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SHORT-TERM AGING OF HOT MIX ASPHALT

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The contents of this report reflect the views of authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Colorado Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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16. Abstract

Short-term aging is defined as the hardening or stiffening of the asphalt cement as well as the asphalt cement absorption into the aggregate as a result of the construction process. The asphalt cement ages during construction when the hot mix asphalt (HMA) is at elevated temperatures. This occurs during mixing, storage, hauling, placing, and compaction operations.

The purpose of this study was to investigate the length of time to short-term age samples mixed in the laboratory in order to simulate the short-term aging that is received in the field. This was done by; 1)measuring the amount of time the HMA stays at elevated temperatures in the field, 2)comparing the quantity of asphalt absorption into the aggregate between field produced and laboratory mixed samples, and 3)comparing test results from the Hamburg wheel-tracking device between field produced and laboratory mixed samples. A previous study has shown the Hamburg wheel-tracking device is very sensitive to short-term aging.

Information gathered from the field indicated that the HMA stayed at elevated temperatures for approximately 1 to 2 hours for a majority of projects. Based on test results from asphalt absorption, the short-term aging time should be 2 to 4 hours; based on test results from the Hamburg wheel-tracking device, the short-term aging should be between 1 and 3 hours.

As expected, the length of short-term aging in the field is quite variable because of the variable field conditions and material properties. It was recommended to short-term age samples mixed in the laboratory for 2 hours to simulate the field aging.

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Short-Term Aging of
Hot Mix Asphalt

Tim Aschenbrener and Nava Far

1.0 Introduction

Short-term aging is defined as the hardening or stiffening of the asphalt cement in the hot mix asphalt (HMA) as well as the asphalt cement absorption into the aggregate as a result of the construction process. The asphalt cement ages during construction when the HMA is at elevated temperatures. This occurs during mixing, storage, hauling, placing and compaction operations.

1.1 Background and Purpose

The Strategic Highway Research Program (SHRP) has recommended a method to short-term age laboratory mixed samples of hot mix asphalt (HMA) to match the short-term aging that occurs during field production. The SHRP recommendation has been documented in SHRP Designation: M-007, and a copy is in Appendix A. In summary, SHRP's recommended short-term aging procedure involves 1) spreading the loose mixture to an even thickness at 12 to 22 kg/m^2 (2.5 to 4.5 lb/ft^2), 2) placing the loose mixture in a forced-draft oven for 4 hours ± 5 minutes at a temperature of 135°C (275°F), and 3) stirring the loose mixture every hour.

The current CDOT practice is different than that recommended by SHRP. CDOT has typically used 2 hours of short-term aging in a forced-draft oven at the compaction temperature. No stirring of the mixture is required. This procedure has been used for two reasons: 1) to bring the HMA to compaction temperature and 2) to allow short-term aging. However, no study has been performed in the past to determine if CDOT's laboratory short-term aging matches the field short-term aging.

In order to implement the SHRP recommendation, research with typical Colorado aggregates and field produced HMA was performed. The purpose of this study is to identify the impact of changing CDOT's current short-term aging practice to that proposed by SHRP.

In this study, results from field produced HMA were compared to laboratory mixed HMA that was short-term aged for various times. The test results from field produced and laboratory mixed HMA samples were compared by:

1) the quantity of asphalt absorption into the aggregate, and
2) test results from the Hamburg wheel-tracking device.

1.2 Previous Studies

A study by Kandhal (*1*) concluded that 4 hours of laboratory short-term aging at 143°C (290°F) matches the asphalt absorption from another laboratory test defined as the bulk impregnated specific gravity method. The bulk impregnated specific gravity is thought to represent the maximum or upper limit of asphalt absorption for an aggregate. However, the data also supports the use of 2 hours. For five of six samples tested, there was no difference (less than 0.1% asphalt content) in asphalt absorption between 2 and 4 hours. The one exception was a very highly absorptive aggregate with a very soft asphalt cement.

Studies by Bell (*2, 3*) have shown that 4 hours of laboratory short-term aging at 135°C (275°F) in a forced-draft oven underestimates the short-term aging that occurs in the field. Resilient diametral modulus values tested at 25°C (77°F) of cores taken from recently constructed highways (6-months to 2-years old) were compared to resilient diametral modulus values from laboratory mixed and laboratory compacted HMA samples. The laboratory mixed HMA was short-term aged for various periods of time, and then compacted in the California kneading compactor. Resilient modulus values of cores from field compacted HMA was found to match laboratory mixed and compacted HMA that had been short-term aged for 4.5 to 12 hours. A short-term aging time of 4 hours was recommended for future use. It is not clear what influence the different compaction methods (field vs. laboratory) had. This study measured the difference in aging but also had two other confounding variables: 1) modulus values were compared between field and laboratory compacted samples, and 2) materials for the field and laboratory aging comparison were sampled 6 months to 2 years apart. It is not clear what influences these differences had on the results.

In Pennsylvania, Kandhal (*4*) has shown that laboratory mixed HMA requires 6 hours of oven aging at 143°C (290°F) on laboratory mixed samples to match the field aging. Short-term aging included mechanical energy and manipulation of the mix in the pugmill, storage in silo, hauling to job site, and remixing in paver. The recommended short-term aging times were 6 hours for laboratory mixed samples, 1 to 2 hours for samples obtained at the plant, and zero hours for samples obtained behind the paver. No field data was presented. It was interesting to note that increased aging on absorptive aggregates increased the theoretical maximum specific gravity of the HMA (AASHTO T 209) by 0.055.

In NCHRP 338 (*5*), a new asphalt-aggregate mixture analysis system (AAMAS) was created. Part of this system included the short-term aging of the HMA. Short-term aging was defined to occur through HMA production and mixing in an HMA plant. The asphalt cements from 5 different projects were recovered after short-term aging in the field and measured for penetration (AASHTO T 49 @ 25°C) and viscosity (AASHTO T 202 @ 60°C). The original, unaged asphalt cement was mixed with the same aggregates in the laboratory and short-term aged for various periods of time in a forced-draft oven at 135°C (275°F). The asphalt cement was then recovered and the recovered asphalt was tested for penetration and viscosity. The short-term aging times required in the laboratory to match the field ranged from 1.8 to 13.5 hours. Four hours was the overall average for viscosity, and six hours was the overall average for penetration. It was most interesting to note that HMAs which contained liquid antistripping additives required significantly longer short-term aging times in the laboratory. When HMA with liquid anti-stripping additives were removed, the time to match field aging ranged from 1.8 to 4.6 hours. When additional data was included, a short-term aging time of 3 hours was selected.

A study by Parr and Brock (*6*) compared the short-term aging of HMA directly out of a pugmill of a batch plant to the HMA that had been stored in a silo for 7 days. The comparison was made with penetration values on the asphalt cement that was recovered after extraction testing. The additional storage decreased the penetration from 80 dmm to 60 dmm.

A study by Middleton (*7*) compared the short-term aging of HMA directly out of a pugmill of a batch plant to the HMA that had been stored in a silo for just over 4 days. The comparison was made with penetration values on the asphalt cement that was recovered after extraction testing. The additional storage decreased the penetration from 75 dmm to 52 dmm.

These previous studies have made recommendations with national impact. There are still several questions that could be the subject of future research.

1) Is 4 hours really much better at simulating the field than 2 hours?

2) The compaction temperature can be different than the recommended short-term aging temperature. None of the previous studies addressed how to bring the sample to the compaction temperature. After 4 hours of short-term aging, should a sample be placed in another oven for ½ to 1 hour at the compaction temperature? What influence would this have on the short-term aging? Should the temperature in the short-term aging oven be adjusted to the compaction temperature after 3 hours so the sample is ready for compaction after 4 hours? It is not clear how to address the difference that exists between the short-term aging temperature and the compaction temperature.

3) Some studies use forced-draft ovens and others did not. Should forced-draft ovens really be used? What type of forced-draft oven specifications for blowing capacity are needed?

4) What is the procedure for testing field produced HMA? If short-term aging is to model aging during construction, how should construction samples be aged, with the same procedure as laboratory mixed samples, or a different procedure?

5) How do a wide variety of HMA mixing plants influence the short-term aging?

These questions need to be addressed in order to implement the SHRP short-term aging procedure. Unfortunately, only the first question was investigated for this study.

2.0 Experimental Grid

2.1 Experimental Grid

Nine projects were selected throughout Colorado and monitored for this research project. Information was collected from each project during construction. Additionally, materials were sampled from each project for testing in the laboratory.

The information obtained from each project is shown in Table 1. Mixing was accomplished with a drum mixer or batch plant. The temperature at the discharge was recorded. The HMA is then stored in a silo and the time of storage was recorded. The type of haul truck could be a live-bottom, belly-dump, end-dump or tandem with pup. The haul time and temperature behind the paver were recorded. A compaction study was performed to document the number of rollers, roller passes, temperature after each pass, and time it took for the mat to cool to 85°C (185°F).

Table 1. Project Information Gathered from Each Site.

	Equipment	Time	Temperature
Mixing	X		X
Silo		X	
Haul	X	X	X
Compaction	X	X	X

X - Information was collected.

It was important to document the amount of time the HMA stayed at elevated temperatures. This would be useful information to compare to the recommended short-term aging times and temperatures. For example, if it is recommended to short-term age samples for 4 hours at 135°C (275°F) in a forced draft oven, and the HMA only stays at elevated temperatures for less than 1 hour in the field; something might be different.

Material from each site was sampled, and the tests performed on the material from each of the nine sites are shown in Table 2.

Table 2. Materials Sampled and Tests Performed for Each Project.

	Aggre-gates	Asphalt Cement	Laboratory Mixed HMA, Short-Term Aging Time (hours)				Field Produced HMA
			0	2	4	8	
Agg. Bulk S.G.	X						
SHRP Binder Tests		X					
AASHTO T 209			X	X	X	X	X
Hamburg Wheel-Tracking Device			X	X	X	X	X
Moisture Retention							X

X - Tests performed for this experiment.

2.2 Description of Laboratory Tests

2.2.1 Asphalt Absorption

The percent of asphalt absorption into the aggregate by weight of aggregate was determined according to the procedure in the Asphalt Institute, Manual Series 2.

The maximum specific gravity of the mix, G_{mm}, otherwise known as the Rice test was performed according to AASHTO T 209 on laboratory mixed samples that were short-term aged for 0, 2, 4, and 8 hours. The effective specific gravity of the aggregate, G_{se}, was calculated for each short-term aging period using:

$$G_{mm} = \frac{100}{\left(\frac{P_s}{G_{se}} + \frac{P_b}{G_b}\right)} \qquad \textit{Equation 1}$$

where:

G_{mm} = maximum specific gravity of mixture,

P_s = aggregate, percent by total weight of mixture,

P_b = asphalt cement, percent by total weight of mixture,

G_{se} = effective specific gravity of aggregate, and

G_b = specific gravity of asphalt cement (assumed to be 1.03).

Additionally, the bulk specific gravity of the fine and coarse aggregates, G_{sb}, was obtained from AASHTO T 84 and AASHTO T 85, respectively. The amount of water absorption into the aggregates was calculated. The percent of asphalt absorption into the aggregate, P_{ba}, by weight of aggregate could then be calculated using:

$$P_{ba} = 100 \left(\frac{G_{se} - G_{sb}}{G_{sb}\, G_{se}}\right) G_b \qquad \textit{Equation 2}$$

where:

P_{ba} = absorbed asphalt, percent by weight of aggregate, and

G_{sb} = bulk specific gravity of aggregate.

The asphalt absorption of the field produced HMA was compared with the asphalt absorption of the laboratory mixed HMA that had different short-term aging times. A laboratory short-term aging time could then be selected that provided an equal amount of asphalt absorption as the field produced HMA.

2.2.2 Retained Moisture

During field production, the amount of moisture remaining in the HMA was measured. A sample of HMA was taken behind the paver, placed in a mason jar, and sealed. The sample was then tared. The moisture retained was determined by heating the sample for 16 hours in a 121°C (250°F) oven. The moisture retention is also measured on the project with a microwave oven. The two moisture retention values were compared, and the results were similar.

The moisture retention was measured because the retained moisture might influence the amount of asphalt absorption.

2.2.3 Hamburg Wheel-Tracking Device

The Hamburg wheel-tracking device is manufactured by Helmut-Wind Inc. of Hamburg, Germany as shown in Figures 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 7% $\pm$ 1% 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 per minute over each sample. 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.

The results from the Hamburg wheel-tracking device include the creep slope, stripping slope and stripping inflection point as shown in Figure 3. These results have been defined by Hines (*8*). The <u>creep slope</u> 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 <u>stripping slope</u> 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 <u>stripping inflection point</u> 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.

It has previously been shown that the amount of short-term aging received by the HMA can influence the results from the Hamburg wheel-tracking device (*9*). The longer the short-term aging time, the better the test results. By comparing the test results from the field produced HMA with the laboratory mixed HMA, a laboratory short-term aging time could be identified to match the field short-term aging.

2.2.4 SHRP Binder Tests

The asphalt cement tests developed by SHRP were performed. The AASHTO interim procedures were used. A full series of tests were performed to determine the SHRP Performance Grade (PG) of each asphalt cement. The testing devices were the Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR). The tests were performed on asphalt cements that were unaged (tank), Thin Film Oven Test (TFOT) aged (AASHTO T 179), and Pressure Aging Vessel (PAV) aged.

The DSR is used to measure the ability of the asphalt cement to resist permanent deformation at high temperatures and resist fatigue cracking at moderate temperatures. The BBR is used to measure the ability of the asphalt cement to resist thermal cracking at low temperatures.

The SHRP binder tests were primarily performed to identify the aging potential of each asphalt cement. Some asphalt cements have a tendency to age faster than others. Testing with the SHRP binder equipment could identify the differences in these asphalt cements.

2.3 Short-Term Aging Procedure

The short-term aging procedure recommended by SHRP is in Appendix A. The short-term aging procedure used in this study is defined in this section. SHRP recommended a surface area of 12 to 21 kg/m^2. For the AASHTO T 209 tests, the surface area was 21 kg/m^2 (4.3 lb/ft^2). The surface area of the sample exposed to the forced draft was modified for the Hamburg wheel-tracking device. For the Hamburg wheel-tracking device tests, the surface area was 77 kg/m^2 (15.9 lb/ft^2).

The forced-draft oven used was a Despatch 0.91 m^3 (32 ft^3), and the blowing capacity was 45 m^3/min (1600 cfm). The compaction temperatures used in this study were equal to the short-term aging temperatures. The compaction and short-term aging temperatures are shown in Table 3. The temperatures in Table 3 will provide a uniform viscosity of 280 cSt for an unaged asphalt cement. It should be noted that the asphalt cements may not have a uniform viscosity after short-term aging.

Table 3. Compaction and Short-Term Aging Temperatures.

Grade	Temperature
AC-10	135°C (275°F)
AC-20	143°C (289°F)
AC-20P AC-20R	150°C (302°F)

2.3.1 Field Produced Samples

Field produced samples obtained behind the paver were placed in metal cans and covered. These samples were returned to the central laboratory. The samples were stored at room temperature, in a closed container, for between 1 and 2 weeks. The covered samples were heated for 2 hours at 135°C (285°F) to be split into testing size. The maximum specific gravity, AASHTO T 209, samples were placed on paper and allowed to cool. The Hamburg wheel-tracking device samples were returned to their covered container and placed in the oven for 4 hours at the compaction temperature. The field produced samples received additional short-term aging during sample preparation in the laboratory.

2.3.2 Laboratory Mixed Samples

After mixing aggregate and asphalt cement, the AASHTO T 209 samples aged for zero hours were placed on paper and allowed to cool. No additional heating after mixing was applied. After mixing, the Hamburg wheel-tracking device samples were placed in the oven at the compaction temperature for 30 minutes in a closed container. The samples reached the compaction temperature after the 30 minutes and were then compacted.

After mixing, the samples short-term aged for 2 and 4 hours for the AASHTO T 209 and Hamburg wheel-tracking device were put in open pans at the compaction temperature. The HMA was spread approximately 21 kg/m^2 (4.3 lb/ft^2) for the AASHTO T 209 tests and 77 kg/m^2 (15.9 lb/ft^2) for the Hamburg wheel-tracking device tests. After the appropriate aging time expired, the AASHTO T 209 samples were spread on paper and allowed to cool; the Hamburg wheel-tracking device samples were compacted.

After mixing, the samples short-term aged for 8 hours were placed in an open pan and allowed to cool. The next day, they were placed in the oven at the compaction temperature for 8 hours. The AASHTO T 209 samples were then spread on paper and allowed to cool; the Hamburg wheel-tracking device samples were compacted.

2.4 Sampling Locations

The aggregates were sampled from the stockpiles. The asphalt cement was sampled from the storage tank at the plant. The HMA was sampled behind the paver.

Figure 1. The Hamburg Wheel-Tracking Device

Figure 2. Close-Up of the Hamburg Wheel-Tracking Device

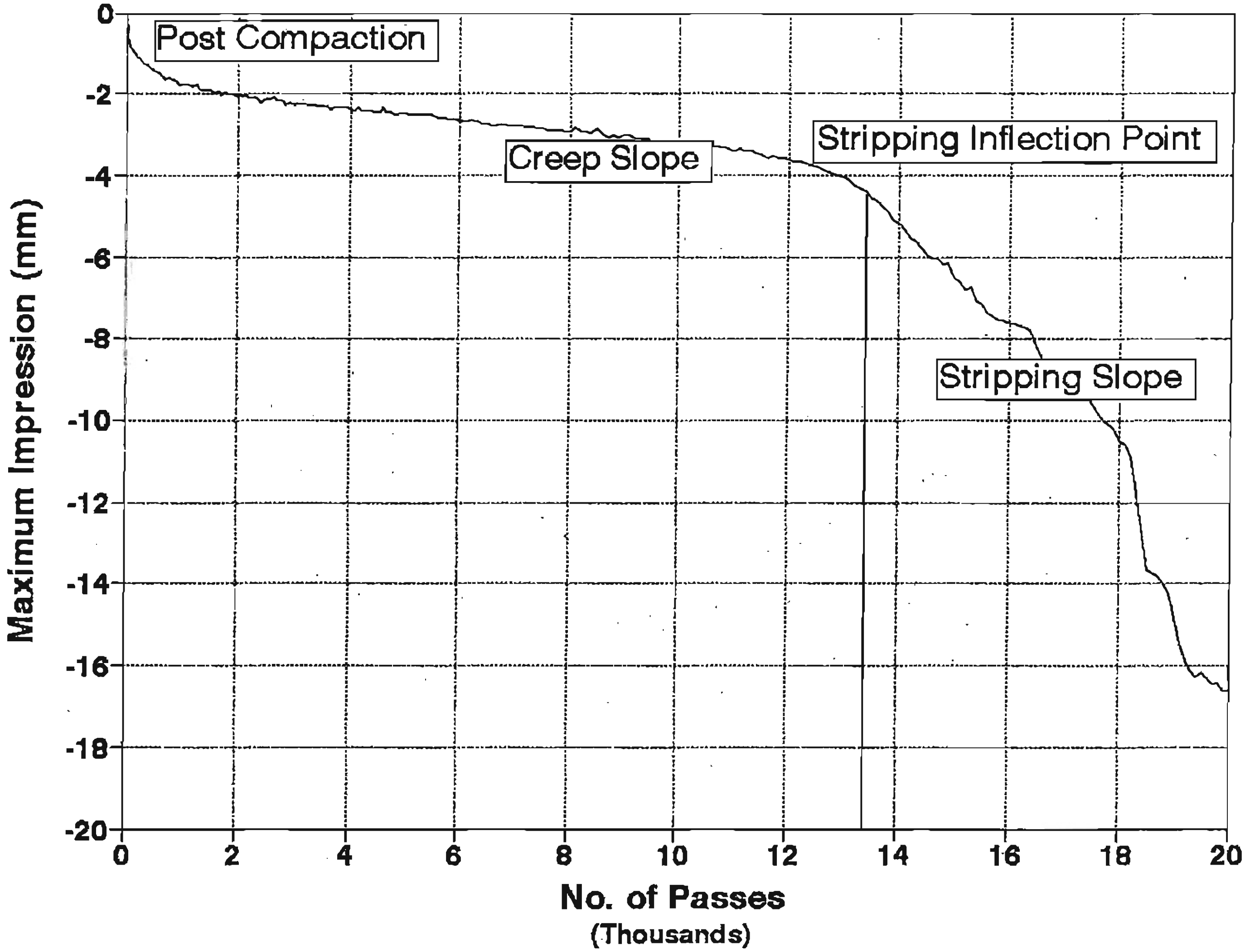

Figure 3. Summary of Results from the Hamburg Wheel-Tracking Device

3.0 Field Sites

Nine projects were selected for this study. A brief description of each project is provided in this section. The detailed roller pass study from each site is shown in Appendix B.

A summary of the time the HMA stayed at elevated temperatures during construction is shown in Table 4. The time it took the HMA to go from mixing in the plant to placement behind the paver is shown in Table 4. Also, the average temperature during that time is included, and the time it took the HMA to cool to 85°C (185°F) once it was placed. In most cases, the HMA stayed at elevated temperatures no longer than 90 minutes; the median value was 78 minutes. Using Site 7A as an example, the rate of heat loss that occurred to the HMA is shown in Figure 4.

Table 4. Time the HMA Stayed at Elevated Temperatures.

Site	Mixing to Placement		Placement to 85°C (185°F)	Total Time at Elevated Temperature (minutes)	Plant Location	Project Location
	Time minutes	Temperature °C (°F)	Time minutes			
1	20	155 (311)	34	54	Comm.	Metro.
2	50	118 (245)	15	65	Comm.	Metro.
3	41	140 (284)	51	92	Port.	Remote
4	16	147 (296)	16	32	Port.	Remote
5	60	136 (276)	35	95	Comm.	Metro.
6	20	148 (299)	37	57	Port.	Remote
7A	240	138 (280)	46	286	Comm.	Remote
7B	1211	142 (288)	46	1257	Comm.	Remote
8	60	173 (343)	100	160	Comm.	Metro.
9	25	141 (286)	37	62	Comm.	Metro.
Med.	45	141 (286)	37	78		

Placement is defined as the time when the HMA exits the paver.
Med. - Median values.

