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16. Abstract

This study resulted from reports of emulsions used in the construction of chip seals taking an excessively long time to cure. This led to shelling of the stone from the pavement within a few hours or even days after construction. These failures were often attributed to the emulsion formulation even though the material passed all specifications.

The objective of this study was to develop a test method which would identify the curing time of asphalt emulsions ensuring better field performance. Several test methods were investigated which led to the development of the TTI Cohesion test. The concept for the test was derived from an existing test used for determining the cure time for slurry seals. The TTI Cohesion Test requires the preparation of an emulsion chip seal sample in the laboratory. The sample is then placed beneath a pneumatically actuated rubber foot, and a pressure is applied to the sample. The rubber foot is twisted by means of a motor which is connected to a torque sensor thereby supplying a plot of torque versus displacement of the rubber foot. The test is repeated at different time intervals and an undisturbed site on the sample is selected for each time-interval test. The testing is continued until the torque remains constant which indicating the sample has cured.

Results from laboratory testing indicated that the TTI Cohesion Test can be used to monitor the curing process of asphalt emulsion chip seal samples. Two parameters taken from the Cohesion Test may be used as qualitative indicators of the curing process of asphalt emulsion chip seals. These parameters are called Curing Index and t_{95}. The Curing Index is the percentage of the total cure that has occurred at six hours. The t_{95} value is the time required to reach 95 percent of the maximum torque value or the time at which 95 percent of the total cure has occurred.

Rapid-setting emulsion laboratory chip seals should have Curing Indices of 75 or more. In other words, in six hours, a rapid-setting emulsion laboratory chip seal should have reached 75 percent of its total cure. Rapid-setting emulsion laboratory chip seals should have t_{95} values of 35 hours or less. In other words, a rapid-setting emulsion laboratory chip seal should have reached 95 percent of its total cure within 35 hours.

17. Key Words

Chip seal, seal coat, emulsion, break point, curing rate, test method, setting time

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INVESTIGATION OF LABORATORY TEST METHODS FOR DETERMINING THE CURING RATE OF ASPHALT EMULSIONS

Research Study No. 2-9-87-1157

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Sponsored by the
State Department of
Highways and Public Transportation

Texas Transportation Institute
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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	centimetres squared	cm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

TEMPERATURE (exact)

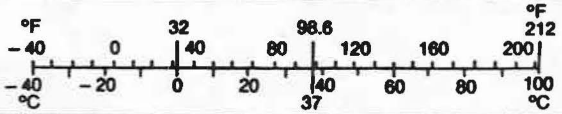
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

TEMPERATURE (exact)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

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* SI is the symbol for the International System of Measurements

SUMMARY

This study resulted from reports of emulsions used in the construction of chip seals taking an excessively long time to cure. This led to shelling of the stone from the pavement within a few hours or even days after construction. These failures were often attributed to the emulsion formulation even though the material passed all specifications.

The objective of this study was to develop a test method which would identify the curing time of asphalt emulsions as used in chip seal construction. This test method could then be used to develop specifications for asphalt emulsions thereby ensuring better field performance. Several test methods were investigated which led to the development of the TTI Cohesion Test. The concept for the test was derived from an existing test used for determining the cure time for slurry seals. The TTI Cohesion Test requires the preparation of an emulsion chip seal sample in the laboratory. The sample is then placed beneath a pneumatically actuated rubber foot and a pressure is applied to the sample. The rubber foot is twisted by means of a motor which is connected to a torque sensor thereby supplying a plot of torque versus displacement of the rubber foot. The test is repeated at different time intervals, and an undisturbed site on the sample is selected for each time-interval test. The testing is continued until the torque remains constant which indicates the sample has cured.

Results from laboratory testing indicated that the TTI Cohesion Test can be used to monitor the curing process of asphalt emulsion chip seal samples. Two parameters taken from the Cohesion Test may be used as qualitative indicators of the curing process of asphalt emulsion chip seals. These parameters are called Curing Index and t_{95}. The Curing Index is the percentage of the total cure that has occurred at six hours. The t_{95} value is the time required to reach 95 percent of the maximum torque value or the time at which 95 percent of the total cure has occurred.

Rapid-setting emulsion laboratory chip seals should have Curing Indices of 75 or more. In other words, in six hours, a rapid-setting emulsion laboratory chip seal should have reached 75 percent of its total cure. Rapid-setting emulsion laboratory chip seals should have t_{95} values of 35

hours or less. In other words, a rapid-setting emulsion laboratory chip seal should have reached 95 percent of its total cure within 35 hours.

IMPLEMENTATION STATEMENT

The findings of this study warrant the application of a new test device called the TTI Cohesion Test; a procedure to the measure setting rate of asphalt emulsion-aggregate chip seals. Routine use of this test will help identify slow setting emulsion chip seals and minimize catastrophic loss of aggregate when traffic is allowed on a chip seal too soon. The device has also demonstrated the ability to quantify differences in cohesive strength of chip seals prepared using different construction materials as well as wet and dry aggregate.

Plans have been provided in the report for construction of the test device developed in this study which could be used by district personnel. The approximate cost to reproduce the test device is $4500.00. The TTI Cohesion Tester developed in this study will be transferred to the Materials and Tests Division (D-9) of the Texas State Department of Highways and Public Transportation for further evaluation.

Preliminary guidelines have been given in the report for new specifications; however, it is recommended that substantially more laboratory testing and field verification be performed before the recommendations are put into practice.

DISCLAIMER

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SUMMARY

PROBLEM

In 1990, the Texas State Department of Highways and Public Transportation (SDHPT) placed more than 14,000 lane miles (1) of chip seals. In 1988, according to the Materials and Tests Division (D-9) of the Texas SDHPT, the Department used more than 200,000 tons of asphalt emulsion. Most of this emulsion was used for the construction of chip seals. Asphalt emulsions are used quite extensively in Texas for chip seal construction.

