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INFLUENCE OF TESTING VARIABLES ON THE RESULTS FROM THE HAMBURG WHEEL-TRACKING DEVICE

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16. Abstract

The Hamburg wheel-tracking device can be used to predict the moisture susceptibility of a hot mix asphalt pavement. The test results are influenced by testing temperature, asphalt cement stiffness, air void content, short-term aging, and the presence of lime. The variables are important to control in the laboratory environment to ensure repeatability. Additionally, these variables are also considered important to the moisture resistance of a pavement in the field.

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Influence of Testing Variables on the Results from the Hamburg Wheel-Tracking Device

Tim Aschenbrener and Gray Currier

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 (2). The next step was to investigate several testing variables that influence the results in order to better understand the test results and their repeatability.

The purpose of this report is to identify the influence of four testing variables on the results from the Hamburg wheel-tracking device. The variables investigated in this study are 1) testing temperature and asphalt cement stiffness, 2) air voids of compacted samples, 3) short-term aging, and 4) method of lime addition. It is important to understand how these variables influence the test results so the laboratory procedure can be written to ensure repeatability. Further, these variables are also considered important to the moisture resistance of a pavement in the field. Any test that hopes to predict the moisture susceptibility of an HMA pavement should be sensitive to these variables.

2.0 HAMBURG WHEEL-TRACKING DEVICE

2.1 Equipment and Procedures

The Hamburg wheel-tracking device is manufactured by Helmut-Wind Inc. of Hamburg, Germany as shown in Figs. 1 and 2. A pair of samples are tested simultaneously. A sample is typically 260 mm (10.2 in.) wide, 320 mm (12.6 in.) long, and 40 mm (1.6 in.) deep. A sample's mass is approximately 7.5 kg (16.5 lbs.), and it is compacted to approximately 7% air voids. For this study, samples were compacted with the linear kneading 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 occurs. Approximately 6-1/2 hours are required for a test.

2.2 Results and Specifications

The results from the Hamburg wheel-tracking device include the creep slope, stripping slope and stripping inflection point as shown in Fig. 3. These results have been defined by Hines (3). 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.

A sample is required by the City of Hamburg to have less than 4 mm rut depth after 20,000 passes. Testing by the CDOT has indicated this specification is very severe (2).

Fig. 1. The Hamburg Wheel-Tracking Device.

Fig. 2. Close-up of Hamburg Wheel Tracking Device.

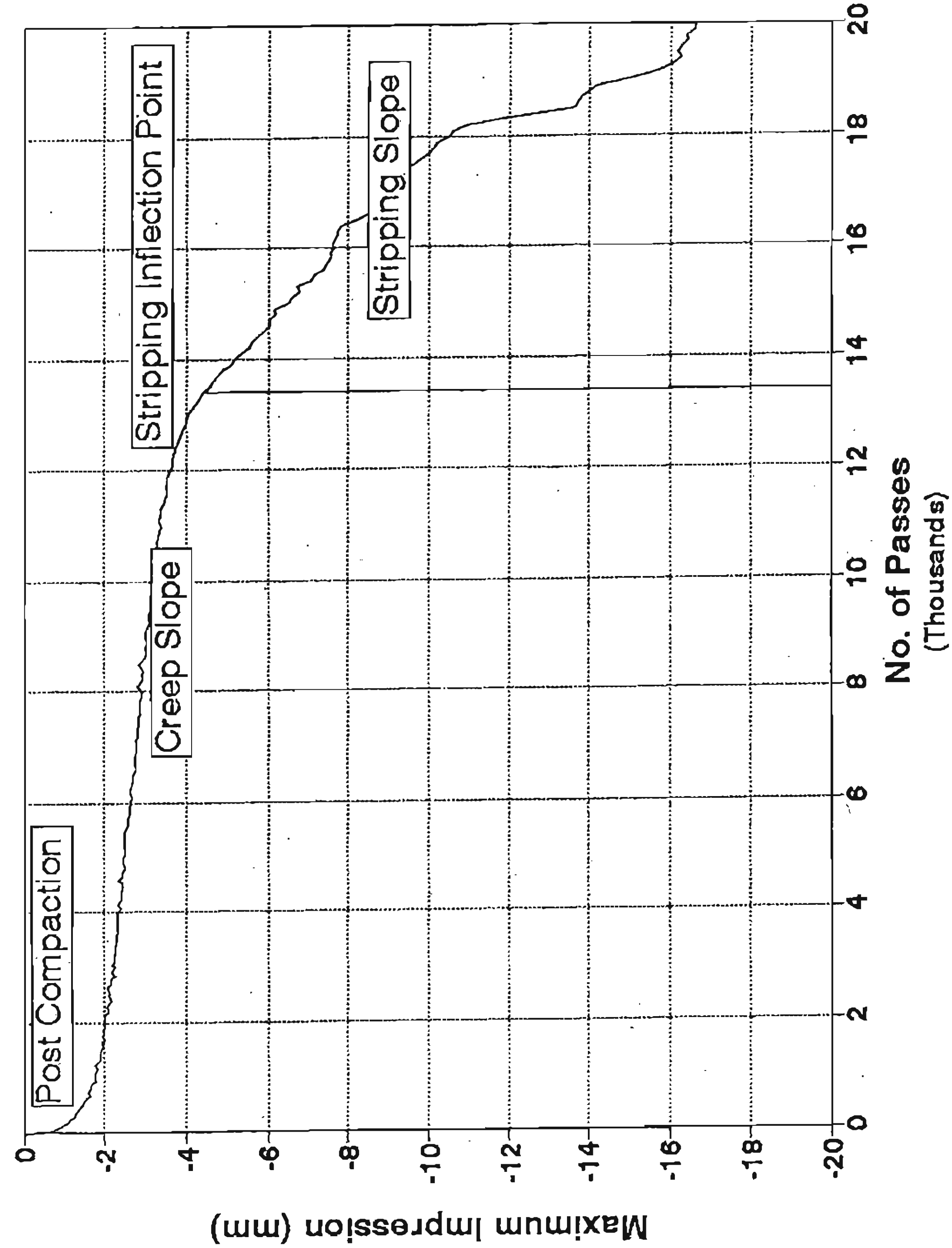


Fig. 3. Results from the Hamburg Wheel-Tracking Device.

3.0 MATERIAL DESCRIPTIONS

3.1 Asphalt Cements

It was desired to test asphalt cements with a variety of high temperature properties. Three neat asphalt cements were used in this study and were provided by Frontier Refinery in Cheyenne, Wyoming. The asphalt cements were AC-5, AC-10, and AC-20 (AASHTO M 226, Table 2). Additionally, one polymer modified asphalt cement, AC-20P (AASHTO Task Force 31, Type I-D), was provided by Koch Materials. The properties of the asphalt cements were measured with the penetration at 25°C (AASHTO T 49), viscosity at 60°C (AASHTO T 202), ring and ball softening point (AASHTO T 53), and the SHRP Dynamic Shear Rheometer (DSR) tests. Results are shown in Table 1. For the DSR, the unaged asphalt cement would have a stiffness of 1.0 kPa at the temperature listed in Table 1. The possible high-temperature performance grade (PG) of the asphalt cement as classified by SHRP is included.

Table 1. Asphalt Cement Properties.

	Viscosity @ 60°C (poises)	Penetration @ 25°C (dmm)	Ring & Ball Softening Point (°C)	DSR (°C) @ 1 kPa Stiffness	High Temperature PG
AC-5	520	155	45.0	56.2	52
AC-10	1030	99	47.7	61.6	58
AC-20	1980	67	52.8	67.5	64
AC-20P	10280	74	62.2	77.4	70

3.2 Aggregates

Aggregates used for this study came from a variety of sources with a variety of performance histories. The aggregates and combinations were selected to provide a variety of results, good to poor, in the Hamburg wheel-tracking device. All mixtures used quarried aggregate. Two different types of natural sands were added to help vary the performance of each mixture.

The aggregates for Mix 1 were entirely from a quarried source that has had a history of good performance. The aggregates for Mix 2 were primarily from a different quarry with a good history of performance. However, a poor quality natural sand was added. Although the natural sand is non-plastic, it does have clay present.

The aggregate for Mix 3 was from a quarry with a mixed history of good and marginal performance. A clean natural sand that has been associated with many HMA pavements that have stripped was added. The natural sand does not adhere to asphalt cement very well. The aggregate for Mix 4 was from a quarry with a history of poor performance. The poor quality natural sand with clay used in Mix 2 was also added to Mix 4.

3.3 Hot Mix Asphalt

The optimum asphalt content for each of the mixtures was determined with the Texas gyratory in general accordance with ASTM D 4013. The pre-gyration stress, end point stress and consolidation stress used were 210, 690, and 17,240 kPa (30, 100, 2500 psi), respectively. These stresses simulate the loads applied to the HMA pavements by high levels of traffic in Colorado.

The optimum asphalt content was determined for each HMA with the Frontier AC-20 and AC-5 using equi-viscous mixing and compaction temperatures. The optimum asphalt contents at 4% air voids are shown in Table 2. There was not a significant difference in optimum asphalt content with the different grades of asphalt cement. The asphalt contents of the mixtures used in this study are also shown in Table 2.

All mixes were treated with an anti-stripping additive. When a liquid anti-stripping additive was used, it was Pave Bond Special provided by Morton International. When hydrated lime was used, it was provided by Chemstar Lime Company.

Table 2. Optimum Asphalt Contents for the Mixes Used in this Study.

	Optimum Asphalt Content (%)		
	AC-20	AC-5	Used in This Study
Mix 1	5.1	5.1	5.1
Mix 2	5.1	5.1	5.1
Mix 3	5.2	5.1	5.2
Mix 4	5.3	5.1	5.3

4.0 INFLUENCE OF TEST TEMPERATURE ON RESULTS

The purpose of this study is to determine the influence of the testing temperature on results obtained from the Hamburg wheel-tracking device.

4.1 Experimental Grid

The specified testing temperature in Hamburg is 50°C, and the asphalt cement used is typically a 70 to 100 dmm penetration (AASHTO T 49 at 25°C). Since Colorado uses grades of asphalt cement different from those used in the City of Hamburg, it was desired to determine the influence of the testing temperature for different grades of asphalt cement.

The four grades of asphalt cement used in this study were the most commonly used grades in Colorado: AC-5, AC-10, AC-20, and AC-20P. Since the quality of the mixture was thought to have an influence on the results, four different HMAs were selected. Testing temperatures used ranged from 35°C to 65°C. Each grade of asphalt cement was tested at three temperatures. The temperatures were selected based on the performance of each mix in the Hamburg wheel-tracking device. The full experimental grid is shown in Table 3. Some of the targeted testing temperatures in Table 3 were adjusted based on the performance of each mix.

4.2 Results and Discussions

The samples were compacted on the linear kneading compactor to 7 $\pm$ 1.5% air voids. Replicate samples were always tested. Results are plotted in Appendix A.

The stripping inflection point for each of the four mixes at the different combinations of temperature and asphalt cement stiffness are shown in Tables 4 through 7. Plots of the stripping inflection point versus test temperature for each of the mixes are shown in Figs. 4 through 7. In all cases, the stripping inflection point increases as either the testing temperature decreases or the asphalt cement stiffness increases.

Table 3. Experimental Grid for the Study to Determine the Influence of Testing Temperature.

	AC-20P			AC-20			AC-10			AC-5		
	45° C	50° C	55° C	40° C	45° C	50° C	40° C	45° C	50° C	35° C	40° C	45° C
Mix 1 - Excellent	X	X	X	X	X	X	X	X	X	X	X	X
Mix 2 - Marginal	X	X	X	X	X	X	X	X	X	NT	X	X
Mix 3 - Marginal	X	X	X	X	X	X	X	X	NT	NT	X	X
Mix 4 - Terrible	X	X	X	X	X	X	X	X	X	X	X	X

X - Replicate samples were tested.

NT - Not Tested

Table 4. Results of the Test Temperature Study for Mix 1.

	Stripping Inflection Point (Passes)					
	40°C	45°C	50°C	55°C	60°C	65°C
AC-5	20,000	7,300	3,000	NT	NT	NT
AC-10	NT	17,000	13,200	3,100	NT	NT
AC-20	NT	+20,000	+20,000	9,800	NT	NT
AC-20P	NT	NT	NT	+20,000	+20,000	20,000

NT - Not Tested

Table 5. Results of the Test Temperature Study for Mix 2.

	Stripping Inflection Point (Passes)				
	40°C	45°C	50°C	55°C	60°C
AC-5	18,200	6,300	NT	NT	NT
AC-10	NT	+20,000	10,700	5,300	NT
AC-20	NT	+20,000	12,500	7,500	NT
AC-20P	NT	NT	+20,000	+20,000	17,800

NT - Not Tested

Table 6. Results of the Test Temperature Study for Mix 3.

	Stripping Inflection Point (Passes)				
	35°C	40°C	45°C	50°C	55°C
AC-5	5,500	1,100	NT	NT	NT
AC-10	10,000	3,200	NT	NT	NT
AC-20	NT	6,200	5,000	600	NT
AC-20P	NT	NT	+20,000	8,100	5,600

NT - Not Tested

Table 7. Results of the Test Temperature Study for Mix 4.

	Stripping Inflection Point (Passes)			
	35°C	40°C	45°C	50°C
AC-5	15,300	5,500	3,300	NT
AC-10	NT	17,300	11,900	4,600
AC-20	NT	+20,000	14,900	8,800
AC-20P	NT	+20,000	+20,000	15,400

NT - Not Tested

4.2.1 Differential Test Temperature

When placing an HMA in the colder parts of Colorado, a soft asphalt cement is generally used. This mix should be tested with a low temperature on the Hamburg wheel-tracking device, because the highest field temperatures are usually not very high. When placing an HMA in the hottest parts of Colorado, a stiff asphalt cement is generally used. When testing this mix in the Hamburg wheel-tracking device a high temperature should be used to simulate the very high field temperatures.

If one aggregate source is mixed with a soft or stiff asphalt cement for a cool or hot temperature environment, respectively, then the stripping inflection point of both mixes should be the same. In other words, as the grade of asphalt cement changes to accommodate the areas in Colorado with high temperatures that range from cool to hot, the test temperature in the Hamburg wheel-tracking device should be adjusted also. This is extremely important because the test results are very sensitive to test temperature and asphalt cement stiffness.

The temperature differentials that would provide an equal stripping inflection point for the same mix with different asphalt cement stiffnesses are shown in Table 8 as determined from Figs. 8 through 11. The location of the horizontal line drawn in Figs. 8 through 11 is based upon the use of an asphalt cement typically used in Hamburg and tested at 50°C as explained in Section 4.2.2. The temperature of the AC-10 was arbitrarily selected as "x".

As an example, consider Mix 4. The stripping inflection point of 7,000 passes was selected from Fig. 11 based upon an AC-15 being tested at 50°C. To obtain a stripping inflection point of 7,000 passes for an AC-5, the test would have to be performed at 9°C lower than with an AC-10. To obtain a stripping inflection point of 7,000 passes for an AC-20, the test would have to be performed at a temperature 4°C higher than with an AC-10. To obtain a stripping inflection point of 7,000 passes for an AC-20P, the test would have to be performed at a temperature 10°C higher than with an AC-10. These temperature differentials are shown in Table 8.

As expected, as the asphalt cement stiffness increased, the test temperature should increase to result in the same stripping inflection point. Generally, each time the asphalt cement increases one grade in stiffness, the test temperature should increase approximately 5°C to result in the same stripping inflection point.

Table 8. Differential Test Temperature Between Various Asphalt Cements That Would Provide Equal Stripping Inflection Points.

	Temperature Differential (°C)					
	Mix 1	Mix 2	Mix 3	Mix 4	Avg.	DSR
AC-5	x - 4	x - 6	x - 3.5	x - 9	x - 6	x - 5.4
AC-10	x	x	x	x	x	x
AC-20	x + 6	x + 3	x + 6	x + 4	x + 5	x + 5.9
AC-20P	x + (>20)*	x + 15	x + 12	x + 10	x + (>14)	x + 15.8

* not possible to determine exactly because the sample did not strip

It was extremely interesting to compare the temperature differential required to obtain equal stripping inflection points with the Hamburg wheel-tracking device to the temperature differential required to obtain a 1 kPa stiffness from the Dynamic Shear Rheometer (DSR). The comparison is shown in Table 8. The differences in high temperature properties of each asphalt cement measured by the Hamburg wheel-tracking device were almost identical to the differences measured by the DSR.

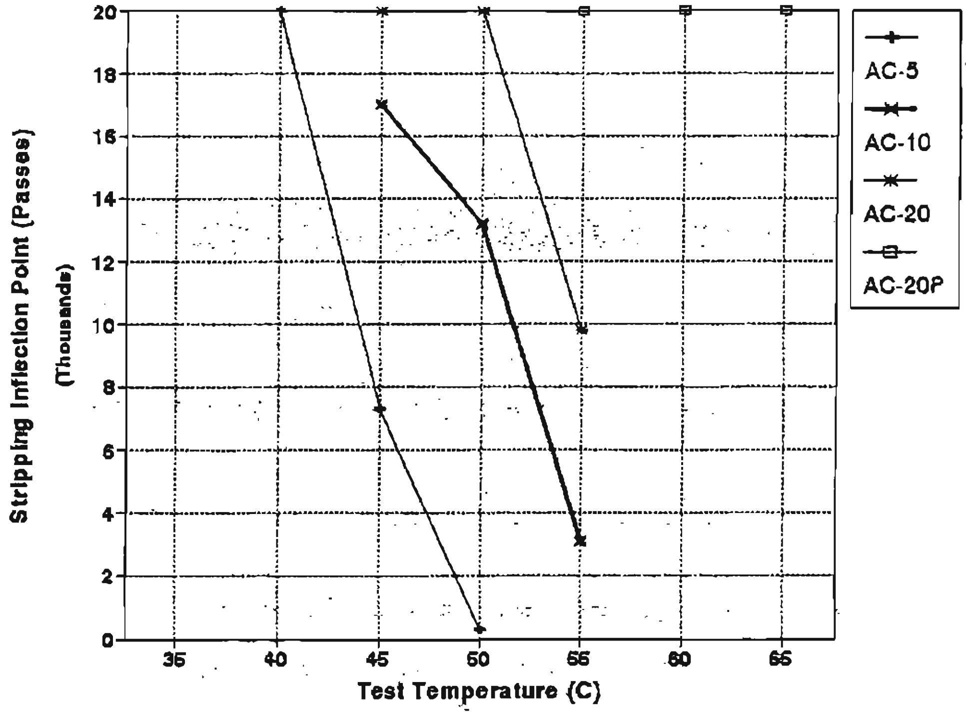


Fig. 4. Influence on Stripping Inflection Point for Various Temperatures and Asphalt Cement Stiffnesses for Mix 1.

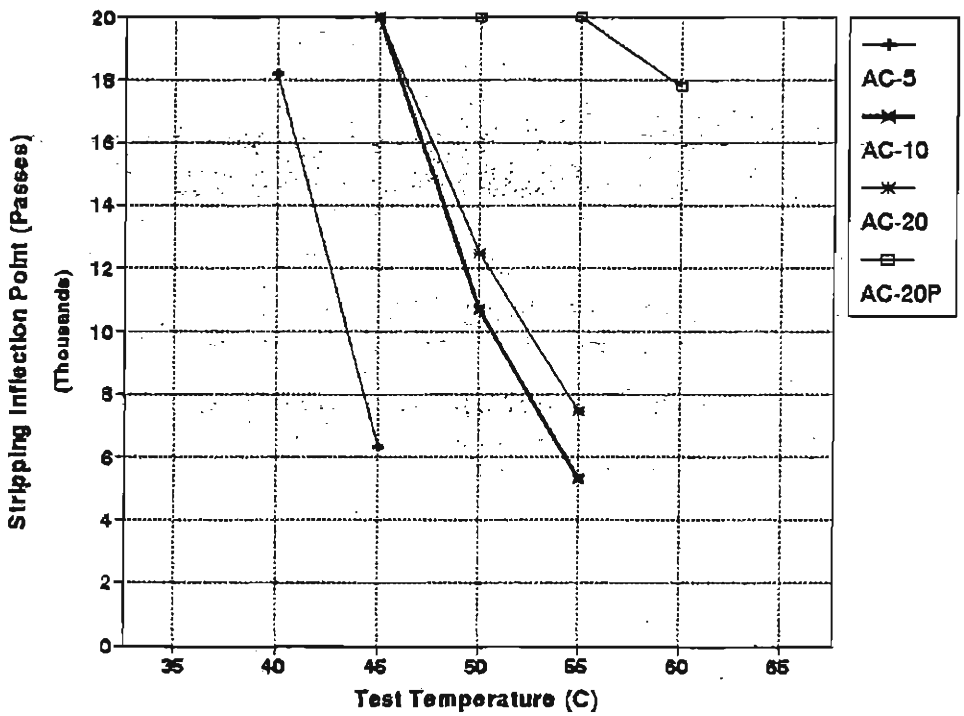


Fig. 5. Influence on Stripping Inflection Point for Various Temperatures and Asphalt Cement Stiffnesses for Mix 2.

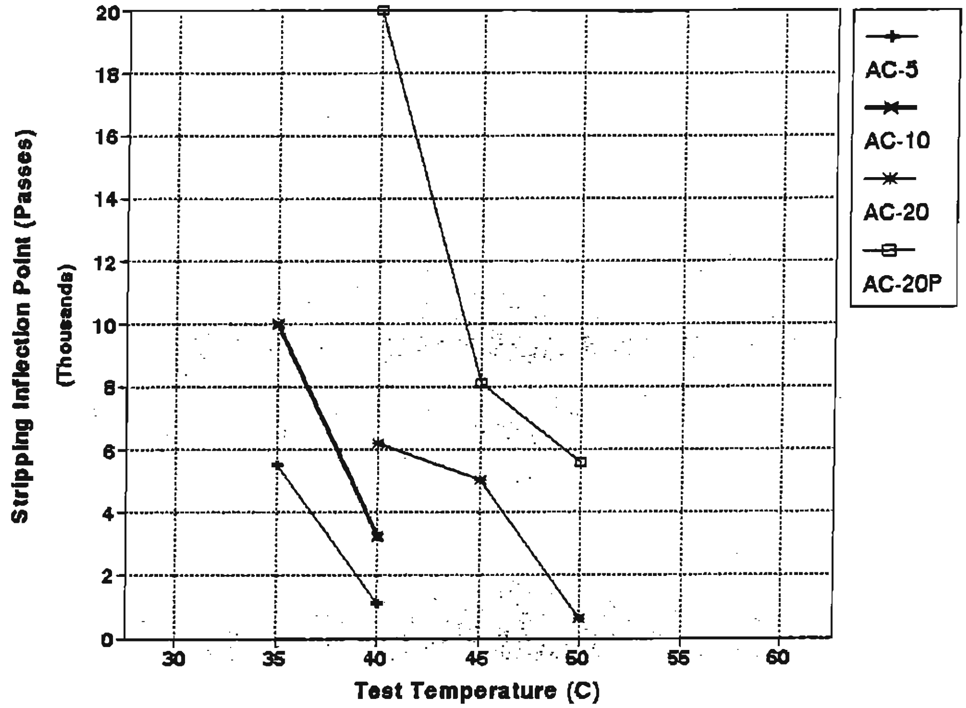


Fig. 6. Influence on Stripping Inflection Point for Various Temperatures and Asphalt Cement Stiffnesses for Mix 3.

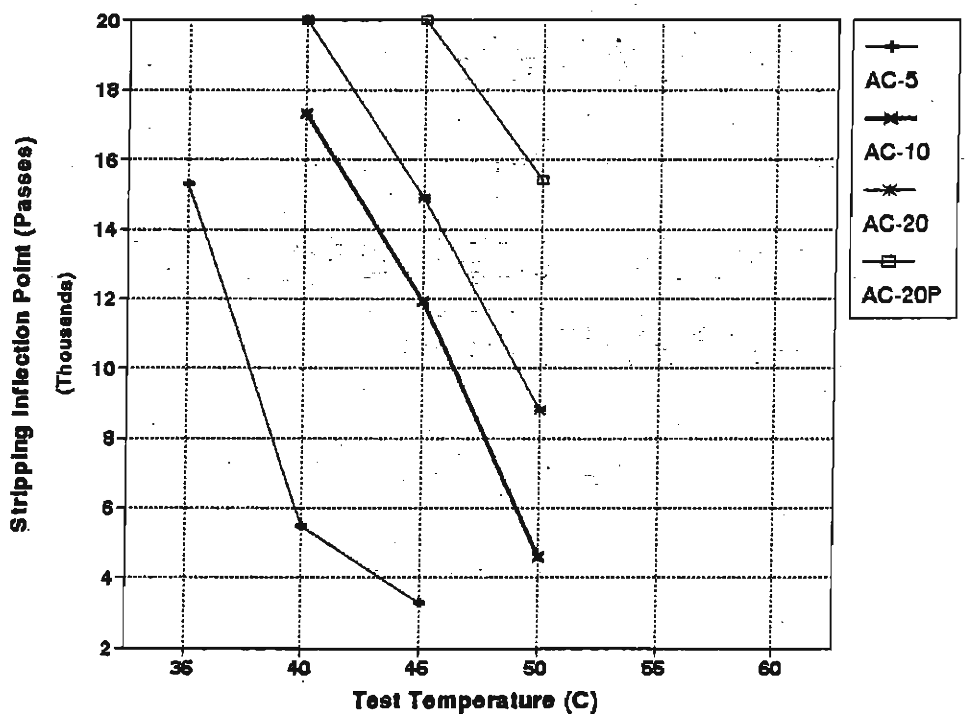


Fig. 7. Influence on Stripping Inflection Point for Various Temperatures and Asphalt Cement Stiffnesses for Mix 4.

4.2.2 *Absolute Test Temperature*

The Hamburg wheel-tracking device is commonly used by the City of Hamburg to approve and accept HMA. Their typical asphalt cement has a penetration at 25°C of 70 to 100 dmm, which is similar to a stiff AC-10 or soft AC-20 used in this study, approximately an AC-15. The high temperature performance grade (PG) of the asphalt cement commonly used in Hamburg would be approximately 64 to 70. Their specified testing temperature in the Hamburg wheel-tracking device is 50°C.

A point was plotted at the 50°C test temperature and the stripping inflection point halfway between the results from the AC-10 and AC-20, approximately an AC-15. This point represents the "typical" test temperature and asphalt cement stiffness used in Hamburg. On Figs. 8 through 11, a horizontal, dashed line representing a constant stripping inflection point was then drawn through the point. As the grade of asphalt changes within each mix, the test temperature required to obtain the same stripping inflection point is shown in Table 9.

For example, consider Mix 4 shown in Fig. 11. The horizontal line is drawn at the stripping inflection point of 7,000 passes because 7,000 passes is at the intersection of the 50°C test temperature and the test results for an AC-15 (halfway between an AC-10 and an AC-20). For this particular mix, an AC-5 would have to be tested at 39°C, and AC-10 at 48°C, an AC-20 at 52°C, and an AC-20P at 58°C to have equal stripping inflection points. These temperatures are shown in Table 9.

It was not possible to compare Mix 3 to the Hamburg test procedure since Mix 3 virtually disintegrated at temperatures lower than 50°C. The line representing the equal inflection point shown in Fig. 10 is presented for information only.

Table 9. Test Temperature That Would Provide Equal Stripping Inflection Points for Various Asphalt Cements.

	Temperature (°C)				
	Mix 1	Mix 2	Mix 3	Mix 4	Avg.
AC-5	42	43	NP	39	41
AC-10	46	49	NP	48	48
AC-20	52	52	NP	52	52
AC-20P	NP	64	NP	58	61

NP - Not Possible

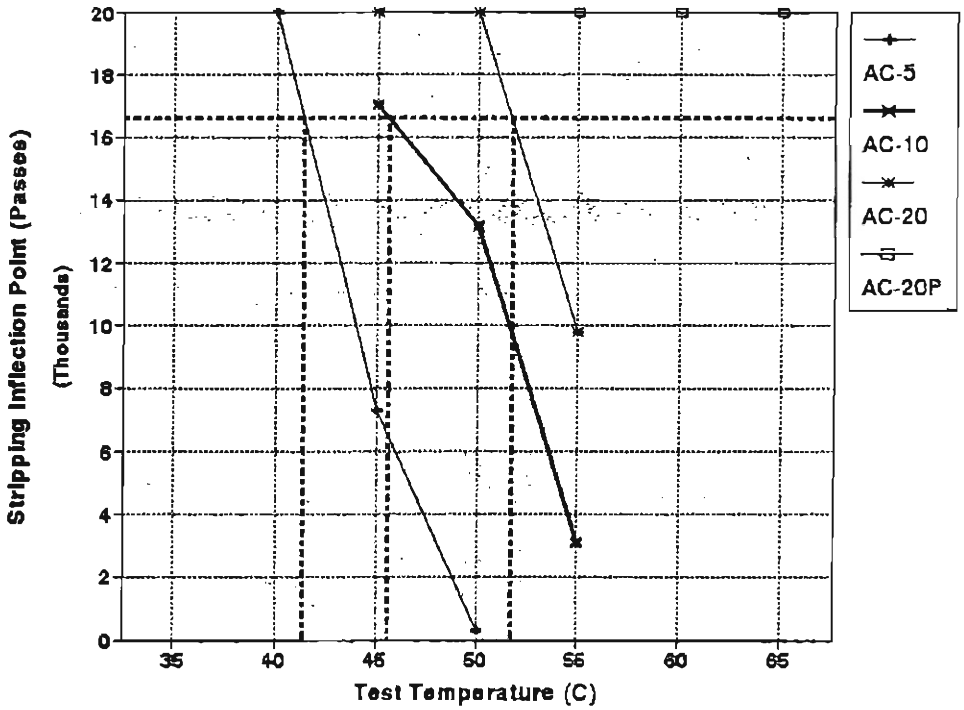


Fig. 8. Temperatures Required to Obtain a Constant Stripping Inflection Point for Various Asphalt Cement Stiffnesses for Mix 1.

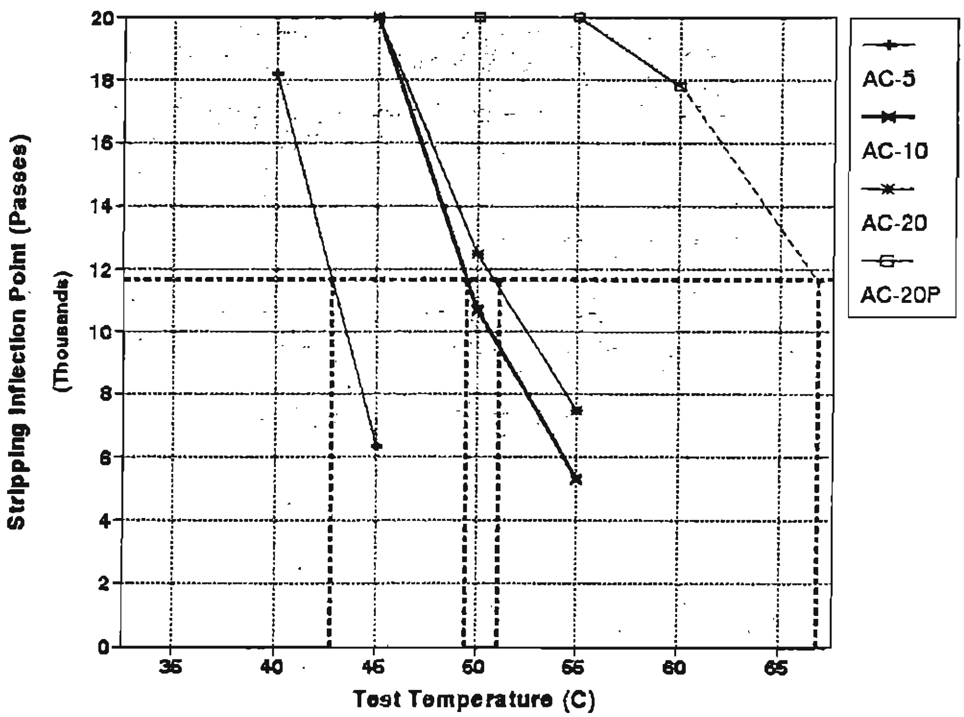


Fig. 9. Temperatures Required to Obtain a Constant Stripping Inflection Point for Various Asphalt Cement Stiffnesses for Mix 2.

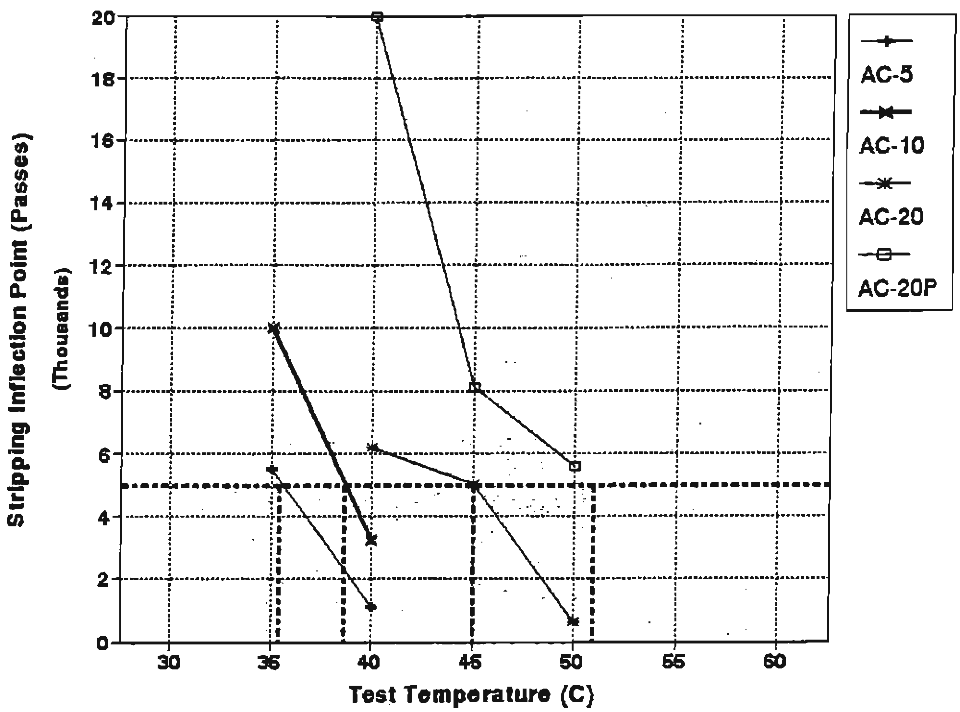


Fig. 10. Temperatures Required to Obtain a Constant Stripping Inflection Point for Various Asphalt Cement Stiffnesses for Mix 3.

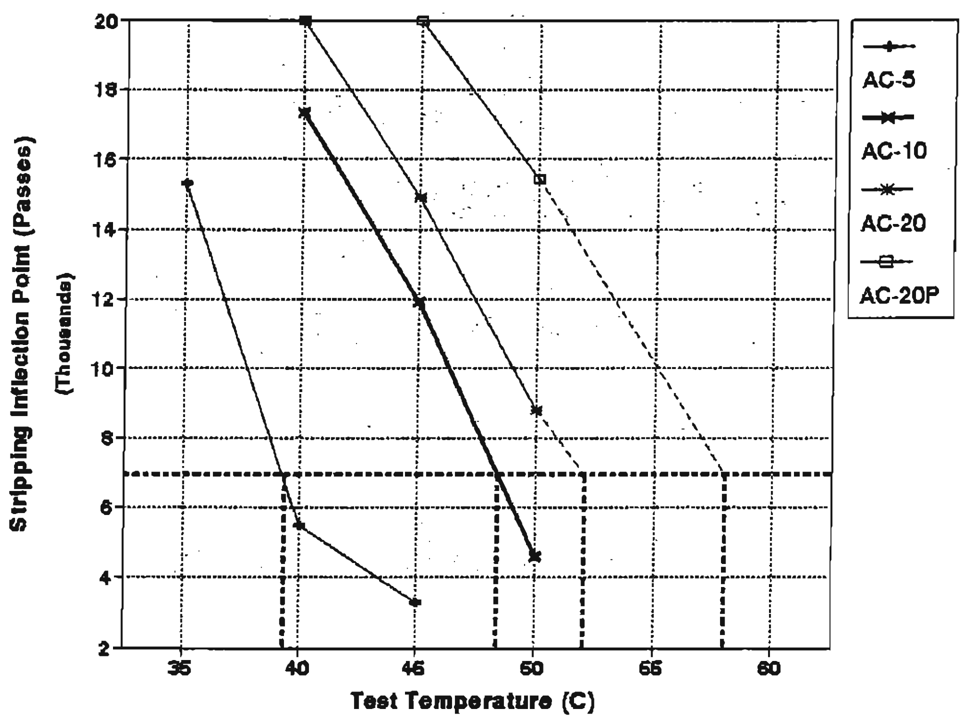


Fig. 11. Temperatures Required to obtain a Constant Stripping Inflection Point for Various Asphalt Cement Stiffnesses for Mix 4.

4.3 Recommendations

The test temperature should relate to the temperature the pavement will experience. The environmental zones within Colorado are defined by county in Fig. 12. Although the environmental zones are not constant within each county, it is shown for approximate information.

The four high temperature categories in Colorado are shown in Table 10. SHRP has developed high temperature gradings for asphalt cements based on the highest pavement temperature at a certain depth. SHRP's corresponding performance grade (PG) recommended in each high temperature category is listed in Table 10. The asphalt cements selected for testing in this experiment are approximately the asphalt cements that would be used in each high temperature category.

The recommended testing temperatures for the Hamburg wheel-tracking device should be selected based on the high temperature environment the pavement will experience as shown in Table 10. These testing temperatures should provide equal stripping inflection points for a mix as the asphalt cement grade is changed. These temperatures would likely correspond with the City of Hamburg test procedure.

Table 10. Recommended Testing Temperature for the Hamburg Wheel-Tracking Device.

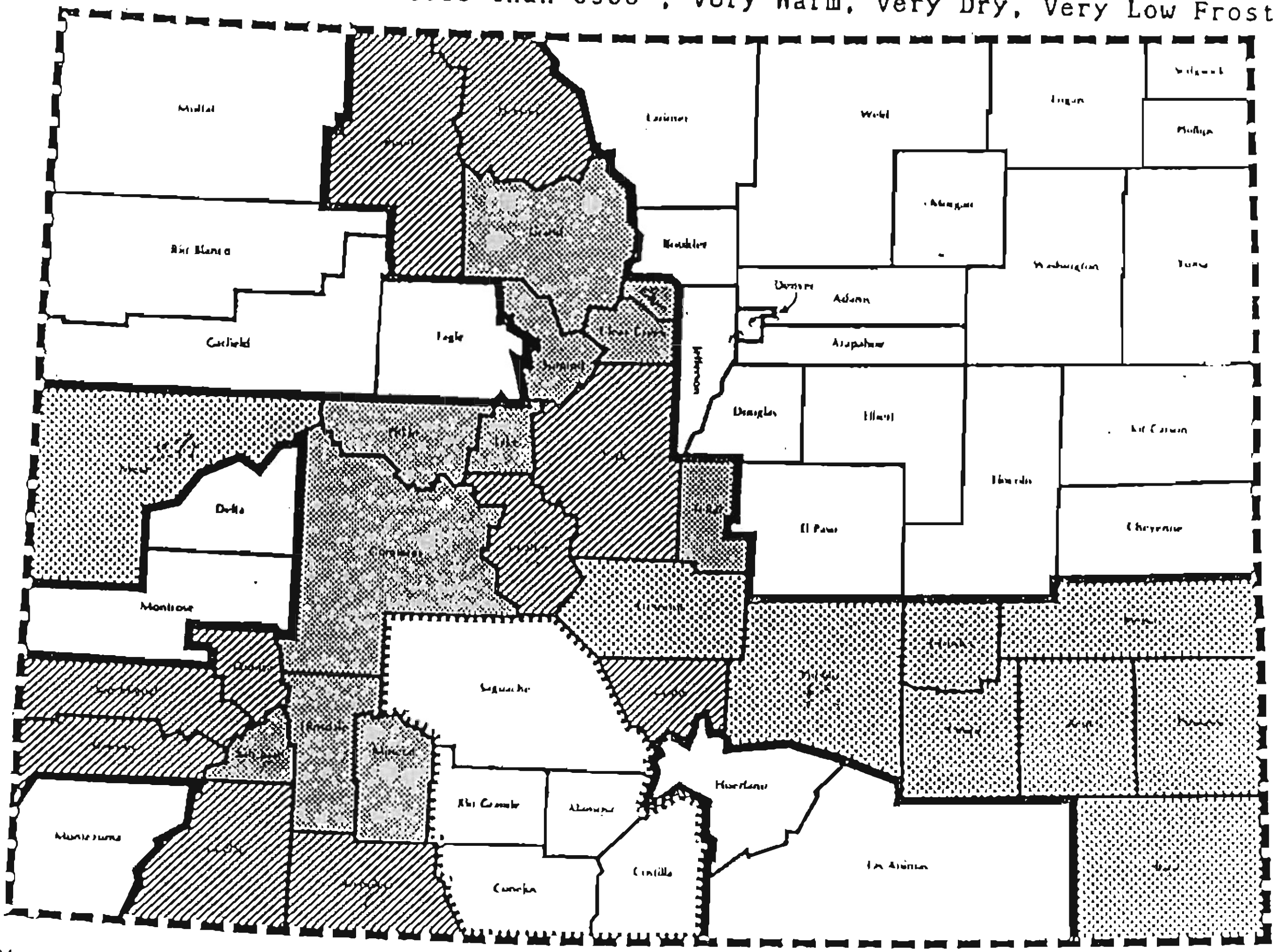
High Temperature Category	Approximate Highest Average 7-Day Air Temperature	High Temp. Performance Grade (PG) °C	Asphalt Cement Grade Meeting the High Temp. PG	Recommended Test Temp. for the Hamburg Device
Very Cool	<27°C	46		35°C
Cool	27 to 31°C	52	AC-5	40°C
Moderate	32 to 36°C	58	AC-10	45°C
Hot	>36°C	64	AC-20	50°C
Very Hot	*	70	AC-20P	55°C

* No pavements in Colorado are at this temperature. A binder with this grade may be appropriate for locations with very heavy and slow moving traffic.

Zone

ENVIRONMENTAL ZONES

1: Elevation over 8500', Cool, Wet, High Frost Penetration
2: Elevation 6500 to 8500', Cool, Wet, High Frost Penetration
3: Elevation 6500 to 8500', Cool, Very Dry, High Frost Penetration
4: Elevation less than 8500', Warm, Dry, Low Frost Penetration
5: Elevation less than 6500', Very Warm, Very Dry, Very Low Frost Penetration



Note: This map does not reflect changes made to a small number of highway segments at the direction of the Engineering District offices.

Fig. 12. Environmental Zones in Colorado.

5.0 INFLUENCE OF AIR VOIDS ON RESULTS

The purpose of this study was to determine the influence of the air void content of the sample on the results from the Hamburg wheel-tracking device.

5.1 Experimental Grid

The experimental grid for this experiment is shown in Table 11. Four different air void contents were targeted: 4%, 6%, 8%, and 10%. These air void contents represent the full range of air void contents in HMA pavements just after construction in Colorado. Four mixtures with different performance histories were used. One testing temperature, 50°C, and one grade of asphalt cement, AC-20, were used for all mixtures in this experiment.

Table 11. Experimental Grid for the Study to Determine the Influence of Air Voids.

	Air Voids			
	4%	6%	8%	10%
Mix 1	X	X	X	X
Mix 2	X	X	X	X
Mix 3	X	X	X	X
Mix 4	X	X	X	X

X - Replicate samples were tested. All samples were mixed with AC-20 and tested at 50°C.

5.2 Results and Discussions

The mixes used for this portion of the study, influence of air voids, were not treated with liquid anti-stripping additives. The liquid anti-stripping additive was inadvertently left out.

Results from each mix are summarized in Tables 12 through 15. Results from each replicate sample are plotted in Appendix B. When testing replicate samples, the results from the two samples were often similar. However in some cases, the results were quite different. It is very important to test replicate samples.

Table 12. Results of Variable Air Voids for Mix 1.

Air Voids (%)	Temperature = 50°C		
	Creep Slope (passes/mm)	Strip Slope (passes/mm)	Strip Inflec. (passes)
4.2	11,100	900	8200
4.7	7500	800	7500
7.8	5400	1200	14700
8.7	9700	1100	7800

Table 13. Results of Variable Air Voids for Mix 2.

Air Voids (%)	Temperature = 50°C		
	Creep Slope (passes/mm)	Strip Slope (passes/mm)	Strip Inflec. (passes)
3.5	2600	900	5000
5.0	3700	700	4900
7.1	4200	1200	5800
8.7	2000	400	5500

Table 14. Results of Variable Air Voids for Mix 3.

Air Voids (%)	Temperature = 50°C		
	Creep Slope (passes/mm)	Strip Slope (passes/mm)	Strip Inflec. (passes)
5.5	1700	500	3200
8.1	1700	500	2100
9.6	700	400	400
10.5	1300	300	2500

Table 15. Results of Variable Air Voids for Mix 4.

Air Voids (%)	Temperature = 50°C		
	Creep Slope (passes/mm)	Strip Slope (passes/mm)	Strip Inflec. (passes)
5.7	4600	1000	5300
7.5	3800	900	5500
9.3	3800	500	8100
10.4	2400	370	7000

The influence of the changing air void properties on the creep slope for the four mixes is shown in Fig. 13. For Mix 2, 3, and 4, the creep slope remains essentially constant as the air voids change. For Mix 1, the creep slope is large at low and high air voids and smaller at intermediate air void contents.

The influence of the changing air void properties on the stripping slope for the four mixes is shown in Fig. 14. The stripping slope may tend to decrease as air voids increase based on the performance of Mixes 3 and 4.

The influence of the changing air void properties on the stripping inflection point for the four mixes is shown in Fig. 15. The stripping inflection point remains constant as air voids change for Mix 2, Mix 3 and Mix 4. The inflection point remains constant for Mix 1 with the exception of the samples between 7 and 8% air voids.

It was hypothesized that higher air voids should produce a lower stripping inflection point on the Hamburg wheel-tracking device. In this particular study, the hypothesis was not proved. However, past testing in the CDOT laboratory using the Hamburg wheel-tracking device has indicated that air voids greater than 10% produce significantly lower stripping inflection points than samples compacted to 6 or 7% air voids.