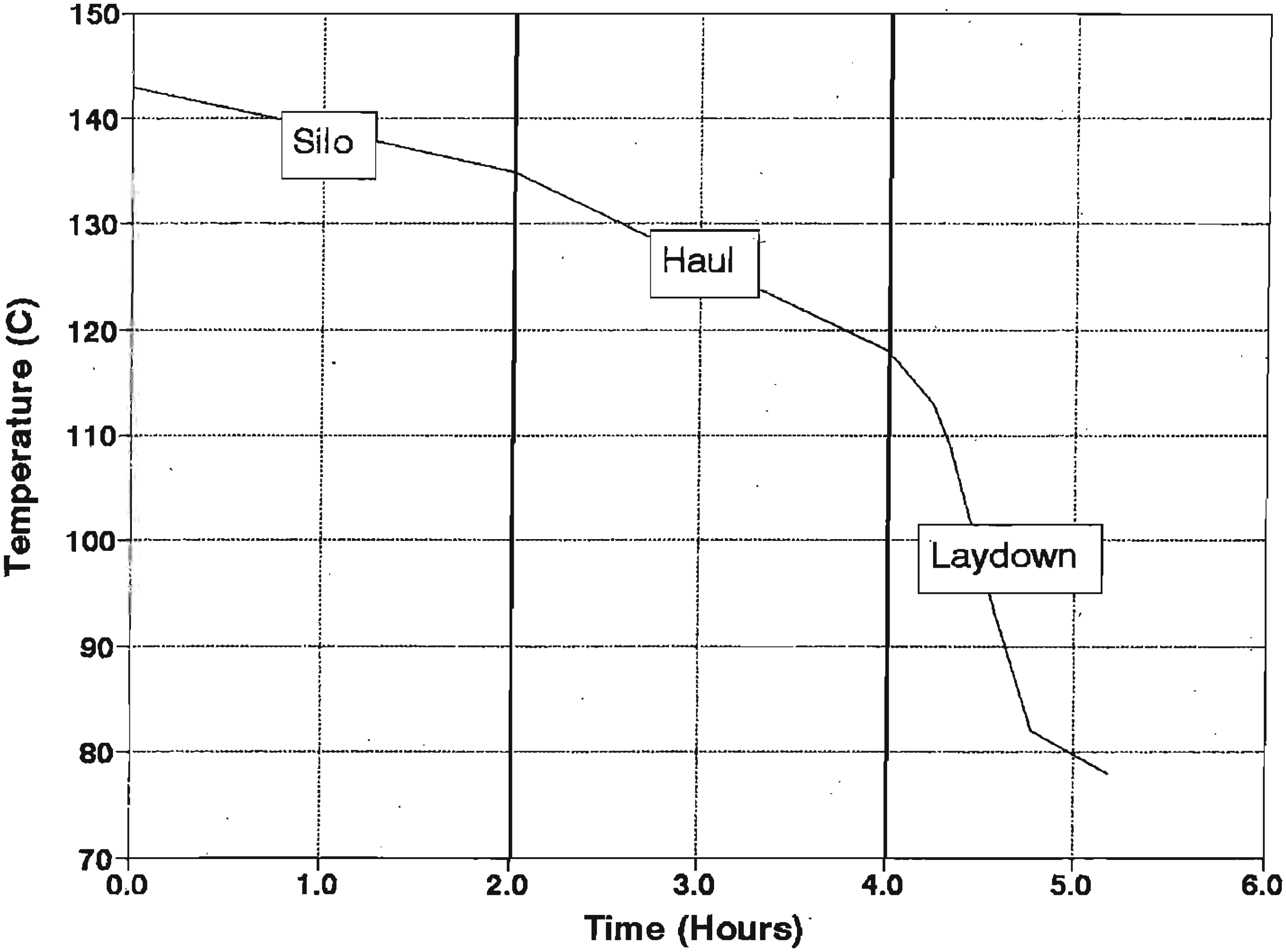

Figure 4. Rate of Heat Loss of the HMA for Site 7A

The location of the plant and project are listed in Table 4. The HMA plants used for each project were defined as commercial or portable. Commercial plants are set up "permanently" and located close to a commercial aggregate supply. Portable plants are moved in for the primary purpose of producing HMA for a specific project. Photographs of the storage silos used at typical commercial and portable plants are shown in Figures 5 and 6, respectively. The projects were identified as either remote or metropolitan. Metropolitan projects were located within a 60 minute haul time of a commercial plant. These projects typically had short haul times but sometimes had very long storage times in the silo. Remote projects were not located near cities with a hot mix asphalt plant. If a portable plant was used for a remote project, the haul time was short. If a commercial plant was used for a remote project, the haul time was long.

3.1 Site Descriptions

The sites are described below and their locations are shown in Figure 7

3.1.1 Site 1

The site is located in Grand Junction, and the project number is MC 0701-139. The plant was a drum mixer. The HMA stayed in the storage silo for 5 minutes and the haul time was 15 minutes. Belly-dump trucks were used. The average temperature from the time of mixing to placement was 155°C (311°F). Once the mix came out from behind the paver, it took 34 minutes to cool to 85°C (185°F). The HMA was at an elevated temperature for 54 minutes.

3.1.2 Site 2

The site is located near Limon, and the project number is FCNH(CX)CY 040-5(13). The plant was a drum mixer. The HMA stayed in the storage silo for 10 minutes and the haul time was 40 minutes. Live-bottom trucks were used. The average temperature from the time of mixing to placement was 118°C (245°F). Once the mix came out from behind the paver, it took 15 minutes to cool to 85°C (185°F). The HMA was at an elevated temperature for 65 minutes.

3.1.3 Site 3

The site is located at the New Mexico state line, and the project number is STA 0251-133. The plant was a drum mixer. The HMA stayed in the storage silo for 4 minutes and the haul time was 37 minutes. Belly-dump trucks were used. The average temperature from the time of

Figure 5. Six, 300-Ton Storage Silos at a Typical Commercial Plant

Figure 6. 60-Ton Storage Silo at a Typical Portable Plant

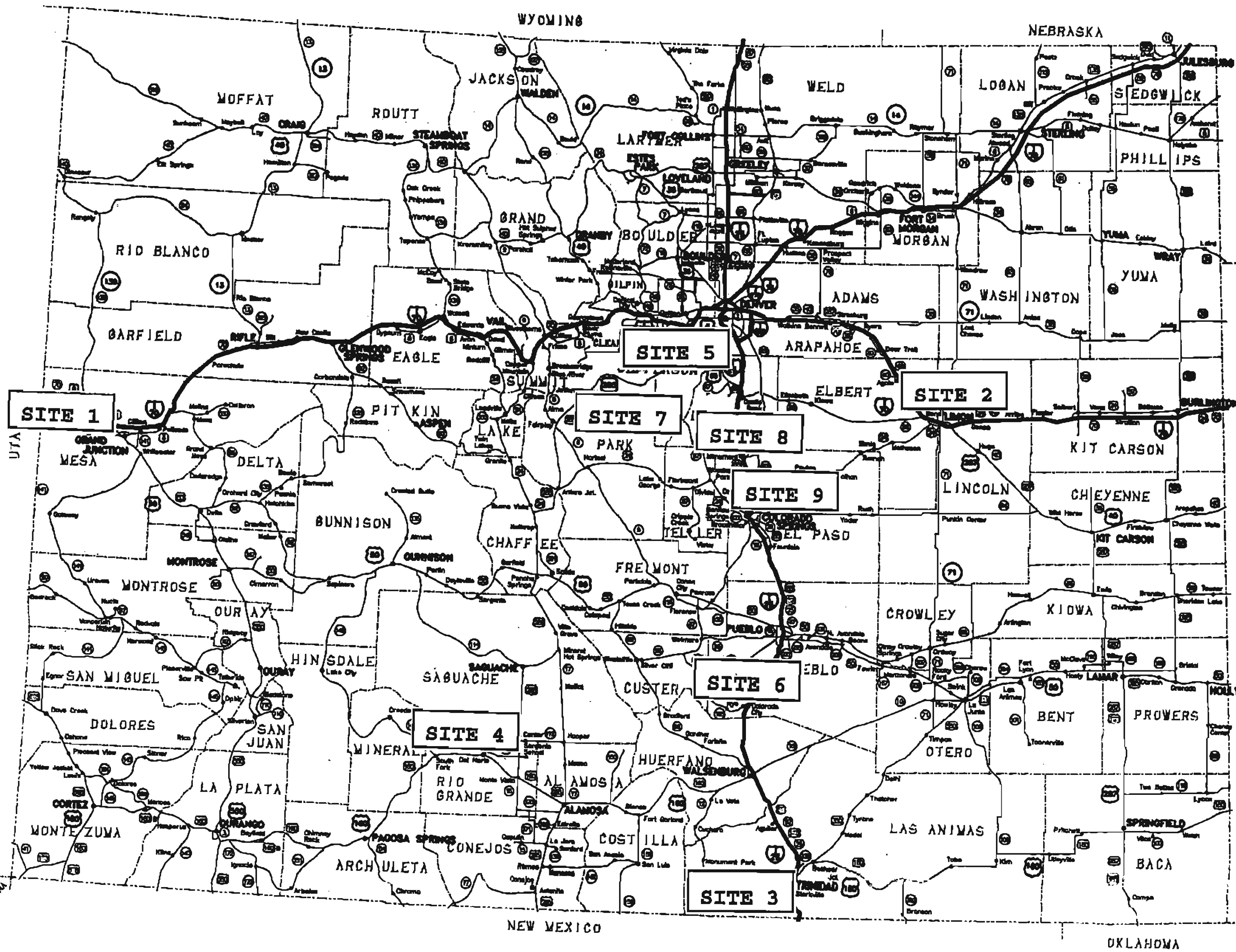

Figure 7. Site Location Map.

mixing to placement was 139°C (282°F). Once the mix came out from behind the paver, it took 51 minutes to cool to 85°C (185°F). The HMA was at an elevated temperature for 92 minutes.

3.1.4 Site 4

The site is located near Del Norte, and the project number is MC 1602-054. The plant was a drum mixer. The HMA stayed in the storage silo for 6 minutes and the haul time was 10 minutes. Belly-dump trucks were used. The average temperature from the time of mixing to placement was 145°C (295°F). Once the mix came out from behind the paver, it took 16 minutes to cool to 85°C (185°F). The HMA was at an elevated temperature for 32 minutes.

3.1.5 Site 5

The site is located near Morrison, and the project number is CX 11-0285-30. The plant was a drum mixer. The HMA stayed in the storage silo for 35 minutes and the haul time was 25 minutes. End-dump trucks were used. The average temperature from the time of mixing to placement was 129°C (265°F). Once the mix came out from behind the paver, it took 35 minutes to cool to 85°C (185°F). The HMA was at an elevated temperature for 95 minutes.

3.1.6 Site 6

The site is located near Colorado City, and the project number is STA 0251-131. The plant was a drum mixer. The HMA stayed in the storage silo for 15 minutes and the haul time was 5 minutes. Belly-dump trucks were used. The average temperature from the time of mixing to placement was 145°C (295°F). Once the mix came out from behind the paver, it took 37 minutes to cool to 85°C (185°F). The HMA was at an elevated temperature for 57 minutes.

3.1.7 Site 7

The site is located near Bailey, and the project number is C 2854-054. The plant was a drum mixer. Two storage silos were used for this mix. In one silo, the HMA had been held for 120 minutes (2 hours). In the other storage silo, the HMA had been produced the previous day and was held for 960 minutes (16 hours). The contractor loaded one truck with the HMA held for 120 minutes (Site 7A) and a second truck with the HMA held for 960 minutes (Site 7B) for this study. The haul time for both trucks was 120 minutes. Belly-dump trucks were used. The average temperature from the time of mixing to placement was 131°C (268°F). Once the mix came out from behind the paver, it took 46 minutes to cool to 85°C (185°F). The HMA was for Site 7A was at an elevated temperature for 286 minutes (4.8 hours), and for Site 7B was 1257 minutes (21.0 hours).

3.1.8 Site 8

The site is located near Monument, and the project number is IM 0252-263. The plant was a batch plant. The HMA stayed in the storage silo for 15 minutes and the haul time was 45 minutes. Live-bottom trucks, end-dump trucks, and tandems with pups were used. The HMA for this site had to be re-sampled because the initial sample did not match the laboratory mix design. When the material was re-sampled, belly-dump trucks were being used. The average temperature from the time of mixing to placement was 171°C (340°F). Once the mix came out from behind the paver, it took 100 minutes to cool to 85°C (185°F). The HMA was at an elevated temperature for 160 minutes.

The asphalt cement used on this project was polymer modified, and it was the same asphalt cement that was used at Site 6. The higher equi-viscous temperature of the polymer modified asphalt cement is the reason the mix discharge temperature was so high, and the reason the mix stayed at elevated temperatures longer than normal. The asphalt cement did not create "smoke" at this high temperature, probably because it was a batch plant.

3.1.9 Site 9

The site is located in Colorado Springs, and the project number is C 0252-265. The plant was a drum mixer. The HMA stayed in the storage silo for 15 minutes and the haul time was 10 minutes. Tandems, end-dump trucks and live-bottom trucks were used. The average temperature from the time of mixing to placement was 141°C (285°F). Once the mix came out from behind the paver, it took 37 minutes to cool to 85°C (185°F). The HMA was at an elevated temperature for 62 minutes.

3.2 Short-Term Aging Based on Time at Elevated Temperatures in the Field

One method of selecting a short-term aging time could be to use the time the HMA stays at elevated temperatures during construction. The median time the HMA was at elevated temperatures was 78 minutes. A time of 60 minutes $\pm$ 30 minutes would include 6 of the 9 projects.

One of the outliers is Site 7, where the HMA was held at elevated temperatures overnight. This happens for projects in Colorado, but the occurrence is rare. Another outlier was Site 8, where a polymer modified asphalt cement was used. Because the polymer modified asphalt cement was mixed and placed at higher temperatures, it stayed at higher temperatures longer. For a majority of projects, the use of a short-term aging time of approximately 60 minutes would be representative.

It should be noted that the median temperature throughout this time was approximately 128°C (263°F). This is the middle point from all of the sites. It indicates that half of the sites had more short-term aging and half of the sites had less. This is based on the following assumptions: 1) the mix discharge temperature is 141°C (286°F), 2) the time in the storage silo is 15 minutes, 3) the haul time is 30 minutes, 4) and the time for the mat to cool to 85°C (185°F) is 37 minutes. During this time, there is no conditioning using forced-draft air.

It is interesting to note that the time and temperature in the field are both significantly shorter and lower, respectively, than the laboratory short-term aging time recommended by others.

4.0 Test Results and Discussion

4.1 Material Properties

4.1.1 Aggregates

The aggregate properties were tested on material sampled from stockpiles and blended together into the proportion that was used by the contractor. The aggregate properties are summarized in Table 5. Sites containing highly absorptive (Sites 3 and 4: greater than 2%), moderately absorptive (Sites 1, 2, 6, and 9: between 1% and 2%), and low absorptive (Sites 5, 7, and 8: less than 1%) aggregates were selected to represent a wide variety of aggregates typically encountered in Colorado. Additionally, it was considered important to have different absorptive characteristics because the absorption might influence the results of an aging study.

Table 5. Summary of Aggregate and Asphalt Cement Properties.

Site	Aggregate		Asphalt Cement	
	Bulk Specific Gravity	Water Absorption (%)	Viscosity Grading	SHRP PG
1	2.561	1.45	AC-20R	64-22
2	2.553	1.57	AC-20	64-22
3	2.546	2.06	AC-10	58-22
4	2.500	1.96	AC-10	58-22
5	2.640	0.71	AC-10	58-22
6	2.603	1.22	AC-20P	64-28
7	2.695	0.55	AC-10	58-22
8	2.614	0.92	AC-20P	64-28
9	2.581	1.41	AC-10	58-28

4.1.2 Asphalt Cements

The asphalt cement properties were tested on the material sampled from the storage tank at the plant. The asphalt cement properties are summarized in Table 5. The viscosity grading is based on AASHTO M 226, Table 2, and the detailed SHRP binder test results are in Appendix C. The asphalt cements used in this study represent a wide variety of stiff and soft asphalt cements that are typically used throughout Colorado. It was considered important to have different asphalt cement stiffnesses because the asphalt cement stiffnesses could influence the results of a short-term aging study.

4.1.3 Hot Mixed Asphalt

All of the HMA used in this study was treated with hydrated lime. None of the HMA had liquid anti-stripping treatment.

The HMA produced in the field was compared with the HMA mixed in the laboratory using various short-term aging procedures. This comparison was performed to evaluate the influence of short-term aging. Unfortunately, short-term aging might not be the only difference between field produced and laboratory mixed samples. To minimize the difference between the two different methods of mixing the samples, the volumetric properties (air voids, voids in the mineral aggregate, asphalt content and Hveem stability) were monitored throughout the production of HMA from each of the sites. Samples were taken from the field when laboratory tests on the field produced HMA indicated it was similar to the laboratory mixed HMA. If a sample was taken from a site that was found to have different volumetric properties than the laboratory mixed sample, the site was re-sampled. The results of the comparison of laboratory mixed and field produced properties are shown in Appendix D. The volumetric properties of the samples prepared in the laboratory were similar to the volumetric properties of the field produced samples.

4.2 Short-Term Aging Based on Absorption Properties

A summary of the percent asphalt absorption into the aggregate by weight of aggregate for the laboratory mixed and field produced HMA is shown in Table 6. The maximum theoretical specific gravities, G_{mm}, measured from AASHTO T 209 that were used to calculate the absorption are shown in Table 7.

Table 6. Summary of Asphalt Absorption of the HMA.

Site	Asphalt Absorption (%)				
	Laboratory Mixed, Short-Term Aging Time (Hours)				Field Produced
	0 Hrs	2 Hrs	4 Hrs	8 Hrs*	
1	0.97	1.03	1.29	1.08	1.02
2	0.96	1.15	1.24	1.06	1.24
3	0.84	1.14	1.60	1.29	1.31
4	0.16	0.49	1.21	0.11	1.05
5	0.15	0.32	0.23	0.29	0.29
6	0.26	0.64	0.94	1.02	0.86
7A	0.01	0.07	0.28	0.04	0.24
7B					0.24
8	0.14	0.74	0.55	0.24	0.68
9	0.44	1.33	0.14	0.14	0.74
Avg.	0.49	0.77	0.83	0.59	0.76

*samples were cooled prior to short-term aging

4.2.1 Asphalt Absorption

It was observed that the asphalt absorption into the aggregate increased as the length of short-term aging increased. This was expected and it was generally true, except for two anomalies. In some cases the aggregates had very low absorption so testing variability over-shadowed the small changes in asphalt absorption. Another anomaly was the asphalt absorption into the samples short-term aged for 8 hours.

Table 7. Summary of Maximum Theoretical Specific Gravity, G_{mm}, of the HMA.

Site	Maximum Theoretical Specific Gravity, G_{mm}				
	Laboratory Mixed, Short-Term Aging (Hours)				Field Produced
	0 Hrs	2 Hrs	4 Hrs	8 Hrs*	
1	2.422	2.425	2.440	2.428	2.425
2	2.414	2.425	2.430	2.420	2.430
3	2.401	2.415	2.443	2.426	2.428
4	2.283	2.298	2.331	2.278	2.323
5	2.460	2.470	2.465	2.436	2.470
6	2.426	2.450	2.466	2.471	2.462
7A	2.463	2.479	2.495	2.477	2.490
7B					2.490
8	2.411	2.450	2.440	2.420	2.461
9	2.410	2.460	2.386	2.355	2.431

*Samples were cooled prior to short-term aging.

It was observed that the G_{mm} for the samples short-term aged for 8 hours was lower than the samples short-term aged for 4 hours, and sometimes it was even lower than the samples short-term aged for 2 hours. This was not an expected result. The G_{mm} should increase with longer short-term aging times as more asphalt absorbs into the aggregate. It should be noted that the samples short-term aged for 8 hours (and sometimes 4 hours) were allowed to cool because of laboratory scheduling. Other samples were short-term aged immediately after mixing. If the lower G_{mm} was caused by the cooling and then reheating, then laboratory mixed samples should not be allowed to cool prior to short-term aging. Laboratory mixed samples should be short-term aged immediately after mixing.

As shown in Table 8, the length of time the laboratory mixed sample should be short-term aged is summarized. The median short-term aging time for the 9 sites was 2¾ hours, and most sites were between 2 and 4 hours. More importantly, the average difference in asphalt absorption between 2 and 4 hours was less than 0.1% asphalt content. In the cases with absorptive aggregates (Sites 3 and 4), the difference was about 0.5% to 0.7% asphalt content. However, when absorptive aggregates are used, it is best to rely on the test results from field produced samples. It should be noted that the field produced samples had additional aging because they were reheated in the laboratory for splitting and compacting.

Table 8. Asphalt Absorption: Laboratory Aging to Match Field Aging.

Site	Field Produced HMA at Elevated Temperature (≈ Hrs.)	Laboratory Mixed HMA STA Time to Match Asphalt Absorption of Field Produced HMA (≈ Hrs.)
1	1	2
2	1	4
3	1½	2½
4	½	3½
5	1½	1½
6	1	3
7A	5	3½
7B	21	3½
8	3	8
9	1	1
Median	1¼	2¾

4.2.2 Short-Term Aging of G_{mm} and G_{mb}

The bulk specific gravity of the compacted mix, G_{mb}, is determined from AASHTO T 166. When testing laboratory mixed samples, it is important to short-term age the samples used for G_{mb} and

G_{mm} for the same amount of time. The value obtained for G_{mm} changes with the amount of short-term aging time. If the compacted samples used to determine G_{mb} are not short-term aged the same length of time as the G_{mm} samples, the air voids calculated for the compacted sample will be incorrect. For example, the G_{mm} from Site 3 changed from 2.401 to 2.443 from zero hours to 4 hours of short-term aging. If the compacted sample was short-term aged for 4 hours, the air voids calculated could be 1.8% apart depending on which G_{mm} was used.

In order to investigate this further, a very absorptive aggregate (4.68% water) was used. After mixing, G_{mm} samples were short-term aged for 15, 120 and 240 minutes prior to spreading on brown paper to cool. G_{mb} samples were short-term aged for 35, 120 and 240 minutes prior to compaction. The individual G_{mm} and G_{mb} values are shown in Table 9, and the air voids calculated with the various combinations of test results are shown in Table 10. As shown in Table 10, the calculated air voids can vary by over 1.7% air voids if the G_{mm} and G_{mb} are short-term aged for different periods of time. Additionally, after 2 hours of short-term aging, the test results from both G_{mm} and G_{mb} seemed to stabilize.

Table 9. Individual G_{mm} and G_{mb} Test Results.

STA Time (min.)	G_{mm}	G_{mb}
15	2.156	NT
35	NT	2.048
120	2.173	2.027
240	2.172	2.027

NT - Not Tested

4.2.3 Water Absorption

After the HMA exited the mixing plant and was placed behind the paver, the moisture retained in the aggregates and the asphalt absorption were measured. These values were compared to the water absorption of the aggregates measured from AASHTO T 84 and T 85 as shown in Table 11. The asphalt absorption was approximately 64% of the water absorption of the aggregates. The trend was for the lower absorptive aggregates to have a higher percentage of asphalt absorption (an average of 67%) than the higher absorptive aggregates (an average of 58%).

Table 10. Air Voids (%) Calculated Using G_{mm} and G_{mb} for Various Lengths of Short-Term Aging.

		Air Voids (%)		
		G_{mb}		
		35 min.	120 min.	240 min.
G_{mm}	15 min.	4.98	5.98	5.95
	120 min.	5.73	6.72	6.69
	240 min.	5.68	6.67	6.65

Table 11. Summary of Absorption Properties.

Site	Aggregate Properties	HMA Properties Field Produced	
	Water Absorption (%)	Moisture Retention (%)	Asphalt Absorption (%)
1	1.45	0.13	1.02
2	0.92	0.06	0.88
3	2.06	0.17	1.31
4	1.96	0.30	1.05
5	0.71	0.08	0.29
6	1.22	0.05	0.86
7	0.55	0.05	0.24
8	0.77	0.01	0.68
9	1.41	0.04	0.74

4.3 Short-Term Aging Based on Hamburg Wheel-Tracking Device Results

The test results from the Hamburg wheel-tracking device are very sensitive to the level of short-term aging as shown in this study and others (*9*). The amount of short-term aging a sample receives needs to be specified and uniformly controlled to obtain meaningful results.

The test results from the Hamburg wheel-tracking device are summarized in Table 12 and graphically in Appendix E. Table 12 lists the mm of deformation after 20,000 passes. In some cases there was greater than (>) 20 mm of deformation because the sample failed prior to reaching 20,000 passes. The test temperatures used in the Hamburg wheel-tracking device were varied based upon the asphalt cement grading.

Table 12. Summary of Hamburg Wheel-Tracking Results.

Site	Deformation (mm) After 20,000 Passes				
	Laboratory Mixed, Short-Term Aging (Hours)				Field Produced
	0 Hrs	2 Hrs	4 Hrs	8 Hrs	
1	12.1	1.9	1.5	1.4	8.5
2	>20	11.2	1.6	1.0	>20
3	>20	>20	8.8	5.2	>20
4	>20	>20	7.5	4.1	10.9
5	>20	18.0	6.3	5.5	20
6	18.1	2.2	1.8	1.3	11.2
7A	>20	3.7	3.5	1.5	6.1
7B					6.0
8	>20	>20	12.9	1.9	>20
9	>20	>20	>20	3.2	12.9

The test results shown in Table 12 could then be used to compare the laboratory mixed samples and the field produced samples. Using the Hamburg wheel-tracking device, the length of short-term aging time in the laboratory to produce similar results to the field produced samples is shown in Table 13. It appears that samples mixed in the laboratory for testing in the Hamburg wheel-tracking device should be short-term aged for 1 to 3 hours in order to match the short-term aging of field produced samples. The median time is very similar to the time the HMA stayed at elevated temperatures in the field. It should be noted that the field produced samples were reheated in the laboratory for splitting and compacting.

