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COMPARISON OF THE HAMBURG WHEEL-TRACKING DEVICE AND THE ENVIRONMENTAL CONDITIONING SYSTEM TO PAVEMENTS OF KNOWN STRIPPING PERFORMANCE

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16. Abstract

Moisture damage to hot mix asphalt pavements has been a sporadic but persistent problem in Colorado, even though laboratory testing is performed to identify moisture susceptible mixtures. The laboratory conditioning was often less severe than the conditioning the hot mix pavement encountered in the field. Twenty sites of known field performance with respect to moisture susceptibility, both acceptable and unacceptable, were identified. Materials from these sites were tested using several new and innovative tests: the hamburg wheel-tracking device, the SHRP Environmental Conditioning system, and tests only the aggregate component of the mix.

Implementation:

Test results indicated the Hamburg wheel-tracking device has very severe moisture conditioning. By modifying the City of Hamburg specification, the results could accurately identify most states of known performance. The ECS test procedure has a mild moisture conditioning. By making the test specification more severe, the results could accurately identify most sites of know filed performance. A combination of methylene blue / Ridgen voids index may identify reasons some sites had poor performance.

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TABLE OF CONTENTS

List of Tables

List of Figures

APPENDICES

COMPARISON OF THE HAMBURG WHEEL-TRACKING DEVICE AND THE ENVIRONMENTAL CONDITIONING SYSTEM TO PAVEMENTS OF KNOWN STRIPPING PERFORMANCE

Tim Aschenbrener, Ronald L. Terrel, and Richard A. Zamora

1.0 INTRODUCTION

In September 1990, a group of individuals representing AASHTO, FHWA, NAPA, SHRP, AI, and TRB participated in a 2-week tour of six European countries. Information on this tour has been published in a "Report on the 1990 European Asphalt Study Tour" (1). Several areas for potential improvement of hot mix asphalt (HMA) pavements were identified, including the use of performance-related testing equipment used in several European countries. The Colorado Department of Transportation (CDOT) and the FHWA Turner-Fairbank Highway Research Center (TFHRC) were selected to demonstrate this equipment.

The first priority of the demonstration was to verify the predictive capabilities of this equipment by performing tests on mixtures of known field performance. Additionally, it was considered necessary to assist the Strategic Highway Research Program (SHRP) when possible. Samples of HMA with a history of moisture susceptibility and of good performance were identified and tested in the Hamburg wheel-tracking device and the Environmental Conditioning System (ECS) developed by SHRP.

The purpose of this report is to compare HMA pavements of known field performance with respect to moisture susceptibility with results from the Hamburg wheel-tracking device and the SHRP ECS. Additionally the Europeans specify several tests on the material passing the No. 200 (75 microns) sieve that relate to moisture susceptibility. The tests performed for this study include the Rigden voids index test, methylene blue, and stiffening power.

A conventional moisture damage test, AASHTO T 283, was performed by Aschenbrener and McGennis (2) on the same sites used in this study. For more information on tests used to identify stripping susceptible mixtures and causes of stripping, Stuart (3) and Hicks (4) performed excellent literature reviews.

2.0 SITE SELECTION

Twenty pavement sites were selected throughout Colorado with a known history of performance with respect to moisture damage. These sites represent a wide variety of performance characteristics and encompass an equally wide variety of material types used for asphalt paving in Colorado. Performance of the sites was categorized as good, high maintenance, complete rehabilitation or disintegrators. The sites are listed in Table 1 by county or nearby city. The highest, 7-day average air temperature and annual moisture are also listed.

Table 1. Sites Used in This Study.

Site	Location	Category	Environment	
			High Temp. (°C)	Moisture (mm)
1	Glenwood Springs	Good	34	409
2	Craig		32	328
3	Delta		36	193
4	Fruita		36	203
5	Grand Junction		36	203
6	Durango		32	566
7	Ft. Collins		32	368
8	Nunn	High Maintenance	35	358
9	Denver		34	389
10	Douglas County		34	389
11	Aurora		34	389
12	Jefferson County		34	389
13	Cedar Point	Complete Rehabilitation	33	240
14	Agate		33	240
15	Arriba		34	240
16	Limon		33	240
17	Trinidad	Disintegrators	33	417
18	Walsenburg		33	378
19	Fleming		36	447
20	Gunnison		29	208

2.1 Good

Some aggregate sources in Colorado have a good history of providing pavements that resist moisture damage. Seven different aggregate sources with a history of excellent performance were selected for investigation. A specific project using each aggregate source was then studied in detail for this investigation.

2.2 High Maintenance

These pavements have received an exceptionally high level of maintenance. Although pavements in this category are still in service after two to five years, their performance is considered unacceptable when compared to their design life. The maintenance required to address problems from moisture damage to the HMA pavements included overlays and significant patching of potholes. A 15-month old pavement that required an overlay on some sections is shown in Fig. 1.

2.3 Complete Rehabilitation

Several pavements in Colorado required complete rehabilitation when less than two years old, and often when less than one year old. The moisture damage was related to a unique pavement design feature, rut-resistant composite pavement, that utilized a plant mixed seal coat (PMSC) as described and evaluated by Harmelink (5). HMA pavements directly below the PMSC exhibited severe moisture damage. The pavement surface (Fig. 2) and a core showing the moisture damage that occurred just below the surface (Fig. 3) are shown for a pavement requiring complete rehabilitation after 12 months. Even though the PMSC was a contributing factor the distress in the underlying HMA, the HMA was still considered to be susceptible to moisture damage since it failed so quickly.

Pavements requiring complete rehabilitation all failed when high levels of precipitation occurred in the hottest part of the summer. The weather conditions were all very similar to that shown in Figure 4. The temperature is the monthly mean maximum temperature, i.e. the average of the daily high temperatures. The precipitation is the total accumulation for the month. The first month and year in each figure represents the end of construction, and the final month and year in each figure represents the time of failure.

Even though all pavements in Colorado are subjected to freeze cycles, the severe moisture damage did not correspond with freezing conditions. The instantaneous failures were directly related to a simultaneous combination of high temperature, high moisture, and high traffic.

The environmental data used in this report was obtained from the weather station located closest to each project and reported by the National Oceanic and Atmospheric Administration's National Climatic Data Center.

2.4 Disintegrators

There are several aggregate sources used in HMA pavements that have a notorious history of severe moisture damage. A 6-month old pavement that disintegrated is shown in Fig. 5. Since contractors have not used these aggregate sources on CDOT projects for many years, specific mix designs for the "disintegrators" were difficult to obtain. The mix designs with the aggregate sources thought to be "disintegrators" were reproduced as closely as possible with the help of experienced, long-term employees of the CDOT.

Fig. 1. A "High Maintenance" Mix Experiencing Ravelling After 15 Months.

Fig. 2. The Surface of a Pavement Requiring "Complete Rehabilitation" in 12 Months.

Fig. 3. A Core Showing Stripping Below the Surface from the Pavement in Figure 2.

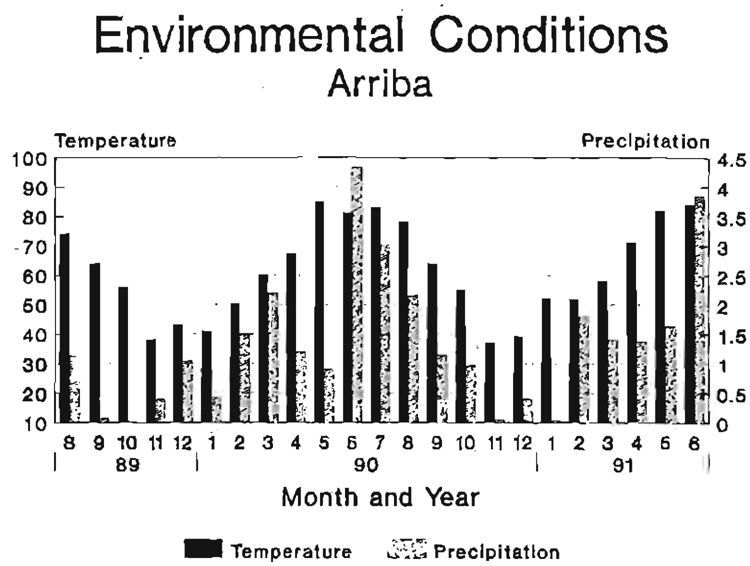

Fig. 4. Environmental Conditions for the Pavement at Arriba Requiring "Complete Rehabilitation" After 24 Months.

Fig. 5. A Disintegrator After 6 Months.

3.0 TEST METHODOLOGY

The original mix design used at each site was identified. Information retrieved included the aggregate sources, percentage of each component aggregate stockpile, component and combined aggregate gradations, optimum asphalt content, asphalt cement source and grade, and anti-stripping treatment.

It was not possible to use the exact aggregates and asphalt cements from the original projects placed two to ten years ago. So, virgin aggregates from the original sources used at each site were samples. Additionally, recently produced asphalt cements and anti-stripping treatments were obtained form the original suppliers of materials to the sites.

The aggregates from each site were then blended to match the gradation used on the project as closely as possible. A mix design was then performed to validate the optimum asphalt content from each site. When the optimum asphalt content of the new mix design matched the optimum asphalt content of the original mix design, the moisture susceptibility testing proceeded. When the optimum asphalt content of the new mix design did not match the optimum asphalt content of the original mix design, it was assumed the aggregates had changed and the new optimum asphalt content was used. No optimum asphalt contents used in this study varied by more than 0.2% from the original designs.

The aggregate gradations and optimum asphalt contents of the HMA mixtures used for this study are shown in Table 2.

Table 2. Aggregate Gradations and Optimum Asphalt Contents for HMA Used in This Study.

Site	AC %	Gradation (mm and inches)								
		19.0 3/4"	12.5 1/2"	9.50 3/8"	4.75 #4	2.36 #8	0.60 #30	0.30 #50	0.15 #100	0.08 #200
1	5.5	100	87	72	51	45	26	18	10	7.0
2	4.5	100	87	72	53	42	24	15	10	6.6
3	5.3	100	93	77	53	37	21	14	9	5.9
4	4.9	100	88	66	50	40	21	14	8	5.1
5	5.0	100	94	80	52	41	31	18	10	7.1
6	6.0	100	100	88	51	37	22	14	10	7.1
7	5.7	100	91	74	49	37	18	12	8	4.7
8	4.8	100	94	77	49	38	24	18	12	8.1
9	5.9	100	100	96	62	41	25	13	10	6.1
10	5.0	100	86	77	55	43	26	18	13	8.6
11	4.9	100	100	97	57	40	21	15	11	7.8
12	5.0	100	86	76	54	42	25	18	13	8.4
13	5.7	100	86	78	60	45	22	15	9	5.7
14	5.3	100	86	78	63	47	25	16	10	7.7
15	5.6	100	85	76	62	49	27	18	13	8.3
16	5.4	100	88	79	61	50	30	20	13	8.3
17	5.6	100	100	95	72	44	24	17	12	7.3
18	5.6	100	100	95	70	39	21	15	11	7.2
19	5.5	100	96	93	83	69	32	20	14	11.7
20	6.5	100	96	80	50	42	26	18	12	8.3

4.0 DESCRIPTION OF TESTS

The experimental grid of the tests performed on samples from the various sites is shown in Table 3. A description of the tests follows.

4.1 Hamburg Wheel-Tracking Device

4.1.1 The Equipment and Procedure

The Hamburg wheel-tracking device is manufactured by Helmut-Wind Inc. of Hamburg, Germany as shown in Fig. 6: a close-up in Fig. 7. A pair of samples are tested simultaneously. A sample is typically 26 cm (10.2 in.) wide, 32 cm (12.6 in.) long, and 40 mm (1.6 in.) deep. Its mass is approximately 7.5 kg (16.5 lbs.), and the sample is compacted to 7 $\pm$ 1% air voids. For this study, samples were compacted with the French plate compactor. The samples are submerged under water at 50°C (122°F), although the temperature can vary from 25°C to 70°C (77°F to 158°F). A steel wheel, 47 mm (1.85 in.) wide, loads the samples with 705 N (158 lbs.) The wheel makes 50 passes over each sample per minute. The maximum velocity of the wheel is 34 cm/sec (1.1 ft/sec) in the center of the sample. Each sample is loaded for 20,000 passes or until 20 mm of deformation occur. Approximately 6-1/2 hours are required for a test.

4.1.2 The Results and Specification

The results from the Hamburg wheel-tracking device include the creep slope, stripping slope and stripping inflection point as shown in Fig. 8. The results have been defined by Hines (6). The creep slope relates to rutting from plastic flow. It is the inverse of the rate of deformation in the linear region of the deformation curve, after post compaction effects have ended and before the onset of stripping. The stripping slope is the inverse of the rate of deformation in the linear region of the deformation curve, after stripping begins and until the end of the test. It is the number of passes required to create a 1 mm impression from stripping. The stripping slope is related to the severity of moisture damage. The stripping inflection point is the number of passes at the intersection of the creep slope and the stripping slope. It is related to the resistance of the HMA to moisture damage.

An acceptable mix is specified by the City of Hamburg to have less than 4 mm rut depth after 20,000 passes.

Table 3. Experimental Grid for the Stripping Study.

	Good Performers							High Maintenance					Complete Rehabilitation				Disintegrators			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Hamburg device (50°C)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	NT	X	X	X	X	X
Hamburg device (45°C)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	NT	X	X	X	X	X
ECS	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
P200 Tests	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

NT - Not Tested

Fig. 6. The Hamburg Wheel-Tracking Device.

Fig. 7. A Close-up of the Hamburg Wheel-Tracking Device.

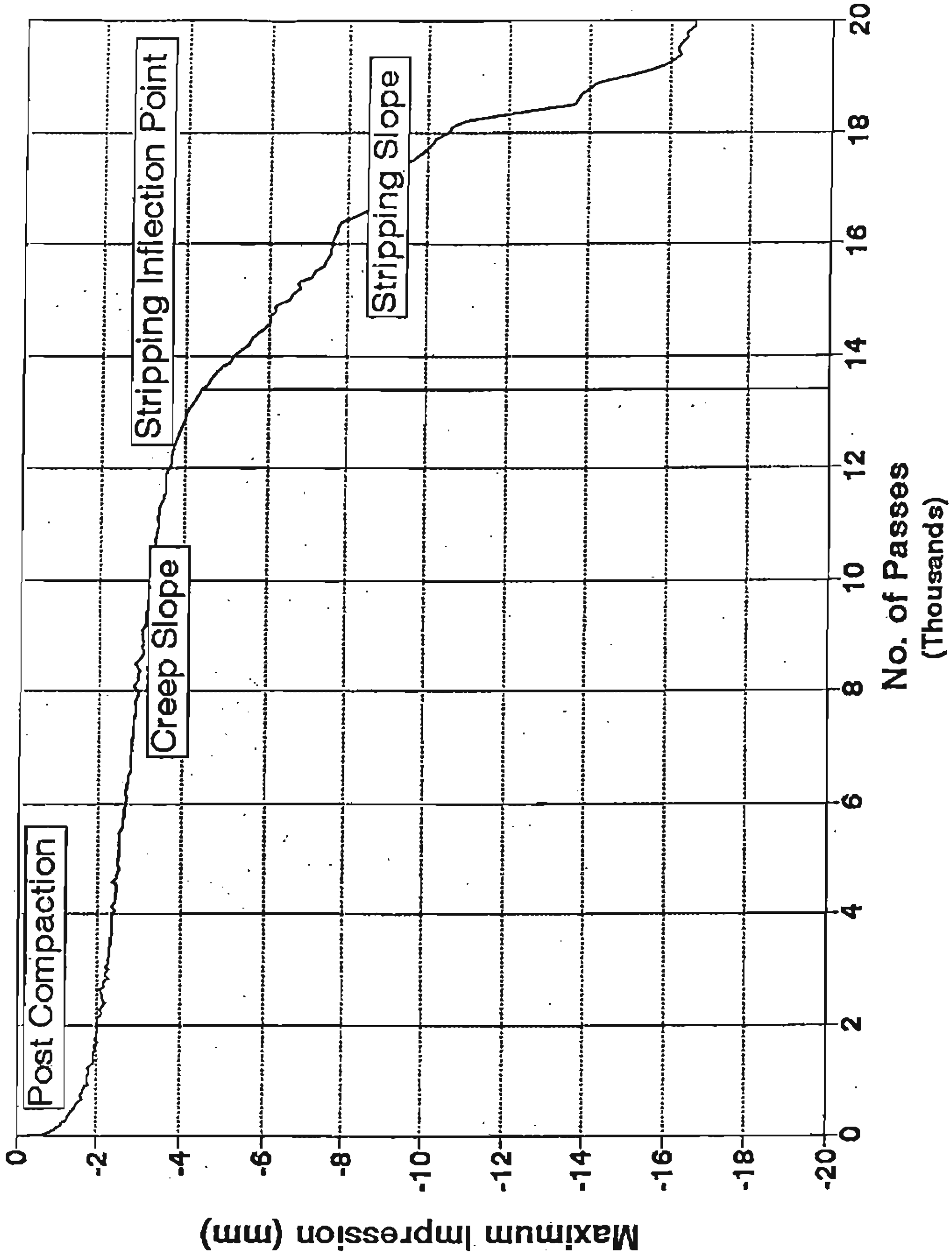

Fig. 8. Definition of the Hamburg Wheel-Tracking Results.

4.2 Environmental Conditioning System

4.2.1 The Equipment and Procedure

The Environmental Conditioning System (ECS) test procedure was developed at Oregon State University (OSU) as a part of SHRP. The ECS procedure subjects a membrane encapsulated specimen measuring 102 mm (4 in.) in diameter by 102 mm in height to cycles of temperature, repeated loading, and moisture conditioning. The ECS test procedure is summarized in Table 4. The procedure is explained in greater detail by Al-Swailmi and Terrel (7).

For this test program, three different load frames and systems were used. Systems A and B are in a large environmental cabinet and this dual system was the prototype ECS developed at OSU. System C is a single load frame in another cabinet; and was manufactured by OEM, Inc. of Corvallis, Oregon. The ECS system used for each specimen tested is noted in Appendix B. Figures 9 and 10 show the configuration for system C with a single load frame.

4.2.2 The Results and Specification

The test results from the ECS procedure are based on the ECS resilient modulus (M_R) determined before conditioning and after each cycle. The ECS-M_R ratio (ratio of conditioned to unconditioned) and the estimate of stripping in the split specimen following conditioning are the bases for evaluation of water damage.

Figure 11 shows how the data are interpreted in the ECS test. The first hot cycle is an indicator of initial water sensitivity. The slope of the curve between cycles 1 and 3 appear to be an indicator of rate of continued damage. The cycle 4 (freezing) is often damaging to the saturated aggregate and may result in additional damage. All specimens were subjected to 4 cycles in this study, but for warm climates, the freeze cycle could be eliminated.

The procedure for interpreting the results are still under development, but the tentative specification requires that the ECS-M_R ratio be greater than 0.70 after the final conditioning cycle. For mixtures that have a flat or upward slope between cycles 1 and 3, and ratio greater than 0.70, no water damage is expected. Mixtures that are above 0.70 but with a downward sloping curves are suspect and may require additives or re-design because they would fail prematurely.

Table 4. **Summary of ECS Test Procedure.**

Step	Description
1	Prepare test specimens as per SHRP protocol.
2	Determine the geometric and volumetric properties of the specimen. Determine the triaxial and diametral modulus using the MTS system.
3	Encapsulate specimen in silicon sealant and latex rubber membrane, allow to cure overnight (24 hours).
4	Place the specimen in the ECS load frame, between two perforated teflon disks, determine air permeability.
5	Determine unconditioned (dry) triaxial resilient modulus.
6	Vacuum condition specimen (subject to vacuum of 51 cm Hg for 10 minutes).
7	Wet specimen by pulling distilled water through specimen for 30 minutes using a 51 cm Hg vacuum.
8	Determine unconditioned water permeability.
9	Heat the specimen to 60°C (140°F) for 6 hours, under repeated loading. This is a hot cycle.
10	Cool the specimen to 25°C (77°F) for at least 4 hours. Measure the triaxial resilient modulus and water permeability.
11	Repeat steps 9 and 10 for 2 more hot cycles.
12	Cool the specimen to -18°C (0°F) for 6 hours without repeated loading. This is a freeze cycle.
13	Heat the specimen to 25°C fir at least 4 hours and measure the triaxial resilient modulus and the water permeability.
14	Split the specimen and perform a visual evaluation of stripping.
15	Plot the triaxial resilient modulus and water permeability ratios.

Some higher quality mixtures may actually show initial ECS-M_R ratios greater than unity, indicating insensitivity to water damage. The stiffer mixture is most likely due to saturation of some or all voids and the incompressibility of the water under repeated loading.

Fig. 9. Overview of the Environmental Conditioning System.

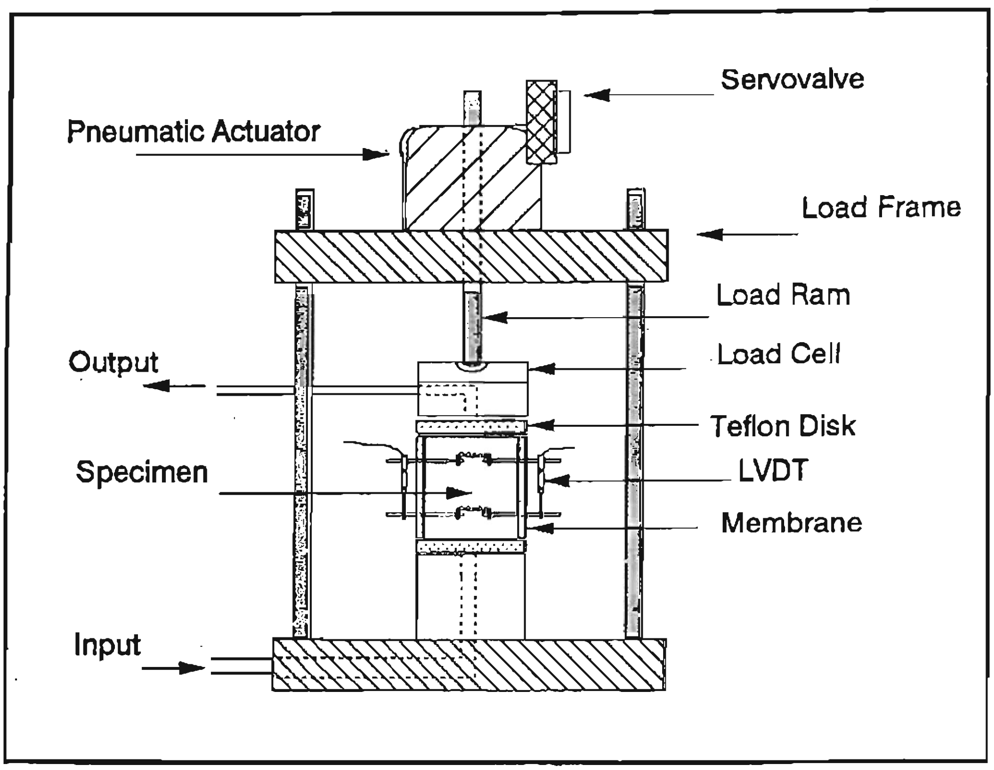

Fig. 10. Load Frame and Specimen Set-Up Inside the ECS.

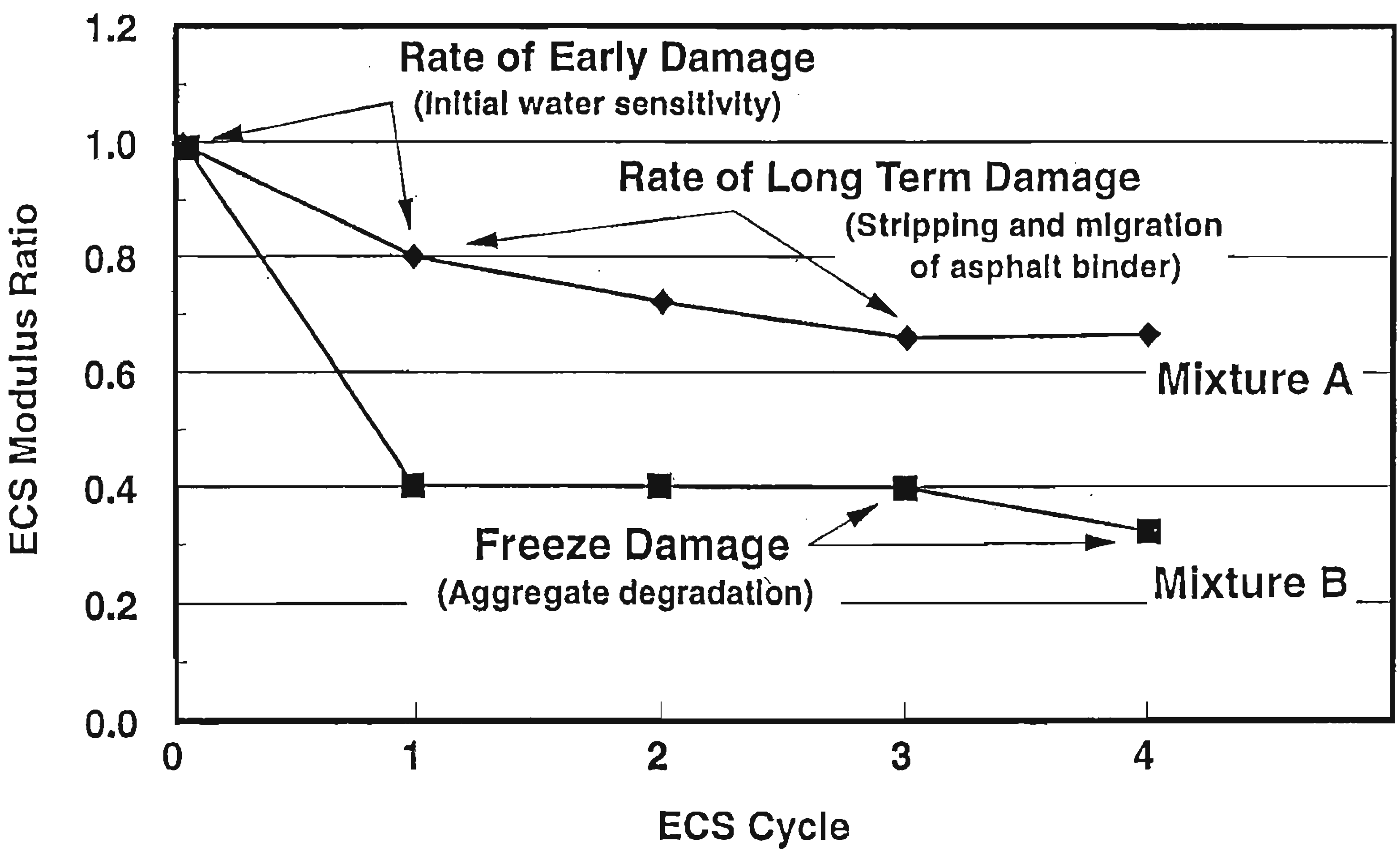

Fig. 11. Interpretation of the ECS Modulus Curve.

4.3 P200 Tests

It should be noted that the ultimate method for determining the suitability of different combinations of aggregates and asphalt cements is to conduct performance-related testing on the HMA. However, when an HMA fails performance related tests, properties of the component aggregates, particularly the material passing the No. 200 (75 μ) sieve (P200) could reveal areas for improving the HMA. The purpose of performing tests on the P200 is to glean an insight into the potential relationship with performance-related tests and to recommend areas for improving the HMA.

The tests performed for this study are used by the French and/or Germans and could potentially relate to the moisture susceptibility characteristics of an HMA. These tests have been described previously by Aschenbrener (8).

4.3.1 Sand Equivalent

The procedure used for the sand equivalent test in this study was AASHTO T 176. The purpose of the test is to quantify the cleanliness of the fine aggregates passing the No. 4 sieve (4.75 mm). The French specify values greater than or equal to 60, 50, and 40 for high, medium, and low traffic, respectively.

4.3.2 Methylene Blue

The purpose of the test is to identify the presence of harmful clays of the smectite group (poor quality P200) and to provide an indication of the surface activity of the aggregate. Active P200 is less moisture susceptible than P200 with low surface activity. Results from the methylene blue test can be interpreted as a general rule-of-thumb as shown in Table 5.

Table 5. Relationship of Methylene Blue Values and Anticipated Pavement Performance.

Methylene Blue (mg/g)	Expected Performance
5-6	Excellent
10-12	Marginally acceptable
16-18	Problems or possible failure
20+	Failure

4.3.3 Rigden Voids Index Test

The Rigden voids index test can be used to limit the quantity of P200 in an HMA mixture. The Rigden voids index test is performed by compacting a sample of P200 and calculating the bulk density and air voids. While the volume of asphalt cement required to fill the air voids is considered fixed asphalt cement, the remaining asphalt cement in the HMA is considered free. If the P200 requires a large quantity of "fixed" asphalt cement, there will not be sufficient "free" asphalt cement to protect the aggregates from moisture damage.

Specifications often require a minimum of 40% free asphalt. Requiring 40% free asphalt cement and knowing the Rigden voids index, the maximum P200 to asphalt ratio can be calculated by Equation 1 as derived by Anderson (9):

$$V_{AFR} = \frac{1 + \frac{D}{A_V}\left(1 - \frac{G_{DS}\,\gamma_W}{\gamma_{DB}}\right)}{1 + \frac{D}{A_V}} \qquad \textit{Equation 1}$$

where:

V_{AFR} = Percent volume of free asphalt cement,

D/A_V = P200 (Dust)/asphalt ratio by volume,

G_{DS} = Specific gravity of P200 (dust) solids,

γ_W = Density of water, and

γ_{DB} = Bulk density of compacted P200 from the Rigden voids index test.

4.3.4 Stiffening Power

The stiffening power test used by the French is the increase in the ring and ball softening point that occurs between a neat asphalt cement and a 60:40 blend by weight of P200 with the same asphalt cement. Minimum and maximum values are specified for the stiffening power.

The minimum value specified by the French relates to angularity. By using a very high P200 to asphalt ratio, 1.5 by weight, the angular P200 particles can interlock and create stiffening. The resultant stiffening of the asphalt cement can be a measure of the P200 angularity. A minimum value of 10°C (18°F) is specified to ensure angularity of the P200. The maximum value relates to the detrimental effects leading to fatigue, thermal cracking, and moisture susceptibility. A maximum value of 20°C (36°F) is specified.

The actual amount of stiffening is the increase in the ring and ball softening point that occurs between a neat asphalt cement and a blend of P200 with the same asphalt cement. Variable blends of P200 and asphalt cement can be used to identify the P200 to asphalt ratio that causes an increase of 11°C (20°F). An increase of 11°C has been shown by Kandhal (10) to be detrimental.

5.0 RESULTS AND DISCUSSION

5.1 Hamburg Wheel-Tracking Device

Results from the individual sites tested in the Hamburg wheel-tracking device are shown in Table 6. Results from both the 50°C and 45°C test temperatures are included. The plots of the results from each site are in Appendix A. The maximum impression plot is the rutting depth at the center of the sample versus the number of passes. The profile plot is the rutting depth from the back of the sample (0 mm) to the front of the sample (226 mm) at various passes.

5.1.1 Correlation With Pass-Fail Criteria

The City of Hamburg specification of a rut depth less than 4 mm after 20,000 passes with a 50°C test temperature is very severe for many pavements in Colorado. Although all but one of the stripping sites (Site 11) were predicted to be unacceptable, four of the acceptable sites (Sites 2, 4, 5, and 6) were predicted to be unacceptable as shown in Table 7.

For the Good sites that failed the specification, there were some interesting observations. Although Site 2 failed the specification, it did not strip. Based on visual observation, the sample failed from plastic flow. Sites 4 and 5 each had less than a 10 mm rut depth. The sites with stripping in the field had greater than 20 mm rut depth, except Site 16 which had a 14 mm rut depth. Site 6 was considered a "good" performer, but was representative of a pavement that lasted about 7 years. Since Site 6 did poorly in the Hamburg device, it is likely the definition of "good" performer in the field may have to be improved.

Table 7. Comparison of Pavements of Known Field Performance with the Hamburg Wheel-Tracking Device (Pass and Fail) at 50°C.

	Good	High Maintenance	Complete Rehab.	Disintegrator
Pass	3	1	0	0
Fail	4	4	3	4

Table 6. Results from the Hamburg Wheel-Tracking Device.

Site	Temperature = 50°C			Temperature = 45°C		
	Creep Slope	Strip Slope	Strip Infl.	Creep Slope	Strip Slope	Strip Infl.
1	19,000	---	+20,000	12,400	---	+20,000
2	1,700	---	+20,000	9,000	---	+20,000
3	9,200	---	+20,000	8,600	---	+20,000
4	4,200	11,000	14,200	17,000	---	+20,000
5	4,300	1,500	14,500	5,900	---	+20,000
6	1,100	500	3,500	7,200	---	18,000
7	11,300	---	+20,000	9,100	---	+20,000
8	2,900	700	9,600	14,400	---	+20,000
9	---	800	1,500	---	1,000	1,500
10	2,200	600	6,200	3,300	1,900	10,700
11	8,800	---	+20,000	12,300	---	+20,000
12	2,000	1,000	4,600	2,600	800	8,400
13	---	600	2,300	---	300	3,300
14	---	400	1,500	---	500	2,000
15	NT	NT	NT	NT	NT	NT
16	---	1,700	1	---	1,100	1
17	---	200	1	---	400	1,500
18	---	300	2,200	2,300	500	5,300
19	---	100	1	---	100	1
20	---	200	1	---	400	1

NT - Not Tested   --- No value could be calculated

Site 11 was identified as an acceptable site at both test temperatures despite poor field performance. It is possible that this particular site may not have been replicated properly or the distress in the field was not related primarily to a material problem.

At the 45°C test temperature, better correlations with known field performance occurred as shown in Table 8. All but one of the stripping sites (Site 11) were predicted to be unacceptable. Only two of the acceptable sites (Site 5 and 6) were predicted to be unacceptable.

The two sites (Sites 5 and 6) with good field performance that did poorly in the Hamburg device had 6 mm of rutting after 20,000 passes, just short of the 4 mm specified. However, of the four high maintenance sites that failed, two sites (Sites 8 and 10) had less than 10 mm rut depths. Although the lower test temperature more accurately predicted the good pavements, the lower test temperature also measured the high maintenance sites more favorably.

Table 8. Comparison of Pavements of Known Field Performance with the Hamburg Wheel-Tracking Device (Pass and Fail) at 45°C.

	Good	High Maintenance	Complete Rehab.	Disintegrator
Pass	5	1	0	0
Fail	2	4	3	4

5.1.2 Correlation With Measured Parameters

The stripping inflection point and the stripping slope were compared to the known field performance. Results at the 50°C test temperature are shown in Table 9. A ranked order plot of the stripping inflection point and stripping slope is shown in Figs. 12 and 13, respectively, for tests performed at 50°C.

The stripping slope did clearly distinguish between the sites that performed well and stripped. The stripping slope was not sensitive to the various levels of field stripping performance.

Table 9. Comparison of Pavements of Known Field Performance with the Hamburg Wheel-Tracking Device (Stripping Slope and Stripping Inflection) at 50°C.

	Good	High Maintenance	Complete Rehab.	Disintegrator
Stripping Slope	---	800	900	200
Stripping Inflection	16,000	8,400	1300	600

The stripping inflection point correlated with the various levels of expected pavement performance. As a rule-of-thumb, a stripping inflection point greater than 14,000 passes may indicate good pavement performance: a pavement that has a 10 to 15 year life. A stripping inflection point between 6,000 and 10,000 passes could indicate excessive maintenance problems before the design life is reached. A stripping inflection point less than 3,000 passes indicates a real problem; a pavement that has a life of less than 3 years.

At the 45°C test temperature, a similar relationship can be obtained as shown in Table 10. A ranked order plot of the stripping inflection point and stripping slope is shown in Figs. 14 and 15, respectively, for tests performed at 45°C. Although the stripping slope was not sensitive to the various levels of pavement performance, the stripping slope did distinguish between the sites that performed well and stripped in the field.

At 45°C, the stripping inflection point was sensitive to the various levels of field stripping performance. A rule-of-thumb could indicate a stripping inflection point greater than 18,000 passes would indicate good performance, between 8,000 and 12,000 passes would indicate excessive maintenance, and less than 3,000 would be expected to perform very poorly.

