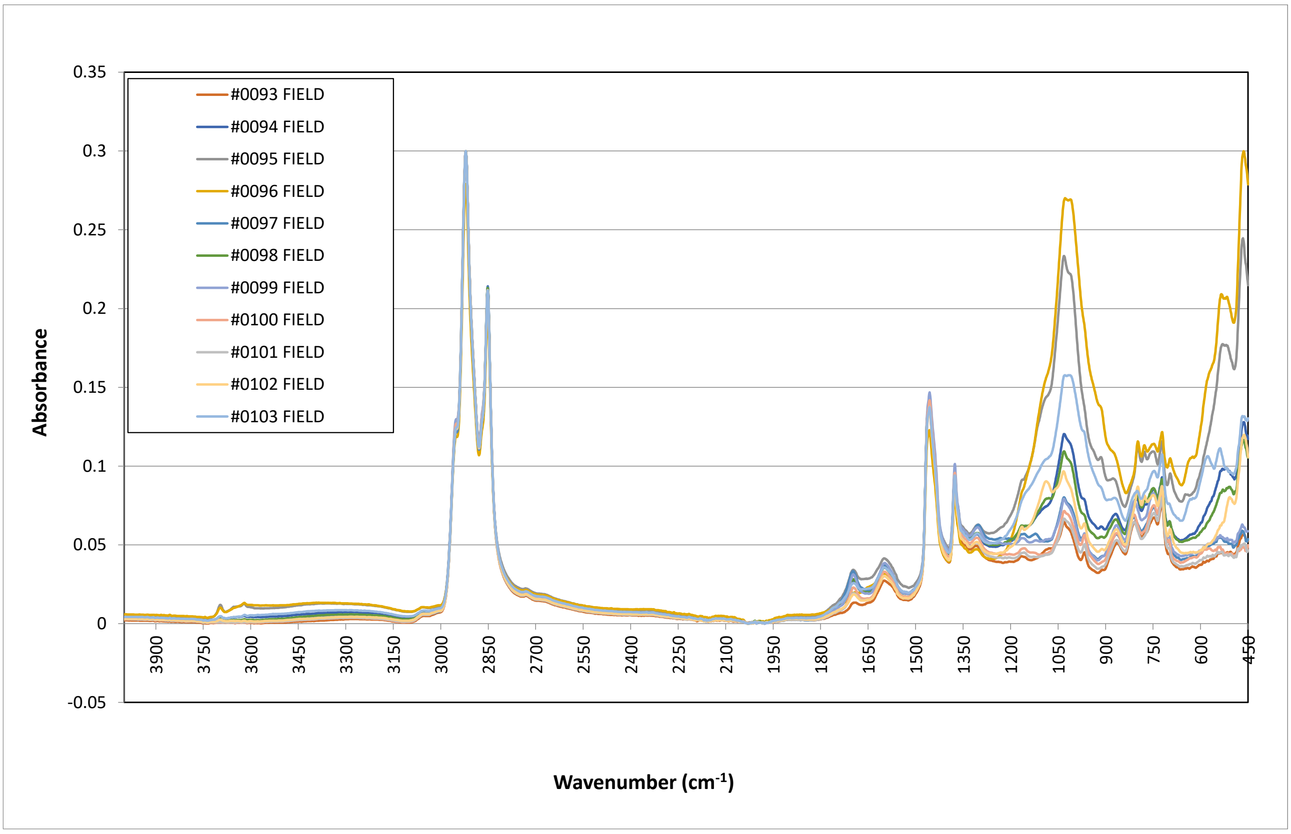




B.13 CENTRAL WEST, QLD

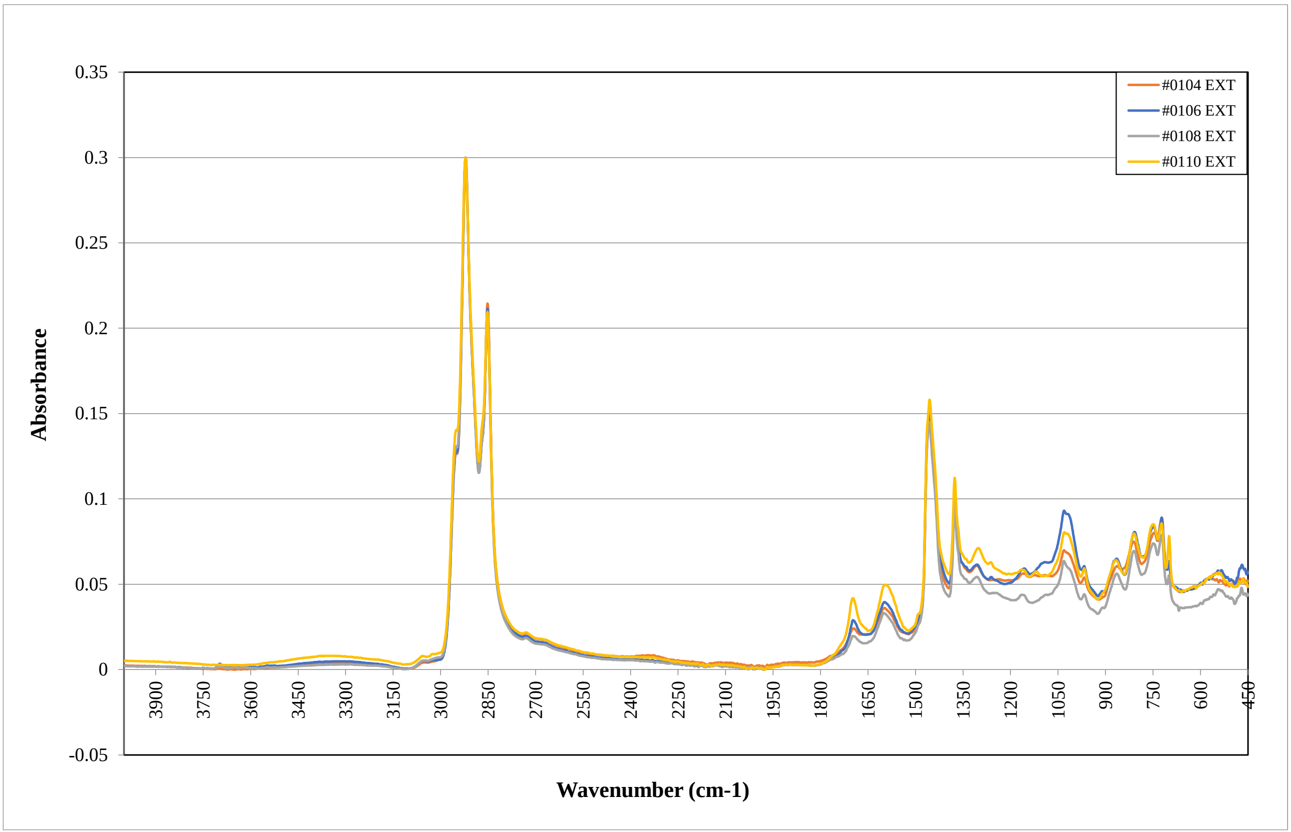
Figure B.12 Normalised spectra – Central West

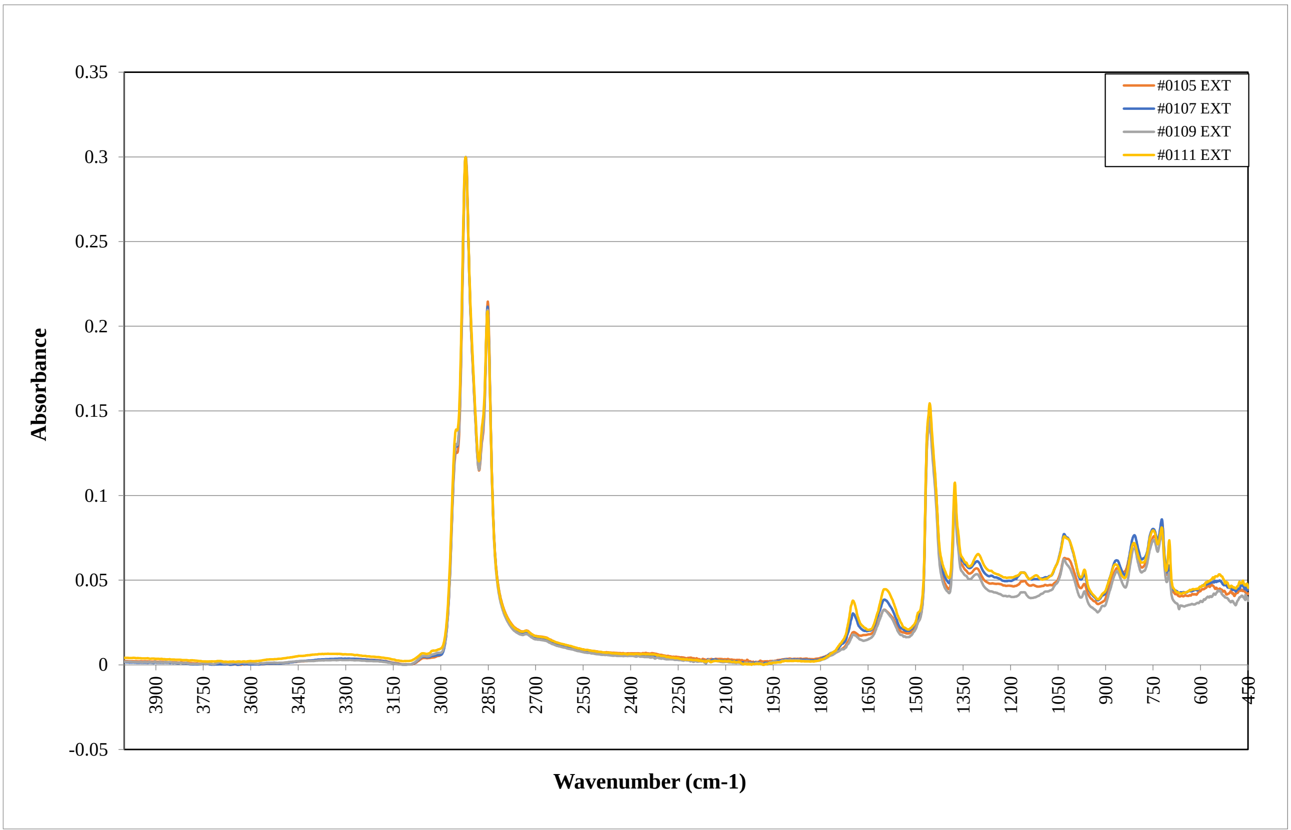


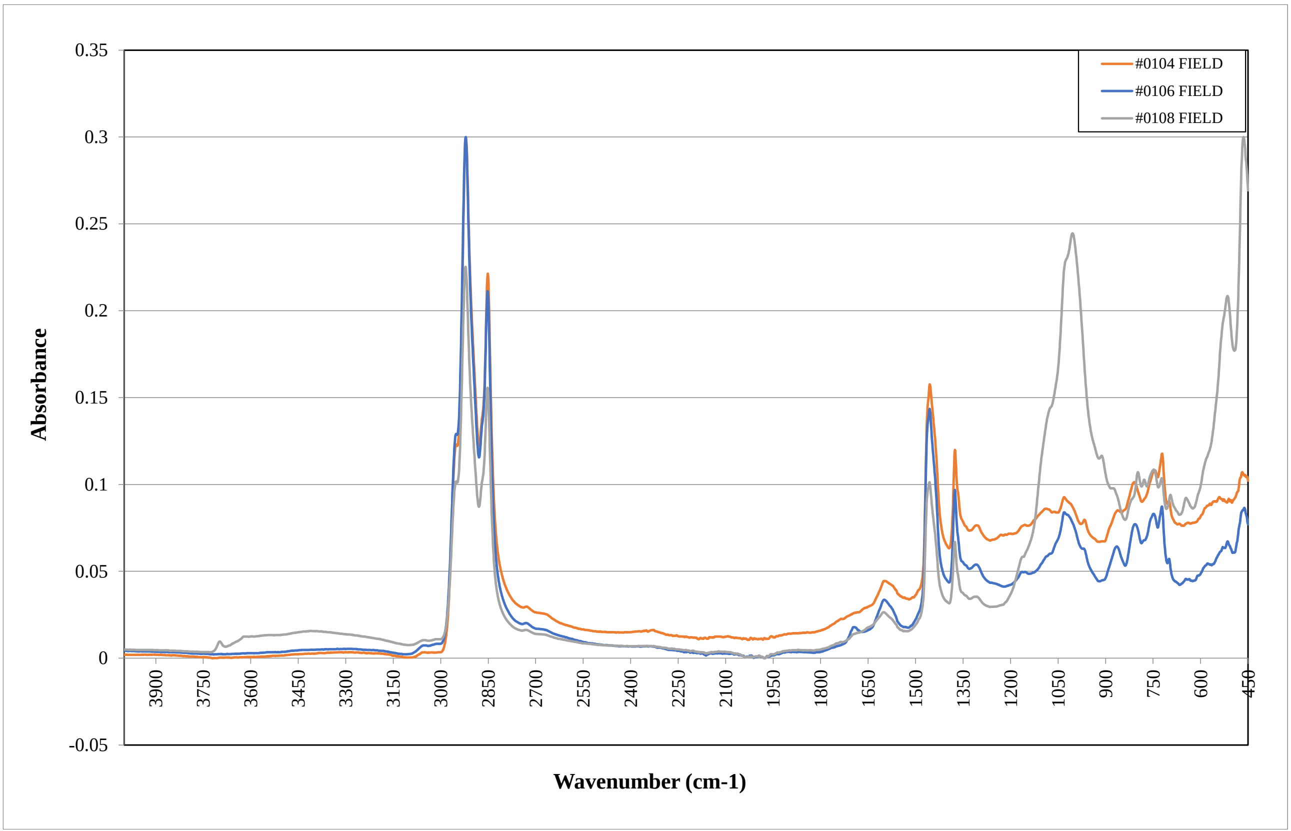


B.14 CANBERRA, ACT

Figure B.13 Normalised spectra – Canberra