Table 13. Hamburg Wheel-Tracking Device: Laboratory Aging to Match Field Aging.

Site	Field Produced HMA at Elevated Temperature (≈ Hrs.)	Laboratory Mixed STA Time to Match Deformation of Field Produced (≈ Hrs.)
1	1	1
2	1	1
3	1½	2½
4	½	3½
5	1½	1½
6	1	1
7A	5	1
7B	21	1
8	3	3
9	1	6
Median	1¼	1¼

4.4 Discussion

The amount of short-term aging can substantially effect the volumetric properties and the strength properties of the HMA. In this study, the volumetric properties were examined by the asphalt absorption into the aggregate, and the strength properties were examined with the Hamburg wheel-tracking device. Based on these results there are several recommendations that could be made.

It should be noted the Hamburg wheel-tracking device test results are sensitive to the short-term aging received by the sample (*9*). Additionally, the SUPERPAVE Shear Tester (SST) is also sensitive to the short-term aging received by the sample (*10*). The SST was recommended by SHRP to evaluate the rutting potential of HMA. A study similar to this should be performed for samples tested on the SST.

4.4.1 Option No. 1: Exact Short-Term Aging in the Laboratory as in the Field

This option is neither possible nor practical. It is not possible because the short-term aging in the field is never known precisely when the mix design is performed. The length of storage in the silo is variable, and the haul time will change from one end of the project to the other. It is not possible to identify all of the variables.

This option is not practical either. Even if it was possible to identify the precise short-term aging time, it would be a laboratory administration nightmare. This option is strongly discouraged.

4.4.2 Option No. 2: Short-Term Age the Laboratory Samples Longer than the Field.

This option has advantages and disadvantages. The disadvantage is that the field produced material will start at a higher asphalt content than should be used. This is a minor disadvantage. If the laboratory sample is short-term aged for a longer period than in the field, then the laboratory sample will have more absorbed asphalt cement than the field sample. The field sample would be on the wet side of the optimum asphalt content. The additional asphalt content could produce lower air voids that might be dangerously close to the rutting threshold. This could be especially dangerous in highly absorptive aggregates where there are large quantities of asphalt absorption.

Another disadvantage is that strength tests that are sensitive to short-term aging might be "fooled" by short-term aging the laboratory mixed samples longer than the field. Passing results from material short-term aged excessively in the laboratory mix design would not match the strength results from the field produced material that would have a shorter length of short-term aging. By short-term aging laboratory mixed samples longer than the field, designs will be unconservative. The field produced material will be closer to failure (worse strength test results) than the laboratory mixed samples, solely because of aging.

The advantage to this option would be that the short-term aging would provide the maximum asphalt absorption that could ever be achieved. This could account for any asphalt absorption that would occur over the long-term performance of the pavement. This is only a minor advantage. Furthermore, this option would minimize differences in test results caused by varying levels of absorption.

4.4.3 Option No. 3: Short-Term Aging the Laboratory Samples Shorter than the Field

This option will produce mixtures that have lower asphalt absorption than in the field, and therefore lower optimum asphalt contents. If the short-term aging in the field is actually longer than in the laboratory, then the field verification air voids would increase. If the field produced air voids are higher, then additional asphalt cement could be added on the project based on field verification. The selected asphalt contents would start on the "dry" side of optimum, away from the rutting threshold because of aging differences.

Strength tests that are sensitive to the length of short-term aging would be more likely to pass with field produced material than with laboratory mixed material. If a passing laboratory mix design were obtained, the field produced material would have a great chance of passing the strength test because the field would have longer short-term aging than in the laboratory. This would be a conservative design.

4.4.4 Summary

Option No. 3 is the most desirable. When checking volumetric properties, this is particularly true for highly absorptive aggregates. Highly absorptive aggregates could have very large volumetric changes with differences in short-term aging times. It would be more desirable to start on the "dry" side of the optimum asphalt content and slowly work towards optimum by using field verification properties, than to start on the "wet" side of optimum and in a potential rutting situation.

When checking strength using a test that is sensitive to short-term aging (such as the Hamburg wheel-tracking device), it would be better to start in the laboratory with a sample that is "weaker" than would be produced solely because of aging. This would give a much better chance of the field produced material to meet or exceed the specified values. Starting in the laboratory with a sample that is "stronger" than could be produced in the field due to short-term aging, might create significant problems or headaches when the field produced material does not meet the required specifications.

5.0 Conclusions

1) The HMA stayed at elevated temperatures in the field for approximately 1 to 2 hours at an average temperature of 128°C (263°F).

2) Based on asphalt absorption, samples prepared in the laboratory should be short-term aged for 1 to 8 hours to match the asphalt absorption that occurred in field produced samples. Six of the nine sites were between 2 and 4 hours. The time was quite variable within the 2 to 4 hour range, and the variability was likely caused by the wide variability in field conditions and material properties. In most cases, the difference in the amount of asphalt absorbed between 2 and 4 hours was less than 0.3% asphalt content, although absorptive aggregates (2.0% water absorption) had up to 0.7% asphalt content difference between 2 and 4 hours. When dealing with highly absorptive aggregates, it is best to rely on the field produced material. The laboratory short-term aging of absorptive aggregates could be very different from the field.

3) The Hamburg wheel-tracking device is very sensitive to the level of short-term aging. The amount of aging a sample mixed in the laboratory needs to be specified and uniformly controlled to obtain meaningful results. Based on the Hamburg wheel-tracking device, samples mixed in the laboratory should be short-term aged for 1 to 3 hours to match field produced samples.

4) When performing short-term aging on laboratory mixed samples, it is critical that the AASHTO T 209 (G_{mm}) samples be short-term aged for the same length of time as the laboratory compacted samples used for AASHTO T 166 (G_{mb}).

Furthermore, when preparing samples in the laboratory, it is important to short-term age the laboratory mixed samples immediately after mixing and not allow them to cool. Re-heating HMA samples that were cooled does not produce the same test results as HMA samples that were not allowed to cool.

6.0 Recommendations

The mix design should be considered as only a starting point for producing a quality HMA pavement. The final adjustments to the HMA should be made on the field verification properties. The following recommendations to test procedures have been made.

1) Laboratory Mixed Samples. Laboratory mixed samples should be short-term aged for 2 hours at the compaction temperature. It is critical to short-term age the AASHTO T 209 (G_{mm}) samples the same amount of time as the laboratory compacted samples used for AASHTO T 166 (G_{mb}). The true amount of aging is the aging that actually occurs in the field. The G_{mm} and G_{mb} obtained from the field produced samples should be used to make the final adjustments to the HMA.

2) Hamburg Wheel-Tracking Device. When preparing samples for the Hamburg wheel-tracking device, the short-term aging can significantly influence the test results. It is recommended that the procedure for short-term aging be as follows.

Laboratory Mixed Samples. Immediately after mixing, the loose mix should be placed in a pan with approximately 77 kg/m^2 (15.9 lb/ft^2). The open pan should be placed in a forced-draft oven for 2 hours at the compaction temperature. After the short-term aging time has expired the sample should be compacted. If experience indicates that longer than 2 hours is necessary, then times longer than 2 hours should be used.

Field Produced Samples. When preparing field produced samples for the Hamburg wheel-tracking device, it is recommended that the sample be heated in a closed container for 2 hours at 110°C (230°F) and then split into the appropriate sample size. The sample should then be returned to a closed container and heated at the compaction temperature for 4 hours. This will allow the sample to reach compaction temperature. The sample can then be compacted.

The procedure for using the Hamburg wheel-tracking device has been put in AASHTO format and is in Appendix F. This procedure was developed as a result of this and numerous other investigations.

7.0 Future Research

7.1 Study #1

Short-term aging can occur with the presence of high temperatures and/or forced-draft air. It is not clear how the short-term aging will be influenced by the presence of 1) high temperature only versus 2) high temperature and forced-draft air. Based on limited data collected, this difference could be significant.

In order to better understand short-term aging and possibly minimize the scatter, a more detailed study should be performed. Different levels of temperature (perhaps 3) and different volumes of forced-draft air (perhaps 3 levels of which one should be no forced draft) should be used. These results could then be correlated to their respective field sites.

7.2 Study #2

A method needs to be established for handling samples that are field produced. This method would likely be different than the level of short-term aging required for samples that are mixed in the laboratory.

8.0 References

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Appendix A:

Short- and Long-Term Aging of Bituminous Mixes.

Standard Method of Test for

Short- and Long-Term Aging of Bituminous Mixes

SHRP Designation: M-007[1]

1. SCOPE

1.1 This method describes the short- and long-term aging procedures for compacted and uncompacted bituminous mixtures. Two types of aging are described: 1) short-term aging of uncompacted mixtures to simulate the precompaction phase of the construction phase, and 2) long-term aging of compacted mixtures to simulate the aging that occurs over the service life of a pavement. The long-term aging procedures should be preceded by the short-term aging procedure. Evaluation of the extent of aging should be performed using a resilient modulus test (ASTM D 4123-82), dynamic modulus test (ASTM D 3497-79) or other approved test.

1.2 *This standard may involve hazardous materials, operations and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.3 The values stated in SI units are to be regarded as the standard. The values in parentheses are for information only.

2. REFERENCED DOCUMENTS

2.1 *AASHTO Documents:*

MP1	Test Method for Performance-Graded Asphalt Binder
R 11	Practice for Indicating Which Places of Figures are to be Considered Significant in Specifying Limiting Values
T2	Methods of Sampling Stone, Slag, Gravel, Sand, and Stone Block for Use as Highway Materials
T27	Method for Sieve Analysis of Fine and Coarse Aggregates
T40	Method of Sampling Bituminous Materials
T164	Methods of Test for Quantitative Extraction of Bitumen fromn Bituminous Paving Material
T168	Methods of Sampling Bituminous Paving Mixtures

[1]This standard is based on SHRP Products 1025 and 1030.

T201	Method of Test for Kinematic Viscosity of Asphalts
T269	Method for Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures
M-002	Preparation of Compacted Specimens of Modified and Unmodified Hot Mix Asphalt by Means of the SHRP Gyratory Compactor
M-008	Preparation of Test Specimens of Bituminous Mixtures by Means of Rolling Wheel Compaction

2.2 *ASTM Documents:*

D 8	Standard Definitions of Terms Relating to Materials for Roads and Pavements
D 3497	Standard Test Methods for Dynamic Modulus of Asphalt Mixtures
D 3549	Method for Thickness or Height of Compacted Bituminous Paving Mixture Specimens
D 4123	Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixes
E 1	Specification for Thermometers

3. TERMINOLOGY

3.1 *Desired Mixing Temperature*—the target temperature for mixing asphalt binder and aggregate in the laboratory. The desired mixing selected should be equivalent to the anticipated field plant mixing temperature. If field mixing temperatures are unknown, select a temperature which corresponds to a kinematic viscosity of 170 ± 20 mm^2/s for the asphalt binder.

3.2 *Desired Mixing Temperature*—the target temperature for mixing asphalt binder and aggregate in the laboratory. The desired mixing temperature should be equivalent to the anticipated field plant mixing temperature. If field mixing temperatures are unknown, select a temperature which corresponds to a kinematic viscosity of 170 ± 20 mm^2/s for the asphalt binder which is used.

3.3 Definitions for many terms common to asphalt are found in the following documents:

3.3.1 ASTM D 8 Standard Definitions

3.3.2 AASHTO MP1 Performance-Graded Asphalt Binder

3.3.3 AASHTO T201 Kinematic Viscosity of Asphalts

4. SUMMARY OF PRACTICE

4.1 For short-term aging, a mixture of aggregate and asphalt binder is aged in a forced draft oven for 4 hours at 135°C. The oven aging is designed to simulate the aging the mixture would undergo during plant mixing and construction.

4.2 For long-term aging, a compacted mixture of aggregate and asphalt binder is aged in a forced draft oven for 5 days at 85°C. The oven aging is designed to simulate the total aging that the compacted mixture will undergo during 7 to 10 years of service.

5. SIGNIFICANCE AND USE

5.1 The short-term aging practice simulates the aging that asphalt concrete mixtures undergo during field plant mixing operations. The long-term aging practice simulates the in-service aging of asphalt concrete mixtures after field placement and compaction.

5.2 The properties and performance of asphalt concrete mixtures may be more accurately predicted by using aged test samples.

6. APPARATUS

6.1 *Aging Test System*—A system that consists of a forced draft oven which possesses the requirements specified in table 1.

Table 1. Minimum Aging Test System Requirements

	Range (°C)	Resolution (°C)	Accuracy (°C)
Temperature Measurement	10–260	<1	±1
Temperature Control	25–250	<0.1	±0.1

6.2 *Oven*—Any oven which is thermostatically controlled and capable of being set to maintain any desired temperature from room temperature to 160°C. The oven shall be used for heating aggregates, asphalt binders, or laboratory equipment.

6.3 *Mixing Apparatus*—Any type of mechanical mixer that: 1) can be maintained at the required mixing temperatures; 2) will provide a well-coated, homogenous mixture of the required amount of asphalt concrete in the allowable time; and 3) allows essentially all of the mixture to be recovered.

6.4 *Miscellaneous Apparatus*

6.4.1 One metal oven pan for heating aggregates

6.4.2 One shallow metal oven pan for heating uncompacted asphalt concrete mixtures

6.4.3 Thermometers that have a range of 50 to 260°C and conform to the requirements prescribed in ASTM Document E 1

6.4.4 One metal spatula or spoon

6.4.5 Oven gloves

7. HAZARDS

7.1 This test method involves the handling of hot asphalt binder, aggregate, and asphalt concrete mixtures. These materials can cause severe burns if allowed to contact skin. Proper precautions must be taken to avoid burns.

8. SAMPLING

8.1 The asphalt binder shall be sampled in accordance with T40.

8.2 The aggregate shall be sampled and tested in accordance with T2 and T27, respectively.

9. SPECIMEN PREPARATION

9.1 Preheat the aggregate for a minimum of 2 h at the desired mixing temperature. The amount of aggregate preheated shall be of sufficient size to obtain a mixture specimen of the desired size..

9.2 Preheat the asphalt binder to the desired mixing temperature. The amount of asphalt binder preheated shall be of sufficient size to obtain the desired asphalt binder content to be tested.

NOTE 1.—Asphalt binders held for more than 2 h at the desired mixing temperature should be discarded.

9.3 Mix the heated aggregate and asphalt binder at the desired asphalt content.

10. PROCEDURE

10.1 Place the mixture on the baking pan and spread it to an even thickness of approximately 21 to 22 kg/m^2. Place the mixture and pan in the forced draft oven for 4 h $\pm$ 5 min at a temperature of 135°C $\pm$ 1°C.

10.2 Stir the mixture every hour to maintain uniform aging.

10.3 After 4 h, remove the mixture from the forced draft oven. The aged mixture is now ready for further conditioning or testing as required. Proceed to section 11 if the specimens are *not* conditioned for the effects of *long-term* aging.

10.4 *Sampling*

10.4.1 Plant-mixed asphalt concrete mixtures shall be sampled in accordance with T164.

10.4.2 Laboratory-mixed asphalt concrete mixtures shall be sampled, prepared and aged in accordance with T164.

10.4.3 Compacted roadway samples shall have a cut test specimen size that is 102 ± 6 mm in diameter by 152 ± 6 mm in height.

10.5 Heat the asphalt concrete to the desired compaction temperature.

10.6 Compact the sample in accordance with M-002 or M-008.

NOTE 2.—Compact a sufficient amount of material to ensure that the final test specimen size is 102 ± 6 mm in diameter by 152 ± 6 mm in height.

10.7 Cool the compacted test specimen to 60°C ± 1°C in an oven set at 60°C.

NOTE 3.—Cooling to 60°C will take approximately 2 h for the test specimen size stated in note 2.

10.8 After cooling the test specimen to 60°C, level the specimen ends by applying a static load to the specimen at a rate of 72.00 ± .05 kN/min. Release the load at the same rate when the specimen ends are level or when the load applied reaches a maximum of 56 kN.

10.9 After cooling the test specimen at room temperature overnight, extrude the specimen from the compaction mold.

10.10 Place the compacted test specimen on a rack in the forced draft oven for 120 ± 0.5 h at a temperature of 85°C ± 1°C.

10.11 After 120 h, turn the oven off, open the doors, and allow the test specimen to cool to room temperature. Do not touch or remove the specimen until it has cooled to room temperature.

NOTE 4.—Cooling to room temperature will take approximately overnight for the test specimen size stated in note 21.

10.12 After cooling to room temperature, remove the test specimen from the oven. The aged specimen is now ready for testing as required.

11. REPORT

11.1 Report the following information:

11.1.1 *Asphalt Binder Grade*

11.1.2 *Asphalt Binder Content*—in percent to the nearest 0.1%

11.1.3 *Aggregate Type and Gradation*

11.1.4 *Short-Term Aging Conditions*—the following information as applicable:

11.1.4.1 *Plant-Mixing Temperature*—in degrees Celsius to the nearest 1°C

11.1.4.2 *Laboratory-Mixing Temperature*—in degrees Celsius to the nearest 1°C

11.1.4.3 *Short-Term Aging Temperature in Laboratory*—in degrees Celsius to the nearest 1°C

11.1.4.4 *Short-Term Aging Duration in Laboratory*—in minutes to the nearest 1 min

11.1.5 *Long-Term Aging Conditions*

11.1.5.1 *Compaction Temperature*—in degrees Celsius to the nearest 1°C

11.1.5.2 *Compacted Specimen Height*—in millimeters to the nearest 1 mm

11.1.5.3 *Compacted Specimen Diameter*—in millimeters to the nearest 1 mm

11.1.5.4 *Compacted Specimen Density*—in kilograms per square meter to the nearest 1 kg/m^2

11.1.5.5 *Compacted Specimen Air Voids*—in percent to the nearest 0.1%

11.1.5.6 *Long-Term Aging Temperature*—in degrees Celsius to the nearest 1°C

11.1.5.7 *Long-Term Aging Duration*—in minutes to the nearest 1 min

12. KEY WORDS

12.1 Aging, asphalt concrete, asphalt concrete aging, bituminous mixtures, bituminous paving mixtures, short-term aging.

Appendix B:

Detailed Roller Pass Studies From Each Site.

ABSORPTIVE AGGREGATE STUDY
PLANT CONDITIONS

Project No. Site #1
Date 4/2/94

Plant Type	Drum Mix Plant
Mix Discharge Temperature	155 C
Mix Time in Silo	Approx. 4 Min.
Mix Haul Time from Plant to Project	15 Min.

FIELD CONDITIONS

Ambient Air Temperature	24 C
Wind Speed	3 kph
Weather Conditions	Sunny
Mat Thickness	50 mm top mat
Base Surface Temperature	49 C
Laydown Temperature	155 C
Time for Mat Surface Temperature to Cool to 85 C (185 F)	48 Min.
Time for Mat Internal Temperature to Cool to 85 C (155 F)	9 Min

ABSORPTIVE AGGREGATE STUDY
PAVING OPERATION

PROJECT NO. Site #1
DATE 4/20/94

PHASE/CODE	MFG./MODEL	TYPE	WT. (kg)	SPEED (kph)
(B) BREAKDOWN	Hyster C766A	Steel Wheel	9625	4.2
(I) INTERMEDIATE	N/A	N/A	N/A	N/A
(F) FINISH	Hyster C330	Steel Wheel	7240	6.5

NUMBER OF PASSES	MAT SURFACE TEMP. (DEG. C)	TIME	MAT INTERNAL TEMP. (DEG. C)	ROLLER TYPE/MODE
0	155	12:04	155	
1	129	12:09	104	BV
2	129	12:13	81	BV
NP	129	12:17	78	
3	117	12:24	73	B
NP	111	12:27	71	
NP	105	12:32	68	
NP	103	12:38	66	
NP	91	12:45	64	
4	88	12:48	64	F
5	88	12:50	64	F
6	87	12:51	64	F
7	87	12:51	64	F
8	85	12:52	63	F
9	85	12:53	63	F
10	83	12:54	63	F

ABSORPTIVE AGGREGATE STUDY
PLANT CONDITIONS

Project No. Site #3
Date 5/24/94

Plant Type	Inline Drum - 600 Ton/Hr
Mix Discharge Temperature	146 C
Mix Time in Silo	Approx. 4 Min.
Mix Haul Time from Plant to Project	37 Min.

FIELD CONDITIONS

Ambient Air Temperature	17.2 C
Wind Speed	8 kph
Weather Conditions	Sunny
Mat Thickness	75 mm
Base Surface Temperature	28 C
Laydown Temperature	132 C
Time for Mat Surface Temperature to Cool to 85 C (185 F)	43 Min.
Time for Mat Internal Temperature to Cool to 85 C (185 F)	55 Min.

ABSORPTIVE AGGREGATE STUDY
PAVING OPERATION

PROJECT NO. Site #3
DATE 5/24/94

PHASE/CODE	MFG./MODEL	TYPE	WT. (kg)	SPEED (kph)
(B) BREAKDOWN	DynaPac CC501	Steel Wheel	15466	5.2
(I) INTERMEDIATE	DynaPac CP30	Pnuematic	27244	13.7
(F) FINISH	Cat CB-614	Steel Wheel	11340	9.2

NUMBER OF PASSES	MAT SURFACE TEMP. (DEG. C)	TIME	MAT INTERNAL TEMP. (DEG. C)	ROLLER TYPE/MODE
NP	129	9:53	132	
NP	116	9:56	132	
NP	109	10:00	131	
1	99	10:04	126	B
2	98	10:08	123	BV
3	97	10:10	121	B
NP	97	10:15	114	
4	94	10:22	102	I
5	94	10:23	102	I
6	92	10:27	97	I
7	92	10:28	97	I
8	87	10:312	96	I
9	87	10:33	96	I
NP	81	10:44	85	
10	78	10:50	82	F
11	74	10:54	76	F

ABSORPTIVE AGGREGATE STUDY
PLANT CONDITIONS

Project No. Site #4
Date 5/23/94

Plant Type	Drum - 265 Ton/Hr
Mix Discharge Temperature	149 C
Mix Time in Silo	Approx. 6 Min.
Mix Haul Time from Plant to Project	10 Min.

FIELD CONDITIONS

Ambient Air Temperature	21 C
Wind Speed	8.1 kph
Weather Conditions	Partly Cloudy
Mat Thickness	25 mm
Base Surface Temperature	46 C
Laydown Temperature	141 C
Time for Mat Surface Temperature to Cool to 85 C (185 F)	16 Min.
Time for Mat Internal Temperature to Cool to 85 C (185 F)	16 Min.

ABSORPTIVE AGGREGATE STUDY
PAVING OPERATION

PROJECT NO. Site #4
DATE 5/23/94

PHASE/CODE	MFG./MODEL	TYPE	WT. (kg)	SPEED (kph)
(B) BREAKDOWN	Hyster 766	Steel Wheel	27149	9
(I) INTERMEDIATE	Hyster C530A	Rubber Tire	13574	9
(F) FINISH	Hyster C350C	Steel Wheel	13574	8

NUMBER OF PASSES	MAT SURFACE TEMP. (DEG. C)	TIME	MAT INTERNAL TEMP. (DEG. C)	ROLLER TYPE/MODE
NP	141	11:39	141	
1	122	11:43	95	B
2	110	11:44	91	B
3	99	11:45	91	B
NP	98	11:47	87	
4	98	11:48	86	I
5	94	11:51	86	I
6	94	11:52	86	F
7	90	11:54	86	F
NP	85	11:55	85	

ABSORPTIVE AGGREGATE STUDY
PLANT CONDITIONS

Project No. Site #5
Date 5/23/94

Plant Type	Continuous Flow Drum - 300 Ton/Hr
Mix Discharge Temperature	141 C
Mix Time in Silo	30 to 35 Min.
Mix Haul Time from Plant to Project	25 Min.