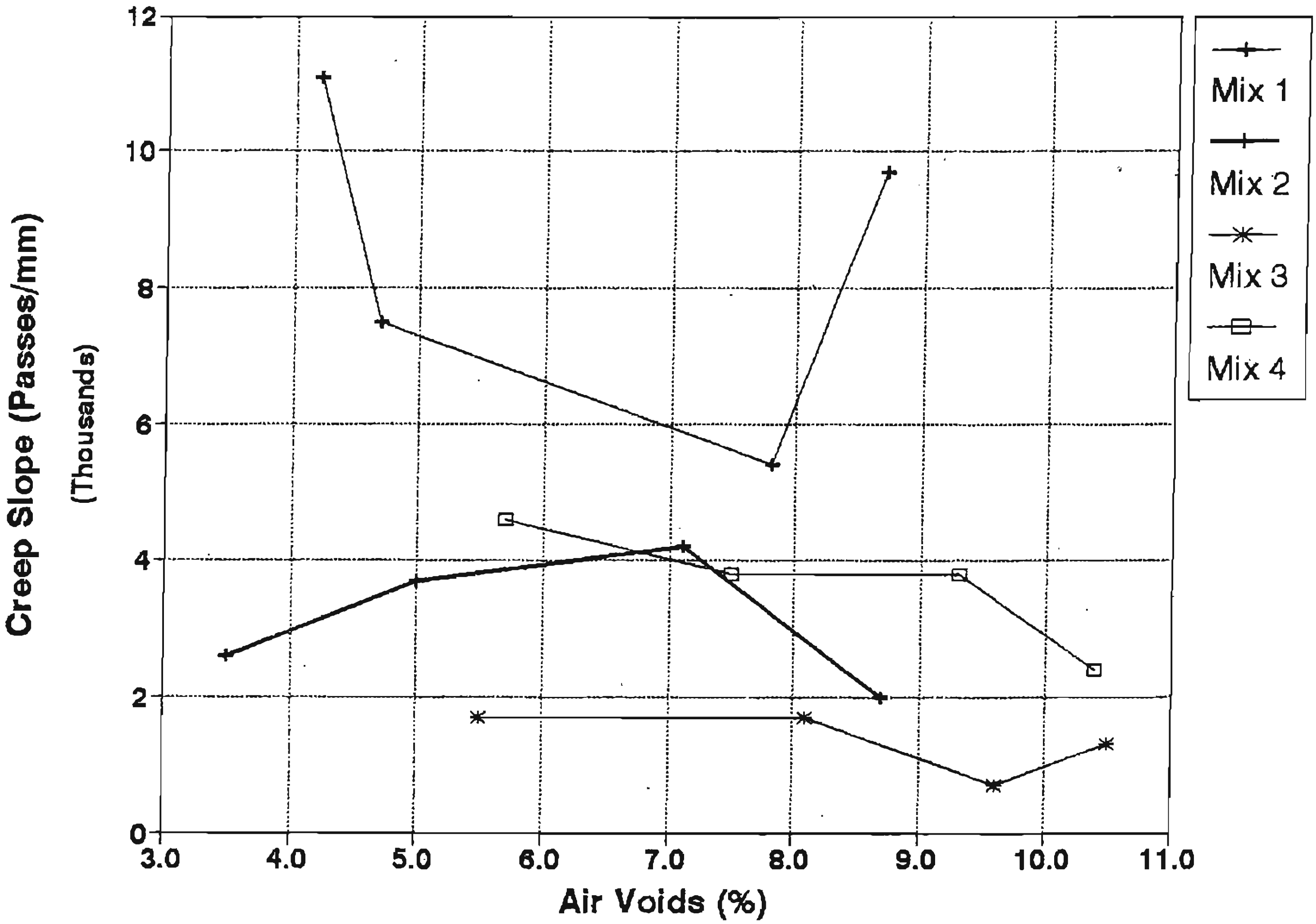


Fig. 13. Influence of Creep Slope with Changing Air Void Contents.

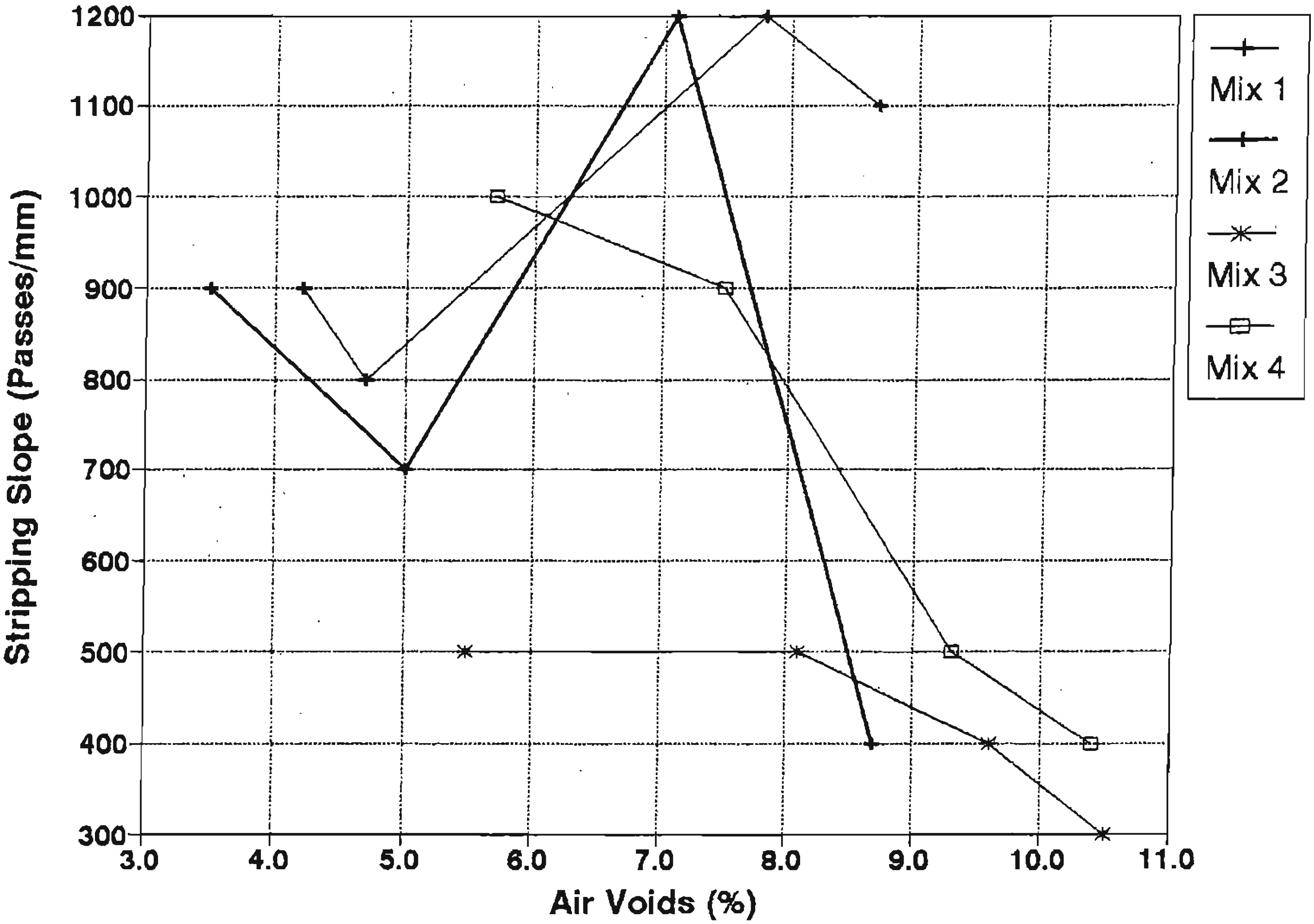


Fig. 14. Influence of Stripping Slope with Changing Air Void Contents.

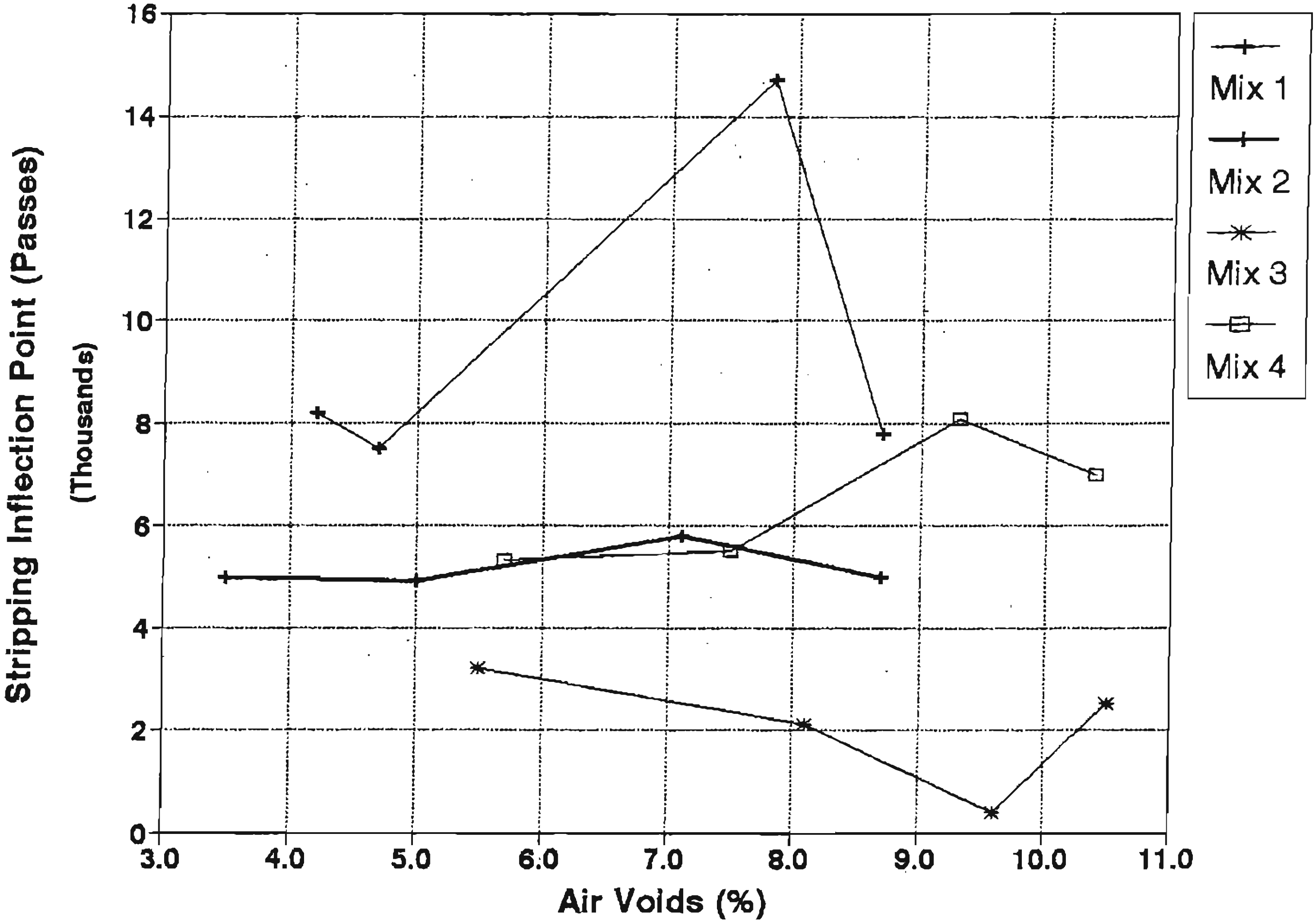


Fig. 15. Influence of Stripping Inflection Point with Changing Air Void Contents.

There could be two potential explanations. First, there were not many samples compacted higher than 9% air voids. The reduction in the stripping inflection point may not occur until the air voids are slightly higher.

Second, the material tested in this portion of the study had no anti-stripping treatment. As a result the stripping inflection points were all very low. The fact that all materials had very low stripping inflection points at normally accepted air void contents could have been the reason the stripping inflection point did not decrease substantially at higher air void contents. Engineering properties (air voids, voids in the mineral aggregate, voids filled with asphalt) are important to good pavement performance. Chemical properties (asphalt cement chemistry, asphalt-aggregate interaction) are also important to good pavement performance. Stripping can likely result from deficient engineering properties, chemical properties, or engineering and chemical properties. A future hypothesis could be: If chemical properties are deficient, the pavement will exhibit moisture damage regardless of engineering properties.

5.3 Recommendations

Based on testing samples at a variety of air void contents, it is recommended to test samples at $6 \pm 1\%$ air voids. In general, the stripping inflection point is not significantly influenced by the air void content in this range. By using a tight control on the air voids, repeatability of the test results should be better than if no control were maintained on air voids. It is very important to test replicate samples.

6.0 INFLUENCE OF SHORT-TERM AGING ON RESULTS

The purpose of this experiment is to determine the influence of short-term aging on the results obtained from the Hamburg wheel-tracking device.

6.1 Experimental Grid

The experimental grid for this experiment is shown in Table 16. Samples were short-term aged at 143°C (290°F) for four different times: 0, 2, 4, and 6 hours. Four mixtures with different performance histories were used. One testing temperature, 45°C, and one grade of asphalt cement, AC-10, were used for all mixtures in this experiment. All mixtures in this study contained hydrated lime.

Table 16. Experimental Grid for the Study to Determine the Influence of Short-Term Aging.

	Short-Term Aging (hours)			
	0	2	4	6
Mix 1	X	X	X	X
Mix 2	X	X	X	X
Mix 3	X	X	X	X
Mix 4	X	X	X	X

X - Replicate samples were tested. All samples were mixed with AC-10 and tested at 45°C.

The loose mix for each sample was placed in an open, rectangular baking pan, of dimensions 27 cm x 30 cm x 6 cm high. The samples weighed between 7.2 and 7.4 kg. Each sample's surface was leveled, and each sample occupied a height of approximately 5 cm within its pan. As a result of the open, low-profile pans, a relatively large surface area of each sample was exposed to the 143°C forced-draft air flow. After each sample had been in the oven precisely the targeted time, it was compacted. For those samples short-term aged zero hours, the mix was placed in the ovens in covered pans for about fifteen minutes, just long enough to return to 143°C before compaction. All samples were compacted in the linear kneading compactor to a targeted air void content of 6 $\pm$ 1%.

6.2 Results and Discussion

The stripping inflection points after the different short-term aging times are shown in Table 17. Plots of the stripping inflection point versus short-term aging time are shown in Fig. 16. Results are plotted in Appendix C. In most cases, the stripping inflection point increased as the period of short-term aging increased. All samples aged for 8 hours had stripping inflection points greater than 20,000 passes. It was not possible to determine the precise stripping inflection point, because the test ended at 20,000 passes.

It was noted that the mixes which had been short-term aged for eight hours had a somewhat burnt odor when they were removed from the ovens, and they were noticeably harder to remove from the pans for compaction. The eight hour exposure to forced-draft hot air physically and chemically changed the binder, giving it the behavior of a stiffer asphalt cement. Although the mix had improved anti-stripping qualities, it may have a greater likelihood of thermal cracking.

An unanticipated outcome of the laboratory short-term aging process was noted during the course of the experiment. It was observed that in every case, as the short-term aging period increased, the air void content decreased. For each doubling of the short-term aging period, air voids dropped by about 0.4%. The cause is not clear. It might be a result of the increased absorption of the binder by the aggregate during prolonged periods in the ovens, but further investigation is needed. The improved stripping inflection point of the short-term aged mixes may be partly attributable to the decrease in the mixes' air void content.

6.3 Recommendations

The duration of laboratory short-term aging was shown to be an important determinant of the behavior of HMA tested in the Hamburg wheel-tracking device. It is recommended to bring the sample to compaction temperature in a covered container for 4 hours. A covered container will minimize the variability in results created by various sizes of containers and various models of ovens that have different forced-air characteristics. For a sample that has just been mixed, a conservative time to heat the sample to compaction temperature is typically 2 hours. Therefore, most samples, including cooled field samples, should reach compaction temperature by 4 hours. Tight control on this procedure will be necessary to obtain repeatable results.

Table 17. Stripping Inflection Point Versus Short-Term Aging Period.

Mix	Stripping Inflection Point (Passes)			
	Short-Term Aging Period (Hours)			
	0	2	4	8
1	3,000	12,600	13,900	>20,000
2	8,900	14,500	10,400	>20,000
3	2,300	4,200	7,200	>20,000
4	5,300	9,700	13,400	>20,000

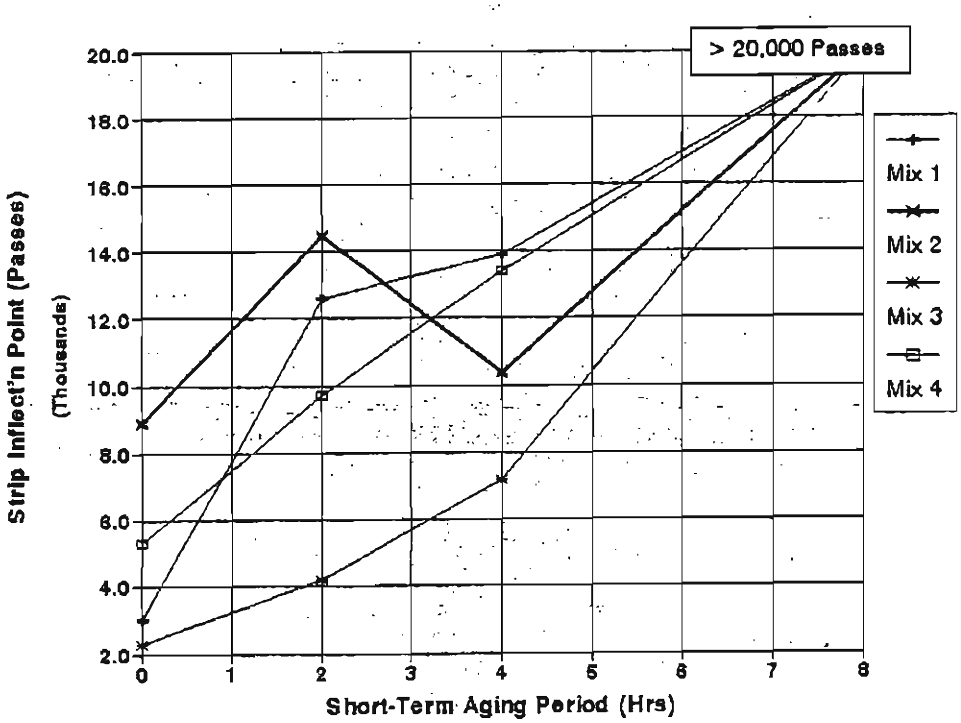


Fig. 16. Influence on Stripping Inflection Point of Various Short-Term Aging Periods.

7.0 INFLUENCE OF LIME MIXING ON RESULTS

The purpose of this study is to determine the influence of the method of lime addition on results obtained from the Hamburg wheel-tracking device.

7.1 Experimental Grid

Hydrated lime is used as an anti-stripping additive for approximately 90% of the HMA placed in Colorado. Specifications require the contractor to use an approved pugmill to mix the aggregate and lime. The moisture required during mixing is 3% above the saturated surface dry moisture content of the aggregate. Despite the specification, there is a wide variety of mixing methods and moisture contents used throughout the state. This experiment was designed to determine if the specification should be enforced more strictly than it presently is. The experimental grid is shown in Table 18.

Table 18. Experimental Grid for the Study to Determine the Influence of Lime Mixing.

	Method of Lime Addition				
	No Lime No Moisture No "Mellow"	1% Lime No Moisture No "Mellow"	1% Lime 2% Moisture No "Mellow"	1% Lime 4% Moisture No "Mellow"	1% Lime 4% Moisture 3-Day "Mellow"
Mix 1	X	X	X	X	X
Mix 2	X	X	X	X	X
Mix 3	X	X	X	X	X
Mix 4	X	X	X	X	X

X - Replicate samples were tested. All samples were mixed with AC-10 and tested at 45°C.

One set of samples from each mix contained no added lime. All the other samples had 1% hydrated lime. Hydrated lime was added using three different levels of moisture: no water, 2% water, and 4% water. The presence of water dissolved the hydrated lime and produced uniformly coated aggregates. After water was added, the aggregates were immediately dried and mixed with asphalt cement. For the final set of samples the dry aggregate, lime and 4% water were mixed and then placed in a sealed plastic bucket for 72 hours. At the end of this "mellowing" period, the aggregate was dried, then mixed with asphalt cement. Samples were short-term aged for 4 hours.

7.2 Results and Discussions

The stripping inflection points for the different tests are shown in Table 19. Results are plotted in Appendix D. In all cases, the stripping inflection point increased after lime was added. Even the addition of dry lime alone improved the mix performance. In some instances a stripping inflection point developed when lime was present, but the stripping slope was not very steep. In these cases the deformation at 20,000 passes was less than 10 mm. That could be considered an acceptable test result (2). When no lime was added, the stripping inflection points were very low and the stripping slopes were very steep, indicating an unacceptable material.

Table 19. Stripping Inflection Point Versus Method of Lime Addition.

	Method of Lime Addition				
	No Lime No Moisture No "Mellow"	1% Lime No Moisture No "Mellow"	1% Lime 2% Moisture No "Mellow"	1% Lime 4% Moisture No "Mellow"	1% Lime 4% Moisture 3-Day "Mellow"
Mix 1	5,100	>20,000*	12,200*	13,600*	12,900*
Mix 2	7,900	10,800	10,800	12,500*	>20,000*
Mix 3	2,600	17,700*	6,100	>20,000*	>20,000*
Mix 4	7,400	10,000*	18,300*	>20,000*	11,900*

* Passing test using the 10 mm specification

It is not clear how the method of lime addition influences the HMAs ability to resist moisture damage. However, the presence of hydrated lime helped the moisture resistance of all the mixes tested. Adding 2% to 4% water to the limed aggregate improved the performance of the mix compared to the addition of lime and no water, but the improvement was only slight and probably not significant. It was difficult to quantify the improvement of the mixes by the addition of various amounts of water. What is significant is that the addition of lime improves the anti-stripping performance of all the mixes tested, and that lime mixed with an aggregate moistened to 4% seemed to work well.

The use of the 3-day mellowing period did not substantially improve the performance. Two of the mixes (Mixes 2 and 4) contained aggregates that were non-plastic but did have clay present. Although the mellowing improved the performance of Mix 2 to meet the City of Hamburg specification, the same improvement was not observed in Mix 4.

7.3 Recommendations

Adding 1% lime to aggregate improved the anti-stripping performance of HMA. For uniformity of laboratory procedures, 4% water should be added to the aggregate. Once the aggregate, lime, and moisture are mixed, the laboratory sample should not be "mellowed". If the standard practice of a contractor is to stockpile aggregate treated with lime to "mellow", then the laboratory procedure should include "mellowing"

8.0 CONCLUSIONS

The variables investigated in this study were 1) testing temperature and asphalt cement stiffness, 2) air voids of compacted samples, 3) short-term aging, and 4) lime mixing. These variables can influence the test results so the laboratory procedure should be written to include tight control on these variables to ensure repeatability. Additionally, these variables are also considered important to the moisture resistance of a pavement in the field. Although it is not clear how the method of lime addition influences the HMAs ability to resist moisture damage, it is known that the presence of lime helps the resistance of an HMA to moisture damage. Any test that hopes to predict the moisture susceptibility of an HMA pavement should be sensitive to these variables.

1) The test temperature and high-temperature stiffness of the asphalt cement have significant effects on the results from the Hamburg wheel-tracking device. It is important to select the asphalt cement for an HMA based upon the environmental conditions the pavement will experience. As the environmental conditions change from one part of the state to the next, it is important to select the appropriate asphalt cement stiffness. As these environmental conditions change, it is equally important to adjust the test temperature of the Hamburg wheel-tracking device.

SHRP has recommended the high-temperature grading of asphalt cements be based on an equal stiffness measured by the DSR. The differences in high temperatures to obtain the same stiffness measured by the DSR of the asphalt cements used in this study were about 6°C. The Hamburg wheel-tracking device provides equal stripping inflection points for each grade of asphalt cement when the test temperature is adjusted about 6°C for each grade. The similarity of the temperature differentials of each grade of asphalt cement measured by the DSR and Hamburg wheel-tracking device were amazingly similar. The testing temperatures for the Hamburg wheel-tracking device should be selected based upon the high-temperature environment. The reccmmended test temperatures are shown in Table 10.

2) Based on testing samples at a variety of air void contents, it is recommended to test samples at 6 $\pm$ 1% air voids. In general, the stripping inflection point is not significantly influenced by the air void content in this range. By using a tight control on the air voids, repeatability of the test results should be better than if no control were maintained on air voids.

3) The duration of laboratory short-term aging was shown to be an important determinant of the behavior of HMA tested in the Hamburg wheel-tracking device. It is recommended to short-term age laboratory mixed and field produced samples for 4 hours in a closed container prior to compaction. Tight control on this variable will be necessary to obtain repeatable results.

4) Adding 1% lime to aggregate improved the anti-stripping performance of HMA. For uniformity of laboratory procedures and to facilitate mixing, a standard process should be followed. Dry aggregate and dry lime should be mixed together; 4% water should then be added, and the sample should be mixed again.

9.0 REFERENCES

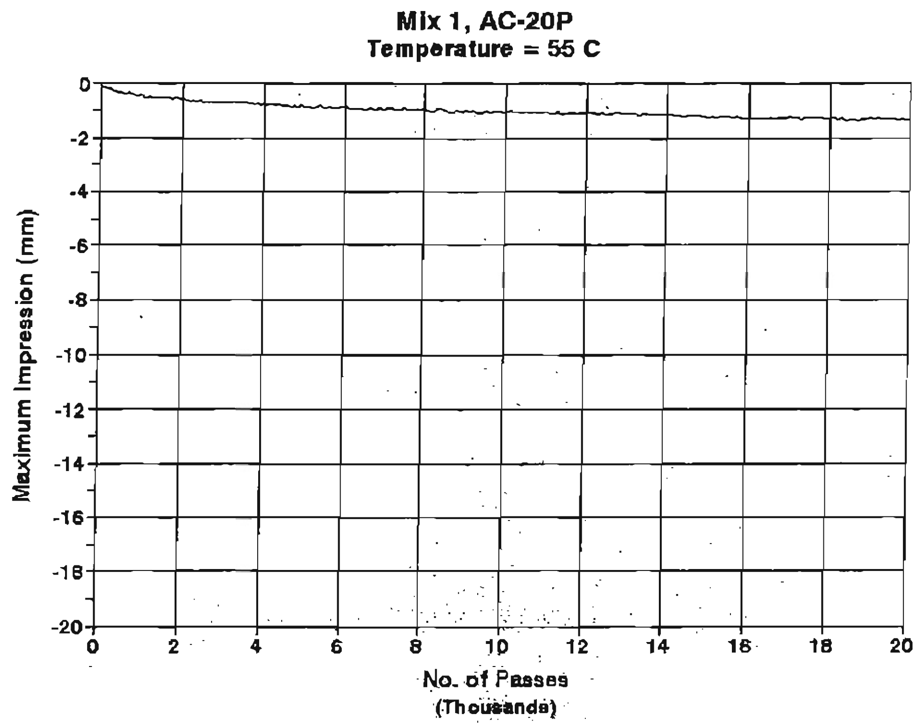
1. Report on the 1990 European Asphalt Study Tour (June 1991), American Association of State Highway and Transportation Officials, Washington, D.C., 115+ pages.

2. Aschenbrener, Tim, R.L. Terrel, and R.A. Zamora (1994), "Comparison of the Hamburg Wheel-Tracking Device and the Environmental Conditioning System to Pavements of Known Stripping Performance," Colorado Department of Transportation, CDOT-DTD-R-94-1.

3. Hines, Mickey (1991), "The Hamburg Wheel-Tracking Device," Proceedings of the Twenty-Eighth Paving and Transportation Conference, Civil Engineering Department, The University of New Mexico, Albuquerque, New Mexico.

Appendix A

Hamburg Wheel-Tracking Results from the Test Temperature Study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-8
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-12
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2
4
6
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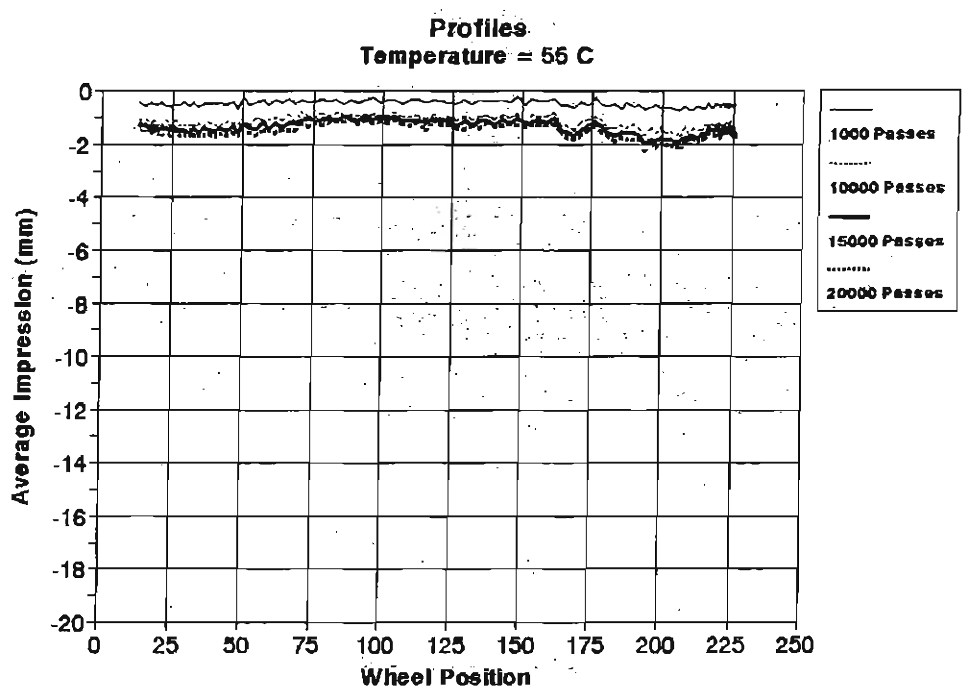
10
12
14
16
18
20
No. of Passes
(Thousands)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-4
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-14
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-18
-20
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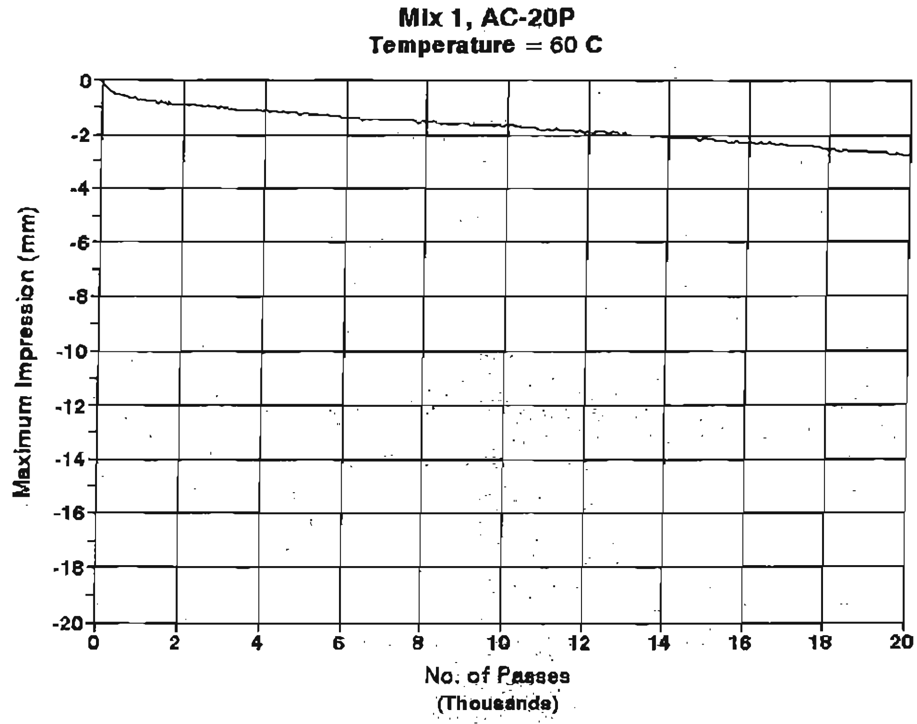
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes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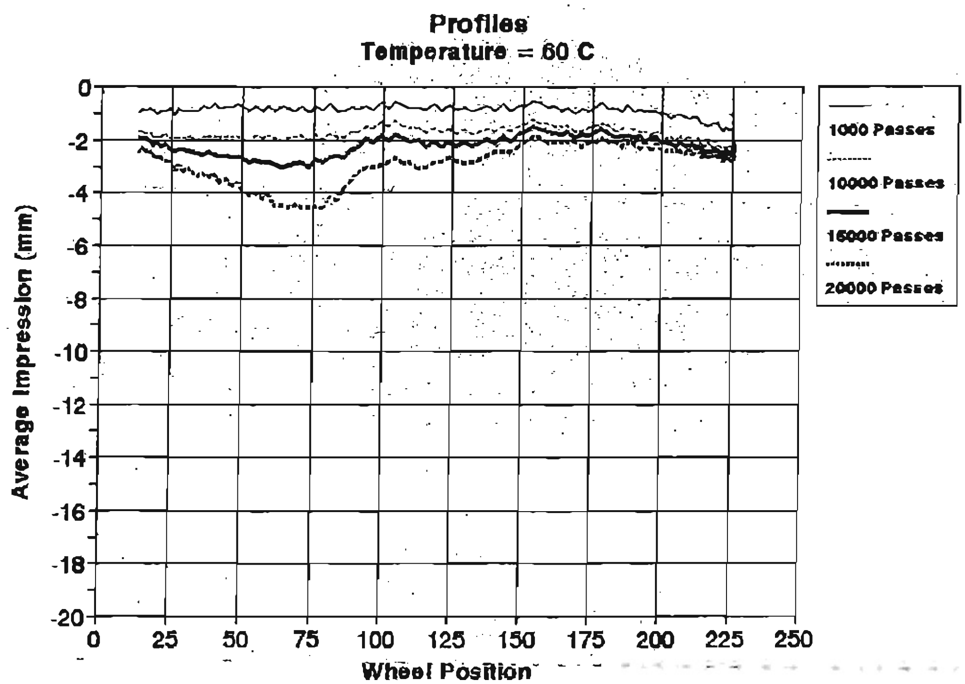
12
14
16
18
20
No. of Passes
(Thousands)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-20
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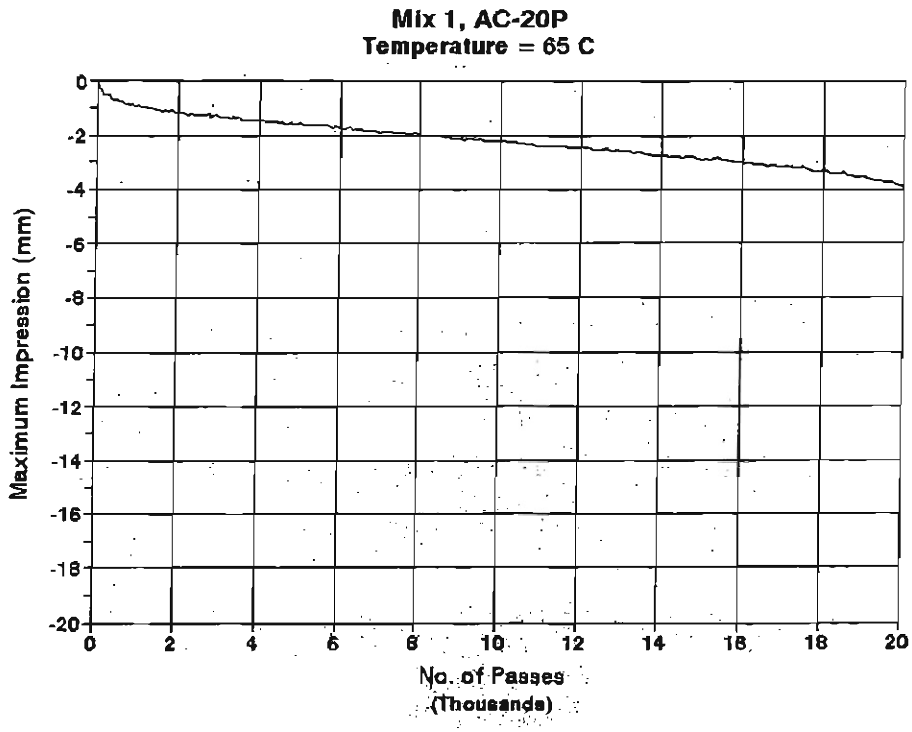
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes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No. of Passes
(Thousands)
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-6
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-18
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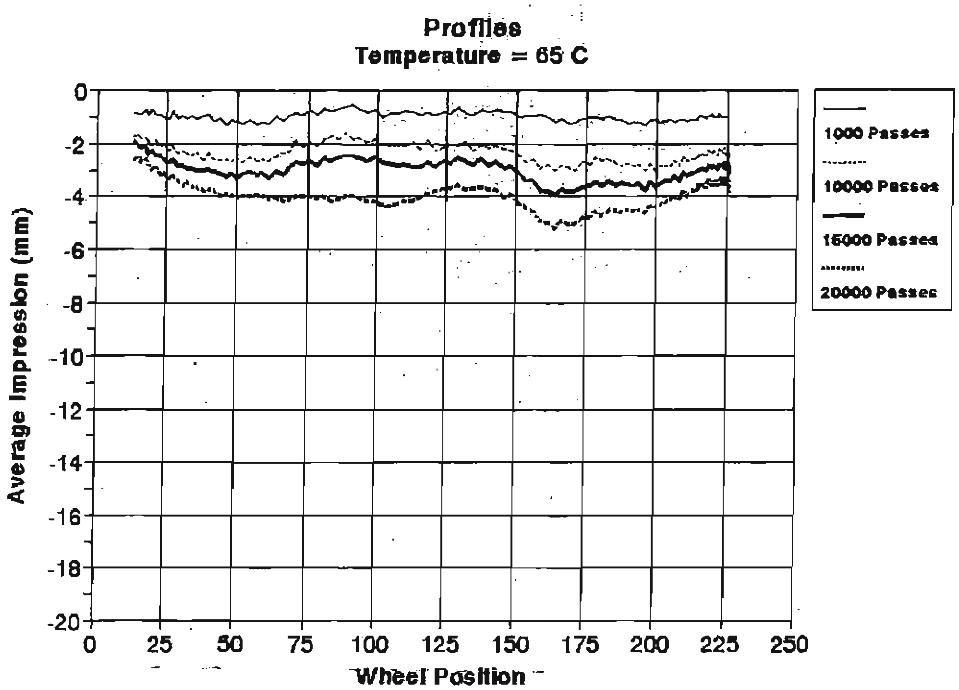
2
4
6
8
10
12
14
16
18
20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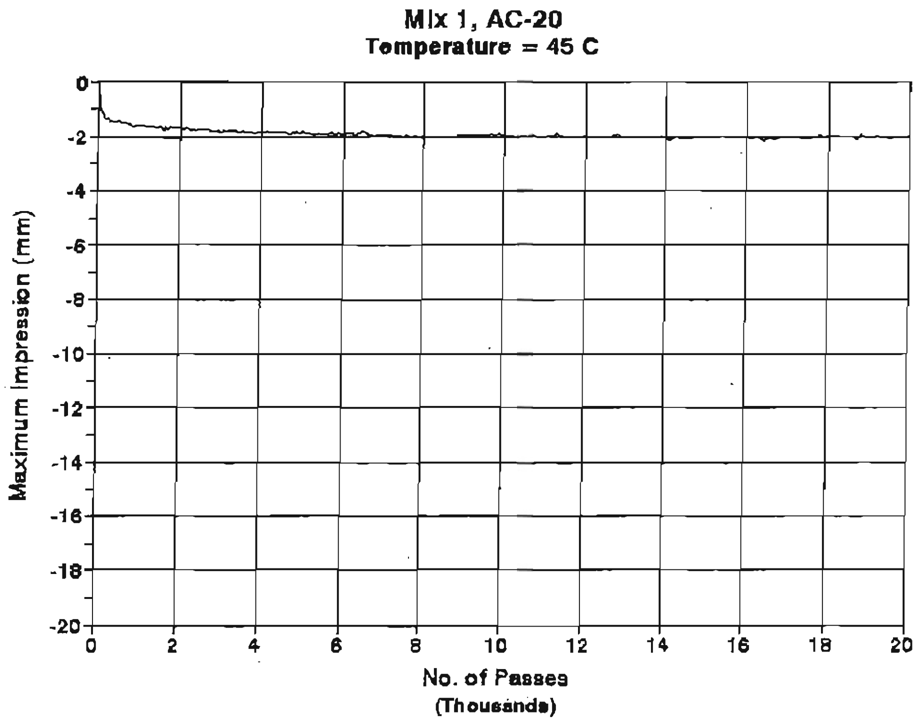

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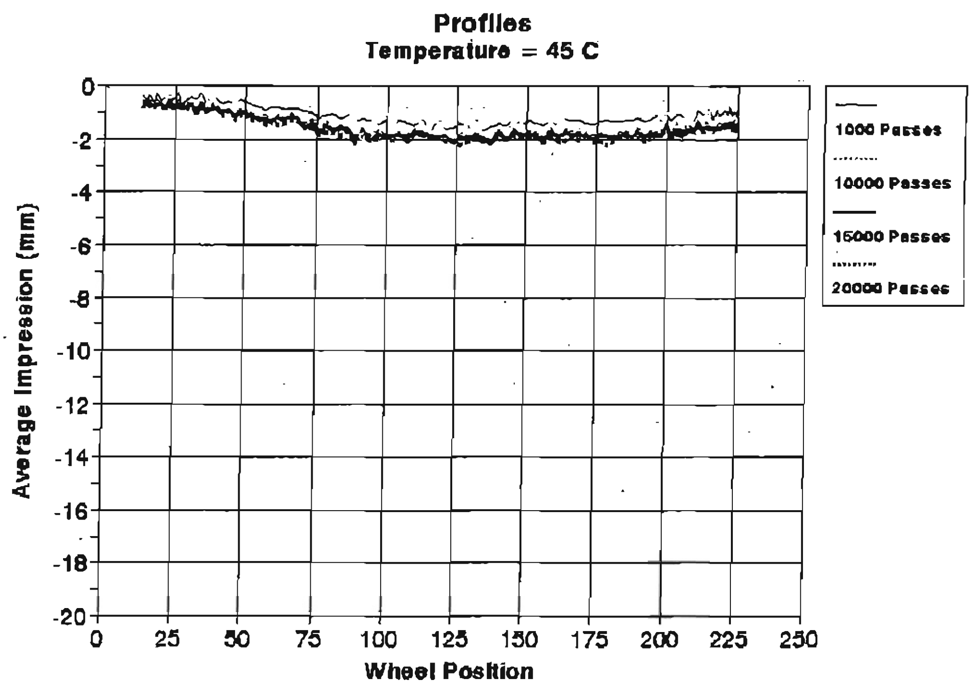
No. of Passes
(Thousands)