The advantage of using asphalt emulsion rather than asphalt cement is mainly due to the ease with which it can be handled. Paving grades of asphalt cement are viscous binders which require considerable heating to render them usable for normal road construction and maintenance operations. For chip seals, asphalt emulsions offer the potential for greater aggregate retention because of the initially higher level at which the asphalt residue begins to adhere to the aggregate.

Asphalt emulsions are generally used quite successfully in chip seal construction; however, there are many documented instances where the emulsion takes an excessively long time to break, and thus, good bond is delayed. This leads to shelling of the stones from the pavement surface, sometimes within a few days or even hours after construction. Obviously, these types of failures cut deeply into the highway maintenance/resurfacing budget. User costs in terms of delays, asphalt-coated automobiles and frustration are also a major concern of any highway engineer who has come face to face with an angry motorist.

The reasons for these problems are often unknown and/or uncontrollable by the engineer. It is suspected by many field engineers that the problem is in the asphalt-emulsion formulation even though the material meets SDHPT specifications.

BACKGROUND AND APPROACH

This study resulted from field reports within the districts that, on occasion, asphalt emulsion chip seals were requiring excessively long times to adequately cure for acceptance of traffic even though the emulsions met all specifications. Field personnel interviewed believed that the problem was in the emulsion formulation.

Field projects visited in an attempt to identify the causes of these problems (Appendix E) were inconclusive. It was determined; however, that the problems which had been experienced in the field were isolated to certain suppliers and by the time this study began, these suppliers had resolved these problems.

Therefore, early in this study, the researchers met with Department personnel to reestablish the focus of the research. At that time, it was agreed that the Department was in need of a laboratory test procedure which could be used to determine the setting or curing rate of asphalt emulsion chip seals in order to identify future problems such as those mentioned above.

Information was solicited from other state highway departments to determine what specifications and test methods were in existence that could be used to evaluate the curing rate of asphalt emulsions. Manufacturers familiar with emulsion chemistry such as Akzo Chemicals, Inc. in Illinois and Westvaco in South Carolina were also interviewed in an attempt to identify promising test methods.

Several laboratory test methods were evaluated and these results are discussed herein.

SUMMARY OF RESULTS

Review of Specifications and Guidelines

1. Most of the states surveyed in this study follow testing and specification guidelines for emulsions established by AASHTO or ASTM.
2. In general, Texas has more stringent emulsion specifications than most other states.
3. The requirements used by Texas for chip-seal aggregates are generally in line with those of other states.
4. Requirements imposed by other states regarding construction of chip seals and emulsion chip seals not specifically included in Texas' standard specifications include the following:
   - Pavement temperature as high as 80°F for the application of emulsion,

- Maximum relative humidity,
- Minimum transverse and longitudinal variation on distribution of binder as determined through specified tests such as ASTM D 2995,
- For use with emulsions, aggregate shall be damp (but not wet) as determined visually,
- Control of traffic speed through the use of pilot vehicles.

Investigation of Laboratory Test Methods

1. Several test methods were investigated for their ability to predict the curing rate of laboratory emulsion chip seals: Duomorph, Zeta Meter, Cohesion Test, Vialet, and Sliding Plate Microviscometer.
2. Due to the innate characteristics in the equipment, the Duomorph and the Zeta Meter were found to be unsuitable as test methods for predicting the curing rate of emulsion chip seals.
3. A test method was developed in this research, herein called the TTI Cohesion Test, which can measure the curing rate of laboratory, emulsion-chip seals. This test is a modified version of a test described in ASTM D3910 used to determine curing rate of laboratory slurry seals.
4. Two parameters taken from the Cohesion Test may be used as qualitative indicators of the curing process of asphalt emulsion chip seals. These parameters are called Curing Index and t_{95}. The Curing Index is the percentage of the total cure that has occurred at six hours. The t_{95} value is the time required to reach 95 percent of the maximum torque value or the time at which 95 percent of the total cure has occurred.
5. Rapid-setting emulsion laboratory chip seals should have Curing Indices of 75 or more. In other words, in six hours, a rapid-setting emulsion laboratory chip seal should have reached 75 percent of its total cure.
6. Rapid-setting emulsion laboratory chip seals should have t_{95} values of 35 hours or less. In other words, a rapid-setting emulsion laboratory chip seal should have reached 95 percent of its total cure within 35 hours.

7. The TTI Cohesion Test can be used to identify slower curing materials. Rapid-setting emulsions tested with saturated, surface-dried (SSD) aggregates (which is an undesirable condition for chip seal aggregate) exhibited Curing Indices ranging from 61 to 68 (i.e., after six hours, 61 to 68 percent of the total cure was achieved). These SSD samples reached 95 percent of their assumed total cure between 56 and 122 hours as compared with the rapid setting emulsions which reached 95 percent of the total cure in 35 hours (t_{95}) or less. An MS-1 emulsion, which is specifically designed to be a slower curing or setting material than an RS designated emulsion had a Curing Index of 65 and t_{95} value of 54 hours indicating that the test is sensitive to different curing rates.
8. The curing times measured using this device are under laboratory conditions. In the field, however, it is likely that the action of rolling equipment, traffic and wind would result in shorter curing times. The values presented here can be used as a guideline for controlled, laboratory conditions to identify potential problems.
9. Curing effects of a polymer-modified emulsion were observed with the TTI Cohesion Test which overall exhibited higher maximum torque values than a corresponding unmodified emulsion.
10. Other research has shown that the Vialet test provides information on the curing rate of emulsions used in chip seal construction. Vialet tests performed in this study under the conditions described in this report did not confirm that the Vialet test provides any information on the curing rate of emulsions.
11. Limited data show that the Sliding Plate Microviscosity Test may have potential as a test for indicating the curing rate of emulsions.
12. While this cohesion test was developed for chip seals, it could of course be used to determine the curing time of slurry seals since the test was derived from a slurry seal test. It may also have other possible uses, such as a test to determine the cohesive strength of a patching material.