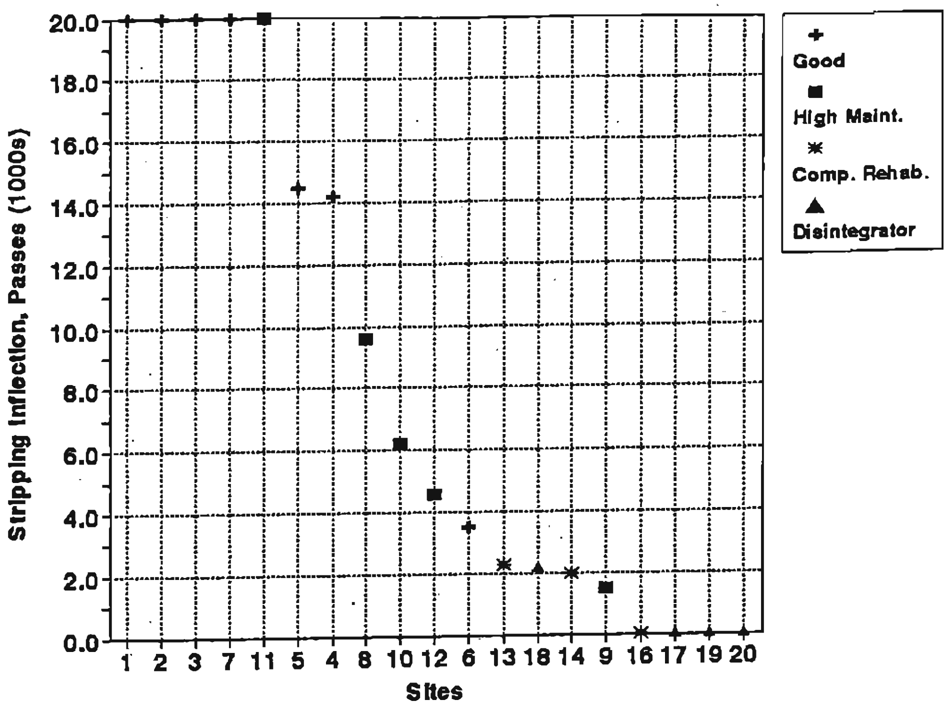

Fig. 12. Ranked Order of the Stripping Inflection Point from the Hamburg Wheel-Tracking Device at 50°C.

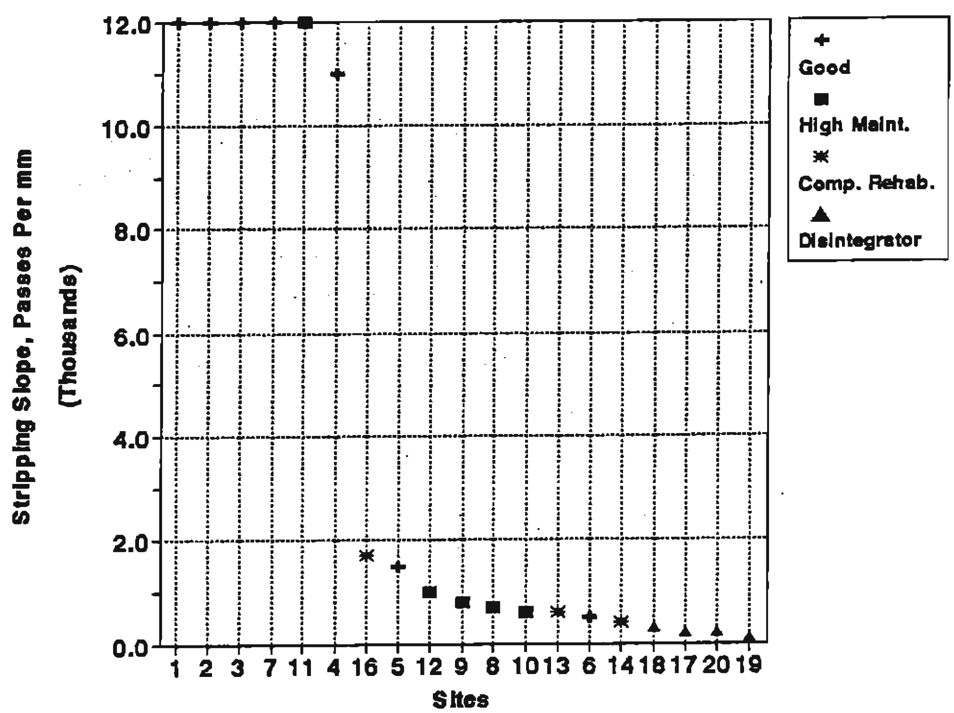

Fig. 13. Ranked Order of the Stripping Slope from the Hamburg Wheel-Tracking Device at 50°C.

Table 10. Comparison of Pavements of Known Field Performance with the Hamburg Wheel-Tracking Device (Stripping Slope and Stripping Inflection) at 45°C.

	Good	High Maintenance	Complete Rehab.	Disintegrator
Stripping Slope	---	---	600	300
Stripping Inflection	19,700	12,000	1800	500

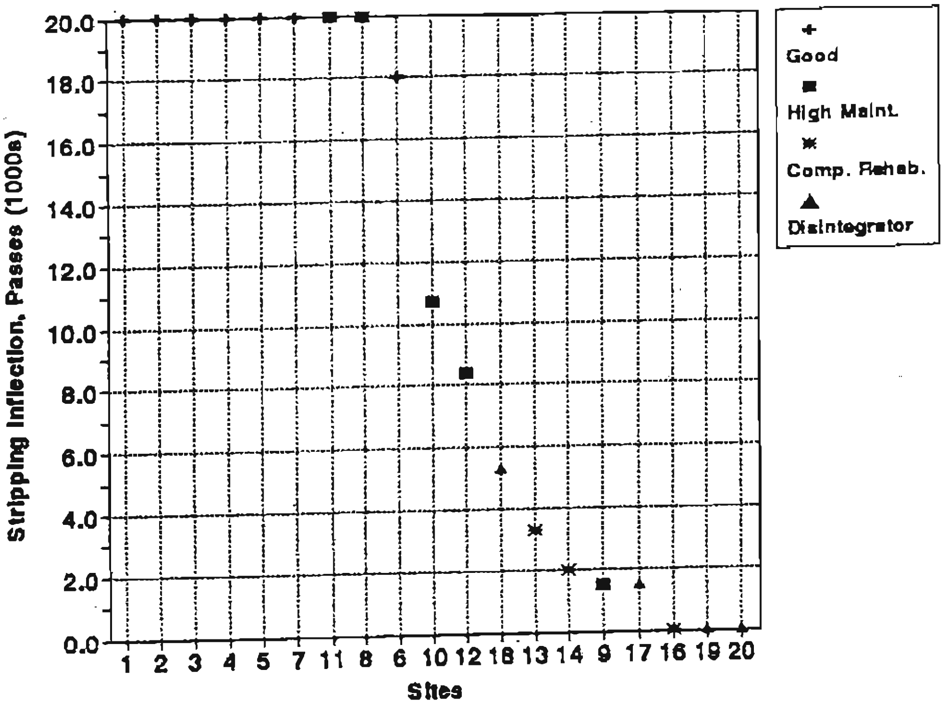

Fig. 14. Ranked Order of the Stripping Inflection Point from the Hamburg Wheel-Tracking Device at 45°C.

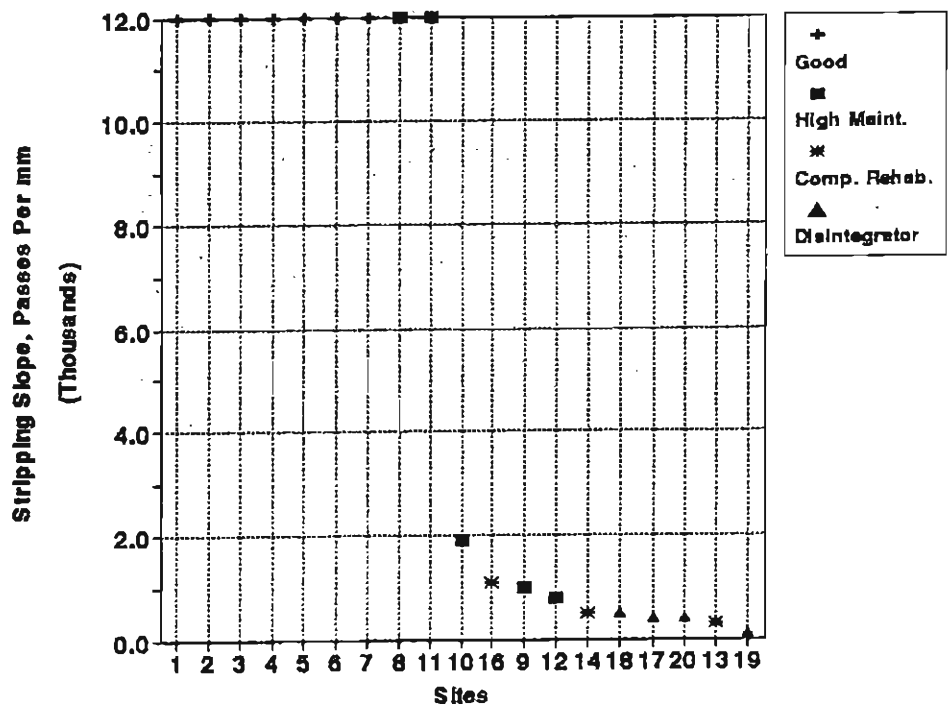

Fig. 15. Ranked Order of the Stripping Slope from the Hamburg Wheel-Tracking Device at 45°C.

5.1.3 Summary

The Hamburg wheel-tracking device applies very severe moisture conditioning cycles. The test appears to be especially severe on the Good sites. It may be necessary to reduce the severity of the specification used by the City of Hamburg.

All but two of the Good sites had less than a 10 mm rut depth at 20,000 passes, and all but one of the stripping sites had greater than a 10 mm rut depth. One of the pavements considered to have good field performance with greater than a 10 mm rut depth (Site 6), had a 7-year life. The expectations of a good performing pavement may have to be increased.

At 10,000 passes all but two of the Good sites had less than a 4 mm rut depth, and all but one of the stripping sites had greater than a 4 mm rut depth.

The results from the Hamburg wheel-tracking device have better correlation to actual field performance of pavements in Colorado by specifying either 1) a minimum rut depth of 10 mm instead of 4 mm at 20,000 passes, or 2) a minimum of 4 mm rut depth at 10,000 passes instead of 20,000.

The stripping slope and stripping inflection point distinguished between good and poor field performance. The stripping inflection point related closely with the various levels of stripping observed in the field.

Additional work should be performed to better correlate the parameters of the Hamburg wheel-tracking device to actual site conditions. The testing temperature should be related to the actual temperatures expected at the site. The stripping inflection point could be correlated with the traffic expected at the site.

5.2 Environmental Conditioning System

Results from the individual sites tested using the ECS procedure are summarized in Table 11. The data and plots from each site are in Appendix B. The data in Appendix B includes the stress and strain values used to calculate M_R. Each mixture had four replicates and the curve for each specimen is shown. In addition, the average ECS-M_R ratio for each site is shown following both 3 and 4 cycles and these are the values summarized in Table 11.

Table 11. Results from the ECS Device.

Site	ECS M_R Ratio Average After 3 Cycles	ECS M_R Ratio Average After 4 Cycles
1	1.11	1.08
2	1.34	1.32
3	1.51	1.78
4	1.39	1.43
5	1.17	1.15
6	1.02	1.02
7	1.04	1.02
8	1.28	1.21
9	0.95	0.88
10	Bad Data	0.75
11	1.24	1.31
12	0.95	1.02
13	1.12	1.03
14	0.54	0.44
15	0.73	0.53
16	1.01	0.99
17	0.91	0.78
18	1.44	1.71
19	0.95	0.80
20	0.72	0.56

5.2.1 Correlation with Pass-Fail Criteria

Using the criteria described earlier (a minimum of 0.70), the ECS-M_R data were compared on a pass-fail basis similar to that used with the Hamburg wheel-tracking device. The data were compared with field site performance in three ways as shown in Tables 12 through 14. Generally good correlation was observed for pavements with Good field performance categories for all three types of correlation. For pavements noted as Complete Rehabilitation and Disintegrator the comparison shown in Table 14 appears to be best. This comparison utilized a combination of ECS-M_R ratio and the trend or slope (a negative or downward slope was unacceptable) of the curve between cycles 1 through 3. In this instance, only six sites appear to perform differently than predicted by the ECS. The High Maintenance Sites did not correlate with the ECS.

Table 12. Comparison of Pavements of Known Field Performance with the ECS Device (Pass and Fail, considering ECS-M_R ratio only) After 3 Cycles.

	Good	High Maintenance	Complete Rehab.	Disintegrator
Pass	7	4	3	3
Fail	0	0	1	1

Table 13. Comparison of Pavements of Known Field Performance with the ECS Device (Pass and Fail, considering ECS-M_R ratio only) After 4 Cycles.

	Good	High Maintenance	Complete Rehab.	Disintegrator
Pass	7	5	2	3
Fail	0	0	2	1

Table 14. Comparison of Pavements of Known Field Performance with the ECS Device (Pass and Fail, considering ECS-M_R ratio and trend) After 4 Cycles.

	Good	High Maintenance	Complete Rehab.	Disintegrator
Pass	7	4	1	1
Fail	0	1	3	3

5.2.2 Correlation with Measured Parameters

Similar to that for the Hamburg wheel-tracking device, the sites were ranked by order of their laboratory behavior in the ECS test. Figure 16 shows the sites ranked by order of the ECS-M_R ratio after 3 cycles, but also shows the values for after cycle 4 (freeze). This ordering after 3 cycles is the preferred method, and it is suggested that by including the test values after cycle 4, an indication of whether low ratios were caused by aggregate rupture. When the cycle 3 ECS-M_R ratio was less than about 0.75, the corresponding cycle 4 ratio is significantly lower, indicating damage during the freeze cycle.

An alternative to Figure 16 is the ranking of sites by slope of the ECS curve between cycles 1 and 3 as shown in Figure 17. A preliminary interpretation of the test results developed in the SHRP work is that negative slopes may indicate the rate at which asphalt pavements will be water damaged, i.e., this slope correlates with expected service life. However it appears that the interpretation should be based on both the ECS-M_R ratio and slope. For example, if a mixture tested in the ECS marginally passed the 0.70 criteria but had a negative slope (1 through 3 cycles), then it would be suspect; it will fail, but not necessarily in the short term.

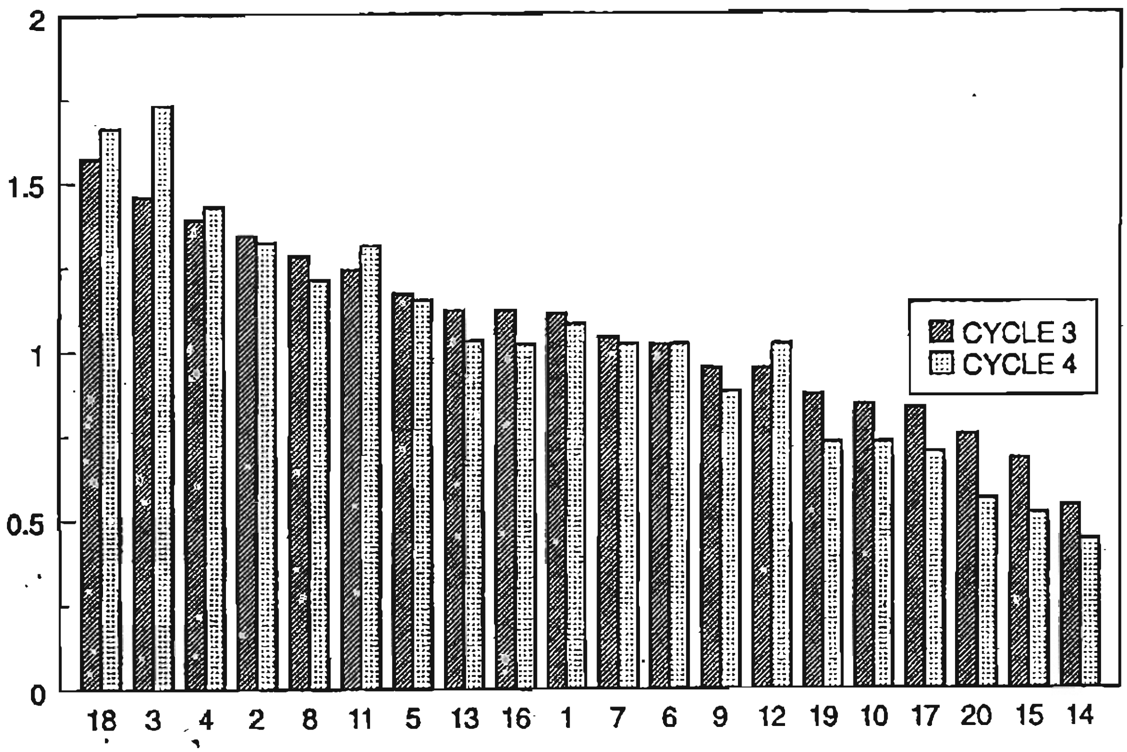

Fig. 16. Mixtures Ranked by ECS-M_R Ratio After 3 Hot Cycles.

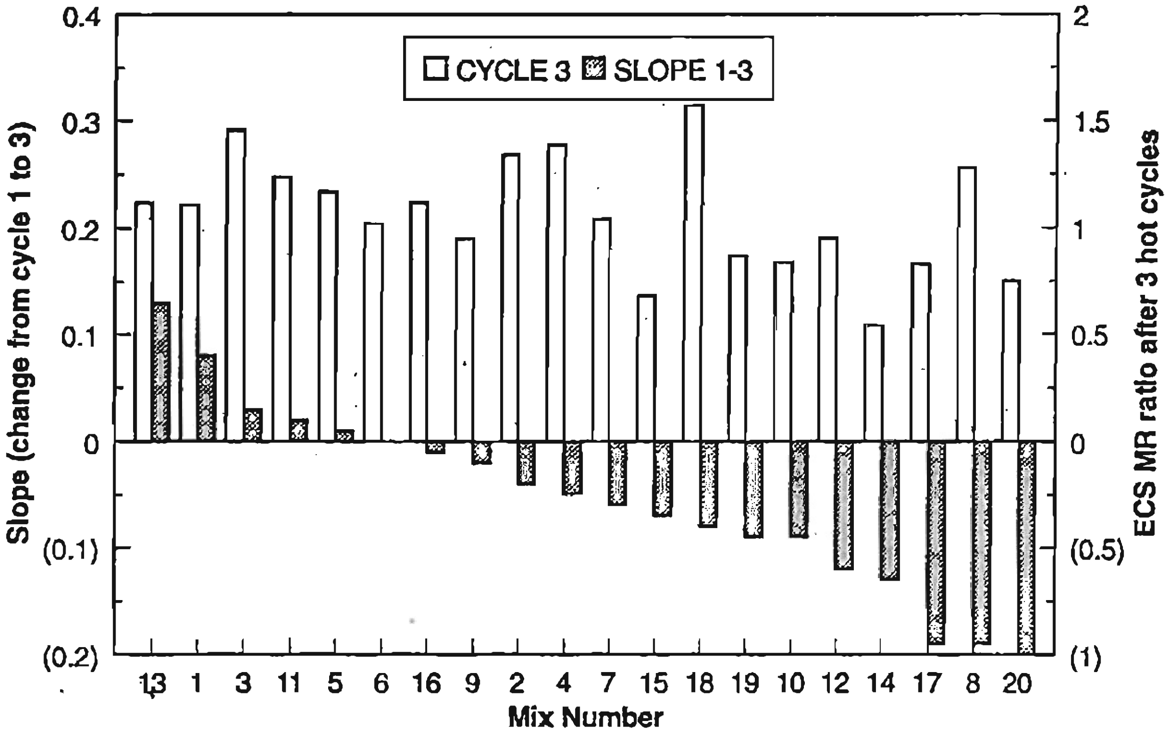

Fig. 17. Mixtures Ranked by Slope of the ECS Curve Between 1 and 3 Hot Cycles.

5.3 P200 Tests

The methylene blue, sand equivalent, Rigden voids and stiffening power tests were performed on the blended P200 portion of the aggregates from each site. A summary of these test results is contained in Table 15.

Table 15. Summary of P200 Test Results.

Site	Sand Equiv.	Methylene Blue (mg/g)	Rigden Voids (% V_{AFX})	Stiffening Power (11°C)		Dust Coating (%)
				P200/A_w	P200/A_v	
1	31	6.8	48.1	1.10:1	0.40:1	0.3
2	60	9.5	47.6	0.90:1	0.33:1	0.6
3	75	2.5	47.8	1.17:1	0.43:1	0.2
4	69	6.4	41.5	1.26:1	0.48:1	0.2
5	56	5.0	45.7	1.18:1	0.44:1	0.4
6	66	12.6	38.7	1.28:1	0.47:1	0.3
7	87	11.9	43.6	1.23:1	0.45:1	0.1
8	33	13.0	48.5	0.95:1	0.35:1	---
9	69	10.6	46.3	1.04:1	0.38:1	0.7
10	91	8.7	44.3	1.18:1	0.42:1	0.2
11	55	4.3	46.3	1.17:1	0.42:1	0.7
12	88	8.3	43.9	1.21:1	0.43:1	0.2
13	55	>20	47.3	1.16:1	0.42:1	0.5
14	35	>20	46.8	1.20:1	0.43:1	1.9
15	47	>20	44.8	1.05:1	0.40:1	---
16	64	14.2	45.3	1.23:1	0.44:1	0.3
17	65	>20	46.4	1.23:1	0.44:1	3.8
18	80	6.6	51.0	1.00:1	0.36:1	2.8
19	69	>20	54.0	0.88:1	0.33:1	---
20	32	>20	50.7	0.95:1	0.34:1	0.5

5.3.1 Sand Equivalent

As can be seen in Table 15, nearly all sites have acceptable sand equivalent values. A ranked order plot (Fig. 18) shows there is poor correlation between the sand equivalent value and field performance with respect to stripping.

5.3.2 Methylene Blue Test

A guideline for interpreting the methylene blue value (MBV) and anticipated pavement performance is given in Table 5. A ranked order plot (Fig. 19) and Table 16 show a good correlation exists between the methylene blue value and stripping performance.

Table 16. Summary of Methylene Blue Test Results.

MBV Anticipated Performance	Actual Stripping Performance			
	Good	High Maint.	Comp. Rehab.	Disint.
Excellent	5	3	0	1
Marginal	2	2	1	0
Failure	0	0	3	3

All of the test results for the Good and High Maintenance sites fall between the recommended MBV ranges for excellent to marginally acceptable anticipated performance. All of the Complete Rehabilitation and Disintegrator sites have unacceptable methylene blue values except Site 18. One possible explanation for the poor stripping performance of Site 18 is the presence of a thick dust coating on the coarse aggregates obtained from this source.

Although the methylene blue value was not able to identify the High Maintenance sites, it is possible that their performance could be predicted by some of the other tests that follow.

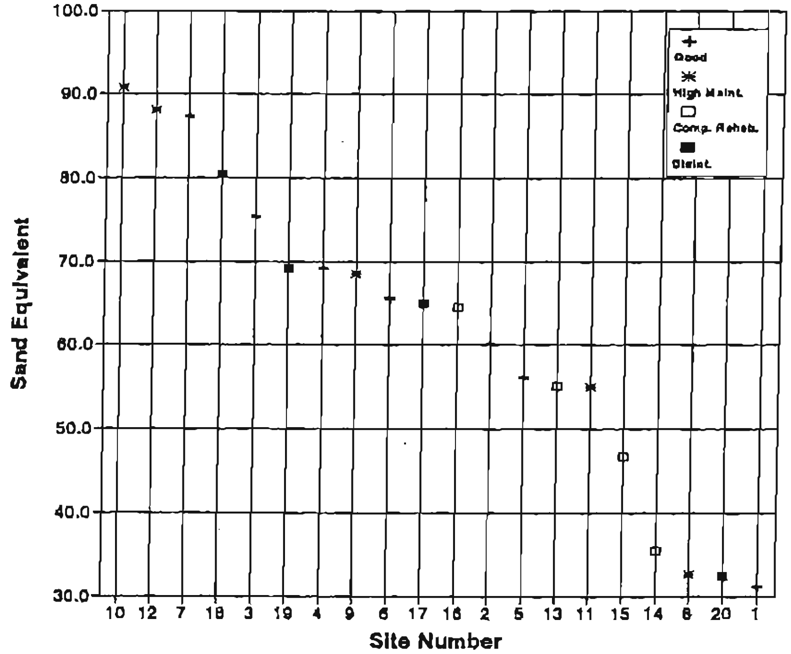

Fig. 18. Ranked Order of Sand Equivalent Values.

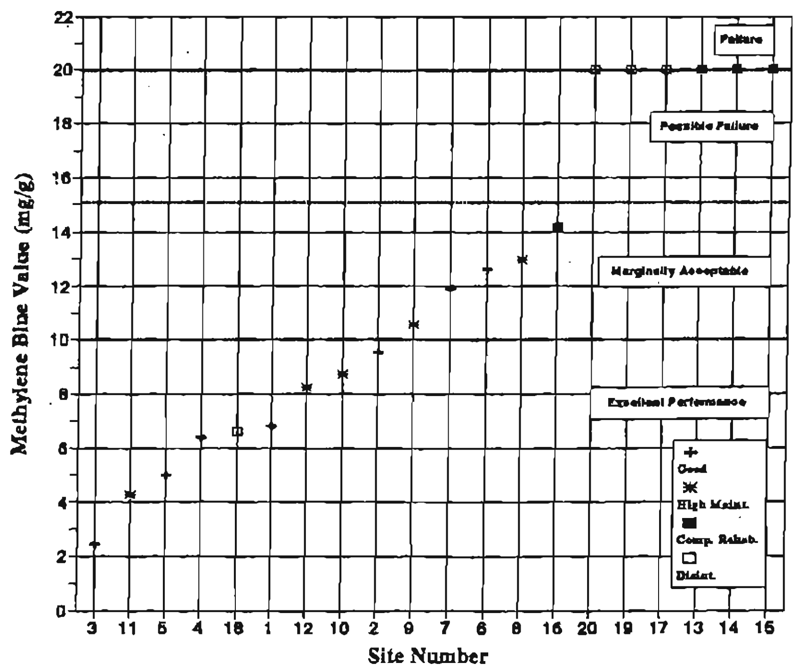

Fig. 19. Ranked Order of Methylene Blue Values.

5.3.3 Rigden Voids Index Test

The Rigden voids index test was performed to determine the fixed asphalt cement and the bulk density of the compacted P200. The free asphalt cement was then be calculated using Equation 1. Very little, if any, correlation between the fixed asphalt cement and field stripping performance. The fixed asphalt cement may relate more to cracking rather than stripping.

The maximum P200 to asphalt cement ratio, by weight ($P200/A_w$), was calculated for each HMA assuming a minimum free asphalt cement of 45%, as recommended by Anderson (11). The theoretical maximum $P200/A_w$ was plotted against the actual $P200/A_w$ in an attempt to find an explanation for the stripping performance of each site. As can be seen in Figure 20 and Table 17, the majority of the pavements with good stripping performance had $P200/A_w$ ratios less than the maximum determined with the Rigden voids index test. The majority of the High Maintenance, Complete Rehabilitation and Disintegrator sites had $P200/A_w$ ratios greater than the theoretical maximum.

Table 17. Summary of Rigden Voids Index Test Maximum $P200/A_w$.

$P200/A_w$	Actual Stripping Performance			
	Good	High Maint.	Comp. Rehab.	Disint.
Max > Actual	4	1	1	0
Max = Actual	0	0	0	0
Max < Actual	3	4	4	4

The ring and ball softening point test was performed to determine the $P200/A_w$ which resulted in an 11°C (20°F) increase in the softening point between the neat asphalt cement and a blend of P200 and the same asphalt cement. The theoretical maximum $P200/A_w$ was plotted against the actual $P200/A_w$. Figure 21 and Table 18 show that the majority of the pavements with good stripping performance had $P200/A_w$ less than that determined by the ring and ball softening point test. The majority of the poorer performing sites had $P200/A_w$ greater than that determined by the ring and ball softening point test.

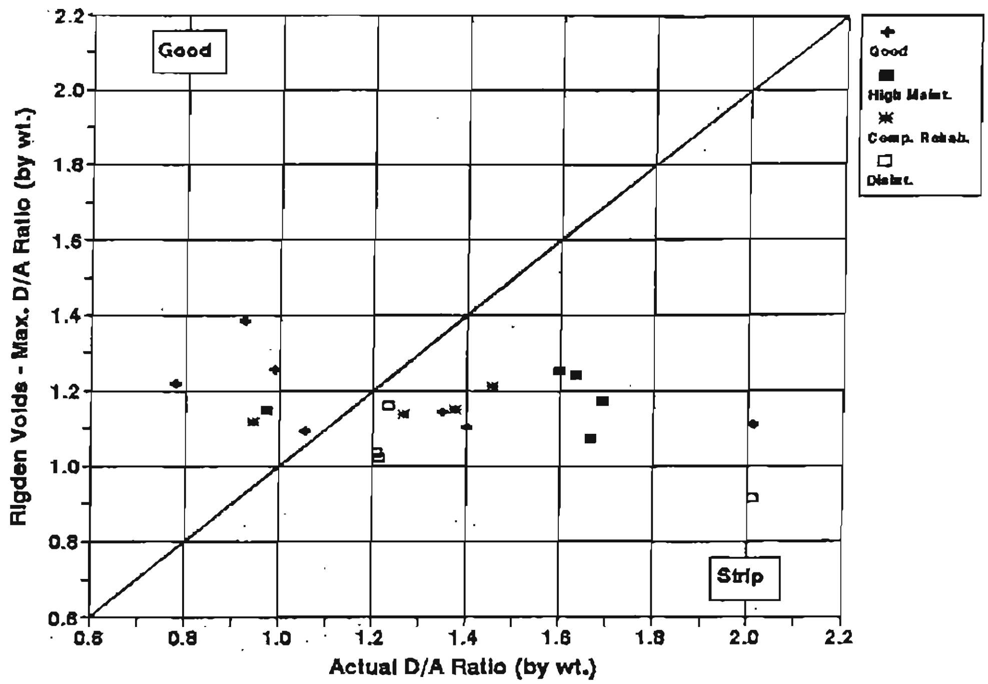

Fig. 20. Correlation Between the Actual P200/A_w and the Maximum P200/A_w as Determined by the Rigden Voids Index Test.

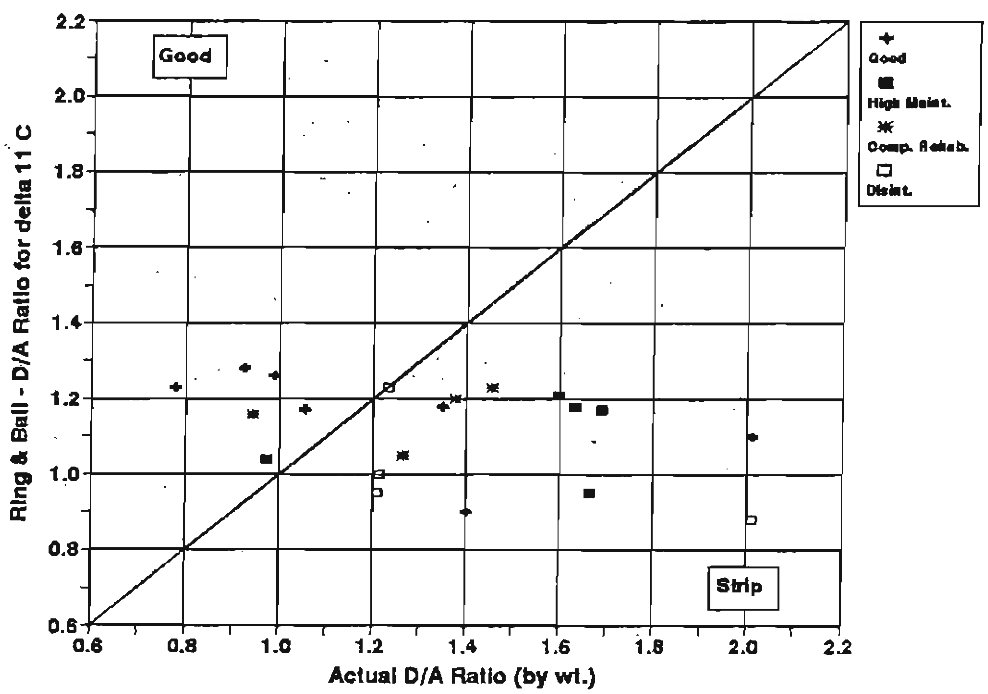

Fig. 21. Correlation Between the Actual P200/A_w and the Maximum P200/A_w as Determined by Maximum Ring and Ball Stiffening.

Table 18. Summary of Ring and Ball Softening Point Test Results.

$P200/A_w$	Actual Stripping Performance			
	Good	High Maint.	Comp. Rehab.	Disint.
Max > Actual	4	0	1	0
Max = Actual	0	1	0	1
Max < Actual	3	4	3	3

5.3.4 Ability of P200 Tests to Predict Stripping Performance

Assuming a marginal methylene blue value is acceptable, Table 19 and Table 20 summarize the ability of combinations of the P200 tests to predict the stripping performance of the HMA.

Table 19. Ability of Methylene Blue and Rigden Voids Index Test to Predict Stripping Performance.

MBV and RVI ($P200/A_w$)	Actual Stripping Performance			
	Good	High Maint.	Comp. Rehab.	Disint.
Pass Both	4	1	0	0
Pass One/Fail One	3	4	2	1
Fail Both	0	0	2	3

Table 20. Ability of Methylene Blue and Stiffening Power to Predict Stripping Performance.

MBV and R&B ($P200/A_w$)	Actual Stripping Performance			
	Good	High Maint.	Comp. Rehab.	Disint.
Pass Both	4	1	0	0
Pass One/Fail One	3	4	2	2
Fail Both	0	0	2	2

As can be seen in the above tables, if an aggregate passes both the methylene blue and stiffening power or Rigden voids, the possibility of failure due to stripping is minimized.

5.3.5 Dust Coating on Aggregates

The amount of P200 coating the aggregates larger than the 4.75 mm (No. 4) sieve was measured by performing a washed gradation on the blend of coarse aggregate from each mix. The P200 washed off the coarse aggregate is shown in Table 15. In most cases the P200 coating the coarse aggregate was less than 1%. The most interesting result was the high quantity of P200 coating the large aggregate from Mix 18. Mix 18 passed every P200 test yet performed poorly in the field. It is possible that the P200 coating the coarse aggregate could have contributed to the mixture's poor performance by preventing the adhesion of the asphalt cement and aggregate.

5.3.6 Correlation Between Tests

An effort was made to determine if a correlation exists between the sand equivalent and methylene blue tests. There was poor correlation between these two tests. The sand equivalent test is more a measure of quantity, rather than quality, of the P200. The methylene blue test is a measure of the quality of the P200.

Attempts were also made to correlate the fixed asphalt cement with the methylene blue and sand equivalent tests but were not successful.

6.0 CONCLUSIONS

The stripping performance of HMA pavements is greatly dependent on the interaction between the asphalt cement and aggregates and the quality of the aggregate components in the HMA. The Hamburg wheel-tracking device and the Environmental Conditioning System are performance-related tests that were used to test HMAs of known stripping performance. If an HMA fails in performance related tests, testing the asphalt cement and aggregate portions of the mix can indicate areas for potential improvement of the mix. The following are conclusions drawn by testing with performance-related equipment and several P200 tests on the aggregates from twenty sites of known stripping performance in Colorado.

1) The Hamburg wheel-tracking device applies very severe moisture conditioning cycles. The test appears to be especially severe on the Good sites. It may be necessary to reduce the severity of the specification used by the City of Hamburg: less than 4 mm rut depth at 20,000 passes. The results have better correlation to actual field performance by specifying either 1) a minimum rut depth of 10 mm instead of 4 mm at 20,000 passes, or 2) a minimum of 4 mm rut depth at 10,000 passes instead of 20,000.

By modifying the specification, results from the Hamburg wheel-tracking device can accurately identify pavements of known field performance. The stripping inflection point correlates to the known level of stripping performance of pavements. The lower the stripping inflection point, the worse the stripping was in the field.

Furthermore, some of the "Good" pavements used in this study may not have been so good. The current definition of good performance may have to be redefined to a higher level of quality.

A future study should examine the use of the 50°C test temperature. This temperature is very severe for many of the environmental conditions in Colorado. The use of test temperature lower than 50°C should be examined for pavements that are not placed in the hottest parts of the State.

2) The ECS test procedure moisture conditions the samples very mildly. Using the M_R-ratio, only

three of the thirteen sites with poor field performance failed in the lab. When the slope was used to evaluate the sites, more of the poor performing sites were considered unacceptable. However, the slope would be very difficult for a state highway agency to quantify and specify. Additional research is needed to assess the ability of the ECS to predict moisture damage.

3) The methylene blue test is a measure of the quality of the P200 and can give insight to potential stripping problems. The rule-of-thumb guidelines for expected performance are very useful in predicting the potential stripping performance of a HMA.