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Wheel Position
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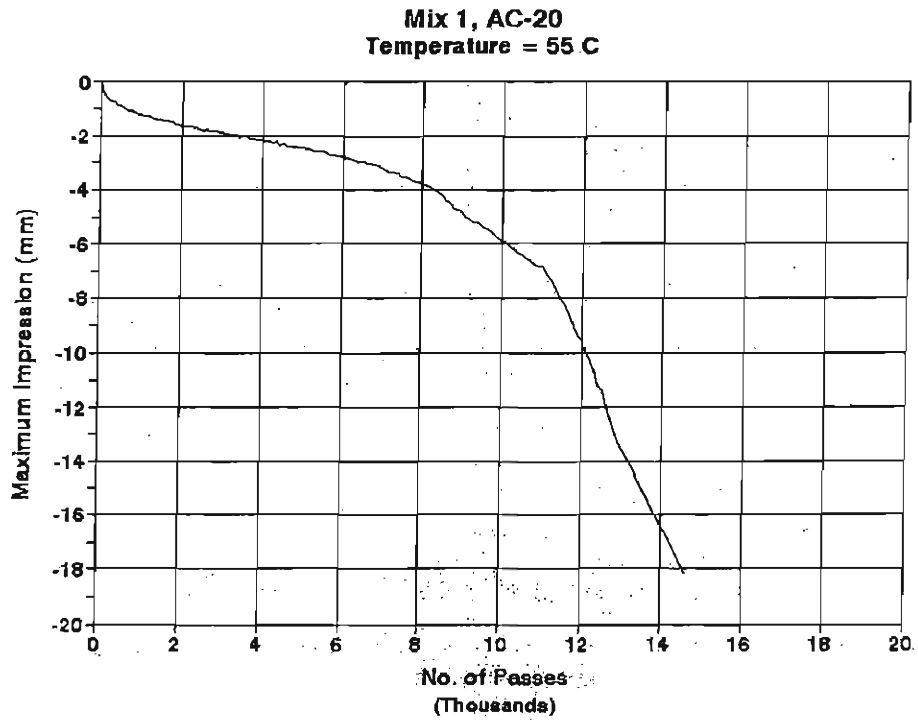
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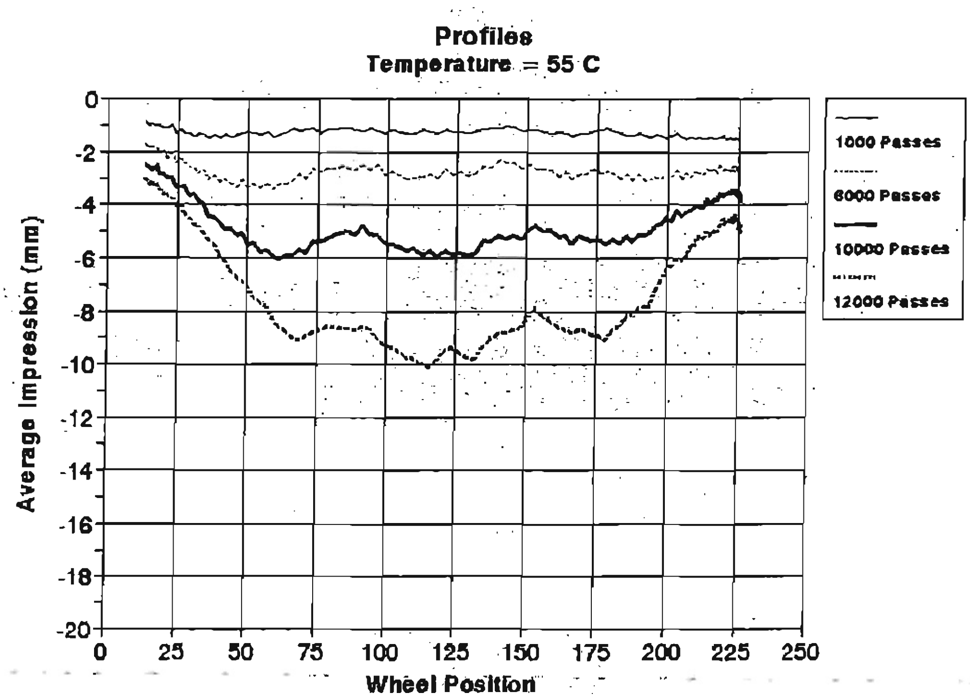
No. of Passes
(Thousands)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Wheel Position
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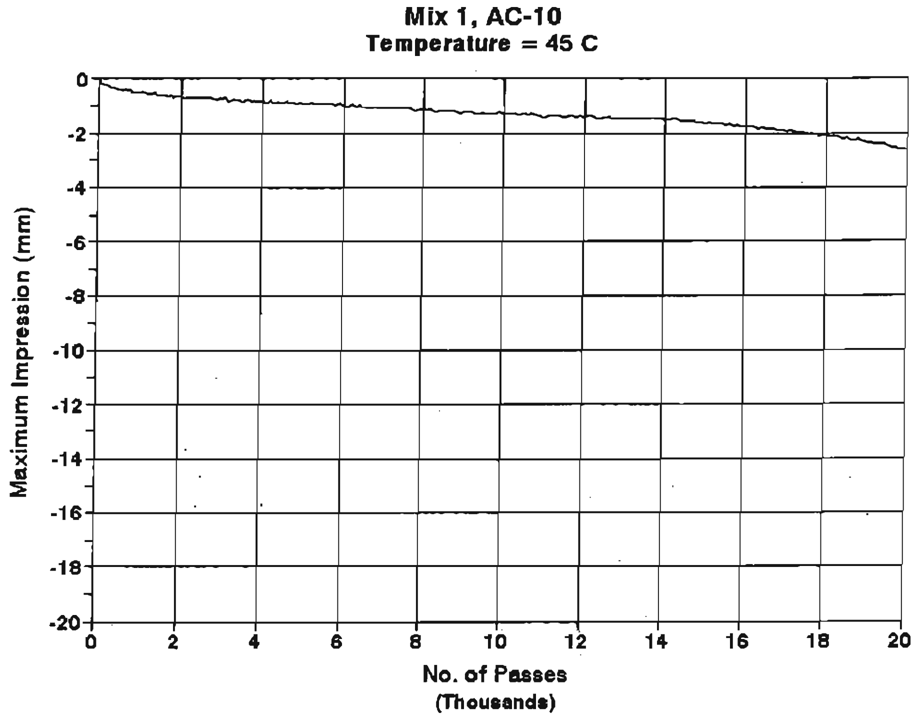
12000 Passes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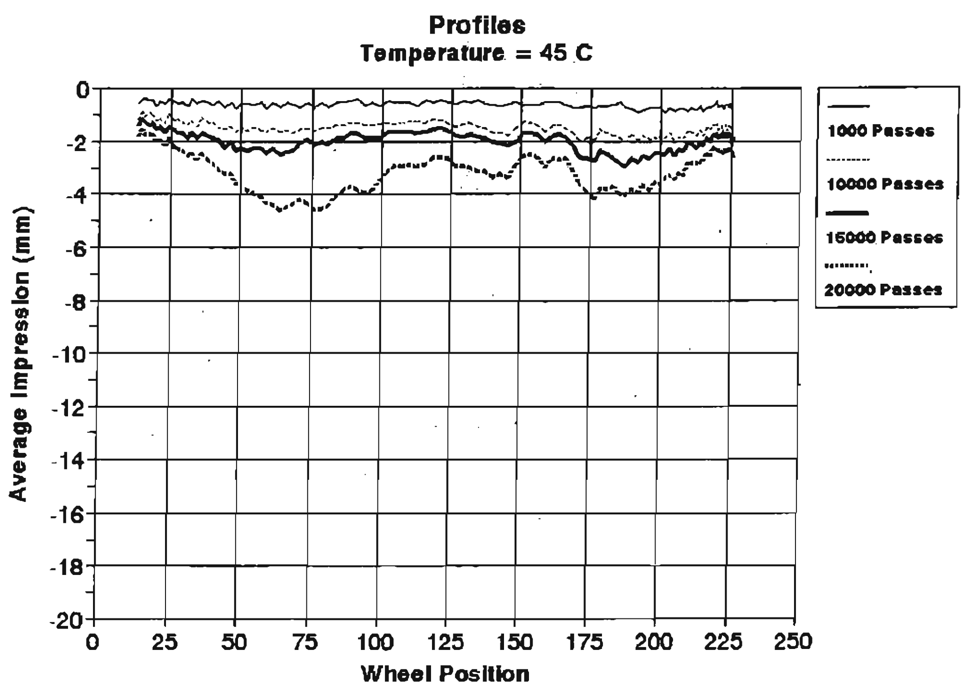
No. of Passes
(Thousands)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Wheel Position
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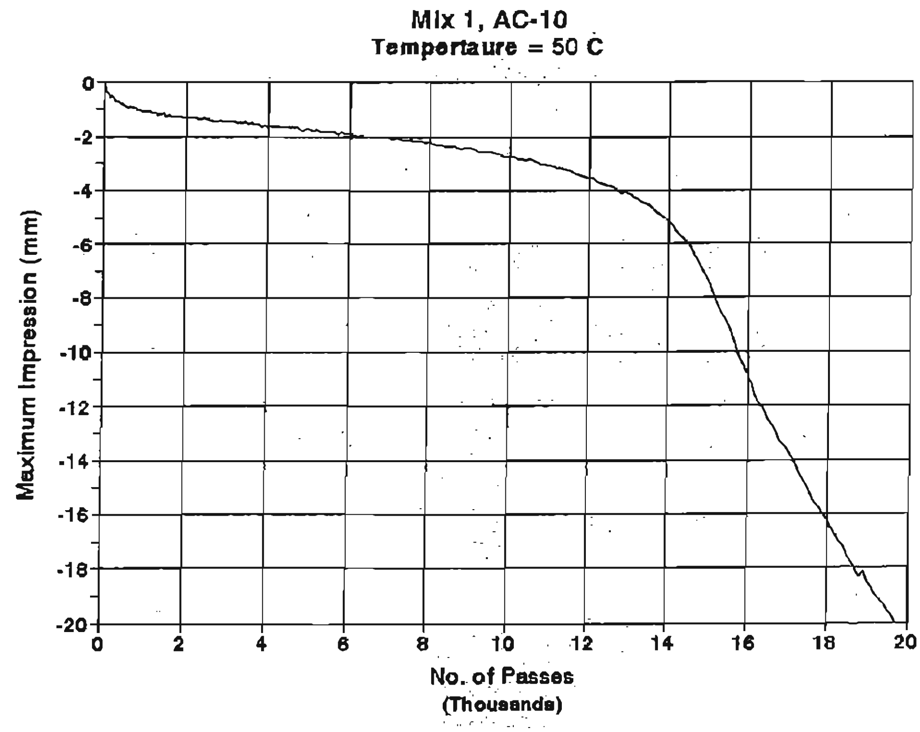
15000 Passes
20000 Passes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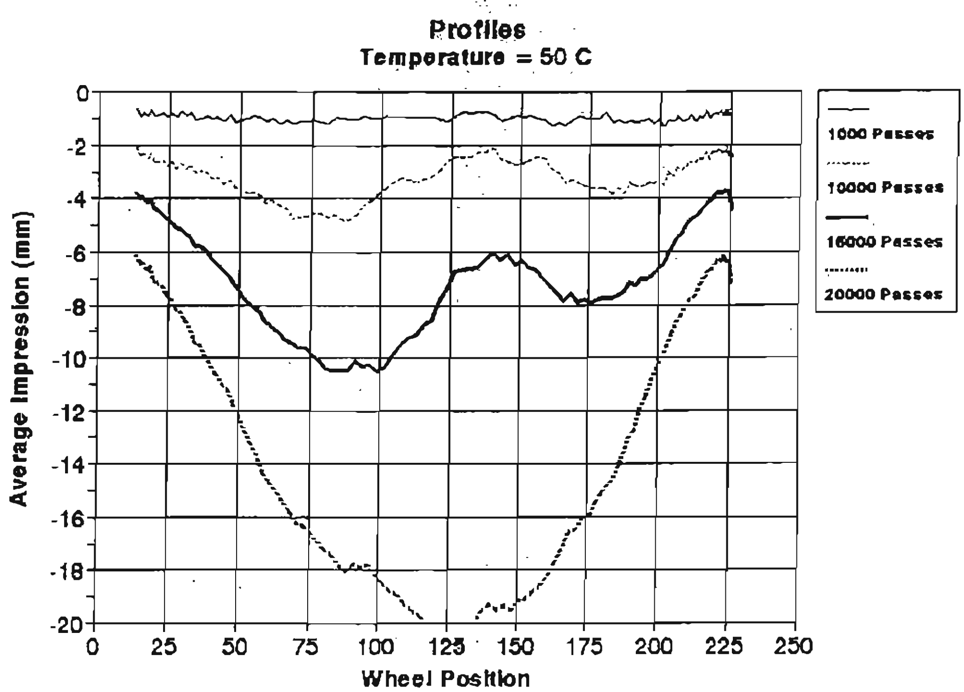
No. of Passes
(Thousands)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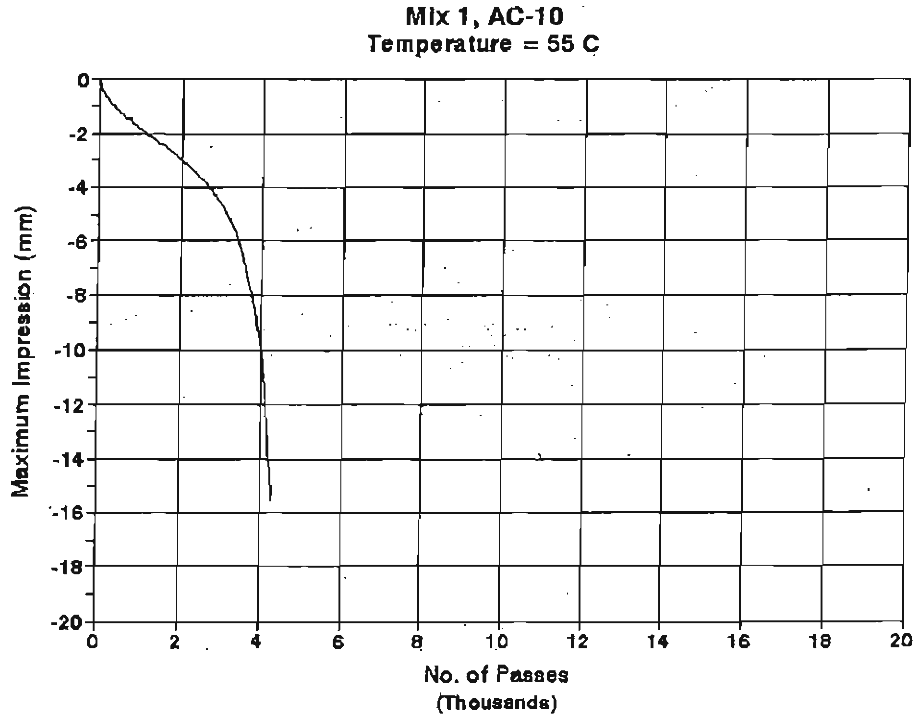
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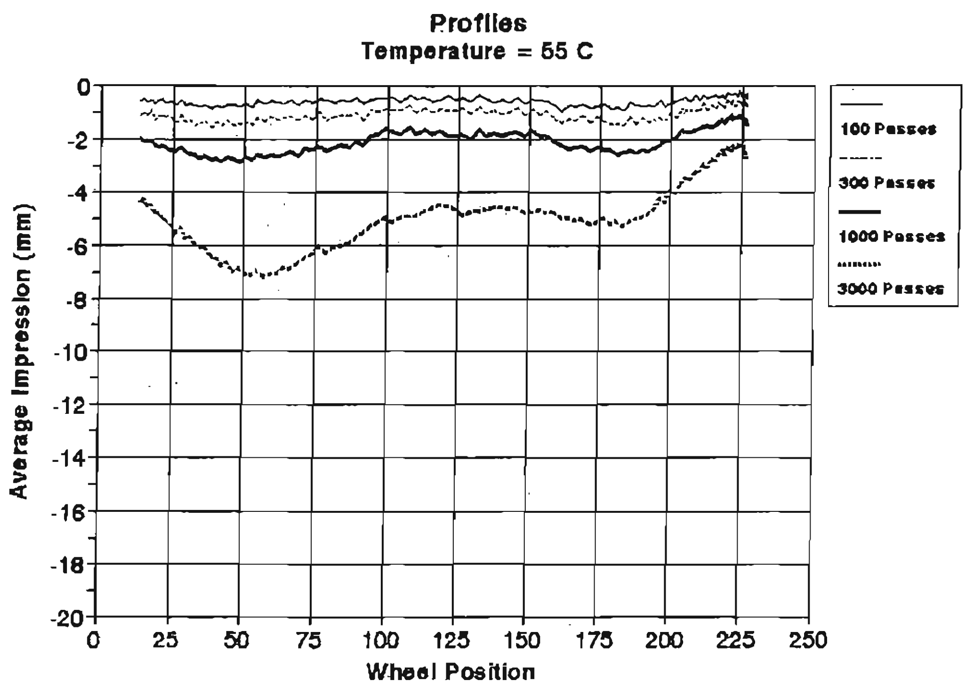
No. of Passes
(Thousands)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200
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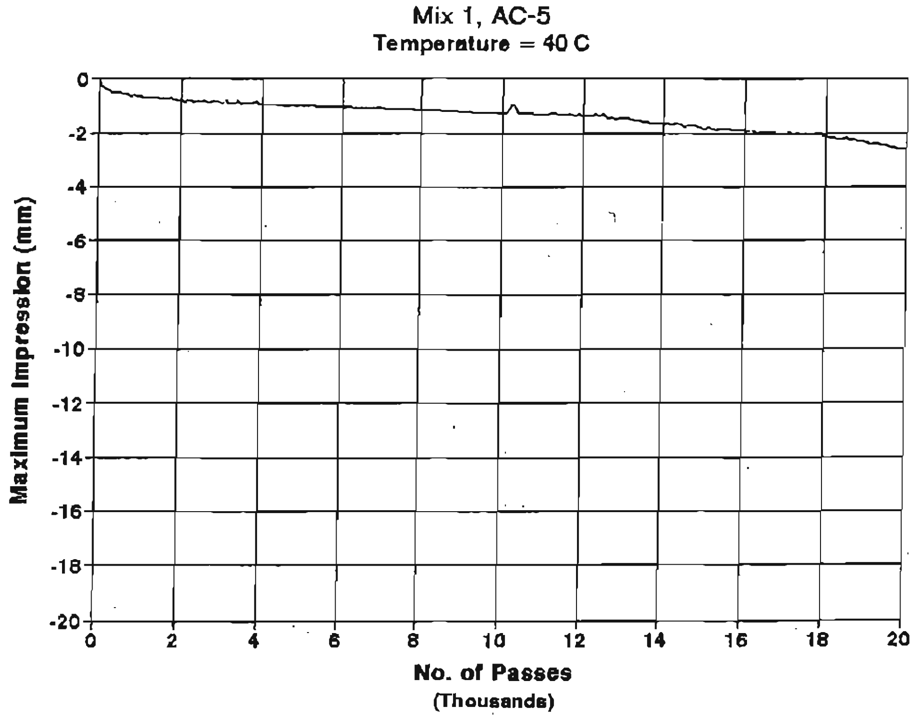
Wheel Position
100 Passes
300 Passes
1000 Passes
3000 Passes



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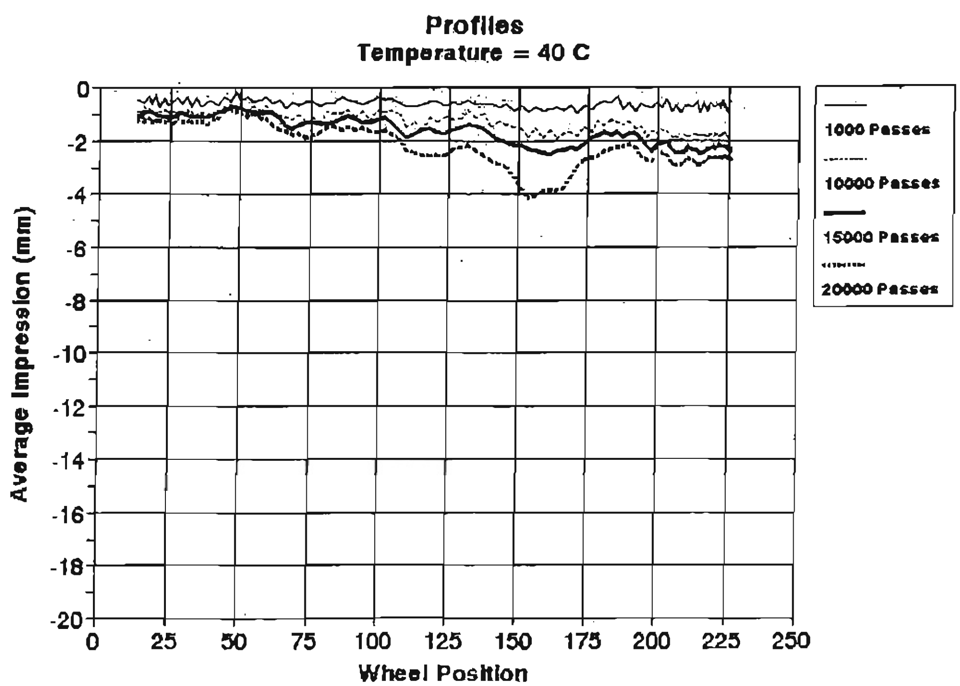
No. of Passes
(Thousands)



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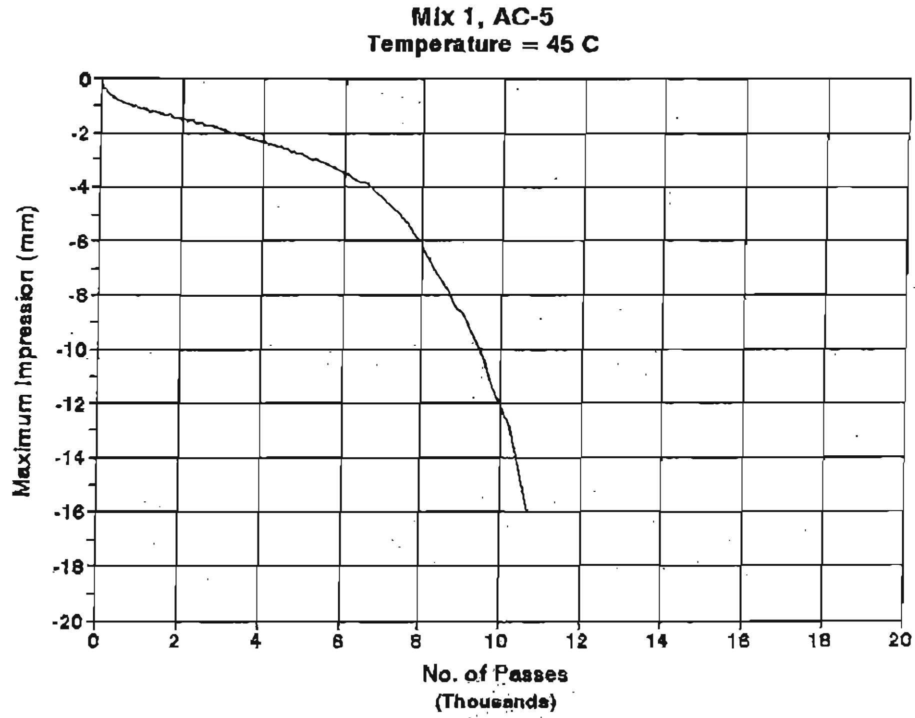
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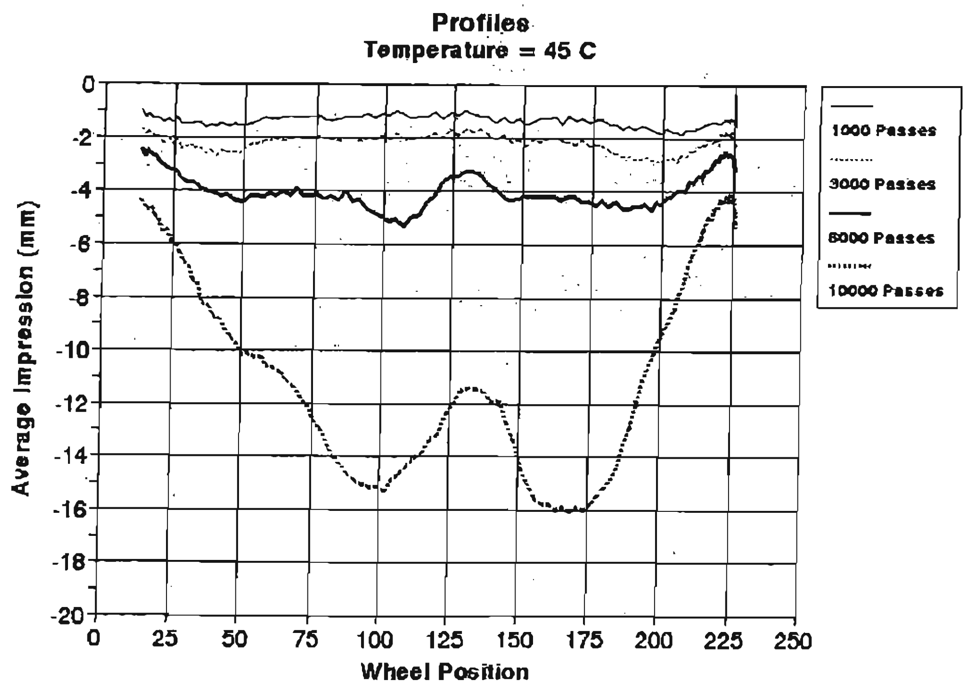
20
No. of Passes
(Thousands)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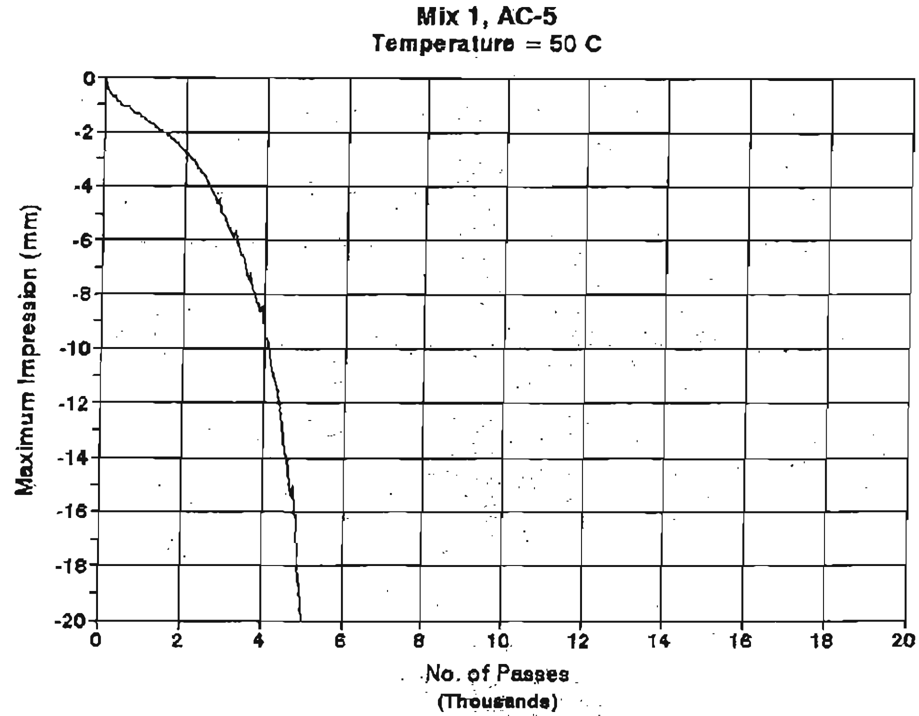
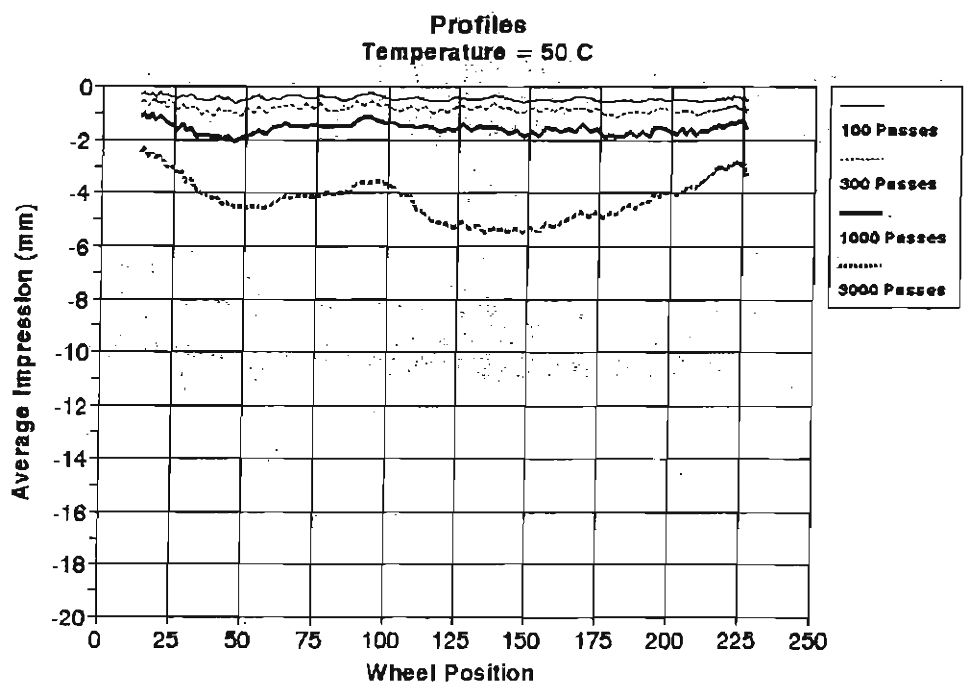
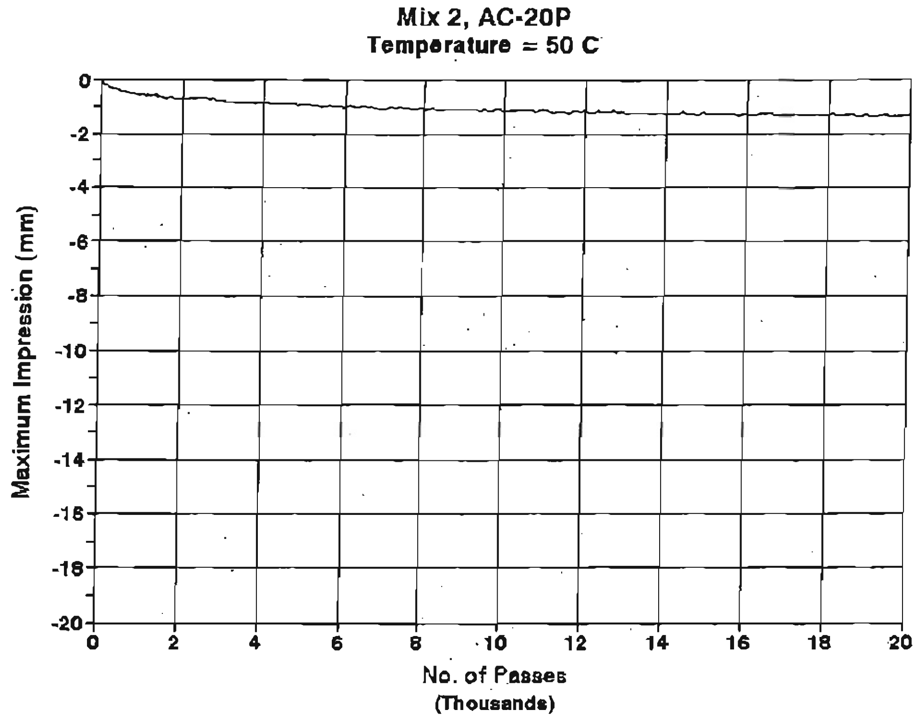
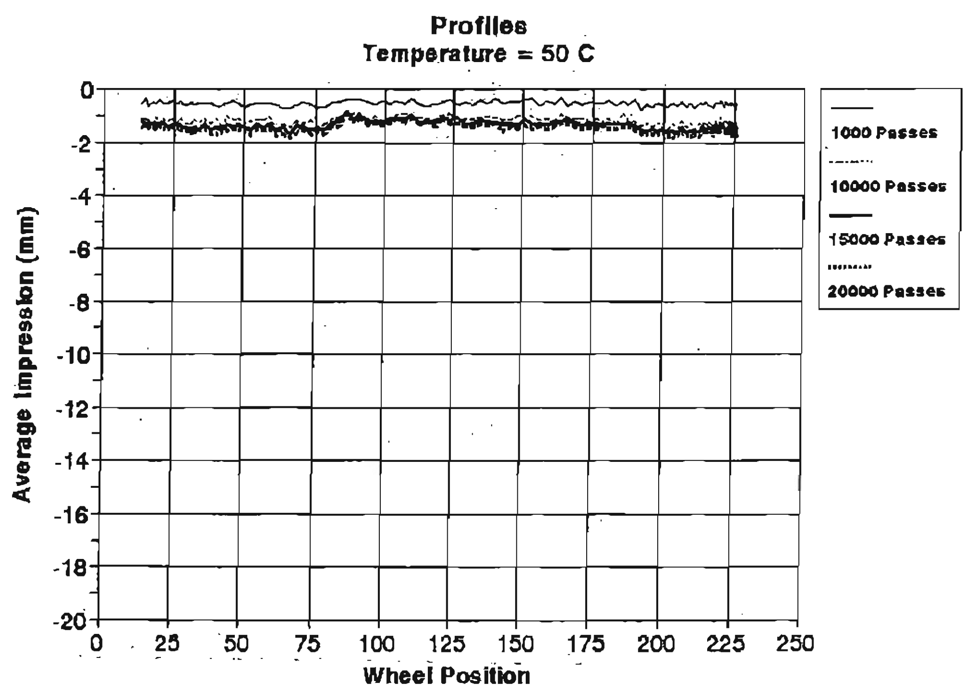
150
175
200
225
250
Wheel Position
1000 Passes
3000 Passes
6000 Passes
10000 Passes


Mix 1, AC-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)

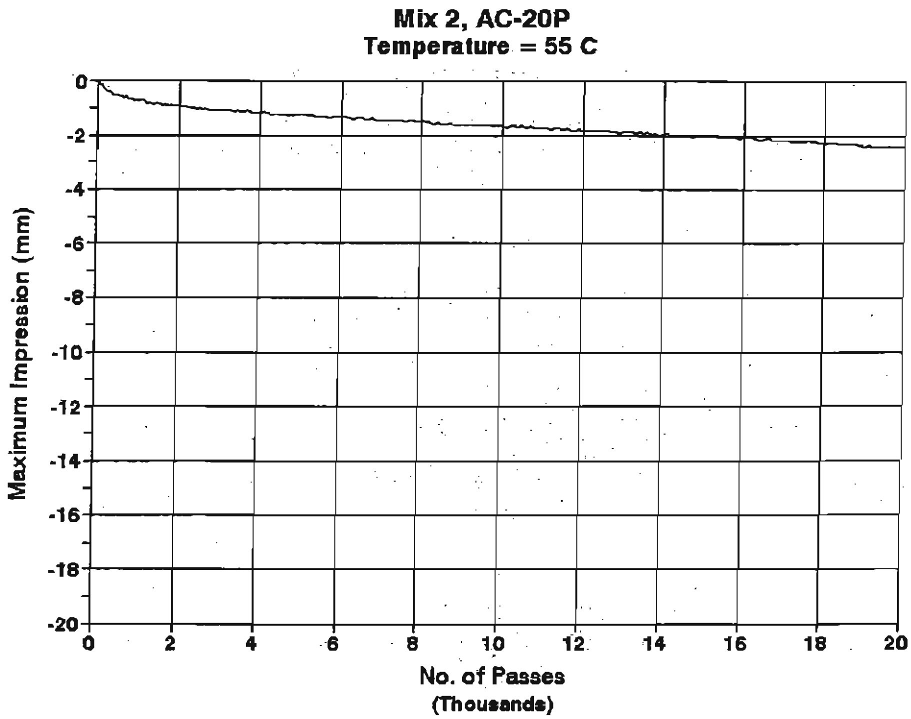

Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
100 Passes
300 Passes
1000 Passes
3000 Passes

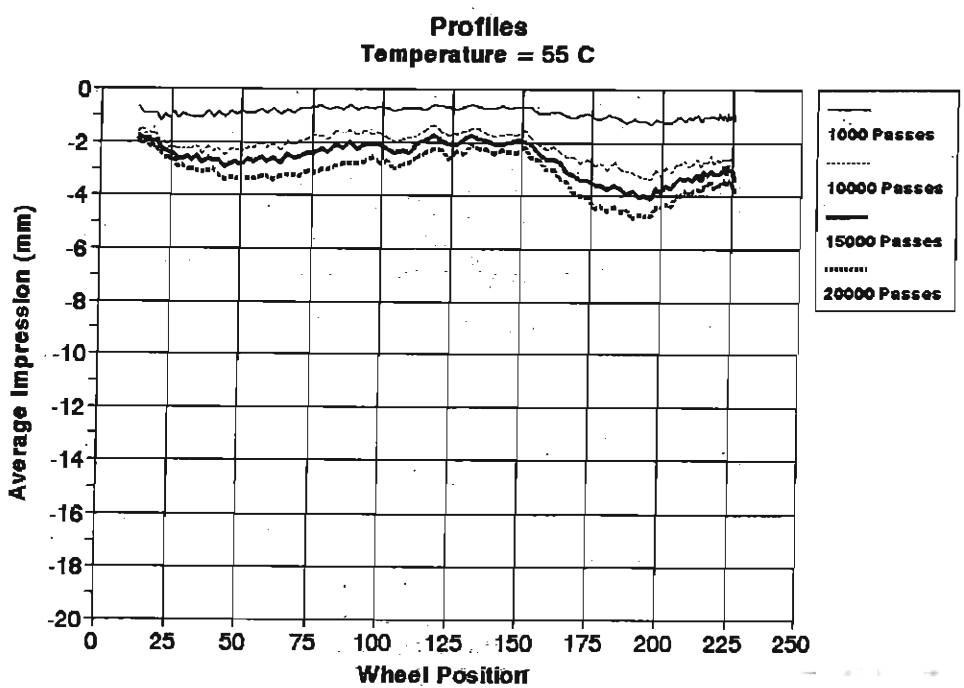


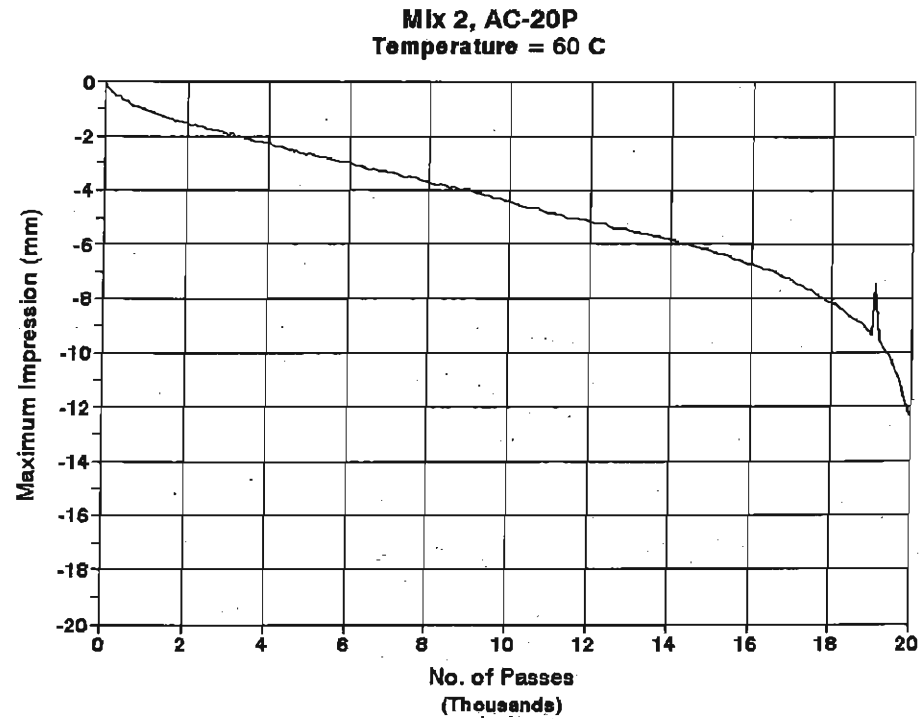
Mix 2, AC-20P
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



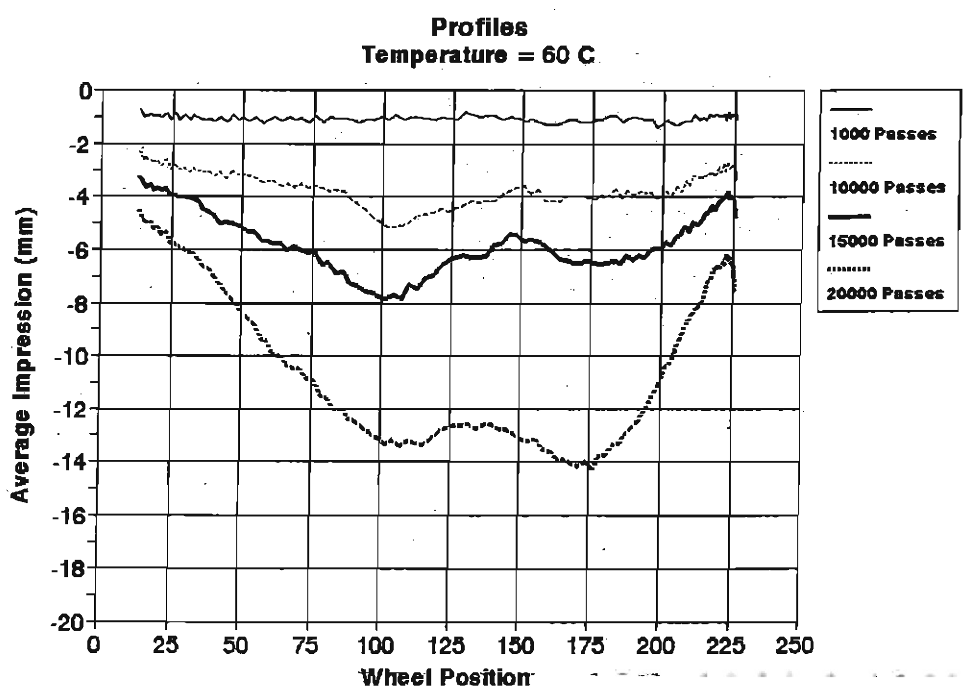
Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes


Mix 2, AC-20P
Temperature = 55 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)

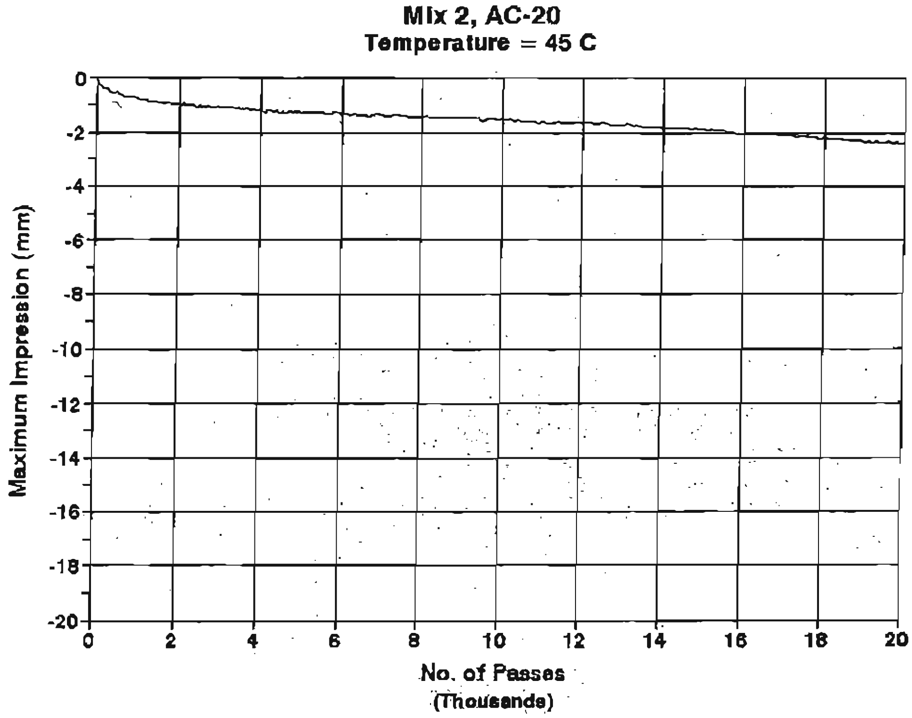

Profiles
Temperature = 55 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes

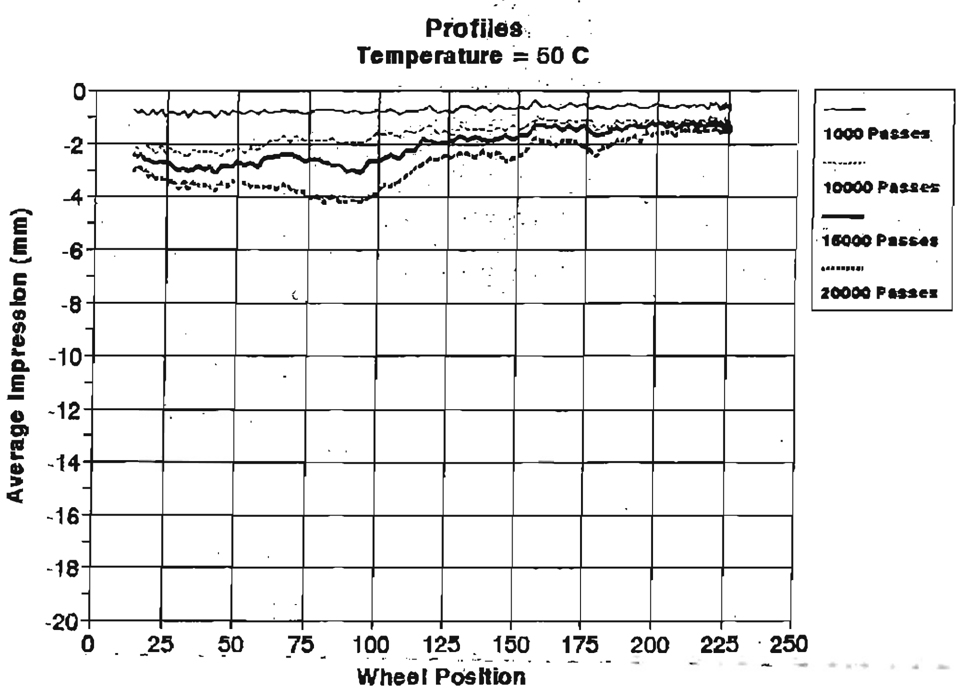


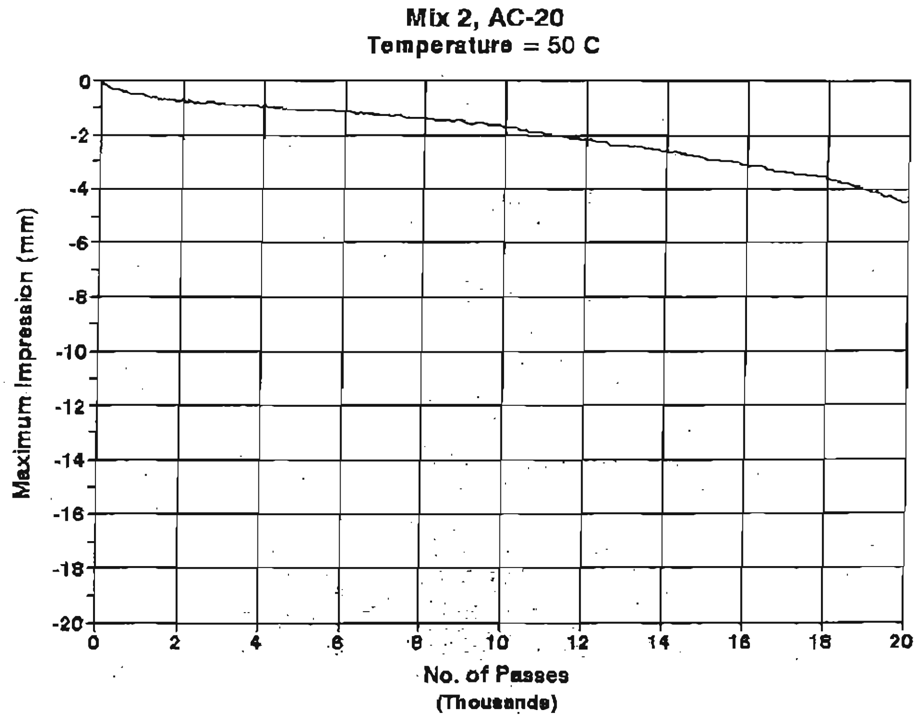
Mix 2, AC-20P
Temperature = 60 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