Specification and Guideline Considerations

1. Preliminary recommended specifications for rapid-setting emulsions tested using the TTI Cohesion Test as described herein are as follows:
   - Curing Index should be 70 or more,
   - t_{95} value should be 40 hours or less.
2. Other research has shown that the binder application rate is one of the most important factors affecting the performance of chip seals. Consideration should be given to providing a testing requirement for the transverse and longitudinal calibration of distributors.
3. This study revealed that aggregates in a saturated, surface-dried condition can adversely affect the curing rate of laboratory, emulsion-chip seals. However, damp aggregates are proclaimed by some to be of benefit in early performance of emulsion-chip seals. Consideration may be given to mention of aggregate moisture in the standard specifications. A moisture content could be specified and controlled with a test, or the desired level of moisture in the aggregate could be visually determined by the Engineer.
4. Consideration should be given to providing a requirement that traffic speed be controlled through the use of pilot vehicles on emulsion-chip seals for 2 hours after construction. This could help accelerate the curing rate of the seal and minimize early aggregate loss.

Recommended Research

1. More laboratory testing and field verification using the TTI Cohesion Test should be performed before specifications are adopted. The range of values for all available emulsions should be fully characterized.
2. Modify the TTI Cohesion Test so that it could be used in the field to characterize field curing rates, and correlate to laboratory performance.
3. Obtain samples of emulsion which have been reported as causing performance problems in the field. Perform Cohesion Test on materials to determine if problems can be identified with test procedure. This opportunity did not exist throughout the course of this study as there were no reports of these problems attributed to the emulsion.

REVIEW OF SPECIFICATIONS AND GUIDELINES

Information was solicited from all of the other states regarding specifications and guidelines for emulsion chip seals. Most of the states which responded to the survey provide three types of specifications regarding emulsion chip seals. A materials specification is provided for the emulsion and the cover aggregate. A third specification is provided for the construction of chip seals.

Test methods were also reviewed for these states. No laboratory test methods involving emulsions other than those covered in AASHTO T59 were discovered.

Emulsion Specifications

Emulsion specifications were reviewed from all states which responded to the survey and compared to Texas and AASHTO specifications. Rapid-setting emulsions are more commonly recommended in the construction of chip seals. AASHTO M140 provides specifications for anionic emulsified asphalt and cationic emulsified asphalt are specified in M208. The AASHTO specifications for rapid-setting emulsions and those provided from other states are summarized in Tables 1 through 7.

AASHTO M140 provides specifications for rapid-setting anionic emulsions through the following tests:

Furol Viscosity,
Storage Stability,
Demulsibility,
Sieve Test,
Residue by Distillation.

For the residue produced by distillation, the following tests are required:

Penetration at 77°F, 100g., 5 sec.,
Ductility at 77°F, 5 cm/min,
Solubility in Trichloroethylene,
Float test (for high-float emulsions).

In addition to the above tests, cationic emulsions must pass a particle charge test and contain no more than 3 percent oil distillate by volume of emulsion. Texas also requires no more than 2 percent oil distillate in

Table 1. Saybolt Furol Viscosity Specification Requirements (Seconds) for Emulsified Asphalts.

Location	Temp. (°F)	RS-1		RS-2		RS-2h		HFRS-2		CRS-1		CRS-2		CRS-2h	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Texas	77	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	150	400	150	400	150	400	-	-	150	400	150	400
AASHTO	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
Alaska	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
Arizona	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	50	400	-	-	-	-	20	100	50	400	-	-
Arkansas	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	500	-	-
California	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
Colorado	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
Connecticut	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
Delaware	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
Florida	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	100	400
Idaho	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	100	400
Illinois	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
Iowa	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
Indiana	77	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	300	-	-	75	300	-	-	-	-	-	-
Kansas[1]	77	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	122	75	300	-	-	-	-	-	-	75	300	-	-	-	-
Kentucky	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	-	-	-	-
Louisiana	77	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	-	-	-	-	-	-	-	-	100	400	-	-
Maryland	77	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
Mississippi	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
Montana	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	150	400	150	400
Nebraska	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
Nevada	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	75	400

[1] Specification is for RS-1h and CRS-1h.

Table 1. Cont'd.

Location	Temp. (°F)	RS-1		RS-2		RS-2h		HFRS-2		CRS-1		CRS-2		CRS-2h	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
New Jersey	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
North Dakota	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
Ohio	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
Oklahoma	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	100	400	-	-	-	-	20	100	100	400	-	-
Pennsylvania	77	-	100	-	-	-	-	-	-	-	100	-	-	-	-
	122	-	-	100	400	-	-	-	-	-	-	100	400	-	-
South Carolina	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
South Dakota	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
Vermont	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
Washington	77	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	-	-	-	-	-	-	20	100	100	400	-	-
West Virginia	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-
Wisconsin	77	20	100	-	-	-	-	-	-	-	-	-	-	-	-
	122	-	-	75	400	-	-	-	-	20	100	100	400	-	-

Table 2. Demulsibility[1] Specification Requirements (Percent) for Emulsified Asphalts.