The Rigden voids index test and the ring and ball softening point can be used to determine the maximum allowable P200 to asphalt cement ratios. The maximum P200 to asphalt cement ratios determined by these tests should not be exceeded to minimize potential stripping problems.

When used in conjunction with one another, the methylene blue, Rigden voids and ring and ball softening point tests accurately identified all but one of the stripping sites. When an HMA fails a performance related stripping test, the methylene blue, Rigden voids and stiffening power can be used to identify some of the problematic components of the HMA.

The sand equivalent test was not a good predictor of stripping performance.

7.0 IMPLEMENTATION

The use of the Hamburg wheel-tracking device or Environmental Conditioning System are not ready for full implementation at this time. Additional research is necessary for their full implementation.

At this time, the Hamburg wheel-tracking device could be used as a referee test. After a passing mix design is obtained, the standard tests could be used to monitor the project. However, the standard tests are not always reliable. When the contractor or state highway agency had reason to question the standard results, the Hamburg wheel-tracking device could then be used as a referee test to settle disputes.

8.0 REFERENCES

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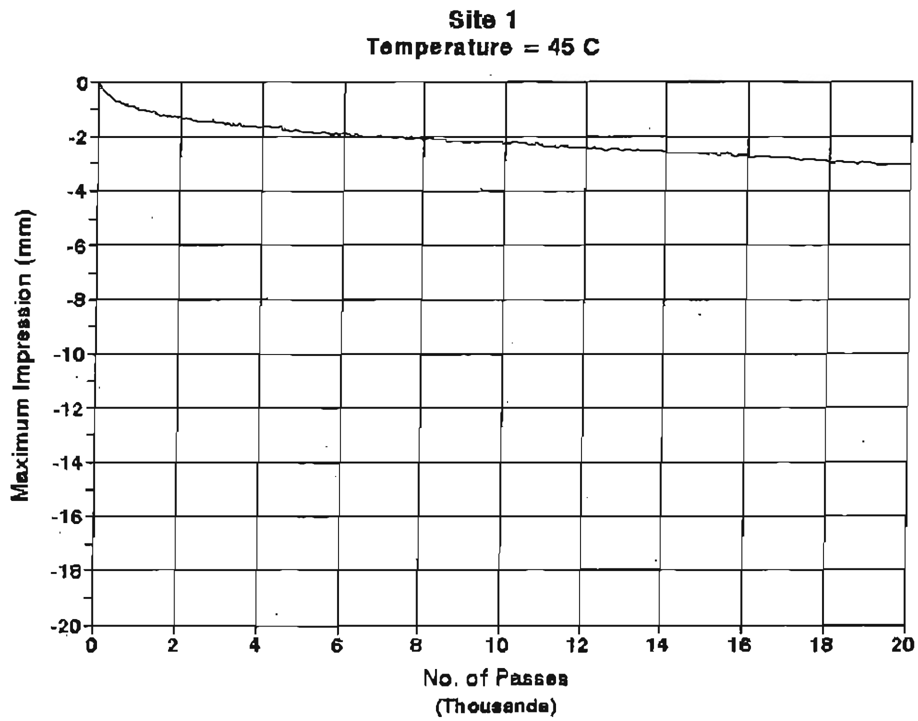
Appendix A

Results from the Hamburg Wheel-Tracking Device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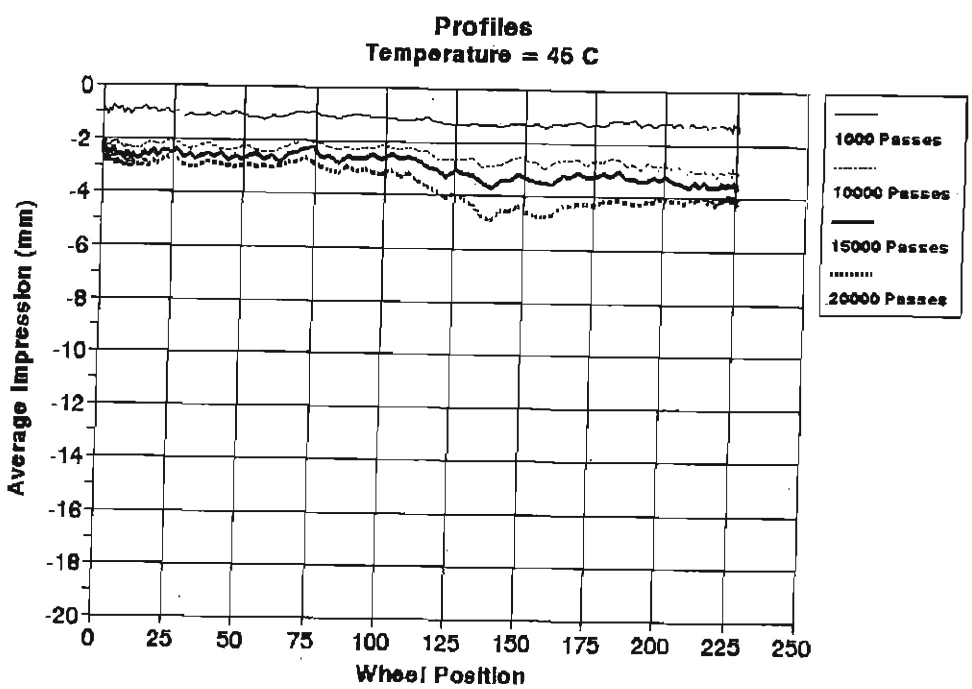
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)


Profiles
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Average Impression (mm)
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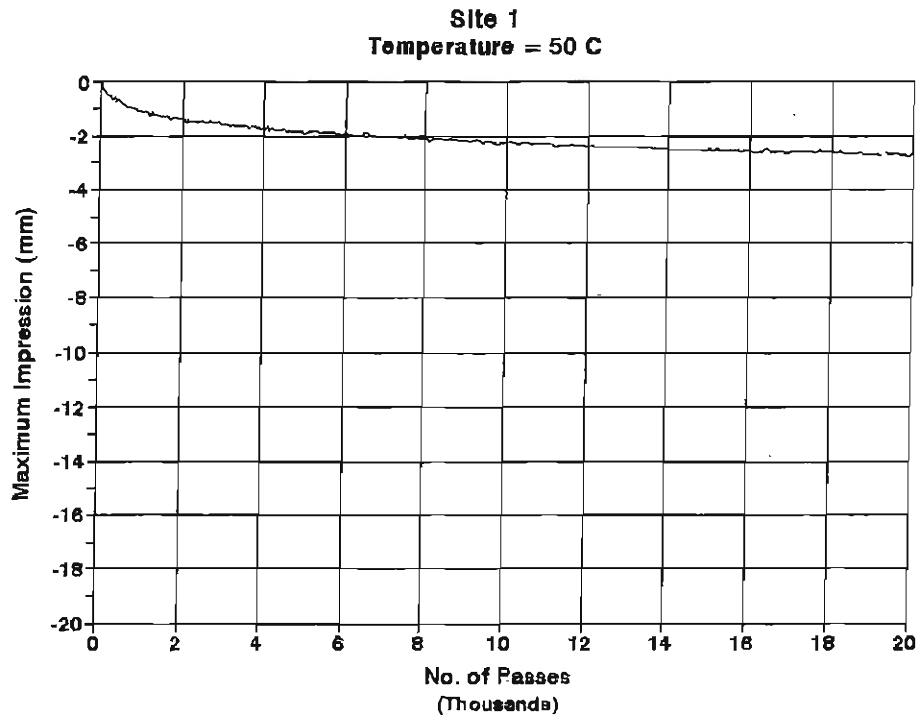
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes



Site 1
Temperature = 50 C
Maximum Impression (mm)
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-8
-10
-12
-14
-16
-18
-20
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4
6
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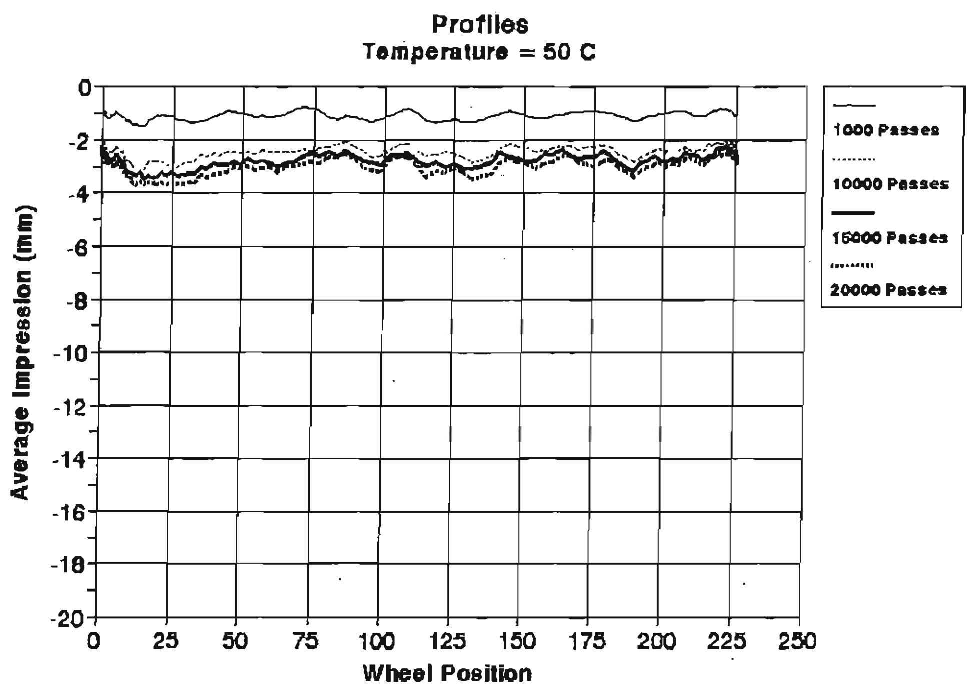
12
14
16
18
20
No. of Passes
(Thousands)



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-10
-12
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-20
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50
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200
225
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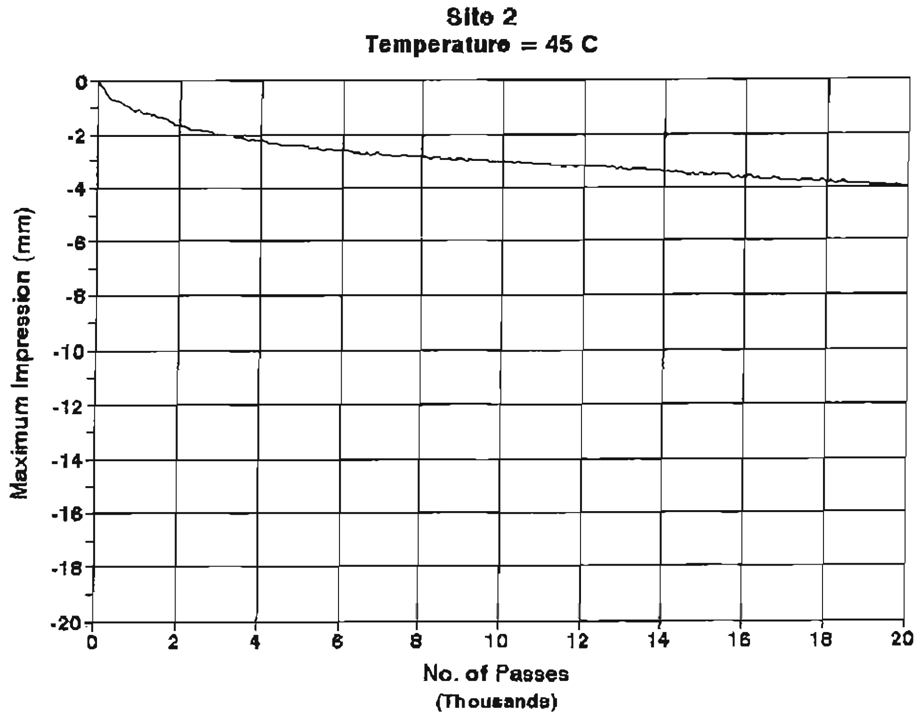
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes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6
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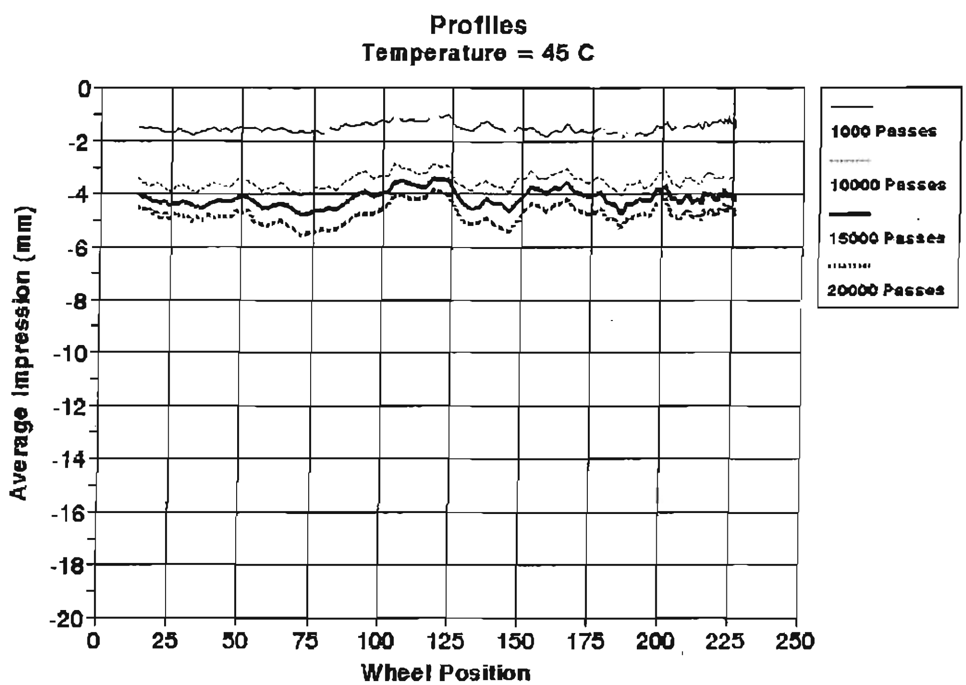
16
18
20
No. of Passes
(Thousands)


Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
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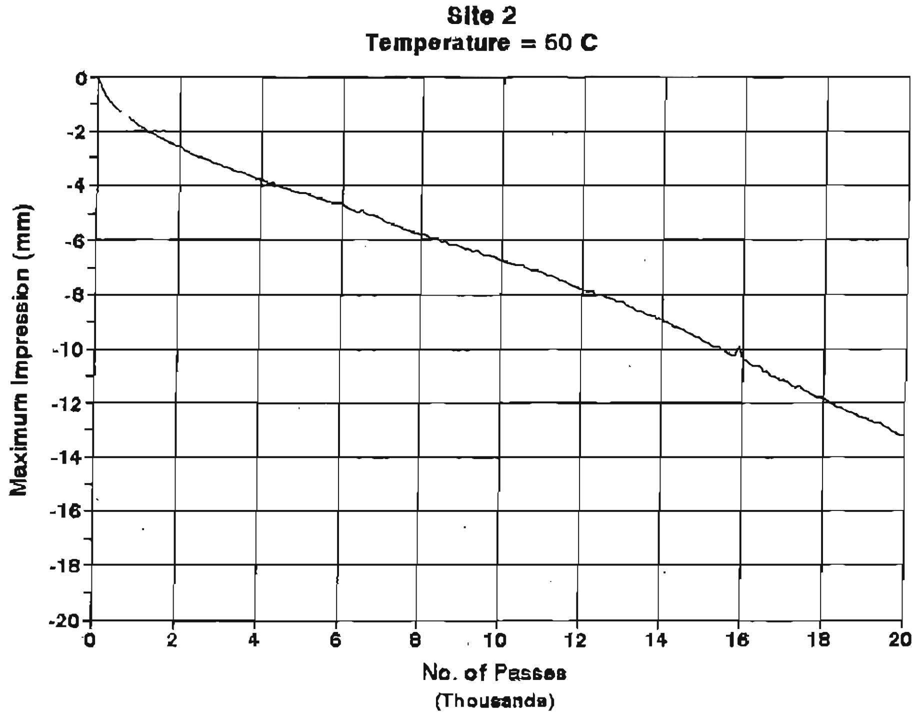
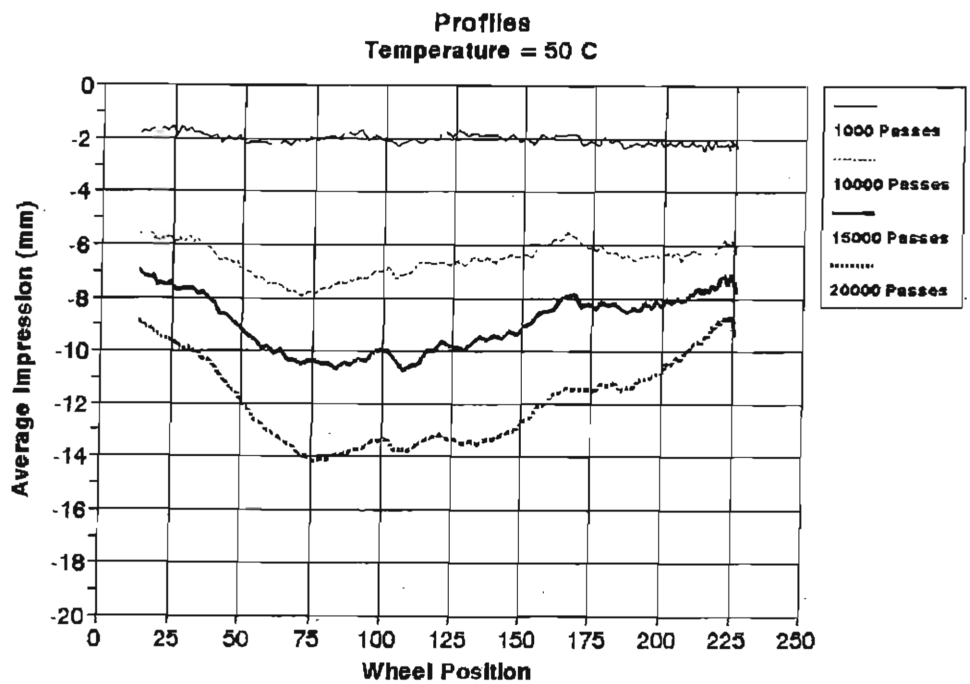
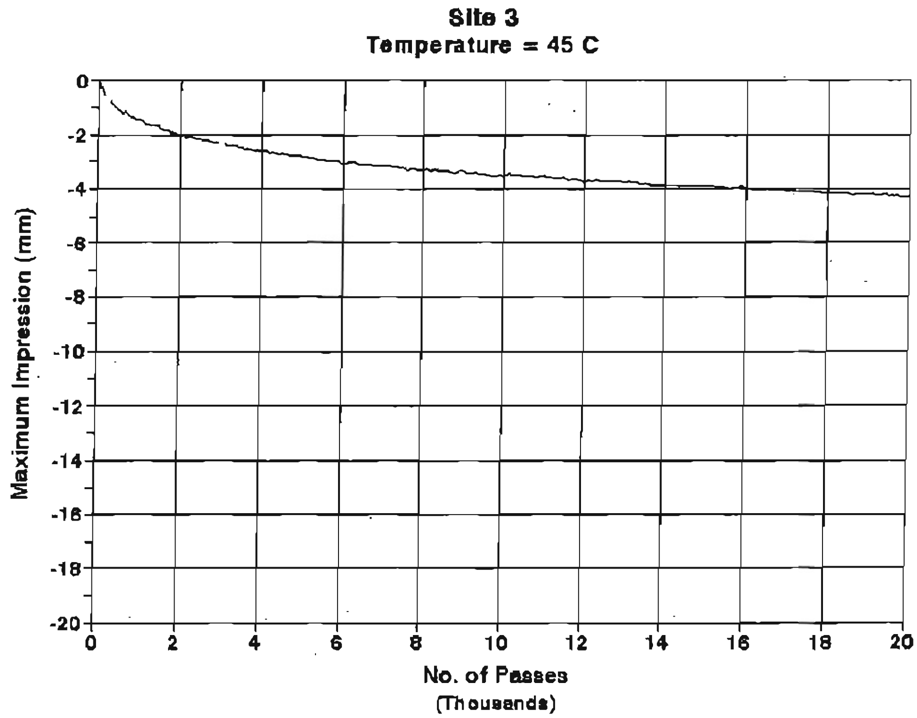
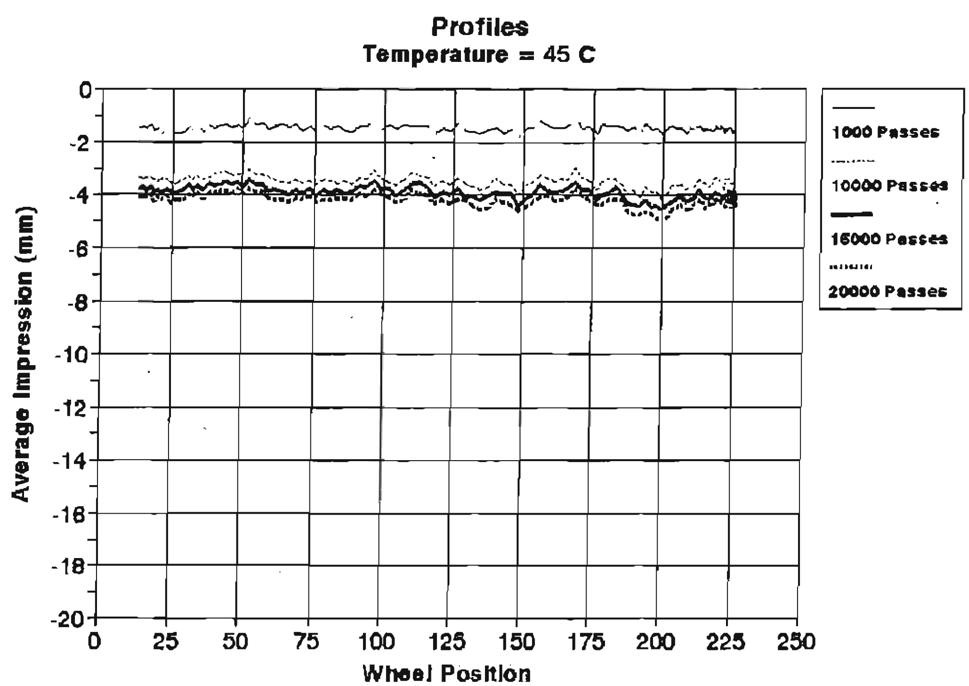
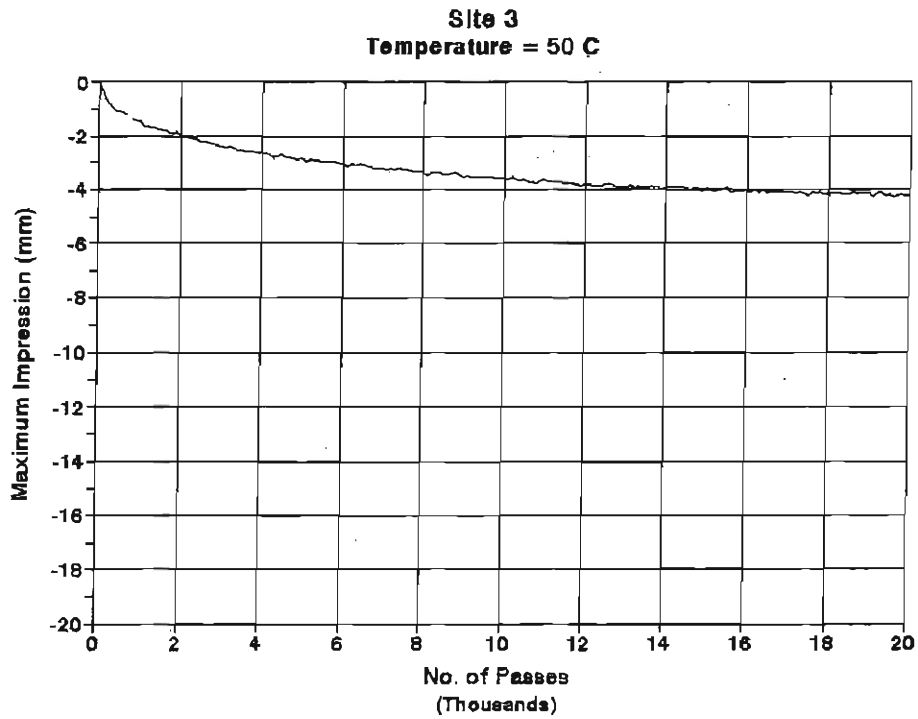
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes

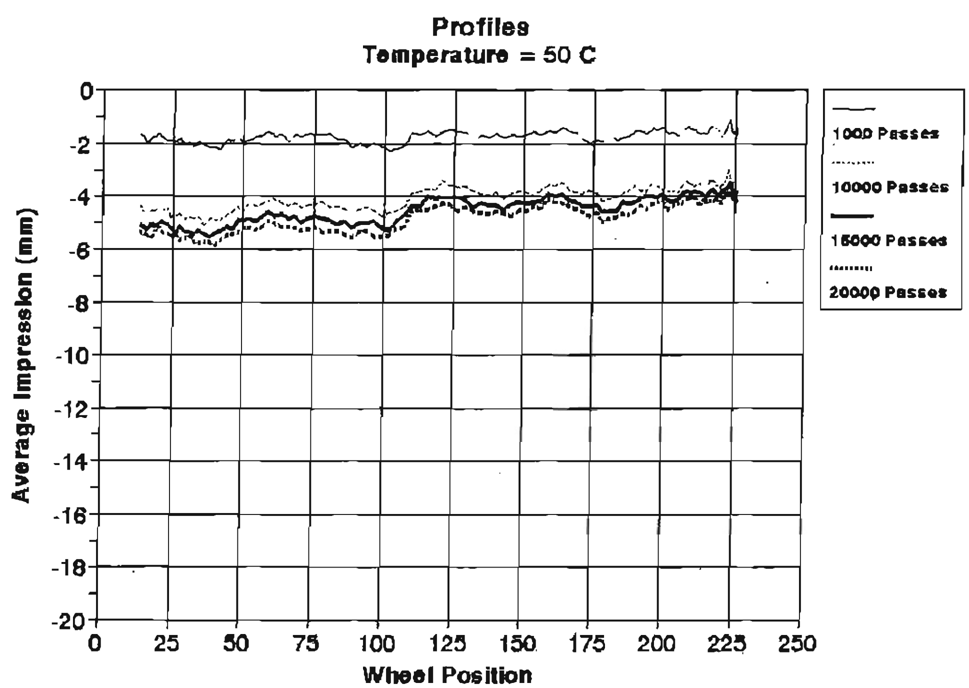

Site 2
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

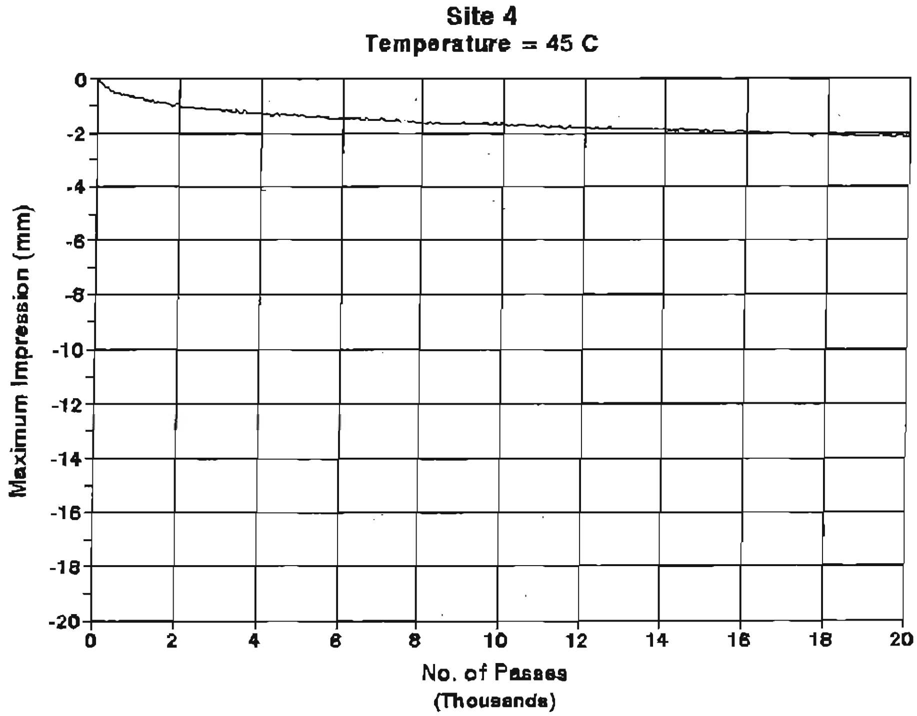

Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes

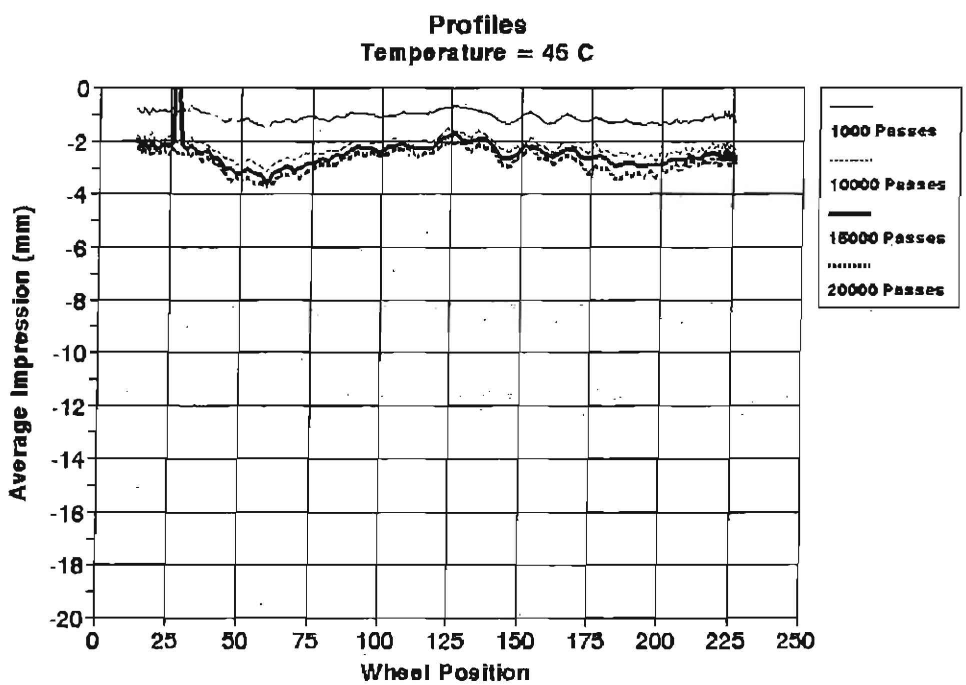

Site 3
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

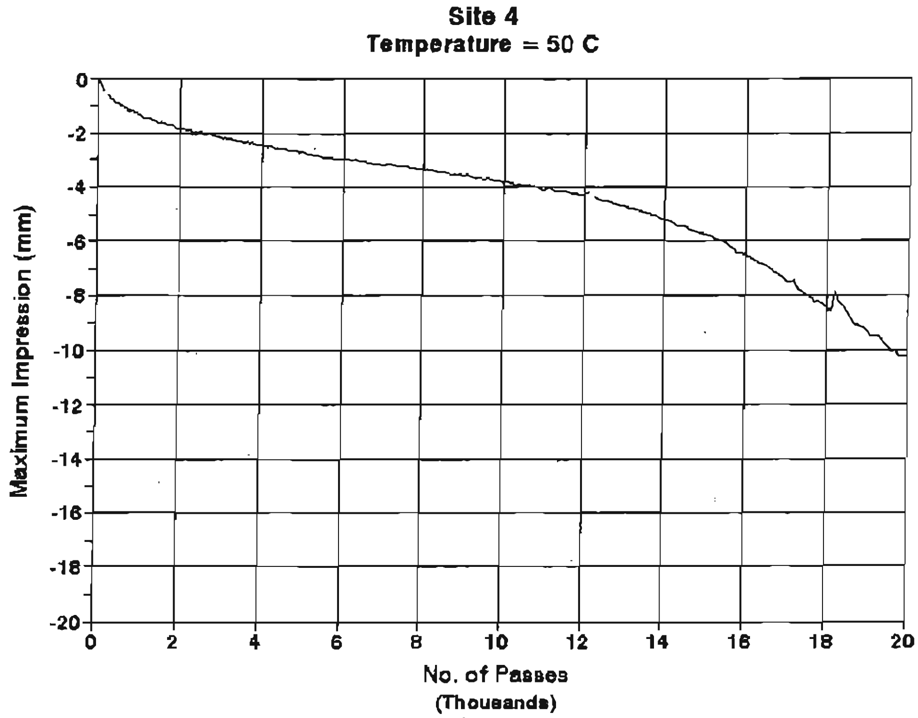

Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes


Site 3
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

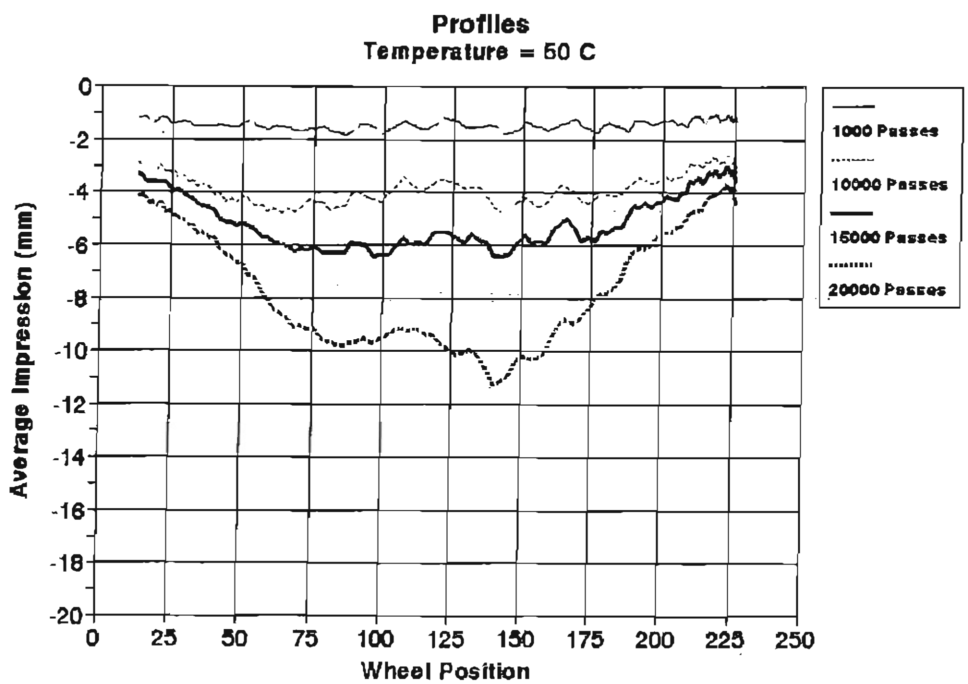

Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes


Site 4
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

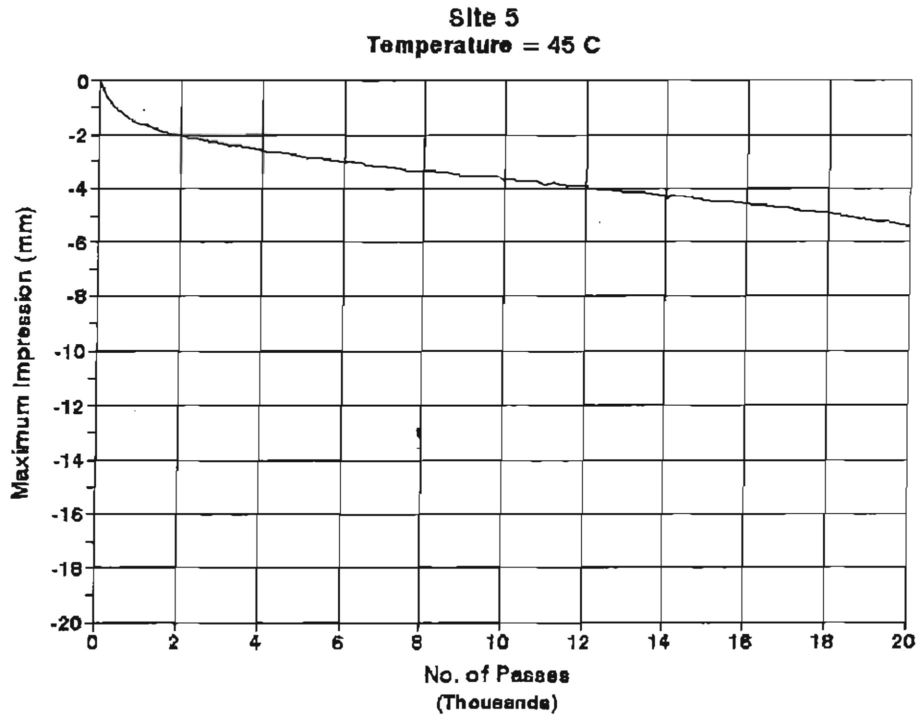

Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes

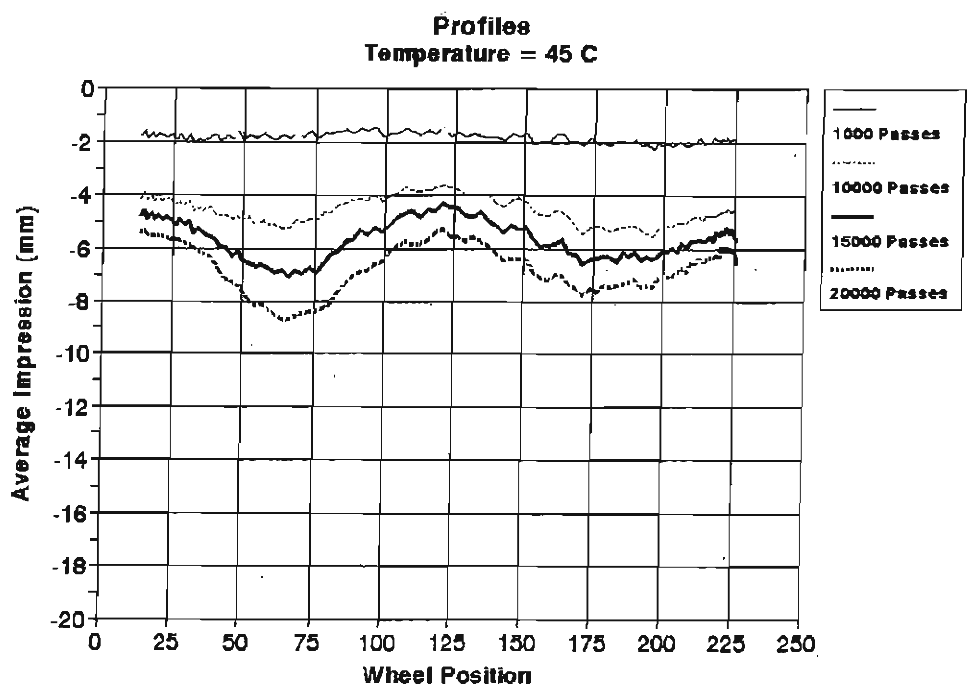


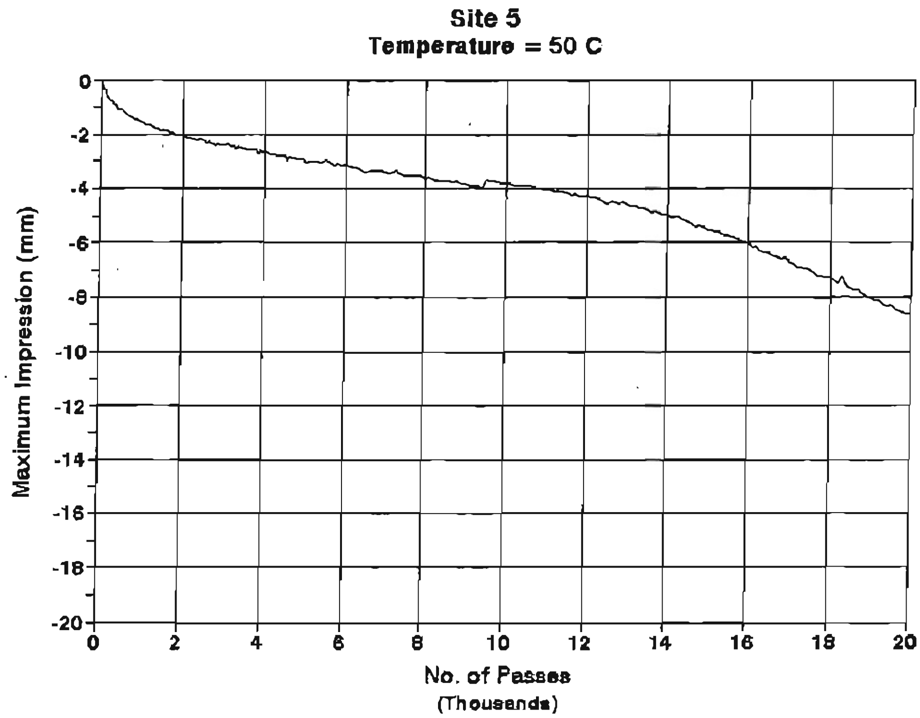
Site 4
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