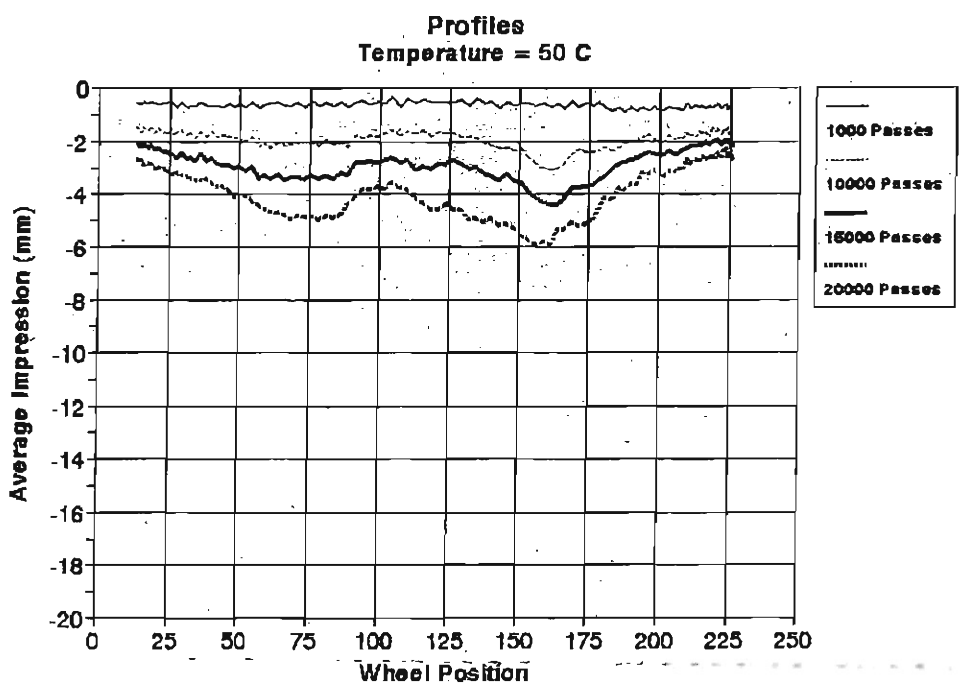


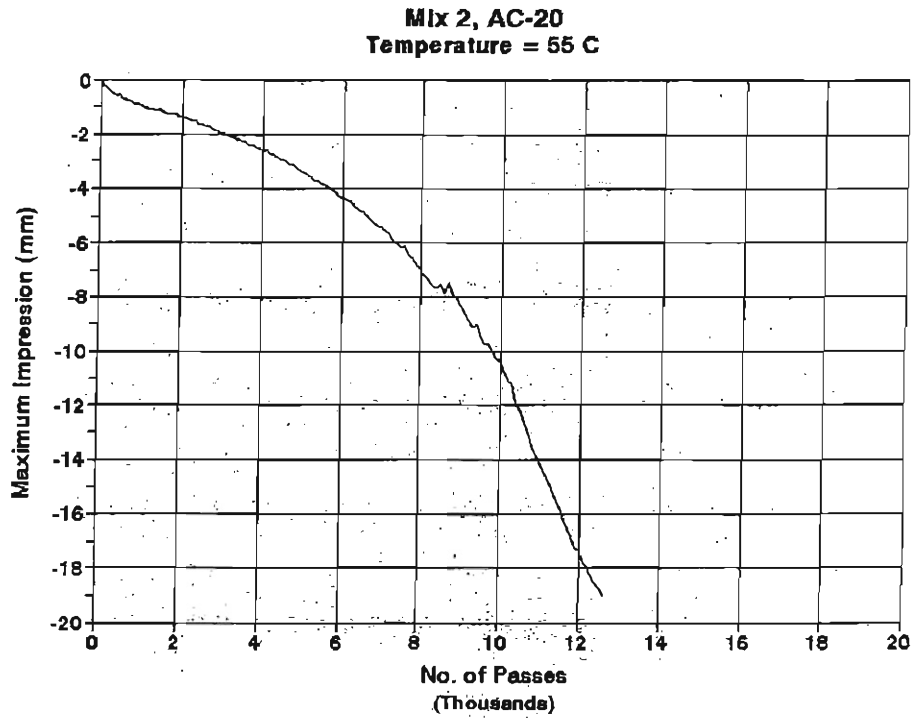
Profiles
Temperature = 60 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes

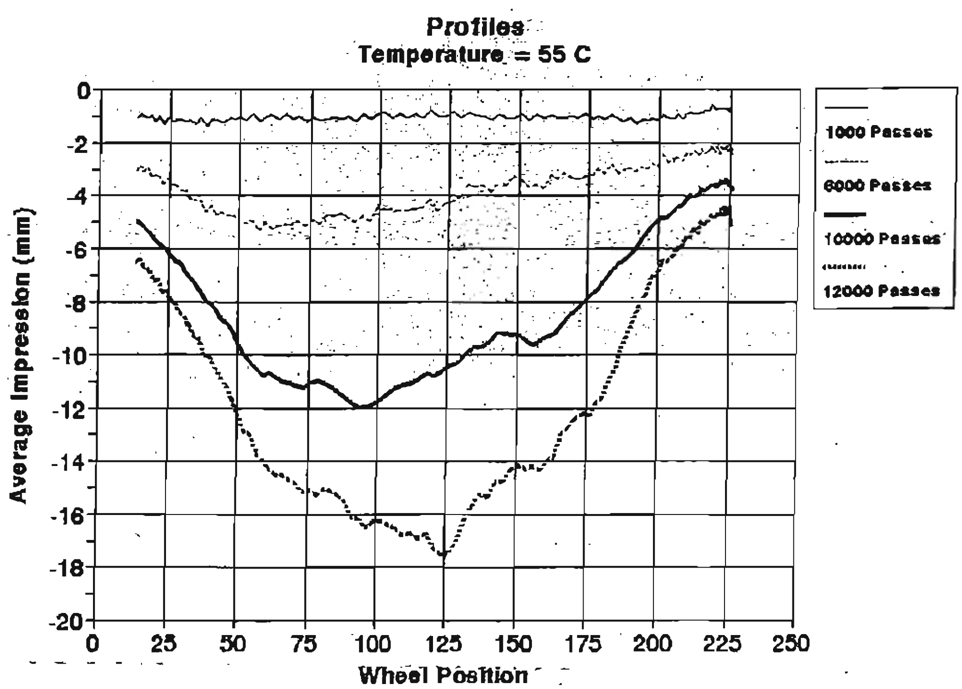

Mix 2, AC-20
Temperature = 45 C
Maximum Impression (mm)
No. of Passes
(Thousands)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20

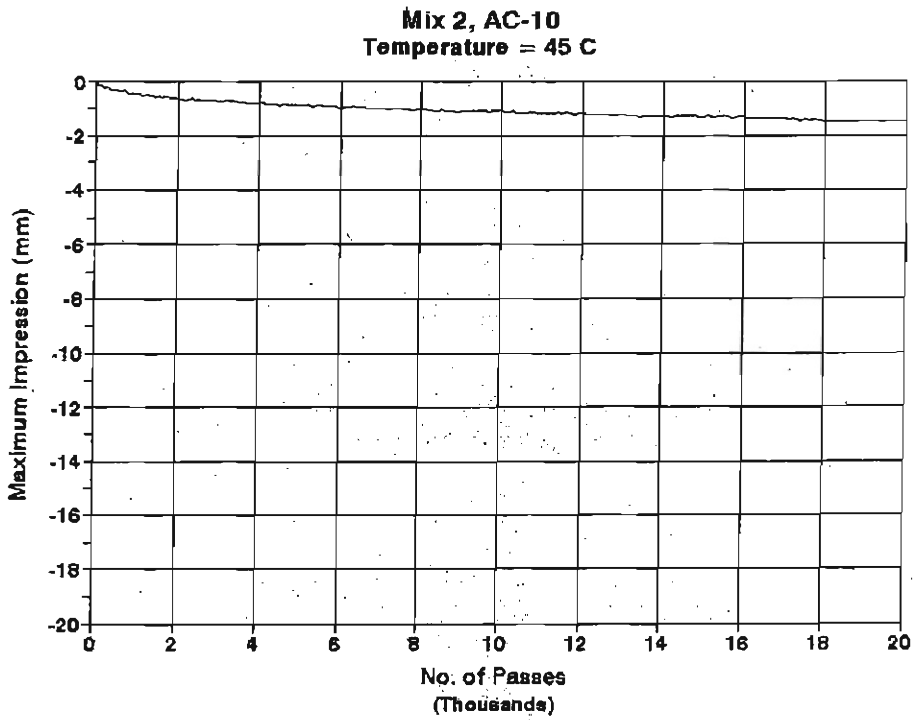

Profiles
Temperature = 50 C
Average Impression (mm)
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250


Mix 2, AC-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)

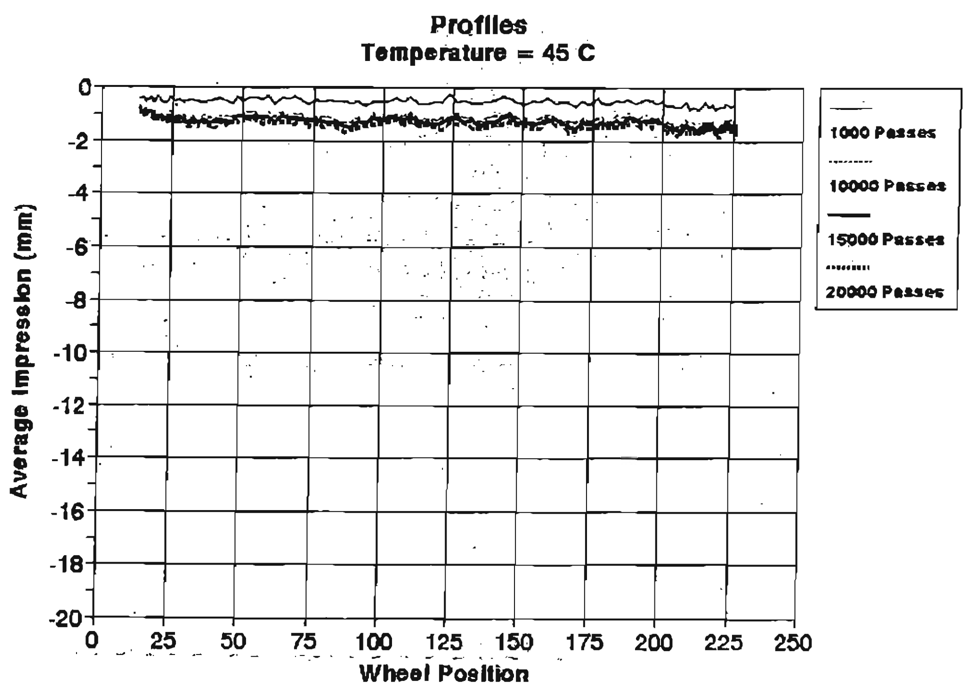

Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes


Mix 2, AC-20
Temperature = 55 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)

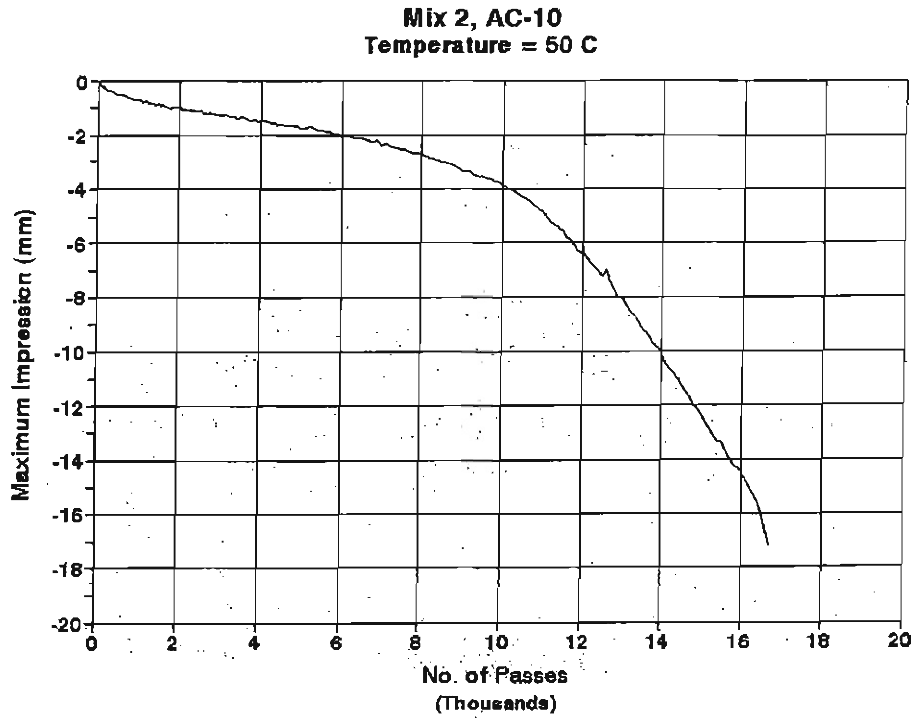

Profiles
Temperature = 55 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
6000 Passes
10000 Passes
12000 Passes



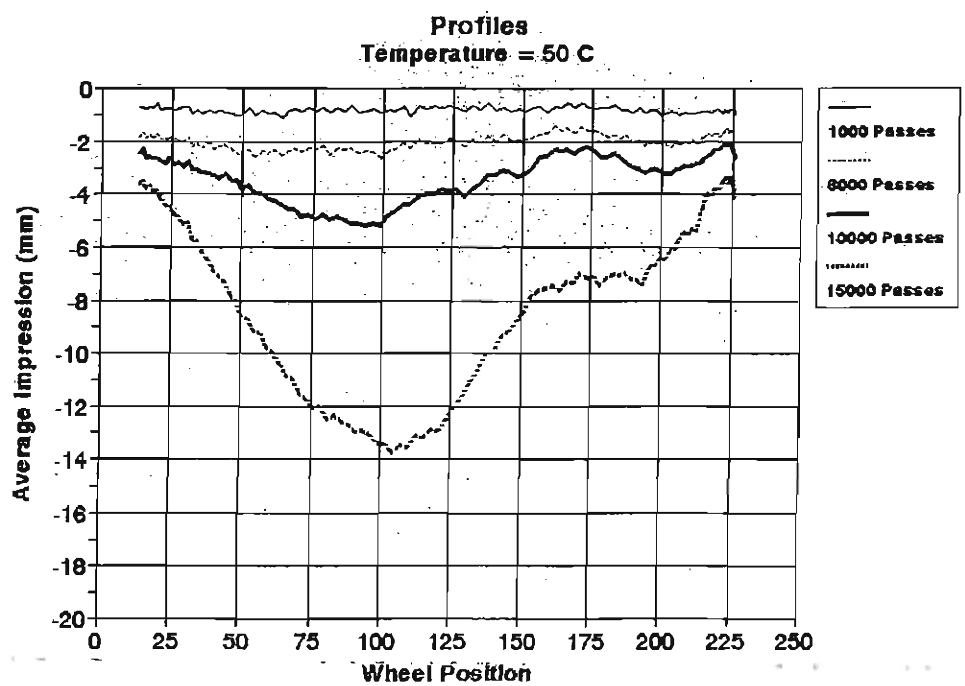
Mix 2, AC-10
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



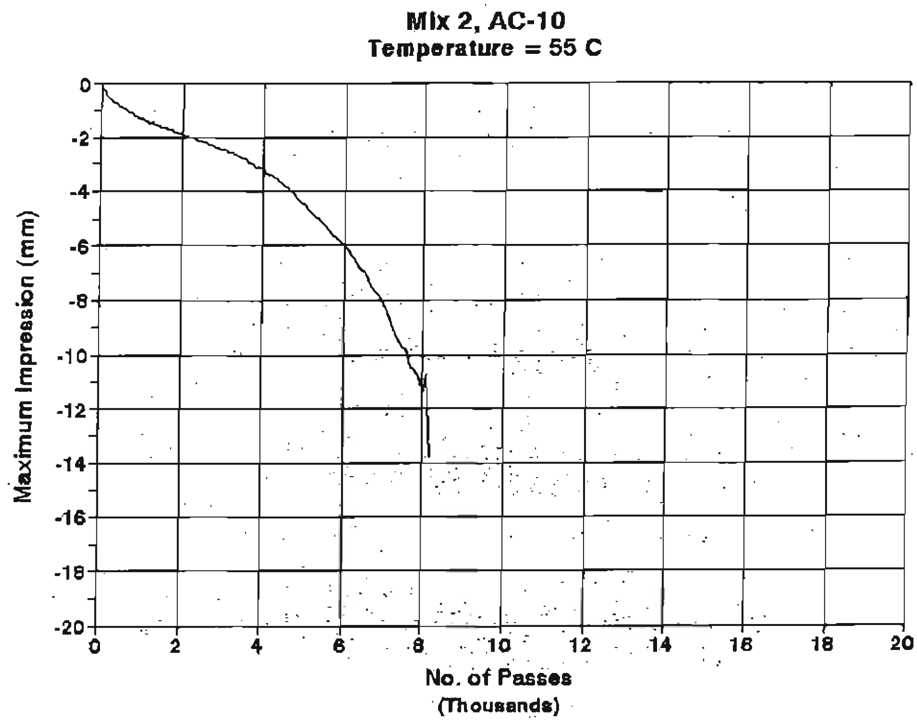
Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes



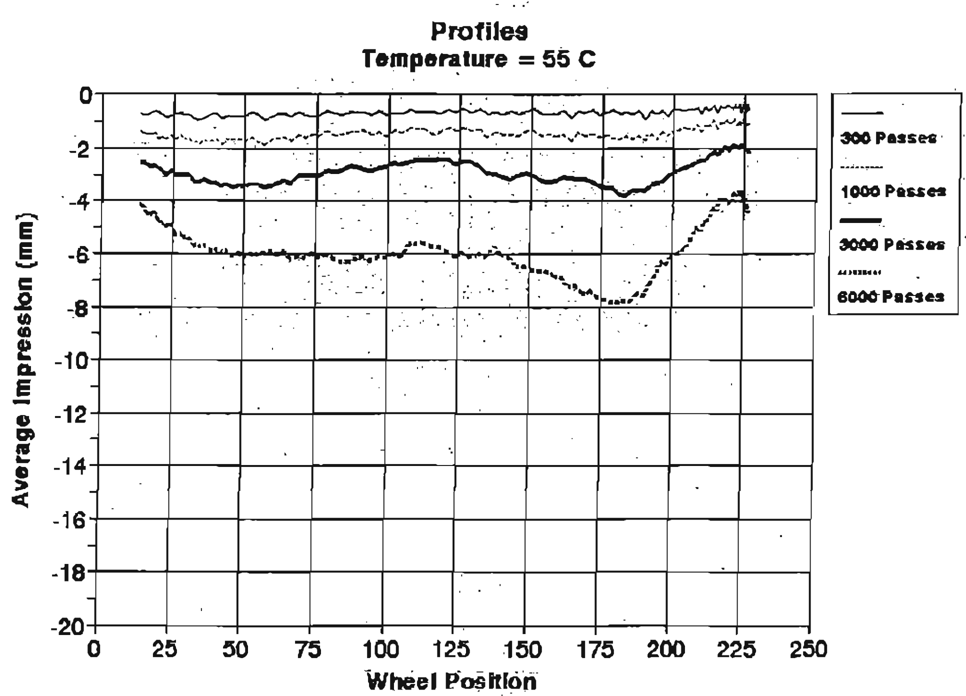
Mix 2, AC-10
Temperature = 50 C
Maximum Impression (mm)
No. of Passes
(Thousands)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20



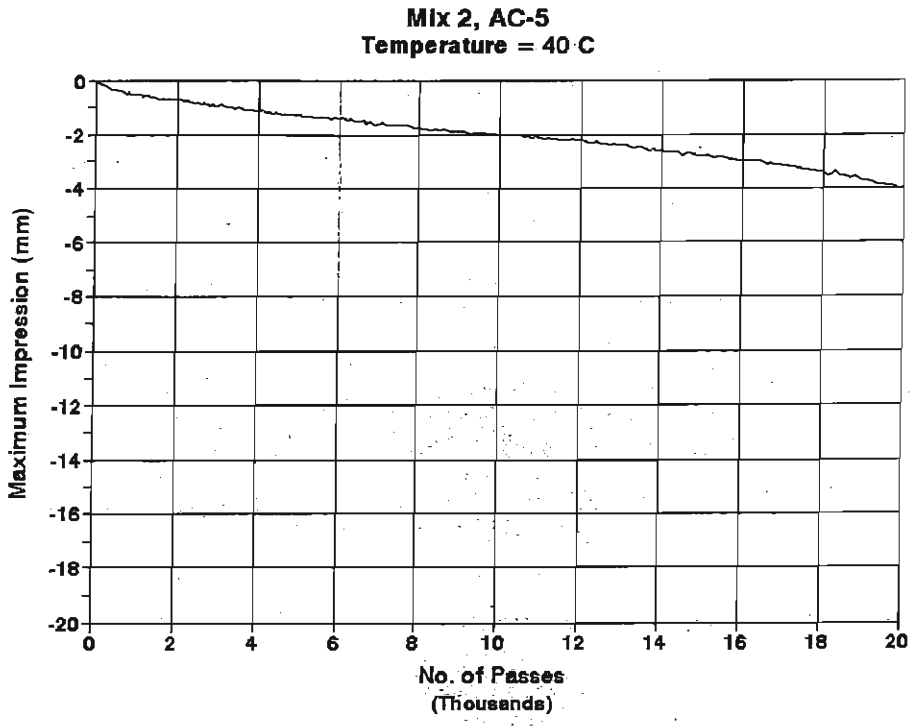
Profiles
Temperature = 50 C
Average Impression (mm)
Wheel Position
1000 Passes
6000 Passes
10000 Passes
15000 Passes
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250

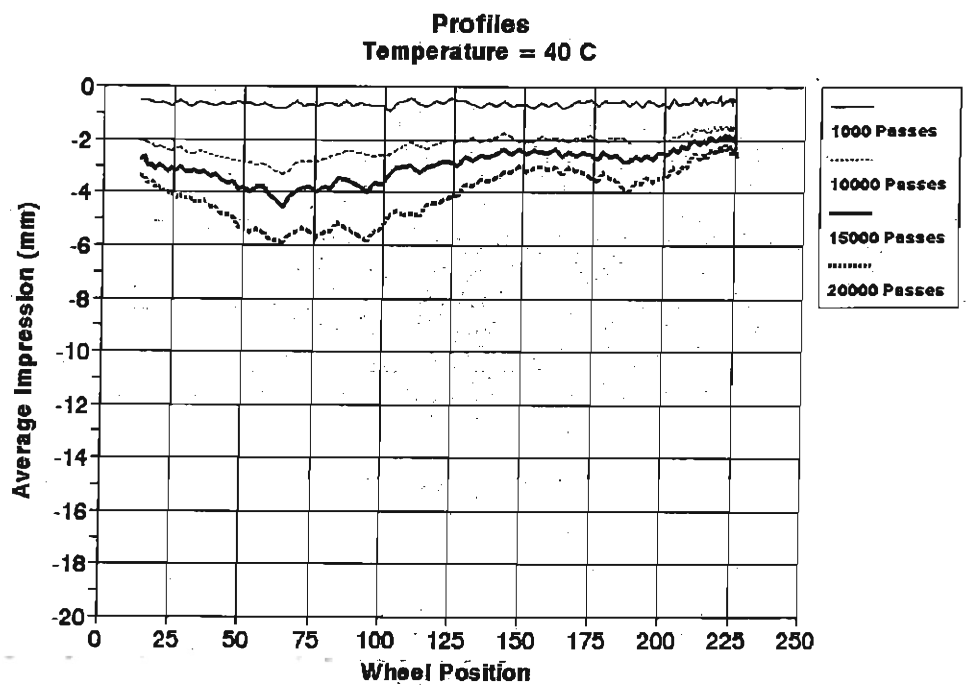


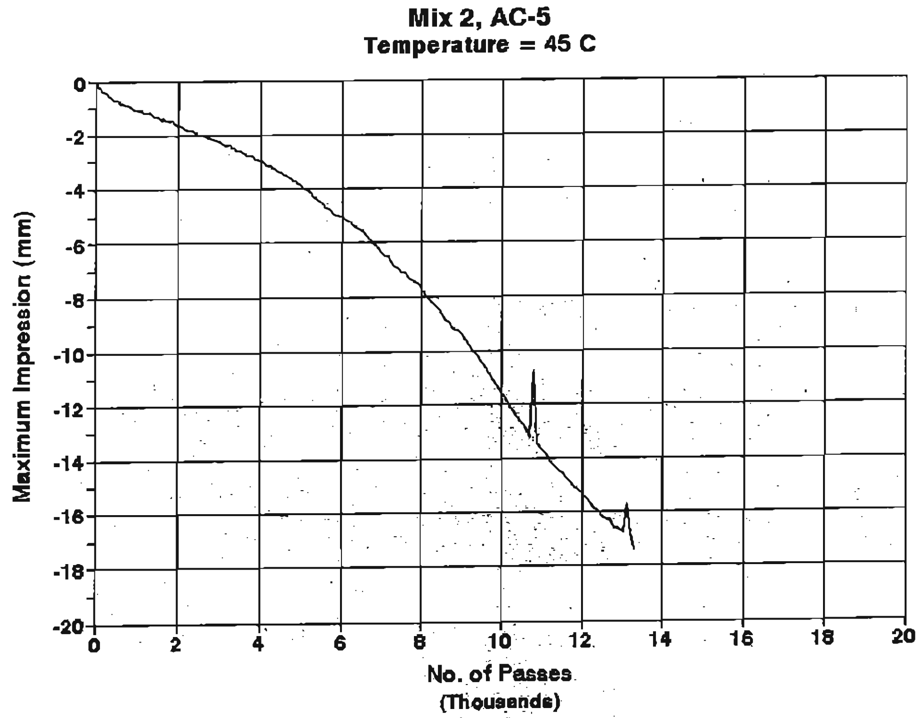
Mix 2, AC-10
Temperature = 55 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

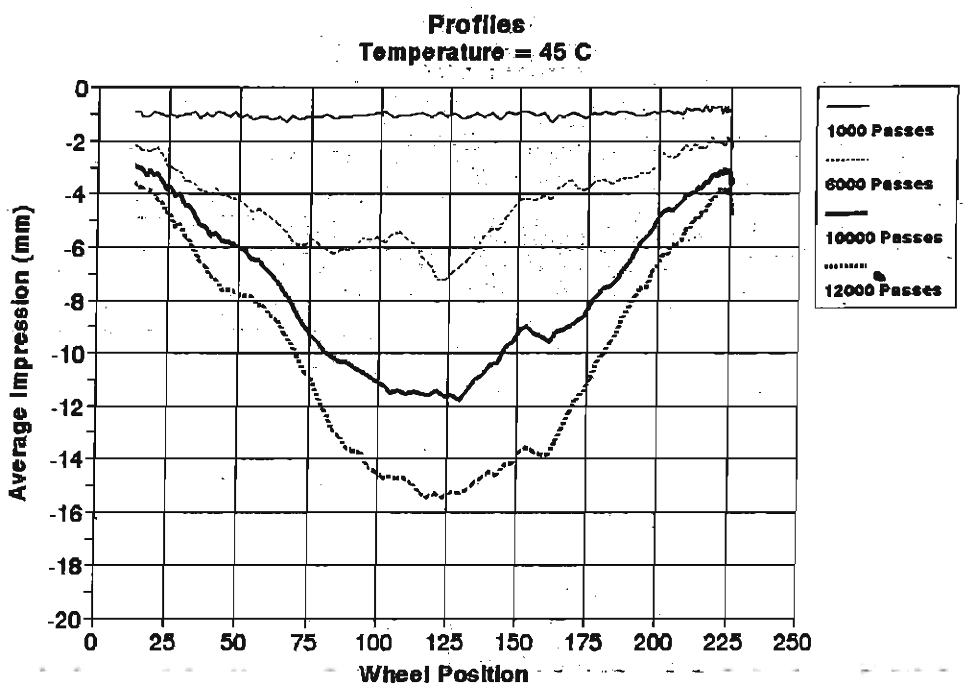


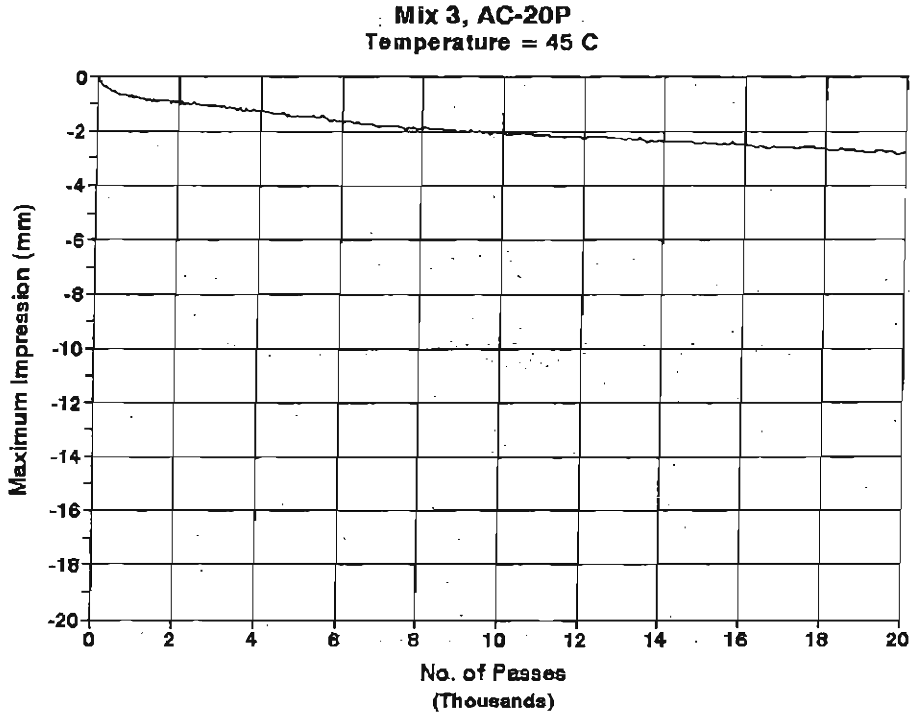
Profiles
Temperature = 55 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
300 Passes
1000 Passes
3000 Passes
6000 Passes


Mix 2, AC-5
Temperature = 40 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)

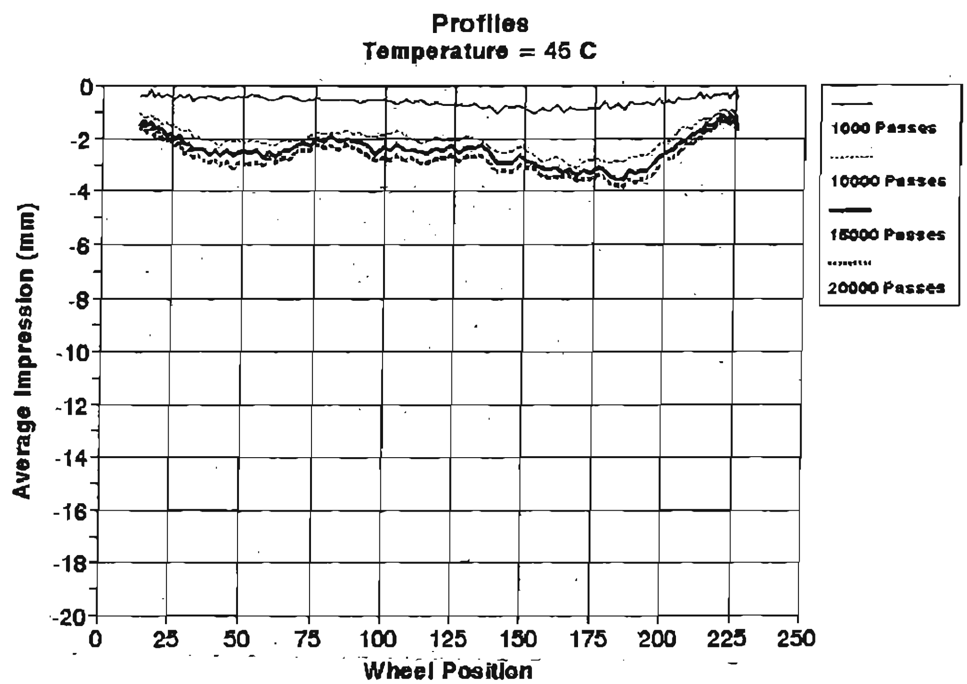

Profiles
Temperature = 40 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes


Mix 2, AC-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)

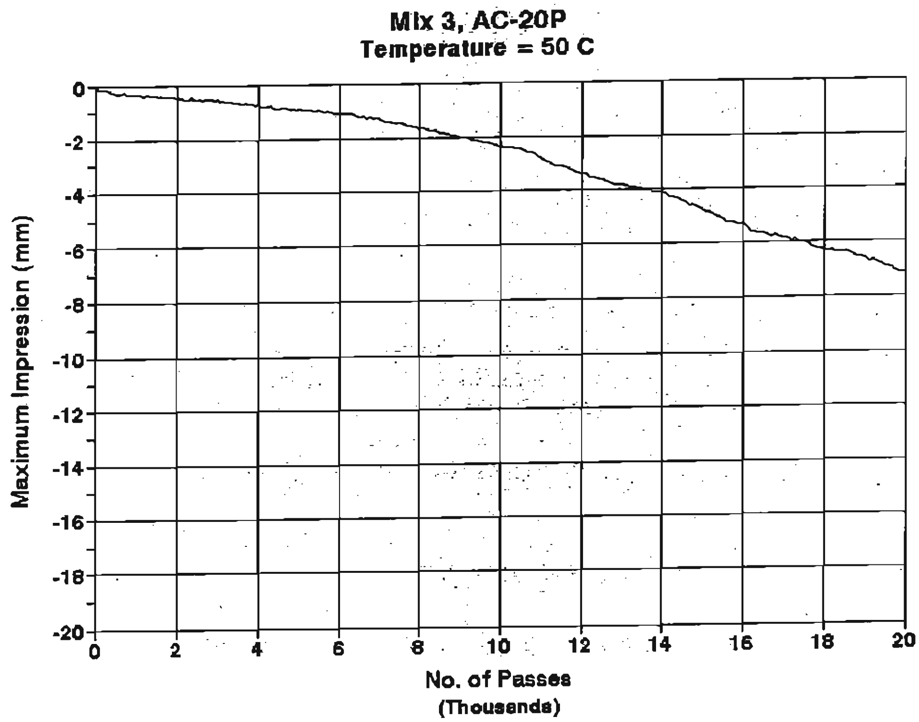

Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
6000 Passes
10000 Passes
12000 Passes



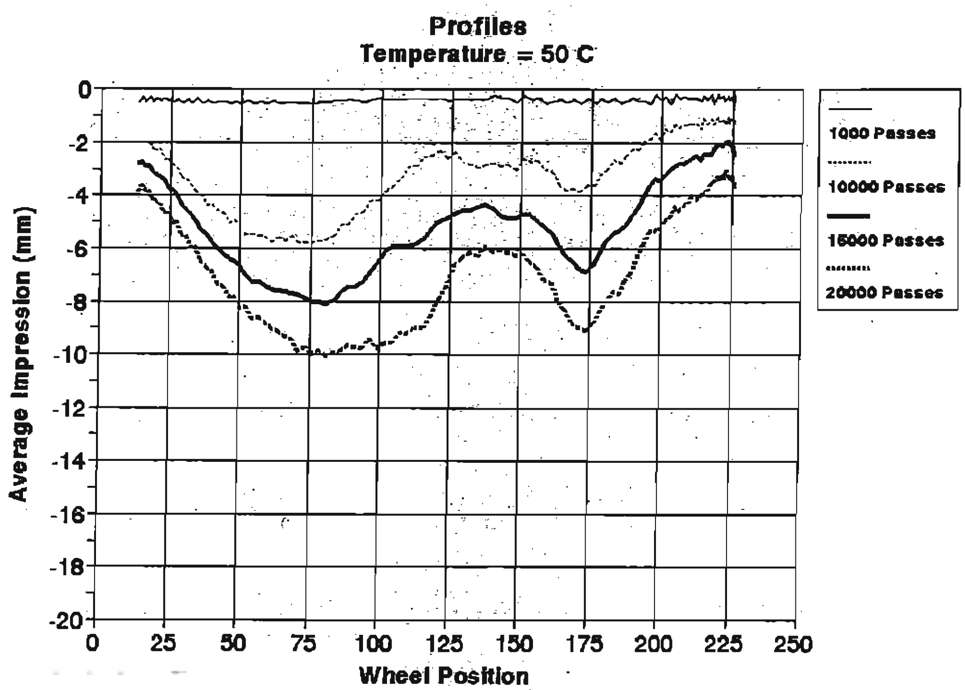
Mix 3, AC-20P
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



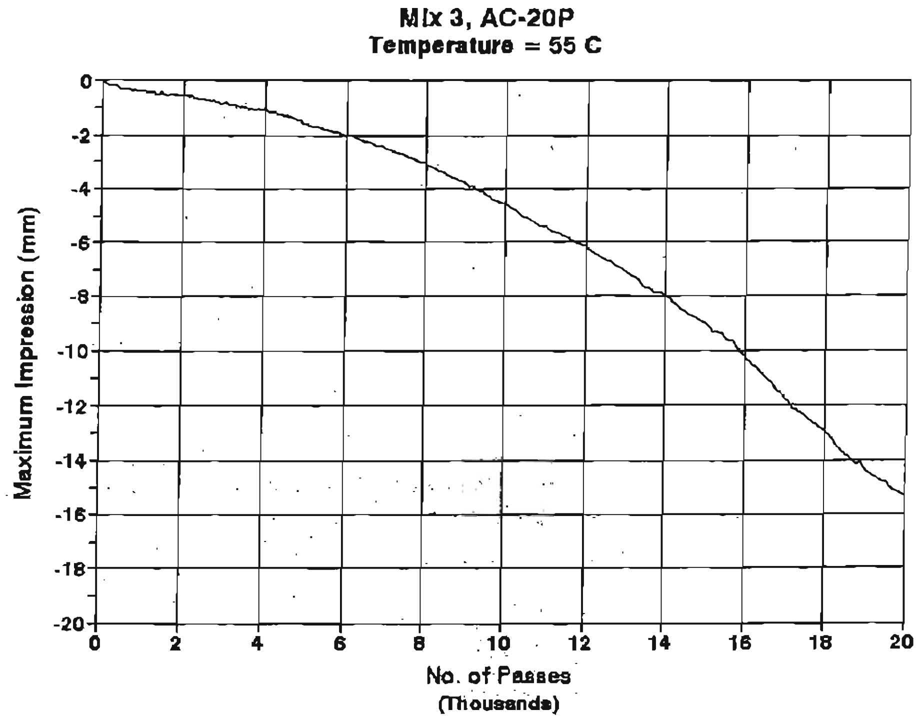
Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes



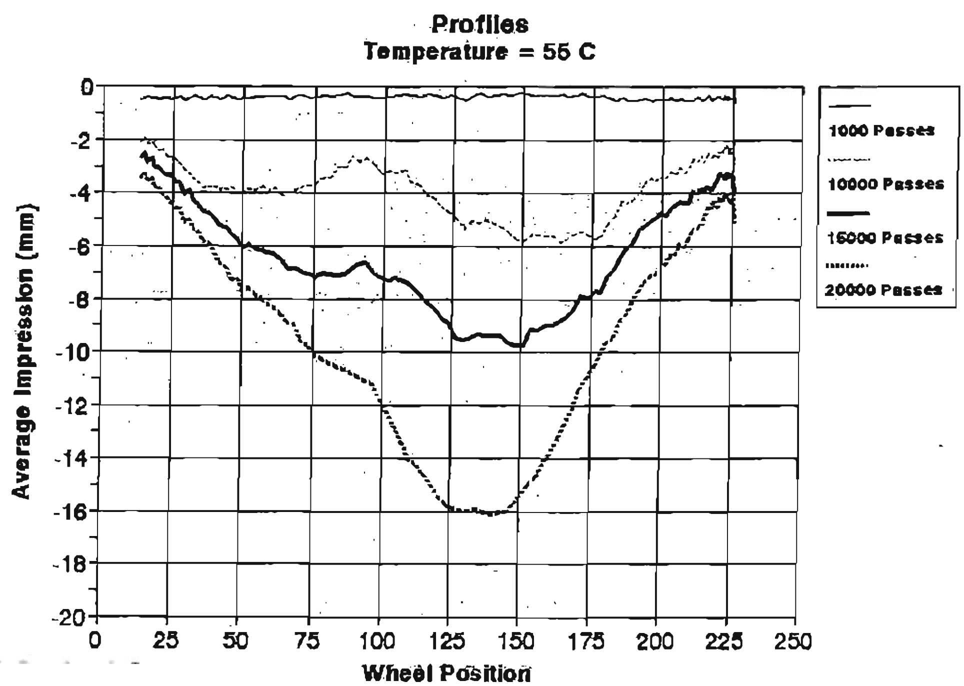
Mix 3, AC-20P
Temperature = 50 C
Maximum Impression (mm)
No. of Passes
(Thousands)



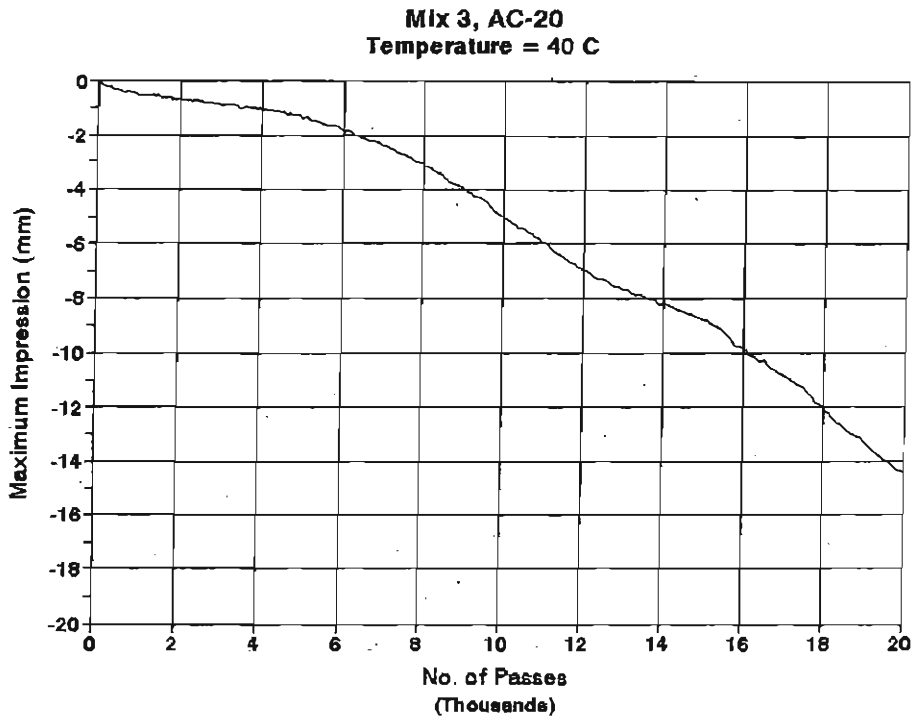
Profiles
Temperature = 50 C
Average Impression (mm)
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes

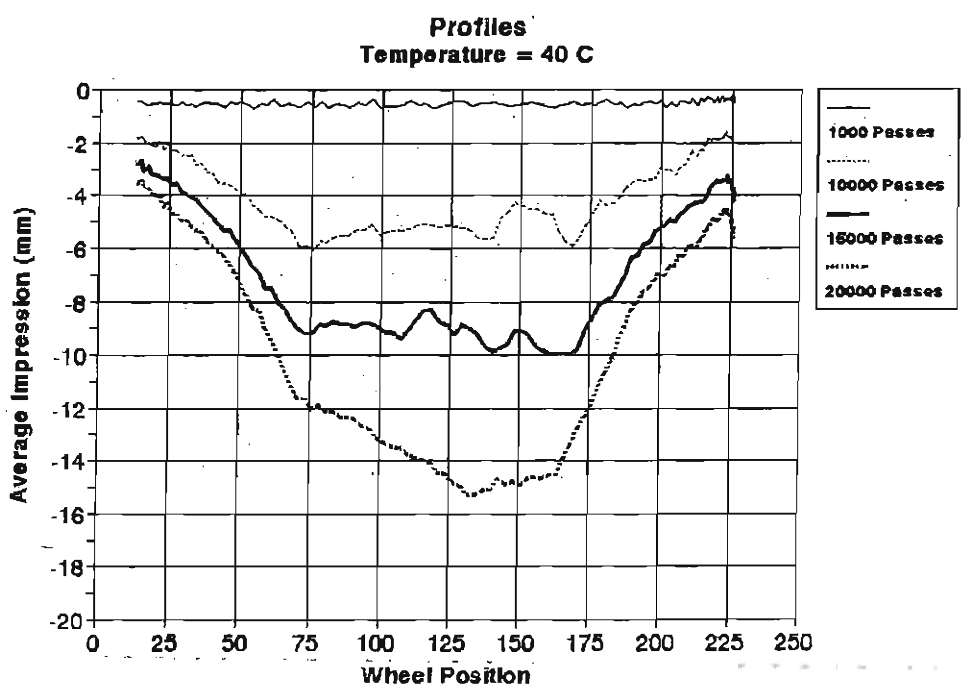


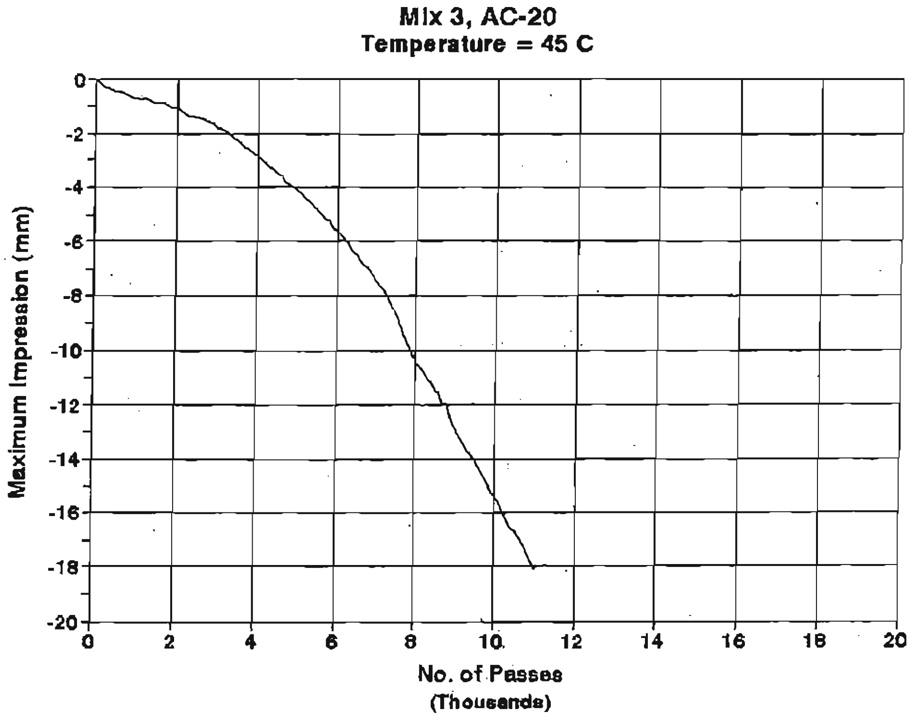
Mix 3, AC-20P
Temperature = 55 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