Location	RS-1		RS-2		RS-2h		HFRS-2		CRS-1		CRS-2		CRS-2h	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Texas	-	-	60	-	60	-	50	-	-	-	40	-	40	-
AASHTO	60	-	60	-	-	-	-	-	40	-	40	-	-	-
Alaska	60	-	60	-	-	-	-	-	40	-	40	-	-	-
Arizona	60	-	60	-	-	-	-	-	-	-	-	-	-	-
Arkansas	60	-	60	-	-	-	-	-	40	-	40	-	-	-
California	60	-	60	-	-	-	-	-	40	-	40	-	-	-
Colorado	60	-	60	-	-	-	-	-	40	-	40	-	-	-
Connecticut	60	-	60	-	-	-	-	-	-	-	-	-	-	-
Delaware	60	-	60	-	-	-	-	-	40	-	40	-	-	-
Florida	60	-	60	-	-	-	-	-	40	-	40	-	40	-
Idaho	60	-	60	-	-	-	-	-	40	-	40	-	40	-
Illinois	60	-	60	-	-	-	-	-	40	-	40	-	-	-
Iowa	60	-	60	-	-	-	-	-	40	-	40	-	-	-
Indiana	-	-	50	-	-	-	50	-	-	-	-	-	-	-
Kansas[2]	60	-	-	-	-	-	-	-	-	-	-	-	-	-
Kentucky	60	-	60	-	-	-	-	-	40	-	40	-	-	-
Louisiana	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Maryland	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	60	-	60	-	-	-	-	-	40	-	40	-	-	-
Mississippi	60	-	60	-	-	-	-	-	40	-	40	-	-	-
Montana	60	-	60	-	-	-	-	-	40	-	40	-	40	-
Nebraska	60	-	60	-	-	-	-	-	40	-	40	-	-	-
Nevada	60	-	50	-	-	-	-	-	-	-	-	-	-	-
New Jersey	60	-	60	-	-	-	-	-	40	-	40	-	-	-
North Dakota	60	-	60	-	-	-	-	-	40	-	40	-	-	-
Ohio	60	-	60	-	-	-	-	-	40	-	40	-	-	-
Oklahoma	60	-	60	-	-	-	-	-	40	-	40	-	-	-
Pennsylvania	60	-	60	-	-	-	-	-	40	-	-	-	-	-
South Carolina	60	-	60	-	-	-	-	-	40	-	40	-	-	-
South Dakota	60	-	60	-	-	-	-	-	40	-	40	-	-	-
Vermont	60	-	60	-	-	-	-	-	40	-	40	-	-	-
Washington	-	-	-	-	-	-	-	-	40	-	40	-	-	-
W. Virginia	60	-	60	-	-	-	-	-	40	-	40	-	-	-
Wisconsin	60	-	60	-	-	-	-	-	40	-	40	-	-	-

[1] Anionic Emulsions: @ 35 ml, 0.02 NCaCl$_2$.
Cationic Emuslions: @ 35 ml, 0.8% Sodium Dioctyl Sulfosucinate.

[2] Specificaiton is for RS-1h.

Table 3. Sieve Test Specification Requirements (Percent) for Emulsified Asphalts.

Location	RS-1		RS-2		RS-2h		HFRS-2		CRS-1		CRS-2		CRS-2h	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Texas	-	-	-	0.1	-	0.1	-	0.1	-	-	-	0.1	-	0.1
AASHTO	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
Alaska	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
Arizona	-	0.1	-	0.1	-	-	-	-	-	0.1	-	-	-	-
Arkansas	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
California	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
Colorado	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
Connecticut	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
Delaware	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
Florida	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	0.1
Idaho	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	0.1
Illinois	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
Iowa	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
Indiana	-	-	-	0.1	-	-		0.1	-	-	-	-	-	-
Kansas[1]	-	0.5	-	-	-	-	-	-	-	0.5	-	-	-	-
Kentucky	-	0.1	-	0.1	-	-	-	-	-	0.1	-	-	-	-
Louisiana	-	-	-	-	-	-	-	-	-	-	-	0.1	-	-
Maryland	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
Mississippi	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
Montana	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	0.1
Nebraska	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
Nevada	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	0.1
New Jersey	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
North Dakota	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
Ohio	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
Oklahoma	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
Pennsylvania	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
South Carolina	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
South Dakota	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
Vermont	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
Washington	-	-	-	-	-	-	-	-	-	0.1	-	0.1	-	-
W. Virginia	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-
Wisconsin	-	0.1	-	0.1	-	-	-	-	-	0.1	-	0.1	-	-

[1] Specification is for RS-1h and CRS-1h.

Table 4. Residue by Distillation Specification Requirements (Percent) for Emulsified Asphalts.

Location	RS-1		RS-2		RS-2h		HFRS-2		CRS-1		CRS-2		CRS-2h	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Texas	-	-	65	-	65	-	65	-	-	-	65	-	65	-
AASHTO	55	-	63	-	-	-	-	-	60	-	65	-	-	-
Alaska	55	-	63	-	-	-	-	-	60	-	65	-	-	-
Arizona	55	-	63	-	-	-	-	-	60	-	68	-	-	-
Arkansas	55	-	63	-	-	-	-	-	60	-	65	-	-	-
California	55	-	63	-	-	-	-	-	60	-	65	-	-	-
Colorado	55	-	63	-	-	-	-	-	60	-	65	-	-	-
Connecticut	55	-	63	-	-	-	-	-	60	-	65	-	-	-
Delaware	55	-	63	-	-	-	-	-	60	-	65	-	-	-
Florida	55	-	63	-	-	-	-	-	60	-	65	-	65	-
Idaho	55	-	63	-	-	-	-	-	60	-	65	-	65	-
Illinois	55	-	63	-	-	-	-	-	60	-	65	-	-	-
Iowa	55	-	63	-	-	-	-	-	60	-	65	-	-	-
Indiana	-	-	68	-	-	-	68	-	-	-	-	-	-	-
Kansas[2]	65	-	-	-	-	-	-	-	65	-	-	-	-	-
Kentucky	55	-	63	-	-	-	-	-	60	-	-	-	-	-
Louisiana	-	-	-	-	-	-	-	-	-	-	65	-	-	-
Maryland	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	55	-	63	-	-	-	-	-	60	-	65	-	-	-
Mississippi[1]	55	-	63	-	-	-	-	-	60	-	65	-	-	-
Montana	55	-	63	-	-	-	-	-	60	-	65	-	65	-
Nebraska	55	-	63	-	-	-	-	-	60	-	65	-	-	-
Nevada	57	-	62	-	-	-	-	-	60	-	65	-	65	-
New Jersey	55	-	63	-	-	-	-	-	60	-	65	-	-	-
North Dakota	55	-	63	-	-	-	-	-	60	-	65	-	-	-
Ohio	55	-	63	-	-	-	-	-	60	-	65	-	-	-
Oklahoma	55	-	63	-	-	-	-	-	60	-	65	-	-	-
Pennsylvania	55	-	63	-	-	-	-	-	60	-	65	-	-	-
South Carolina	55	-	63	-	-	-	-	-	60	-	65	-	-	-
South Dakota	55	-	63	-	-	-	-	-	60	-	65	-	-	-
Vermont	55	-	63	-	-	-	-	-	60	-	65	-	-	-
Washington	-	-	-	-	-	-	-	-	60	-	65	-	-	-
W. Virginia	55	-	63	-	-	-	-	-	60	-	65	-	-	-
Wisconsin	55	-	63	-	-	-	-	-	60	-	65	-	-	-