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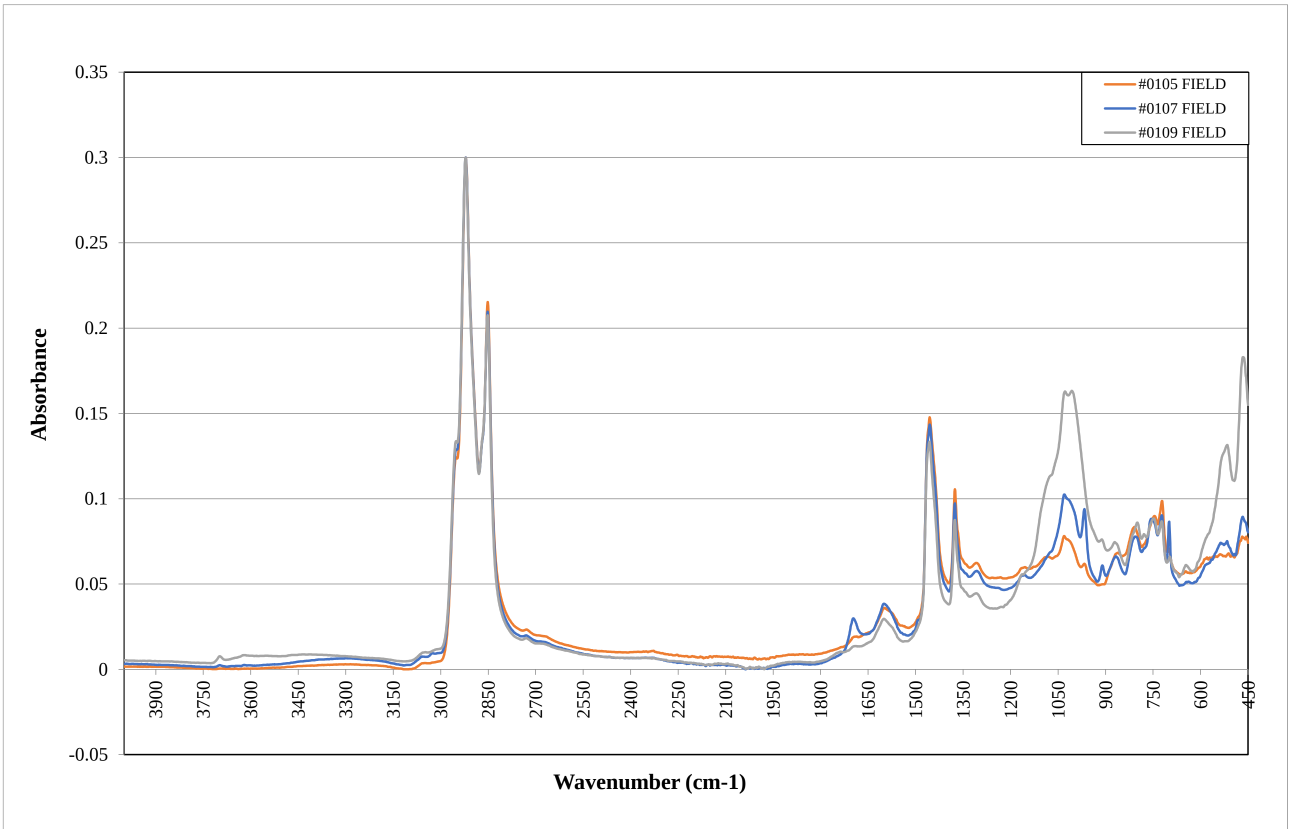
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
Absorbance
3900
3750
3600
3450
3300
3150
3000
2850
2700
2550
2400
2250
2100
1950
1800
1650
1500
1350
1200
1050
900
750
600
450
Wavenumber (cm-1)
#0104 FIELD