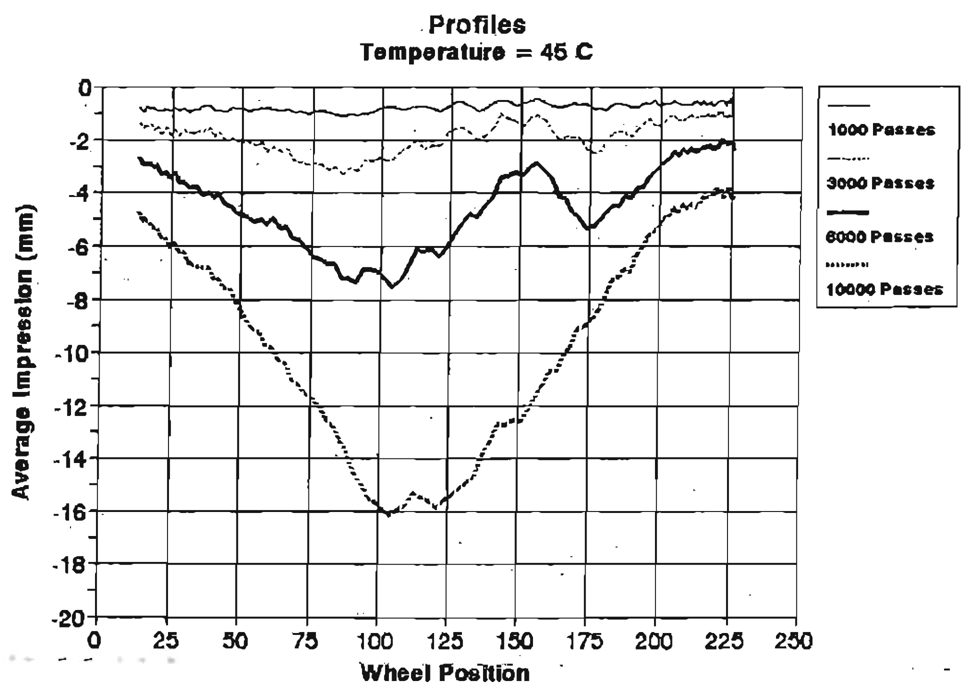


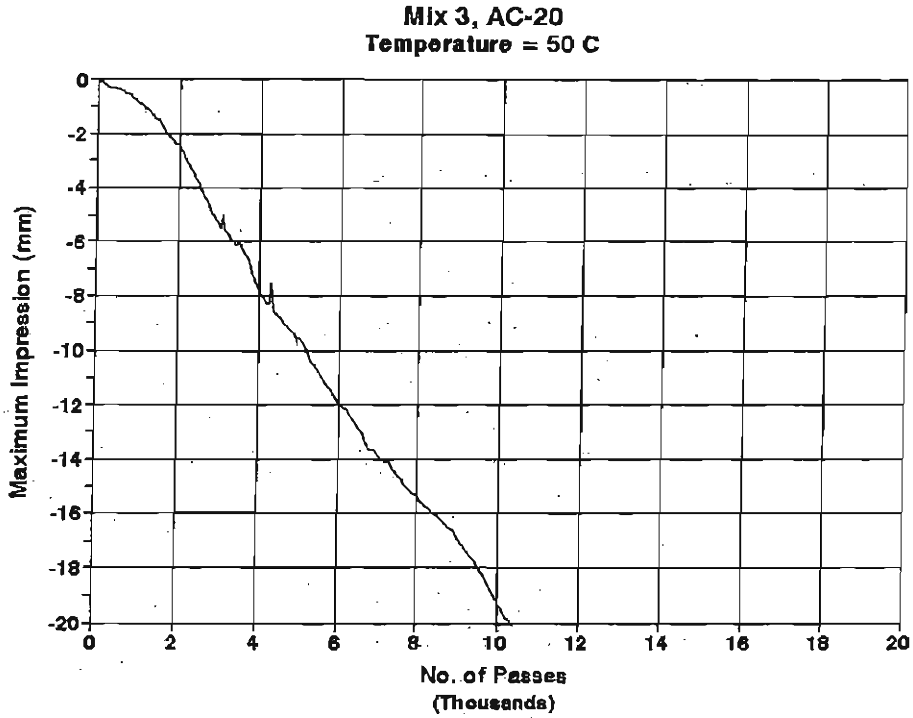
Profiles
Temperature = 55 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes


Mix 3, AC-20
Temperature = 40 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)

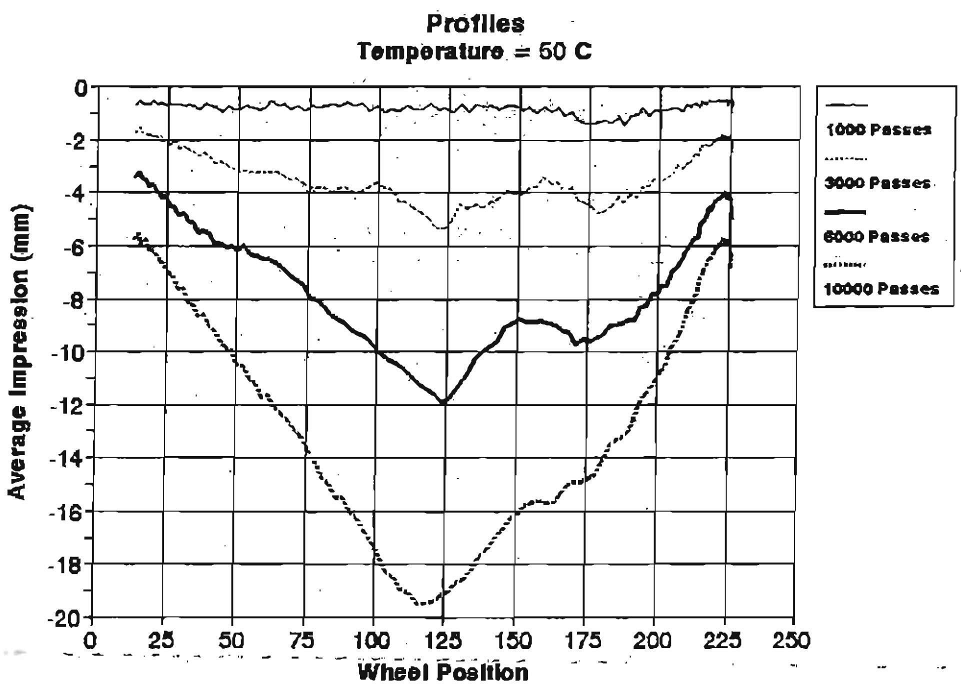

Profiles
Temperature = 40 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes


Mix 3, AC-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)

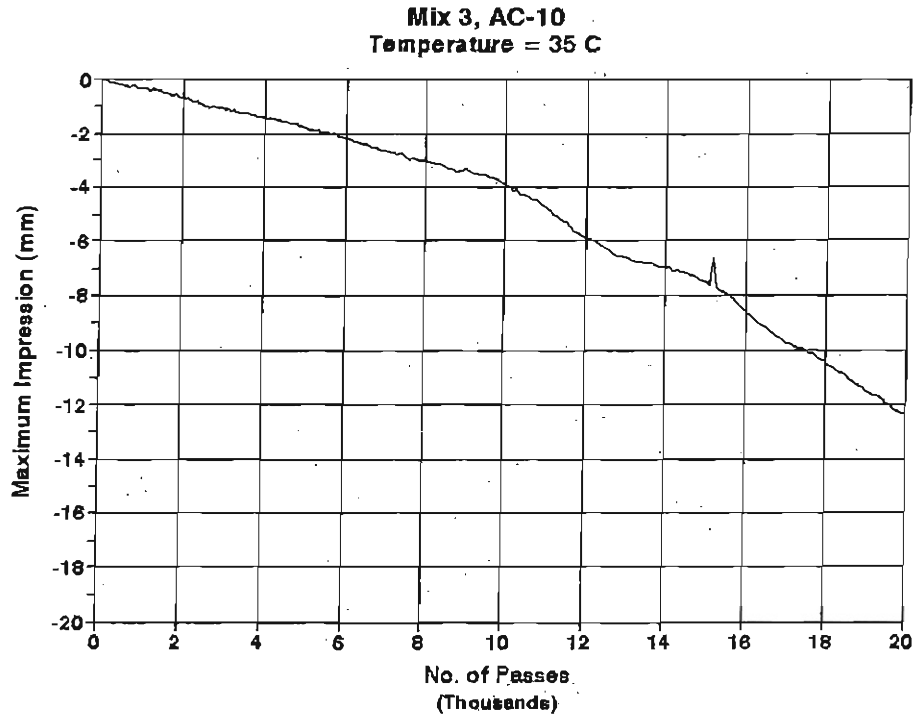

Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
3000 Passes
6000 Passes
10000 Passes



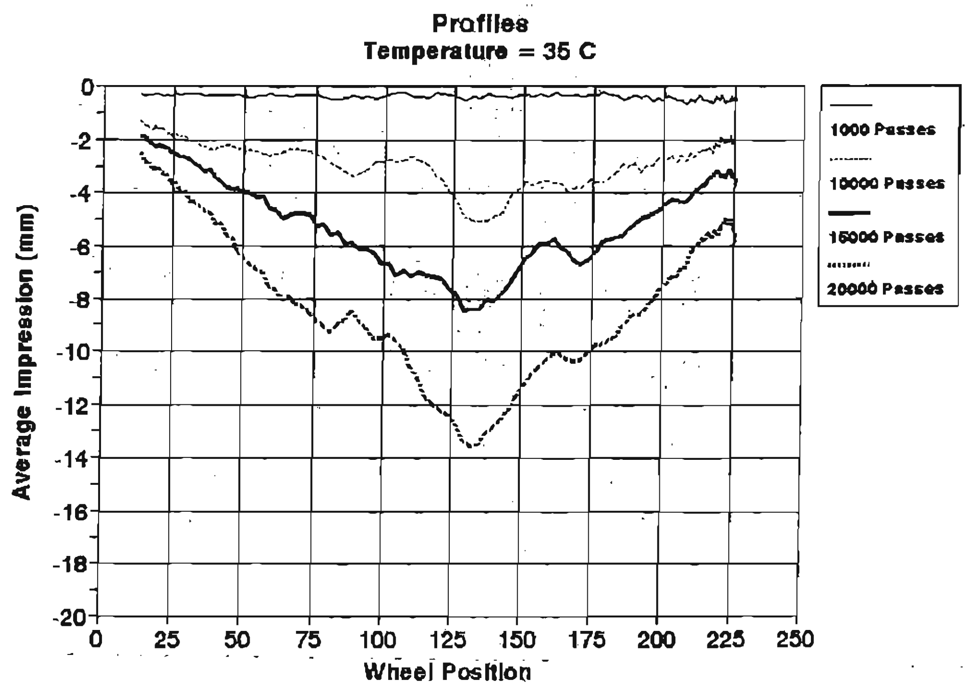
Mix 3, AC-20
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



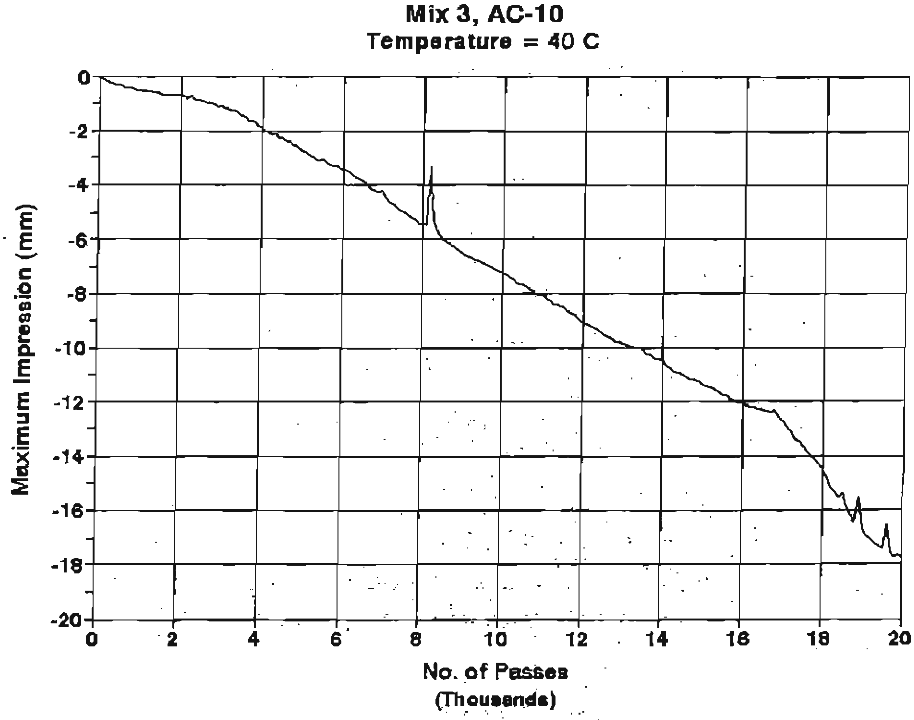
Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
3000 Passes
6000 Passes
10000 Passes

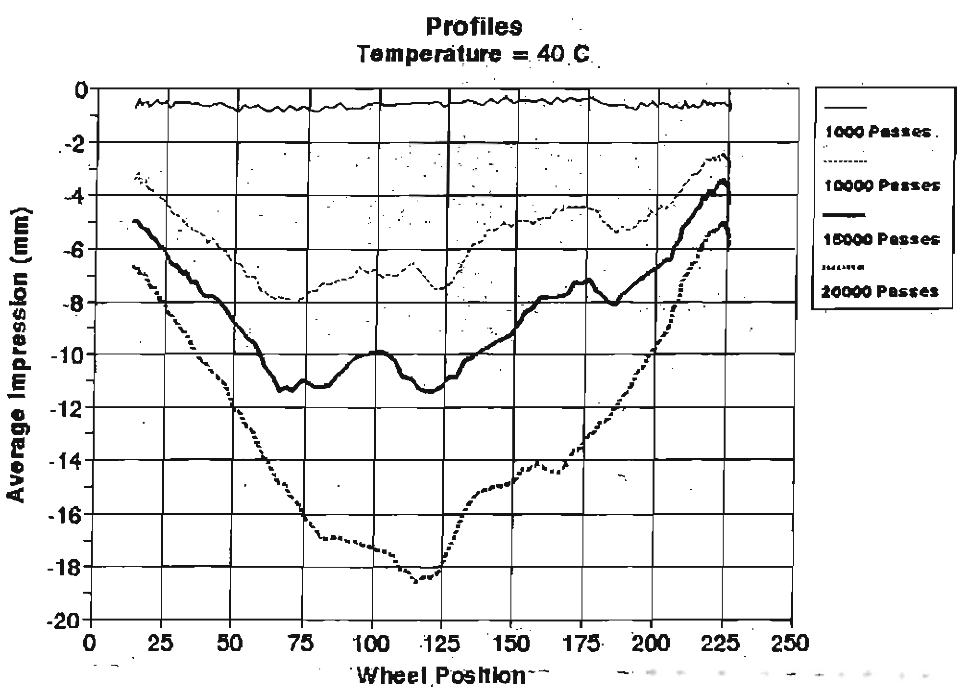


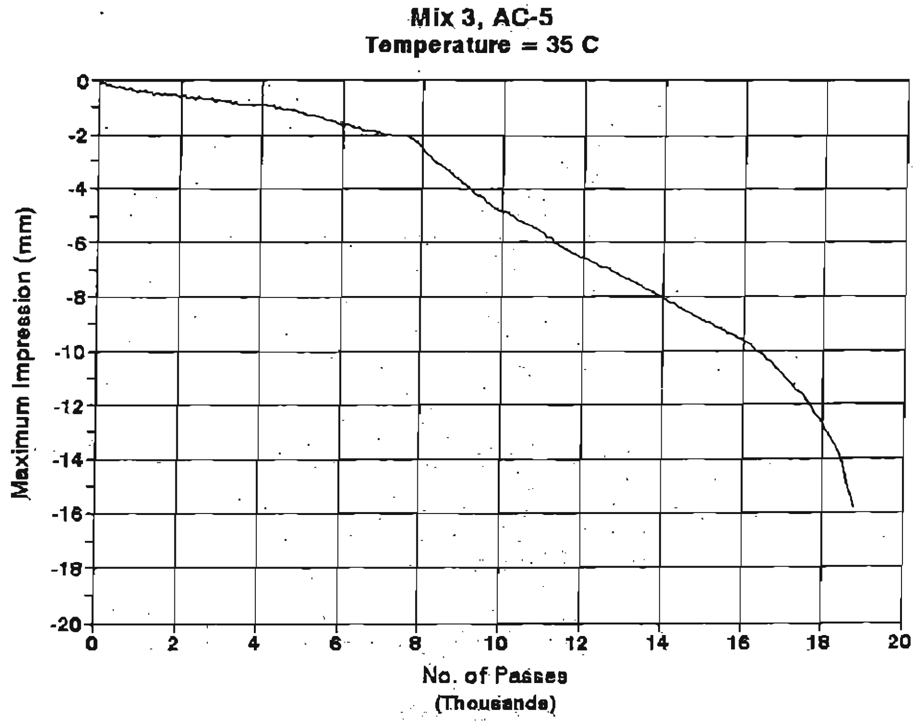
Mix 3, AC-10
Temperature = 35 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

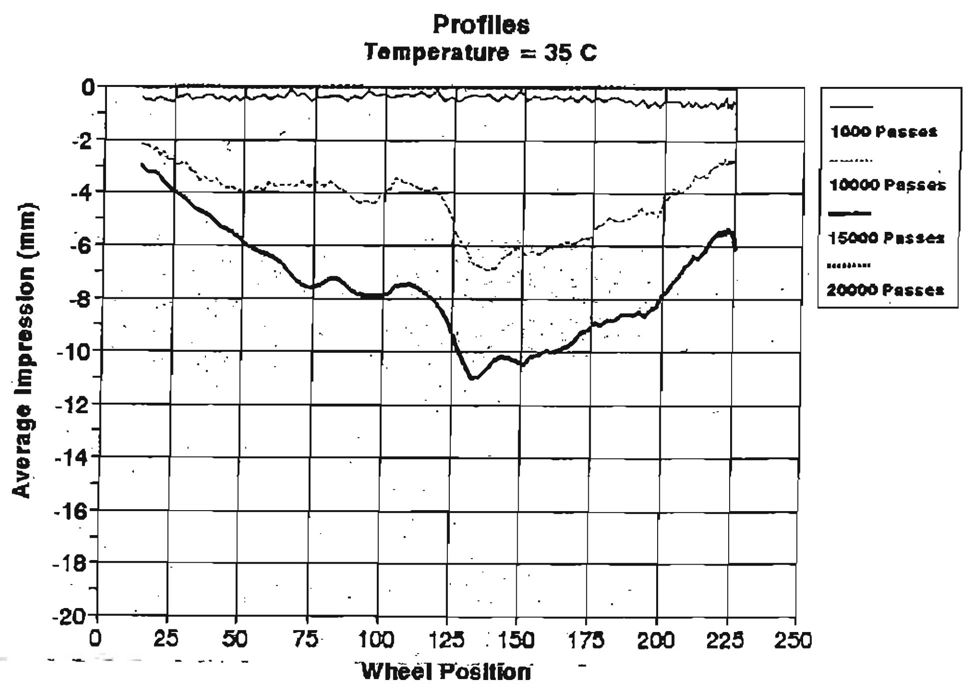


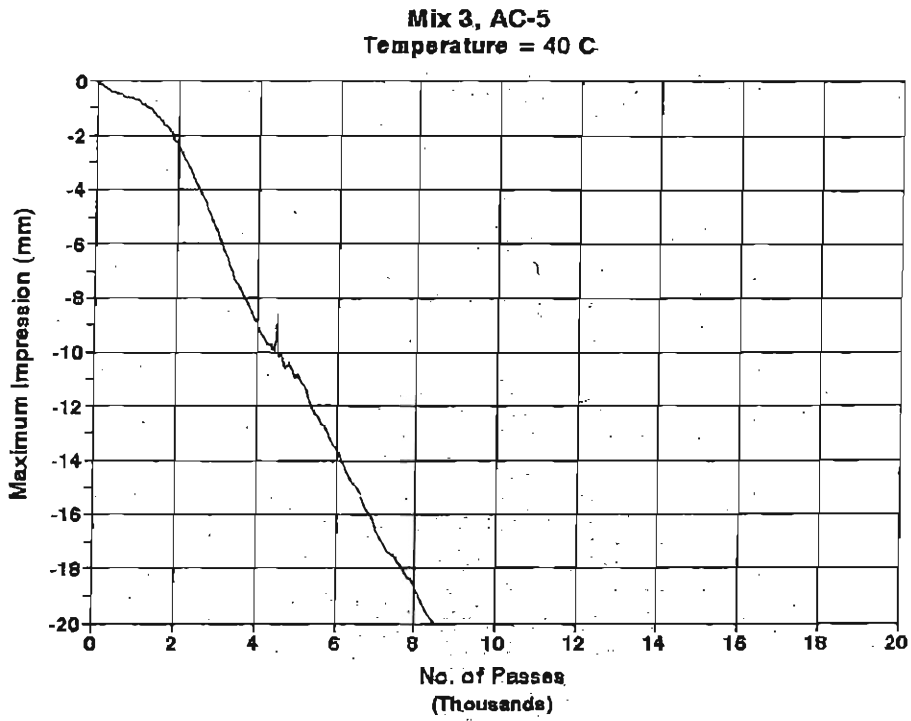
Profiles
Temperature = 35 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes


Mix 3, AC-10
Temperature = 40 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

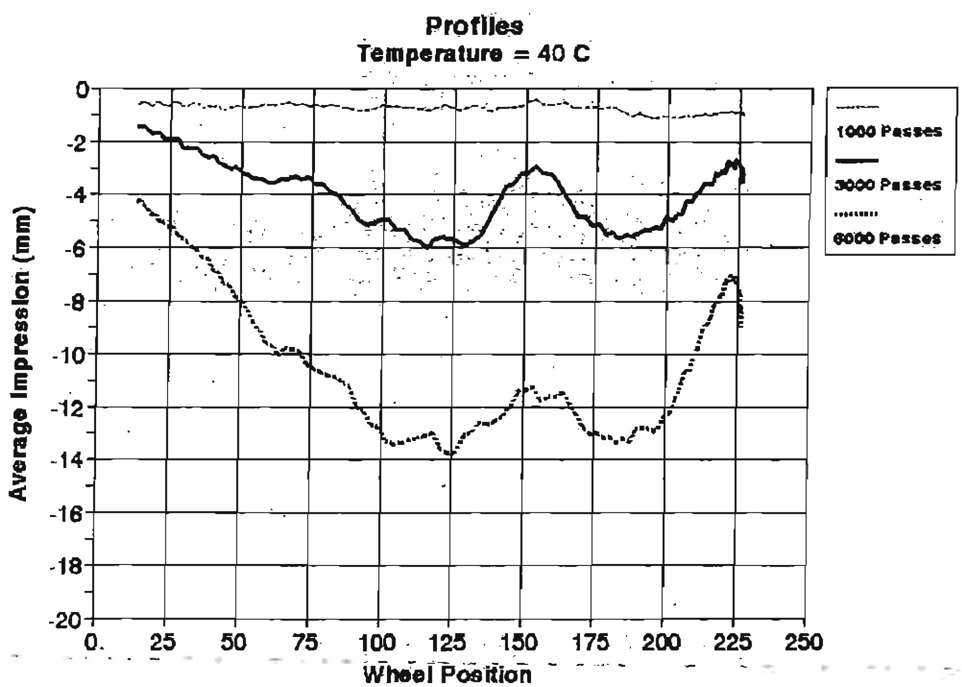

Profiles
Temperature = 40 C
Average Impression (mm)
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250


Mix 3, AC-5
Temperature = 35 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)

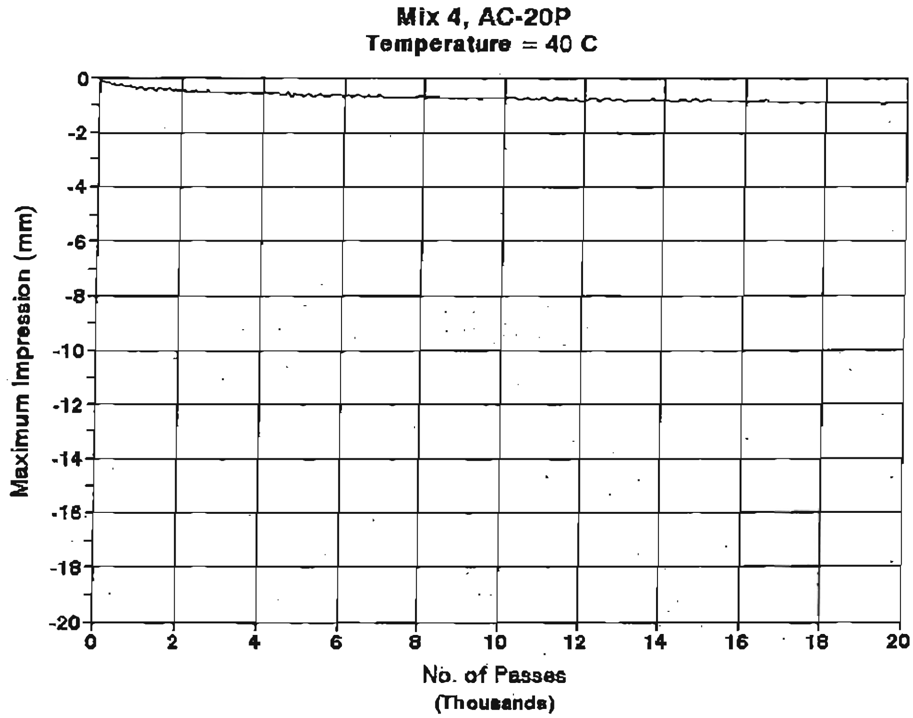

Profiles
Temperature = 35 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes

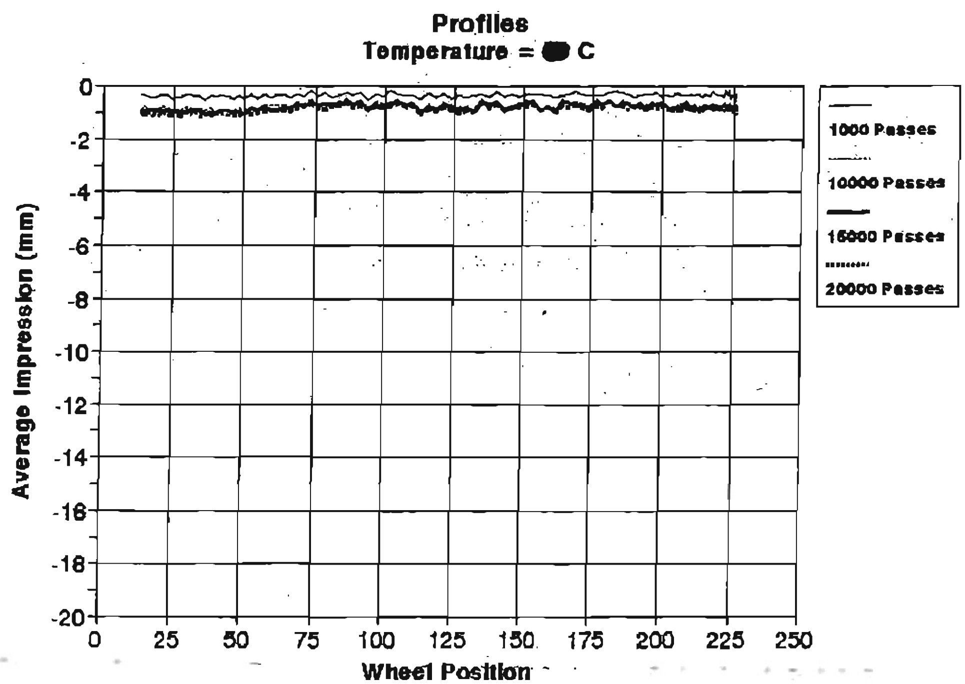


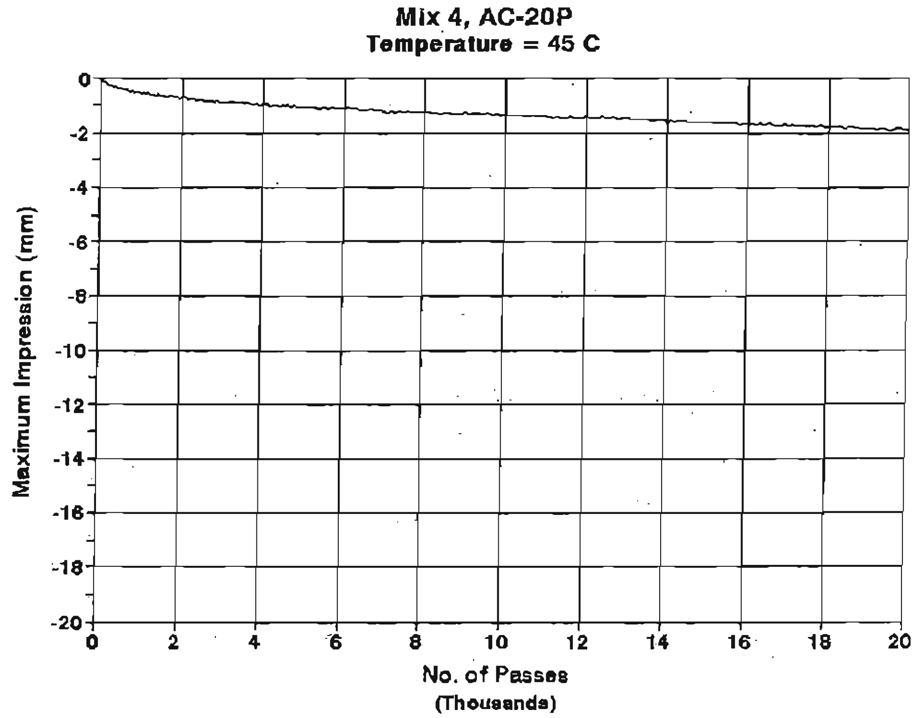
Mix 3, AC-5
Temperature = 40 C
Maximum Impression (mm)
No. of Passes
(Thousands)



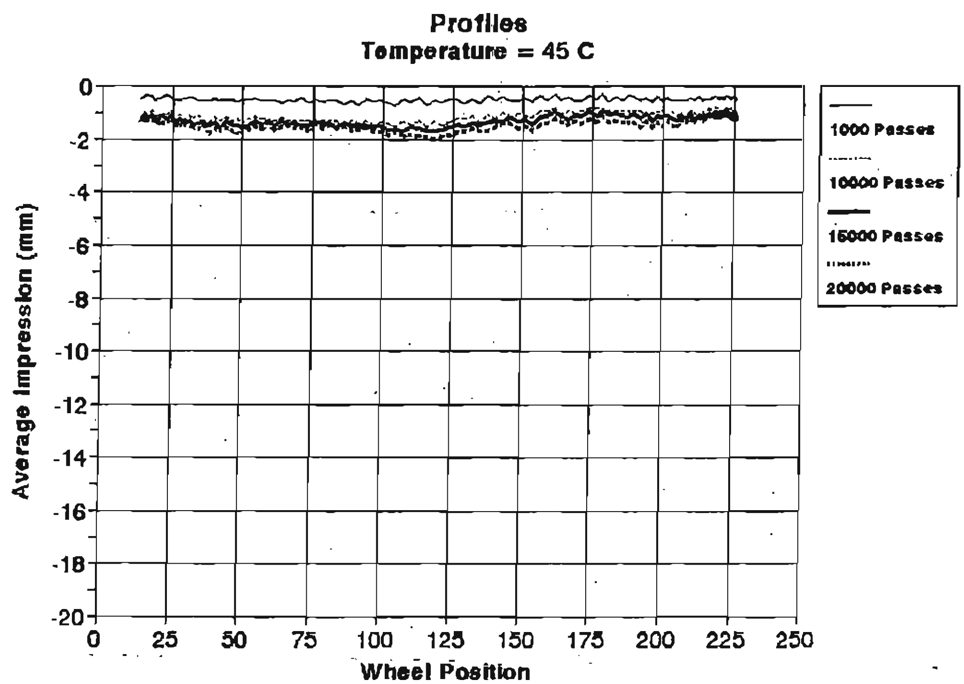
Profiles
Temperature = 40 C
Average Impression (mm)
Wheel Position
1000 Passes
3000 Passes
6000 Passes


Mix 4, AC-20P
Temperature = 40 C
Maximum Impression (mm)
No. of Passes
(Thousands)

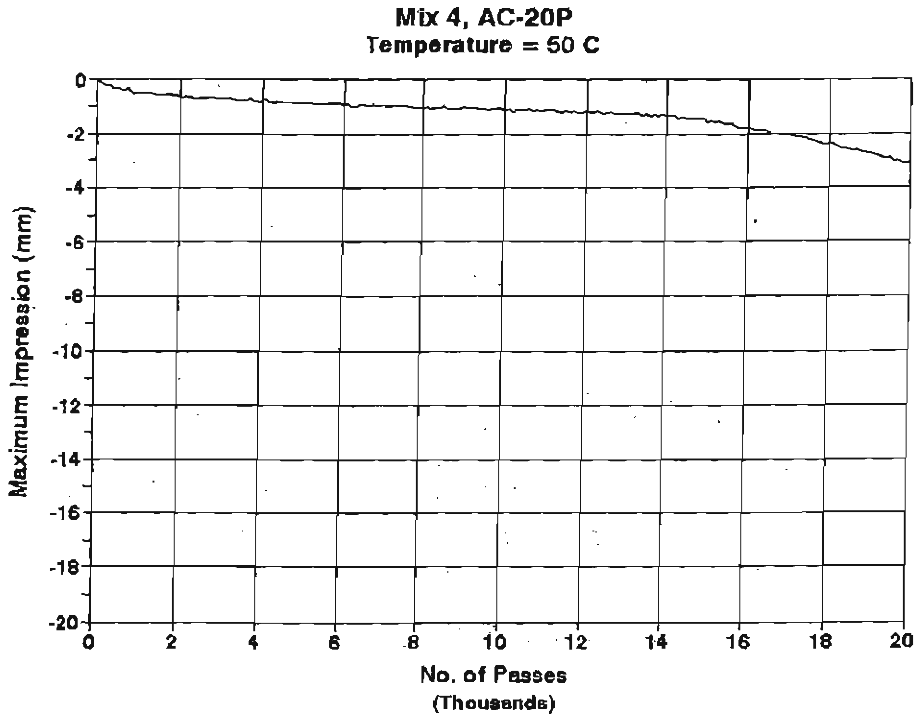

Profiles
Temperature = C
Average Impression (mm)
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes



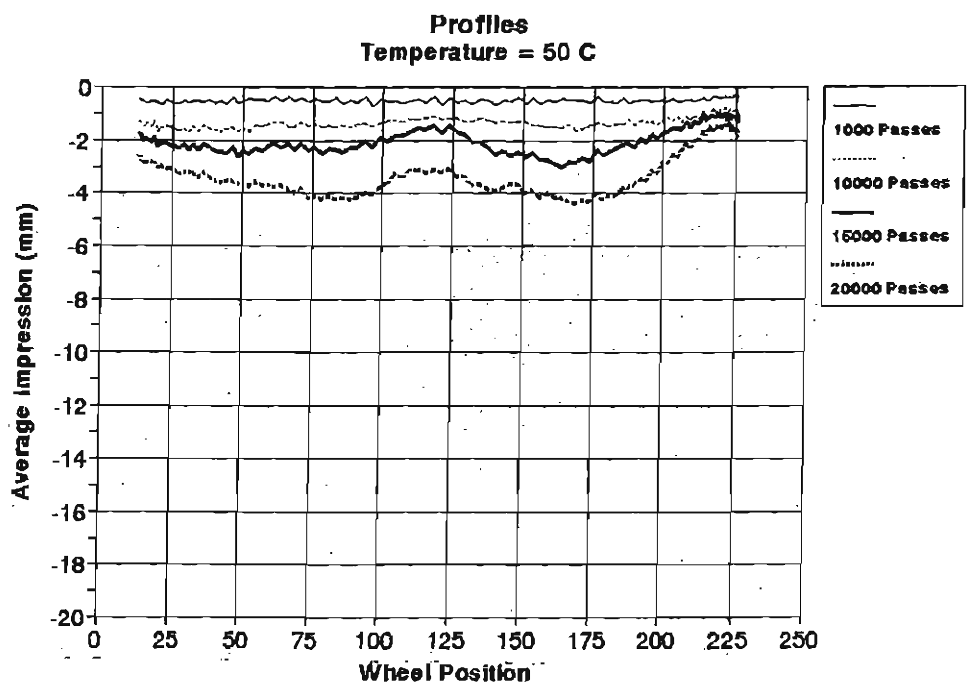
Mix 4, AC-20P
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



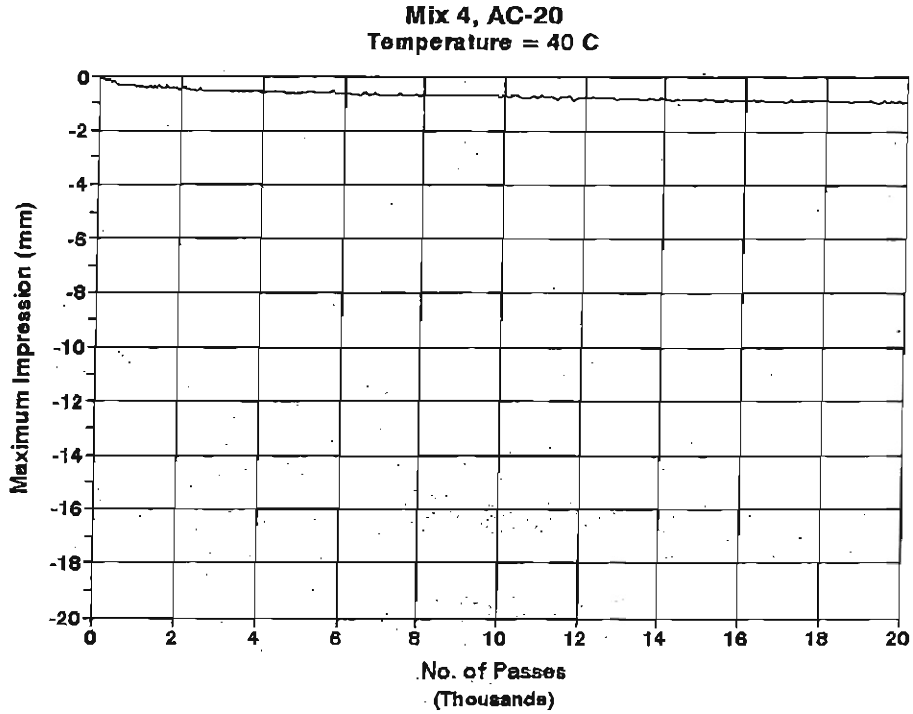
Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes



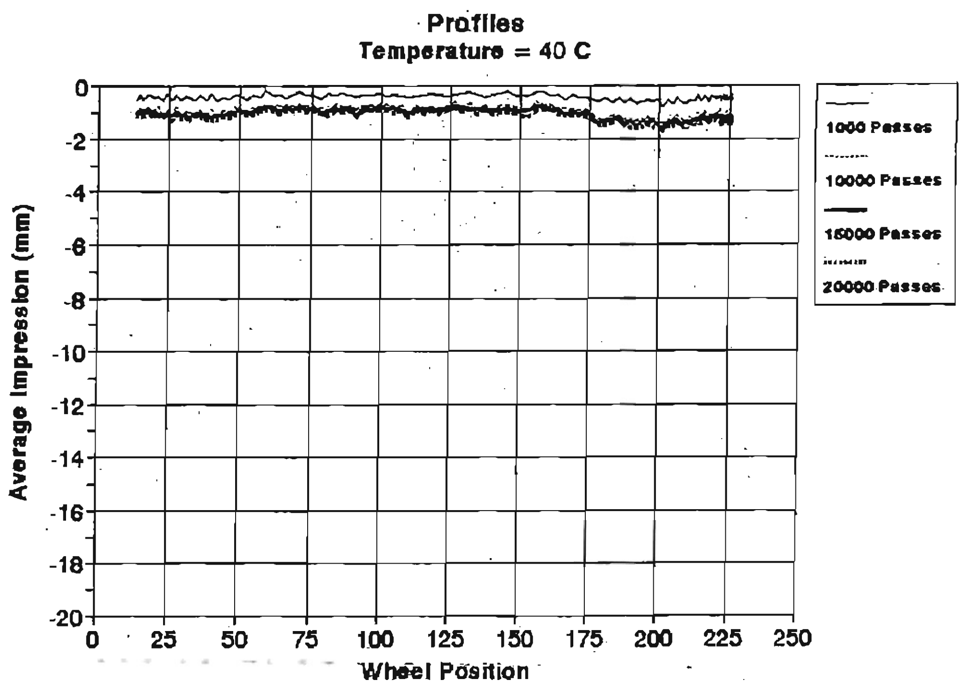
Mix 4, AC-20P
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



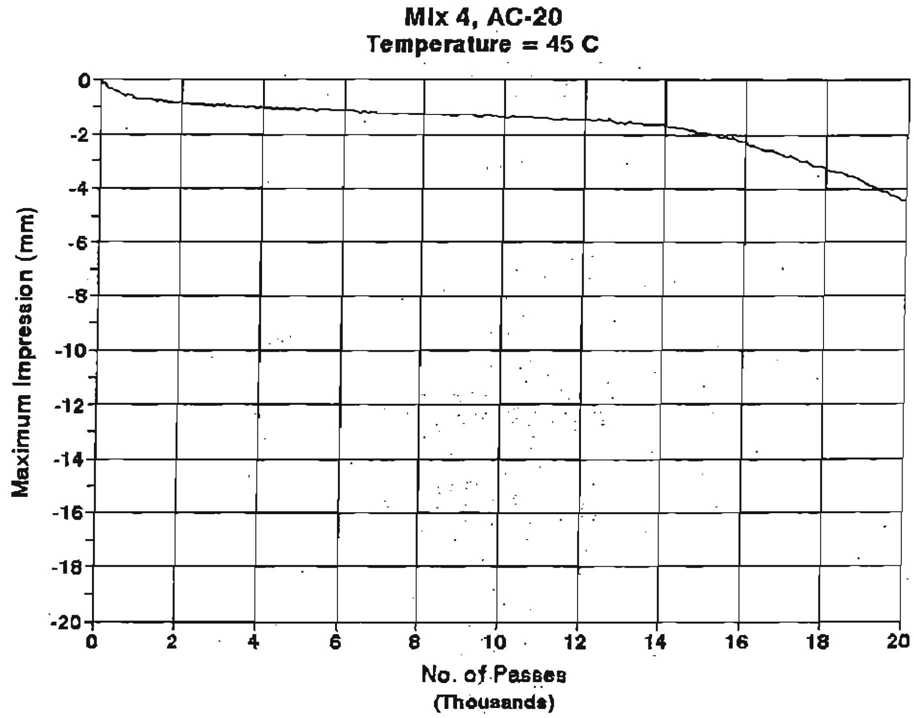
Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes

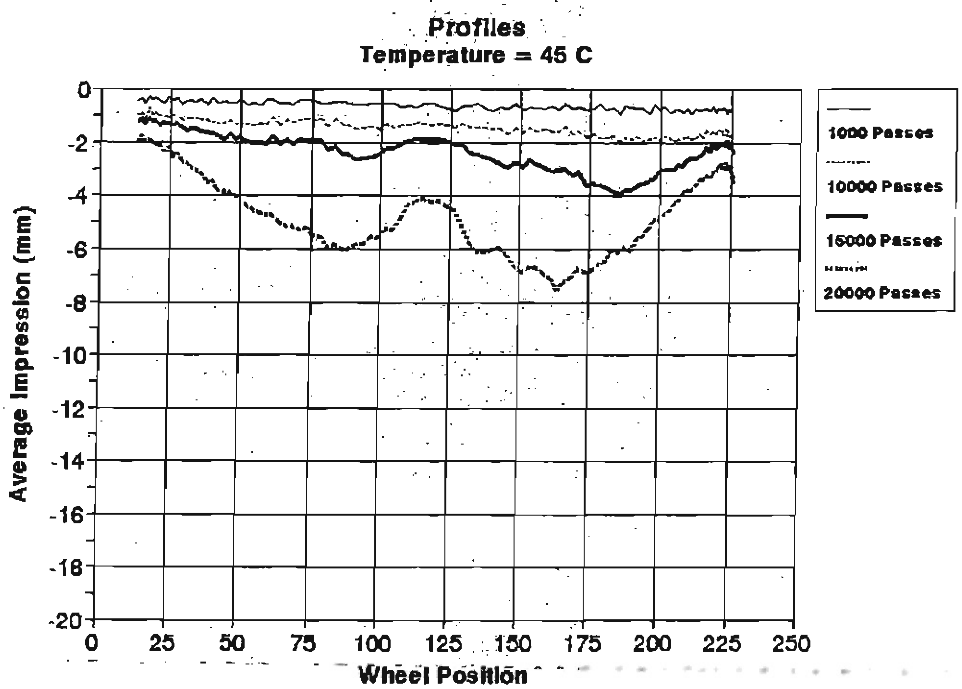


Mix 4, AC-20
Temperature = 40 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

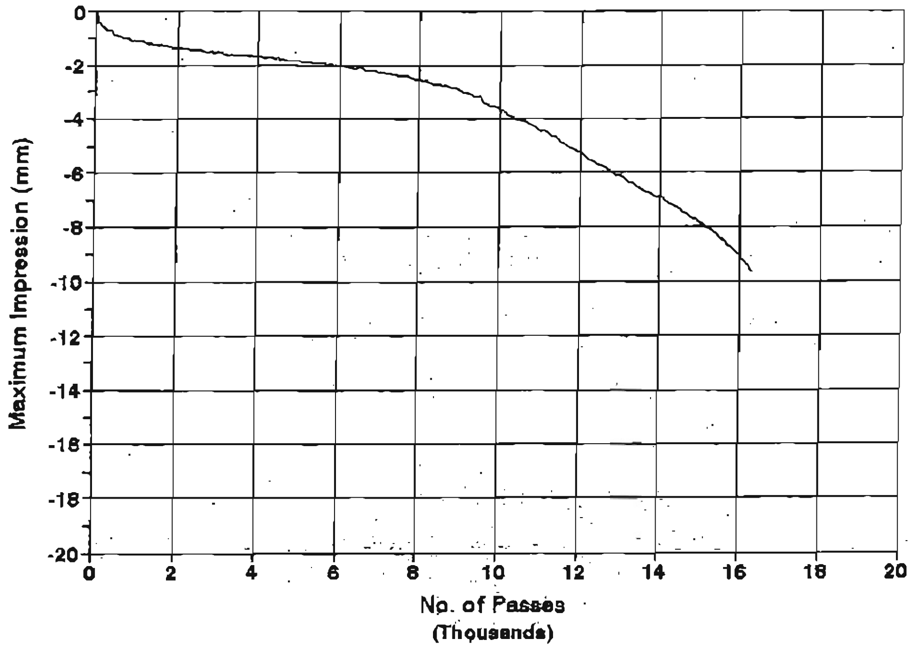


Profiles
Temperature = 40 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes

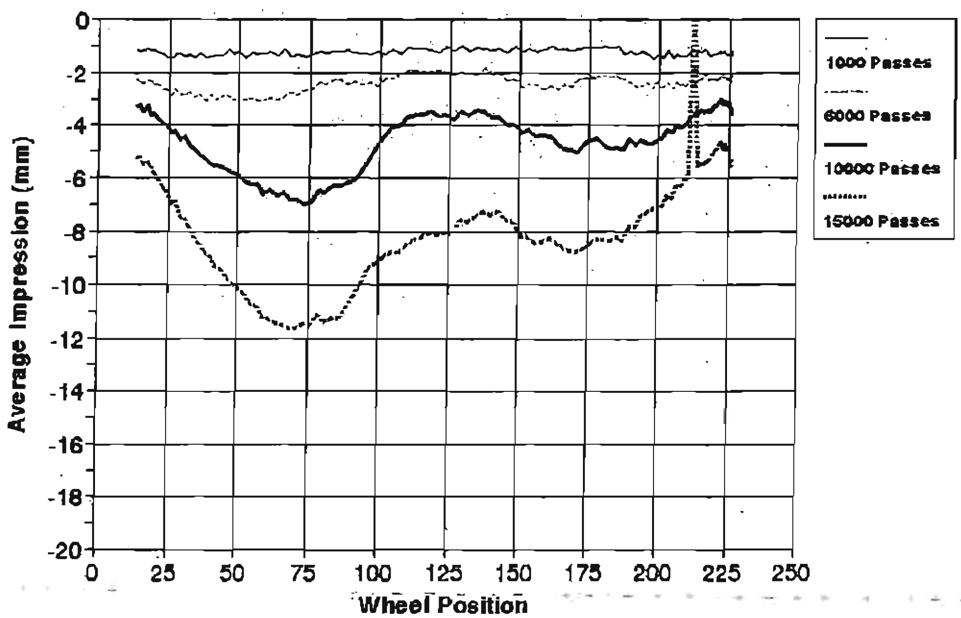

Mix 4, AC-20
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

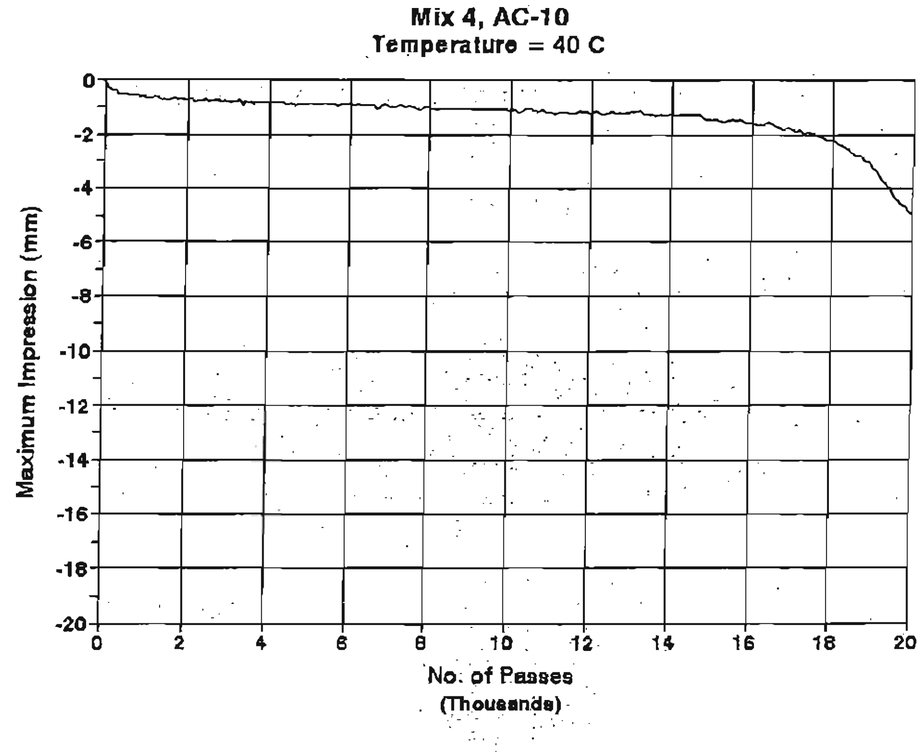

Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes

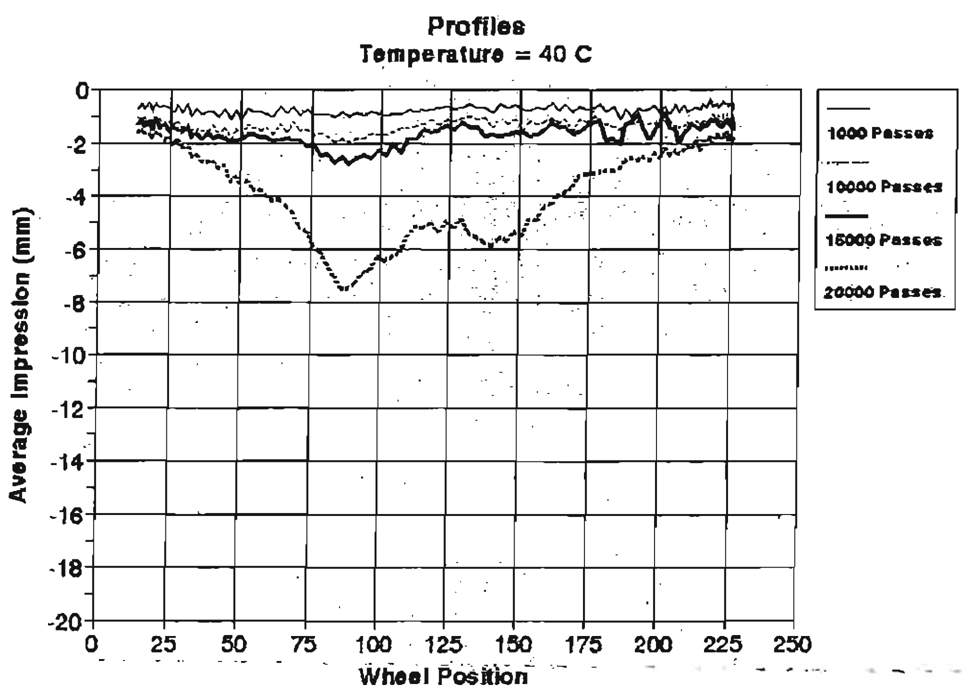
Mix 4, AC-20
Temperature = 50 C

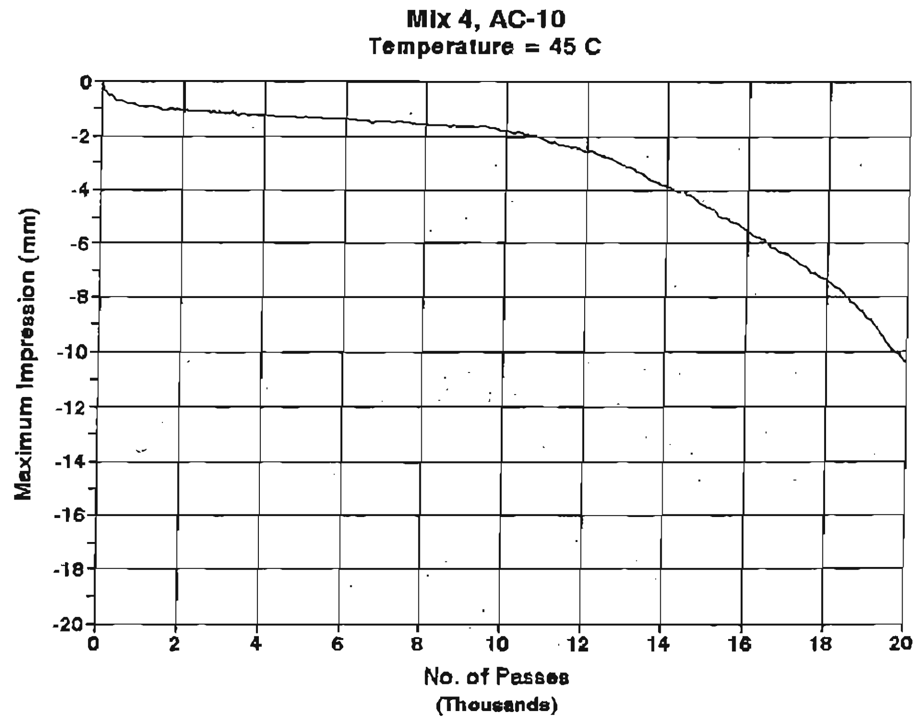


Profiles
Temperature = 50 C

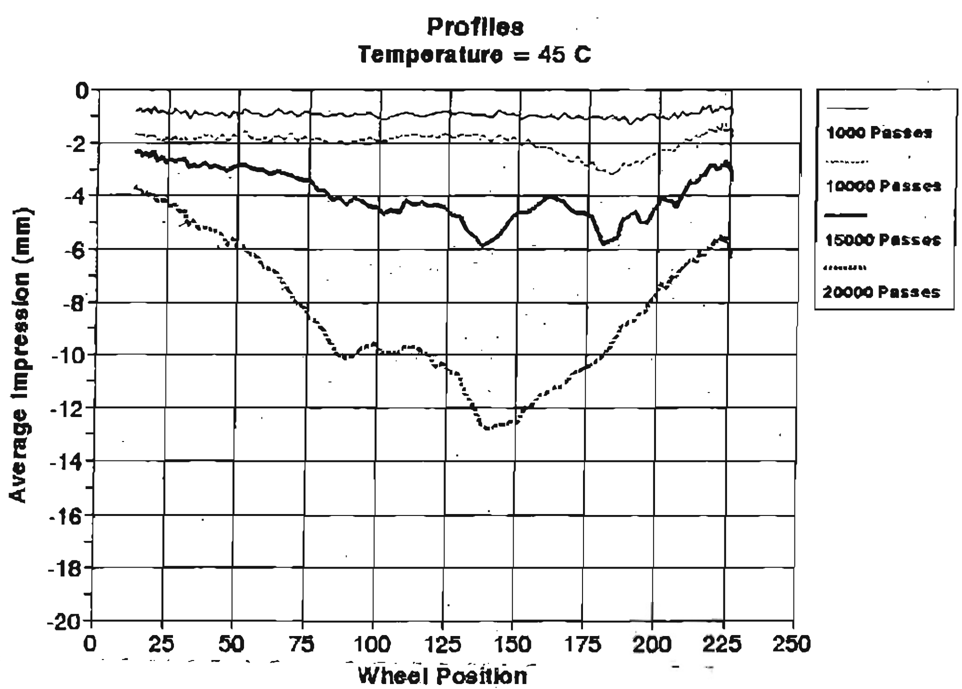



Mix 4, AC-10
Temperature = 40 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

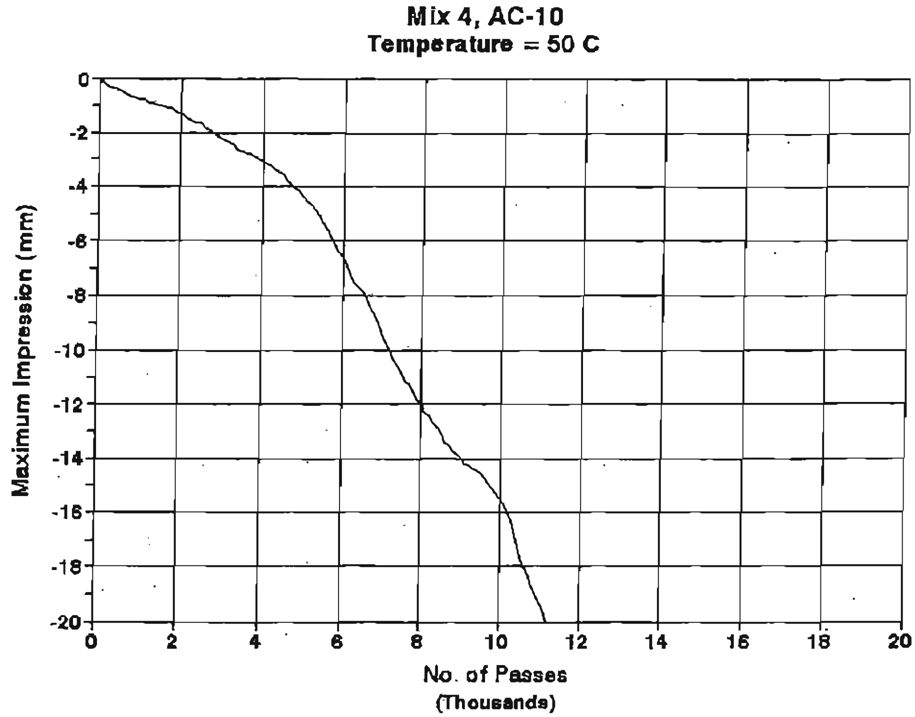

Profiles
Temperature = 40 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes



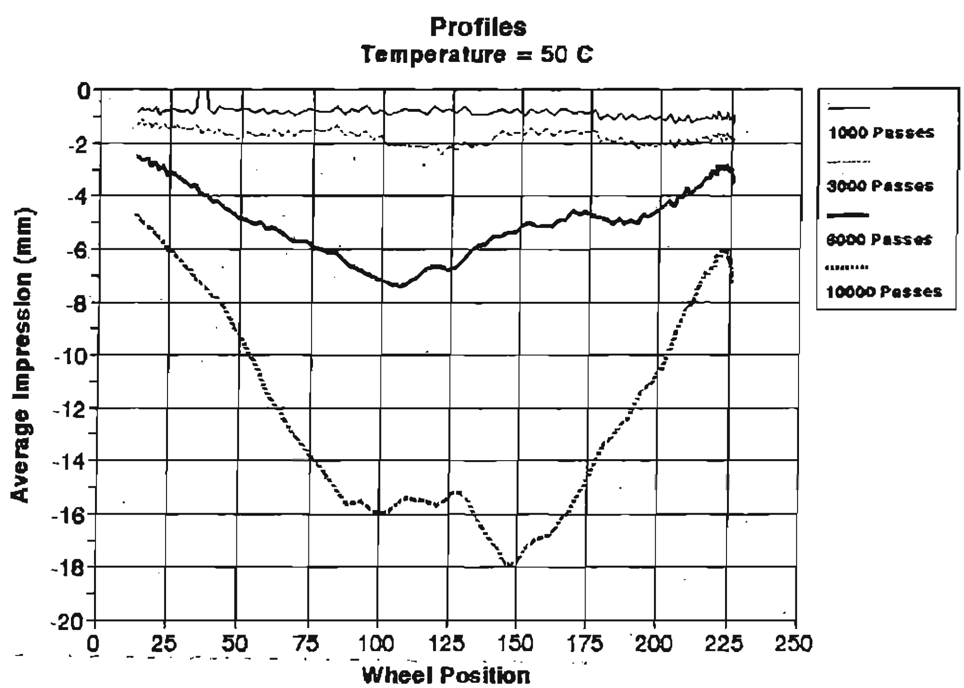
Mix 4, AC-10
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



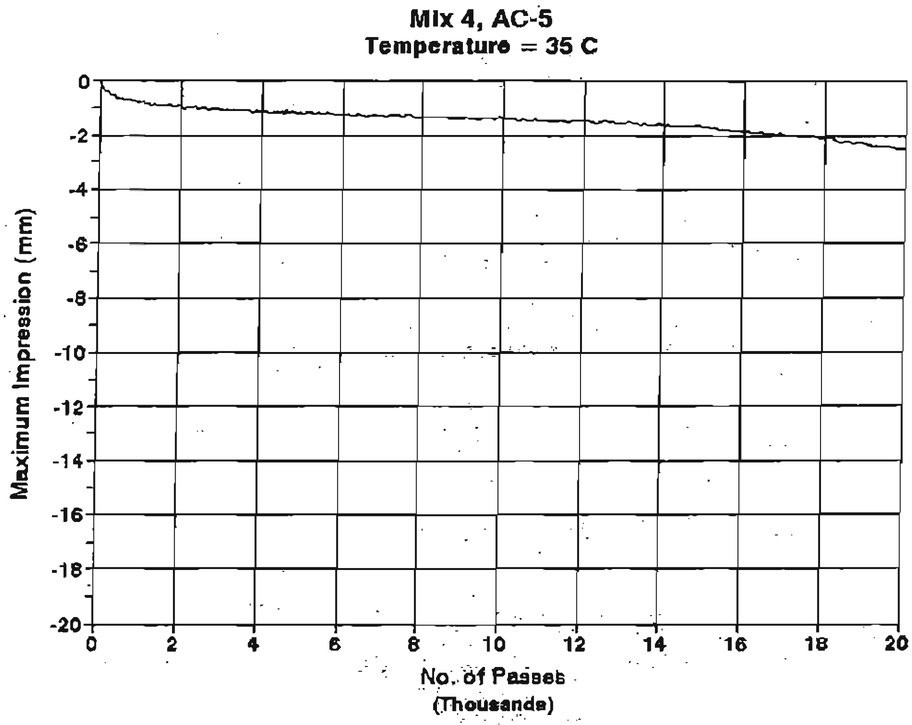
Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes



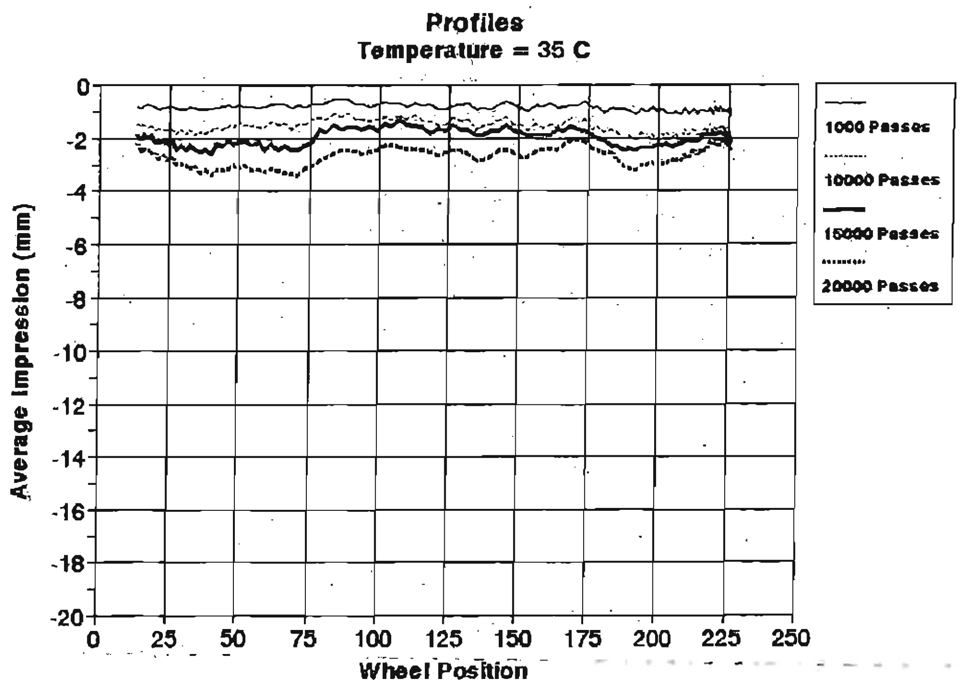
Mix 4, AC-10
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



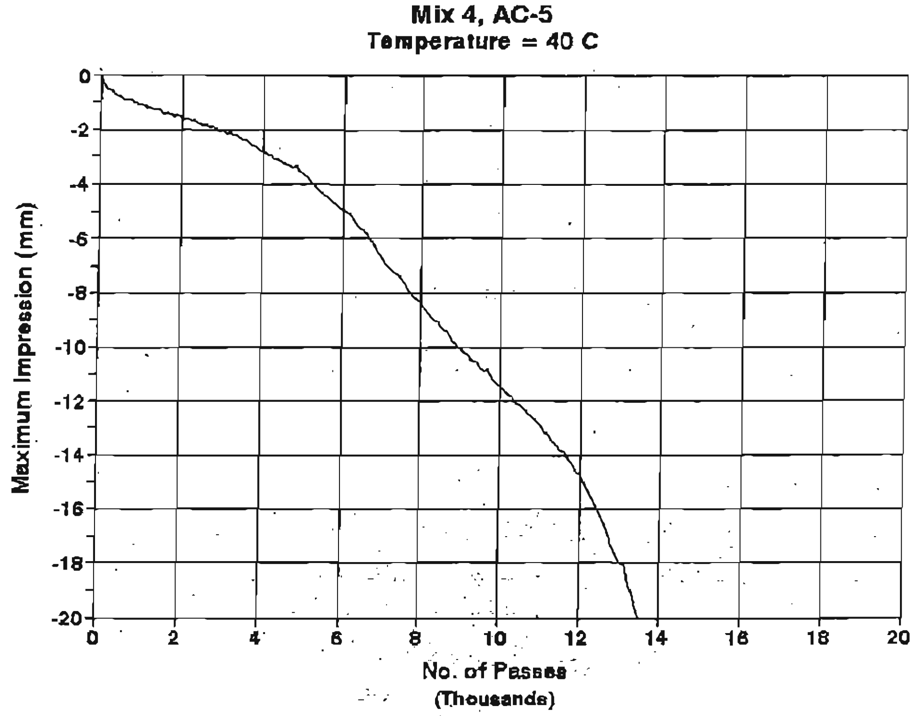
Profiles
Temperature = 50 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
3000 Passes
6000 Passes
10000 Passes



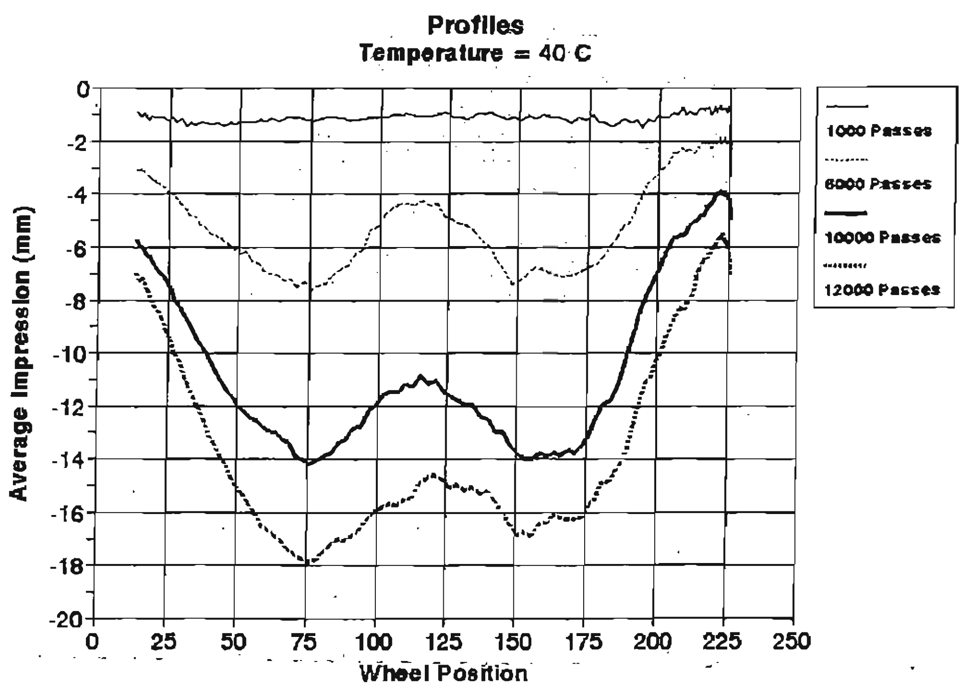
Mix 4, AC-5
Temperature = 35 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



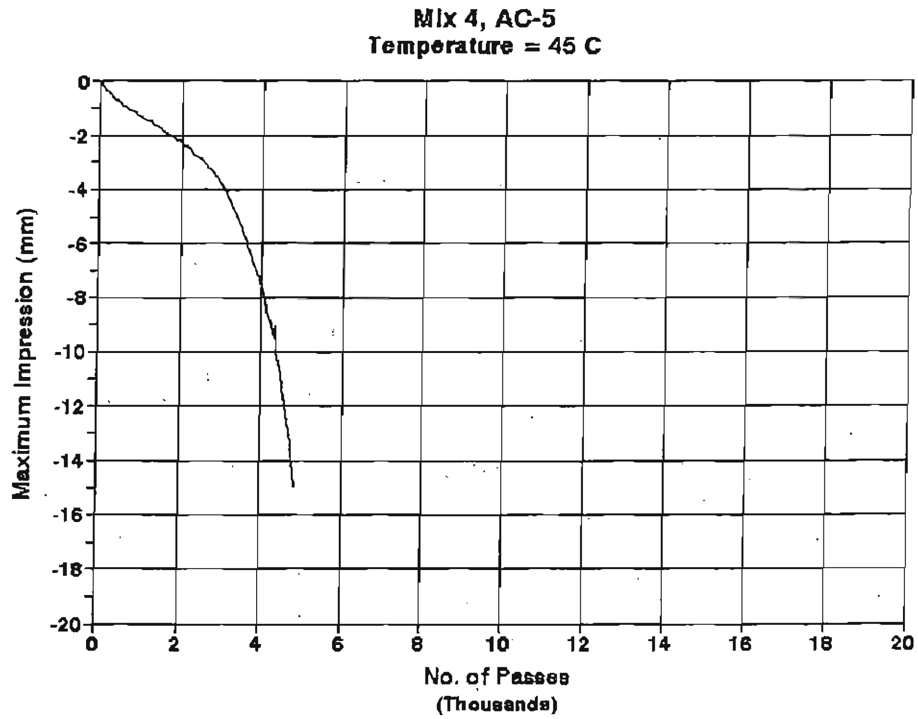
Profiles
Temperature = 35 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
1000 Passes
10000 Passes
15000 Passes
20000 Passes



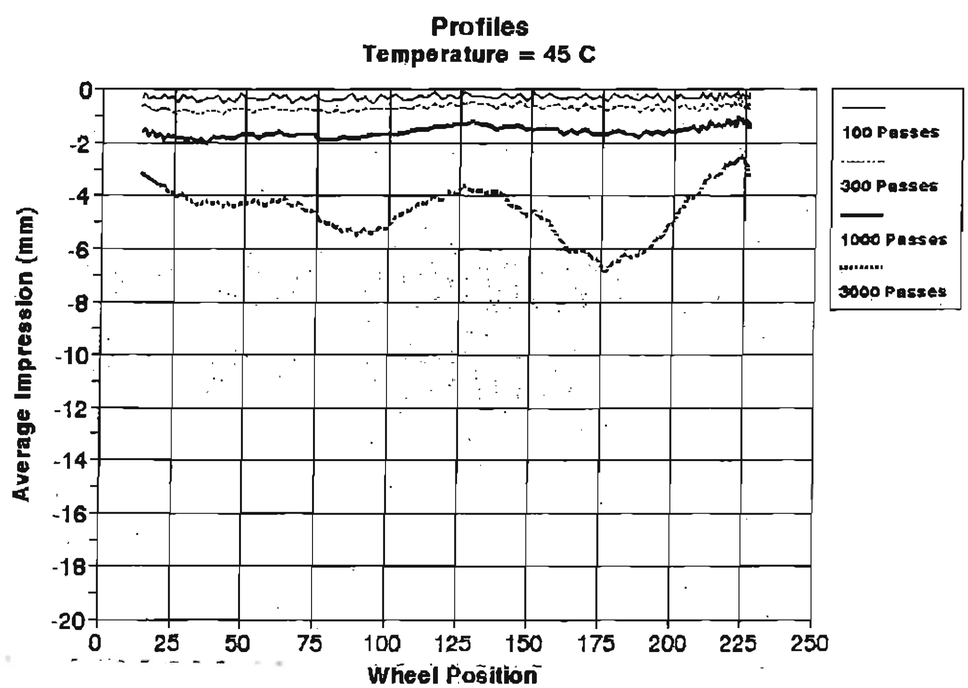
Mix 4, AC-5
Temperature = 40 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



Profiles
Temperature = 40 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



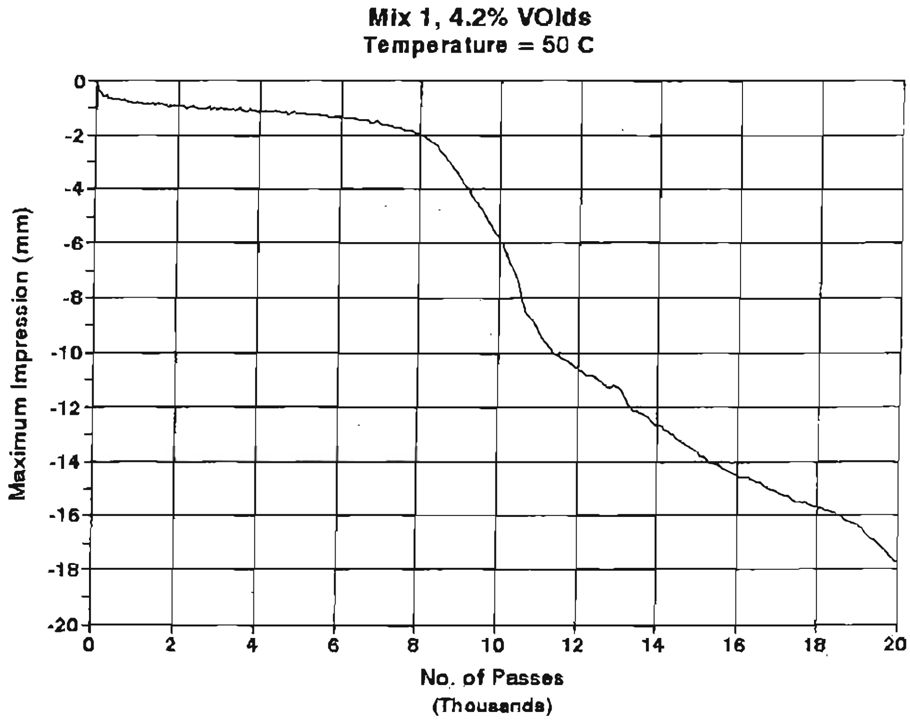
Mix 4, AC-5
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

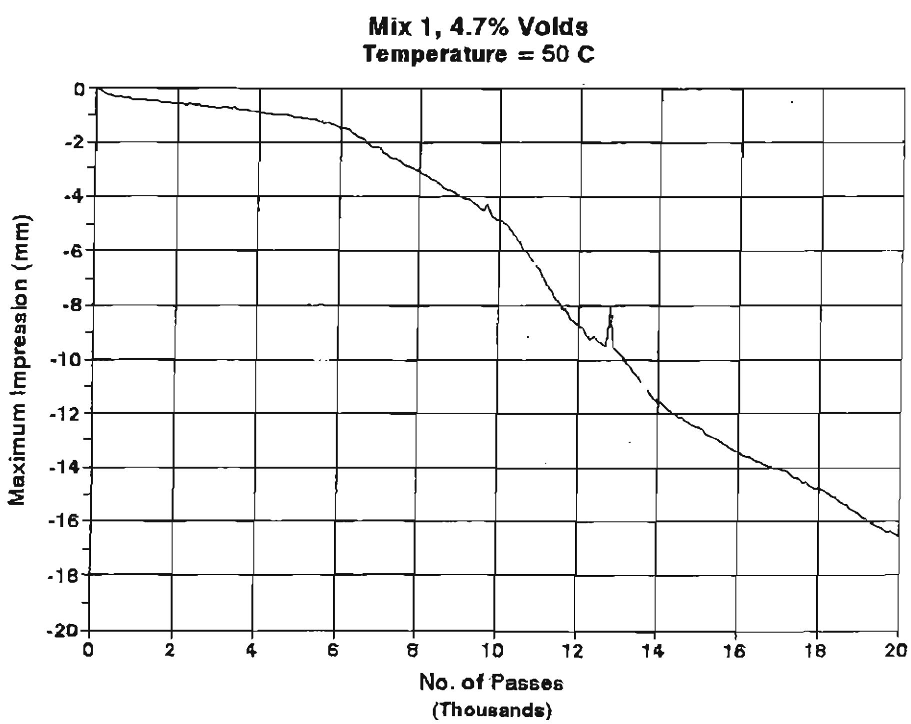


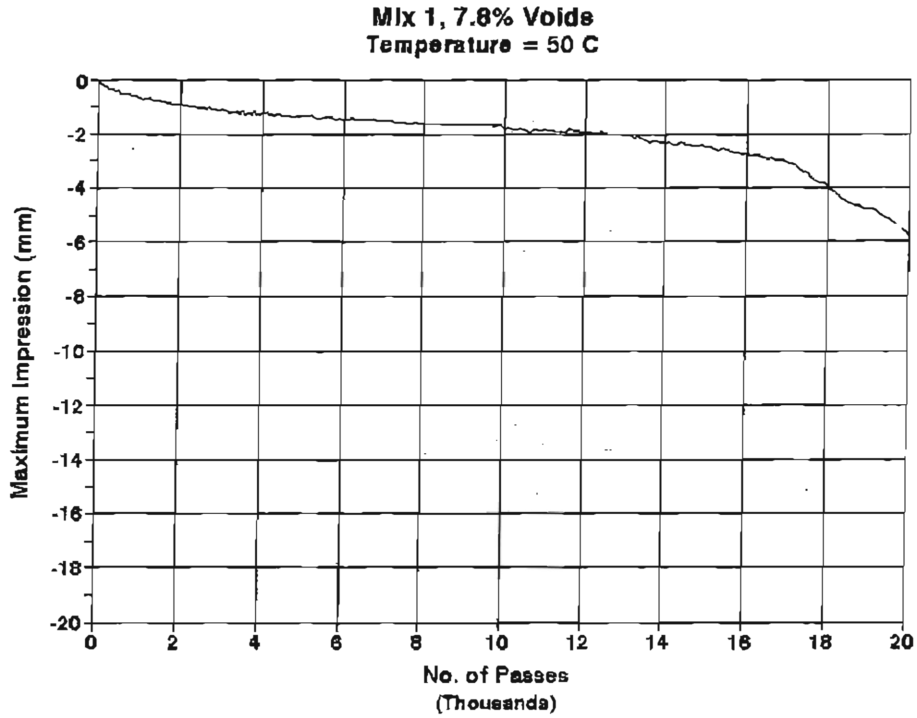
Profiles
Temperature = 45 C
Average Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
25
50
75
100
125
150
175
200
225
250
Wheel Position
100 Passes
300 Passes
1000 Passes
3000 Passes

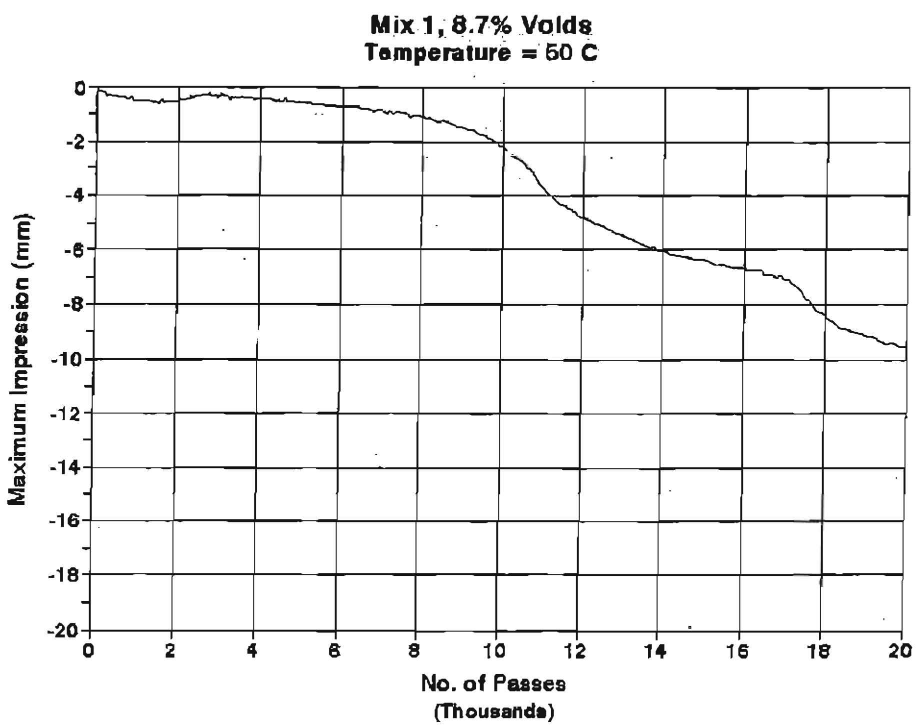
Appendix B

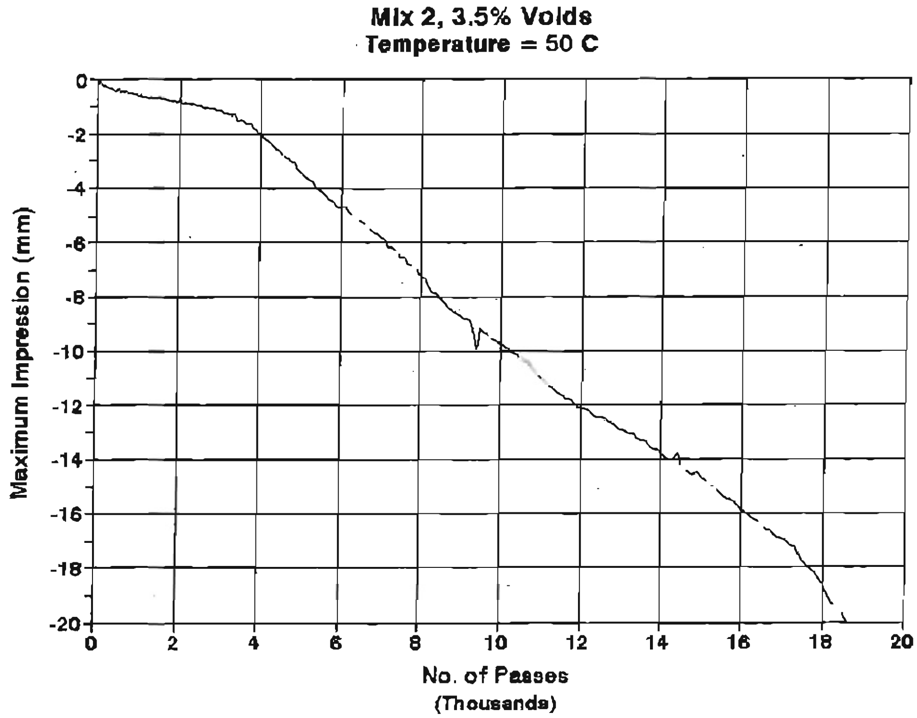
Hamburg Wheel-Tracking Results from the Influence of Air Void Study