[1] Residue may be determined by evaporation.
[2] Specification is for RS-1h and CRS-1h.

Table 5. Ductility (cm) Specification Requirements for Asphalt-Emulsion Residue.

Location	RS-1		RS-2		RS-2h		HFRS-2		CRS-1		CRS-2		CRS-2h	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Texas	-	-	100	-	100	-	100	-	-	-	100	-	100	-
AASHTO	40	-	40	-	-	-	-	-	40	-	40	-	-	-
Alaska	40	-	40	-	-	-	-	-	40	-	40	-	-	-
Arizona[1]	75	-	75	-	-	-	-	-	75	-	75	-	-	-
Arkansas	40	-	40	-	-	-	-	-	40	-	40	-	-	-
California	40	-	40	-	-	-	-	-	40	-	40	-	-	-
Colorado	40	-	40	-	-	-	-	-	40	-	40	-	-	-
Connecticut	40	-	40	-	-	-	-	-	40	-	40	-	-	-
Delaware	40	-	40	-	-	-	-	-	40	-	40	-	-	-
Florida	40	-	40	-	-	-	-	-	40	-	40	-	40	-
Idaho	40	-	40	-	-	-	-	-	40	-	40	-	40	-
Illinois	40	-	40	-	-	-	-	-	40	-	40	-	-	-
Iowa	40	-	40	-	-	-	-	-	40	-	40	-	-	-
Indiana	-	-	40	-	-	-	40	-	-	-	-	-	-	-
Kansas[2]	80	-	-	-	-	-	-	-	80	-	-	-	-	-
Kentucky	40	-	40	-	-	-	-	-	40	-	-	-	-	-
Louisiana	-	-	-	-	-	-	-	-	-	-	80	-	-	-
Maryland	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	60	-	60	-	-	-	-	-	60	-	60	-	-	-
Mississippi	40	-	40	-	-	-	-	-	40	-	40	-	-	-
Montana	40	-	40	-	-	-	-	-	40	-	40	-	40	-
Nebraska	40	-	40	-	-	-	-	-	40	-	40	-	-	-
Nevada	40	-	40	-	-	-	-	-	40	-	40	-	40	-
New Jersey	40	-	40	-	-	-	-	-	40	-	40	-	-	-
North Dakota	40	-	40	-	-	-	-	-	40	-	40	-	-	-
Ohio	40	-	40	-	-	-	-	-	40	-	40	-	-	-
Oklahoma	40	-	40	-	-	-	-	-	40	-	40	-	-	-
Pennsylvania	40	-	40	-	-	-	-	-	40	-	40	-	-	-
South Carolina	40	-	40	-	-	-	-	-	40	-	40	-	-	-
South Dakota	40	-	40	-	-	-	-	-	40	-	40	-	-	-
Vermont	40	-	40	-	-	-	-	-	40	-	40	-	-	-
Washington	-	-	-	-	-	-	-	-	40	-	40	-	-	-
W. Virginia	40	-	40	-	-	-	-	-	40	-	40	-	-	-
Wisconsin	40	-	40	-	-	-	-	-	40	-	40	-	-	-

[1] Residue must meet requirements of AC-20.

[2] Specification is for RS-1h and CRS-1h.

Table 6. Solubility in Trichloroethylene (Percent) Specification Requirements for Asphalt-Emulsion Residue.

Location	RS-1		RS-2		RS-2h		HFRS-2		CRS-1		CRS-2		CRS-2h	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Texas	-	-	97.5	-	97.5	-	97.5	-	-	-	97.5	-	97.5	-
AASHTO M-140, M-208	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
Alaska	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
Arizona[1]	99	-	99	-	-	-	-	-	99	-	99	-	-	-
Arkansas	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
California	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
Colorado	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
Connecticut	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
Delaware	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
Florida	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	97.5	-
Idaho	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	97.5	-
Illinois	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	97.5	-
Iowa	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
Indiana[2]	-	-	97.5	-	-	-	97.5	-	-	-	-	-	-	-
Kansas	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Kentucky	97.5	-	97.5	-	-	-	-	-	97.5	-	-	-	-	-
Louisiana	-	-	-	-	-	-	-	-	-	-	97.5	-	-	-
Maryland	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
Mississippi[3]	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
Montana	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	97.5	-
Nebraska	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
Nevada	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	97.5	-
New Jersey	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
North Dakota	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
Ohio	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
Oklahoma	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
Pennsylvania	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
South Carolina	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
South Dakota	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
Vermont	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
Washington	-	-	-	-	-	-	-	-	97.5	-	97.5	-	-	-
W. Virginia	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-
Wisconsin	97.5	-	97.5	-	-	-	-	-	97.5	-	97.5	-	-	-

[1] Residue must meet requirements of AC-20.

[2] Solvent must be organic.

[3] Solvent must be trichlorethane.

Table 7. Penetration at 77°F Specification Requirements for Asphalt-Emulsion Residue.