#0106 FIELD
#0108 FIELD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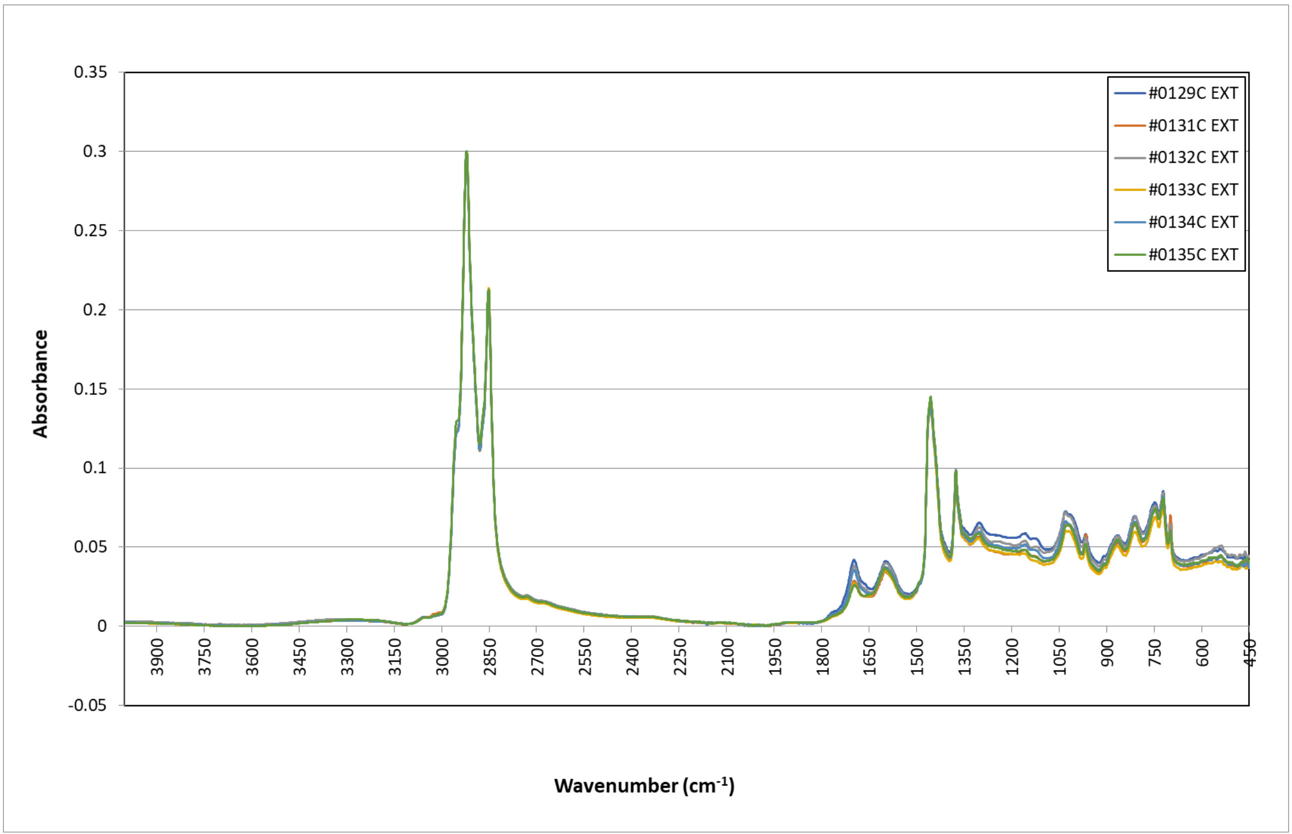
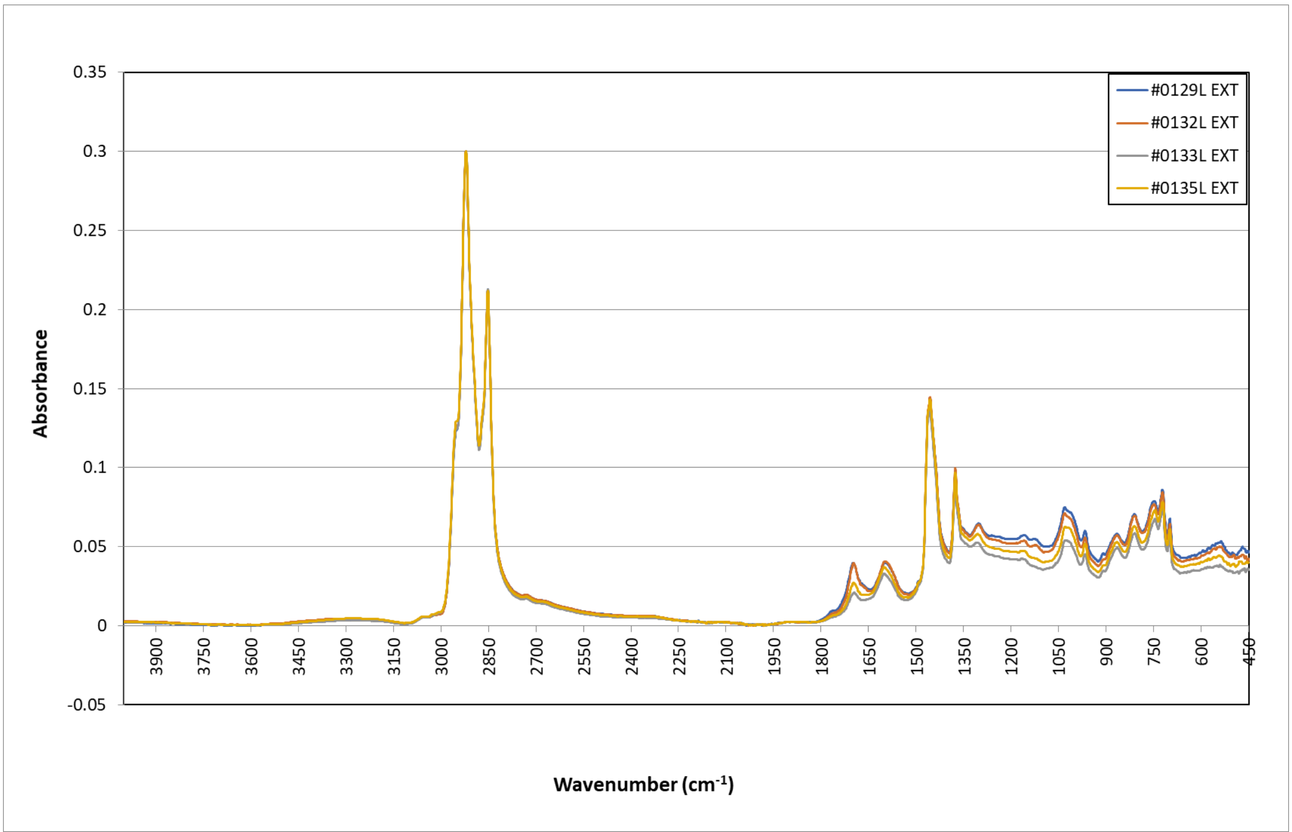
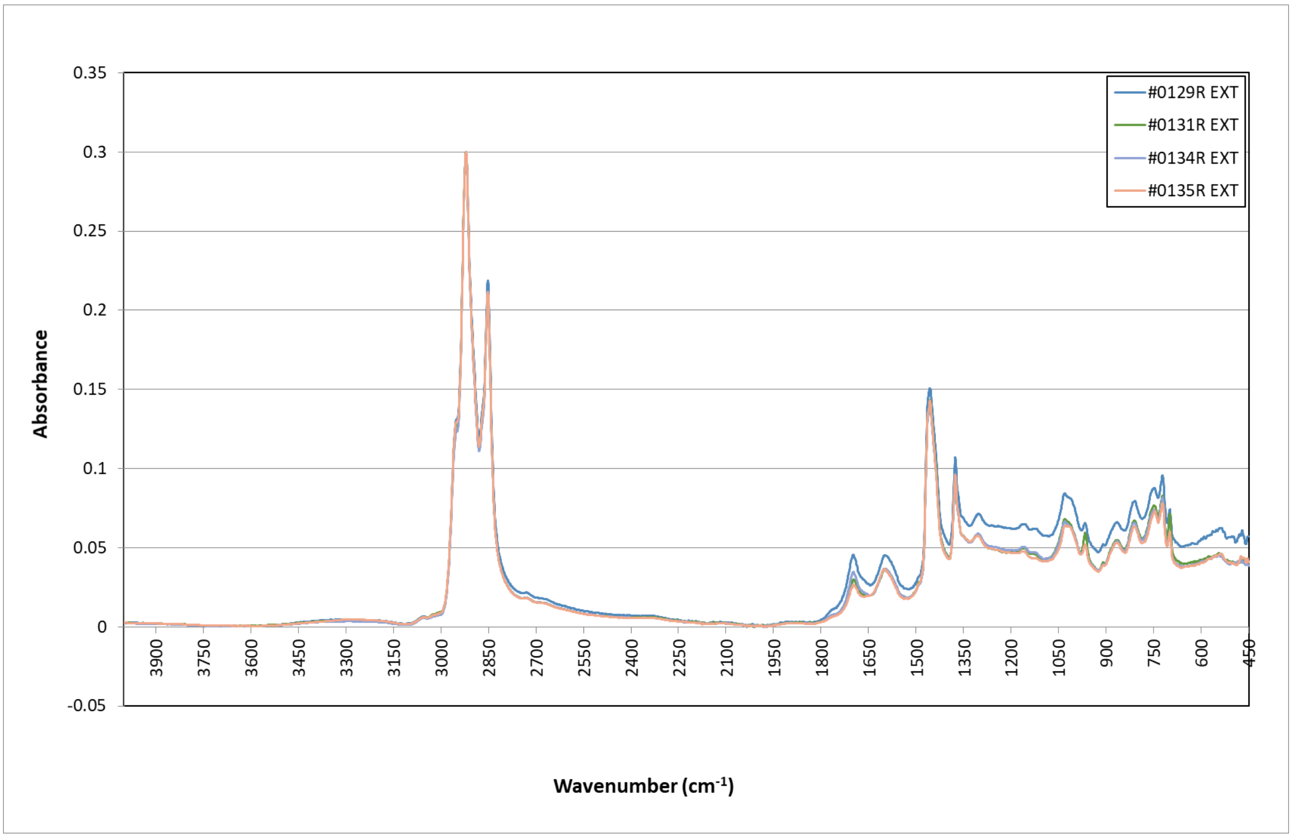
0.25
0.2
0.15
0.1
0.05
0
-0.05
Absorbance
3900
3750
3600
3450
3300
3150
3000
2850
2700
2550
2400
2250
2100