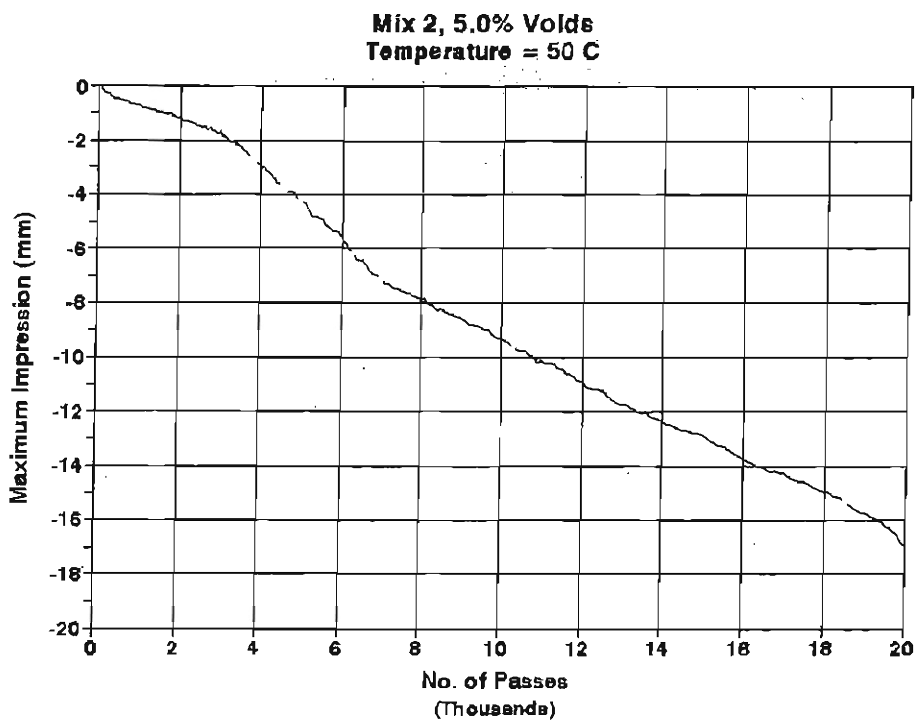

Mix 1, 4.2% VOlds
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

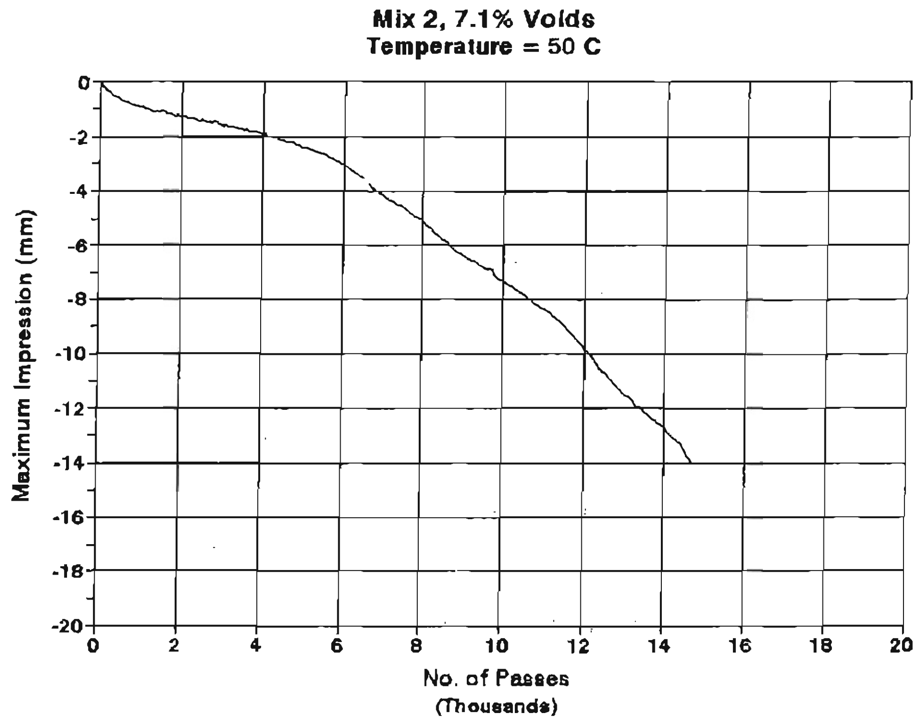

Mix 1, 4.7% Volds
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

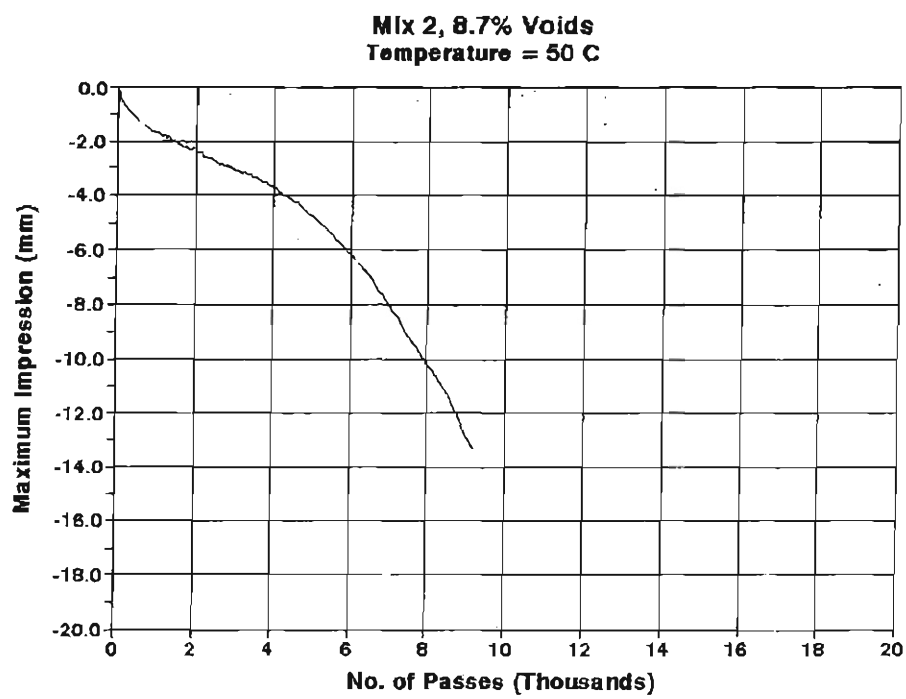

Mix 1, 7.8% Voids
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

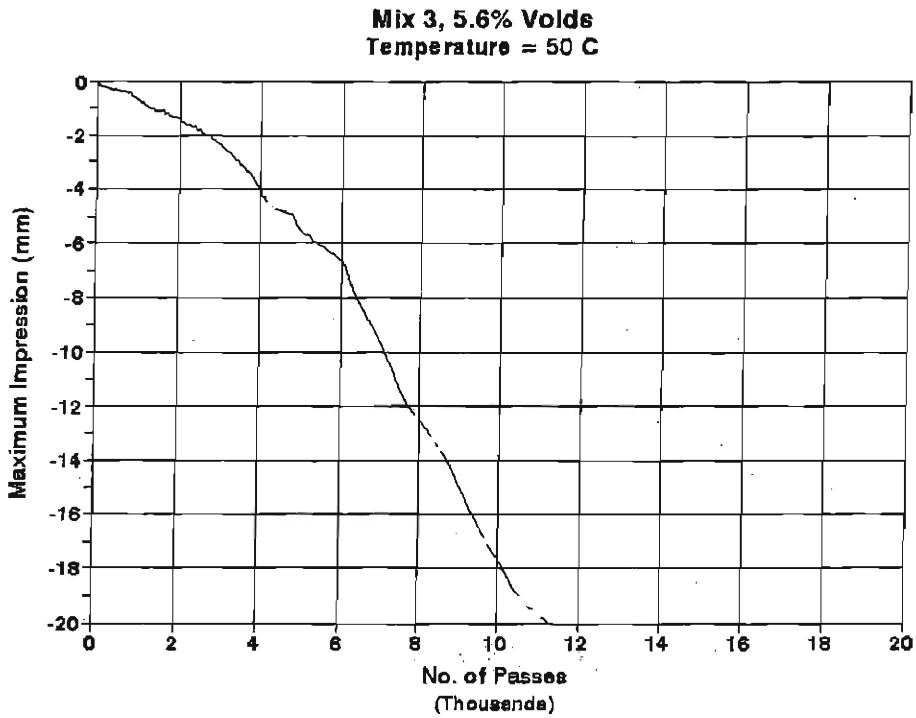

Mix 1, 8.7% Voids
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

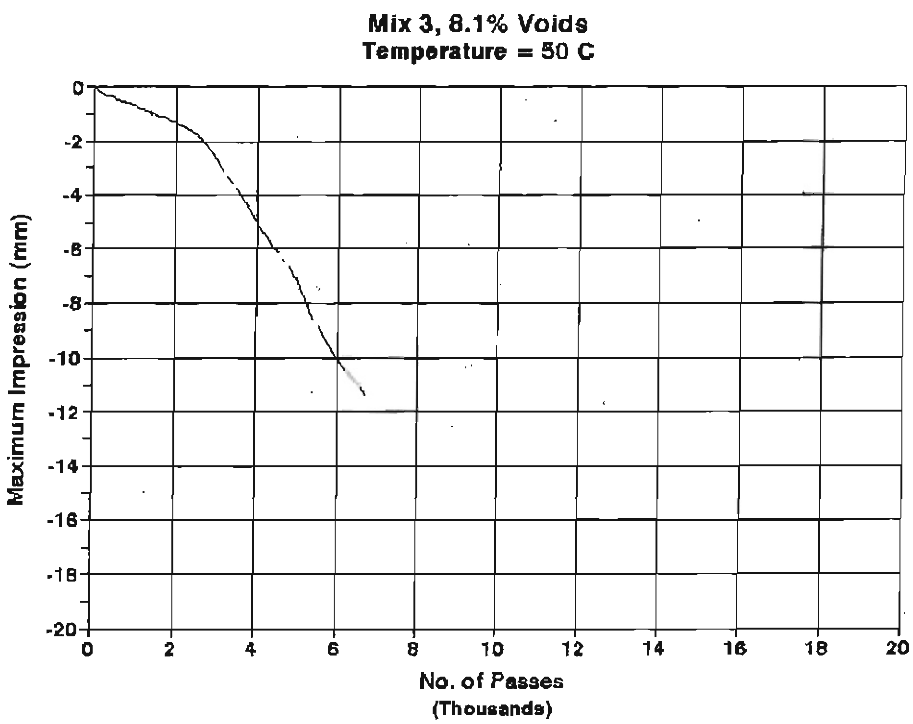

Mix 2, 3.5% Voids
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

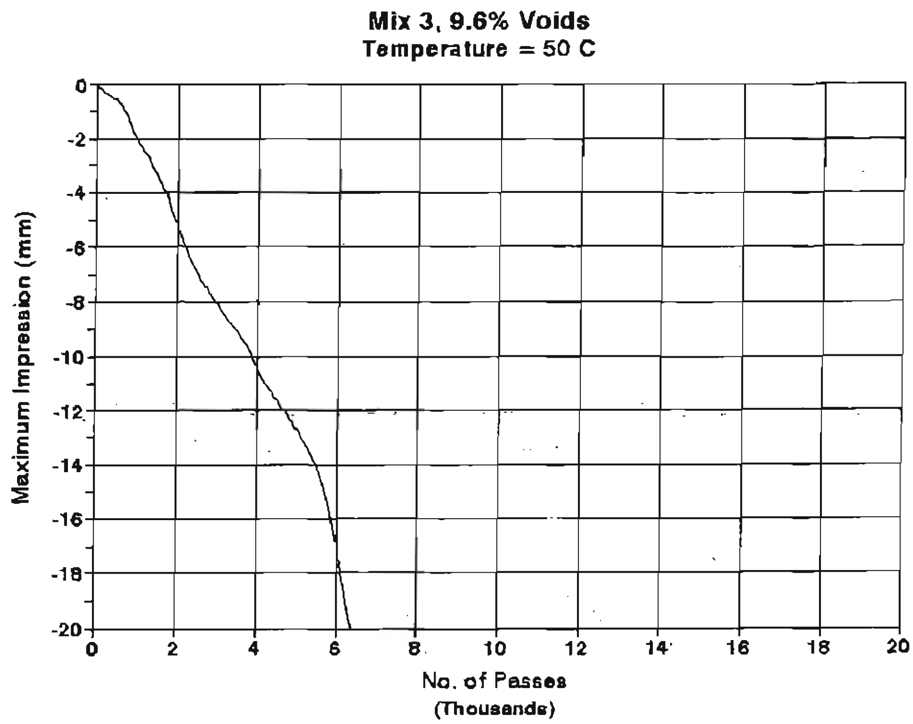

Mix 2, 5.0% Voids
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

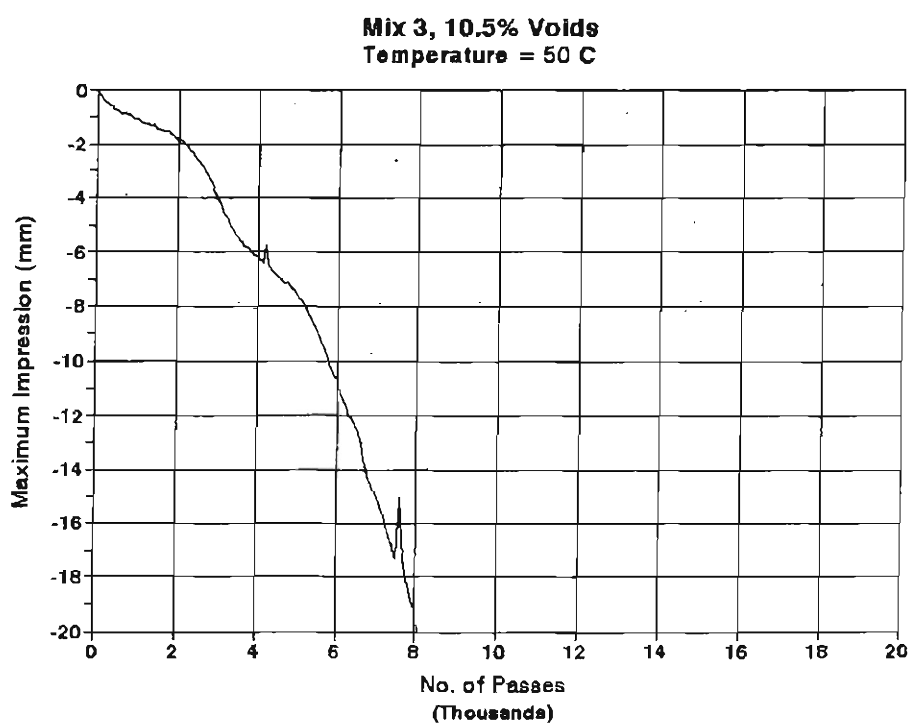

Mix 2, 7.1% Voids
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

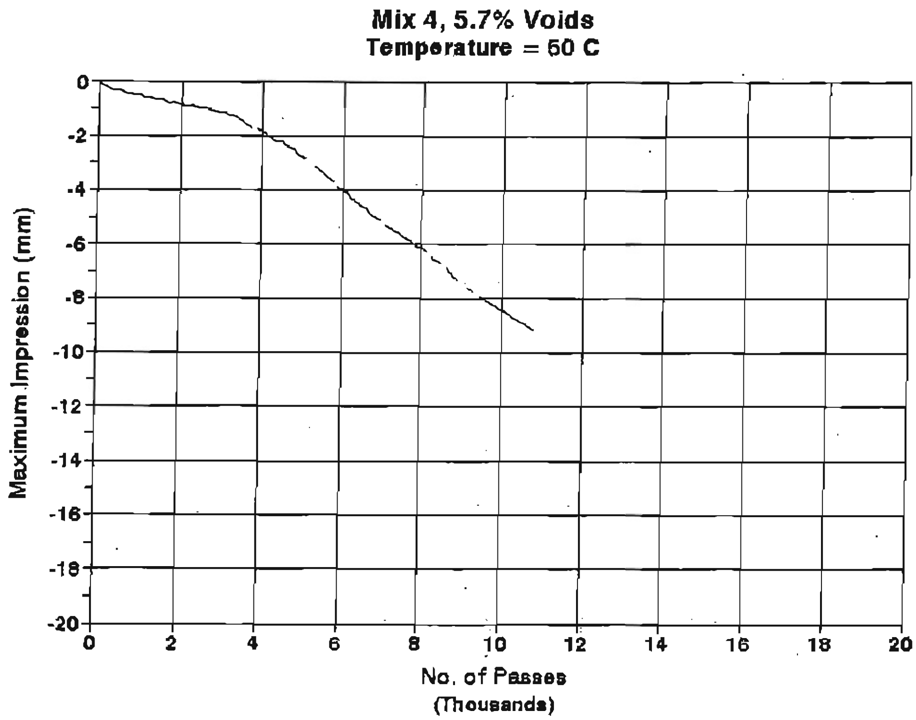

Mix 2, 8.7% Voids
Temperature = 50 C
Maximum Impression (mm)
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
-14.0
-16.0
-18.0
-20.0
0
2
4
6
8
10
12
14
16
18
20
No. of Passes (Thousands)

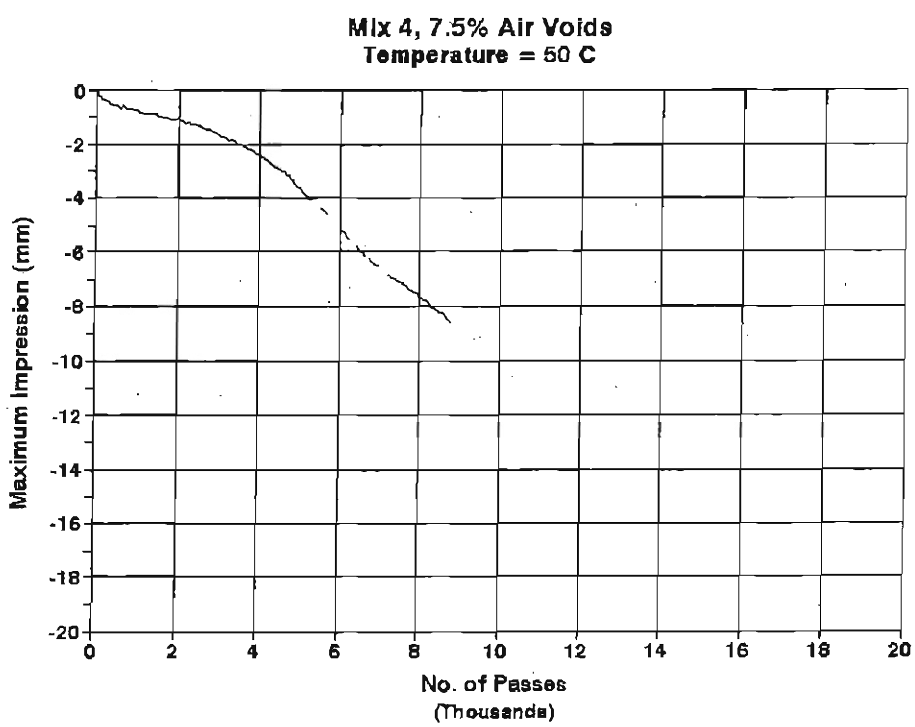

Mix 3, 5.6% Voids
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

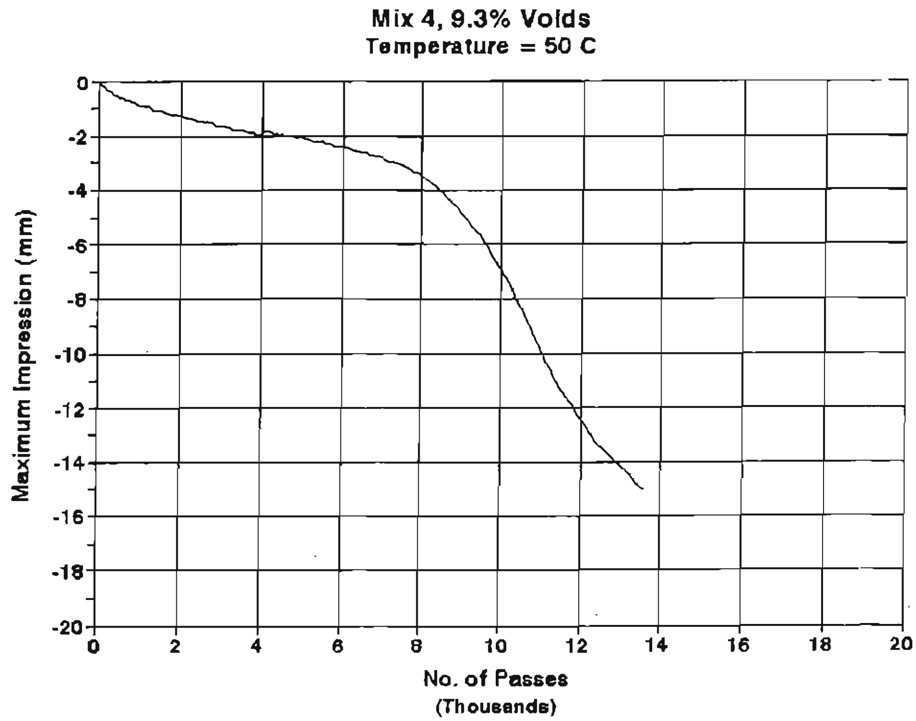

Mix 3, 8.1% Voids
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

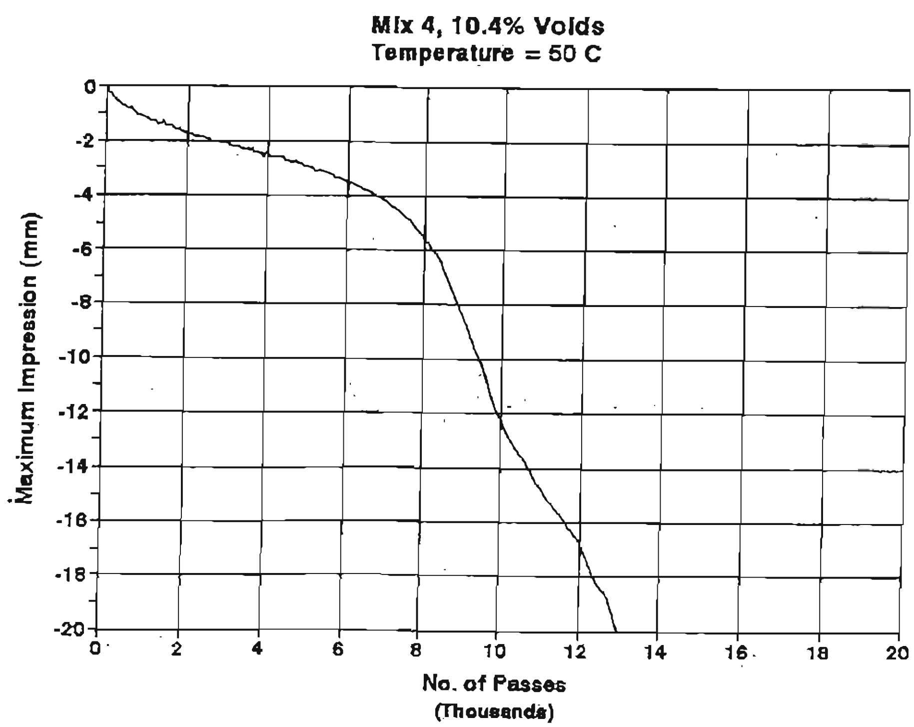

Mix 3, 9.6% Voids
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)


Mix 3, 10.5% Voids
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)


Mix 4, 5.7% Voids
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)

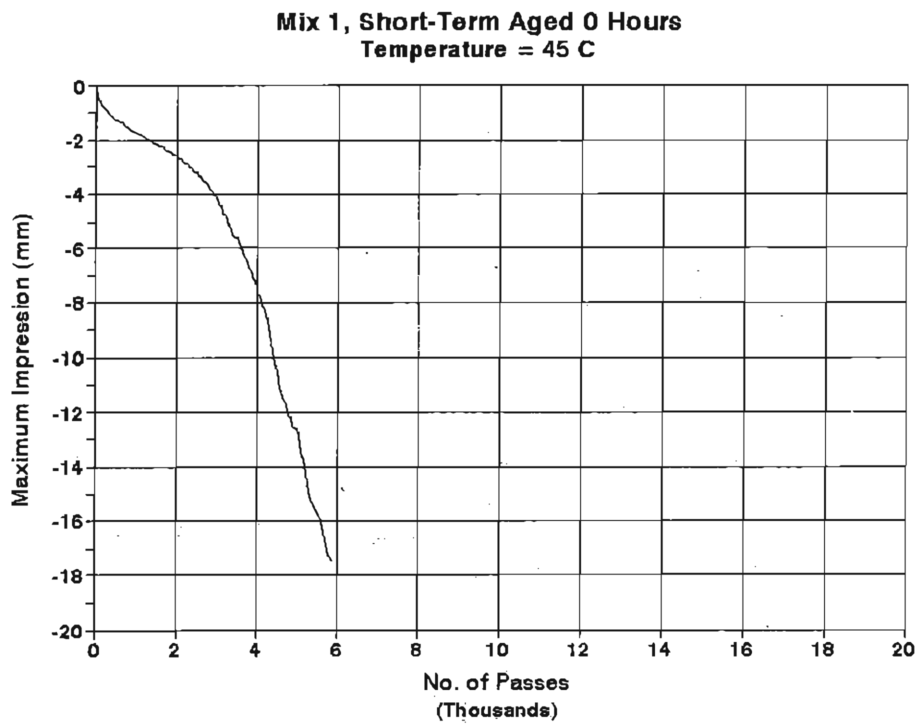

Mix 4, 7.5% Air Voids
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

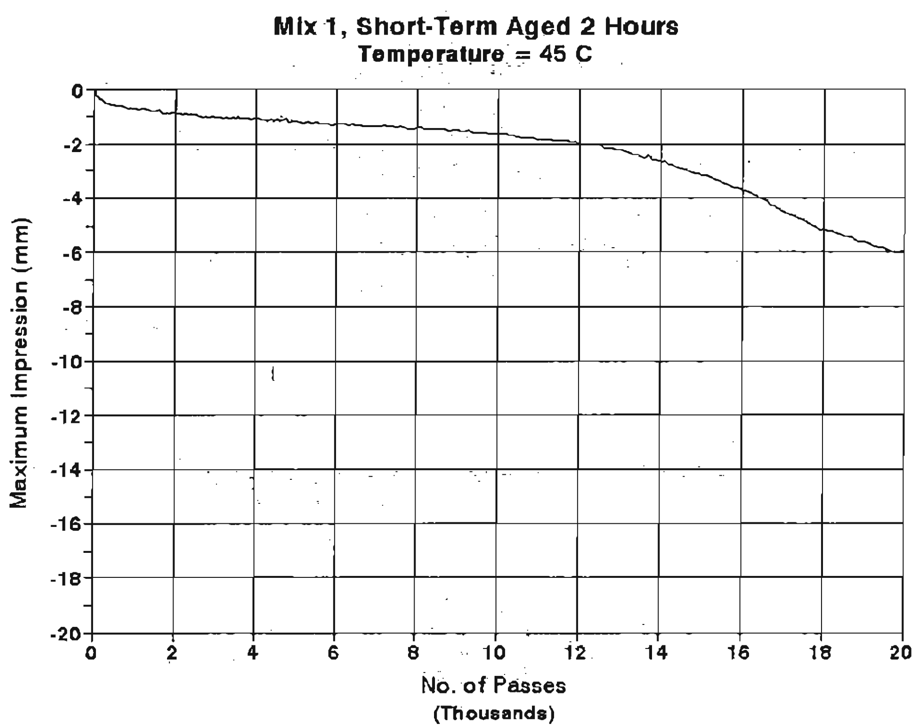

Mix 4, 9.3% Voids
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)


Mix 4, 10.4% Voids
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)

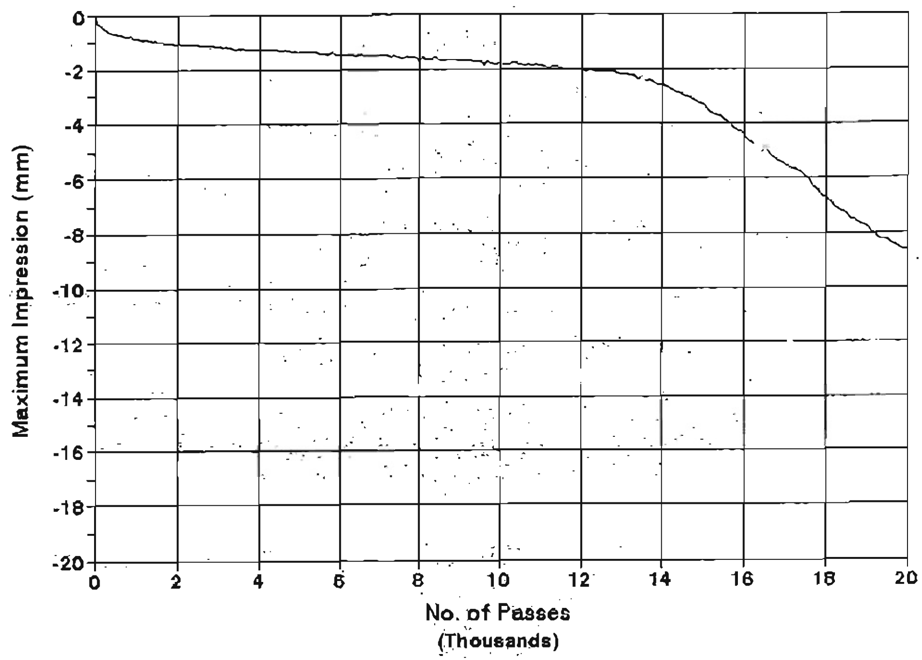
Appendix C

Hamburg Wheel-Tracking Results from the Short-Term Aging Study

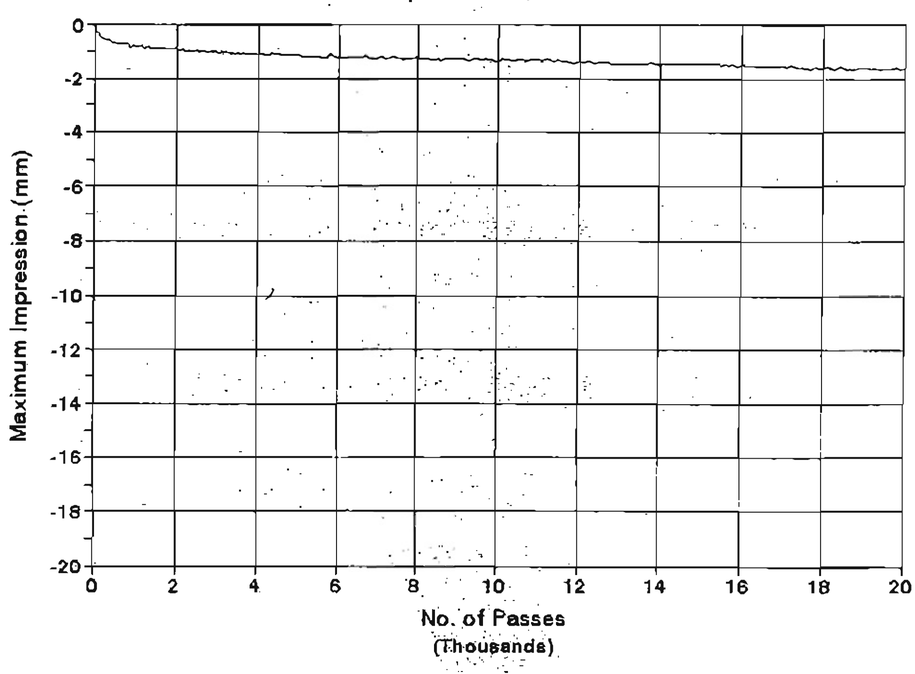

Mix 1, Short-Term Aged 0 Hours
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

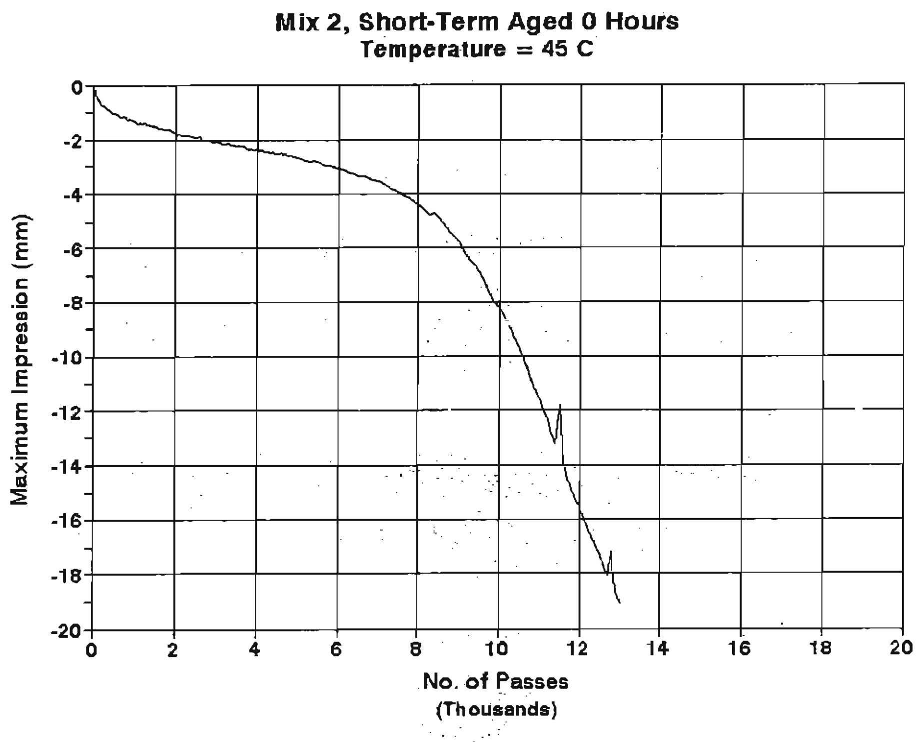

Mix 1, Short-Term Aged 2 Hours
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

Mix 1, Short-Term Aged 4 Hours
Temperature = 45 C

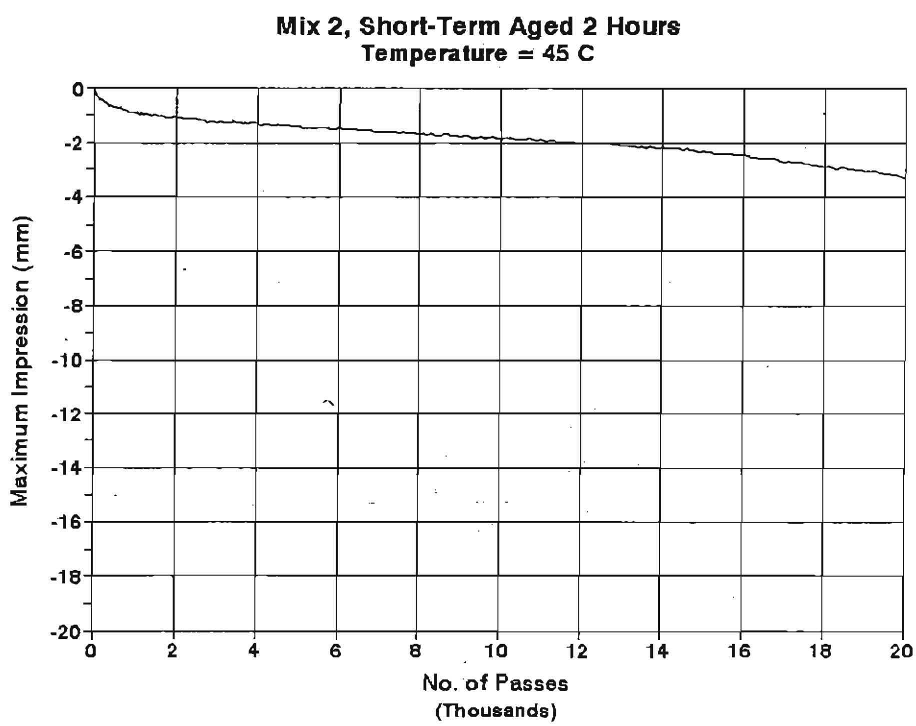


Mix 1, Short-Term Aged 8 Hours
Temperature = 45 C

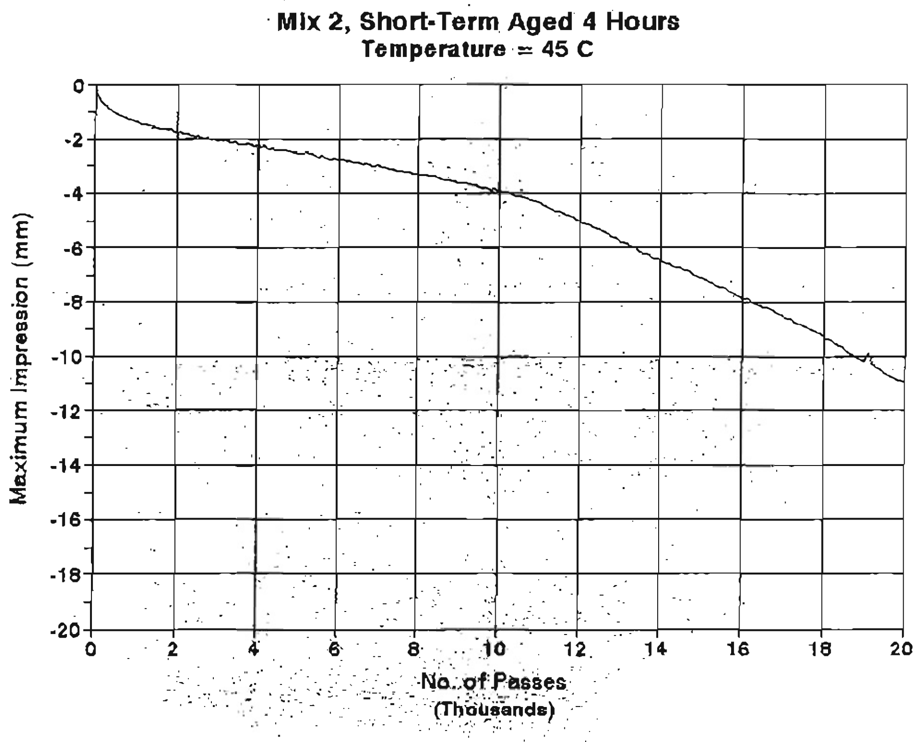


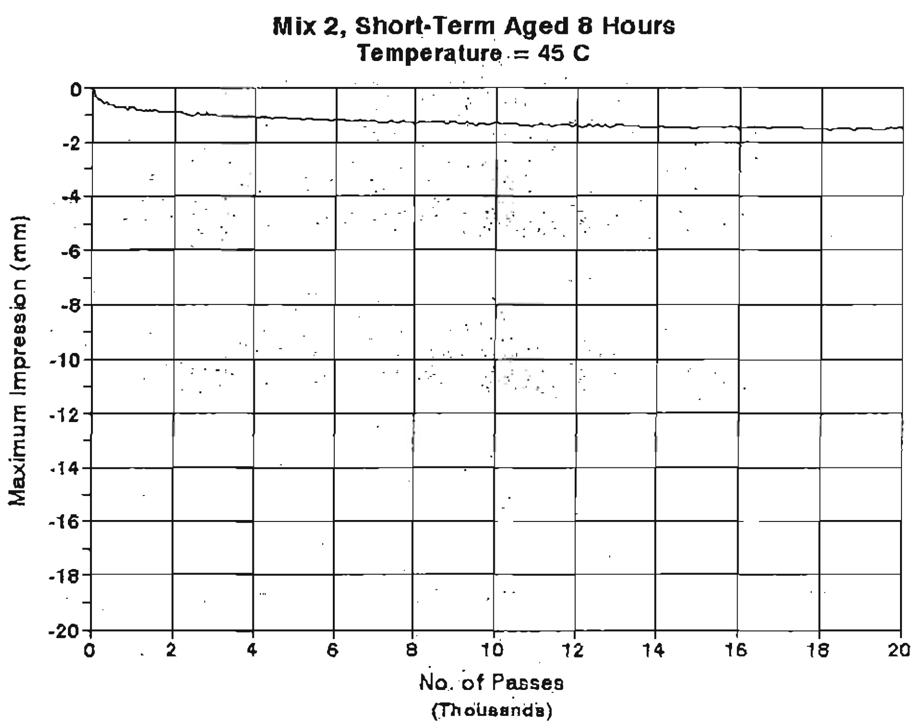


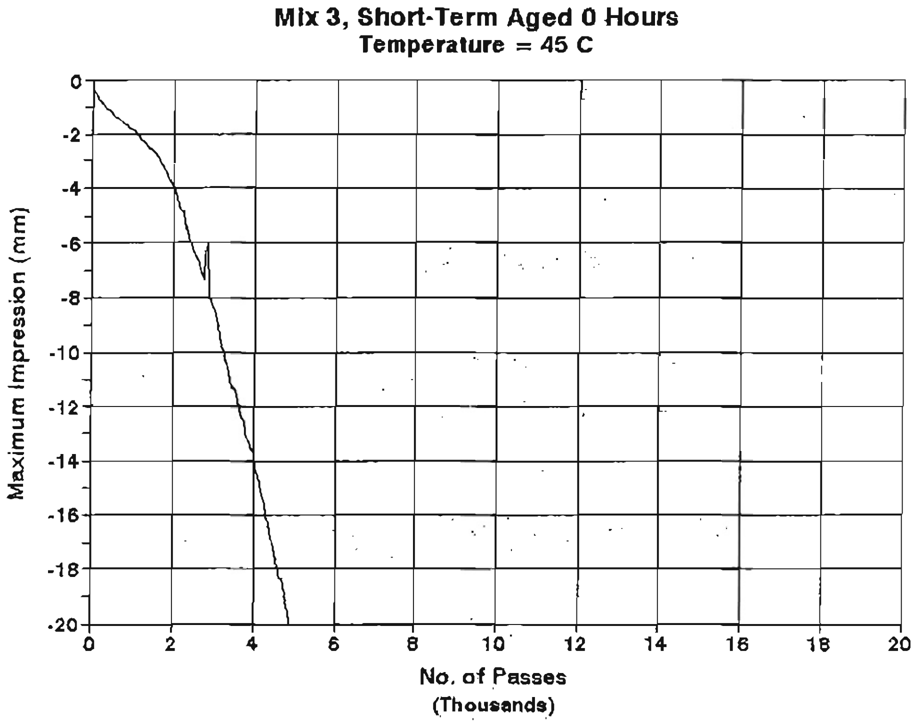
Mix 2, Short-Term Aged 0 Hours
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



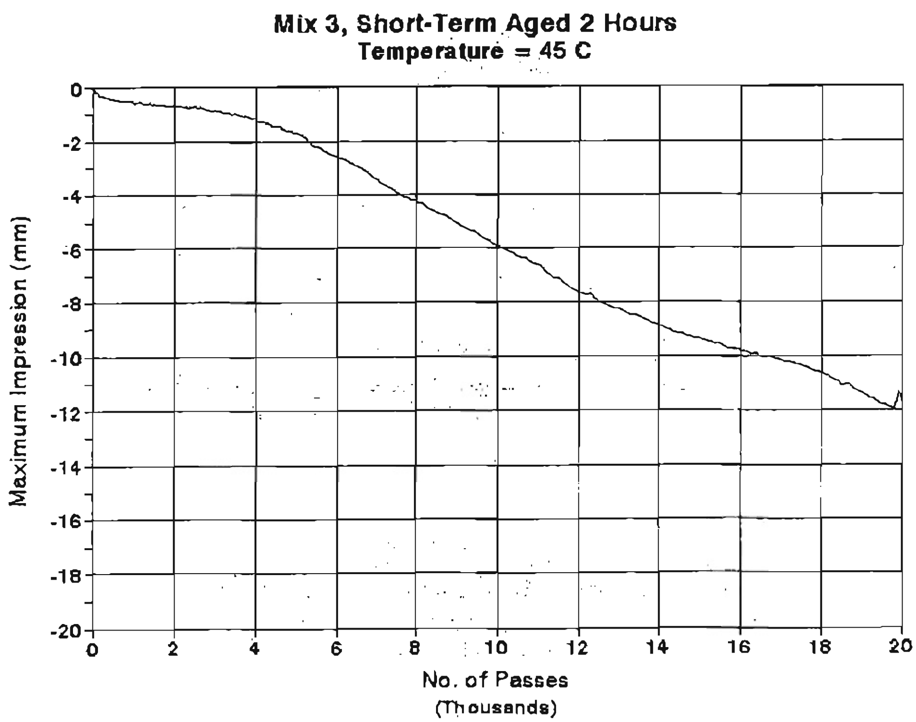
Mix 2, Short-Term Aged 2 Hours
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)


Mix 2, Short-Term Aged 4 Hours
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)

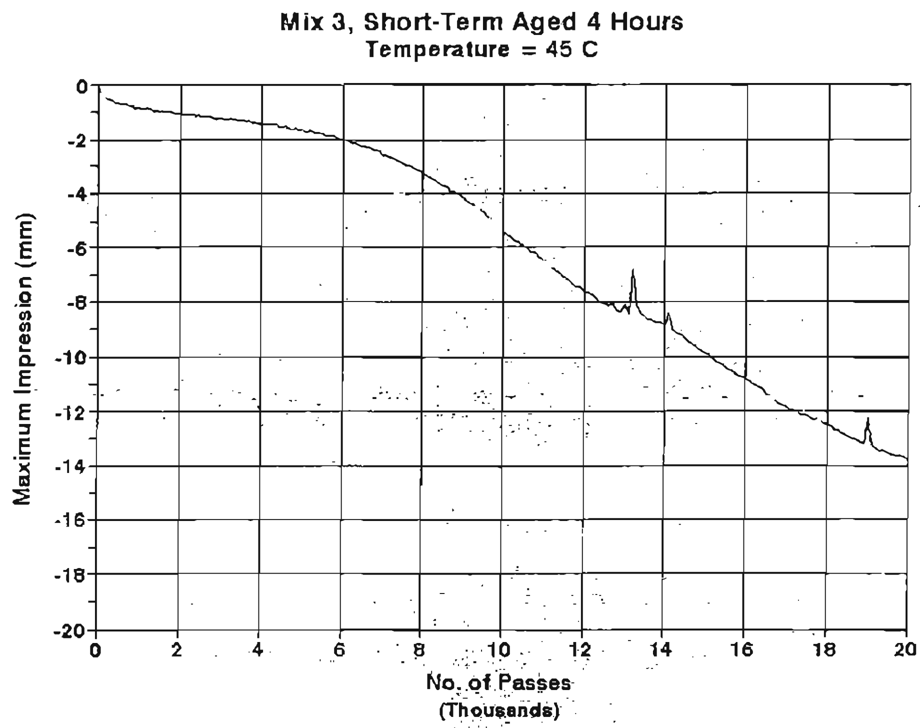

Mix 2, Short-Term Aged 8 Hours
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

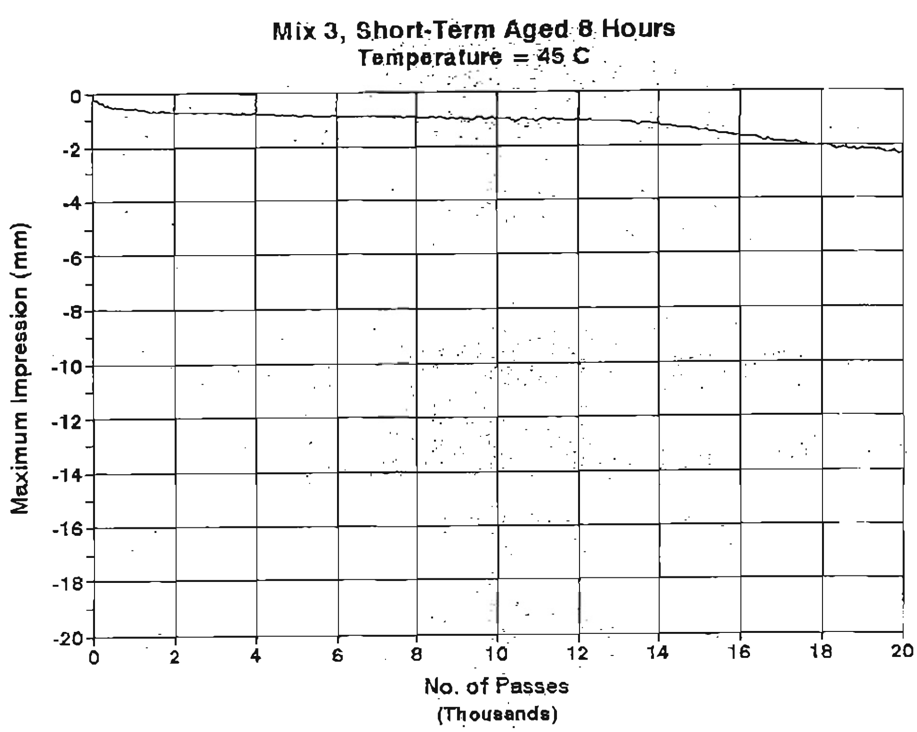


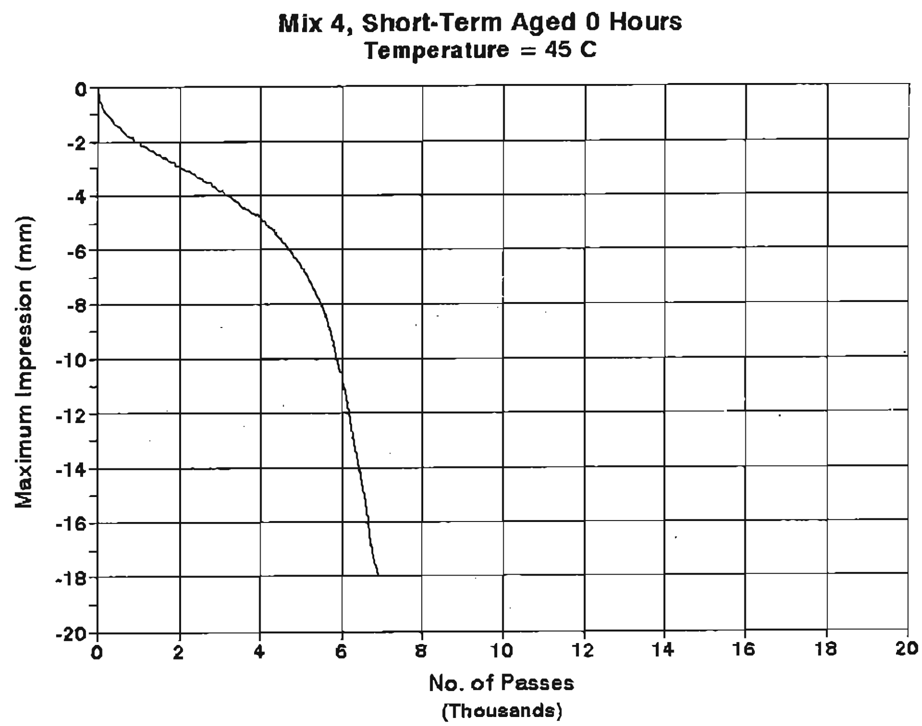
Mix 3, Short-Term Aged 0 Hours
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



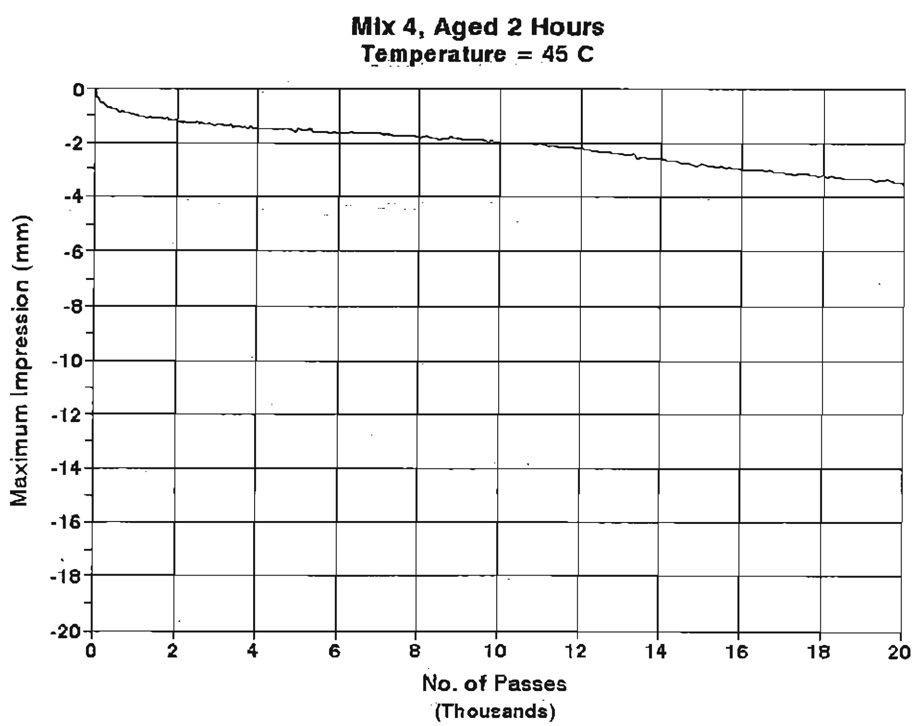
Mix 3, Short-Term Aged 2 Hours
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)