Location	RS-1		RS-2		RS-2h		HFRS-2		CRS-1		CRS-2		CRS-2h	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Texas	-	-	120	160	80	110	100	140	-	-	120	160	80	110
AASHTO	100	200	100	200	-	-	-	-	100	250	100	250	-	-
Alaska	100	200	100	200	-	-	-	-	100	250	100	250	-	-
Arizona[1]	40	-	40	-	-	-	-	-	40	-	40	-	-	-
Arkansas	100	200	100	200	-	-	-	-	100	250	100	250	-	-
California	100	200	100	200	-	-	-	-	100	250	100	250	-	-
Colorado	100	200	100	200	-	-	-	-	100	250	100	250	-	-
Connecticut	100	200	100	200	-	-	-	-	100	250	100	250	-	-
Delaware	100	200	100	200	-	-	-	-	100	250	100	250	-	-
Florida	40	-	100	200	-	-	-	-	100	250	100	250	80	140
Idaho	100	200	100	200	-	-	-	-	100	250	100	250	50	100
Illinois	100	200	100	200	-	-	-	-	100	250	100	250	-	-
Iowa	100	200	100	200	-	-	-	-	100	250	100	250	-	-
Indiana	-	-	100	200	-	-	100	200	-	-	-	-	-	-
Kansas[2]	75	150	-	-	-	-	-	-	75	150	-	-	-	-
Kentucky	100	200	100	200	-	-	-	-	100	250	-	-	-	-
Louisiana	-	-	-	-	-	-	-	-	-	-	100	250	-	-
Maryland	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	100	200	100	200	-	-	-	-	100	250	100	250	-	-
Mississippi	100	200	100	200	-	-	-	-	100	250	100	250	-	-
Montana	100	200	100	200	-	-	-	-	100	250	100	250	40	90
Nebraska	100	200	100	200	-	-	-	-	100	250	100	250	-	-
Nevada	100	200	100	200	-	-	-	-	100	250	100	250	60	100
New Jersey	100	200	100	200	-	-	-	-	100	250	100	250	-	-
North Dakota	100	200	100	200	-	-	-	-	100	250	100	250	-	-
Ohio	100	200	100	200	-	-	-	-	100	250	100	250	-	-
Oklahoma	100	200	100	200	-	-	-	-	100	250	100	250	-	-
Pennsylvania	100	200	100	200	-	-	-	-	100	250	100	250	-	-
S. Carolina	100	200	100	200	-	-	-	-	100	250	100	250	-	-
South Dakota	100	200	100	200	-	-	-	-	100	250	100	250	-	-
Vermont	100	200	100	200	-	-	-	-	100	250	100	250	-	-
Washington	-	-	-	-	-	-	-	-	100	250	100	250	-	-
W. Virginia	100	200	100	200	-	-	-	-	100	250	100	250	-	-
Wisconsin	100	200	100	200	-	-	-	-	100	250	100	250	-	-

[1] Residue must meet requirements of AC-20.
[2] Specification is for RS-1h and CRS-1h.

anionic emulsions. No other states surveyed had an oil distillate requirement.for anionic emulsions.

As shown in Tables 1 through 7, the majority of states which responded to the survey generally conform to the specification guidelines provided by AASHTO. The storage stability requirement is not noted in these tables; however, most states had either a storage stability or a settlement specification.

Texas does not provide a standard specification for RS-1 or CRS-1 emulsions but was one of only two states providing a requirement for HFRS-2 emulsions. Texas generally has more stringent emulsion specifications that most of the other states. The minimum Furol viscosity requirement in Texas is higher than most other specifications (Table 1). As shown in Table 4, Texas requires 65 percent residue for RS-2 emulsions where most other states require 63 percent, except for Indiana which requires 68. Ductility and penetration requirements for the emulsion residue are also more stringent in the Texas specifications (Table 5 and Table 7).

Aggregate Specifications

Texas specifications for seal coat aggregates require that the aggregate be composed of clean, tough and durable particles of gravel, crushed gravel, crushed stone, crushed slag or natural limestone rock asphalt. These materials shall not contain more than 5 percent by weight of soft particles and other deleterious material as determined by Test Method Tex-217-F, Part I. In addition Texas has requirements regarding gradation, impurities in the aggregate, percent of wear, crushed faces, polish value and flakiness index. A separate specification is provided for lightweight aggregate which includes a requirement for freeze-thaw loss, pressure slaking value, and quantity of dust.

The chip-seal aggregate requirements used by Texas are generally in line with those of other states.

Construction Requirements

Weather Limitations. Texas specifications state that seal coats shall not be applied when the air temperature is below 60°F and is falling, but may be applied when the air temperature is above 50°F and is rising, the air temperature being taken in the shade and away from artificial heat. Seal coats shall not be applied when the temperature of the roadway surface is below 60°F. Asphaltic material shall not be placed when general weather conditions, in the opinion of the Engineer, are not suitable. Most other states have similar requirements. More northern states allow a cooler pavement temperature and some of the more western states require a warmer temperature.

California DOT allows only asphalt emulsion to be used in the construction of chip seals and requires that emulsion not be applied when the pavement temperature is below 80°F. Arizona requires that the pavement surface temperature be at least 85°F for the application of bituminous material.

Minnesota DOT restricts the construction season from June 1 through September 15 and requires that the relative humidity be less than 75 percent. Kansas also restricts construction season from June 1 through September 15 for emulsified asphalt.

Preparation for Chip Seal. Texas, like most other states, requires that the area to be treated be cleaned of dirt, dust or other deleterious matter by sweeping or other approved methods.

Binder Application. The Texas specification regarding application of the chip seal binder is as follows:

> "Asphaltic material shall be applied on the cleaned surface by an approved type of self-propelled pressure distributor so operated as to distribute the material in the quantity specified, evenly and smoothly, under a pressure necessary for proper distribution. The Contractor shall provide all necessary facilities for determining the temperature of the asphaltic material in all of the heating equipment and in the distributor, for determining the rate at which it is applied, and for securing uniformity at the junction of two distributor loads. The distributor shall have been recently calibrated and the Engineer shall be furnished an accurate and satisfactory record of such calibration. After beginning the work, should the yield on the asphaltic material appear to be in error, the distributor shall be calibrated in a manner satisfactory to the Engineer before proceeding with the work.
>
> Asphaltic material may be applied for the full width of the seal

> coat in one application unless the width exceeds 26 feet. Asphaltic material shall not be applied until immediate covering with aggregate is assured."