FIELD CONDITIONS

Ambient Air Temperature	24 C
Wind Speed	4.8 kph
Weather Conditions	Sunny
Mat Thickness	50 mm
Base Surface Temperature	44 C
Laydown Temperature	118 C
Time for Mat Surface Temperature to Cool to 85 C (185 F)	
Time for Mat Internal Temperature to Cool to 85 C (185 F)	

ABSORPTIVE AGGREGATE STUDY
PAVING OPERATION

PROJECT NO. Site #5
DATE 6/1/94

PHASE/CODE	MFG./MODEL	TYPE	WT. (kg)	SPEED (kph)
(B) BREAKDOWN	Hyster 776	Steel Wheel	14479	5.6
(I) INTERMEDIATE	Hyster 530	Rubber Tire	15000	
(F) FINISH	Hyster 350	Steel Wheel	10860	

NUMBER OF PASSES	MAT SURFACE TEMP. (DEG. C)	TIME	MAT INTERNAL TEMP. (DEG. C)	ROLLER TYPE/MODE
NP	111	11:45	118	
1	109	11:48	113	
NP	111	11:53	107	BV
NP	91	12:01	98	
NP	86	12:08	92	
2	79	12:20	82	BV
3	78	12:24	79	B
NP	75	12:32	77	
NP	73	12:42	73	
NP	71	12:50	70	
NP	70	12:55	69	
NP	68	1:00	68	

ABSORPTIVE AGGREGATE STUDY
PLANT CONDITIONS

Project No. Site #6
Date 6/20/94

Plant Type	Parellel Flow Drum Capable of 400 tons/hr
Mix Discharge Temperature	149 C
Mix Time in Silo	15 Min.
Mix Haul Time from Plant to Project	5 Min.

FIELD CONDITIONS

Ambient Air Temperature	29 C
Wind Speed	0 to 4.8 kph
Weather Conditions	Partly Cloudy
Mat Thickness	50 mm
Base Surface Temperature	45 C
Laydown Temperature	138 C
Time for Mat Surface Temperature to Cool to 85 C (185 F)	44 Min.
Time for Mat Internal Temperature to Cool to 85 C (185 F)	37 Min.

ABSORPTIVE AGGREGATE STUDY
PAVING OPERATION

PROJECT NO. Site #6
DATE 6/20/94

PHASE/CODE	MFG./MODEL	TYPE	WT. (kg)	SPEED (kph)
(B) BREAKDOWN	DynaPac CC50	Steel Wheel	14479	5.5
(I) INTERMEDIATE	Caterpillar CB-634	Steel Wheel	15000	6.1
(F) FINISH	NA	NA	NA	NA

NUMBER OF PASSES	MAT SURFACE TEMP. (DEG. C)	TIME	MAT INTERNAL TEMP. (DEG. C)	ROLLER TYPE/MODE
NP	137	10:28	144	
1	119	10:36	137	BV
2	116	10:38	129	BV
NP	116	10:41	122	
NP	112	10:46	113	
3	102	10:48	112	BV
4	100	10:50	107	BV
5	93	10:55	92	B
6	92	10:58	94	B
7	90	11:05	85	IV
8	89	11:07	85	IV
9	84	11:12	79	IV
10	84	11:13	79	I
11	83	11:23	75	I

ABSORPTIVE AGGREGATE STUDY
PLANT CONDITIONS

Project No. Site #7
Date 6/23/94

Plant Type	Drum Mixer Capable of 400 tons/hr
Mix Discharge Temperature	143 C
Mix Time in Silo	Sample A - 2 Hrs. Sample B - 16 Hrs.
Mix Haul Time from Plant to Project	2 Hrs.

FIELD CONDITIONS

Ambient Air Temperature	21 C
Wind Speed	3.2 kph
Weather Conditions	Sunny
Mat Thickness	50 mm
Base Surface Temperature	39 C
Laydown Temperature	118 C
Time for Mat Surface Temperature to Cool to 85 C (185 F)	35 Min.
Time for Mat Internal Temperature to Cool to 85 C (185 F)	46 Min.

ABSORPTIVE AGGREGATE STUDY
PAVING OPERATION

PROJECT NO. Site #7
DATE 6/23/94

PHASE/CODE	MFG./MODEL	TYPE	WT. (kg)	SPEED (kph)
(B) BREAKDOWN	Caterpiller CB-534	Steel Wheel	11764	9 sec. /100'
(I) INTERMEDIATE	Ingram 9 Wheel Roller	Rubber Tire		11 sec /100'
(F) FINISH	Caterpiller CB-534B	Steel Wheel	11764	10 sec /100'

NUMBER OF PASSES	MAT SURFACE TEMP. (DEG. C)	TIME	MAT INTERNAL TEMP. (DEG. C)	ROLLER TYPE/MODE
NP	118	11:07	122	
1	106	11:17	118	BV
2	106	11:18	117	BV
NP	104	11:20	116	
3	102	11:22	113	I
4	102	11:22	113	I
5	102	11:23	113	I
6	102	11:24	113	I
NP	97	11:25	112	
7	96	11:27	109	B
NP	88	11:42	93	
NP	82	11:53	86	
NP	80	12:10	79	
NP	77	12:14	79	
8	74	12:18	78	F
NP	74	12:22	78	

ABSORPTIVE AGGREGATE STUDY
PLANT CONDITIONS

Project No. Site #8
Date 6/30/94

Plant Type	Batch Capable of 400 tons/hr
Mix Discharge Temperature	177 C
Mix Time in Silo	20 min.
Mix Haul Time from Plant to Project	45 min.

FIELD CONDITIONS

Ambient Air Temperature	27 C
Wind Speed	0 kph
Weather Conditions	Partly Cloudy
Mat Thickness	50 mm
Base Surface Temperature	44 C
Laydown Temperature	166 C
Time for Mat Surface Temperature to Cool to 85 C (185 F)	110 Min.
Time for Mat Internal Temperature to Cool to 85 C (185 F)	100 Min.

ABSORPTIVE AGGREGATE STUDY
PAVING OPERATION

PROJECT NO. Site #8
DATE 6/30/94

PHASE/CODE	MFG./MODEL	TYPE	WT. (kg)	SPEED (kph)
(B) BREAKDOWN	Ingersoll Rand DD 110	Steel Wheel	10,000	4.7
(I) INTERMEDIATE	Ingersoll Rand PT 120R	Rubber Tire	8,000	8.0
(F) FINISH	Hamm DV-8	Steel Wheel	9,000	8.0

NUMBER OF PASSES	MAT SURFACE TEMP. (DEG. C)	TIME	MAT INTERNAL TEMP. (DEG. C)	ROLLER TYPE/MODE
NP	166	11:30		
1	154	11:32		BV
2	138	11:41		BV
NP	135	11:50	143	
NP	130	11:55	133	
3	117	12:04	124	I
4	117	12:05	124	I
5	111	12:13	114	F
6	109	12:18	114	F
NP	110	12:23	108	
NP	94	1:02	88	
NP	92	1:09	85	

ABSORPTIVE AGGREGATE STUDY
PLANT CONDITIONS

Project No. Site #9
Date 6/30/94

Plant Type	Drum Mixer Capable of 450 tons/hr
Mix Discharge Temperature	143 C
Mix Time in Silo	15 min.
Mix Haul Time from Plant to Project	10 min.

FIELD CONDITIONS

Ambient Air Temperature	29 C
Wind Speed	0 kph
Weather Conditions	Night
Mat Thickness	50 mm
Base Surface Temperature	30 C
Laydown Temperature	140 C
Time for Mat Surface Temperature to Cool to 85 C (185 F)	39 Min.
Time for Mat Internal Temperature to Cool to 85 C (185 F)	55 Min.

ABSORPTIVE AGGREGATE STUDY
PAVING OPERATION

PROJECT NO. Site #9
DATE 6/30/94

PHASE/CODE	MFG./MODEL	TYPE	WT. (kg)	SPEED (kph)
(B) BREAKDOWN	Ingersoll Rand DD 90	Steel Wheel	9,000	5.3
(I) INTERMEDIATE	Hyster C550	Rubber Tire	11,000	5.1
(F) FINISH	DynaPac CC-42	Steel Wheel	7,000	4.7

NUMBER OF PASSES	MAT SURFACE TEMP. (DEG. C)	TIME	MAT INTERNAL TEMP. (DEG. C)	ROLLER TYPE/MODE
NP	140	8:20	139	
1	127	8:23	126	BV
2	126	8:24	126	BV
3	122	8:25	125	I
4	119	8:27	122	BV
NP	117	8:32	121	
5	112	8:33	122	I
6	112	8:35	121	B
7	113	8:39	119	BV
NP	103	8:44	114	
8	95	8:45	114	I
9	95	8:47	114	I
10	95	8:48	112	F
NP	95	8:53	99	
11	89	8:55	95	F
12	87	8:57	94	I
13	86	8:58	94	F
14	85	8:59	93	I
NP	76	9:07		

Appendix C:

SHRP Binder Test Results.

Aging	Test	Test Temp. °C	Units of Results	Site		
				1	2	3
Tank	Sp.Gr.	25		1.0142	1.0318	1.0270
	Flash		°C	338	350+	350+
	Ab.Vis.	60	poises	2167	1937	989
	Pen	25	dmm	117	74	115
	DSR	58	kPa	2910	3310	1600
		64	kPa	1490	1400	720
		70	kPa	810	630	
TFOT	LOH	163	%	0.10	0.05	0.08
	Ab.Vis.	60	poises	6400	6010	2750
	DSR	58	kPa	4600	9990	4620
		64	kPa	270	4280	2050
		70	kPa	1180	1920	970
PAV	DSR	25	kPa	2630	2920	2260
		22	kPa	3670	4100	3250
		19	kPa	5070	5530	4580
		16	kPa			6400
		13	kPa			
	BBR Stiffness (S)	-12	MPa	88	108	81
		-18	MPa	181	209	177
		-24	MPa			300
	BBR Slope (m)	-12		0.334	0.309	0.337
		-18		0.267	0.276	0.297
		-24				0.251

Aging	Test	Test Temp. °C	Units of Results	Site		
				4	5	6*
Tank	Sp.Gr.	25		0.9981		
	Flash		°C	350+	330+	
	Ab.Vis.	60	poises	1130	1023	
	Pen	25	dmm	61	85	
	DSR	52	kPa			
		58	kPa	2030	1840	
		64	kPa	920	820	
TFOT	LOH	163	%	0.05	0.08	
	Ab.Vis.	60	poises	2590	2180	
	DSR	52	kPa	10020	9990	
		58	kPa	4050	4160	
		64	kPa	1840	1740	
PAV	DSR	25	kPa	2210	3340	
		22	kPa	3370	4920	
		19	kPa	4870	7190	
		16	kPa	7110		
		13	kPa			
	BBR Stiffness (S)	-12	MPa	147	127	
		-18	MPa	477	254	
	BBR Slope (m)	-12		0.317	0.331	
		-18		0.268	0.259	

* Same as Site 8

Aging	Test	Test Temp. °C	Units of Results	Site		
				7	8	9
Tank	Sp.Gr.	25		1.0292		1.0295
	Flash		°C	500+	500+	500+
	Ab.Vis.	60	poises	1080	4140	1080
	Pen	25	dmm	103	75	105
	DSR	52	kPa	4020		4260
		58	kPa	1770	4490	1750
		64	kPa	770	2160	790
		70	kPa		1280	
TFOT	LOH	163	%	0.065	0.03	0.22
	Ab.Vis.	60	poises	2933	8313	2770
	DSR	52	kPa	9700		10170
		58	kPa	4550	7290	4480
		64	kPa	1930	3760	1950
		70	kPa		1950	
PAV	DSR	25	kPa	2230	2400	2140
		22	kPa	3400	3400	3220
		19	kPa	4950	4990	4600
		16	kPa	7140	6770	6460
		13	kPa			
	BBR Stiffness (S)	-12	MPa	84	60	75
		-18	MPa	188	143	189
		-24	MPa		276	326
	BBR Slope (m)	-12		0.361	0.371	0.350
		-18		0.302	0.306	0.304
		-24			0.265	0.246

Appendix D:

Comparison of Field Produced and Laboratory Mixed HMA.

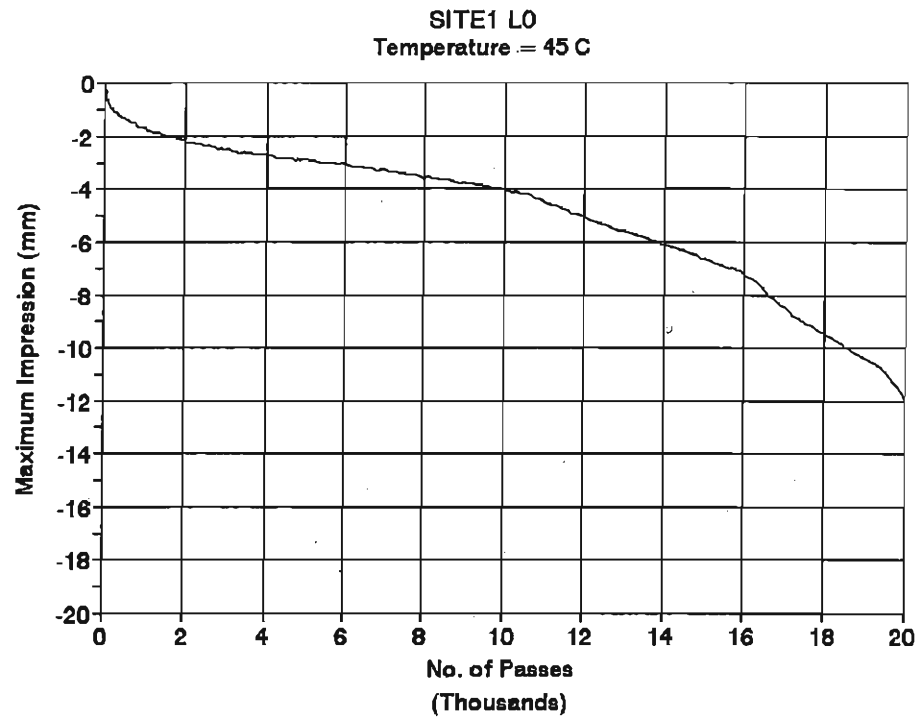
Site	Asphalt Content (%)		Air Voids (%)		VMA (%)		Hveem Stability	
	Lab	Field	Lab	Field	Lab	Field	Lab	Field
1	5.4	5.3	4.0	4.0	14.0	13.5	42	46
2	5.7	5.6	4.0	4.6	14.9	15.7	47	40
3	5.4	5.0	4.0	3.4	14.1	12.8	46	50
4	7.0	7.3	4.0	3.2	16.7	16.6	36	43
5	5.2	5.0	4.0	3.8	14.0	14.4	40	42
6	5.4	5.1	4.0	4.3	13.6	13.8	38	44
7	5.4	5.3	4.0	3.7	14.5	14.4	41	46
8	4.6	4.6	4.0	3.8	13.6	13.8	53	55
9	5.4	5.1	4.0	4.1	14.4	14.7	44	45

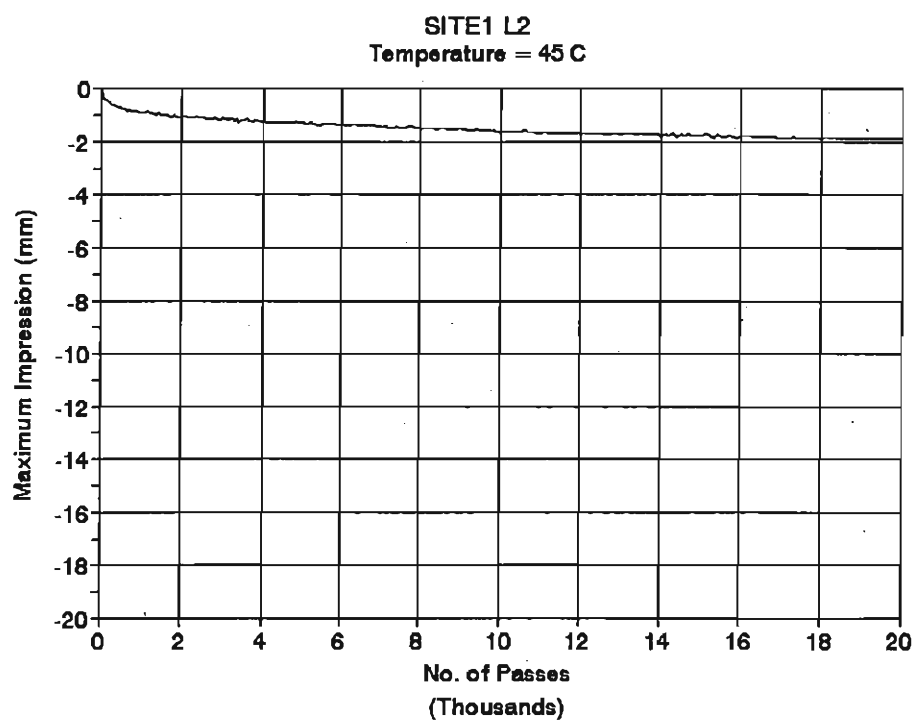
Lab - Test results from the laboratory mix design using aggregates mixed in the laboratory.
Field - Test results from the field produced HMA at the time samples were taken for this study.

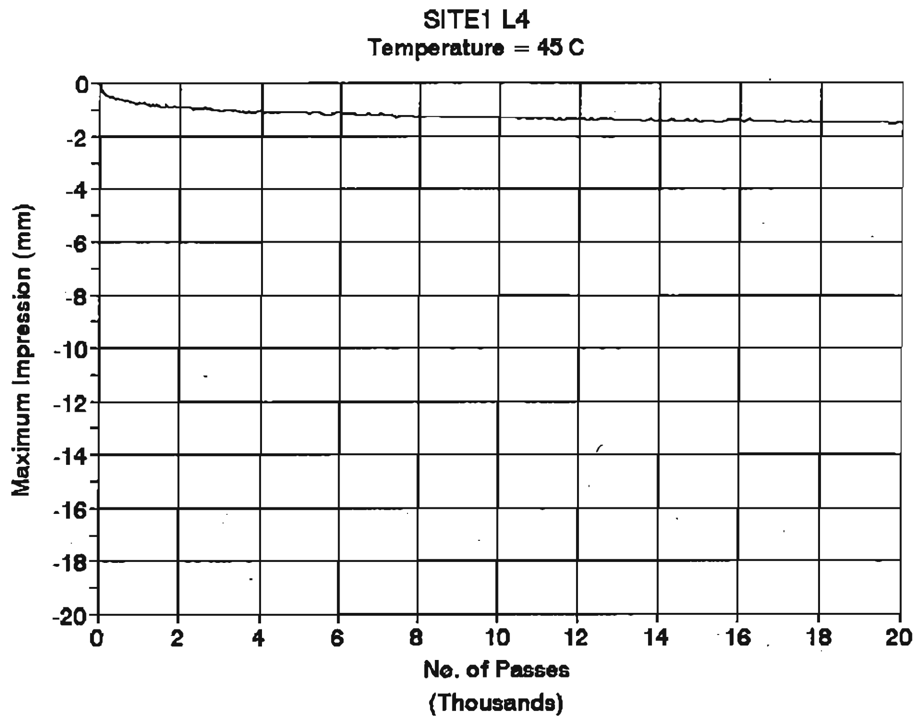
Appendix E:
Hamburg Wheel-Tracking Device Test Results.

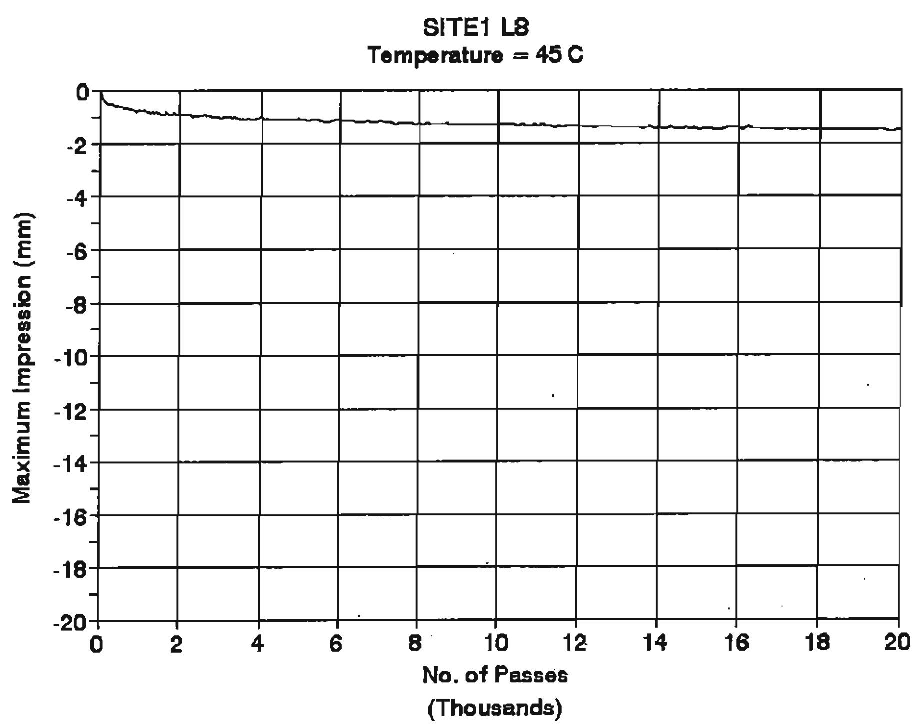
Legend:

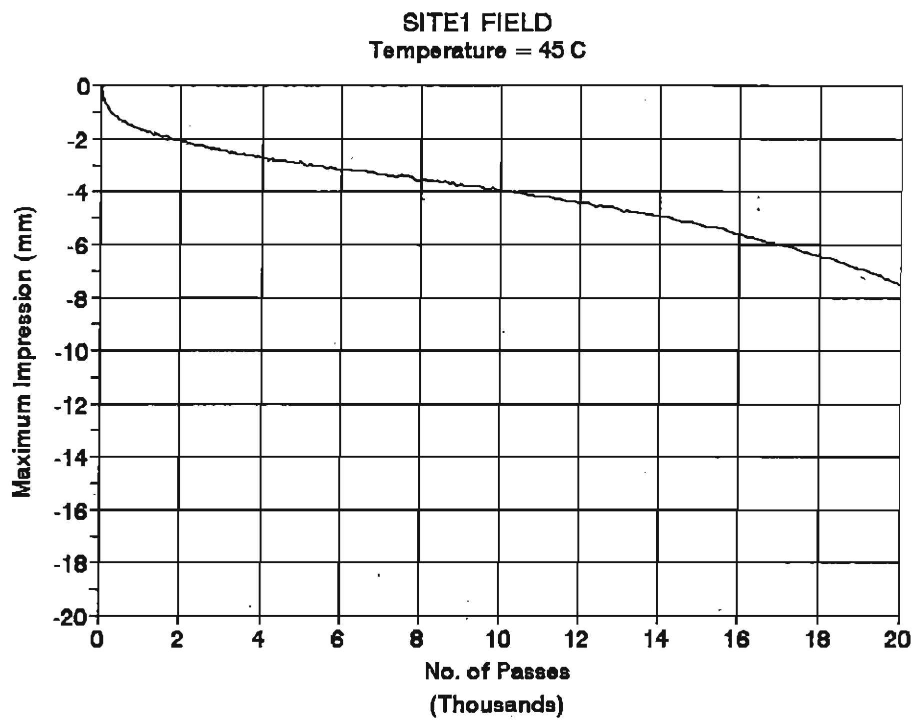
- L0 - Laboratory mixed sample that was short-term aged for 0 hours
- L2 - Laboratory mixed sample that was short-term aged for 2 hours
- L4 - Laboratory mixed sample that was short-term aged for 4 hours
- L8 - Laboratory mixed sample that was short-term aged for 8 hours
- Field - Field produced mix sampled behind the paver