Mix 3, Short-Term Aged 4 Hours
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)

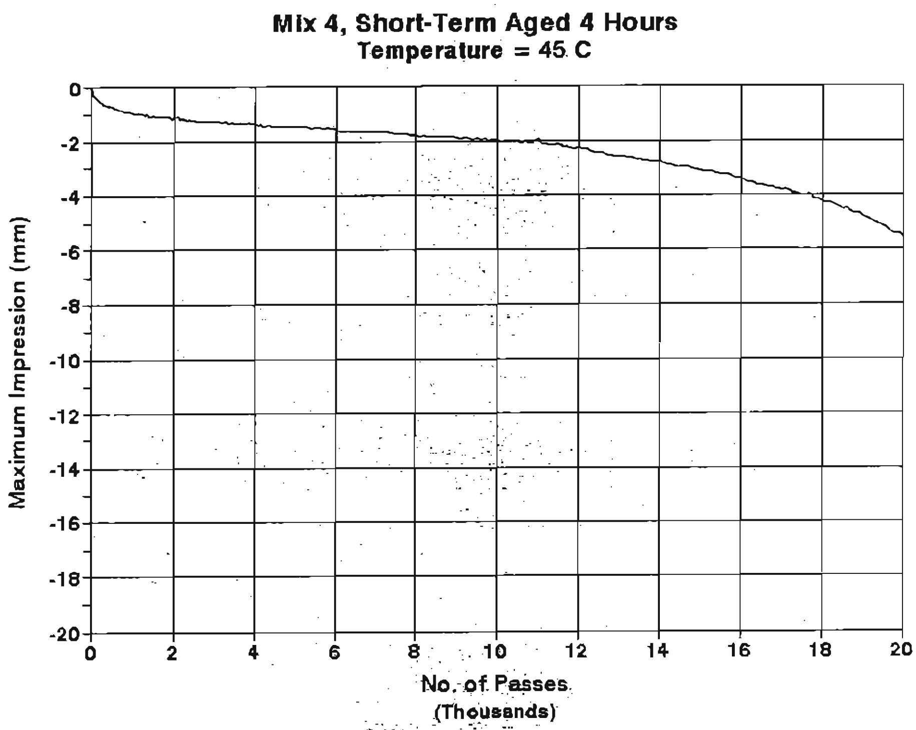

Mix 3, Short-Term Aged 8 Hours
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

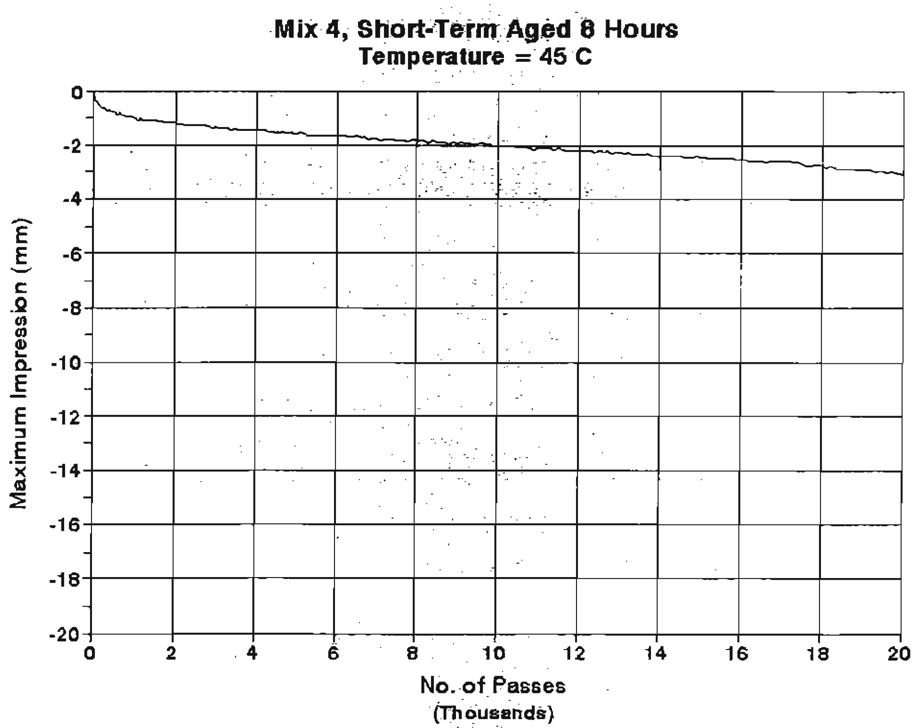


Mix 4, Short-Term Aged 0 Hours
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)



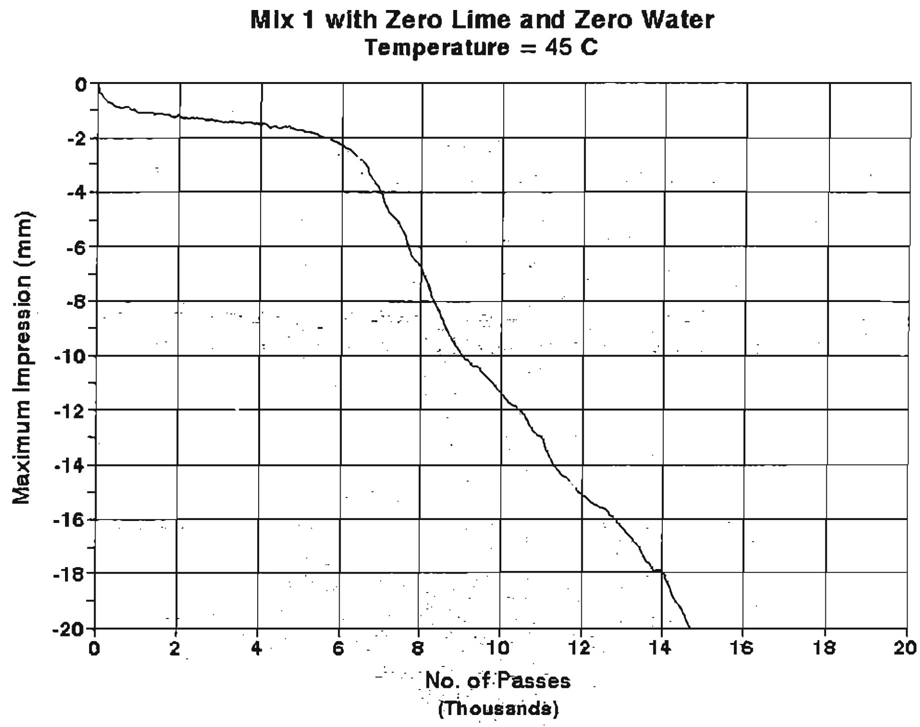
Mix 4, Aged 2 Hours
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)


Mix 4, Short-Term Aged 4 Hours
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)

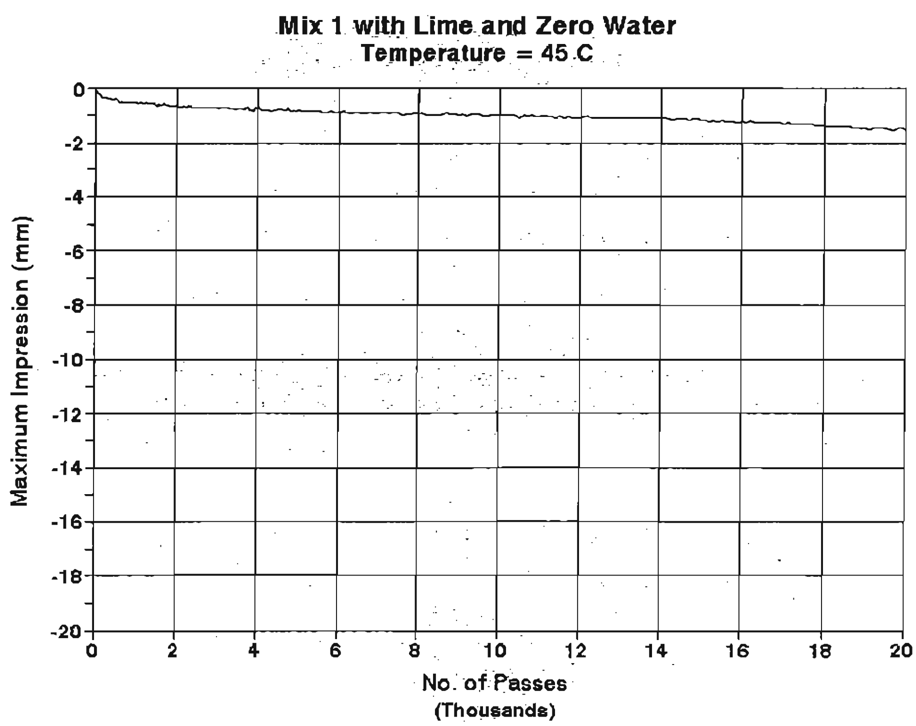

Mix 4, Short-Term Aged 8 Hours
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

Appendix D

Hamburg Wheel-Tracking Results from the Lime Mixing Study

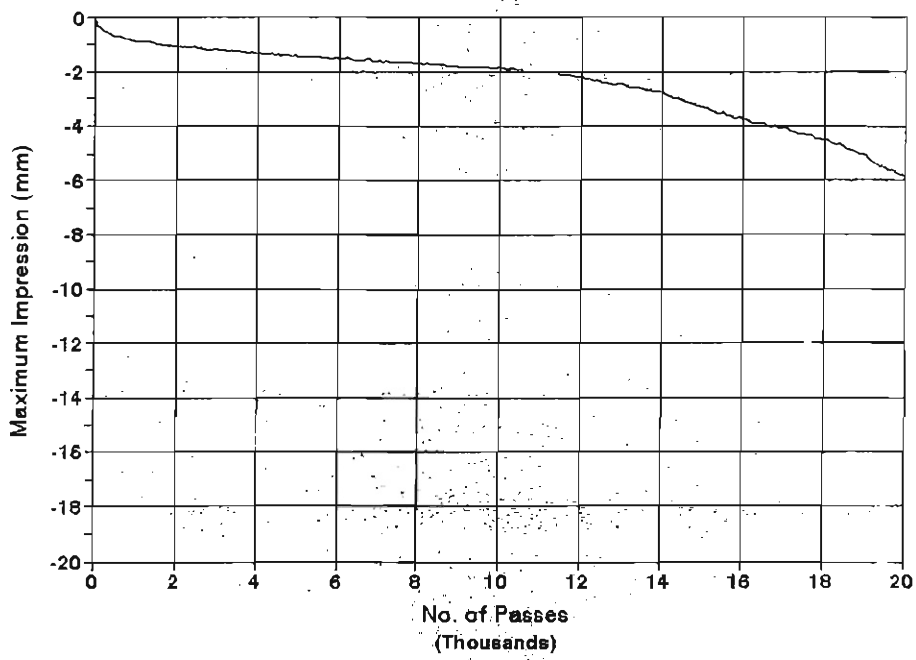


Mix 1 with Zero Lime and Zero Water
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

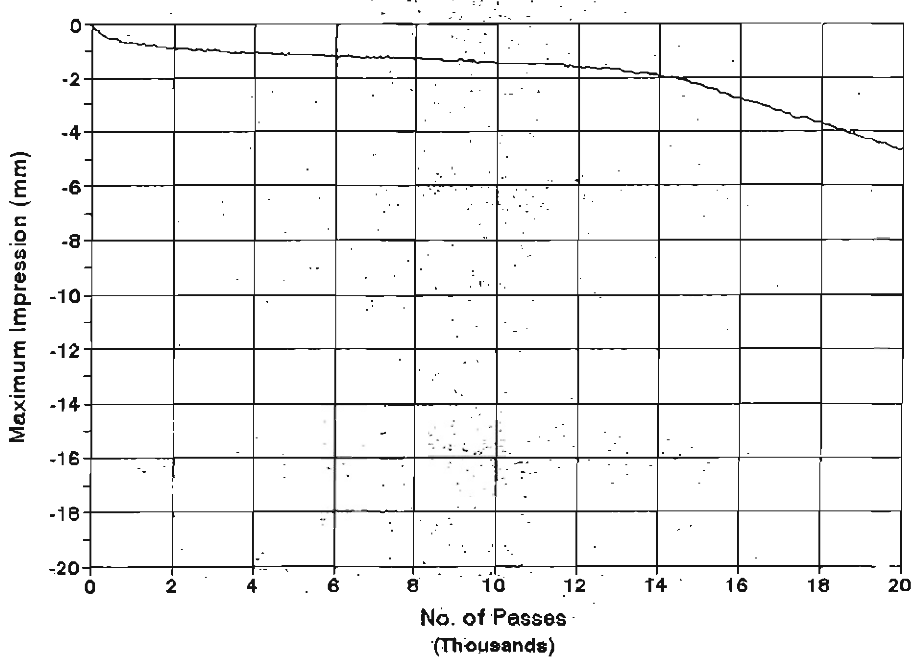


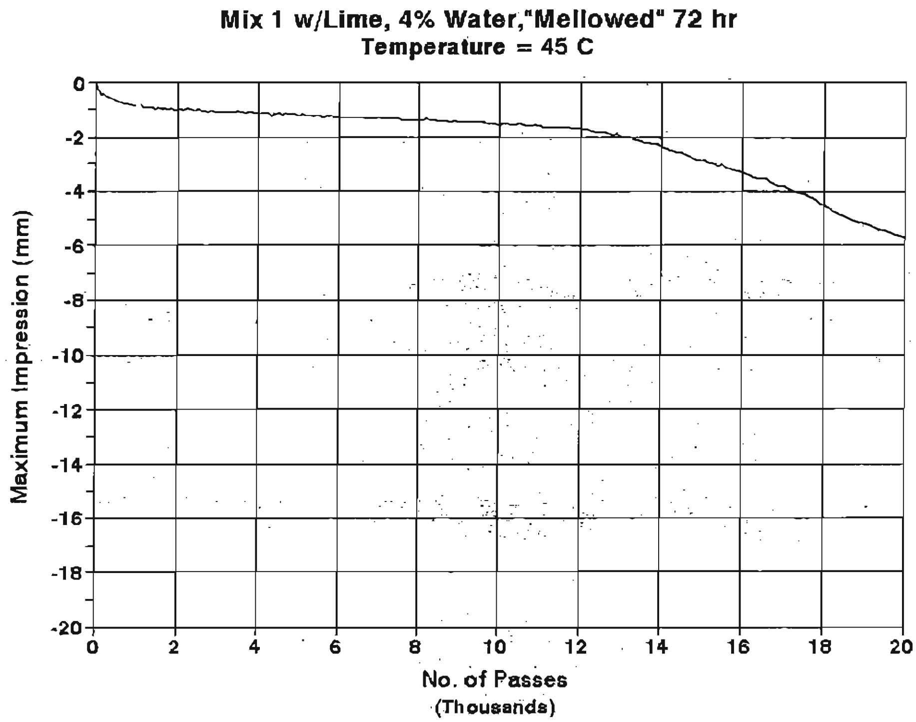
Mix 1 with Lime and Zero Water
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

Mix 1 with Lime and 2% Water
Temperature = 45 C

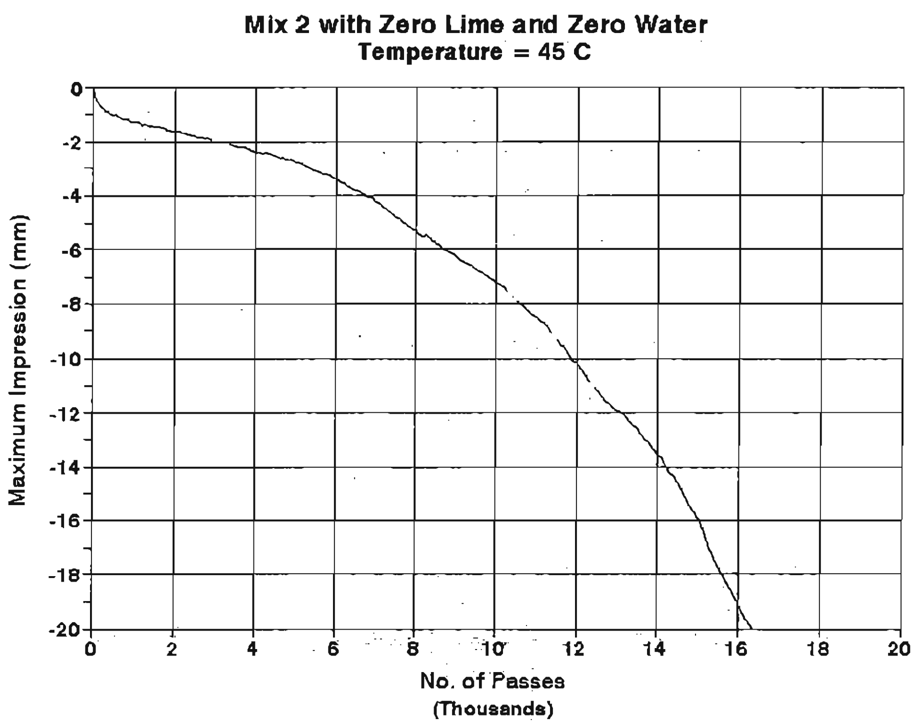


Mix 1 with Lime and 4% Water
Temperature = 45 C



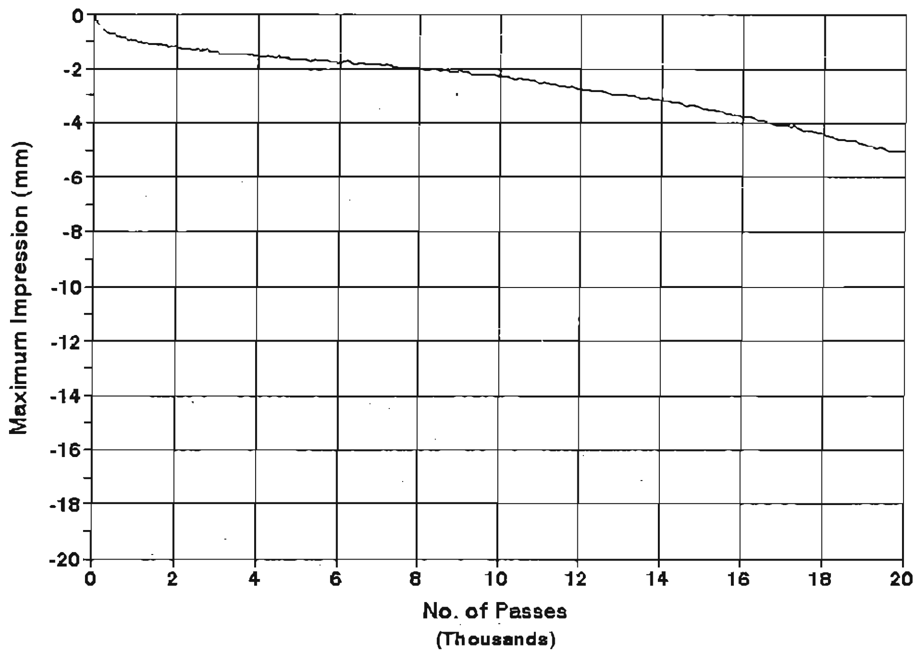


Mix 1 w/Lime, 4% Water,"Mellowed" 72 hr
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

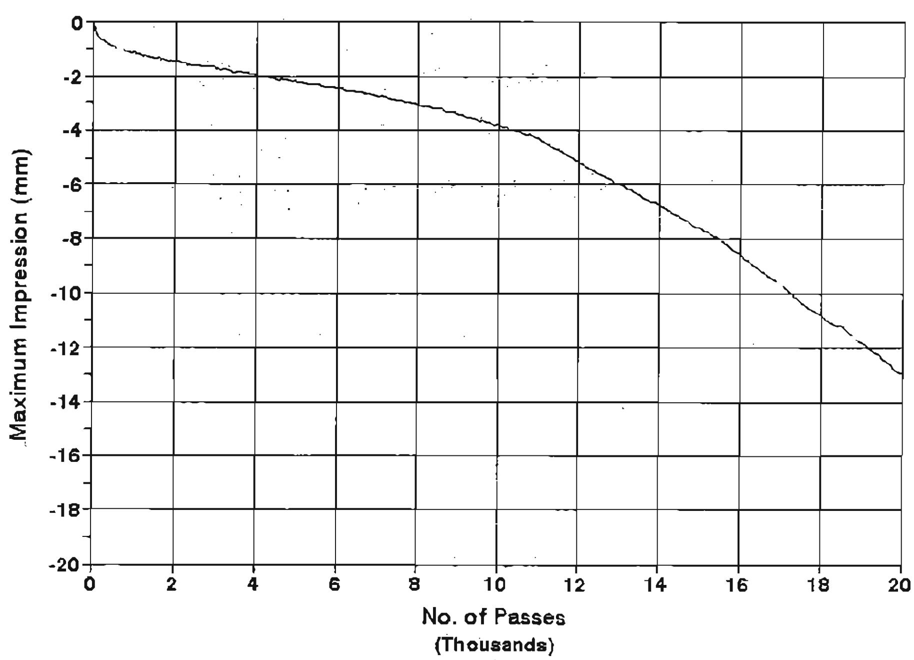


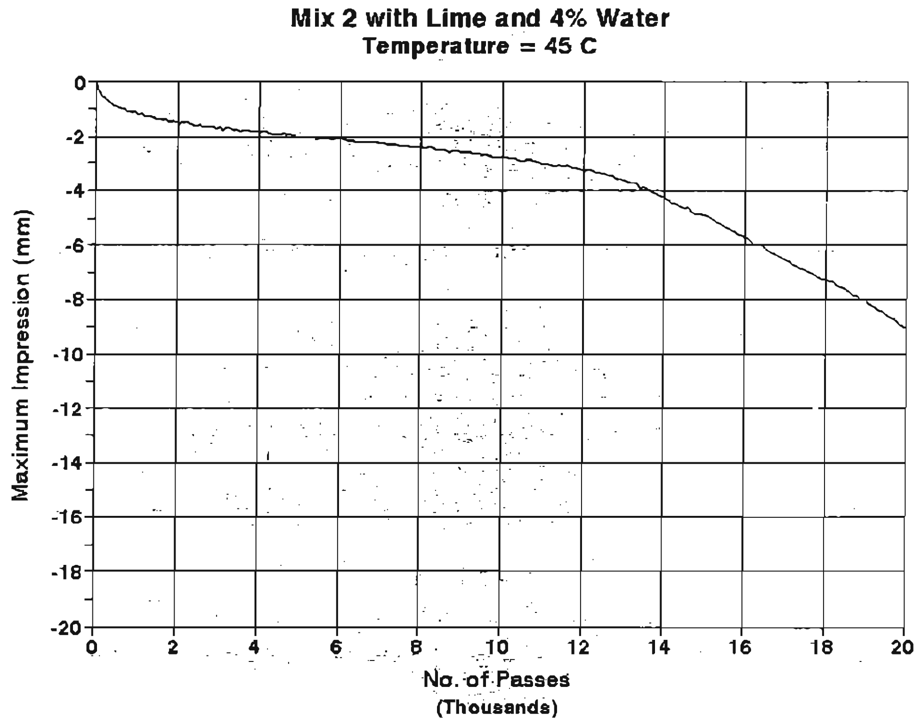
Mix 2 with Zero Lime and Zero Water
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

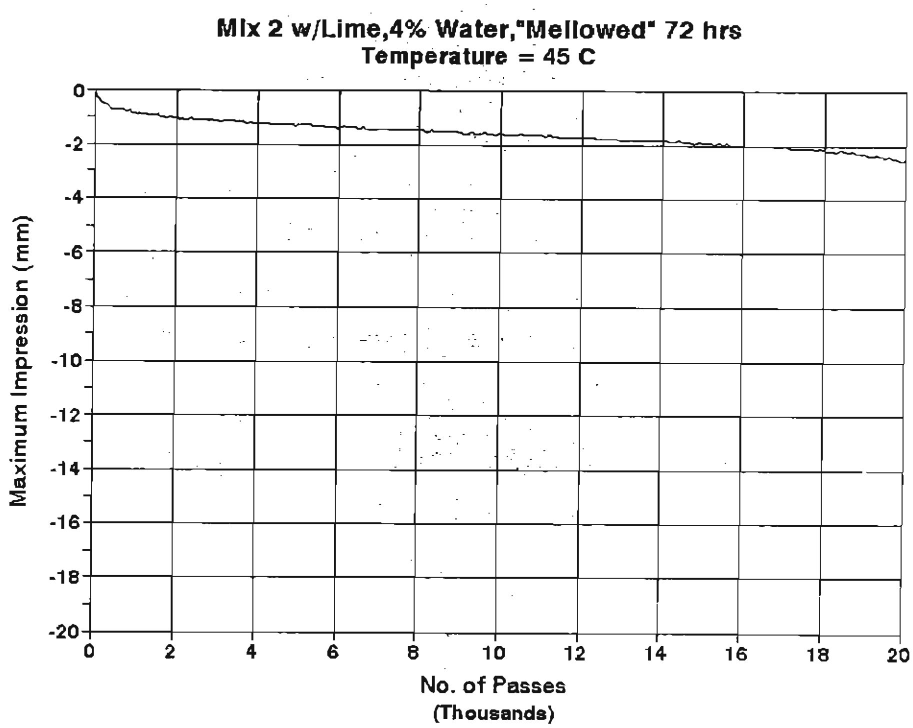
Mix 2 with Lime and Zero Water
Temperature = 45 C



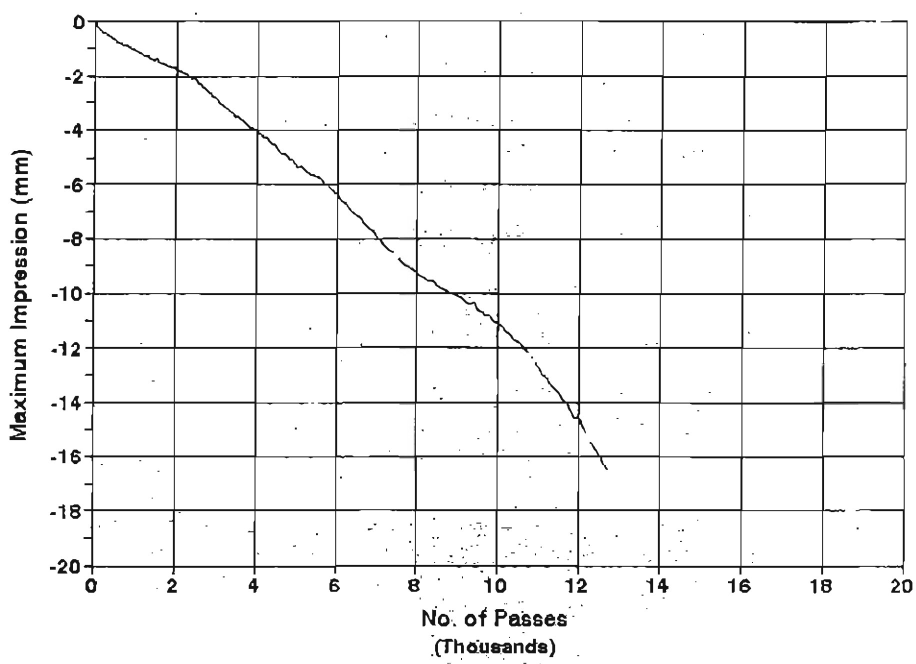
Mix 2 with Lime and 2% Water
Temperature = 45 C



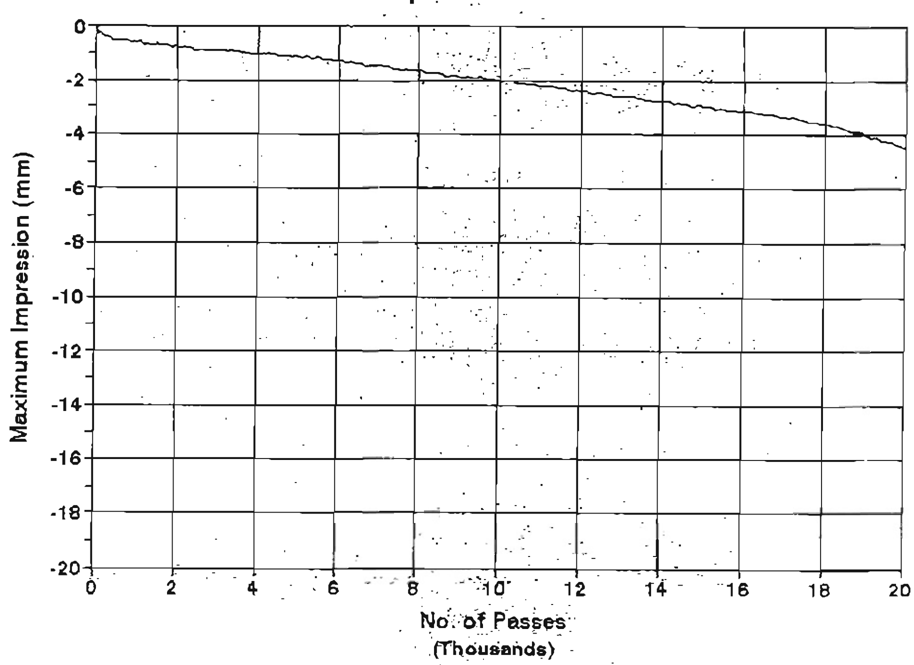

Mix 2 with Lime and 4% Water
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

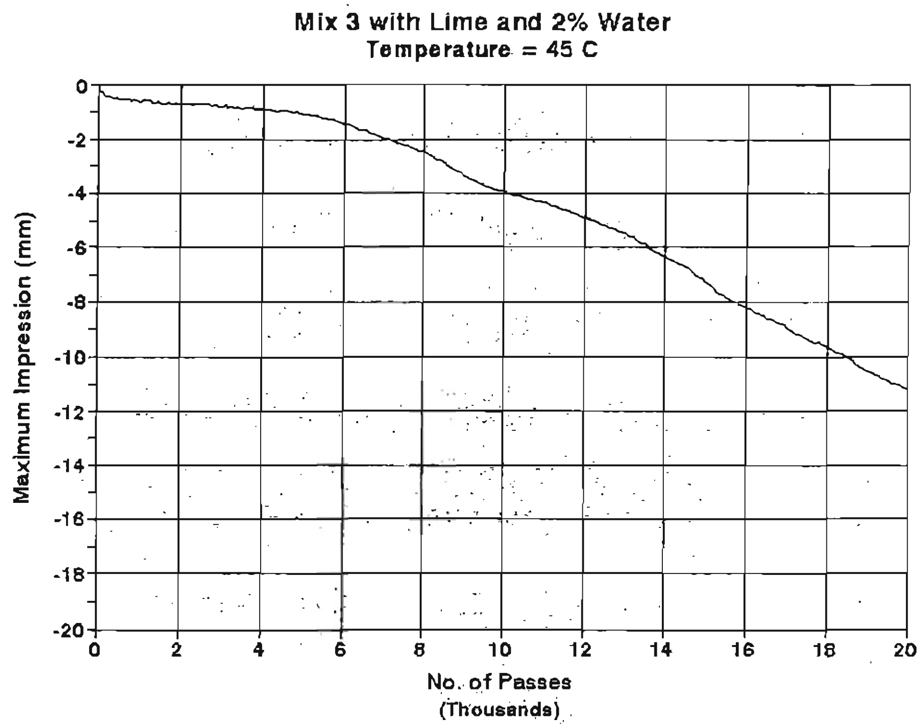

Mix 2 w/Lime,4% Water,"Mellowed" 72 hrs
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

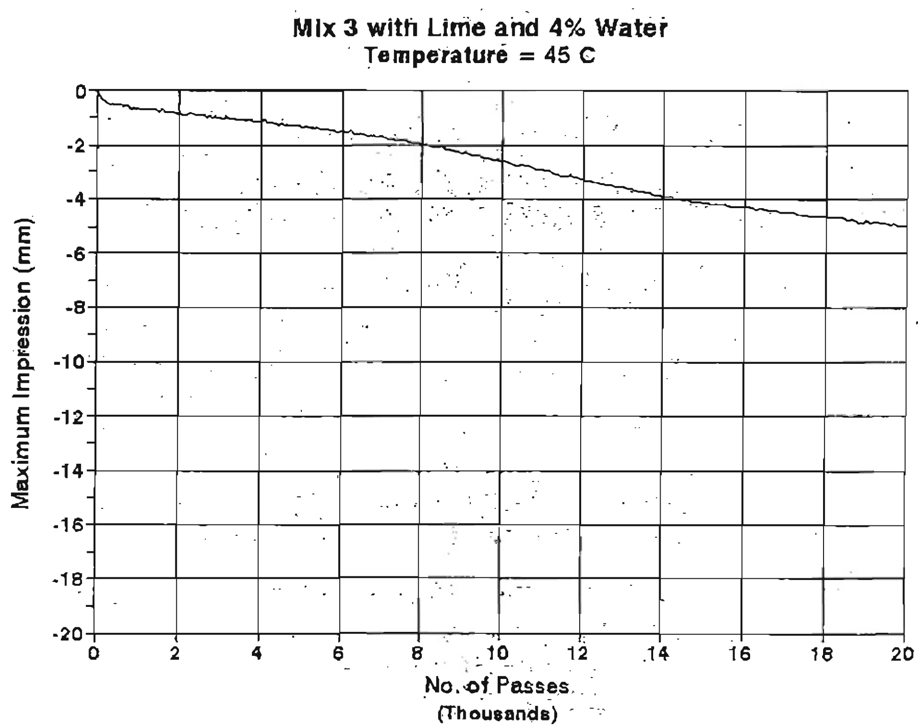
Mix 3 with Zero Lime and Zero Water
Temperature = 45 C



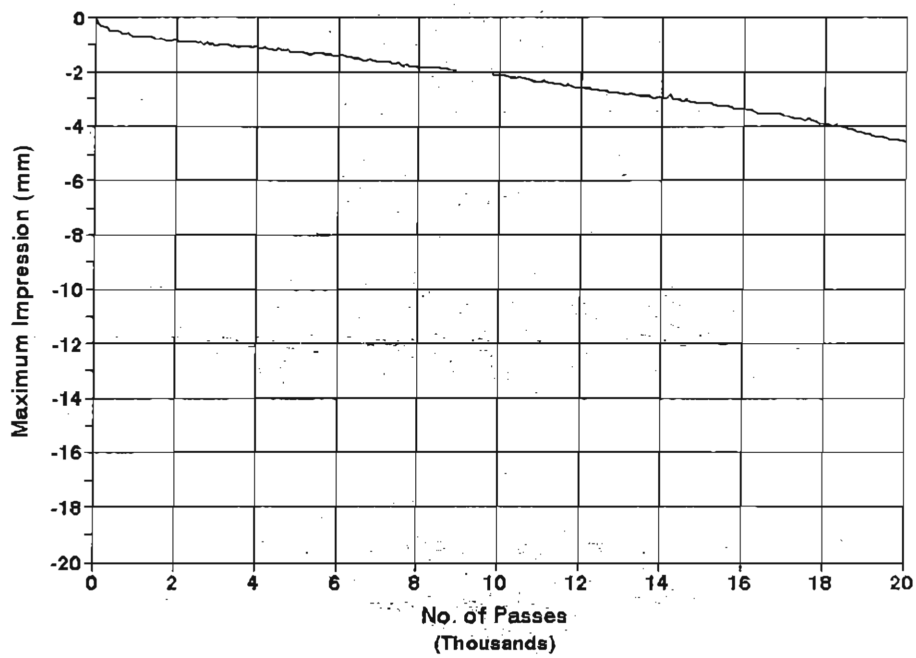
Mix 3 with Lime and Zero Water
Temperature = 45 C



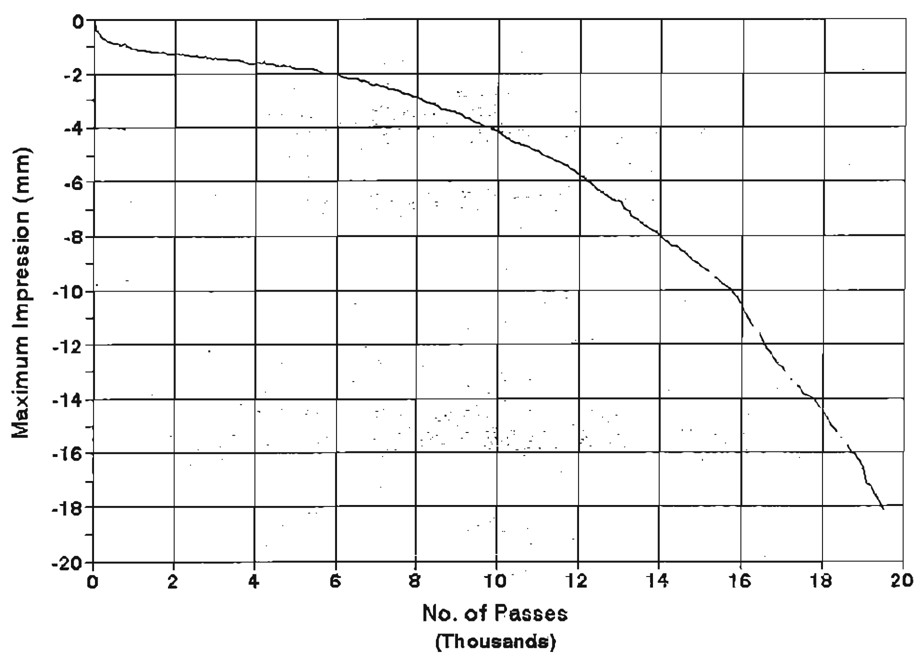

Mix 3 with Lime and 2% Water
Temperature = 45 C
Maximum Impression (mm)
No. of Passes
(Thousands)

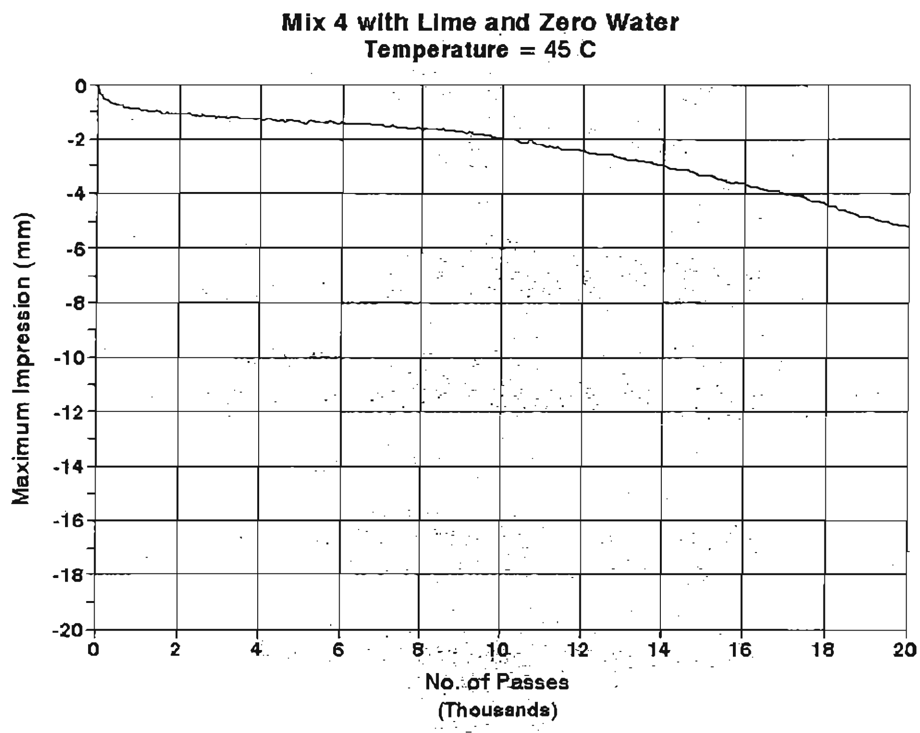

Mix 3 with Lime and 4% Water
Temperature = 45 C
Maximum Impression (mm)
No. of Passes
(Thousands)

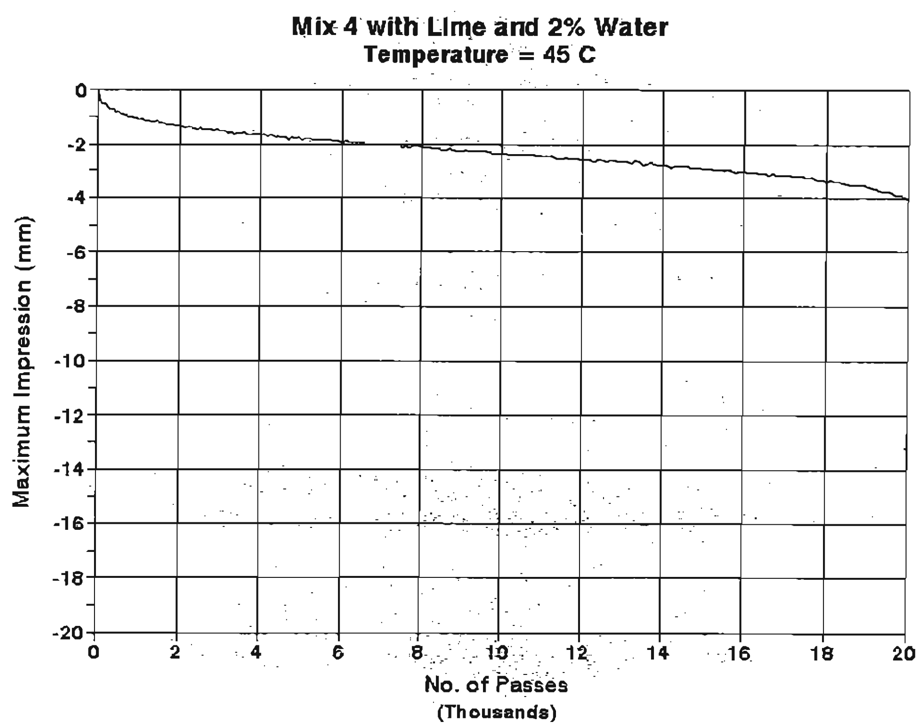
Mix 3 w/Lime, 4% Water,"Mellowed" 72 hr
Temperature = 45 C

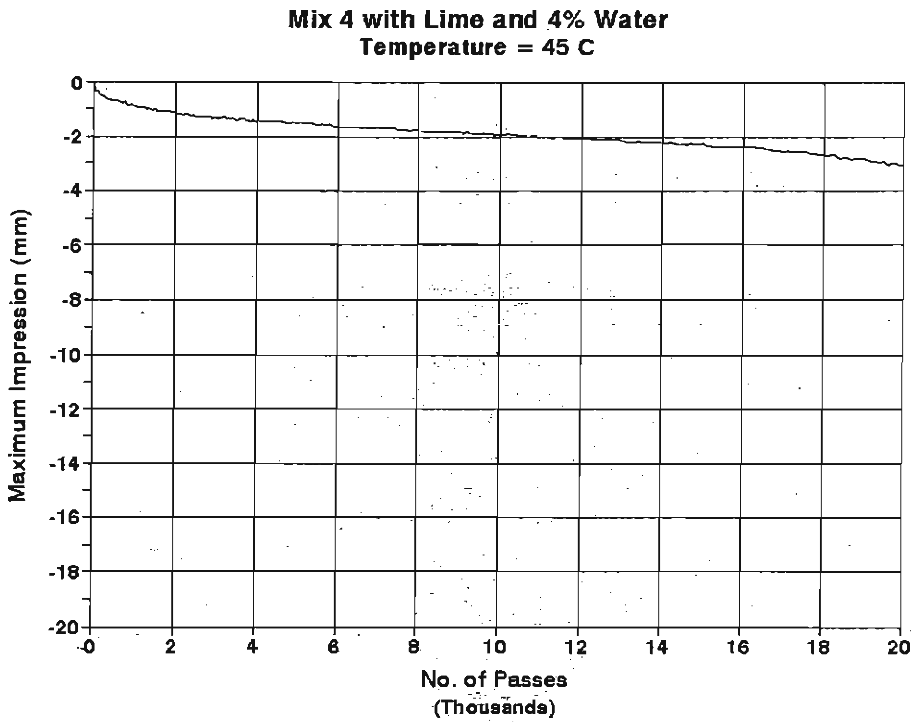


Mix 4 with Zero Lime and Zero Water
Temperature = 45 C

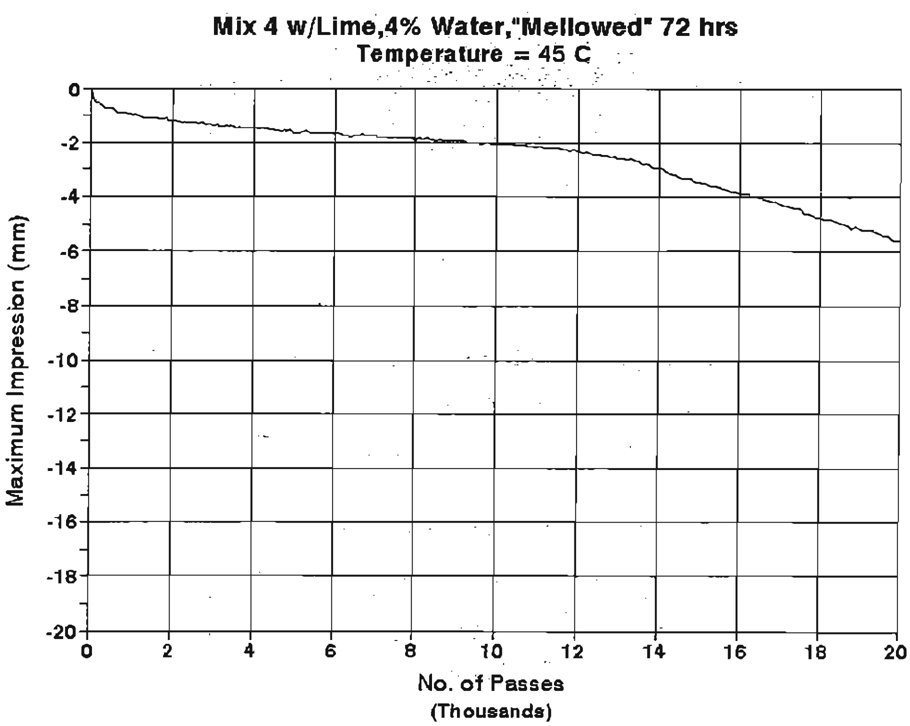



Mix 4 with Lime and Zero Water
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)


Mix 4 with Lime and 2% Water
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)



Mix 4 with Lime and 4% Water
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)



Mix 4 w/Lime,4% Water,"Mellowed" 72 hrs
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)