Arizona, California, and Idaho require that the rate of transverse spread be determined for each distributor. California and Idaho specifications state that the distribution of the asphaltic material shall not vary by more than 15 percent transversely from the average as determined by tests, nor more than 10 percent longitudinally from the specified rate of application. ASTM Designation D 2995 provides a standard for determining the transverse and longitudinal application rate of bituminous distributors.

Many state standard specifications require that the cut-off of asphalt material by the distributor be made on building paper or similar material spread over the surface. Specifications further state that paper shall also be placed over the treated surface for a sufficient length at the beginning of a spread to avoid spraying existing pavement or previously placed aggregate and so that the nozzles are spreading properly when the uncovered surface is reached. This seems to be standard practice by any experienced paving contractor.

California specifications require that the emulsion be applied to only one traffic lane at a time and that the entire width of the lane be covered in one operation.

Several states have detailed specifications for the distributor truck and its required components: tachometer, pressure gauges, accurate volume measuring devices, power unit for the pump, and spray bars.

Cover-Stone Application. The standard specification regarding application of the cover stone in Texas is as follows:

> "Aggregate shall be immediately and uniformly applied and spread by an approved self-propelled continuous feed aggregate spreader, unless otherwise shown on the plans or authorized by the Engineer in writing. The aggregate shall be applied at the approximate rates indicated on the plans and as directed by the Engineer.
>
> The entire surface shall be broomed, bladed or raked as required by the Engineer and shall be thoroughly rolled with the

type or types of rollers specified on the plans. Rolling equipment shall meet the governing specification for the Item, 'Rolling'."

In addition to the requirements above, many states make some reference to the moisture content of the stone. Arizona states that when emulsified asphalt is used, the cover material shall be wet but free of running water at the time of spreading. California requires that the aggregate (used with emulsions) be surface damp at the time of application, but excess water on the aggregate surface will not be permitted. California specifications further state that aggregate shall be redampened in the vehicles prior to delivery to the spreader when directed by the Engineer.

Montana specifications state that when emulsified asphalt is used, the cover aggregate shall be visibly wet when applied to the roadway. The aggregate shall be watered in the stockpiles at least 3 days prior to spreading and as directed by the Engineer. Specification requirements in Kansas state that at the time of delivery to the roadway, the moisture content of the cover material shall not exceed three percent by weight plus one-half the water absorption of the aggregate (does not apply to lightweight aggregate).

The Asphalt Emulsion Manufacturer's Association also recommends that the cover stone be damp when applied but never wet.

Some of the states surveyed require the use of a pilot car to control traffic upon completion of rolling. Pilot cars are required to control the traffic speed to 15 miles per hour (mph) from 2 to 4 hours. However, in a recent paper by Shuler (2), it was noted that cars tend to pass the pilot vehicles if the speed is as low as 15 mph. The pilot car speed was subsequently changed to 25 mph and this solved the problem of impatience on the part of the motorists without having a detrimental effect on the chip-seal surface. (2)

INVESTIGATION OF LABORATORY TEST METHODS

A recent study conducted by the Pennsylvania Transportation Institute evaluated the effect of specific construction, traffic, and materials variables on the performance of bituminous chip seals (3). It was concluded in this study that the emulsion application rate and amount of aggregate retained were the most important factors governing chip seal performance. Therefore, both the distributor and the chip spreader must be calibrated properly. Another observation noted in this study was that currently used specification tests for asphalt emulsions are not sufficiently discriminating to predict the performance of chip seals. However, the non-specification tests used in this study to characterize the emulsions were performed on the residue and did not address the issue of concern in this study: curing time of the emulsion.

A discussion of research on laboratory test methods for asphalt emulsions and some of the test methods investigated in this study follows.

OTHER RESEARCH ON LABORATORY TEST METHODS

The Texas SDHPT currently has a test method, TEX-532-C (4), which can be used to identify the rate of cure for high-float, anionic asphalt emulsions. It consists of placing a thin film of emulsion between two mortar blocks, allowing the specimen to cure, and then determining the tensile strength of the bond developed between the blocks. This test procedure has been used successfully for high-float, anionic emulsions.

Correlations were established for TEX-532-C to field aggregate retention rates by Romine and Hazlett (5) for polymer-modified, high-float, rapid-set (HFRS) emulsions. Field aggregate retention rates were measured using a "modified" Vialet test (5, 6). This modified Vialet procedure entails obtaining six, chip-seal samples as-constructed in the field on one-gallon can lids. A sample is tested at 15-minute intervals after completion of construction rolling.

Twelve chip seal projects were evaluated using these two test procedures. The conclusions extracted from this study were as follows:

1. TEX-532-C can distinguish "slow" curing HFRS-2P emulsions as evidenced by a slower cure rate in the field when TEX-532-C testing

shows strengths less than 5 psi,

2. TEX-532-C can distinguish "fast" curing HFRS-2P emulsions as evidenced by a faster cure rate in the field when TEX-532-C testing shows strengths greater than or equal to 8 psi,
3. TEX-532-C did not distinguish between "slow" and "fast" curing HFRS-2P emulsions, as evidenced by field modified Vialet tests, when the TEX-532-C strength was between 5 and 8 psi.