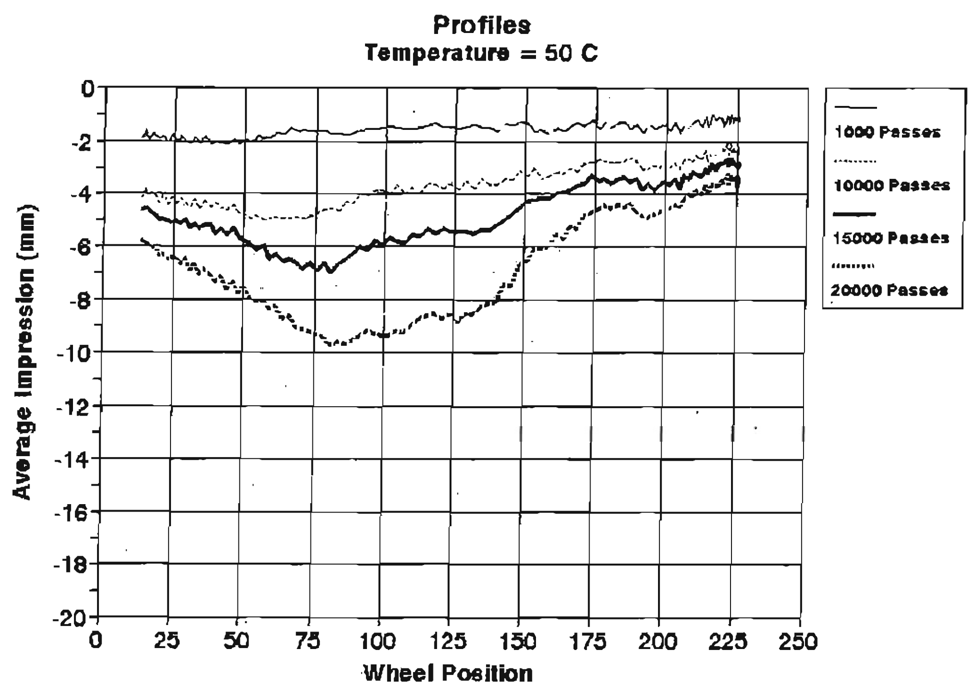


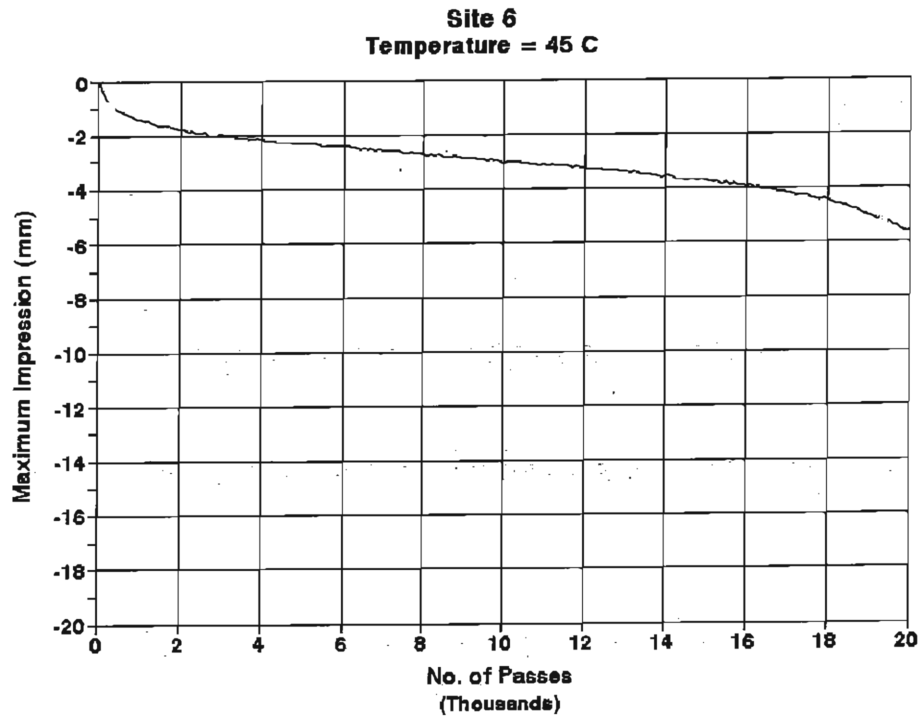
Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes


Site 5
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

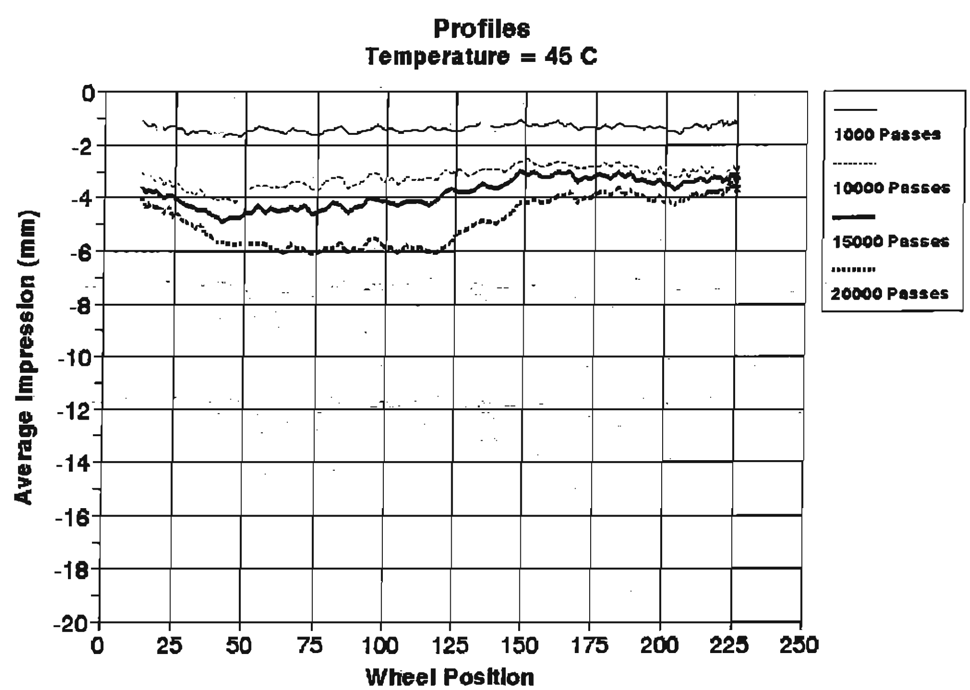

Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes


Site 5
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

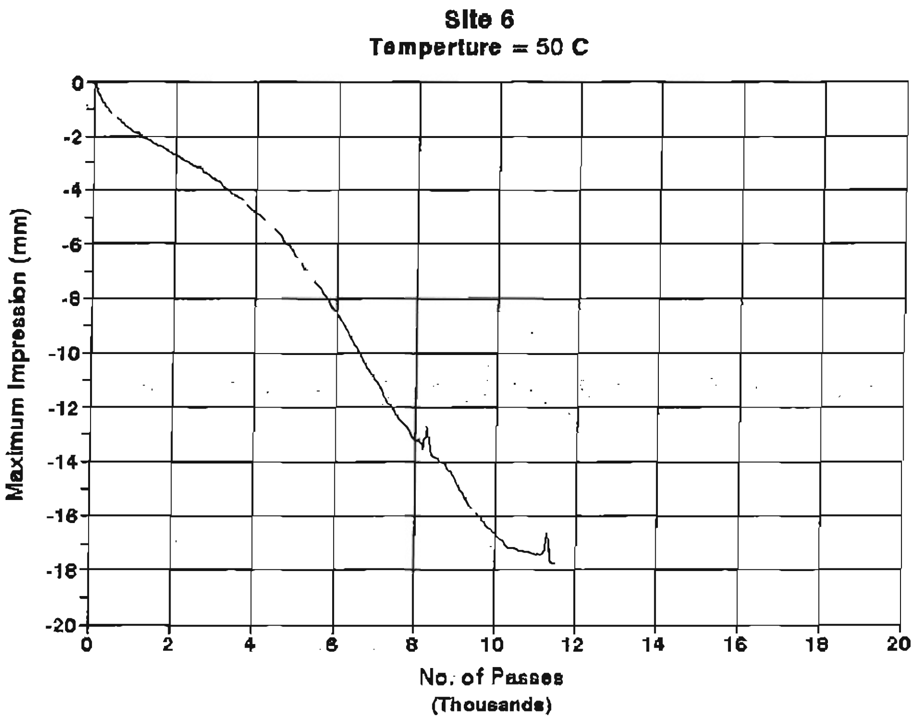

Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes



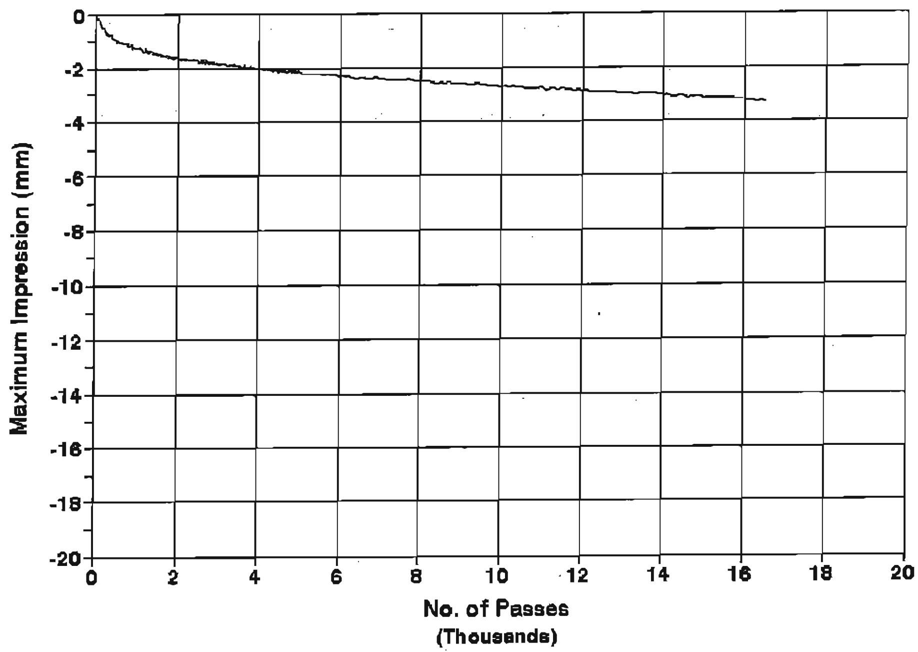
Site 6
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



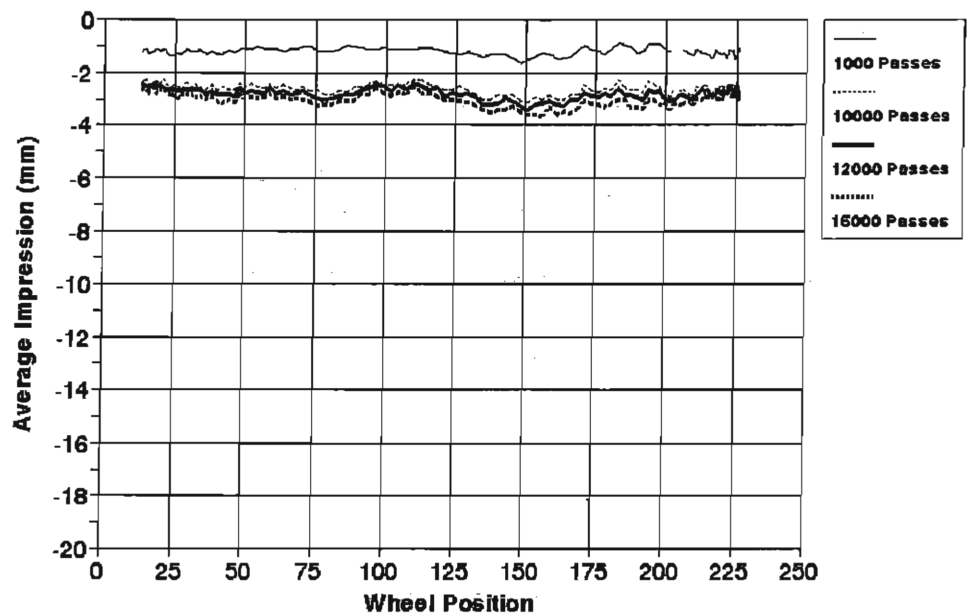
Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes

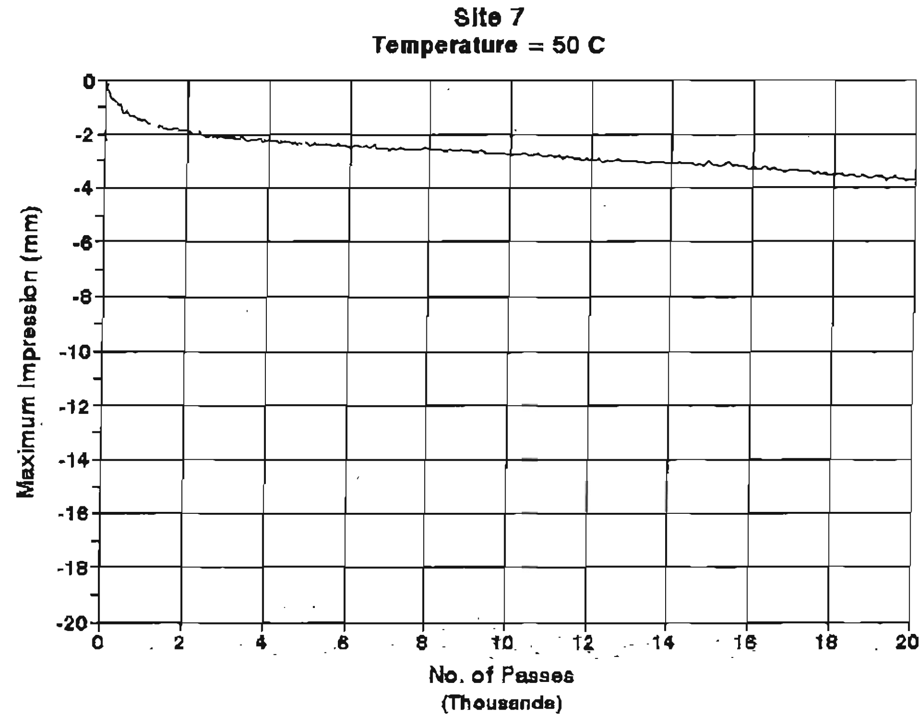

Site 6
Temperture = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

Site 7
Temperature = 45 C

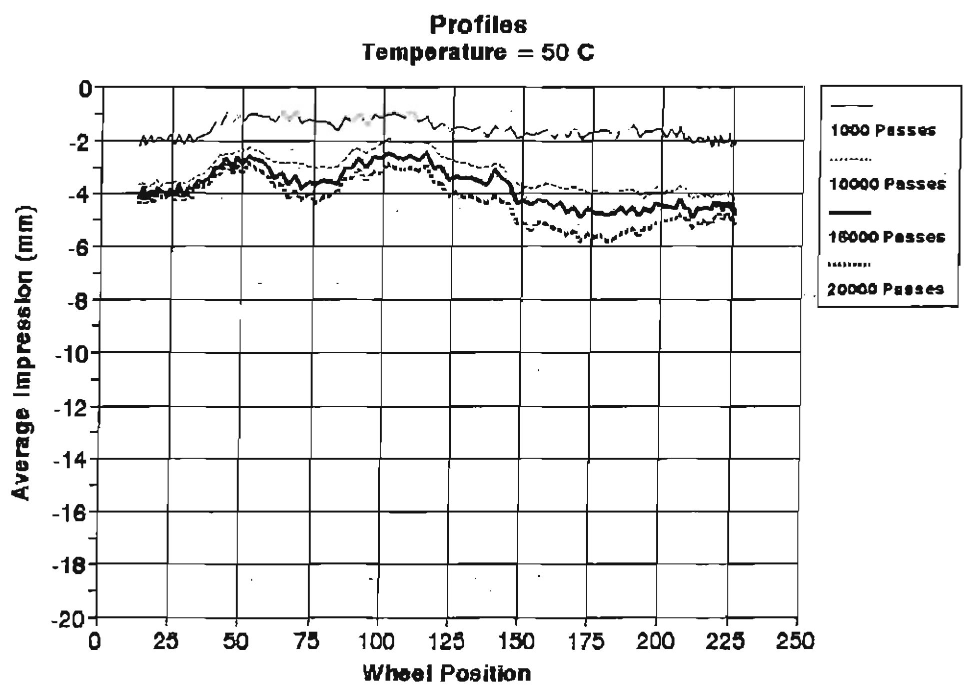


Profiles
Temperature = 45 C

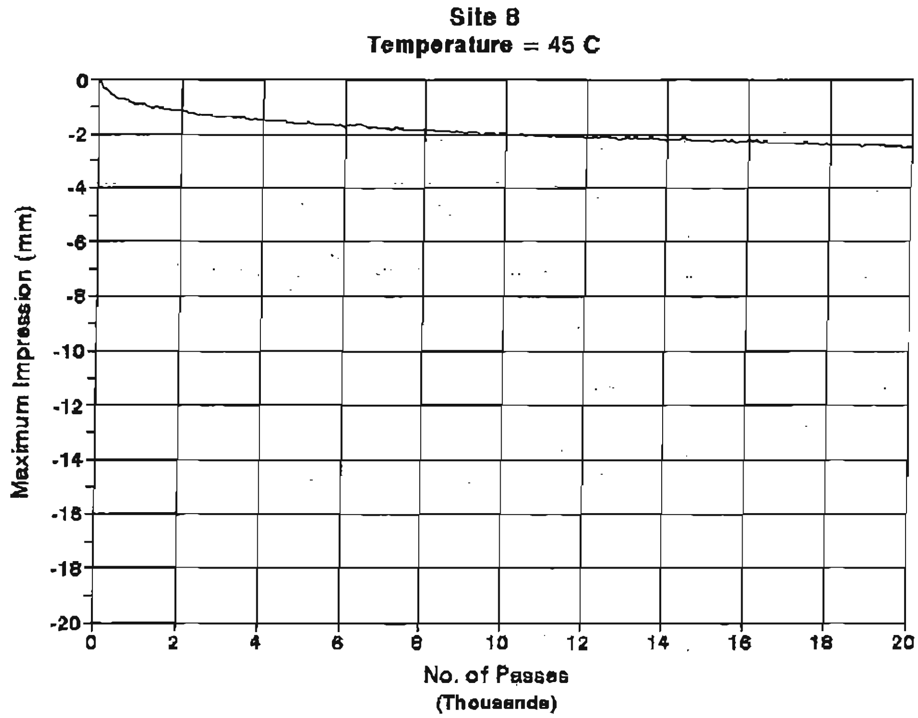


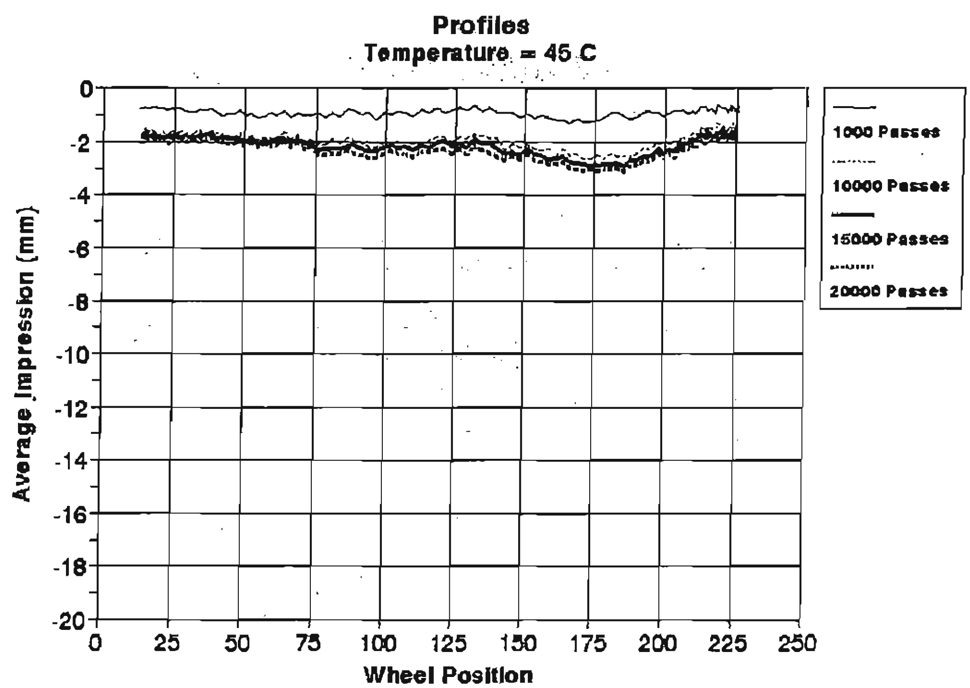


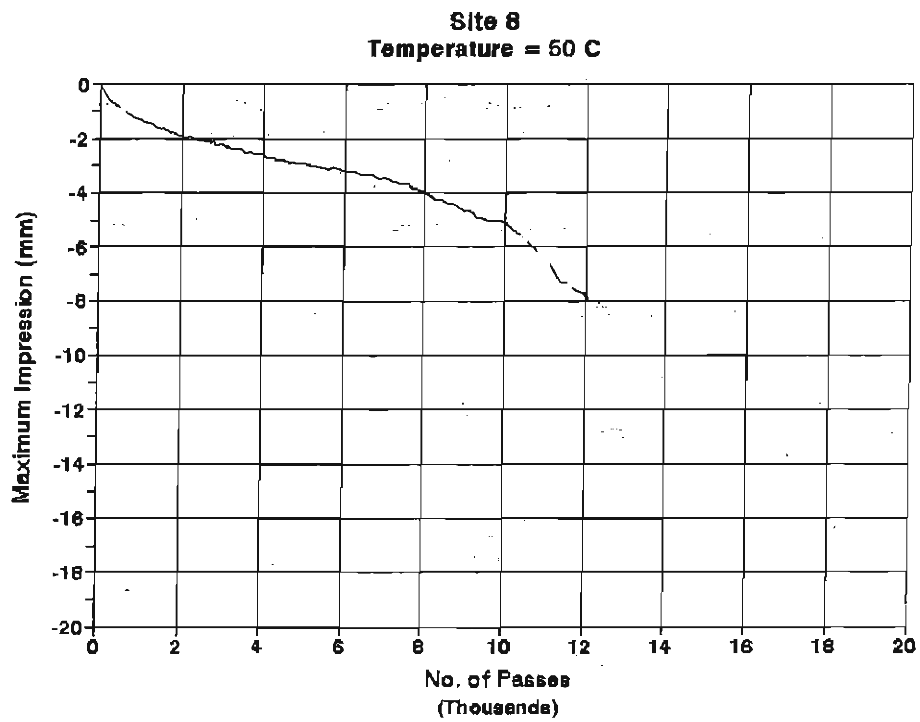
Site 7
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

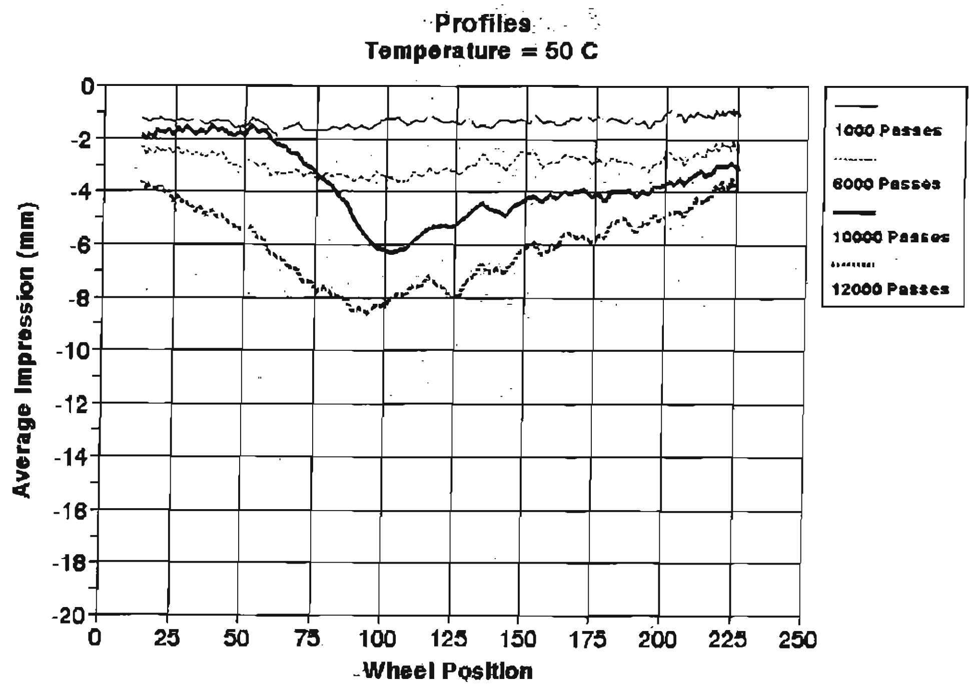


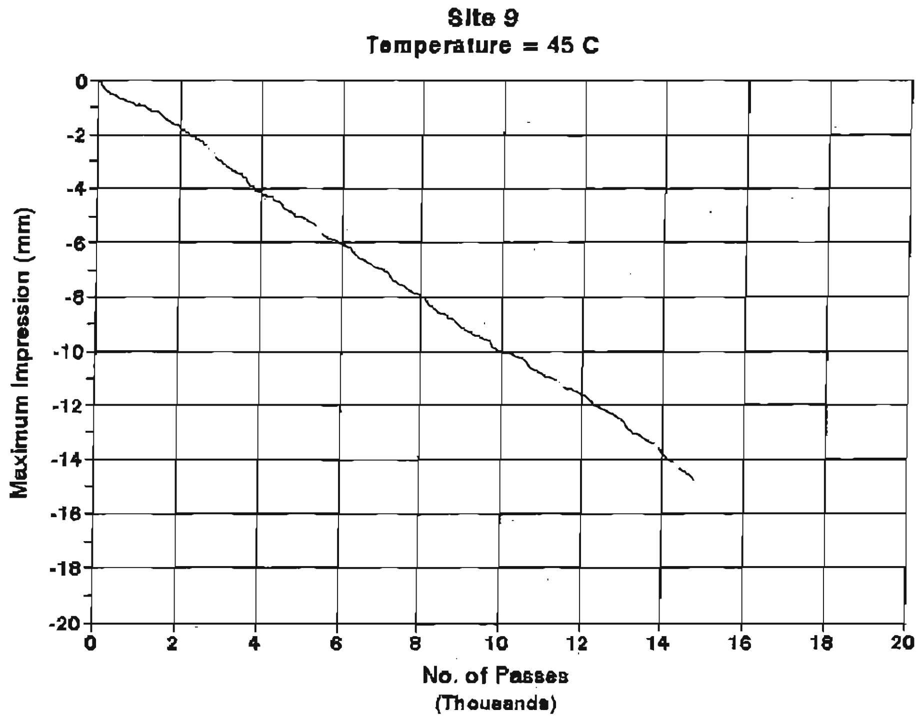
Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes


Site 8
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

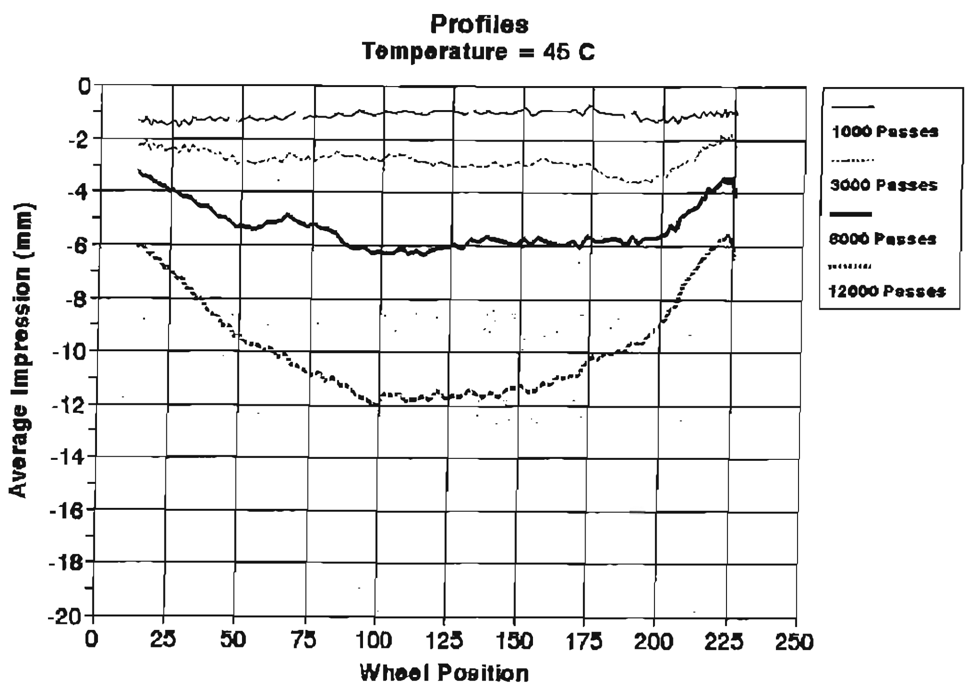

Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes


Site 8
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

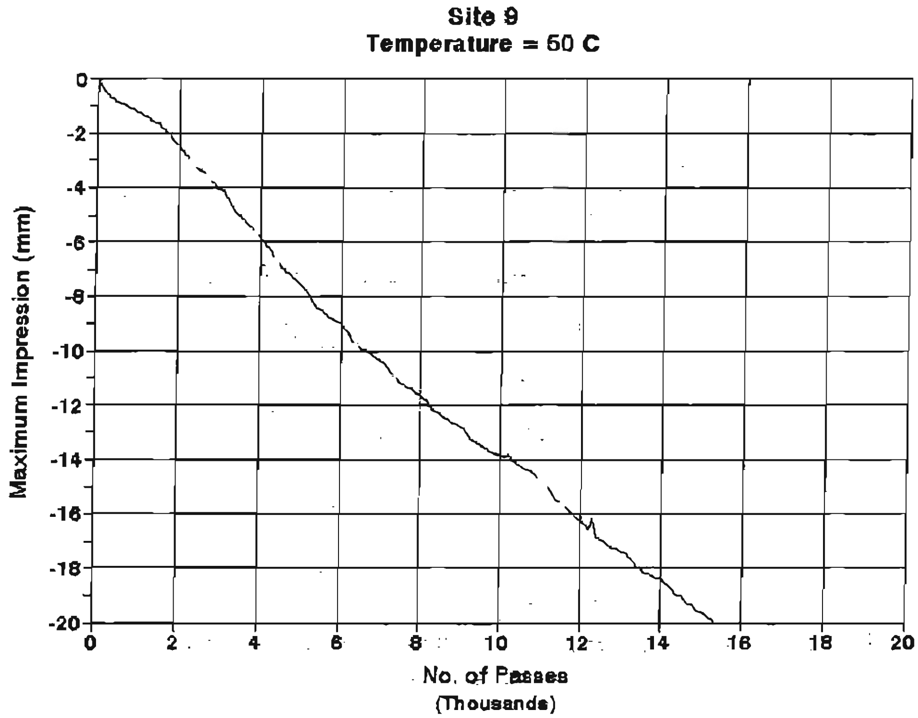

Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
6000 Passes
10000 Passes
12000 Passes