1950
1800
1650
1500
1350
1200
1050
900
750
600
450
Wavenumber (cm-1)
#0105 FIELD
#0107 FIELD
#0109 FIELD

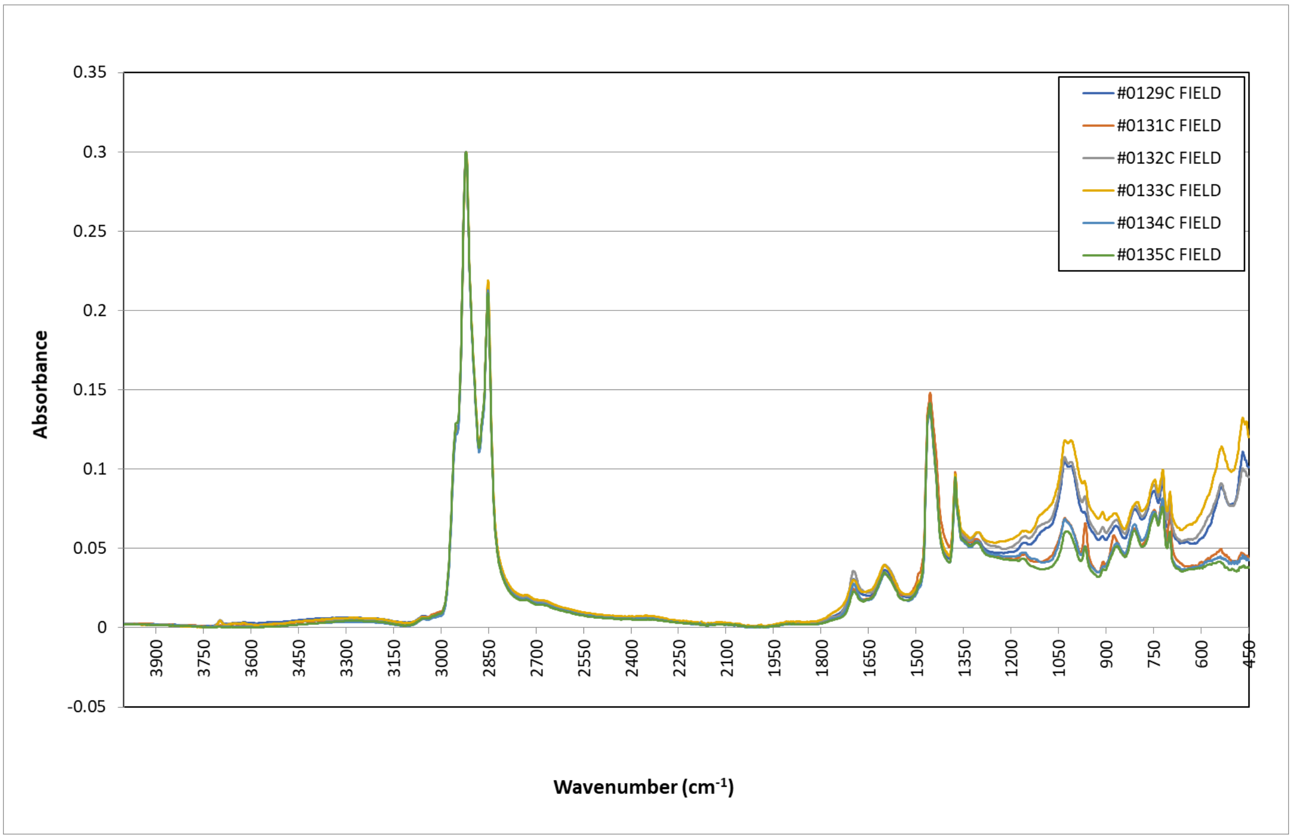
B.15 DARWIN, NT

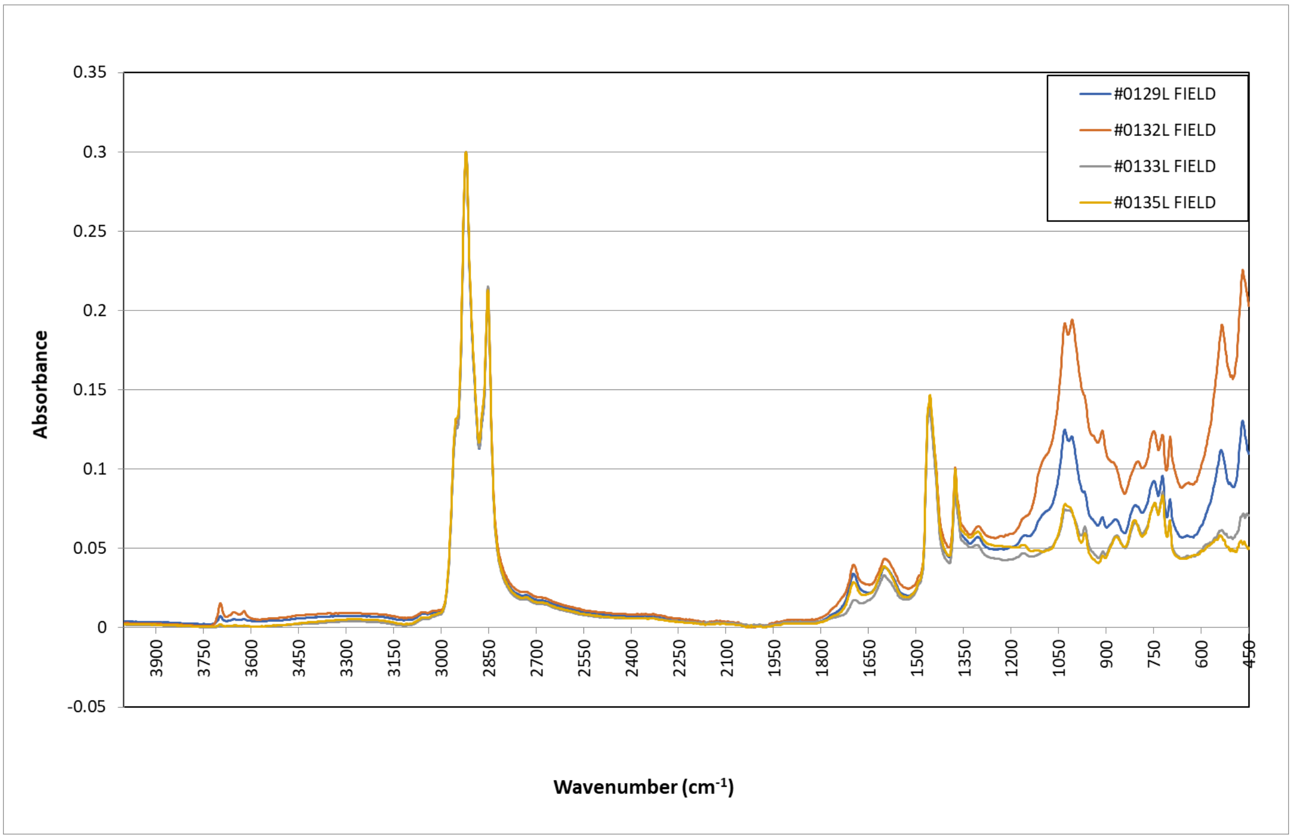
Figure B.14 Normalised spectra – Darwin






#0129R EXT
#0131R EXT
#0134R EXT
#0135R EXT
Absorbance