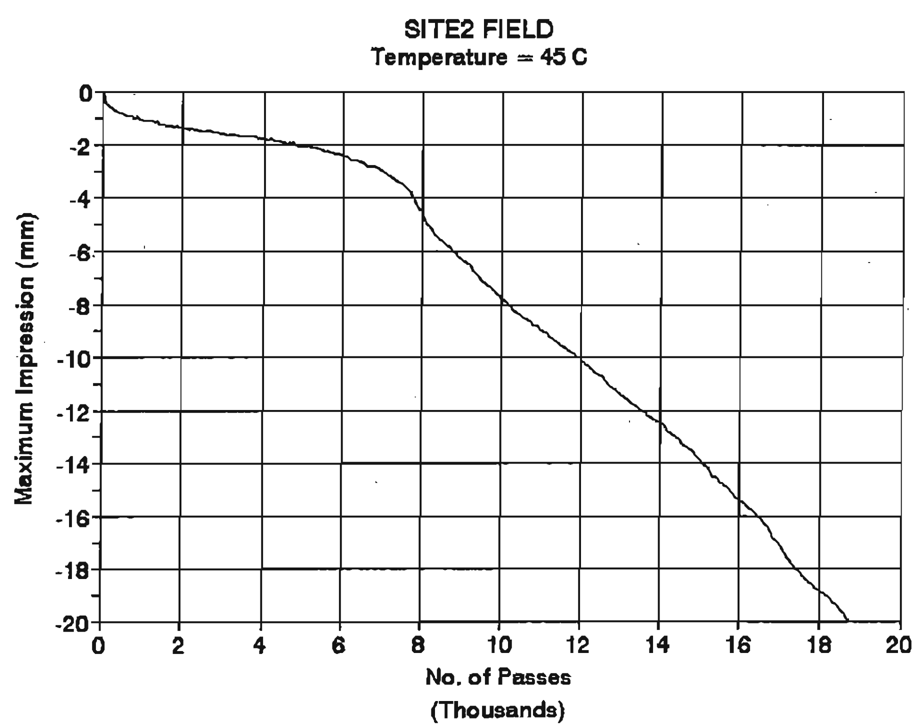

SITE1 L0
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

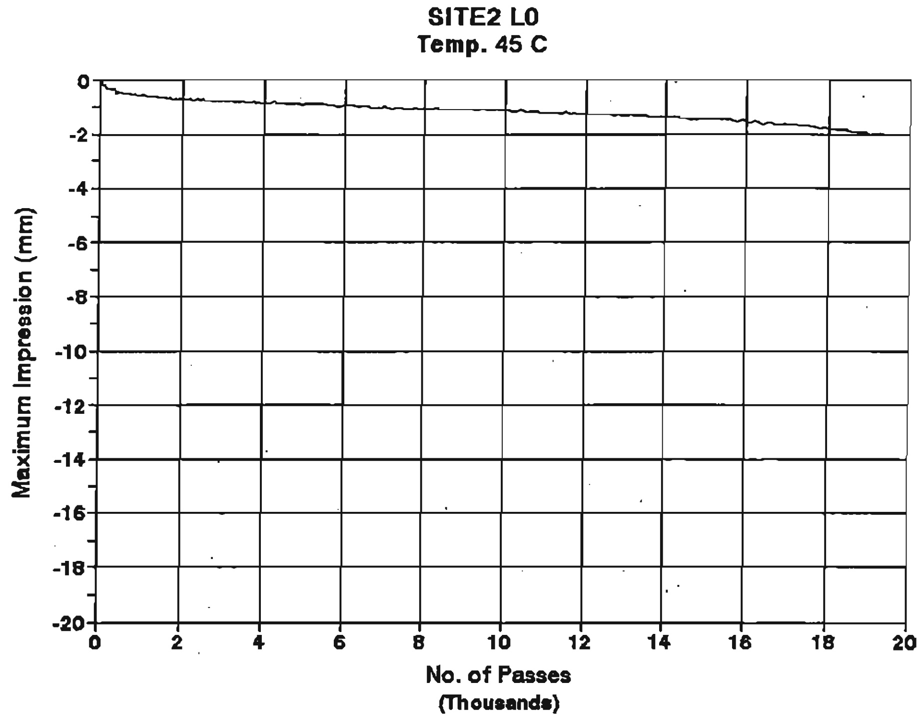

SITE1 L2
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

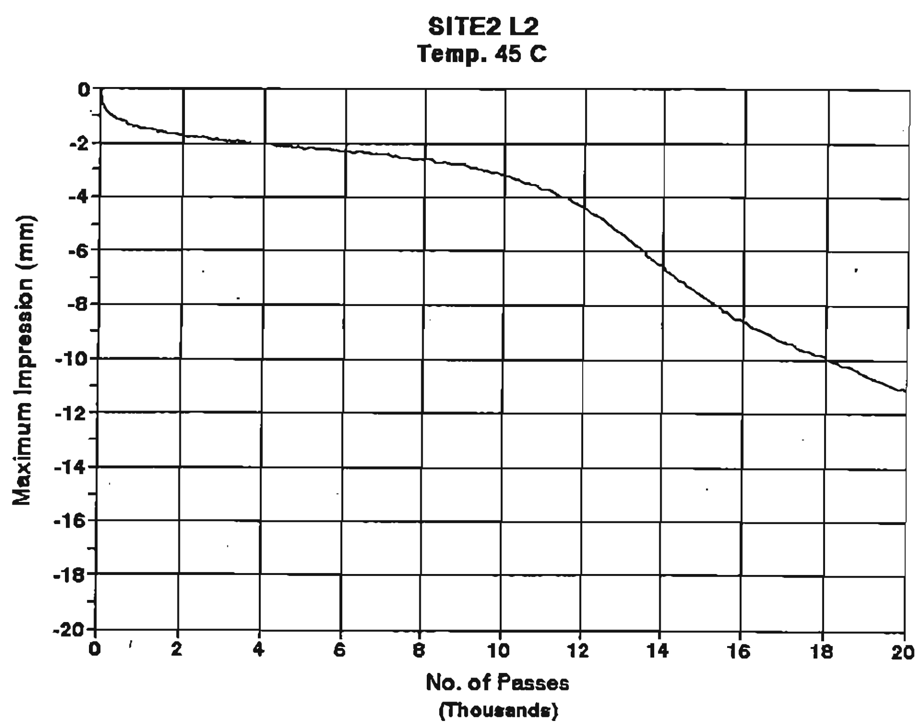

SITE1 L4
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

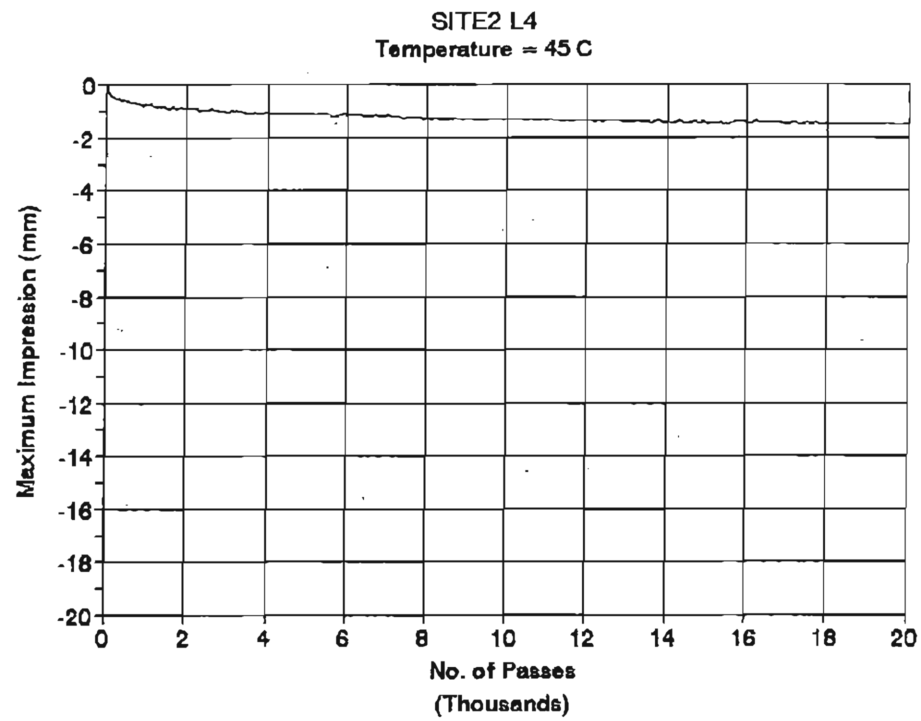

SITE1 L8
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

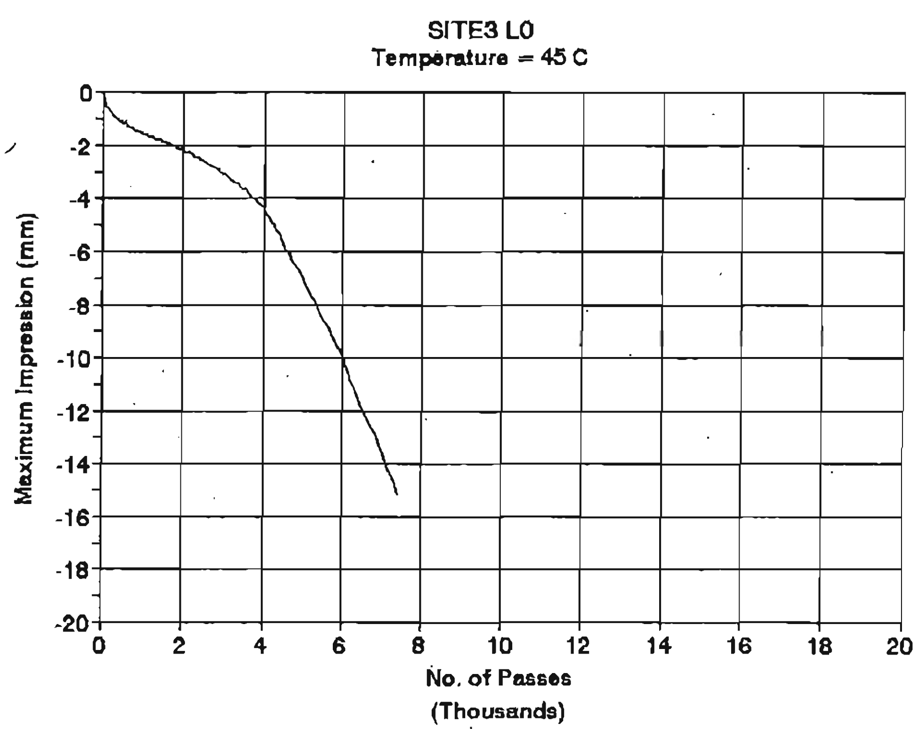

SITE1 FIELD
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

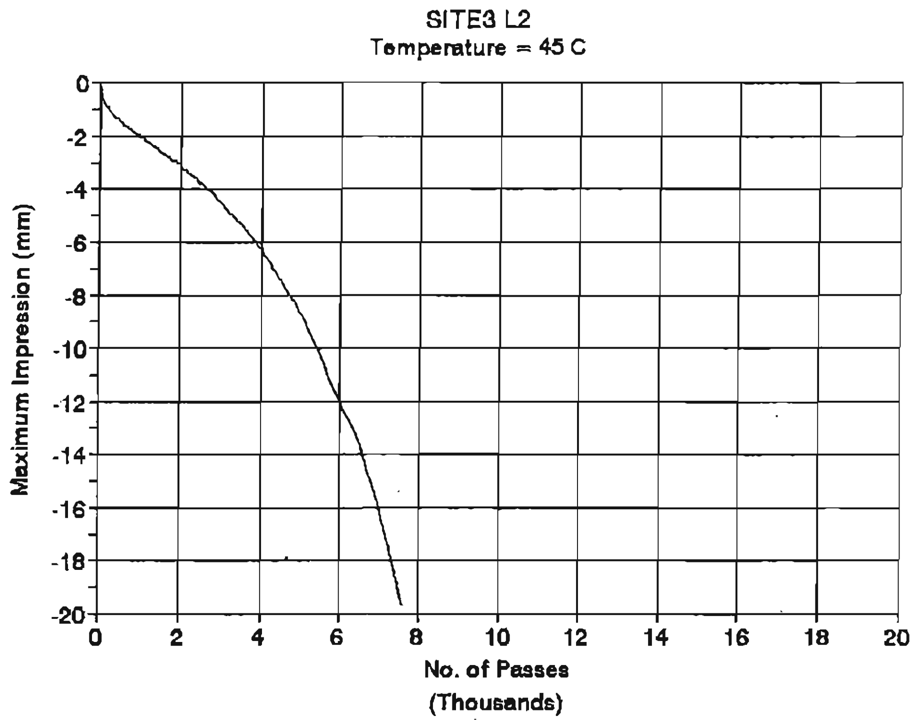

SITE2 FIELD
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

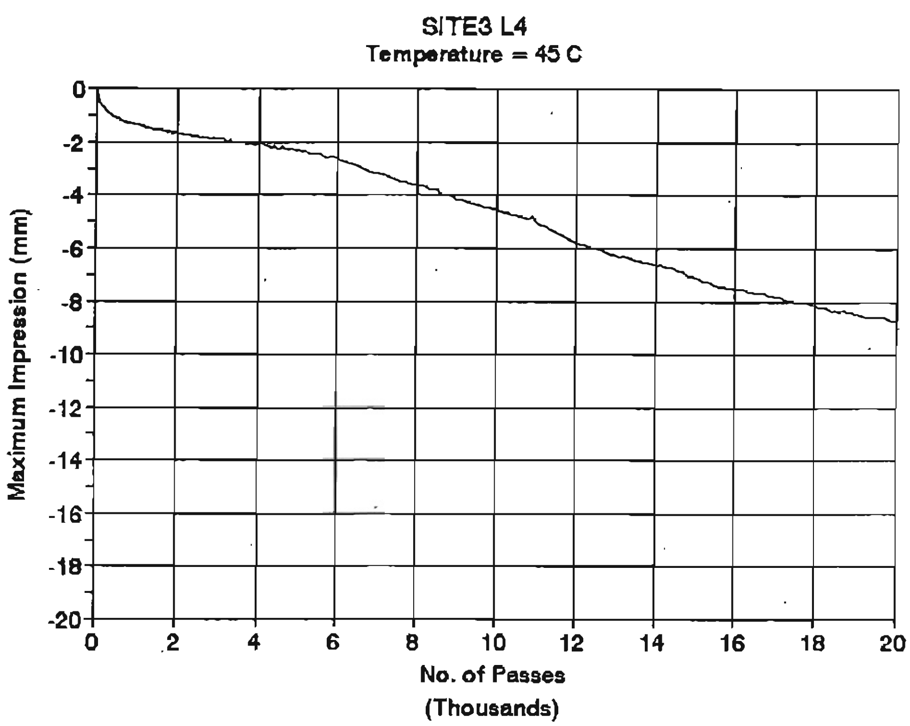

SITE2 L0
Temp. 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

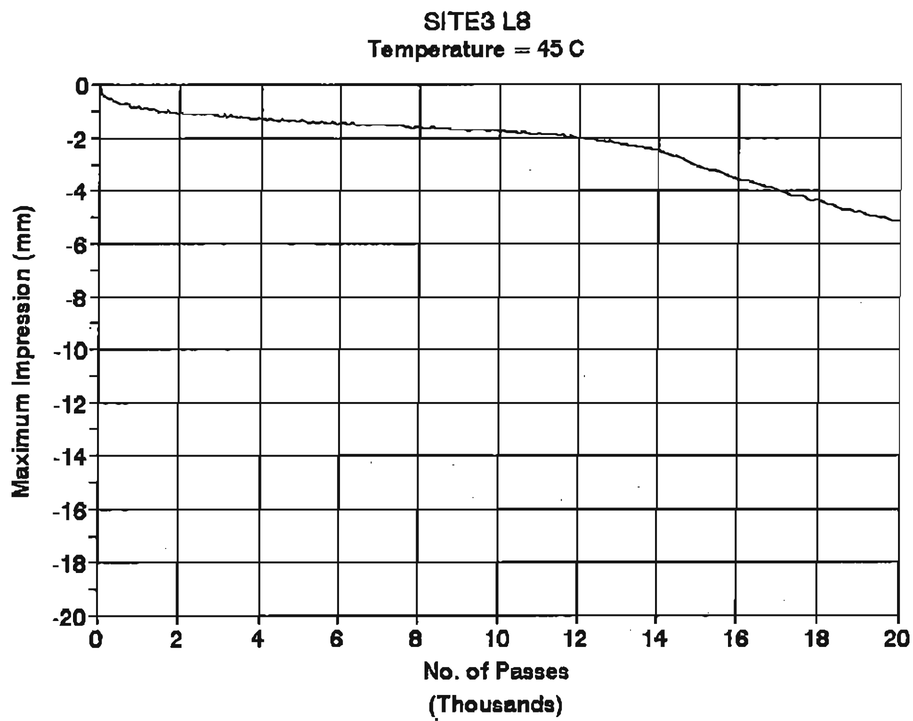

SITE2 L2
Temp. 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

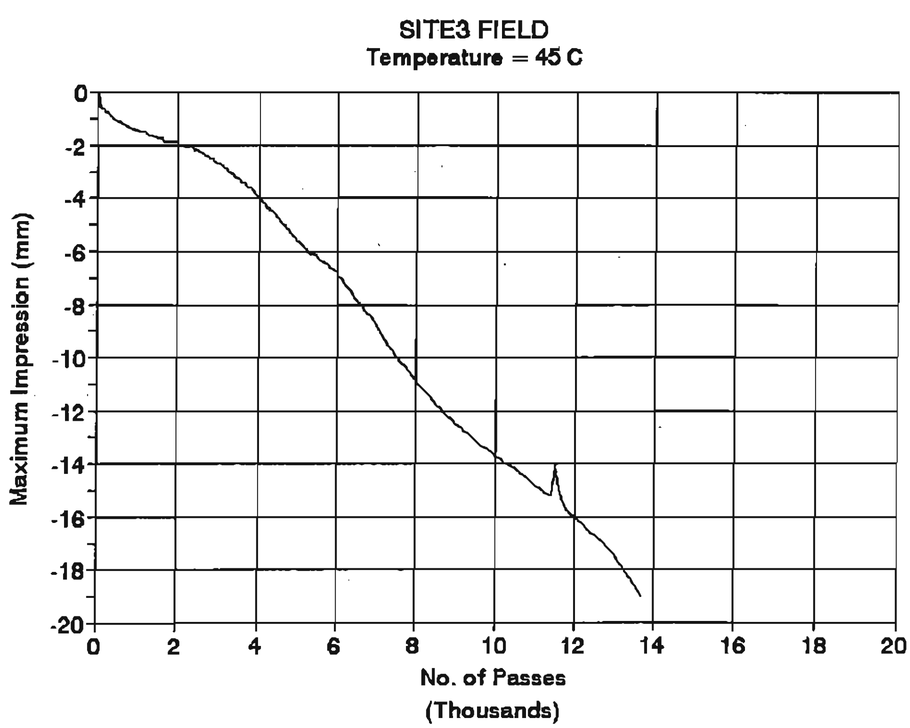

SITE2 L4
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

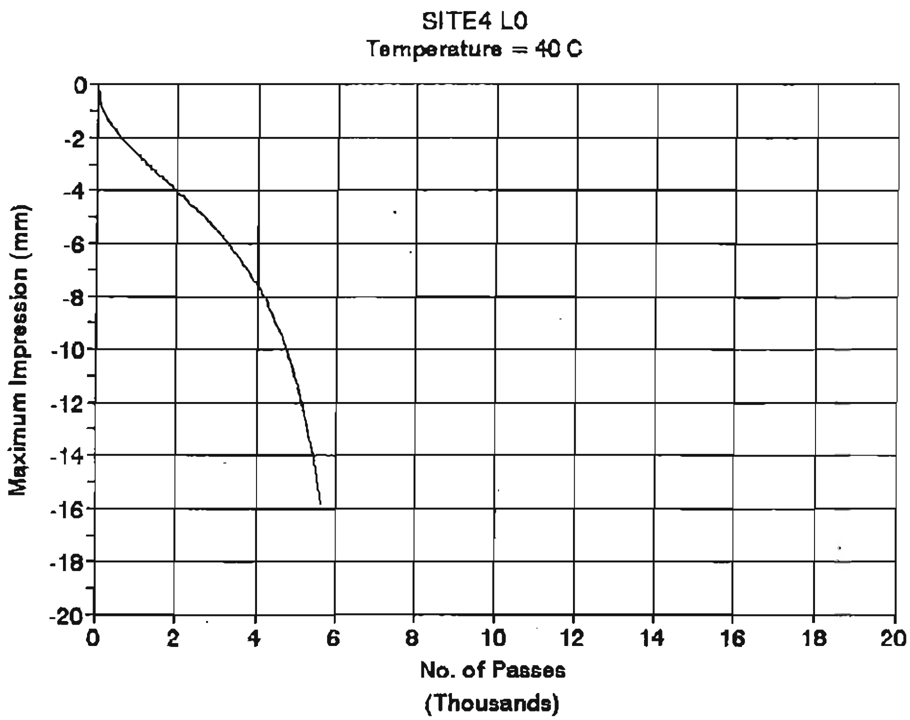

SITE3 L0
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

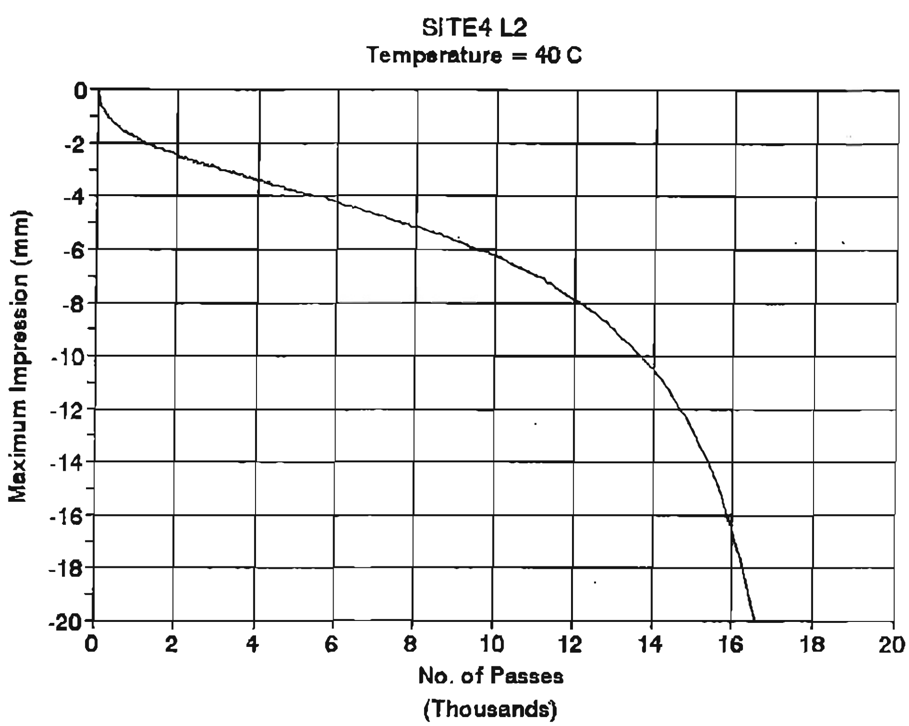

SITE3 L2
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)


SITE3 L4
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)