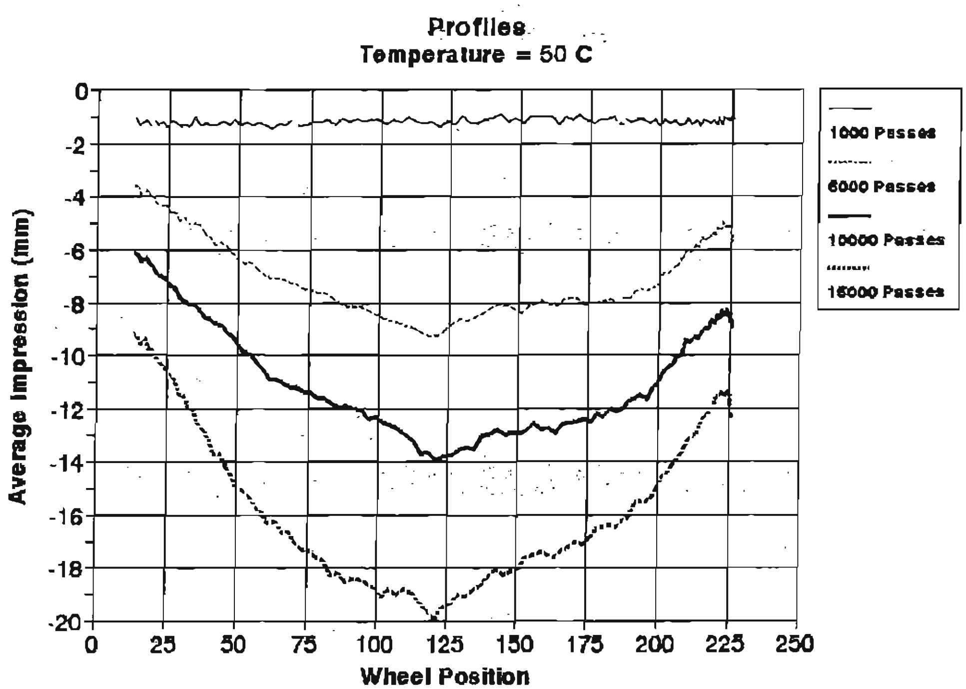
Site 9
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



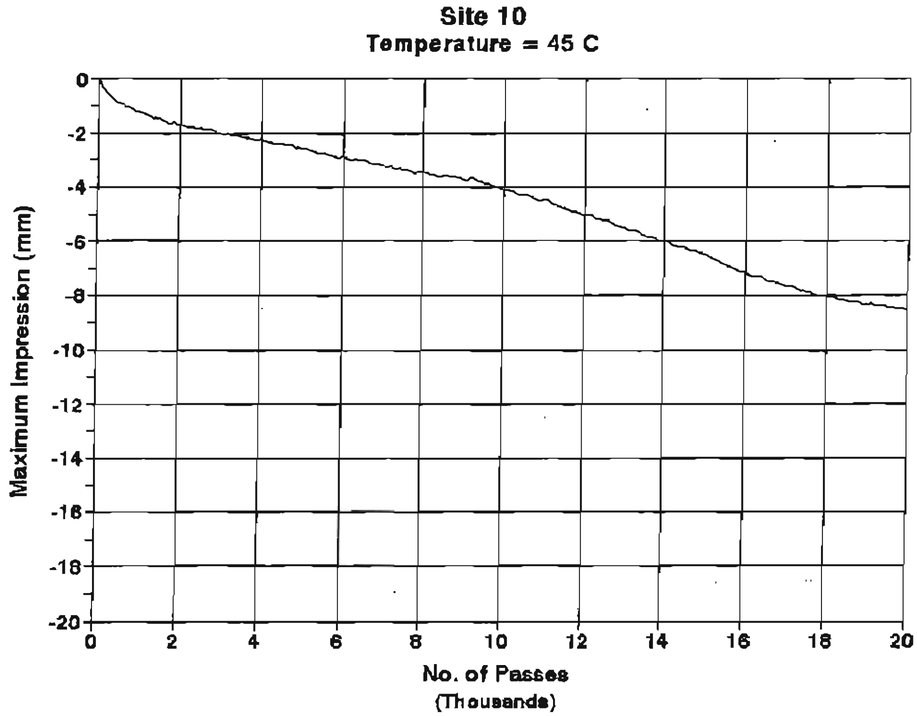
Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
3000 Passes
6000 Passes
12000 Passes



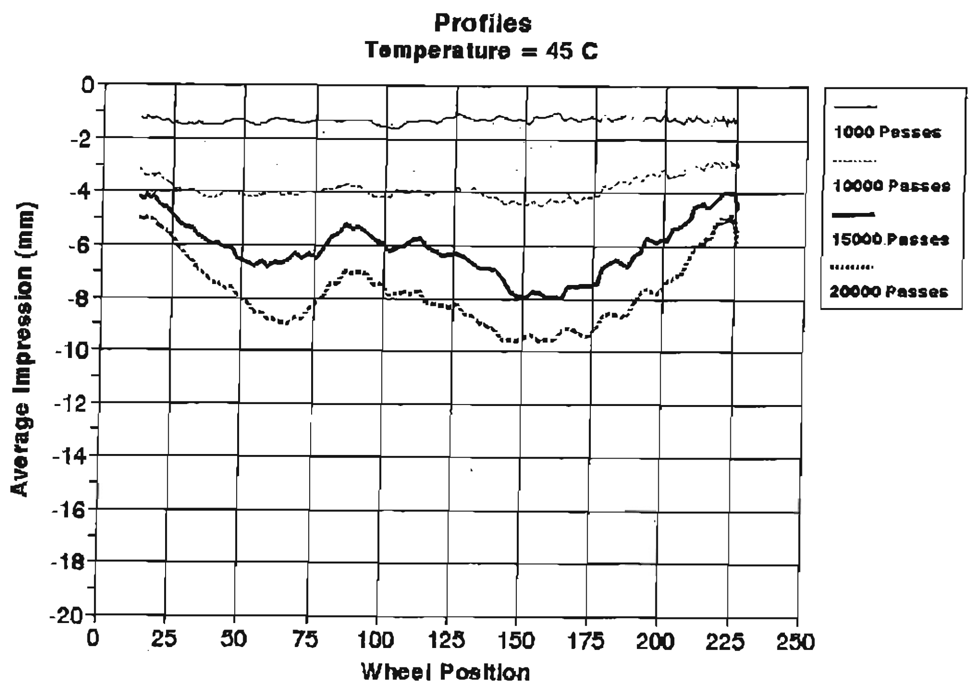
Site 9
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



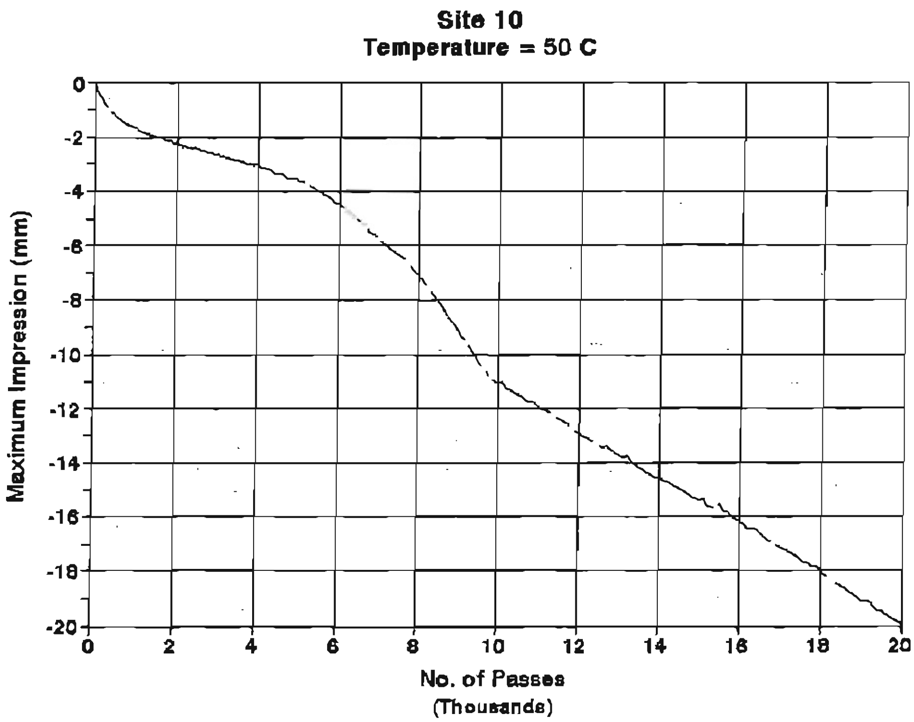
Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
6000 Passes
10000 Passes
16000 Passes

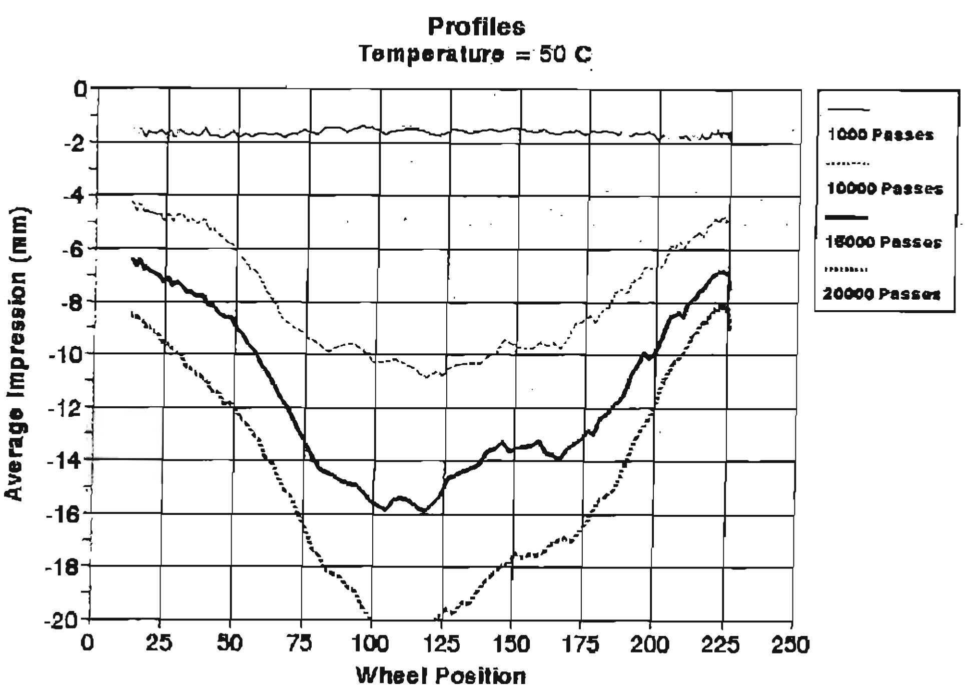


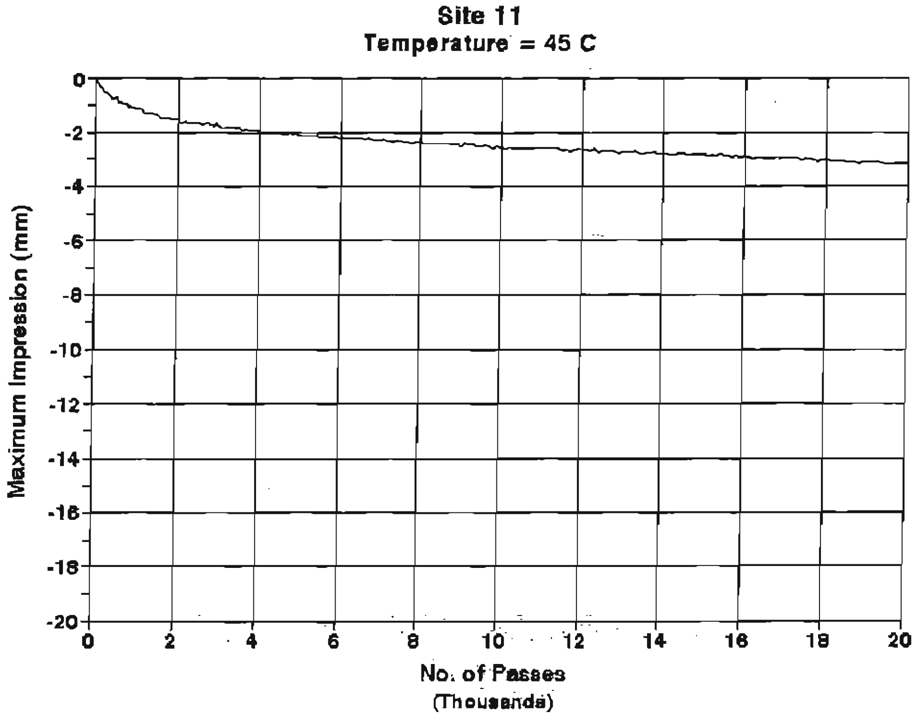
Site 10
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



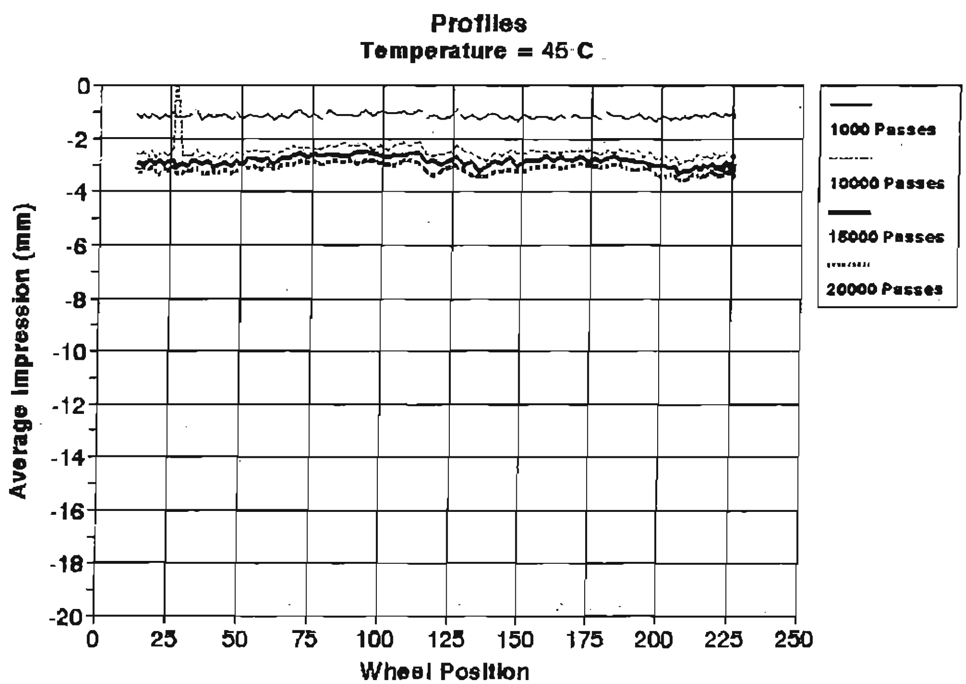
Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes


Site 10
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

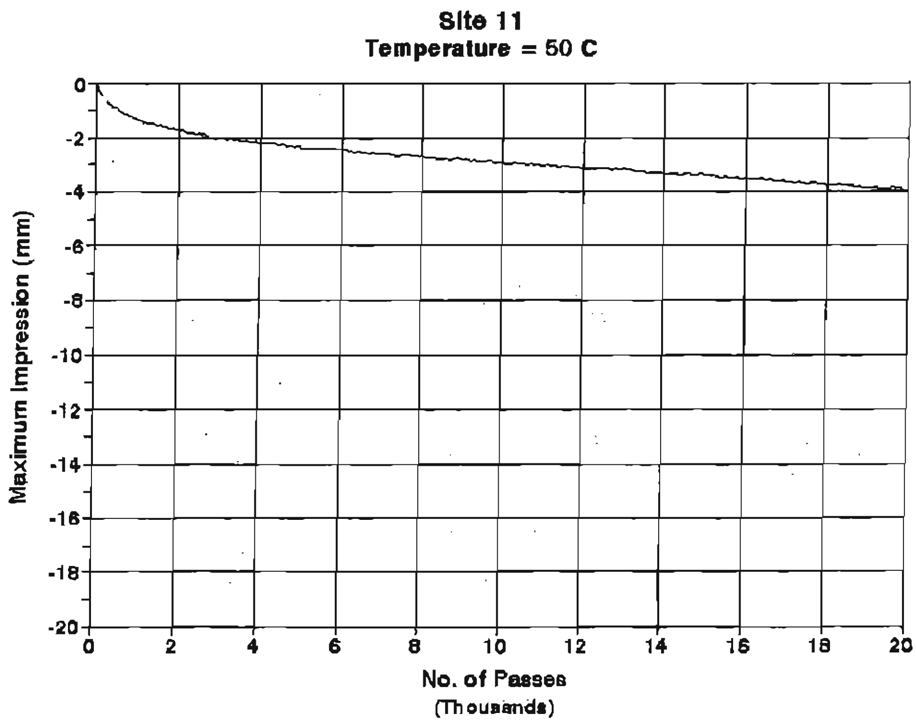

Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes

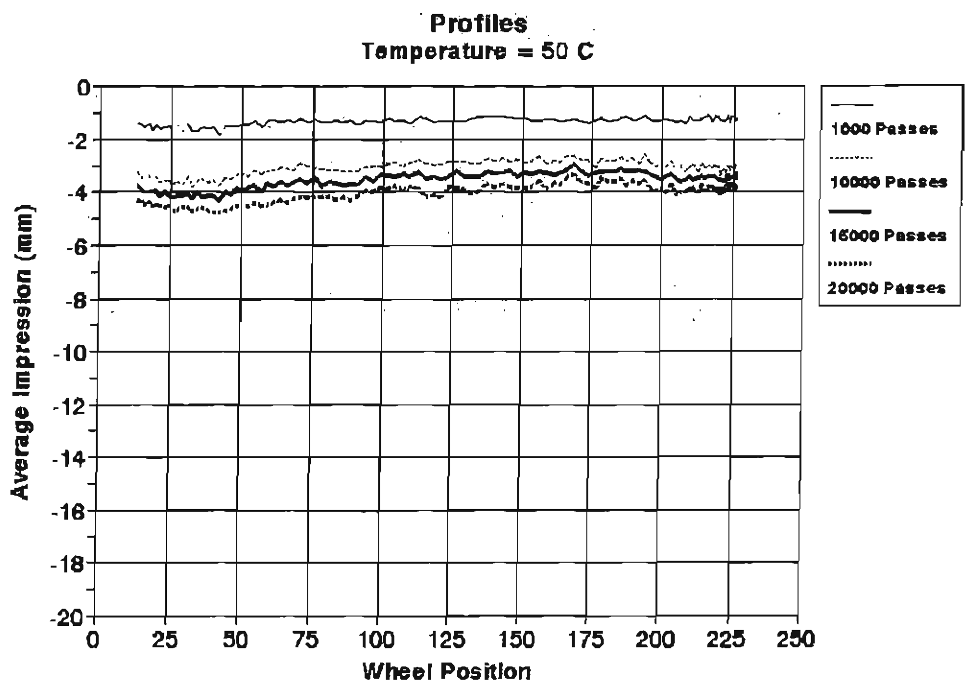


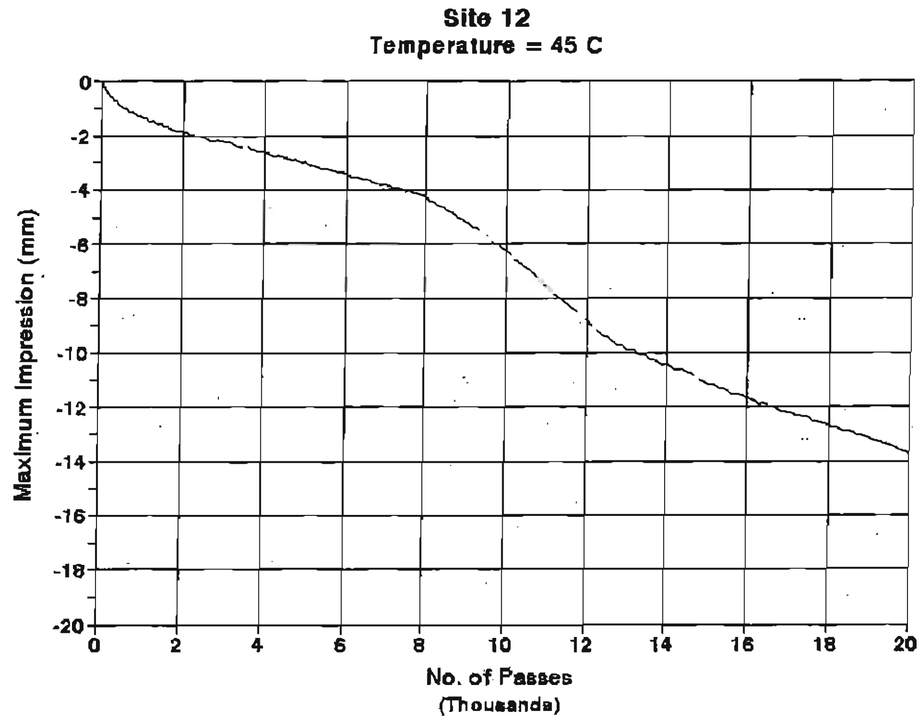
Site 11
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

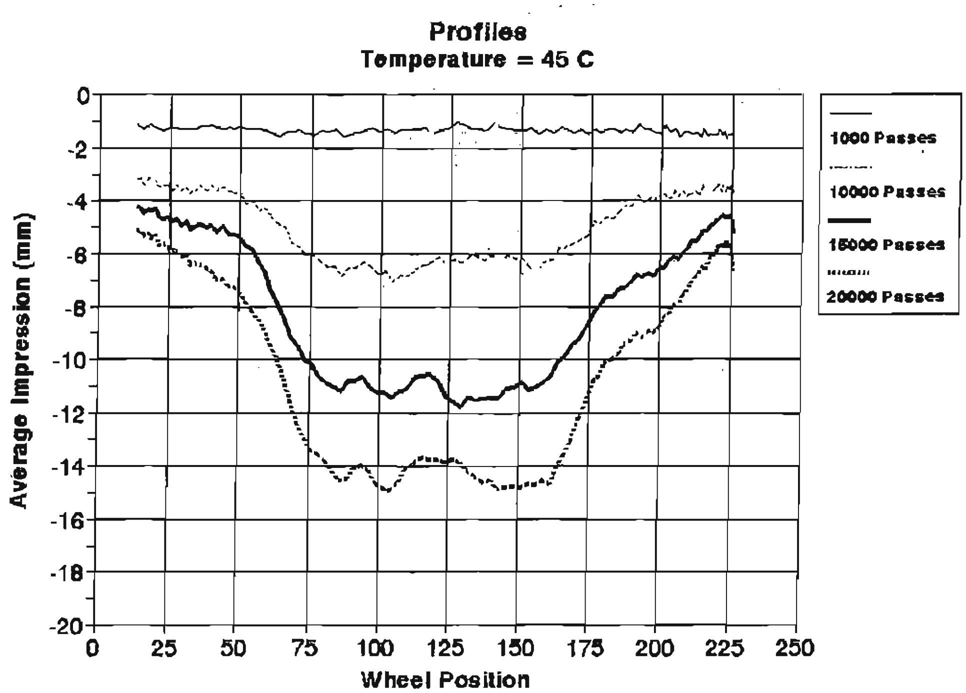


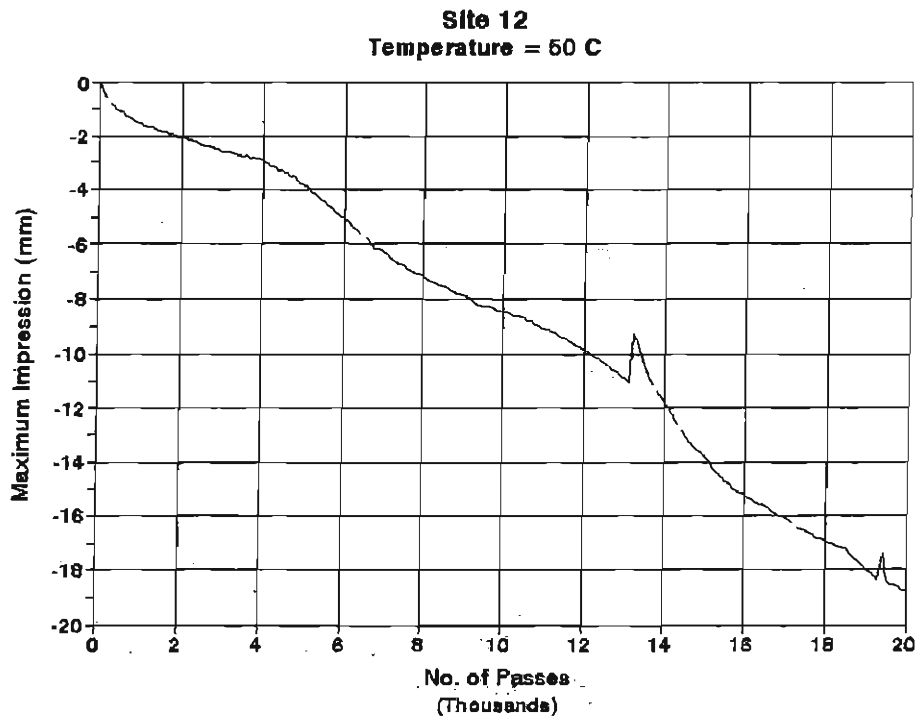
Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes

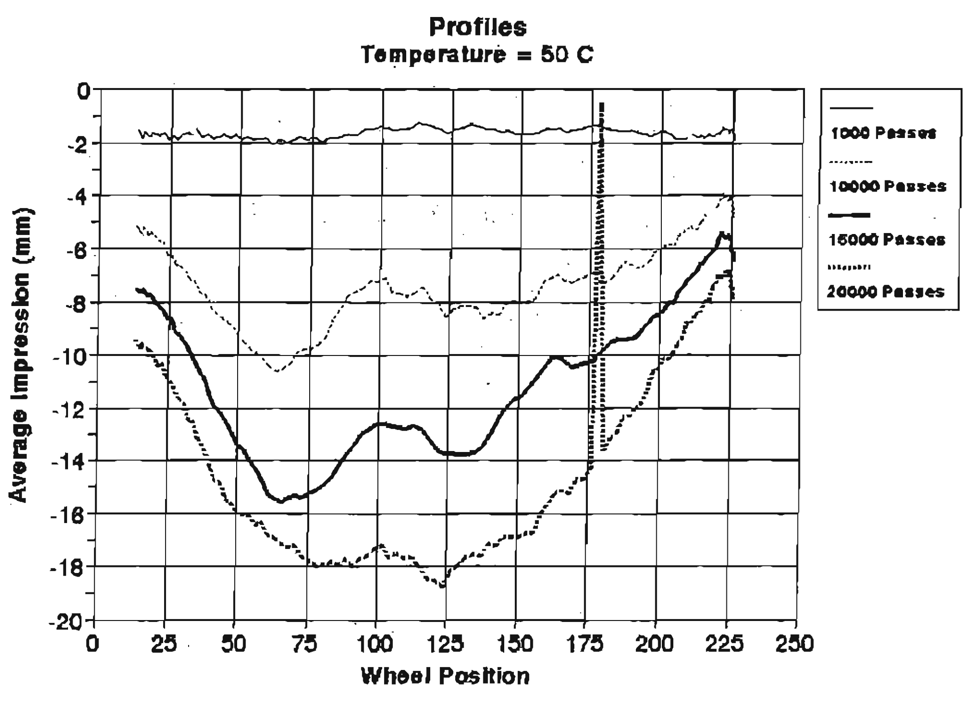

Site 11
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0 2 4 6 8 10 12 14 16 18 20
No. of Passes
(Thousands)

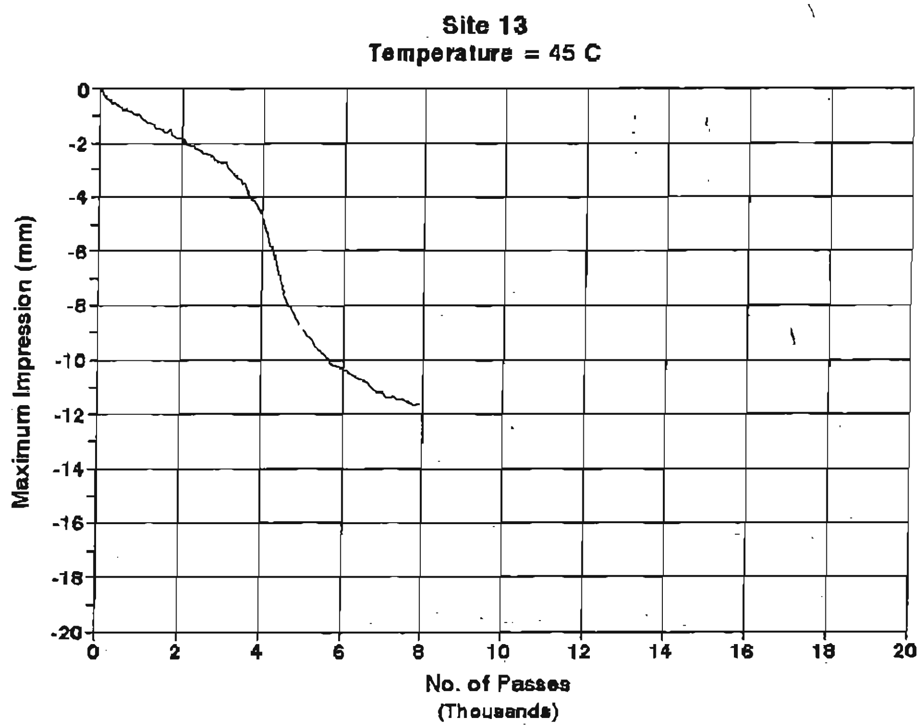

Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0 25 50 75 100 125 150 175 200 225 250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes

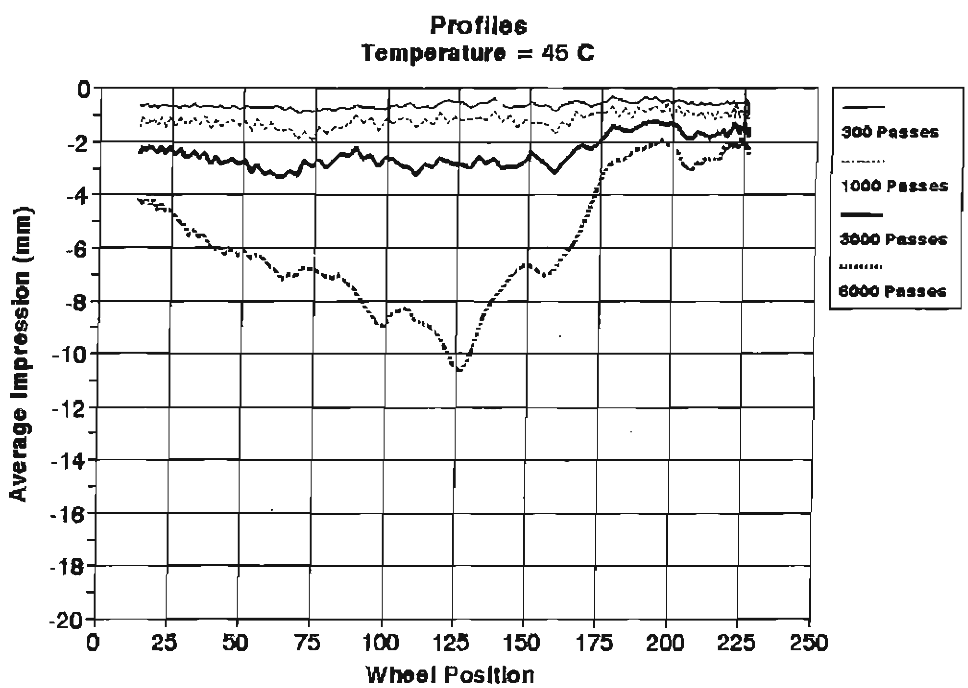

Site 12
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

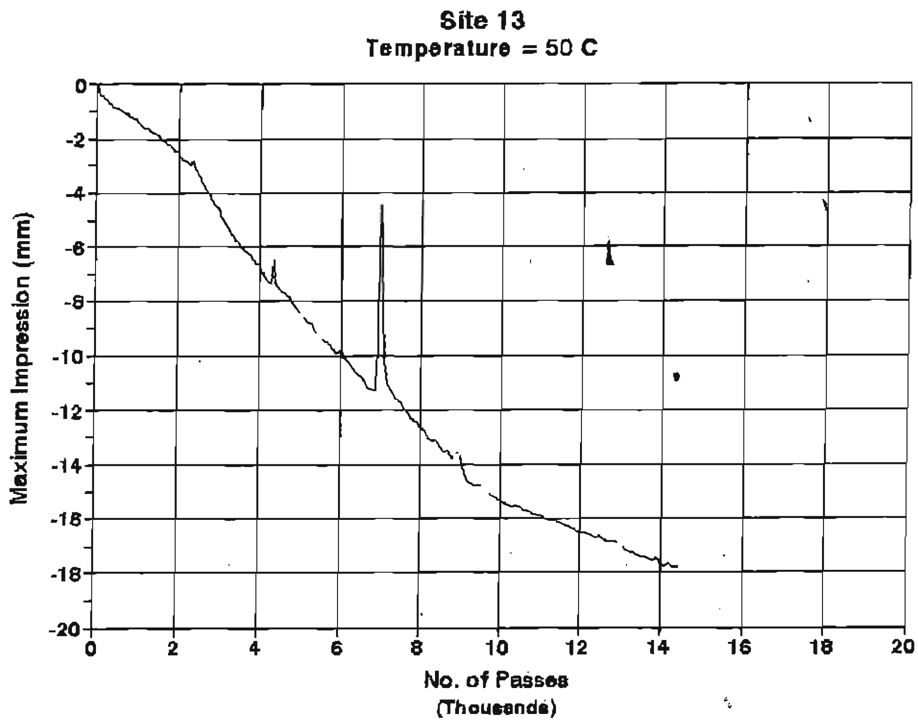

Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes

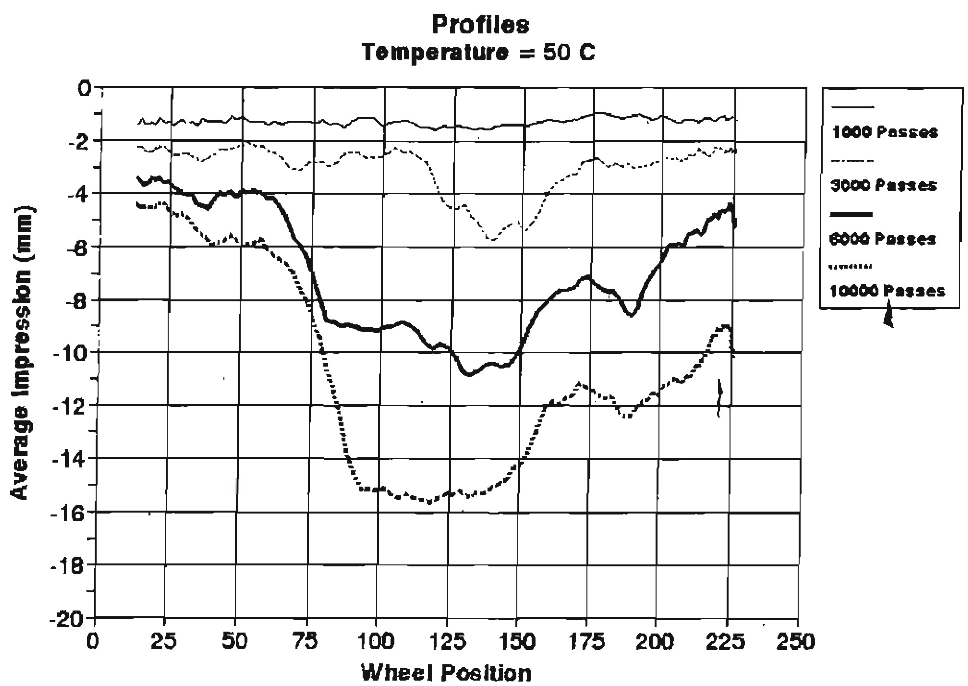

Site 12
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)


Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes

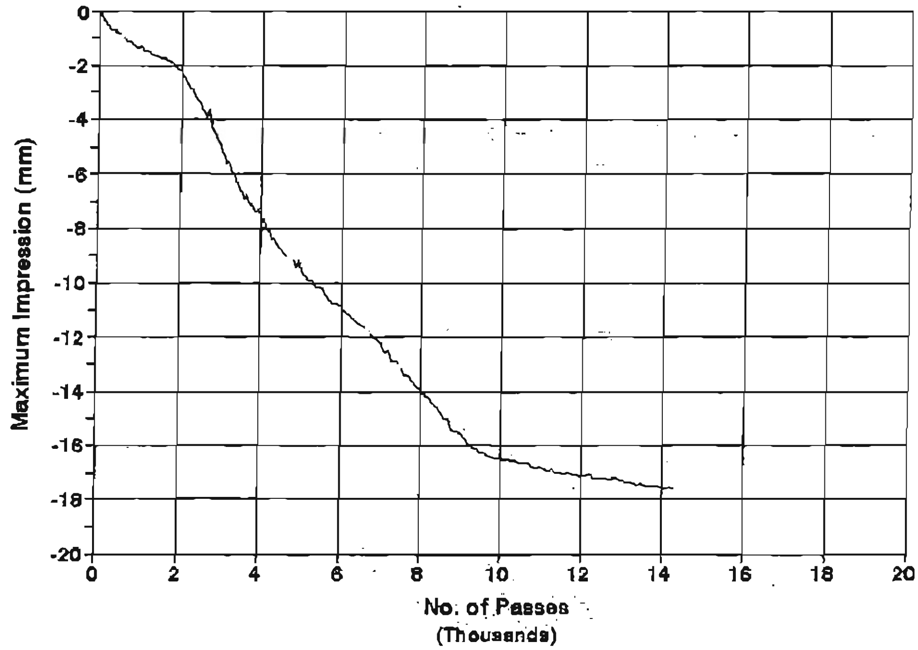

Site 13
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)


Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
300 Passes
1000 Passes
3000 Passes
6000 Passes

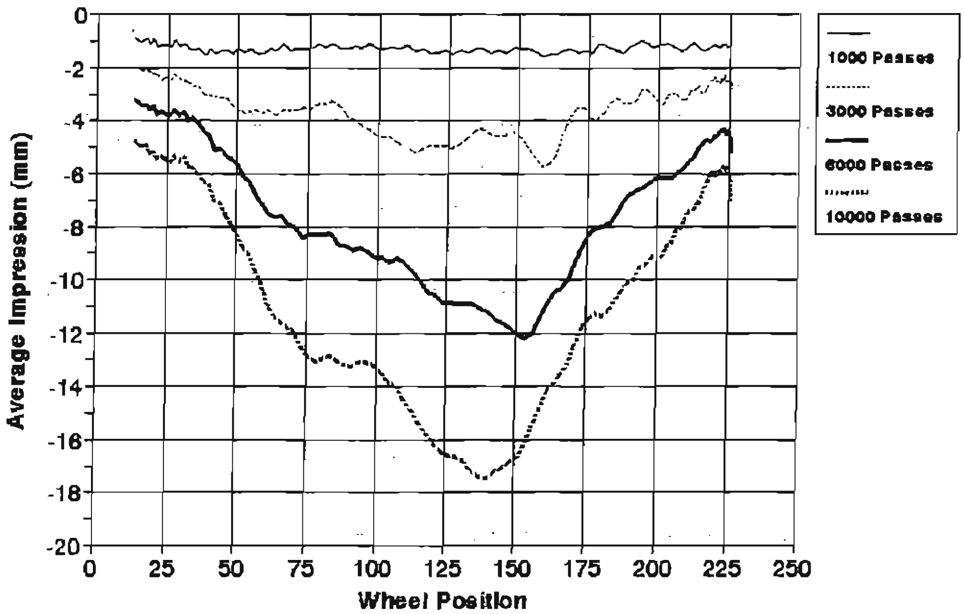

Site 13
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

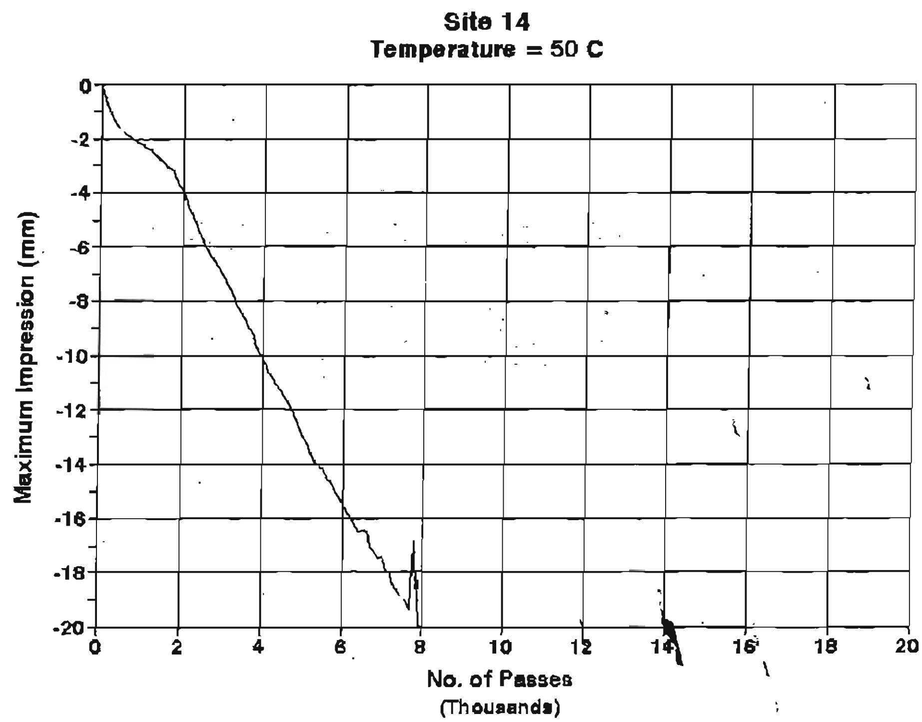

Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
3000 Passes
6000 Passes
10000 Passes

Site 14
Temperature = 45 C

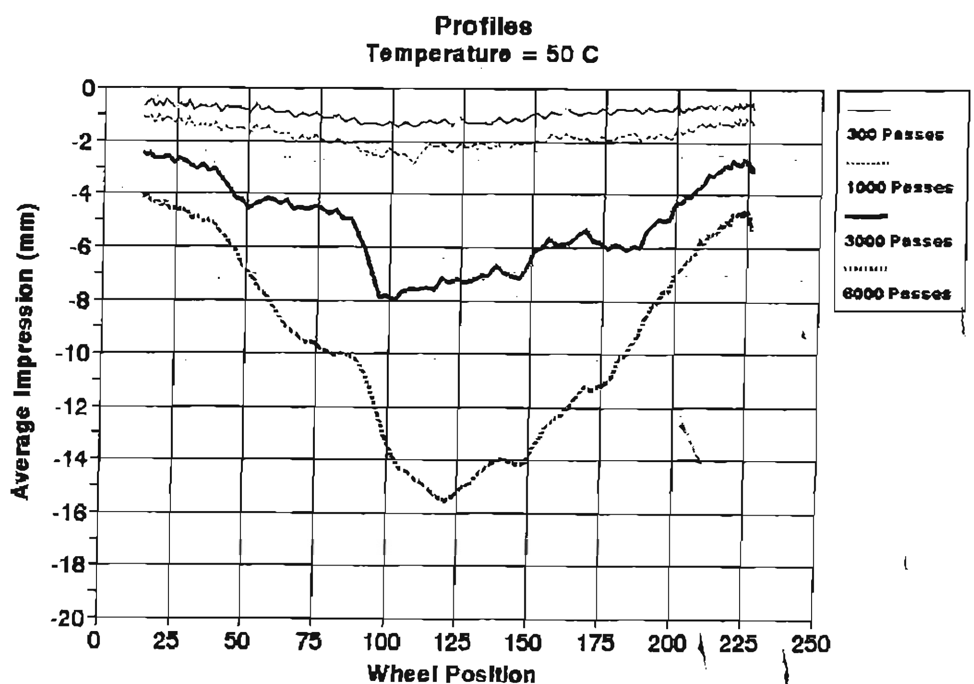


Profiles
Temperature = 45 C

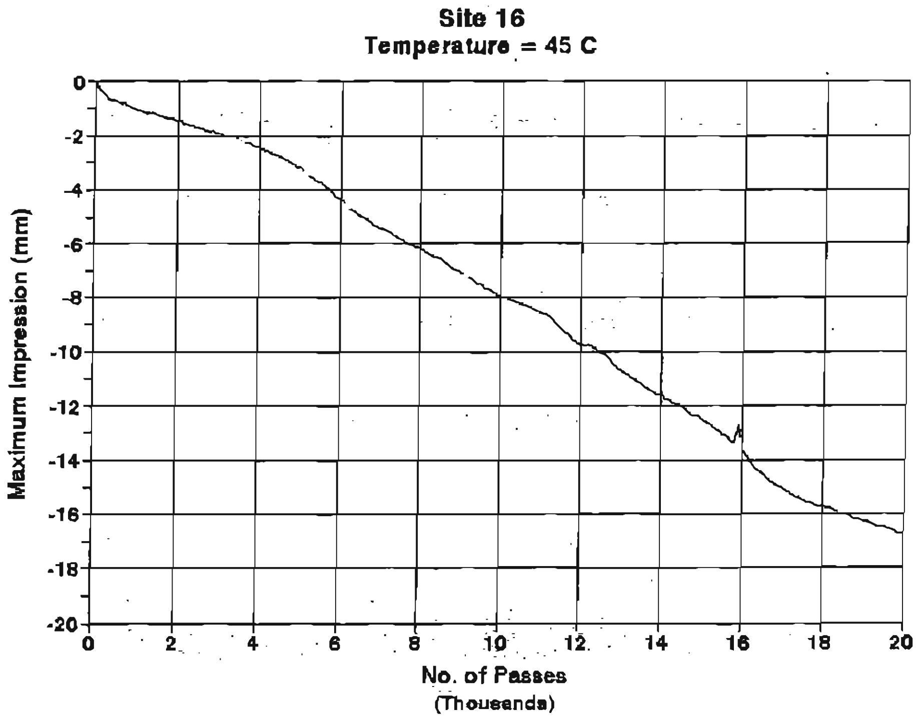


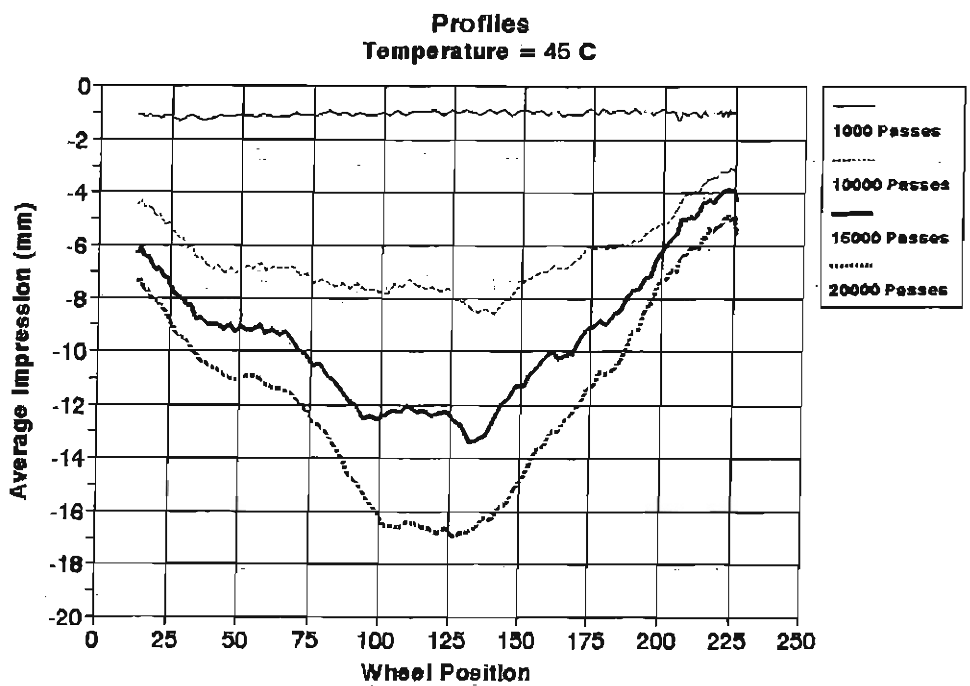


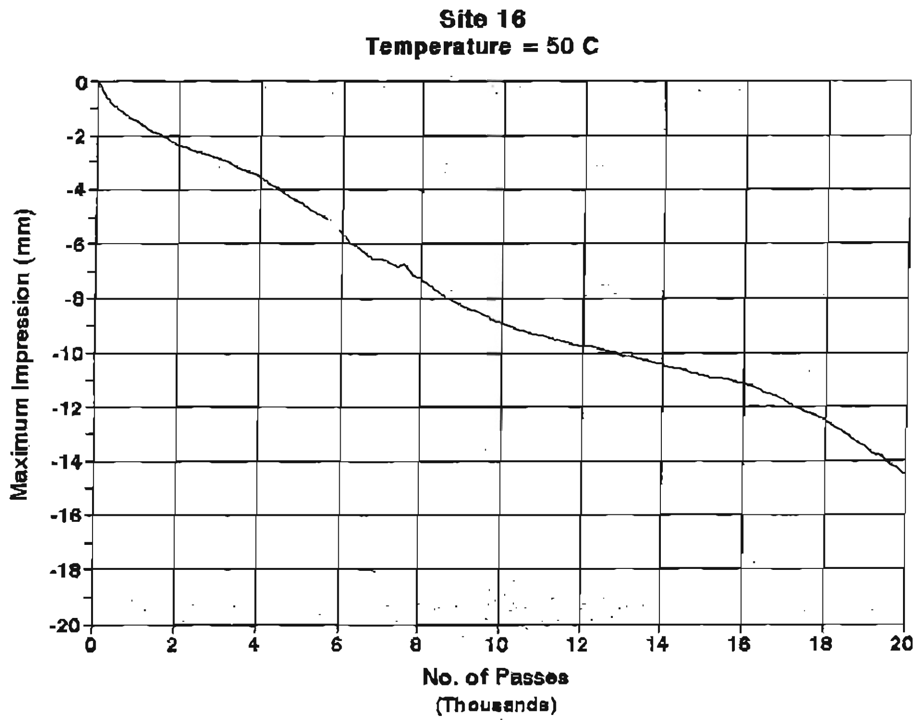
Site 14
Temperature = 50 C
Maximum Impression (mm)
No. of Passes
(Thousands)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20



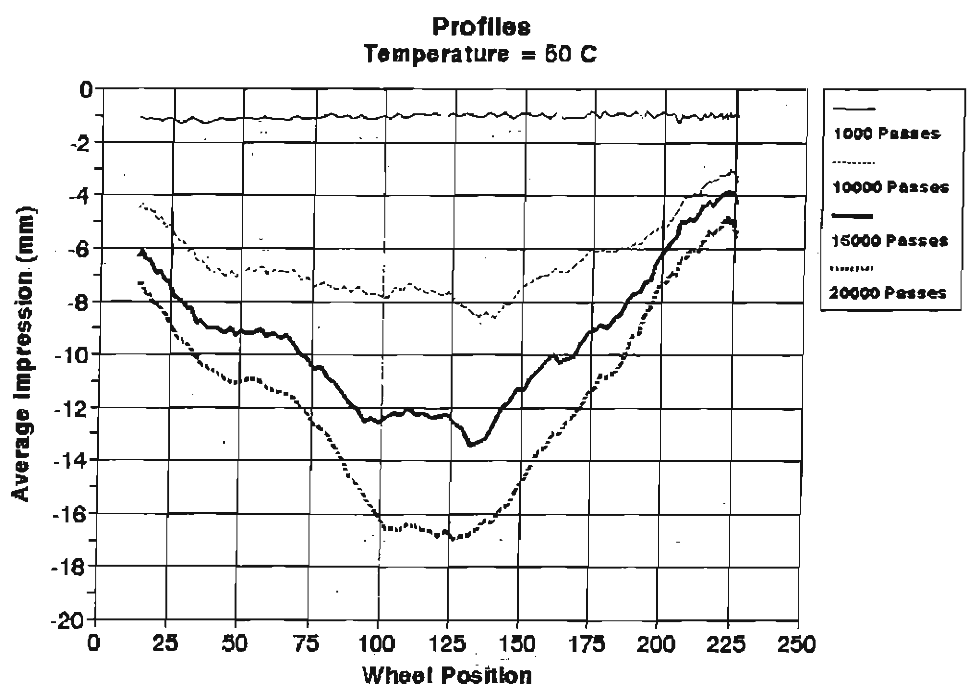
Profiles
Temperature = 50 C
Average Impression (mm)
Wheel Position
300 Passes
1000 Passes
3000 Passes
6000 Passes
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250


Site 16
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

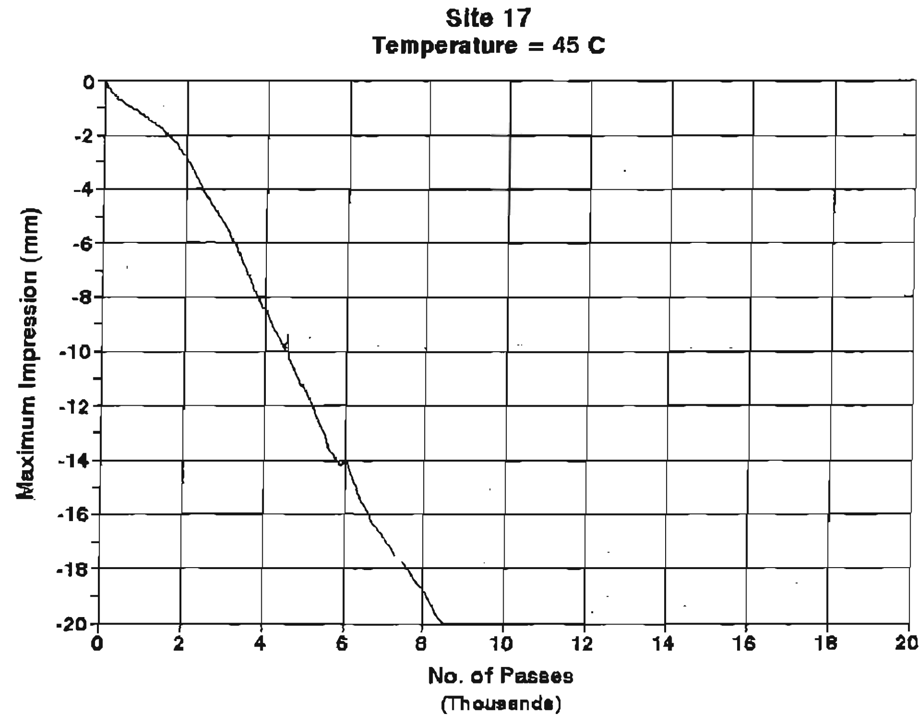

Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes

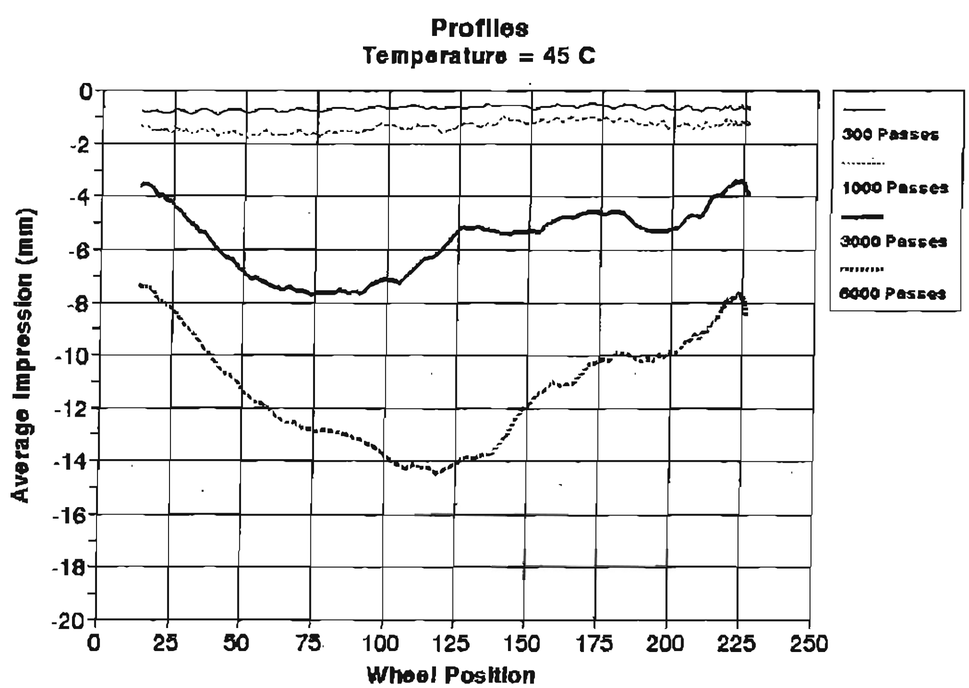


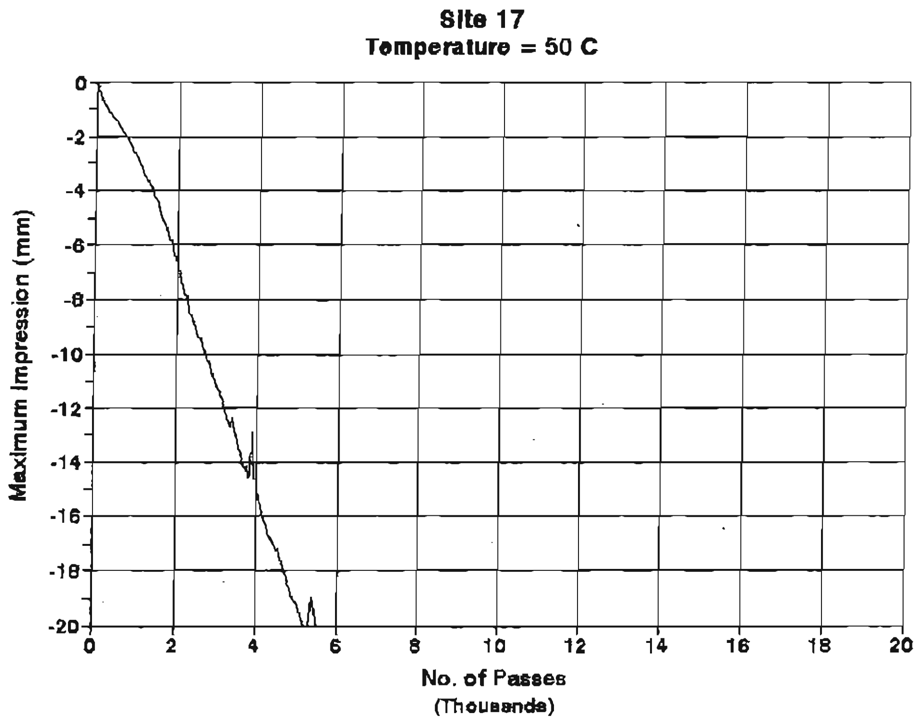
Site 16
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



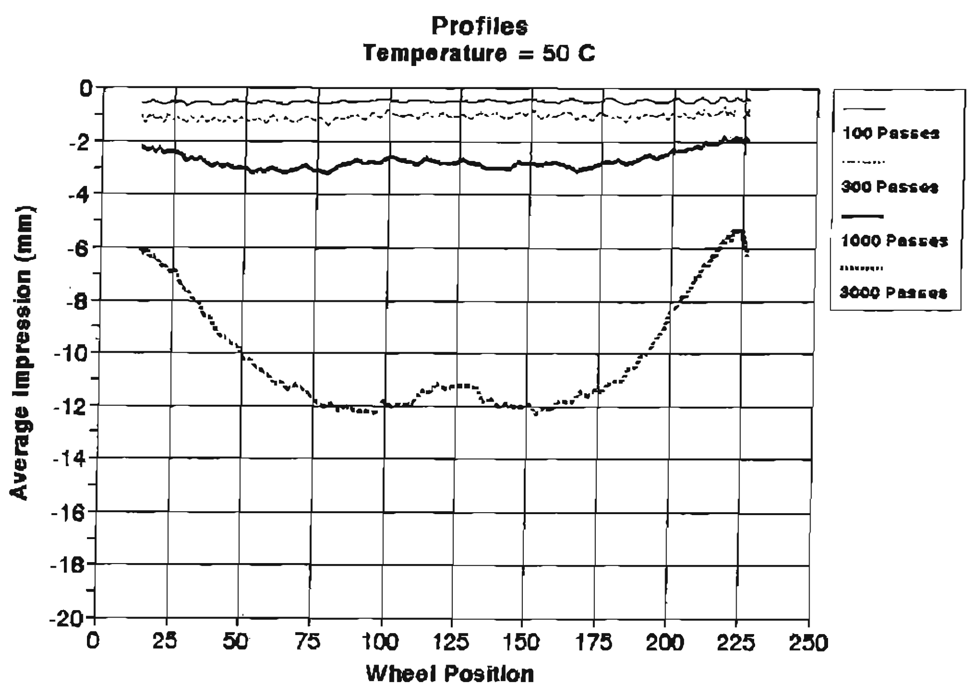
Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes


Site 17
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

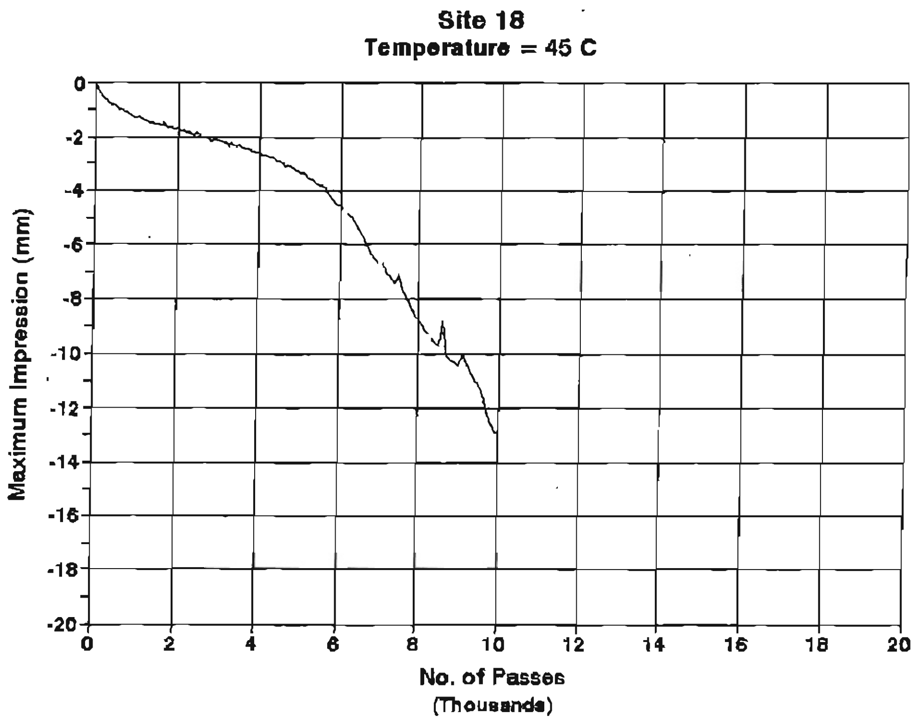

Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
300 Passes
1000 Passes
3000 Passes
6000 Passes

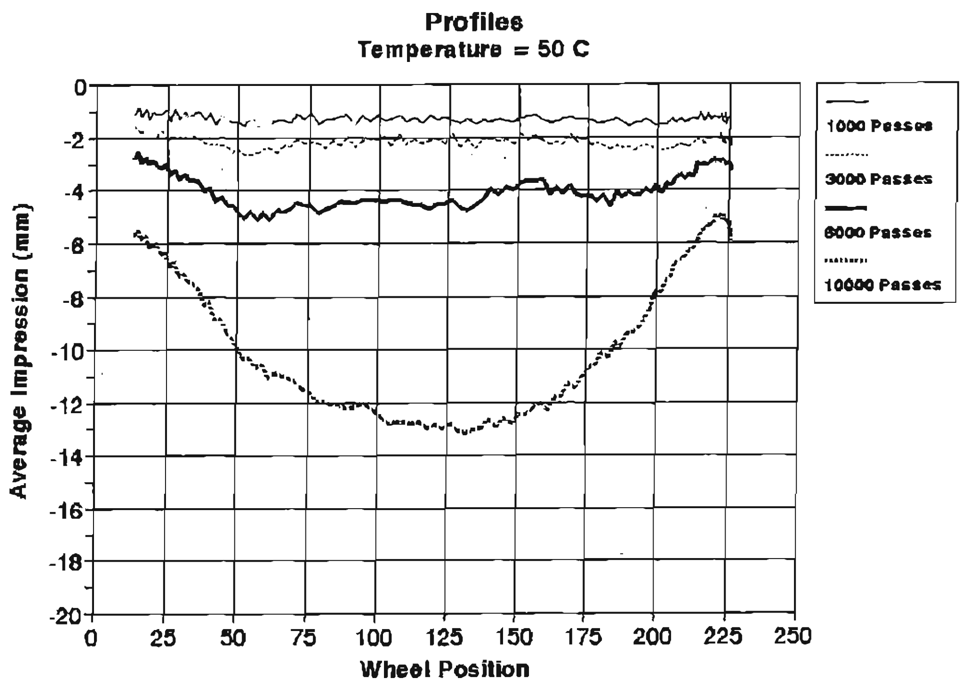


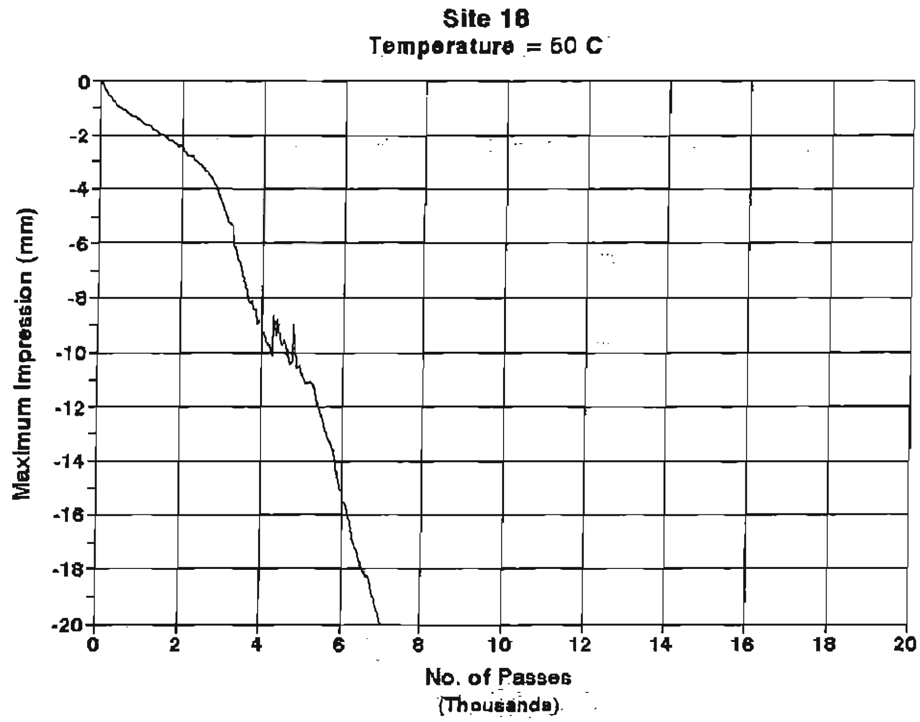
Site 17
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

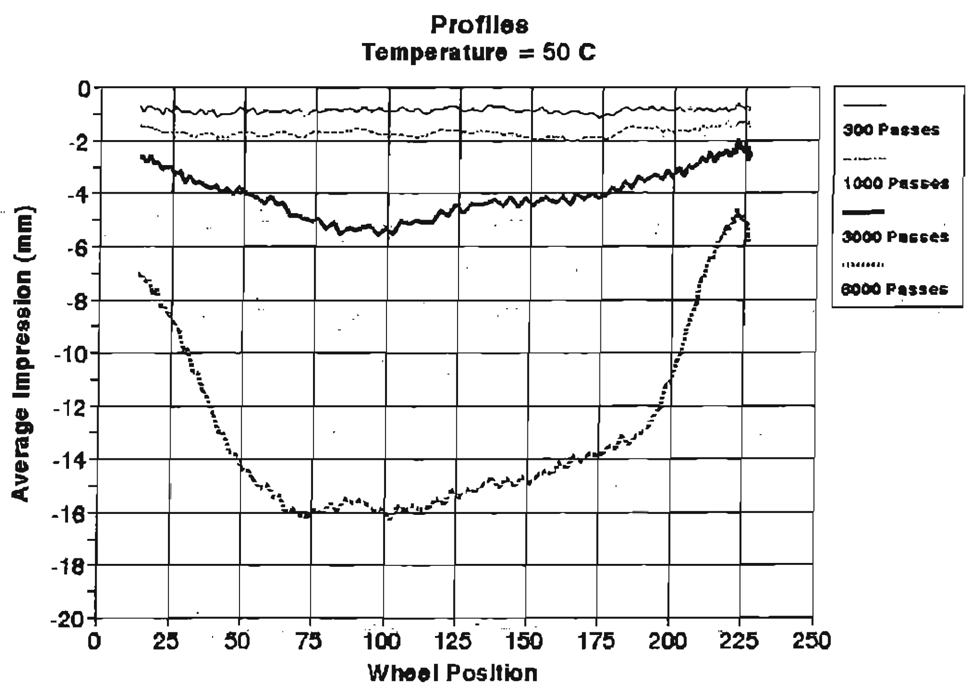


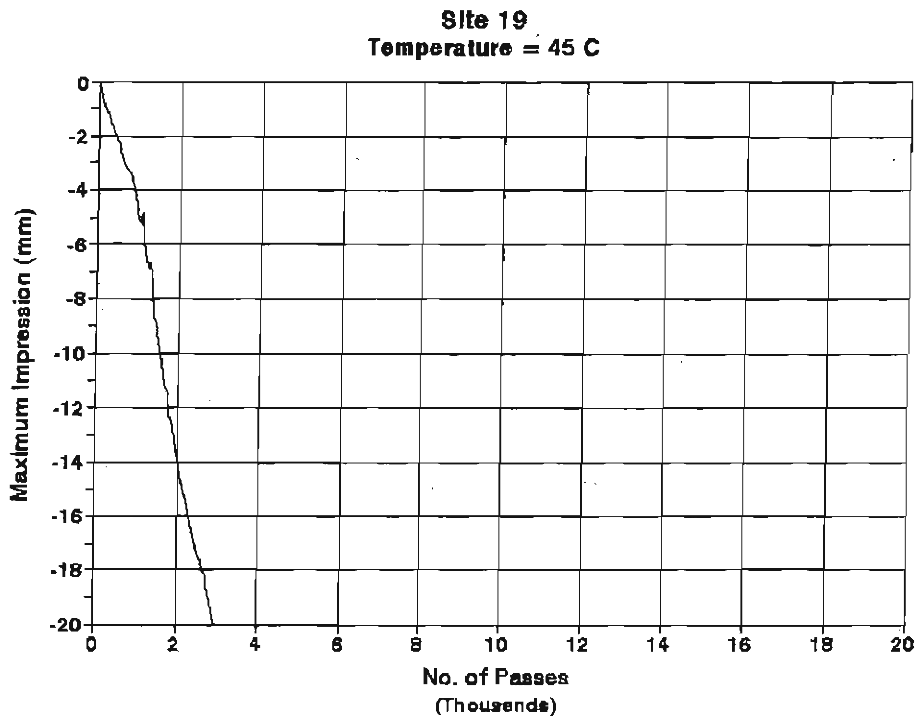
Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
100 Passes
300 Passes
1000 Passes
3000 Passes