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
3900
3750
3600
3450
3300
3150
3000
2850
2700
2550
2400
2250
2100
1950
1800
1650
1500
1350
1200
1050
900
750
600
450
Wavenumber (cm-1)


#0129C FIELD
#0131C FIELD
#0132C FIELD
#0133C FIELD
#0134C FIELD
#0135C FIELD
Absorbance
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
3900
3750
3600
3450
3300
3150
3000
2850
2700
2550
2400
2250
2100
1950
1800
1650
1500
1350
1200
1050
900
750
600
450
Wavenumber (cm-1)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#0132L FIELD
#0133L FIELD
#0135L FIELD
Absorbance
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0.25
0.2
0.15
0.1
0.05
0
-0.05
3900
3750
3600
3450
3300
3150
3000
2850
2700
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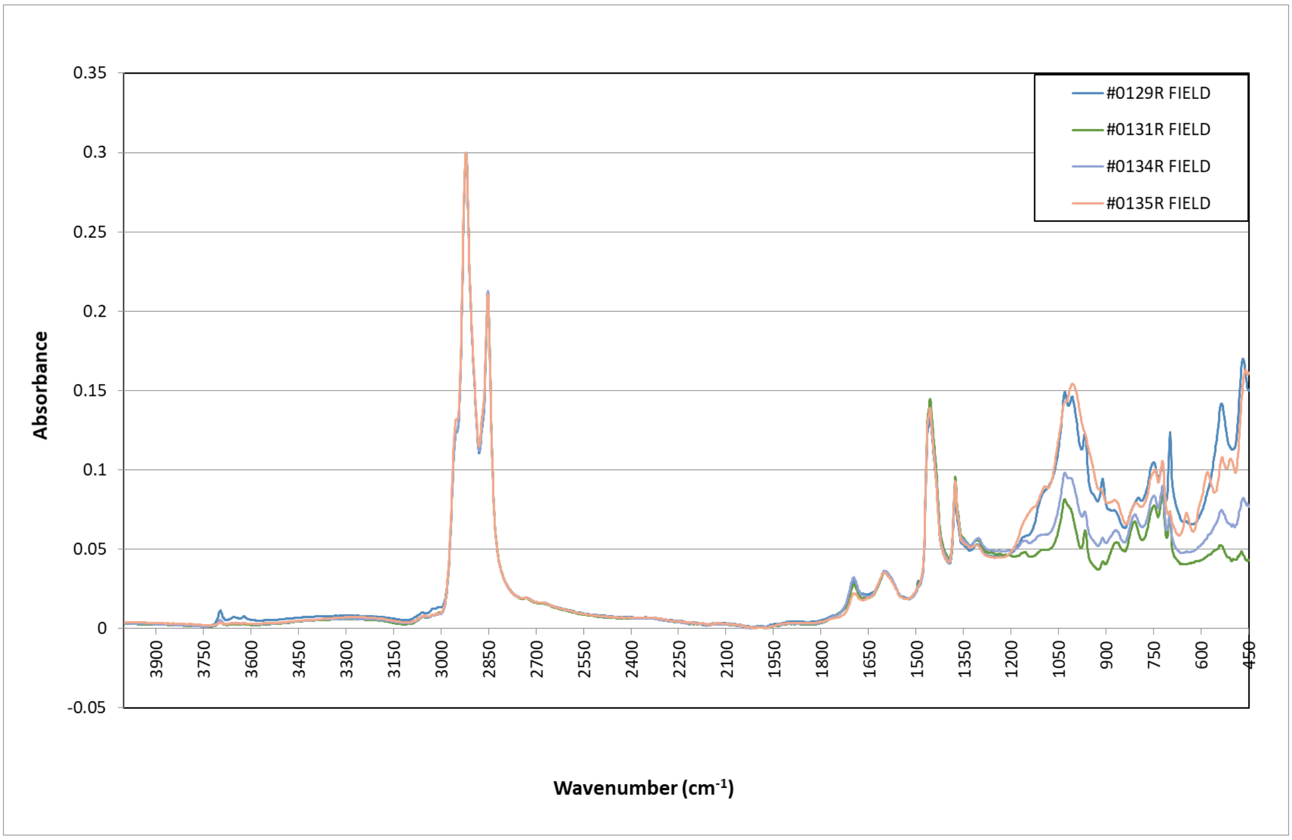
2400
2250
2100
1950
1800
1650
1500
1350
1200
1050
900
750
600
450
Wavenumber (cm-1)


#0129R FIELD
#0131R FIELD
#0134R FIELD
#0135R FIELD
Absorbance
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
3900
3750
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3450
3300
3150
3000
2850
2700
2550
2400
2250
2100
1950
1800
1650
1500
1350
1200
1050
900
750
600
450
Wavenumber (cm-1)

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