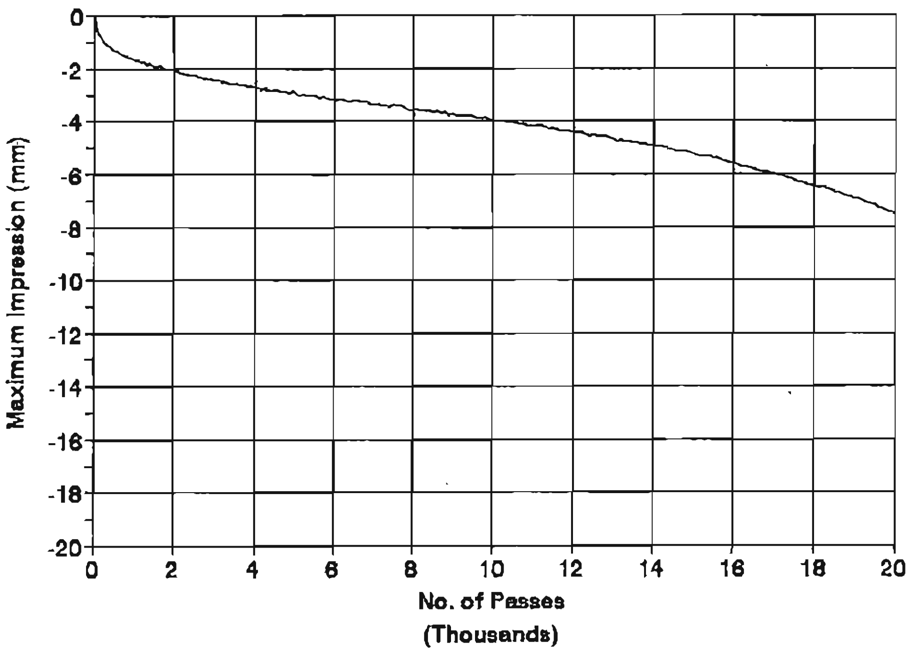

SITE3 L8
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)


SITE3 FIELD
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)

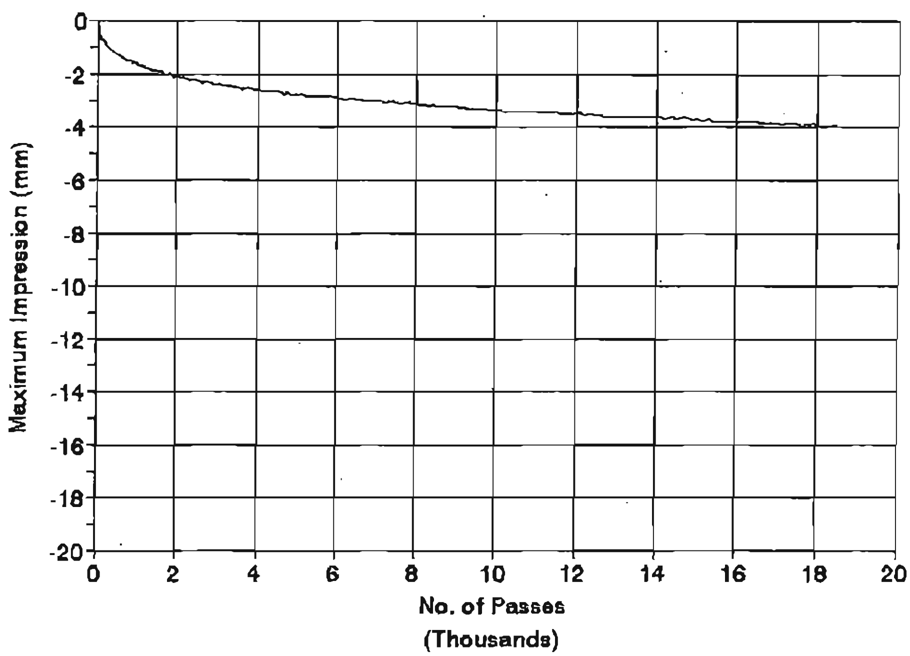

SITE4 L0
Temperature = 40 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

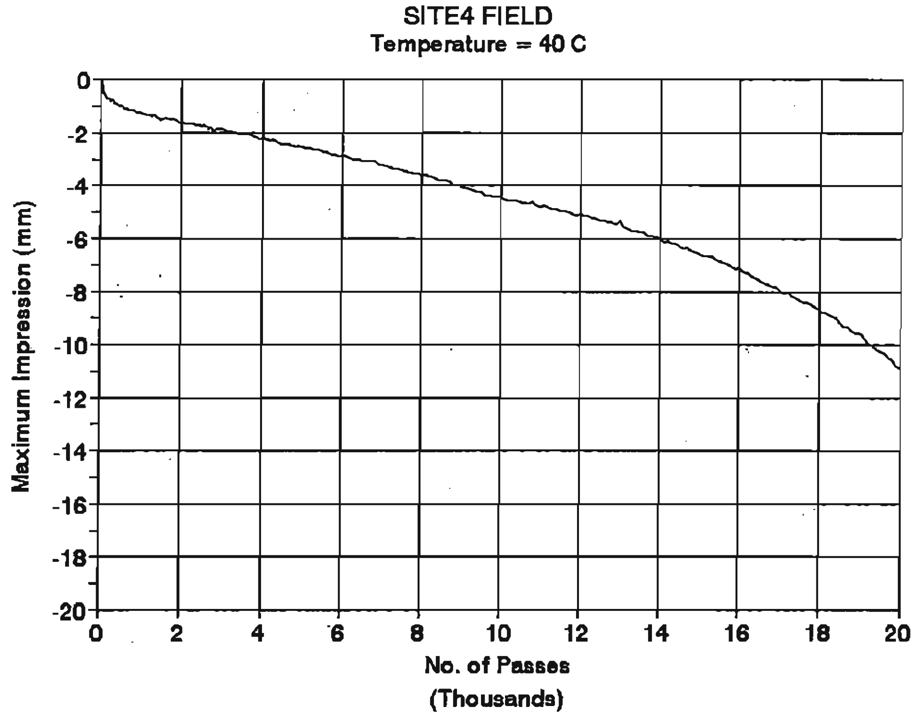

SITE4 L2
Temperature = 40 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

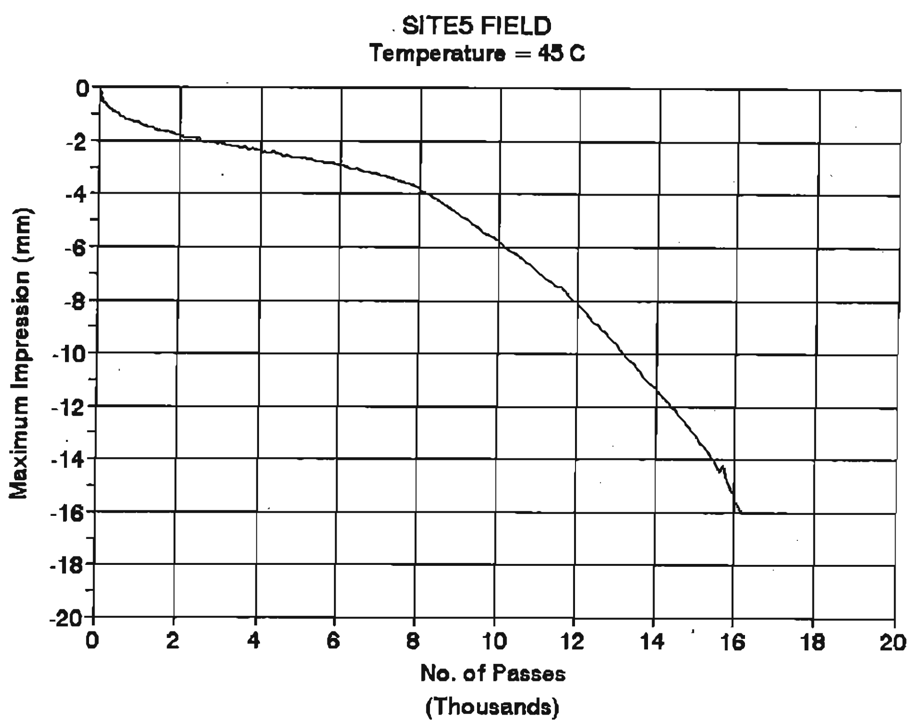
SITE4 L4
Temperature = 40 C

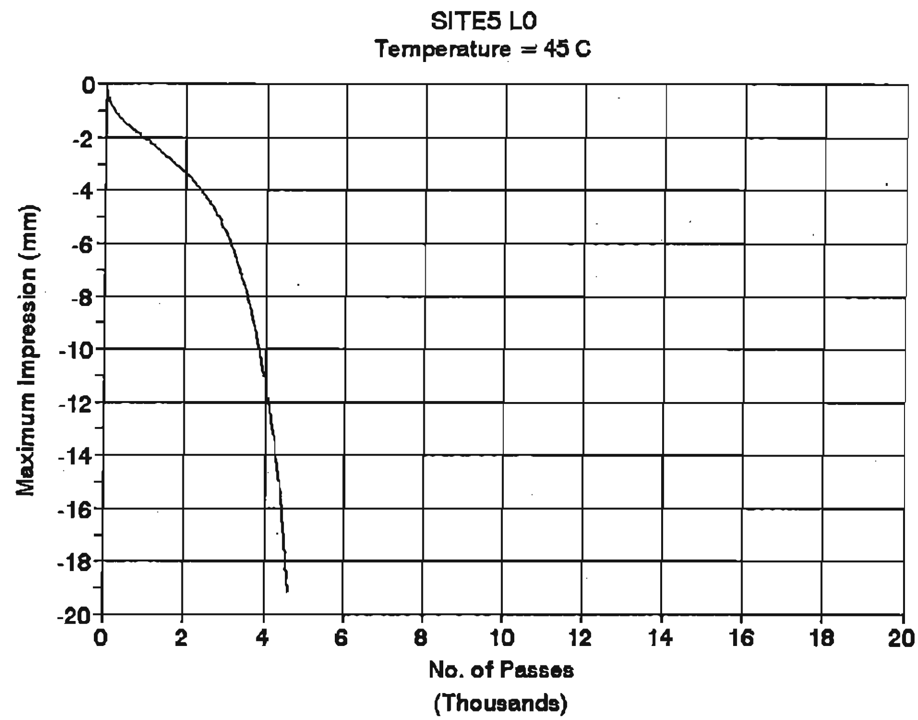


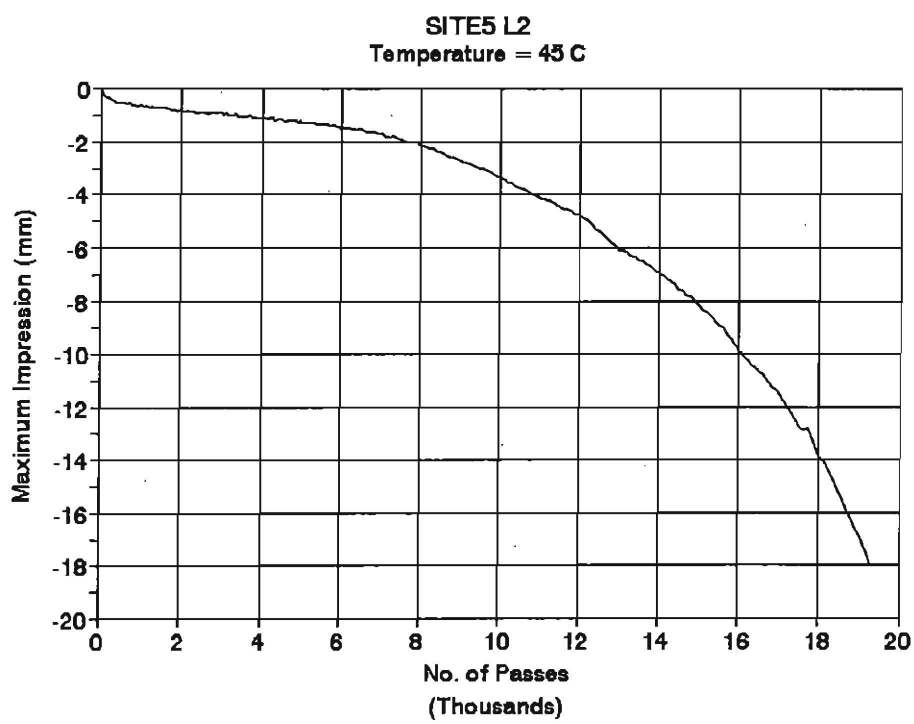
SITE4 L8
Temperature = 40 C

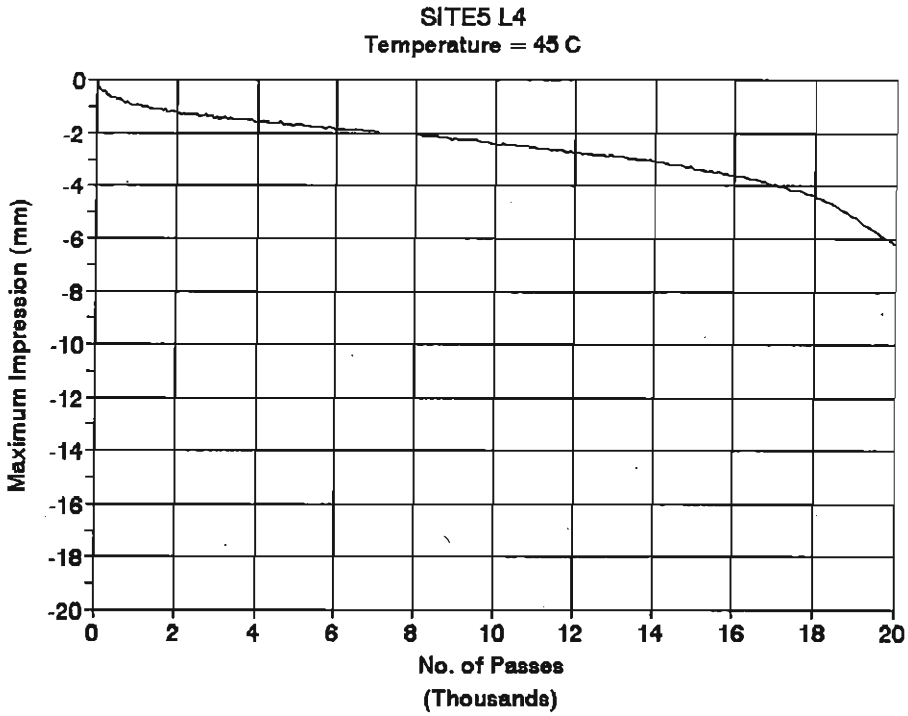


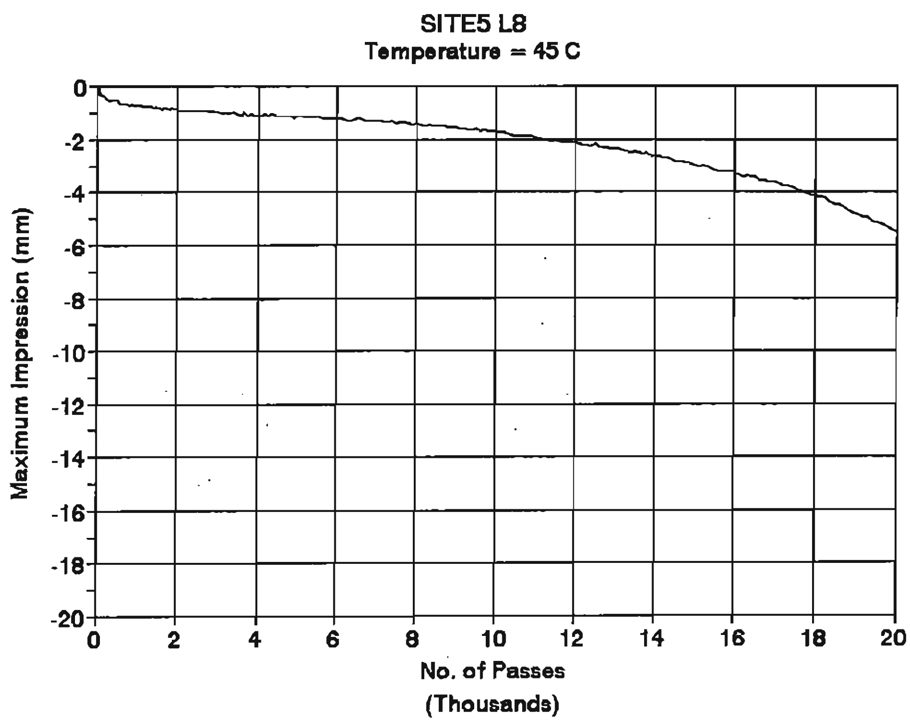

SITE4 FIELD
Temperature = 40 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

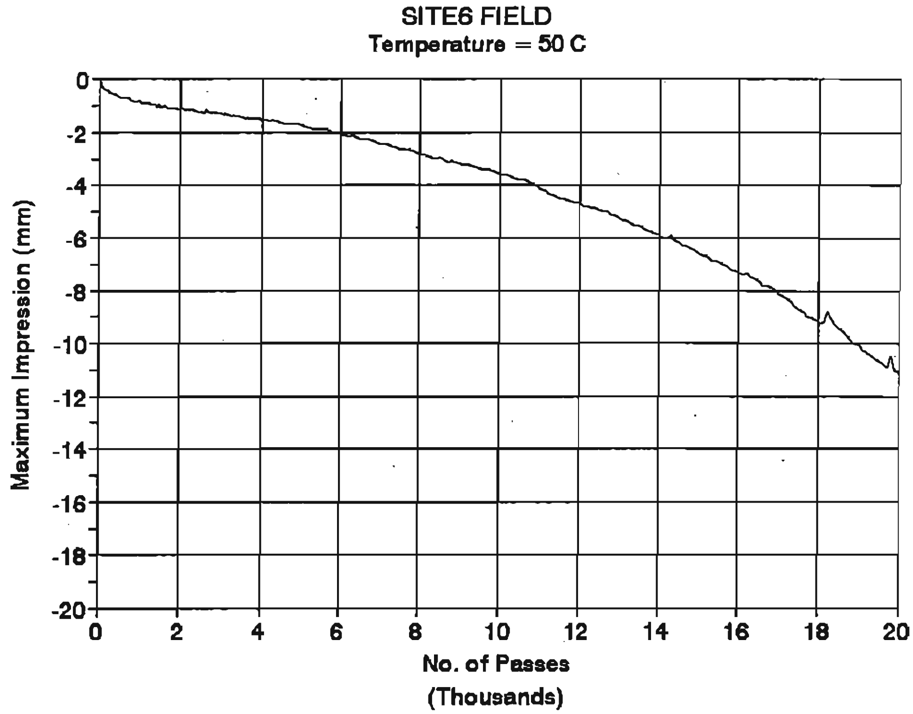

SITE5 FIELD
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

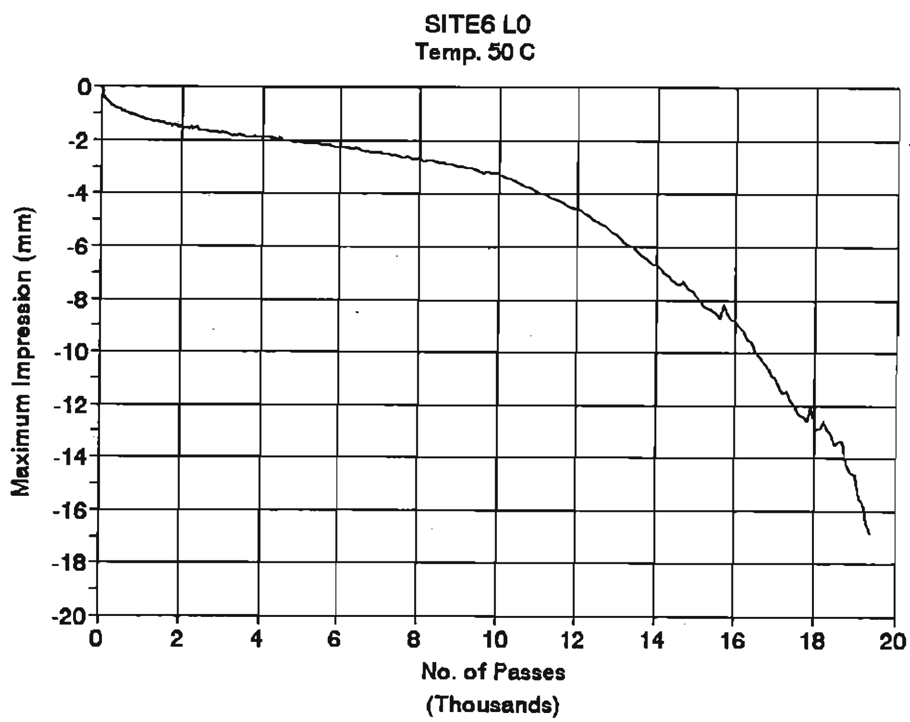

SITE5 L0
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

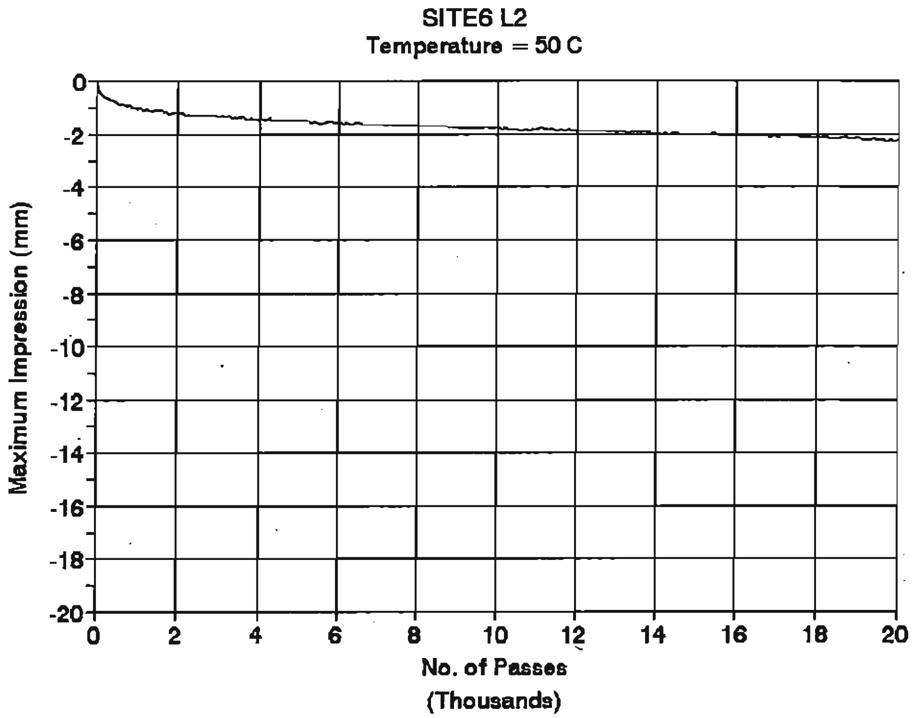

SITE5 L2
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

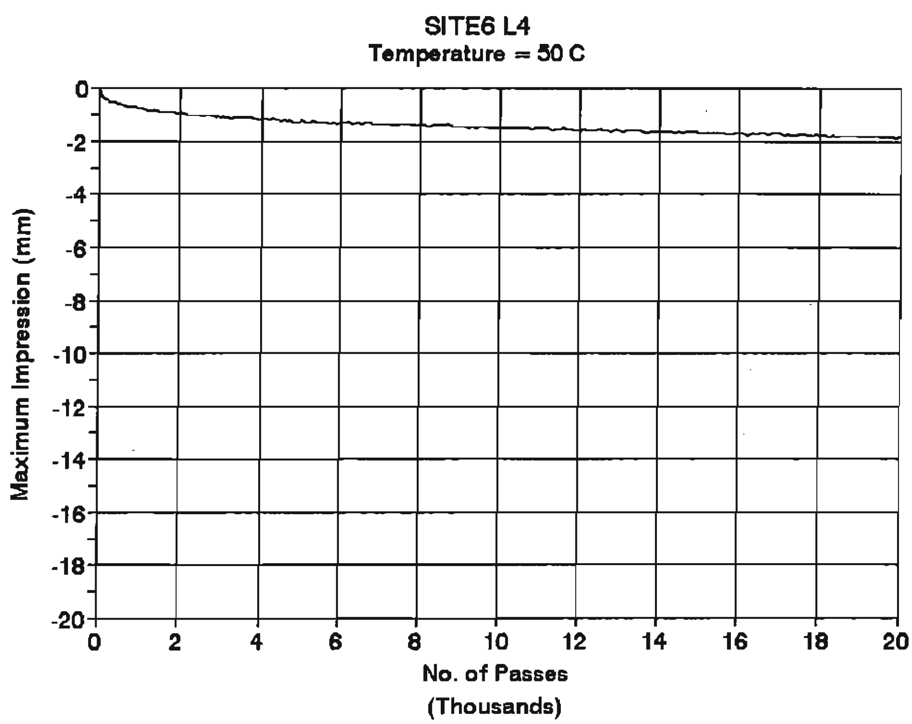

SITE5 L4
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

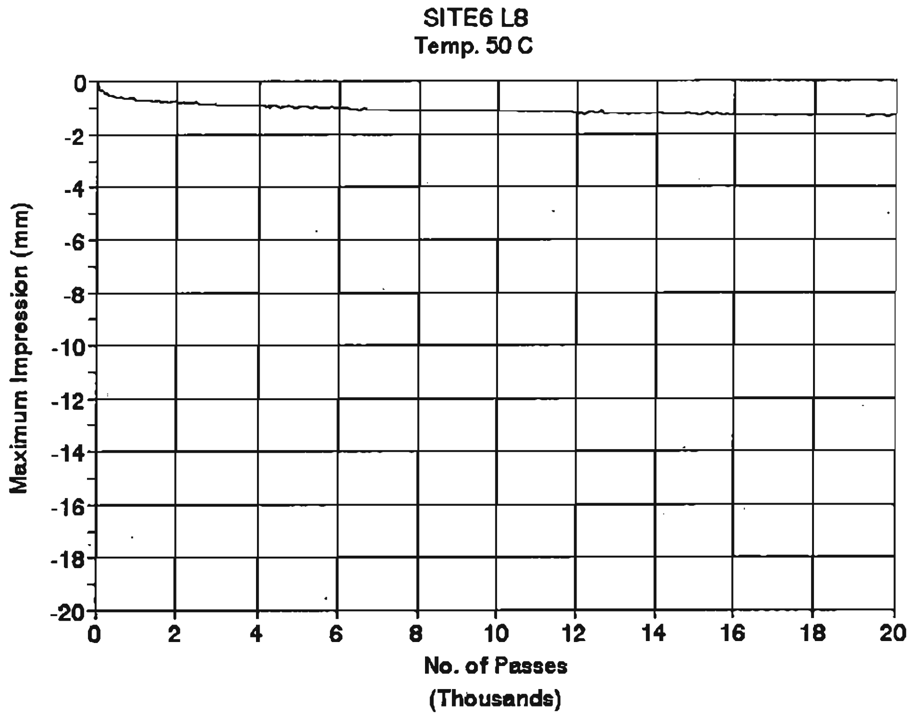

SITE5 L8
Temperature = 45 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)