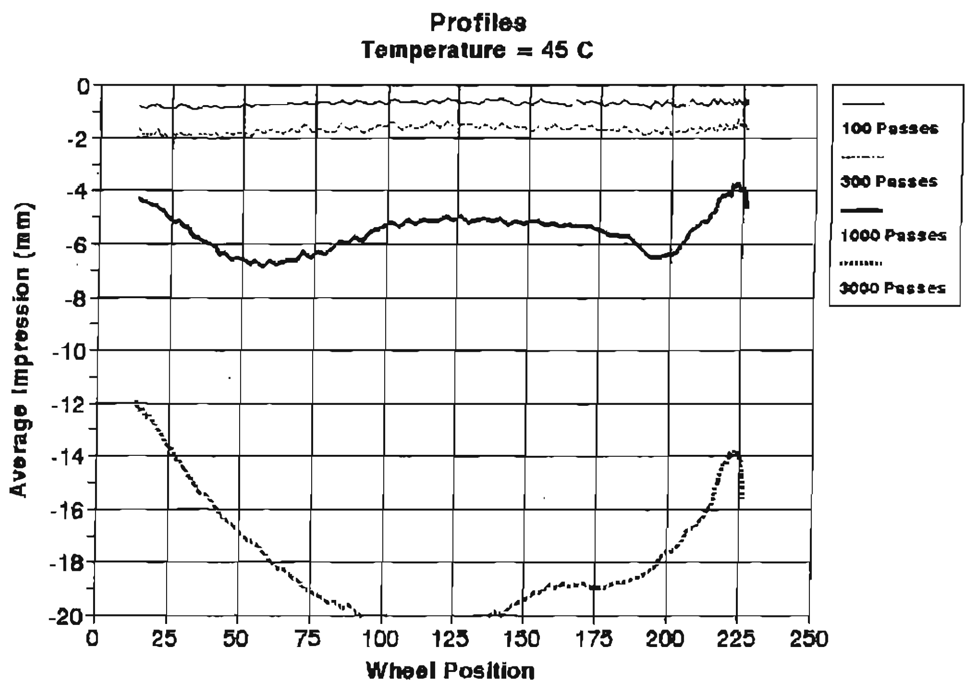

Site 18
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

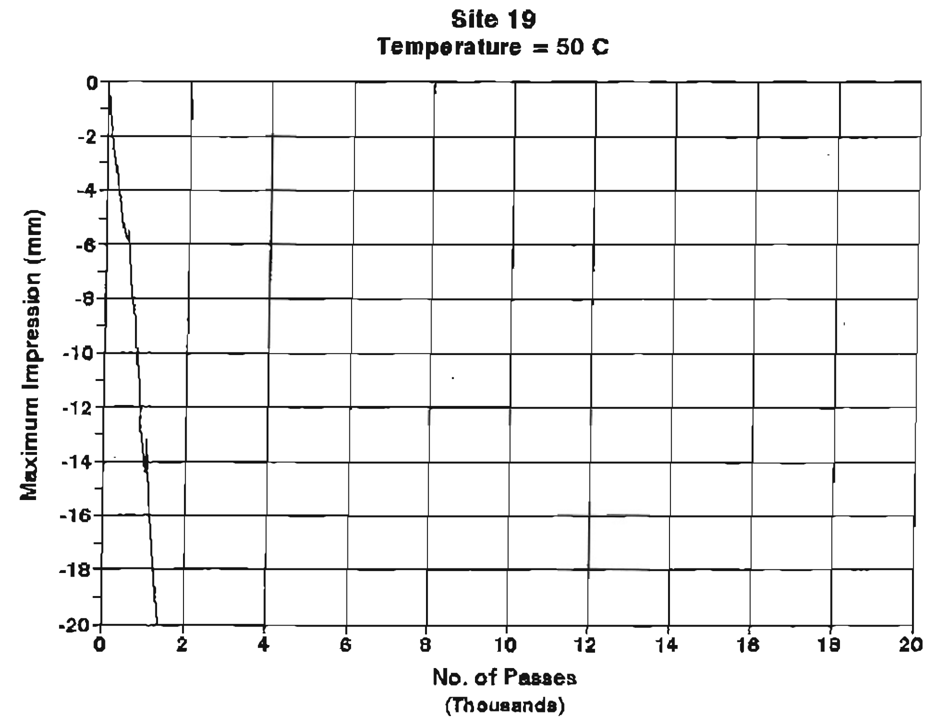

Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
3000 Passes
6000 Passes
10000 Passes

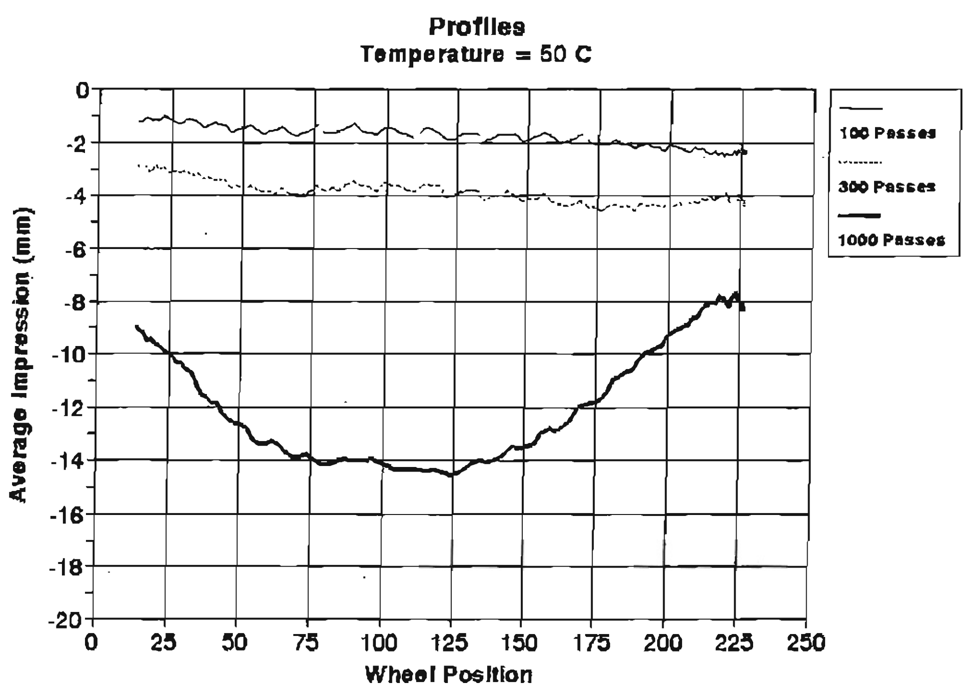

Site 18
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

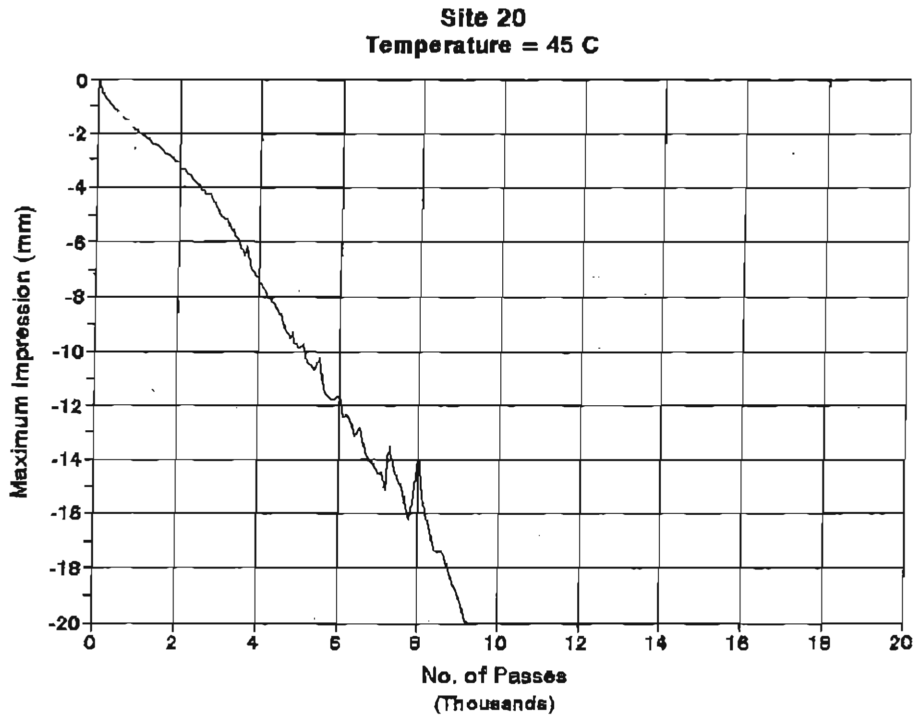

Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
300 Passes
1000 Passes
3000 Passes
6000 Passes


Site 19
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

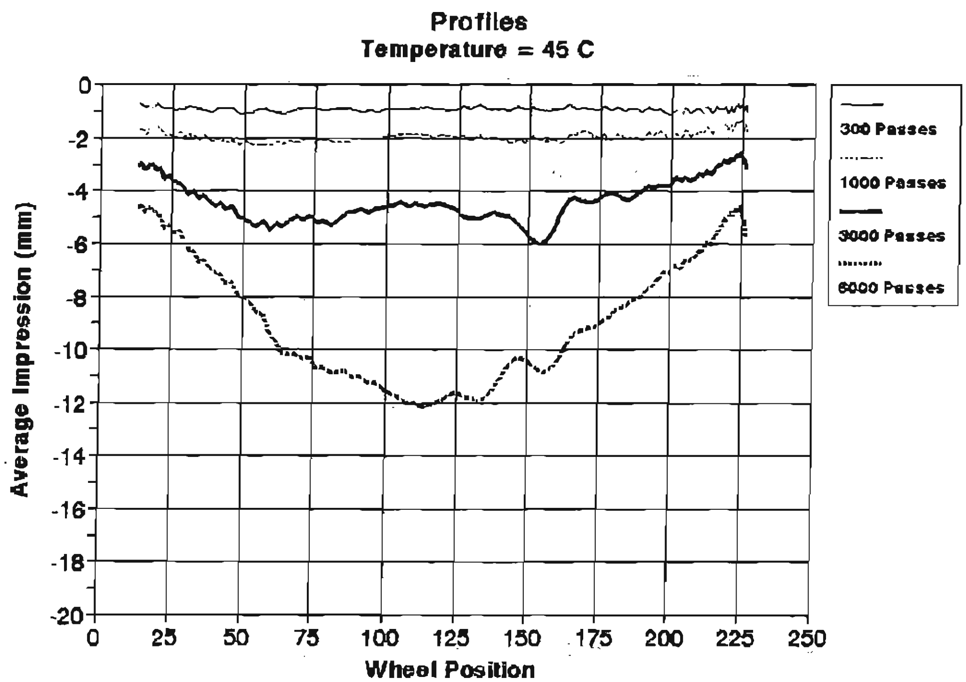

Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
100 Passes
300 Passes
1000 Passes
3000 Passes


Site 19
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

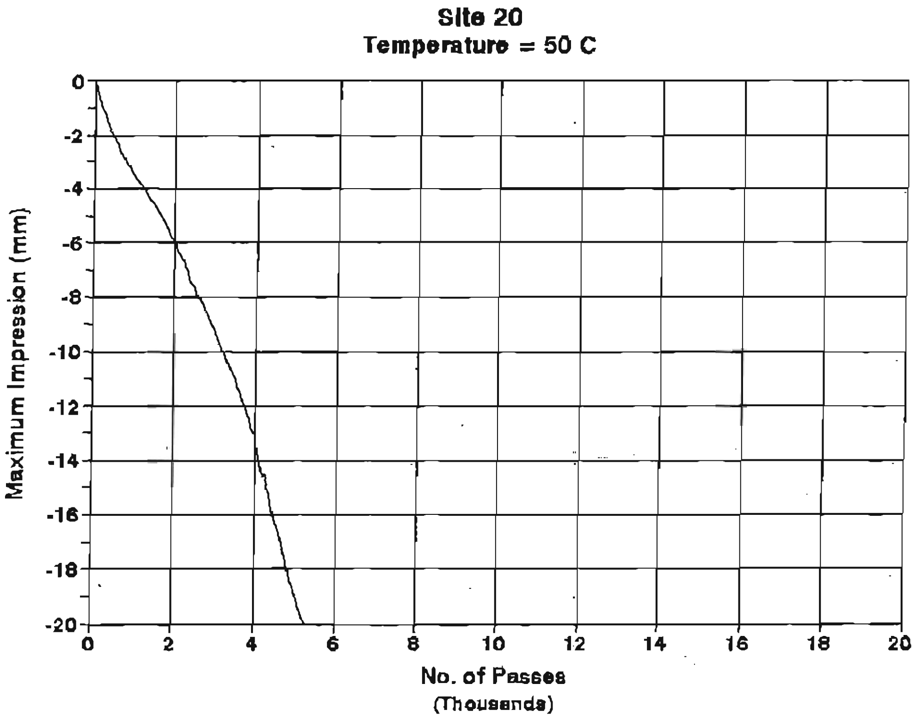

Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
100 Passes
300 Passes
1000 Passes



Site 20
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
300 Passes
1000 Passes
3000 Passes
6000 Passes



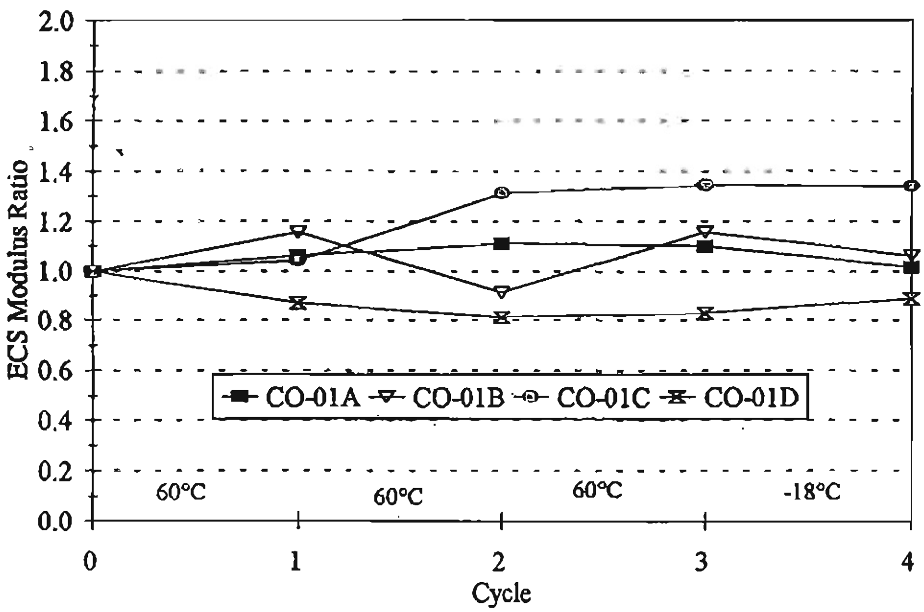
Site 20
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

Appendix B

Results from the Environmental Conditioning System

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-01A	A	0	34.1	98.2	347.5	1.00	0-5%
		1	35.8	97.0	369.0	1.06	
		2	38.2	99.0	385.8	1.11	
		3	39.3	102.9	382.3	1.10	
		4	36.1	102.2	353.5	1.02	
CO-01B	A	0	43.4	99.5	436.4	1.00	0-5%
		1	51.4	101.8	505.6	1.16	
		2	40.8	102.4	398.7	0.91	
		3	51.4	101.8	505.6	1.16	
		4	44.9	96.8	464.2	1.06	
CO-01C	B	0	31.0	105.0	295.6	1.00	0-5%
		1	31.2	101.3	308.4	1.04	
		2	39.8	102.6	388.5	1.31	
		3	39.7	99.6	398.3	1.35	
		4	39.7	100.1	396.9	1.34	
CO-01D	B	0	31.3	76.6	408.7	1.00	0-5%
		1	32.1	90.1	355.9	0.87	
		2	32.5	98.0	332.1	0.81	
		3	31.8	93.8	339.2	0.83	
		4	31.3	86.5	363.3	0.89	

Average ECS Modulus Ratio after 3 cycles = 1.11
Average ECS Modulus Ratio after 4 cycles = 1.08

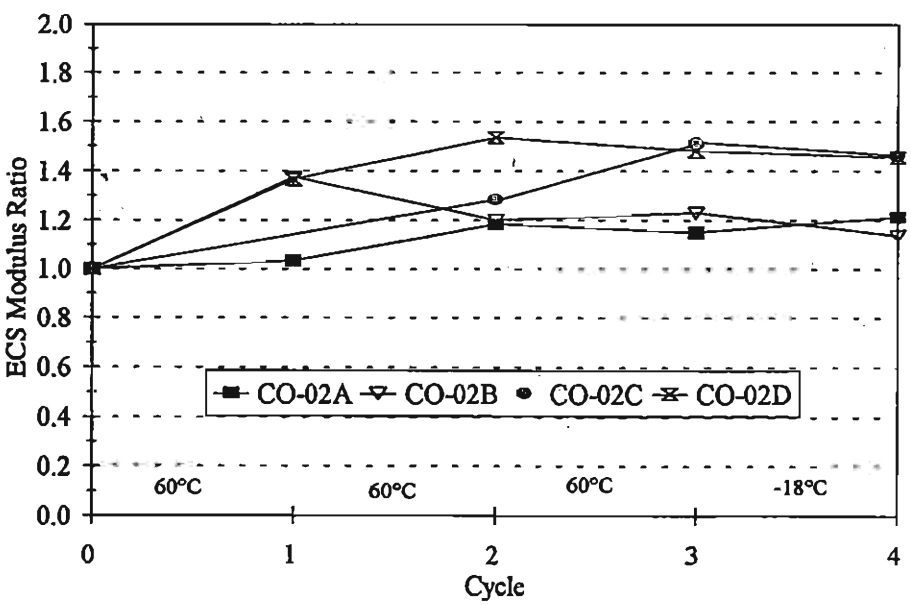


ECS Modulus Ratio Results
Glenwood Springs (Mix 1)

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)		ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-02A	C	0	70.6		92.4	764.5	1.00	0-5%
		1	72.7		92.1	790.1	1.03	
		2	73.3		81.1	904.6	1.18	
		3	75.5		85.9	878.7	1.15	
		4	75.1	①	81.0	927.6	1.21	
CO-02B	A	0	41.4		104.2	397.6	1.00	0-5%
		1	51.4		94.0	546.9	1.38	
		2	46.5		97.4	477.0	1.20	
		3	47.7		97.4	489.5	1.23	
		4	46.3		102.4	452.7	1.14	
CO-02C	B	0	25.3		98.3	257.0	1.00	0-5%
		1	33.8	①	76.4	442.5	1.72	
		2	31.5		95.7	329.8	1.28	
		3	35.1		90.4	388.0	1.51	
		4	35.2		93.9	375.4	1.46	
CO-02D	C	0	42.8	②	67.9	630.0	1.00	0-5%
		1	57.0	②	66.2	860.3	1.37	
		2	56.5	②	58.4	968.3	1.54	
		3	56.6	②	60.6	932.9	1.48	
		4	57.4	②	62.5	917.9	1.46	

① Probable error in strain reading.
② Test was run at reduced strain level.

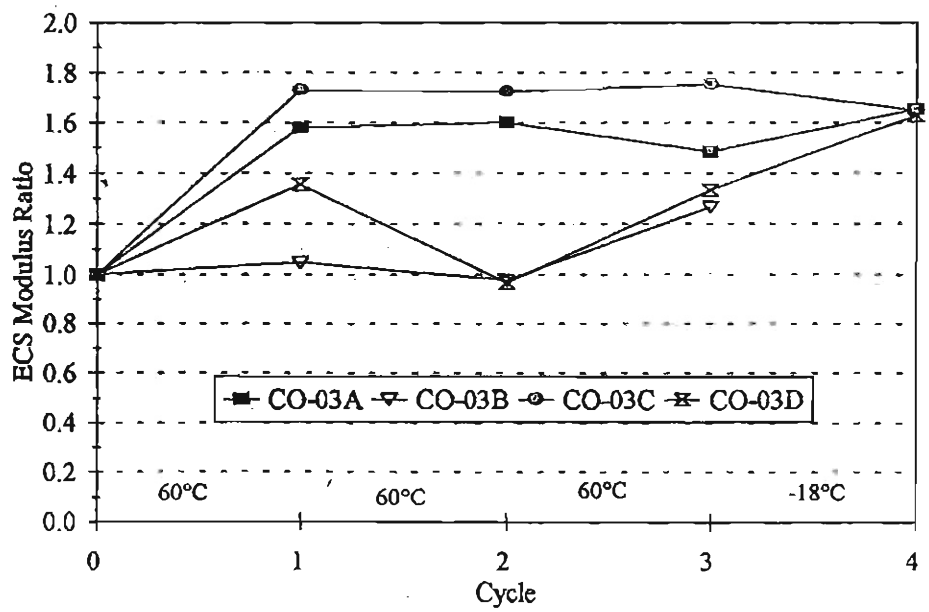
Average ECS Modulus Ratio after 3 cycles = 1.34
Average ECS Modulus Ratio after 4 cycles = 1.32



ECS Modulus Ratio Results
Craig (Mix 2)

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-03A	C	0	50.4	101.0	499.3	1.00	0-5%
		1	58.1	① 73.6	789.6	1.58	
		2	55.5	① 69.5	799.5	1.60	
		3	51.7	① 69.8	740.7	1.48	
		4	58.0	① 70.2	826.4	1.66	
CO-03B	A	0	43.4	97.9	443.6	1.00	0-5%
		1	45.0	97.0	464.3	1.05	
		2	44.1	102.1	432.5	0.97	
		3	51.5	91.8	562.1	1.27	
		4	51.0	① 58.3	883.5	1.99	
CO-03C	C	0	③ 29.4	② 59.6	493.8	1.00	0-5%
		1	51.1	② 59.8	854.3	1.73	
		2	50.8	② 59.6	851.8	1.72	
		3	51.6	② 59.7	865.0	1.75	
		4	48.7	② 59.8	814.9	1.65	
CO-03D	B	0	26.6	100.7	264.2	1.00	0-5%
		1	32.8	91.6	358.0	1.36	
		2	25.3	99.4	255.0	0.97	
		3	32.8	93.2	352.5	1.33	
		4	32.7	① 76.1	430.5	1.63	

① Probable error in strain reading.
② Test was ran at reduced strain level.
③ Probable error in stress reading
Average ECS Modulus Ratio after 3 cycles = 1.46
Average ECS Modulus Ratio after 4 cycles = 1.73

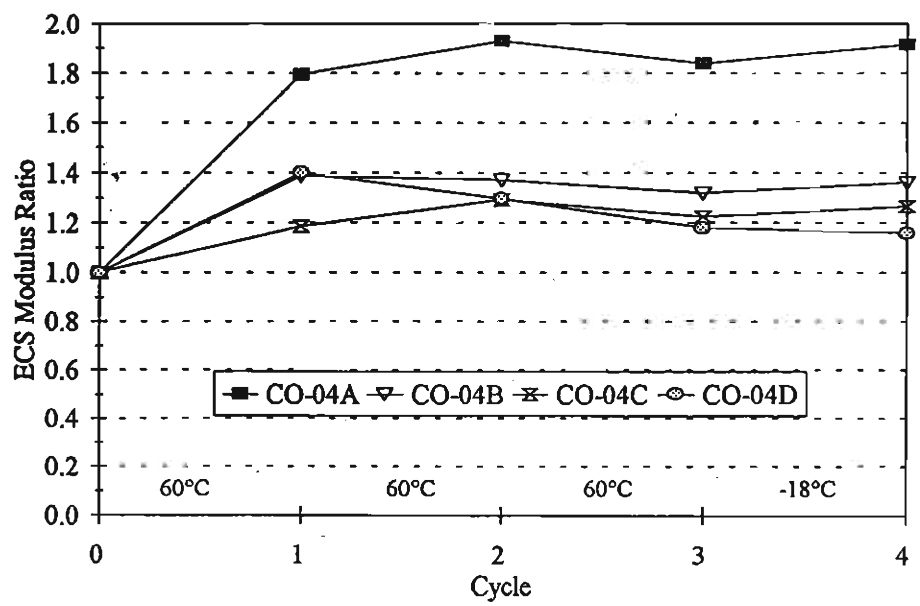


ECS Modulus Ratio Results
Delta (Mix 3)

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-04A	C	0	③ 11.2	100.8	111.0	1.00	0-5%
		1	③ 19.9	100.0	199.3	1.79	
		2	③ 21.5	100.3	214.5	1.93	
		3	③ 20.7	101.0	204.5	1.84	
		4	③ 21.3	99.9	212.7	1.92	
CO-04B	C	0	34.9	100.6	347.4	1.00	0-5%
		1	48.0	99.7	481.8	1.39	
		2	48.5	101.8	476.5	1.37	
		3	46.3	101.0	458.4	1.32	
		4	47.7	100.9	473.1	1.36	
CO-04C	C	0	34.9	100.6	347.4	1.00	0-5%
		1	41.5	100.8	411.7	1.19	
		2	45.6	101.5	449.2	1.29	
		3	42.6	100.1	425.2	1.22	
		4	44.4	100.9	440.0	1.27	
CO-04D	A	0	19.1	99.9	190.8	1.00	0-5%
		1	27.2	101.6	267.5	1.40	
		2	24.3	97.9	247.7	1.30	
		3	22.3	99.2	225.2	1.18	
		4	22.8	103.1	221.1	1.16	

③ Probable error in stress reading

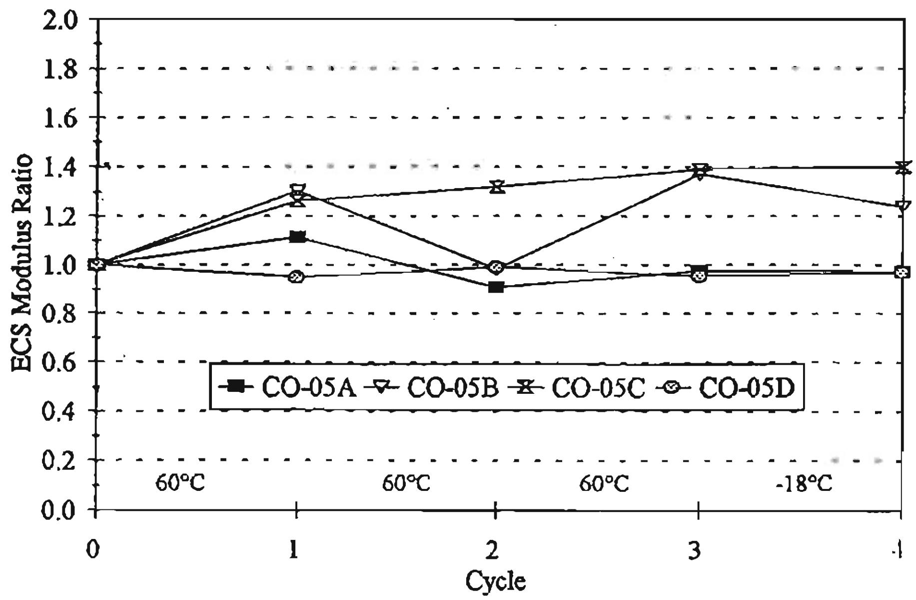
Average ECS Modulus Ratio after 3 cycles = 1.39
Average ECS Modulus Ratio after 4 cycles = 1.43



ECS Modulus Ratio Results
Fruita (Mix 4)

Specimen ID	ECS System	Cond. Cycle		ECS Stress (psi)		ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-05A	A	0		43.5		100.5	432.4	1.00	0-5%
		1		46.0		95.4	481.9	1.11	
		2		39.6		100.9	392.6	0.91	
		3		43.5		103.1	421.5	0.97	
		4		43.0		102.4	420.3	0.97	
CO-05B	B	0		30.3		100.2	303.0	1.00	0-5%
		1		35.4	①	89.6	395.6	1.31	
		2		30.0		100.8	297.8	0.98	
		3		34.2	①	82.3	415.8	1.37	
		4		34.7		92.3	375.8	1.24	
CO-05C	C	0	③	40.2	②	59.8	671.8	1.00	0-5%
		1		49.6	②	58.5	848.6	1.26	
		2		53.7	②	60.5	887.1	1.32	
		3		55.8	②	59.7	935.2	1.39	
		4		55.9	②	59.4	942.1	1.40	
CO-05D	C	0		54.3	②	58.8	922.4	1.00	0-5%
		1		52.6	②	60.1	874.9	0.95	
		2		54.9	②	60.1	913.1	0.99	
		3		53.3	②	60.6	880.0	0.95	
		4		53.9	②	60.5	892.0	0.97	

① Probable error in strain reading.
② Test was ran at reduced strain level.
③ Probable error in stress reading
Average ECS Modulus Ratio after 3 cycles = 1.17
Average ECS Modulus Ratio after 4 cycles = 1.15

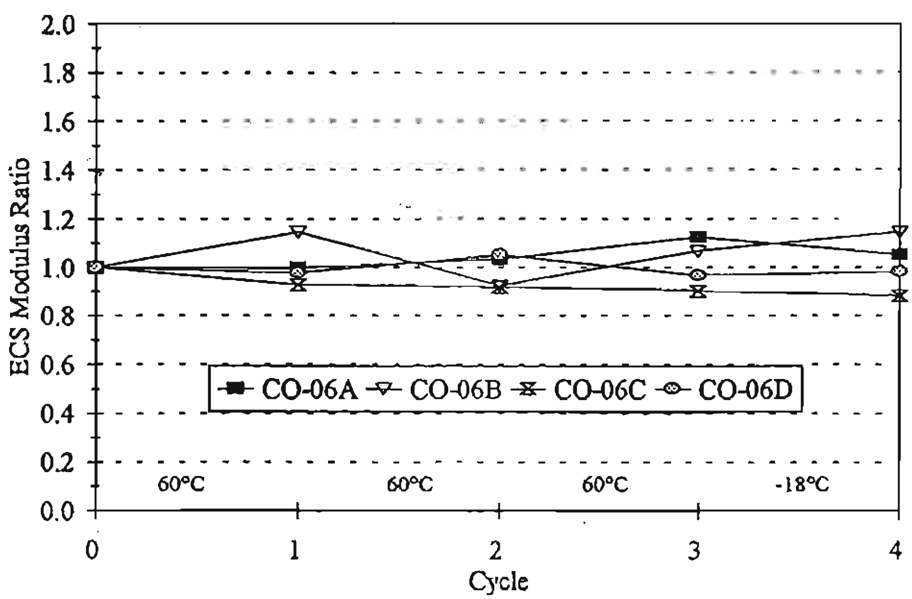


ECS Modulus Ratio Results

Grand Junction (Mix 5)

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-06A	A	0	28.5	102.8	277.2	1.00	0-5%
		1	27.6	99.8	276.4	1.00	
		2	29.3	102.3	286.8	1.03	
		3	31.5	101.1	311.8	1.12	
		4	30.1	103.1	291.7	1.05	
CO-06B	B	0	24.7	101.4	247.0	1.00	0-5%
		1	28.4	100.3	283.5	1.15	
		2	23.9	104.5	228.3	0.92	
		3	26.0	98.5	263.5	1.07	
		4	28.2	99.7	283.0	1.15	
CO-06C	C	0	58.8	100.2	587.1	1.00	5-10%
		1	54.6	100.3	544.0	0.93	
		2	54.1	100.3	539.3	0.92	
		3	53.2	100.3	530.0	0.90	
		4	52.5	101.1	518.7	0.88	
CO-06D	C	0	58.6	100.1	584.9	1.00	0-5%
		1	57.1	99.8	571.6	0.98	
		2	57.9	94.1	615.1	1.05	
		3	56.5	99.9	565.9	0.97	
		4	57.5	100.1	574.9	0.98	

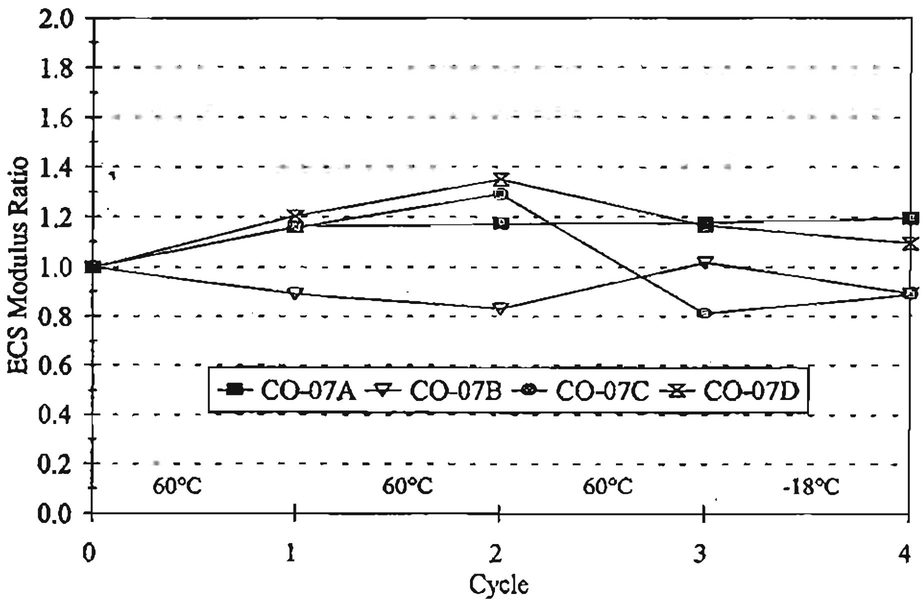
Average ECS Modulus Ratio after 3 cycles = 1.02
Average ECS Modulus Ratio after 4 cycles = 1.02



ECS Modulus Ratio Results
Durango (Mix 6)

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-07A	A	0	25.5	100.6	253.0	1.00	0-5%
		1	29.6	101.1	293.3	1.16	
		2	29.9	100.6	297.3	1.17	
		3	30.5	102.7	297.4	1.18	
		4	30.3	100.2	302.5	1.20	
CO-07B	A	0	42.9	99.2	433.1	1.00	0-5%
		1	39.0	101.0	386.6	0.89	
		2	36.1	100.3	360.0	0.83	
		3	43.4	98.5	440.7	1.02	
		4	39.0	100.8	387.1	0.89	
CO-07C	B	0	21.8	99.7	218.7	1.00	0-5%
		1	25.9	102.4	253.3	1.16	
		2	28.1	99.4	282.6	1.29	
		3	17.2	96.8	177.8	0.81	
		4	18.5	95.3	194.3	0.89	
CO-07D	B	0	22.3	103.1	216.4	1.00	0-5%
		1	25.8	99.1	260.4	1.20	
		2	28.9	98.9	292.6	1.35	
		3	25.7	101.9	252.2	1.17	
		4	23.5	99.3	236.9	1.09	

Average ECS Modulus Ratio after 3 cycles = 1.04
Average ECS Modulus Ratio after 4 cycles = 1.02



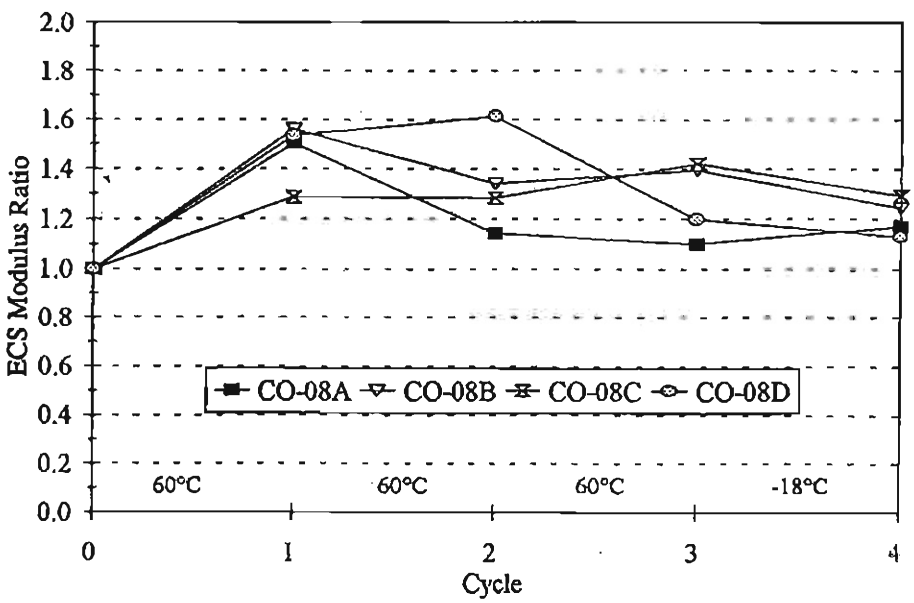
ECS Modulus Ratio Results

Ft. Collins (Mix 7)

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-08A	A	0	③ 37.0	95.0	389.0	1.00	0-5%
		1	47.4	81.1	585.0	1.50	
		2	42.6	95.9	444.5	1.14	
		3	42.3	100.0	427.5	1.10	
		4	45.7	100.3	455.3	1.17	
CO-08B	A	0	③ 34.1	100.2	340.3	1.00	0-5%
		1	51.0	95.9	531.6	1.56	
		2	47.4	103.8	456.4	1.34	
		3	46.8	98.4	475.2	1.40	
		4	43.1	101.8	423.6	1.24	
CO-08C	B	0	③ 28.1	98.8	284.2	1.00	0-5%
		1	35.2	96.1	366.0	1.29	
		2	35.2	96.4	364.8	1.28	
		3	39.4	97.6	403.8	1.42	
		4	37.1	100.8	367.7	1.29	
CO-08D	B	0	③ 29.2	99.3	294.4	1.00	0-5%
		1	35.7	① 79.2	451.6	1.53	
		2	34.7	① 73.1	474.8	1.61	
		3	36.2	102.6	352.6	1.20	
		4	32.6	97.9	332.7	1.13	