SITE6 FIELD
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)

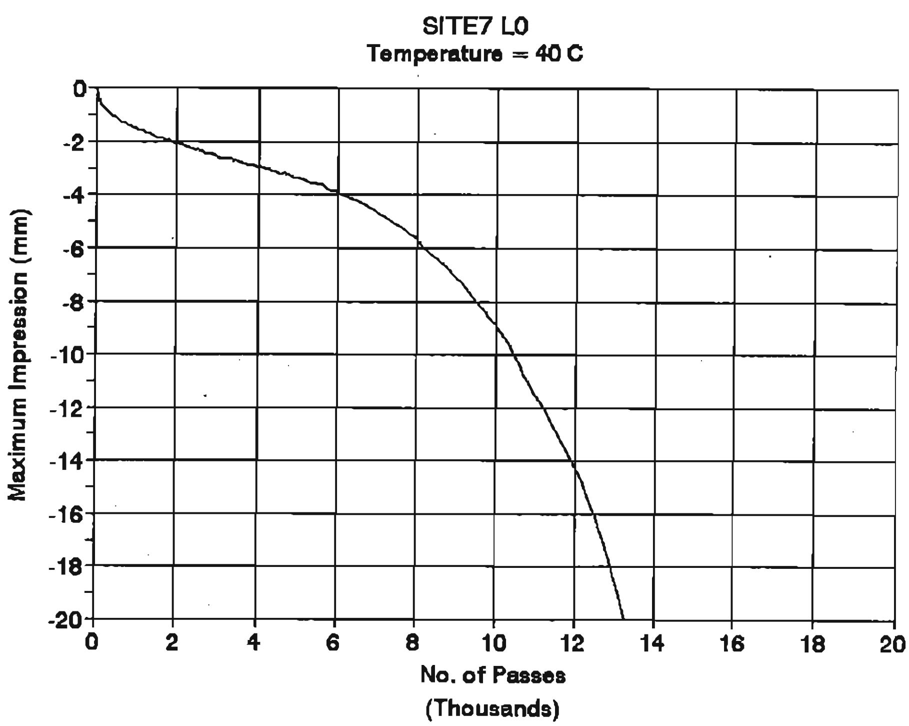

SITE6 LO
Temp. 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)


SITE6 L2
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)

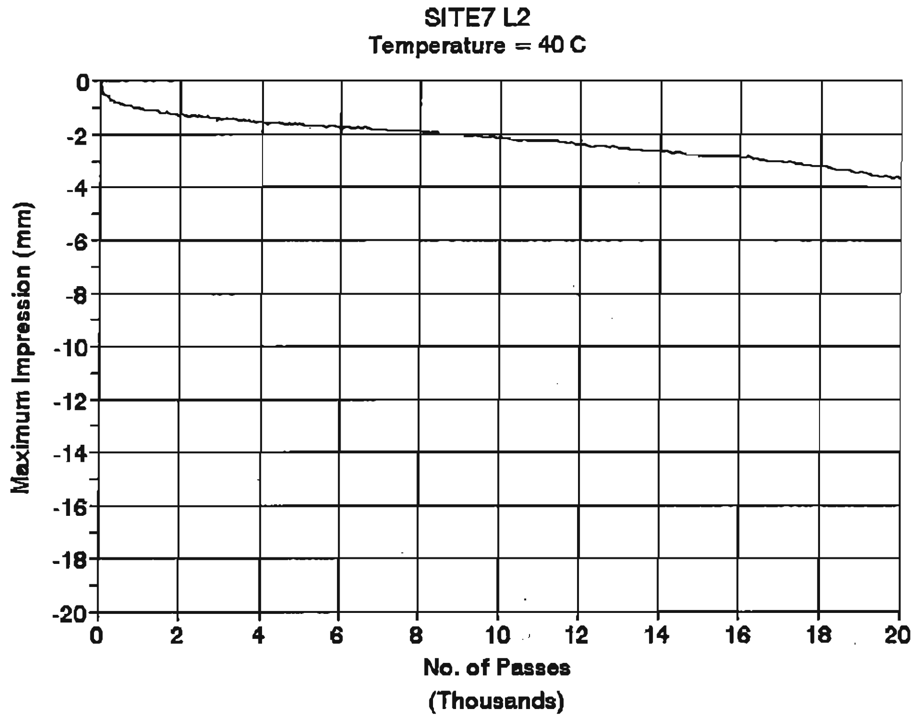

SITE6 L4
Temperature = 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

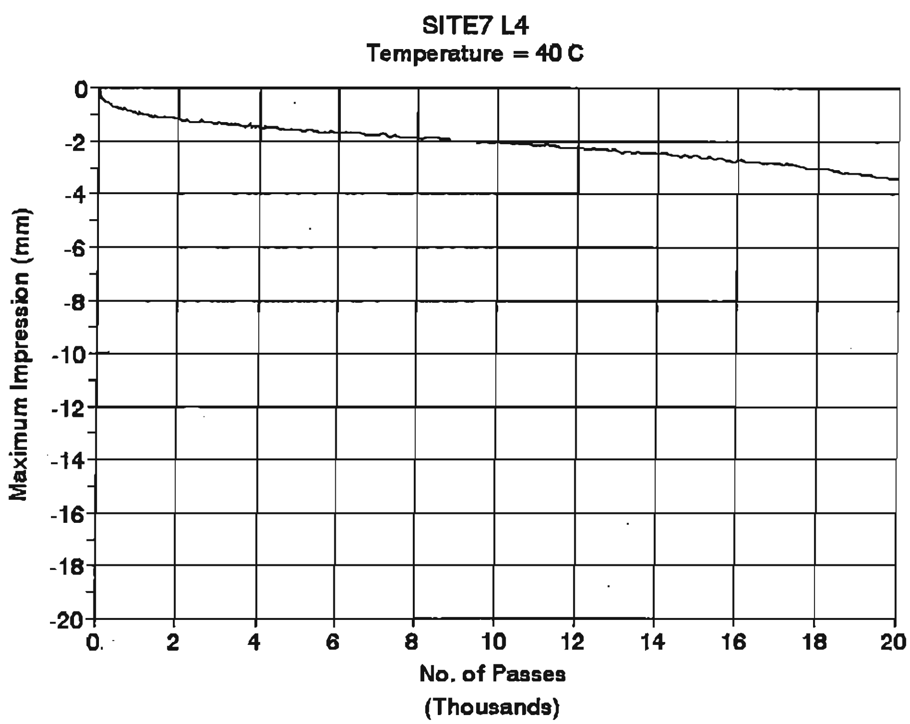


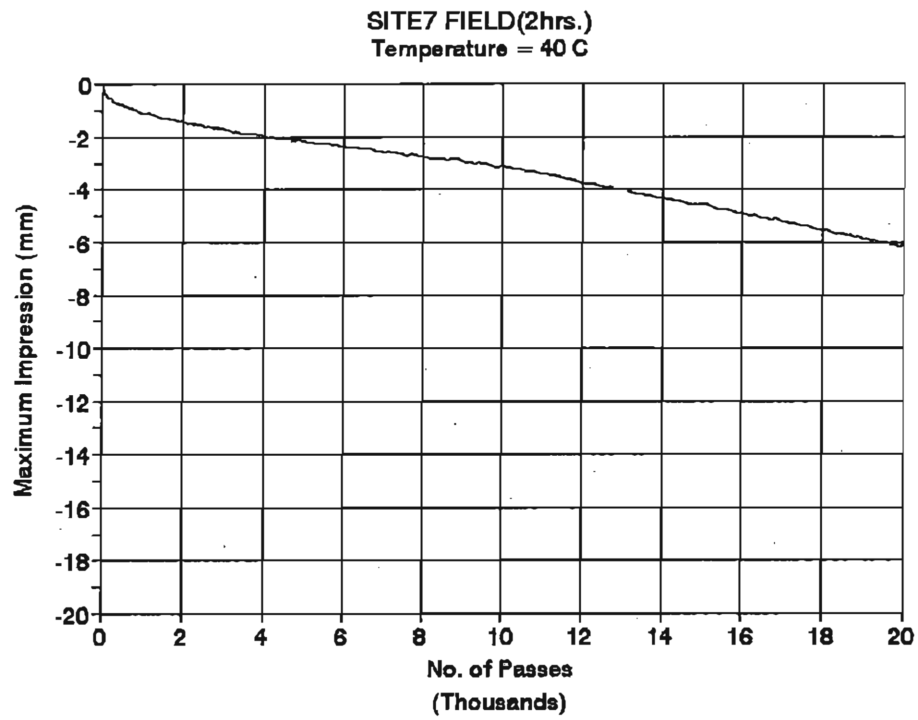
SITE6 L8
Temp. 50 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

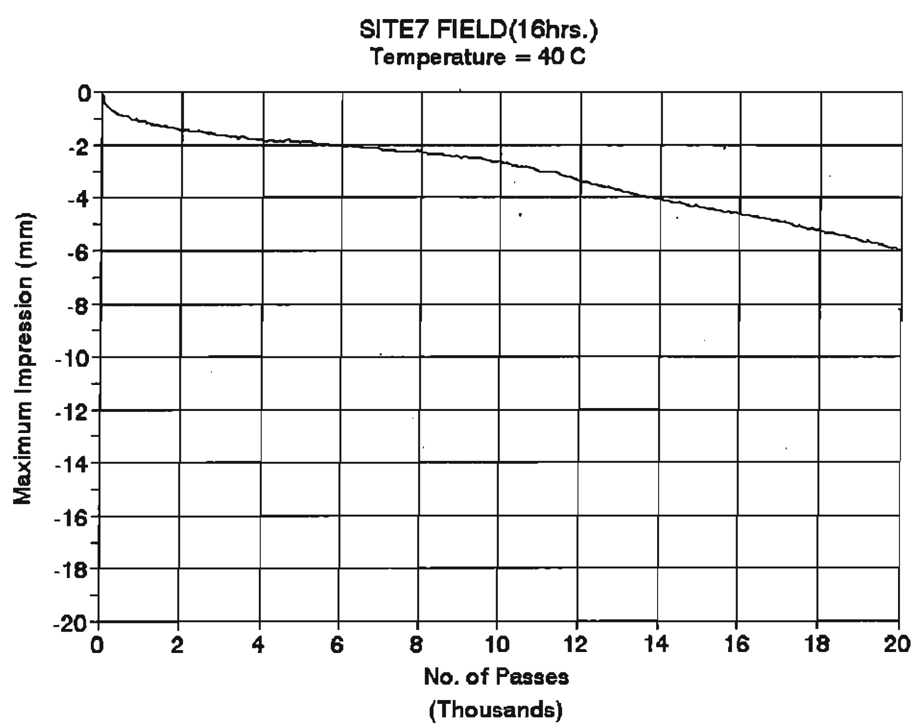


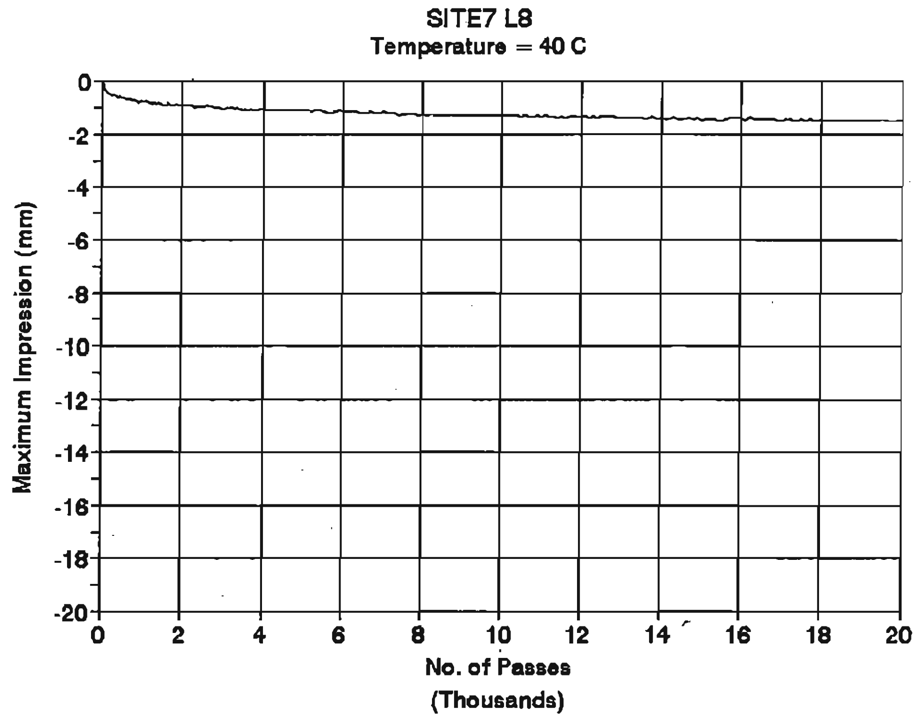
SITE7 L0
Temperature = 40 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

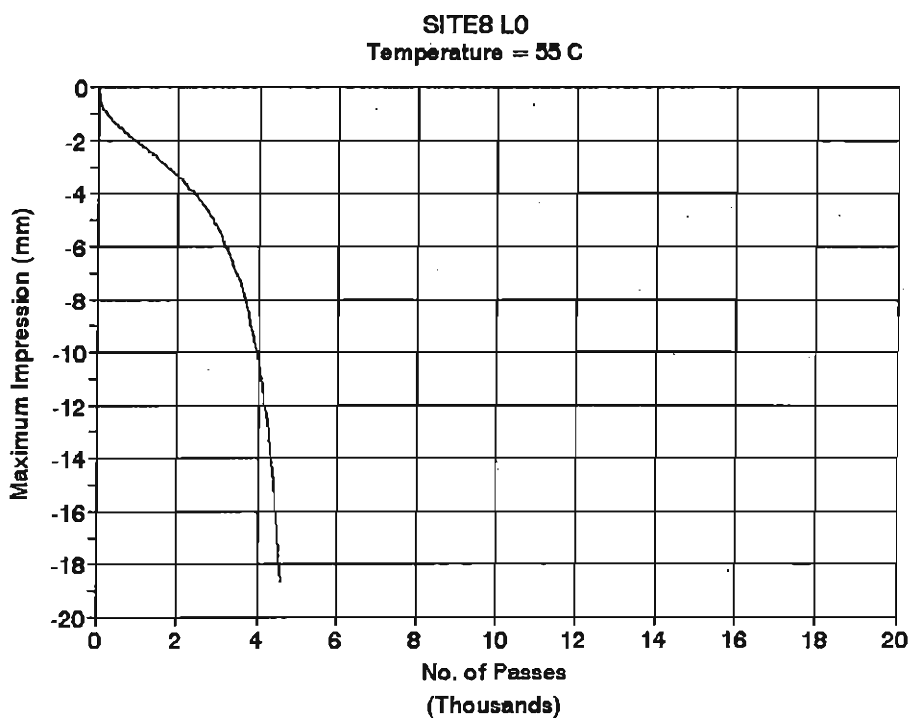

SITE7 L2
Temperature = 40 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

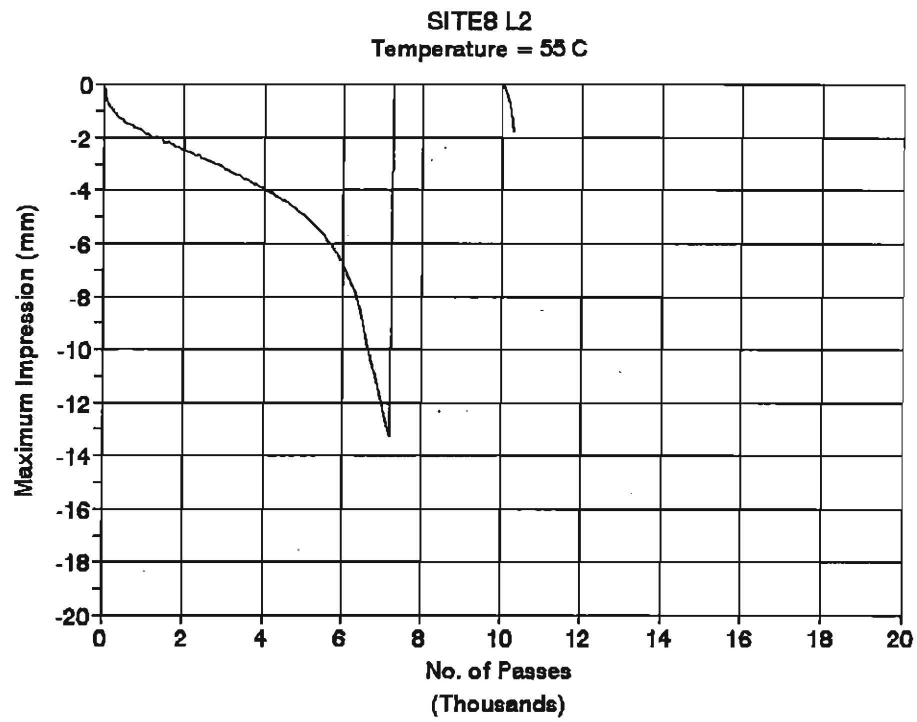

SITE7 L4
Temperature = 40 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

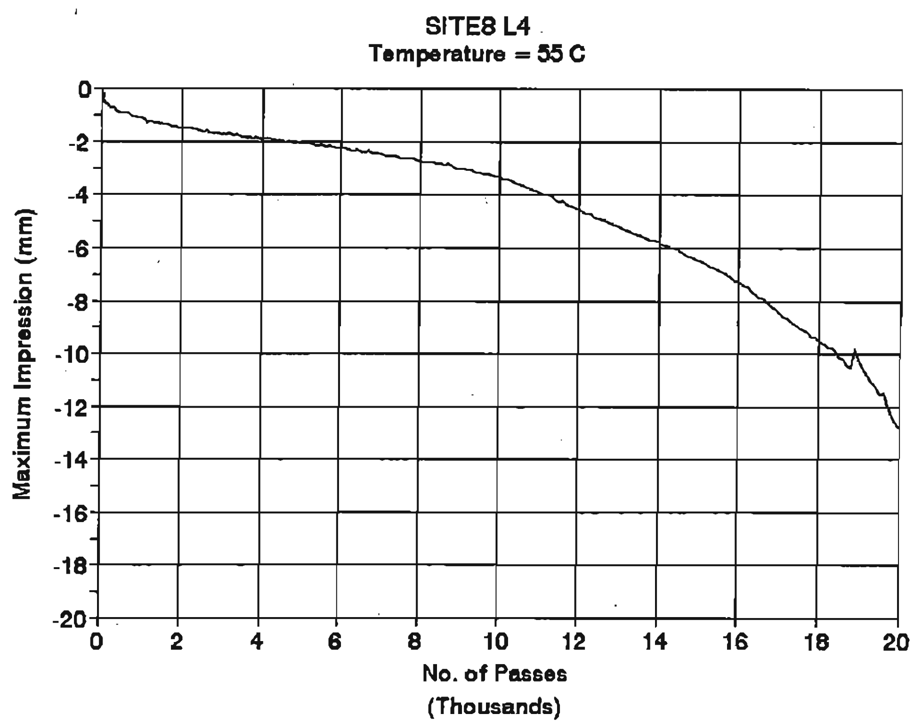

SITE7 FIELD(2hrs.)
Temperature = 40 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

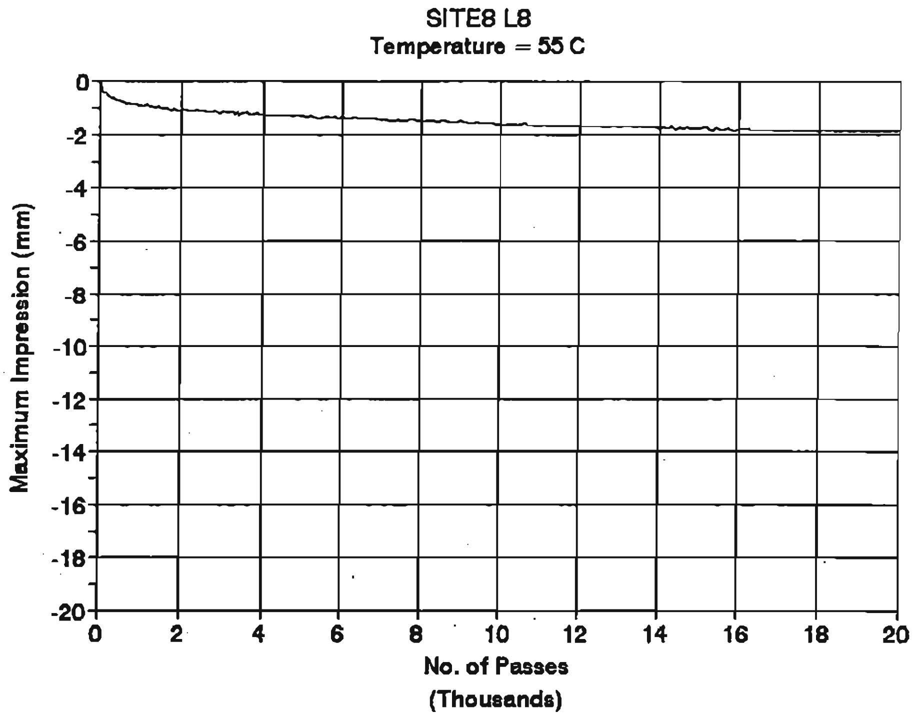

SITE7 FIELD(16hrs.)
Temperature = 40 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

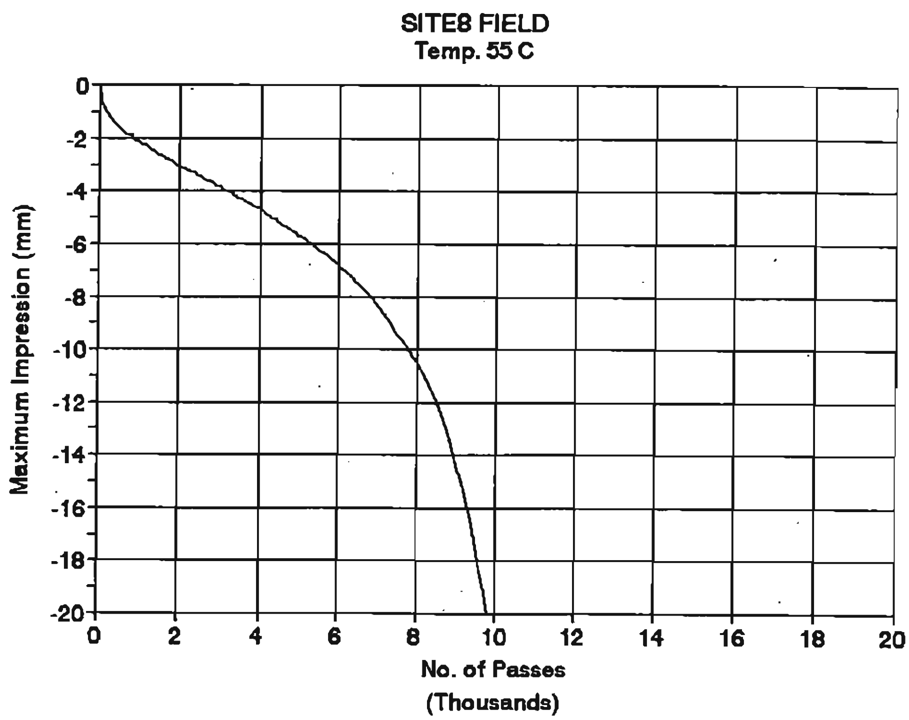

SITE7 L8
Temperature = 40 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

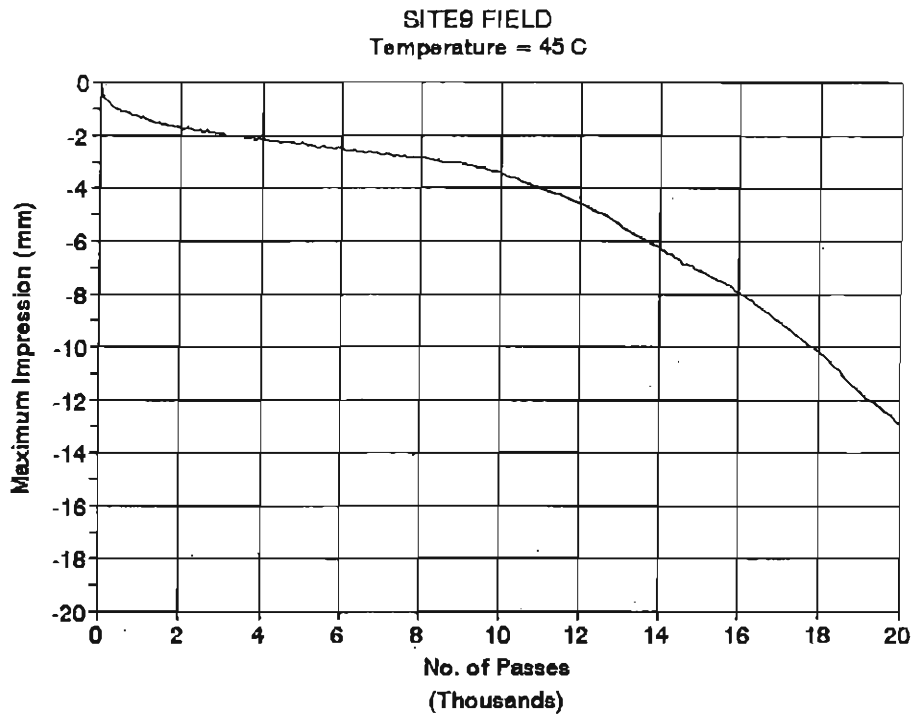

SITE8 L0
Temperature = 55 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

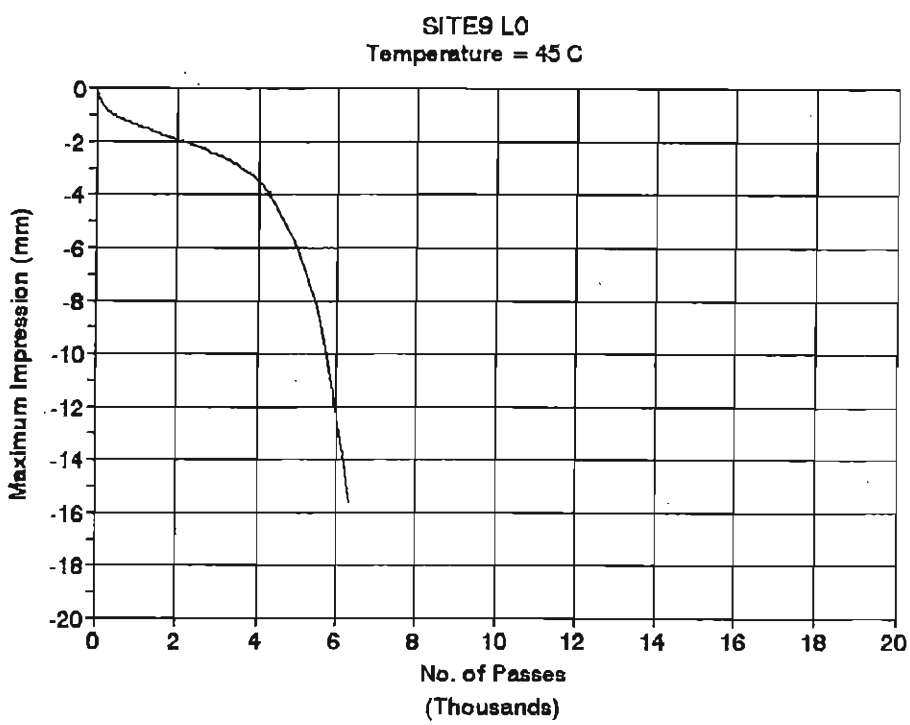

SITE8 L2
Temperature = 55 C
Maximum Impression (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)


SITE8 L4
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)


SITE8 L8
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)


SITE8 FIELD
Temp. 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)


SITE9 FIELD
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)


SITE9 L0
Temperature = 45 C
Maximum Impression (mm)
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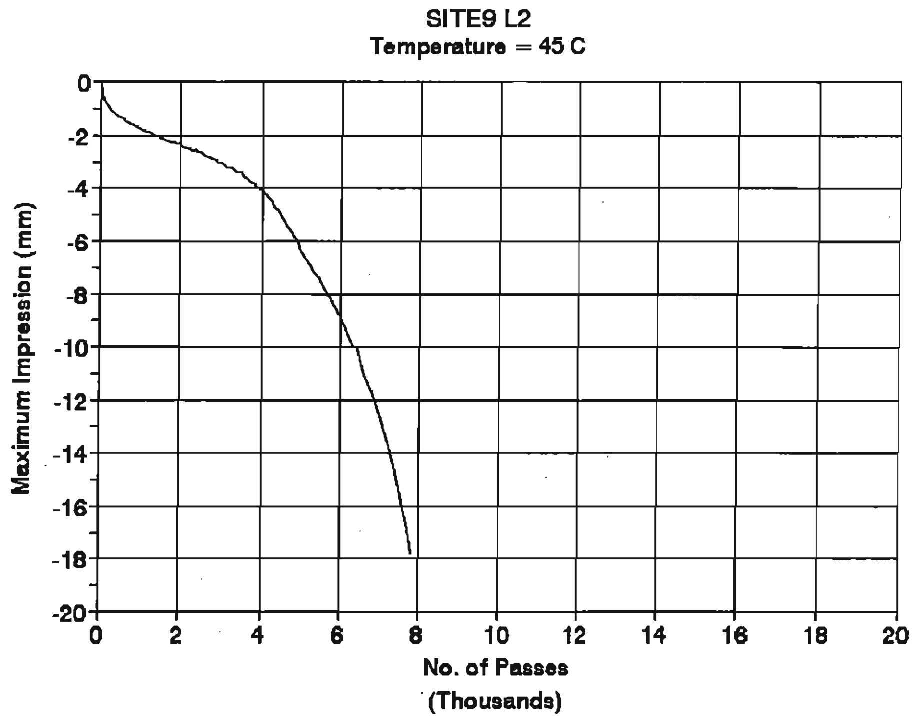
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)


SITE9 L2
Temperature = 45 C
Maximum Impression (mm)
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-4
-6
-8
-10
-12
-14
-16
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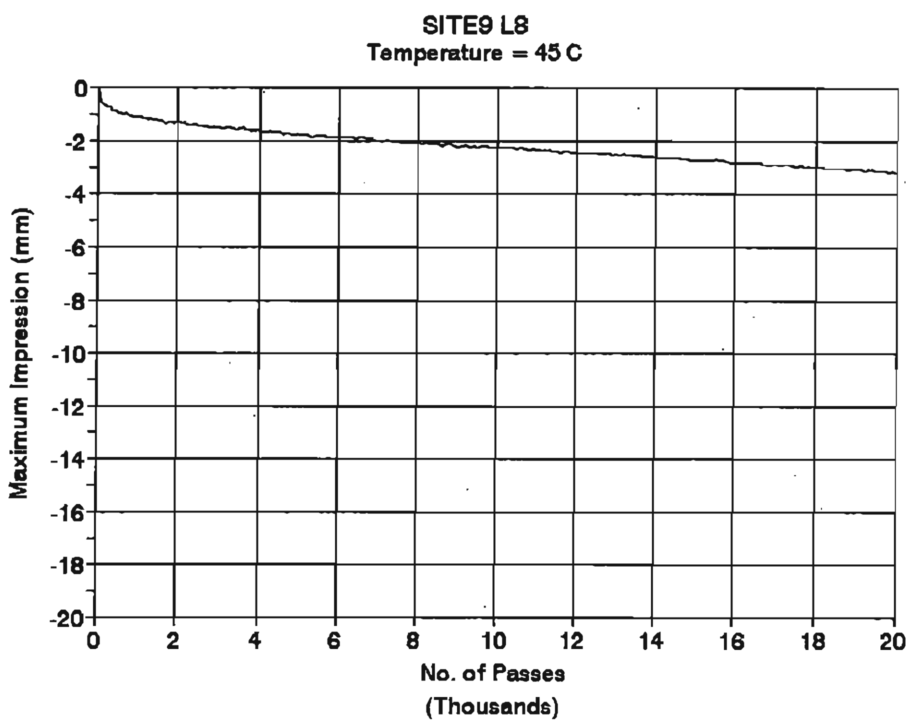
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)


SITE9 L8
Temperature = 45 C
Maximum Impression (mm)
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-6
-8
-10
-12
-14
-16
-18
-20
0
2
4
6
8
10
12
14
16
18
20
No. of Passes
(Thousands)

Appendix F:
Hamburg Wheel-Tracking Device Test Procedure in AASHTO Format.

Colorado Procedure
L 5112

Method of Test For

Hamburg Wheel Track Testing of Compacted Bituminous Mixtures

This document is a description of a test method used by the Colorado Department of Transportation to test samples in the Hamburg Wheel-Tracking Device. The information contained herein is considered interim in nature and future revisions are expected. This document may lack details. This version represents the state of the procedure as of July 22, 1994.

1. SCOPE

1.1 This method describes the testing of compacted bituminous mixtures in a reciprocating rolling wheel device. A special laboratory compactor has been designed to prepare slab specimens. Alternatively, field core samples of large diameter (10 inch) may be tested. This test provides information for the rate of permanent deformation from a moving, concentrated load.

1.2 Additionally, the potential for moisture damage effects is tested, because the specimens are submerged in water during loading.

2. APPLICABLE DOCUMENTS

2.1 AASHTO Test Methods:

T209 Maximum Specific Gravity of Bituminous Paving Mixtures

T166 Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens

3. SUMMARY OF METHOD

3.1 A laboratory compacted slab of a bituminous mixture or a saw-cut field core sample is tested by a loaded, reciprocating steel wheel. The deformation of the wheel into the mixture is measured. The test temperature is typically between 40° and 50° C and is maintained by a water bath.

3.2 The depth of deformation is plotted as a function of the number of wheel passes. When stripping damage occurs during the test, an abrupt increase in the rate of deformation coincides with the emergence of clean aggregate from the specimen.

4. Apparatus

4.1 *Wheel Tracking Machine* - An electrically powered machine capable of moving a 203.6 mm (8.00 inch) diameter, 47.0 mm (1.85 inch) wide steel wheel over the test slab. The load on the wheel is 705 N (158 lbs.). The wheel shall reciprocate over the slab, with the speed varying sinusoidally. The wheel shall make 50 passes over the slabs per minute. The maximum speed of the wheel shall be 0.305 m/s (1.1 ft/sec), and will be reached at the midpoint of the slabs. This configuration results in a 0.1 second loading period and a 1.0 second relaxation period at the midpoint of the slabs.

4.2 *Temperature Control System* - A water bath capable of controlling the temperature within ± 0.5° C over a range of 25° to 70° C. This bath shall have a mechanical circulating system to stabilize temperature within the specimen tank.

4.3 *Impression Measurement System* - An LVDT device capable of measuring the depth of the impression of the wheel within 0.01 mm, over a minimum range of 20 mm. The system shall be mounted to measure the depth of the impression at the midpoint of the wheel's path on the slabs. The impression shall be measured at least every 100 passes of the wheel. This system must be capable of measuring rut depth without stopping the wheel. This measurement must be referenced to the number of wheel passes.

4.4 *Wheel Pass Counter* - A non-contacting solenoid that counts each wheel pass over the slab. The signal from this counter shall be coupled to the wheel impression measurement, allowing for the rut depth to be expressed as a fraction of the wheel passes.

4.5 *Specimen Mounting System* - A stainless steel tray which can be mounted rigidly to the machine. This mounting must restrict shifting of the specimen to within 0.005 mm, during testing. The system shall suspend the specimen, allowing for free circulation of the water bath on all sides. The specimens shall be mounted with a minimum of 2 cm of free circulating water on all sides.

5. TEST SPECIMENS

5.1 *Laboratory Compacted Slabs* - Slabs shall be compacted on the Linear Kneading Compactor or LCPC Compactor de Plaques. Slabs shall be 269 ± 2 mm wide, 320 ± 2 mm long. Slab thicknesses of 38 mm to 100 mm can be used. The slab thickness shall be at least twice the maximum nominal aggregate size.

Linear Kneading Compactor - When compacting a slab using the Linear Kneading Compactor, calculate the amount of mix needed to attain an air void target of 4 to 7 % for a 38 mm tall slab by multiplying 3100 by the sample's maximum specific gravity, then removing a percentage of the mix equal to the targeted air voids. 3100 is only an approximation. The mix weight will need to be adjusted if air voids are out of range.

LCPC Compactor de Plaques - When compacting a slab using the LCPC Compactor de Plaques, calculate the amount of mix needed to attain an air void target of 4 to 7 % for a 50 mm tall slab by multiplying 4660 by the sample's maximum specific gravity, then removing a percentage of the mix equal to the targeted air voids. 4660 is only an approximation. The mix weight will need to be adjusted if air voids are out of range. Slabs made with the LCPC Compactor de Plaques will need to be cut to the proper length with a wet saw.

5.2 *Cored Field Samples* - Shall consist of wet-cut cores taken from pavements. The cores shall have a diameter of 10 inches. The height of the core is typically 120 mm, but may be adjusted to fit the specimen mounting system by wet saw cutting.

6. SAMPLE PREPARATION

6.1 Loose mix compacted in the laboratory shall be short-term aged.

Field Produced. Material sampled from the field shall be returned to the laboratory for compaction and testing. The loose mix shall be placed in a closed container and heated for 2 hours at 110°C (230°F) and then split into the sample size for testing. The sample should be returned to the closed container and short-term aged for four hours at the compaction temperature in a forced-draft oven. The compaction temperatures are:

AC-10	135°C (275°F)
AC-20	143°C (289°F)
Polymer	150°C (302°F)

Laboratory Mixed. Material mixed in the laboratory shall be placed in open pans at 77 kg/m^2 (15.9 lb/ft^2). The open pans should be placed in a forced draft oven at the compaction temperature for 2 hours. If it is known that the material will stay at elevated temperatures in the field for longer than 2 hours, then the short-term aging time can be increased. The sample should then be compacted.

Compacted slabs shall be cooled at normal room temperature on a clean, flat surface for 16 hours.

6.2 The bulk specific gravity shall be determined in accordance with AASHTO T166. Laboratory compacted samples should be between 4 and 7 % air voids.

6.3 Use plaster-of-Paris to rigidly mount the specimens in the mounting trays. The plaster shall be mixed at approximately a 1:1 ratio of plaster to water. The plaster must fill all cracks around the sample and have a height equal to that of the specimen. The plaster layer at the bottom of the specimen shall not exceed 2 mm. Allow the plaster at least an hour to harden.

7. TEST PROCEDURE

7.1 Be sure the red emergency button is pressed and the electricity at the wall is turned off. Choose the spacers needed for the size tray the slab is in. The spacers needed for each size sample tray are as follows:

SHORT TRAY	short, med., and tall spacers
MEDIUM TRAY	tall spacer only
TALL TRAY	no spacers

Put the needed spacers in, then mount the sample trays on top of the spacers and to the wheel-tracking machine. Hand tighten the bolts.

7.2 Check that the height of the slab is between 10 and 18 mm by lowering the wheels onto the slabs and reading the height shown on the micro control unit. The height of the slab can be brought within these limits by adjusting the height of the LVDT with an allen wrench. The LVDT could read between 0 and 20 mm, but adjusting it to read between 10 and 18 mm will allow the machine to shut off more quickly on a badly rutted sample.

7.3 Enter test information into the computer. If the software isn't on the screen, type in either "VF2002_P" or "HAM". Go through the screens entering "continue" and "start test" until a screen appears that asks for testing information. Fill in the test information as follows:

TEMPERATURE	will vary
NAME	use 8 or less characters *
NO. OF PASSES	20,000
NO. OF PREPASSES	10
CYCLE STORING	50
VARIABLE	no
MAXIMUM IMPRESSION	20
HOLD TEMPERATURE	no

* (The "NAME" **must** have a .DAT extension or data will be lost.)

The test temperature should be selected as follows:

Location	Test Temp	SHRP High Temp PG
Mountains	40°C	52
Denver, Plains	45°C	58
Delta, Lamar	50°C	64

Test temperatures 5°C lower should be considered.

Record the filename and other pertinent information onto a yellow sticky paper.

7.4 Be sure the red levers that open and close the drains for both the front and back tanks are closed (they'll be in a horizontal position). Fill the wheel tracking device with hot water using the hose on the wall. Fill until water overflows from the front tank to the back tank and the float device in the back tank floats to a horizontal position.

7.5 Depress the red emergency button and turn on the electricity at the wall to allow the wheel tracking device to bring the water to test temperature. The device will record how long the water has been at test temperature.

7.6 When the slab has been at test temperature for 30 minutes, lower the wheels and press ENTER on the keyboard. If nothing happens, check to be sure the printer is on-line.

7.7 The wheel tracking device will shut off when the micro control unit has a LVDT readout of 40.90 mm for one of the specimens or when 20,000 cycles has occurred. If, before the end of the test, one specimen has clearly failed and it is necessary to raise the wheel off that sample, it is O.K. to do so. **HOWEVER**, both wheels must be down for the data to be saved at the end of the test. To prematurely shut down testing for both specimens, raise one wheel and depress the LVDT beyond 40.90 mm, which will cause the machine to shut off. **BE SURE** to then lower that wheel so the data will be saved.

7.8 At the end of the test, go through the screens entering END until the DOS C prompt appears. Copy the data onto a disk with the either of the following commands:

copy filename.* b:

or, c filename (no extension is necessary).

Take the printer off-line and advance the final page of document. Put the printer back to the on-line position. Place the yellow sticky paper on the sheets of data and place, with the disk of data, by the computer in the office.

8. CLEANING

8.1 Press the red emergency button and turn off the electricity at the wall. To drain the baths, turn both red levers under the tanks so they are pointing downward. Remove the rutted specimens and the spacers

8.2 Clean the baths, heating coils, wheels, and temperature probe with water, COVE-KLEEN III cleaning fluid, and green scouring pads. Use a wet/dry vacuum to remove particles that settled onto the bottom of the baths. Unscrew the filter under the baths and clean with a toothbrush. Replace the clean filter.

8.3 Clean the spacers in a sink that has protection in its bottom (wood frame).

8.4 Remove the screws on the trays containing the rutted slabs. Use a chisel and hammer to pry the rutted slabs away from the bottom of the tray. Remove the slab from the tray and notice, before throwing away the slab, if stripping occurred.

8.5 Clean the tray with water or 140 solvent.

9. REPORT

9.1 The report shall include the following parameters:

The air voids of the test slab;

The average temperature during the test ± 0.5° C; and creep slope, stripping inflection point, and stripping slope.

10. MAINTENANCE

10.1 Grease the first of every month at all grease fittings.

10.2 If the paper supply is running low, reproduction can cut legal size paper to German size paper (210 x 296 mm).

11. SPARE PARTS

The following spare parts may need to be ordered:

RULON BEARINGS
Colorado Bearings and Supply 295-1555
3975 E.56th Ave., Denver
Size: 25 x 47 x 12
Cost: $25 each

FILTER
Grainger 744-8777
95 S. Tejon, Denver
Model: 2P803 (casing) 2P806 (100 micron filter)
Cost $43.65 $15.25

The filter should be pricked with a pin to enlarge the mesh size.

SNAP RING WASHERS (for under float valve)
Hardware Store
Size: No. 10 Mylar Washers
7/32" ID
1/2" OD
.015" Thickness

HEATING ELEMENTS
Ingrid Wind-Schmidt, Mr. Jurgen Schmidt
Germany
Phone #: 011-49-5084-7180
Fax #: 011-49-5084-7042
Cost: DM 145,00

FLOATS
Ingrid Wind-Schmidt, Mr. Jurgen Schmidt
Germany
Phone #: 011-49-5084-7180
Fax #: 011-49-5084-7042
Cost: DM 27,00

or

Imo Delaval Inc.
Gems Sensors Division
Plainville, Ct. 06062-1198

TEMPERATURE PROBE
Ingrid Wind-Schmidt, Mr. Jurgen Schmidt
Germany
Phone #: 011-49-5084-7180
Fax #: 011-49-5084-7042
Cost: DM 68,00

RELAYS
Consolidated Parts 623-5313
555 Quivas, Denver
Part #: RDIN-DC-603-000
Manuf. by: Continental Industries Mesa, Az.
Cost: $17.90

PUMP
Centennial Equipment Company, Inc.
278-8400
15760 W. 6th Ave., Golden, Co. 80401
Type: March Pump AC 5C MD 230V
Cost: $231

PUMP IMPELLER
Centennial Equipment Company, inc.
278-8400
15760 W. 6th Ave., Golden, Co. 80401
Type: March Pump AC 5 MD
Cost: $60