① Probable error in strain reading.
③ Probable error in stress reading

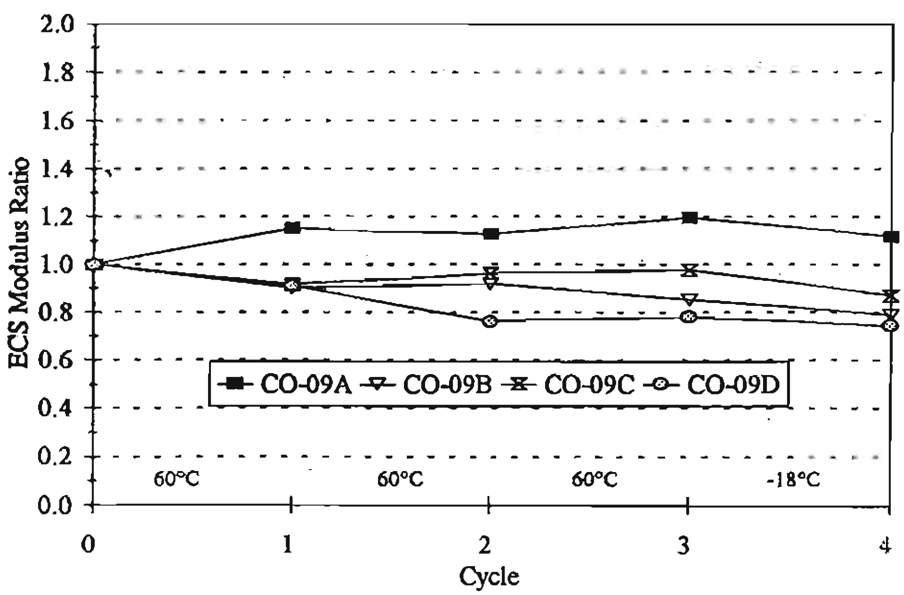
Average ECS Modulus Ratio after 3 cycles = 1.28
Average ECS Modulus Ratio after 4 cycles = 1.21



ECS Modulus Ratio Results
Nunn (Mix 8)

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-09A	A	0	31.2	107.6	290.0	1.00	0-5%
		1	32.2	96.8	333.7	1.15	
		2	33.3	101.8	327.3	1.13	
		3	36.2	104.4	346.9	1.20	
		4	34.4	106.3	324.3	1.12	
CO-09B	A	0	40.6	98.2	413.9	1.00	10-20%
		1	38.2	102.2	373.5	0.90	
		2	36.5	95.9	380.6	0.92	
		3	36.4	102.9	353.8	0.85	
		4	32.6	99.8	327.3	0.79	
CO-09C	B	0	23.8	100.8	236.1	1.00	10-20%
		1	23.0	106.2	216.4	0.92	
		2	23.8	105.0	227.2	0.96	
		3	22.6	98.1	230.5	0.98	
		4	20.7	100.7	205.8	0.87	
CO-09D	B	0	28.6	96.6	296.5	1.00	20-30%
		1	27.5	101.6	270.3	0.91	
		2	22.2	98.6	225.7	0.76	
		3	23.9	103.1	231.7	0.78	
		4	22.2	100.7	220.7	0.74	

Average ECS Modulus Ratio after 3 cycles = 0.95
Average ECS Modulus Ratio after 4 cycles = 0.88



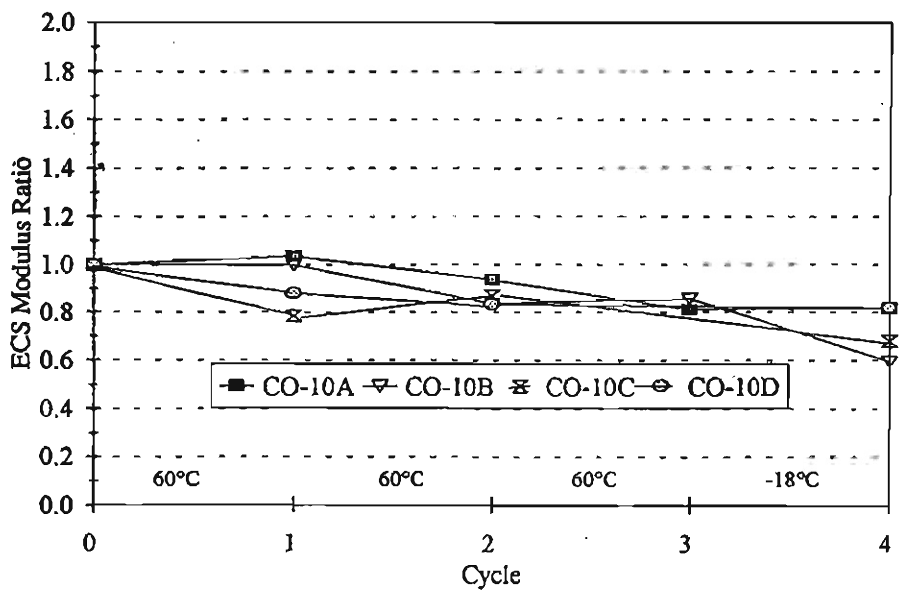
ECS Modulus Ratio Results

Denver (Mix 9)

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-10A	A	0	37.8	98.9	382.2	1.00	10-20%
		1	38.2	96.5	396.1	1.04	
		2	37.6	104.8	358.6	0.94	
		3	31.3	101.0	310.6	0.81	
		4	30.3	97.1	312.5	0.82	
CO-10B	B	0	26.6	101.0	263.4	1.00	5-10%
		1	26.2	99.6	263.1	1.00	
		2	21.6	98.1	220.4	0.84	
		3	22.6	100.0	226.4	0.86	
		4	15.7	99.8	157.3	0.60	
CO-10C	A	0	31.2	102.6	304.5	1.00	10-20%
		1	23.7	99.1	239.5	0.79	
		2	25.7	97.1	265.4	0.87	
		3	④	④	④	④	
		4	21.7	105.0	207.0	0.68	
CO-10D	B	0	26.6	100.8	264.1	1.00	20-30%
		1	22.2	95.4	233.1	0.88	
		2	21.6	98.1	220.4	0.83	
		3	④	④	④	④	
		4	23.6	108.8	216.6	0.82	

④ Computer Error

Average ECS Modulus Ratio after 3 cycles = 0.84
Average ECS Modulus Ratio after 4 cycles = 0.73



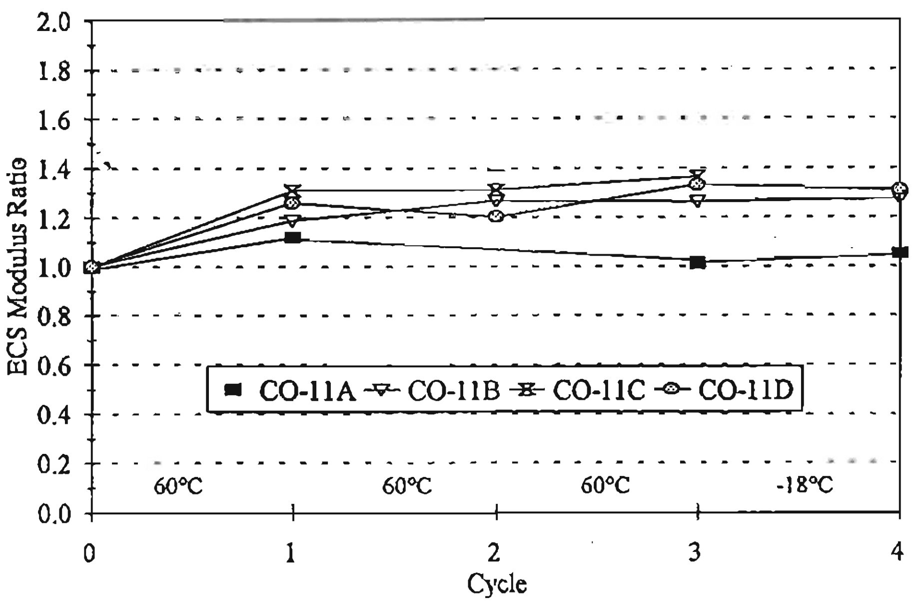
ECS Modulus Ratio Results

Douglas County (Mix 10)

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-11A	A	0	40.5	96.9	417.6	1.00	0-5%
		1	45.2	96.8	467.1	1.12	
		2	③ 52.4	① 89.0	589.1	~~1.41~~	
		3	41.5	98.3	422.2	1.01	
		4	44.5	101.7	437.7	1.05	
CO-11B	C	0	59.5	98.0	607.5	1.00	0-5%
		1	69.9	96.9	721.5	1.19	
		2	70.8	91.9	770.0	1.27	
		3	71.3	93.0	766.9	1.26	
		4	73.7	95.1	774.6	1.27	
CO-11C	B	0	26.6	96.2	276.7	1.00	0-5%
		1	33.5	92.5	362.1	1.31	
		2	33.8	93.0	363.2	1.31	
		3	34.4	91.3	377.2	1.36	
		4	33.9	① 76.7	442.1	1.60	
CO-11D	C	0	56.3	99.1	568.2	1.00	0-5%
		1	67.9	94.9	715.3	1.26	
		2	68.0	99.7	682.8	1.20	
		3	70.9	93.8	756.6	1.33	
		4	69.9	93.9	744.4	1.31	

① Probable error in strain reading.
③ Probable error in stress reading

Average ECS Modulus Ratio after 3 cycles = 1.24
Average ECS Modulus Ratio after 4 cycles = 1.31

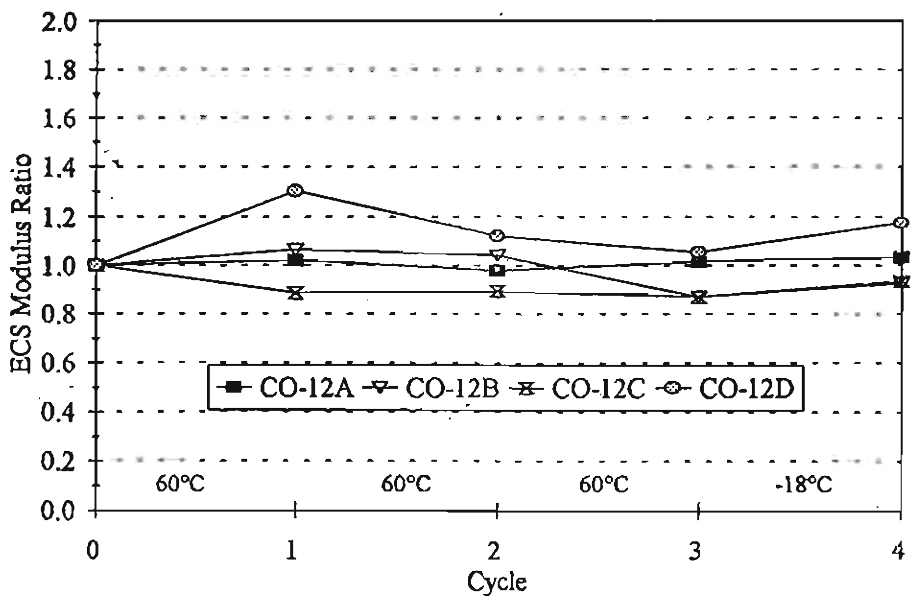


ECS Modulus Ratio Results

Aurora (Mix 11)

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-12A	A	0	31.1	97.4	319.0	1.00	0-5%
		1	32.3	99.4	325.3	1.02	
		2	32.1	103.0	312.1	0.98	
		3	33.2	102.7	323.4	1.01	
		4	32.6	98.9	329.8	1.03	
CO-12B	C	0	45.8	91.3	502.1	1.00	0-5%
		1	48.9	91.5	534.8	1.07	
		2	48.2	92.1	523.0	1.04	
		3	41.0	93.6	438.5	0.87	
		4	43.2	92.7	466.1	0.93	
CO-12C	C	0	54.5	93.0	585.9	1.00	0-5%
		1	47.7	91.8	520.0	0.89	
		2	48.6	92.5	524.9	0.90	
		3	46.8	91.6	510.9	0.87	
		4	50.4	91.7	549.2	0.94	
CO-12D	B	0	20.5	99.3	206.3	1.00	0-5%
		1	27.0	100.4	268.9	1.30	
		2	24.1	104.3	231.2	1.12	
		3	22.3	102.5	217.7	1.06	
		4	25.2	104.0	242.6	1.18	

Average ECS Modulus Ratio after 3 cycles = 0.95
Average ECS Modulus Ratio after 4 cycles = 1.02

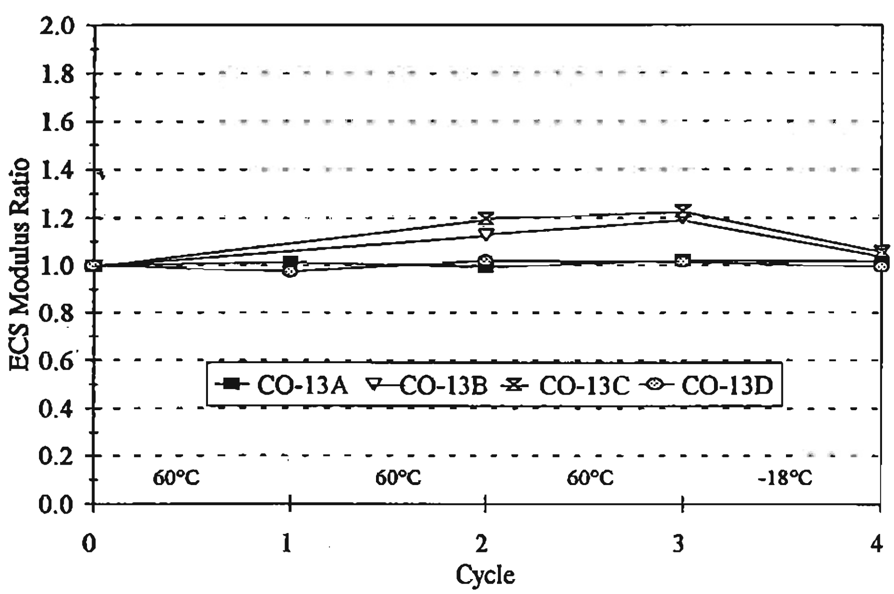


ECS Modulus Ratio Results
Jefferson County (Mix 12)

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-13A	A	0	39.8	100.1	398.0	1.00	10-20%
		1	41.9	103.8	403.7	1.01	
		2	40.2	101.7	395.0	0.99	
		3	40.3	98.9	407.1	1.02	
		4	35.8	89.6	404.4	1.02	
CO-13B	B	0	32.2	103.8	310.0	1.00	10-20%
		1	④	④	④	④	
		2	35.2	97.8	349.5	1.13	
		3	35.1	94.4	372.1	1.20	
		4	34.7	105.6	328.8	1.06	
CO-13C	A	0	27.6	103.7	265.9	1.00	10-20%
		1	④	④	④	④	
		2	32.7	102.8	318.4	1.20	
		3	33.3	101.9	327.0	1.23	
		4	29.9	105.7	282.6	1.06	
CO-13D	B	0	25.6	96.7	265.3	1.00	10-20%
		1	26.6	103.2	258.2	0.97	
		2	27.1	100.2	270.7	1.02	
		3	26.5	98.3	269.2	1.01	
		4	26.8	101.9	263.9	0.99	

④ Computer Error

Average ECS Modulus Ratio after 3 cycles = 1.12
Average ECS Modulus Ratio after 4 cycles = 1.03

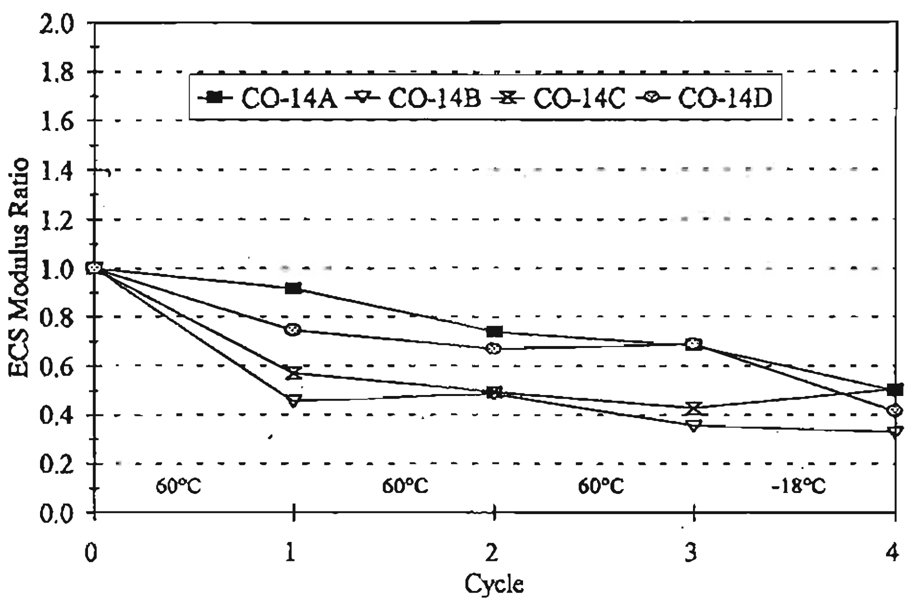


ECS Modulus Ratio Results
Cedar Point (Mix 13)

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-14A See note below	A	0	34.7	99.0	350.4	1.00	10-20%
		1	31.8	99.0	321.4	0.92	
		2	25.2	97.3	259.1	0.74	
		3	24.0	100.1	239.8	0.68	
		4	18.0	103.0	175.3	0.50	
CO-14B See note below	B	0	34.5	79.9	468.6	1.00	20-30%
		1	17.4	81.7	212.7	0.45	
		2	18.4	80.8	227.8	0.49	
		3	16.7	100.6	166.4	0.36	
		4	11.8	77.1	152.9	0.33	
CO-14C	A	0	27.3	100.0	273.1	1.00	10-20%
		1	15.5	99.4	155.7	0.57	
		2	13.1	97.2	135.2	0.50	
		3	12.0	102.9	116.9	0.43	
		4	14.4	104.5	137.8	0.50	
CO-14D See note below	B	0	28.8	100.3	287.0	1.00	10-20%
		1	22.4	104.7	213.8	0.75	
		2	19.1	99.8	191.8	0.67	
		3	19.9	100.6	198.0	0.69	
		4	11.7	98.1	119.6	0.42	

Note: Conditioning cycles were accidentally interrupted during test; end ratios may be slightly low because specimens were subjected to additional conditioning.

Average ECS Modulus Ratio after 3 cycles = 0.54
Average ECS Modulus Ratio after 4 cycles = 0.44



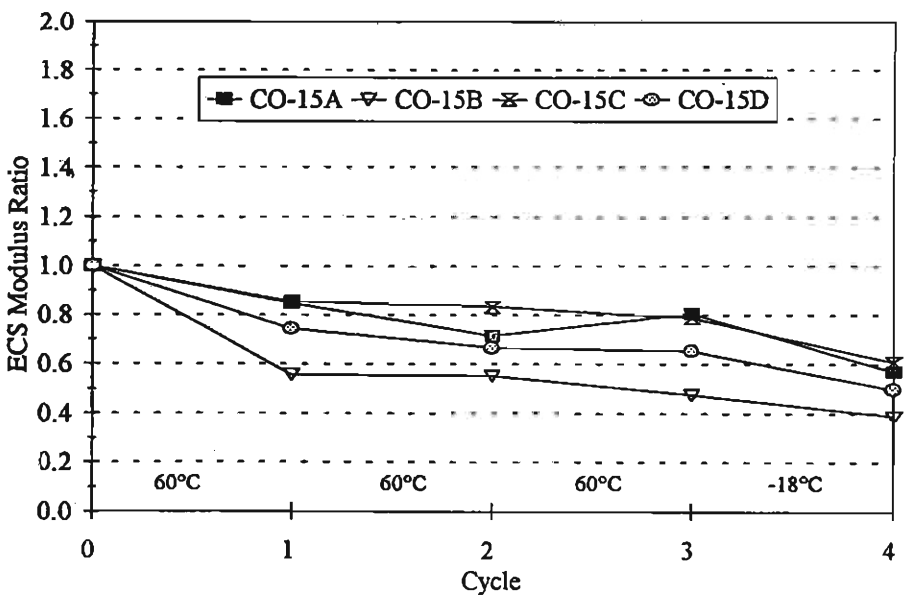
ECS Modulus Ratio Results

Agate (Mix 14)

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-15A	A	0	37.7	96.0	393.2	1.00	10-20%
		1	32.6	97.7	333.3	0.85	
		2	28.2	100.3	281.1	0.71	
		3	30.6	96.5	316.9	0.81	
		4	21.6	96.4	224.1	0.57	
CO-15B	A	0	52.7	① 88.0	598.4	1.00	10-20%
		1	34.4	103.3	333.4	0.56	
		2	34.1	103.3	330.2	0.55	
		3	28.2	99.0	285.1	0.48	
		4	23.6	101.7	232.1	0.39	
CO-15C	B	0	25.3	104.4	242.7	1.00	10-20%
		1	21.1	101.6	207.5	0.85	
		2	20.8	102.9	202.2	0.83	
		3	19.2	100.5	190.9	0.79	
		4	14.3	96.6	147.9	0.61	
CO-15D	B	0	29.6	92.3	321.1	1.00	10-20%
		1	23.2	97.6	238.1	0.74	
		2	21.8	102.2	213.7	0.67	
		3	21.4	101.7	210.3	0.65	
		4	16.2	101.9	159.1	0.50	

① Probable error in strain reading.

Average ECS Modulus Ratio after 3 cycles = 0.68
Average ECS Modulus Ratio after 4 cycles = 0.52



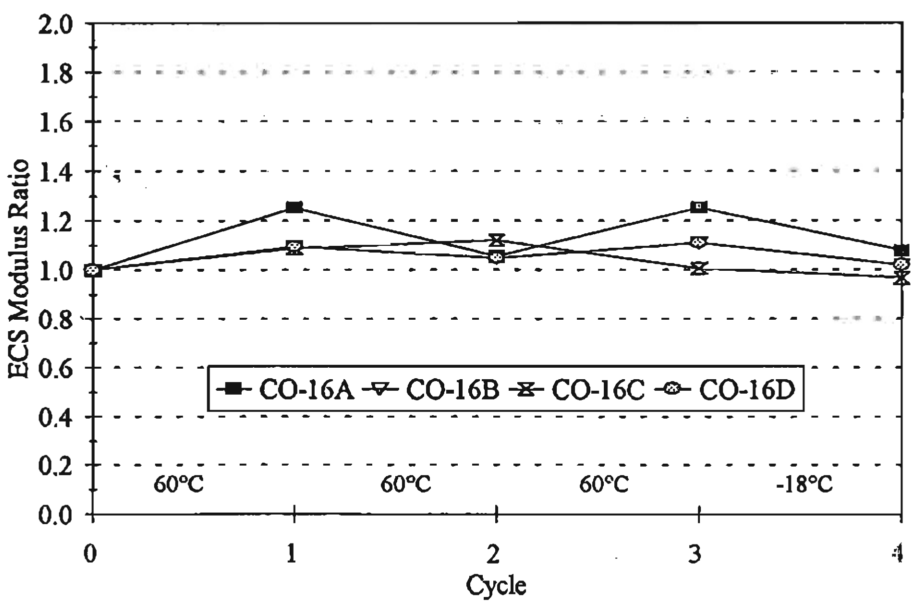
ECS Modulus Ratio Results

Arriba (Mix 15)

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-16A	A	0	26.6	104.2	255.0	1.00	5-10%
		1	30.7	96.1	319.7	1.25	
		2	27.7	102.9	269.1	1.06	
		3	30.7	96.1	319.7	1.25	
		4	27.5	99.9	274.9	1.08	
CO-16B See note below	B	0	27.6	97.1	284.2	1.00	5-10%
		1	30.5	98.1	311.1	1.09	
		2	31.2	104.6	298.1	1.05	
		3	31.0	98.2	315.8	1.11	
		4	30.9	106.6	289.6	1.02	
CO-16C	B	0	36.2	100.8	358.9	1.00	5-10%
		1	38.8	99.5	390.3	1.09	
		2	40.7	101.2	402.5	1.12	
		3	36.3	100.5	361.4	1.01	
		4	36.5	105.0	347.2	0.97	
CO-16D	B	0	27.6	97.1	284.2	1.00	5-10%
		1	30.5	98.1	311.1	1.09	
		2	31.2	104.6	298.1	1.05	
		3	31.0	98.2	315.8	1.11	
		4	30.9	106.6	289.6	1.02	

Note: Samples lack of straightness resulted in eccentric loading; it is unknow if this affected the results.

Average ECS Modulus Ratio after 3 cycles = 1.12
Average ECS Modulus Ratio after 4 cycles = 1.02

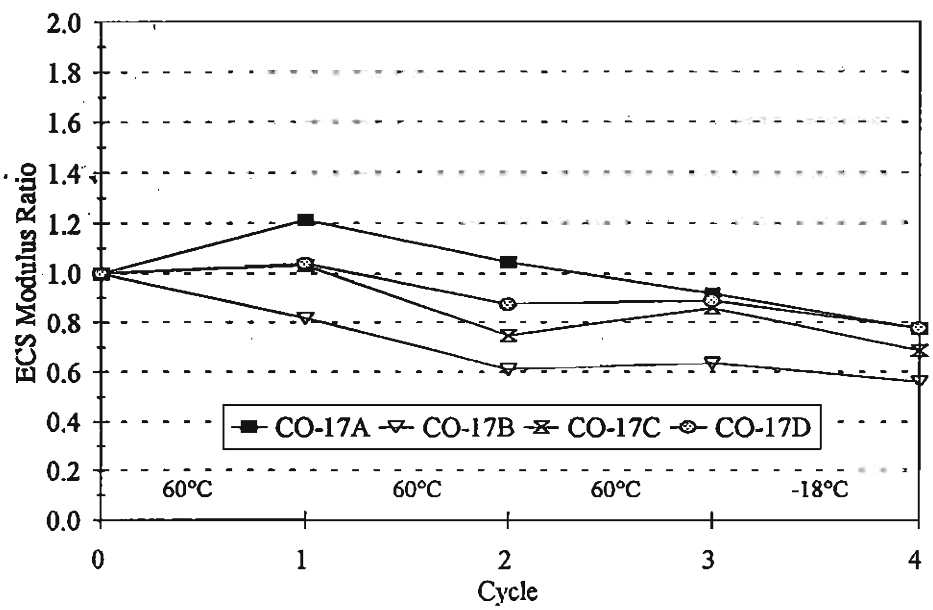


ECS Modulus Ratio Results

Limon (Mix 16)

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-17A	C	0	13.5	98.7	136.8	1.00	5-10%
		1	16.8	101.4	166.0	1.21	
		2	14.9	104.1	142.8	1.04	
		3	12.8	101.7	126.0	0.92	
		4	10.9	102.4	106.0	0.78	
CO-17B	A	0	25.4	96.7	262.2	1.00	5-10%
		1	20.8	96.8	214.8	0.82	
		2	16.0	99.8	160.6	0.61	
		3	16.0	95.8	167.2	0.64	
		4	14.5	98.4	147.5	0.56	
CO-17C	B	0	16.0	98.4	162.5	1.00	5-10%
		1	17.3	102.9	167.8	1.03	
		2	11.8	96.7	121.9	0.75	
		3	13.5	96.6	140.0	0.86	
		4	10.8	96.6	111.7	0.69	
CO-17D	B	0	17.0	100.9	168.8	1.00	5-10%
		1	17.6	100.1	175.5	1.04	
		2	14.9	100.5	147.9	0.88	
		3	15.0	99.8	150.4	0.89	
		4	13.1	99.6	131.1	0.78	

Average ECS Modulus Ratio after 3 cycles = 0.83
Average ECS Modulus Ratio after 4 cycles = 0.70

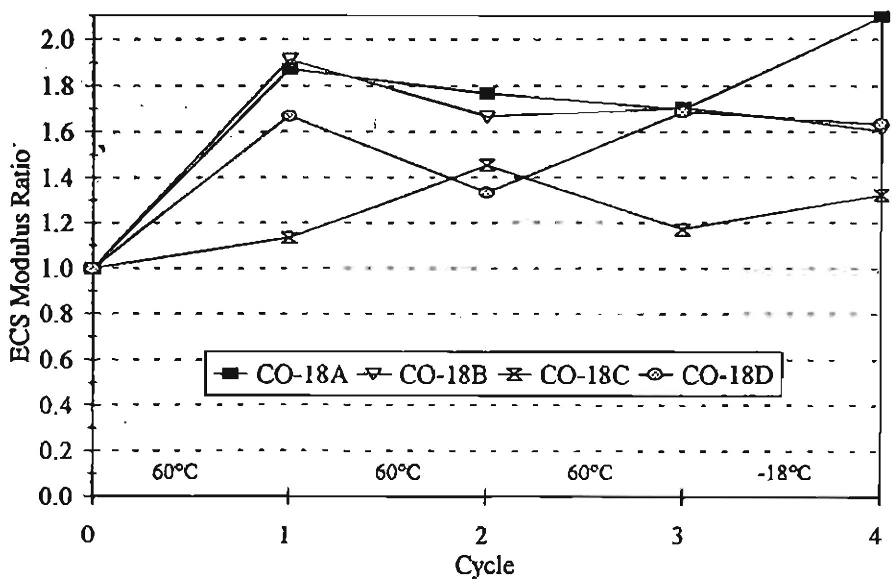


ECS Modulus Ratio Results
Trinidad (Mix 17)

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-18A	C	0	③ 14.5	101.0	146.0	1.00	0-5%
		1	27.7	101.2	273.4	1.87	
		2	26.1	100.9	258.2	1.77	
		3	24.8	99.9	248.2	1.70	
		4	30.5	99.8	306.1	2.10	
CO-18B	C	0	③ 14.6	102.0	143.6	1.00	0-5%
		1	27.6	100.6	275.0	1.92	
		2	23.9	99.8	239.1	1.67	
		3	24.6	100.6	244.6	1.70	
		4	23.0	99.6	230.4	1.60	
CO-18C	C	0	③ 19.9	99.8	199.7	1.00	0-5%
		1	23.1	101.9	227.0	1.14	
		2	29.3	100.7	290.7	1.46	
		3	23.5	100.4	234.1	1.17	
		4	26.6	100.7	264.5	1.32	
CO-18D	C	0	③ 14.5	99.9	145.1	1.00	0-5%
		1	24.5	101.0	242.1	1.67	
		2	19.3	99.8	193.7	1.33	
		3	24.7	101.0	244.6	1.69	
		4	23.7	99.9	237.0	1.63	

③ Probable error in stress reading

Average ECS Modulus Ratio after 3 cycles = 1.57
Average ECS Modulus Ratio after 4 cycles = 1.66

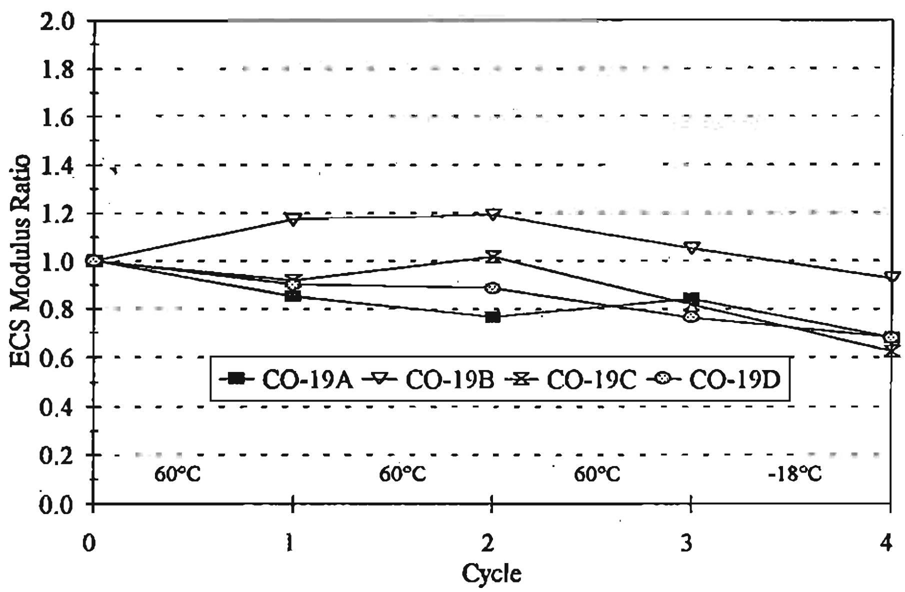


ECS Modulus Ratio Results

Walsenburg (Mix 18)

Specimen ID	ECS System	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-19A	A	0	39.4	101.2	389.3	1.00	30-40%
		1	34.3	103.4	331.9	0.85	
		2	31.2	104.5	298.5	0.77	
		3	32.4	98.7	328.1	0.84	
		4	26.1	98.3	265.4	0.68	
CO-19B	A	0	27.9	101.1	276.4	1.00	30-40%
		1	32.3	99.7	324.3	1.17	
		2	33.6	101.8	329.7	1.19	
		3	28.9	99.7	290.3	1.05	
		4	25.1	98.0	256.5	0.93	
CO-19C	B	0	21.5	99.9	215.2	1.00	30-40%
		1	20.3	102.9	197.7	0.92	
		2	22.4	102.5	219.0	1.02	
		3	18.0	102.4	176.1	0.82	
		4	13.7	101.5	134.7	0.63	
CO-19D	B	0	32.6	96.1	339.6	1.00	30-40%
		1	30.2	98.7	306.2	0.90	
		2	30.4	100.8	301.1	0.89	
		3	25.5	98.5	259.3	0.76	
		4	23.7	102.5	231.5	0.68	

Average ECS Modulus Ratio after 3 cycles = 0.87
Average ECS Modulus Ratio after 4 cycles = 0.73

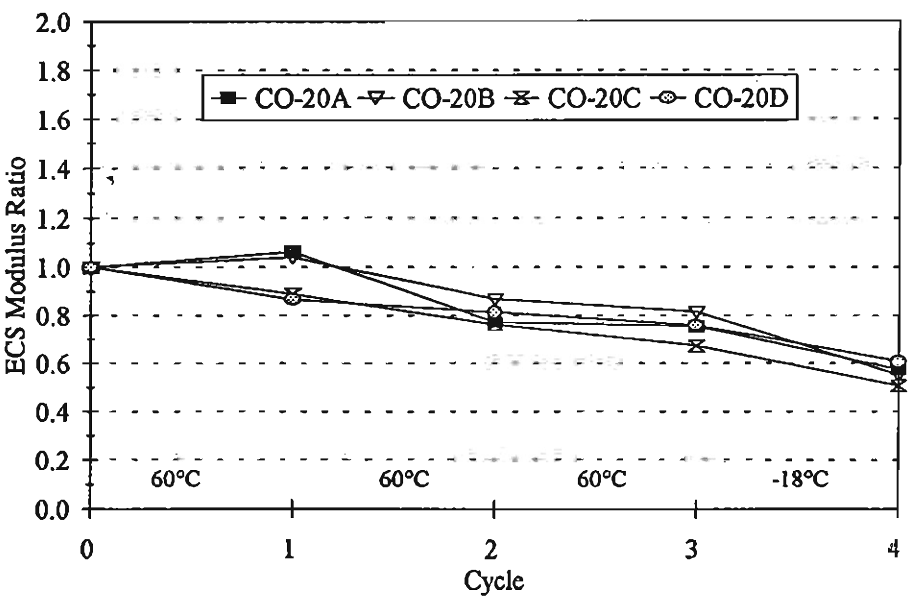


ECS Modulus Ratio Results

Fleming (Mix 19)

Specimen ID	ECS Sys.	Cond. Cycle	ECS Stress (psi)	ECS Strain (ksi)	ECS MR (ksi)	ECS MR Ratio	Visual Stripping (%)
CO-20A	A	0	35.6	95.9	371.3	1.00	5-10%
		1	38.2	96.7	394.6	1.06	
		2	29.8	103.8	286.9	0.77	
		3	28.2	100.8	279.8	0.75	
		4	21.6	101.4	213.5	0.58	
CO-20B	B	0	23.8	103.0	230.6	1.00	5-10%
		1	24.4	102.0	239.7	1.04	
		2	19.4	97.1	200.0	0.87	
		3	19.2	101.9	188.2	0.82	
		4	12.8	101.1	127.0	0.55	
CO-20C	A	0	24.2	102.4	236.6	1.00	5-10%
		1	21.3	101.6	210.3	0.89	
		2	17.6	97.4	180.4	0.76	
		3	16.8	105.6	159.4	0.67	
		4	11.9	98.8	120.1	0.51	
CO-20D	B	0	28.1	97.9	288.0	1.00	5-10%
		1	25.3	101.6	249.3	0.87	
		2	25.0	106.6	234.5	0.81	
		3	22.1	100.8	218.9	0.76	
		4	18.5	106.0	175.0	0.61	

Average ECS Modulus Ratio after 3 cycles = 0.75
Average ECS Modulus Ratio after 4 cycles = 0.56



ECS Modulus Ratio Results

Gunnison (Mix 20)