Research done by Stroup-Gardiner, et. al. (7) established guidelines for avoiding construction problems associated with asphalt emulsion chip seals. Laboratory testing with the Vialet test was performed using construction materials and quantities for 18 chip seal test sections. Laboratory test results were evaluated for the presence of excess aggregates and the set rate of the emulsions. Laboratory results were then compared to field comments. In general, Vialet test results of less than 30 percent material retained indicated that problems with aggregate pickup on rollers could be expected. Results of less than 65 percent indicated potential damage by early brooming of new chip seals. Results greater than 80 percent provided satisfactory field performance after one month of low-volume traffic.

A recent publication of a paper by Marchal (8) describes an evaporation-filtration test for emulsions. This test was developed to characterize asphalt emulsions by inversion point. At usual asphalt contents, emulsions are of the oil-in-water type. After spraying onto the pavement surface, the water evaporates from the emulsion and the asphalt content increases, leading to coalescence, which would be expressed in terms of inversion to the water-in-oil type. (8) Another term often used by field engineers for this inversion point is "break point".

RESEARCH IN THIS STUDY ON LABORATORY TEST METHODS

Throughout the course of this research study, several novel test methods were investigated which appeared to have potential for monitoring the emulsion curing process. Three of these tests (a) the Zeta Meter, (b) the Duomorph and (c) the development of a cohesion test will be discussed below.

Duomorph

The Duomorph was originally designed as an in-situ, mechanical behavior characterization device for viscoelastic materials. It had been used to monitor aging of particulate filled polymeric materials such as solid propellants (8) and asphaltic concretes (10).

The Duomorph sensor consists of two radially expanding piezoelectric (PZT) ceramic crystals bonded together into a circular bending plate. When excited by an electric field, the plate is distorted into a parabolic surface due to radial expansion and/or contraction of the crystals. As the polarity of the excitation is cycled, the disc goes into a reversed bending mode. Strain gages cemented to the face of the sensor measure deformations during excitation. If the device is to be used for surface measurements, only the face of the sensor is used. If used as an embedded device, strain gages must be mounted on both surfaces.

Changes in polymer stiffness during cure are monitored as a response to the strain-amplitude cyclic input of the device. The resulting stiffnesses are expressed in complex form as:

$$E^* = E' + iE''$$

where E^* is the complex modulus
E' is the real (elastic) modulus
E'' is the imaginary (viscous) modulus.

The loss tangent, Tan ϕ, is the ratio of the imaginary to the real modulus (i.e. E''/E') and represents an index of the type of chemical changes the polymer is undergoing.

If Tan ϕ increases with age, that is E'' is increasing relative to E', this is an indication of polymer softening such as might be produced during hydrolization or polymer chain scission. On the other hand, a decrease in Tan ϕ is an indication of cross-linking typical for oxidative degradation. It was felt that these indices of polymeric behavior could be extended to the monitoring of the emulsion curing process.

The main design objective in creating a Duomorph for this purpose is to use a PZT crystal with a sufficiently high compliance (i.e. low stiffness) to detect the low magnitude modulus changes in the emulsion as it encounters the break point and final cure. Several vendors were contacted who provided crystals for use in this study. These crystals permitted the monitoring moduli in the range of 700 to 7000 MPa (10^5 to 10^6 psi). This is about two orders of magnitude greater than required and thus did not give any of the Duomorphs used the sensitivity needed to follow the intended events.

Another problem with this device was its use with samples containing aggregate. The protrusion of the aggregate above the surface of the emulsion prevented the intimate, continuous contact necessary for meaningful results. This coupled with the inability to obtain suitable PZT crystals brought about the decision to discontinue this activity on this project.

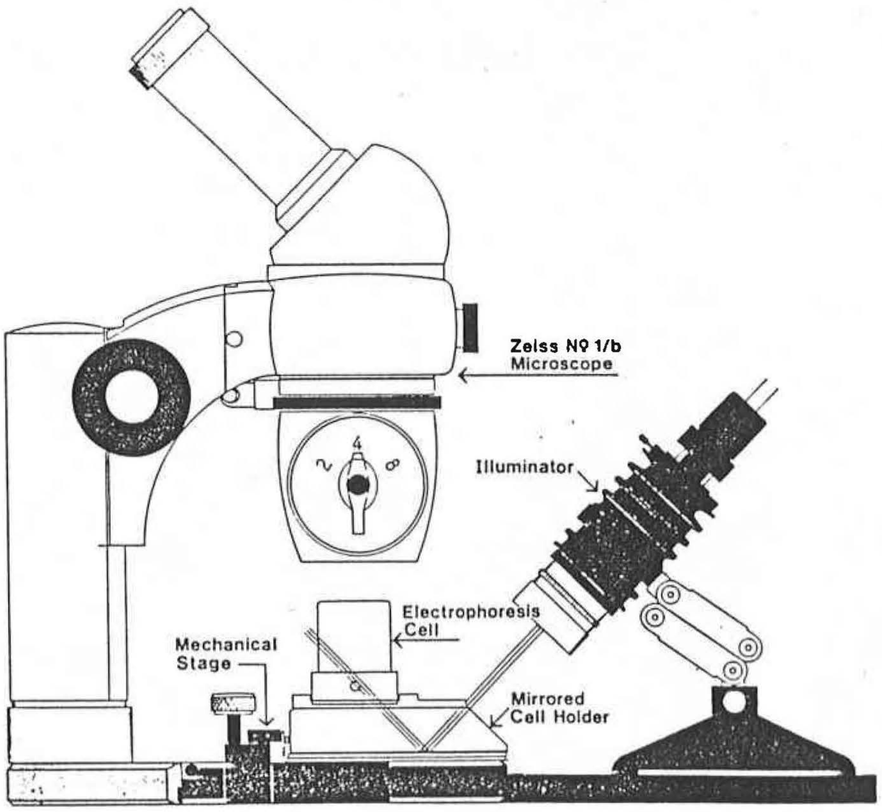
It should be mentioned that if suitable crystals can be developed, the Duomorph could provide an excellent tool for monitoring both curing and aging properties in neat binders. A more detailed treatment of this device is given in Appendix D.

Zeta Meter

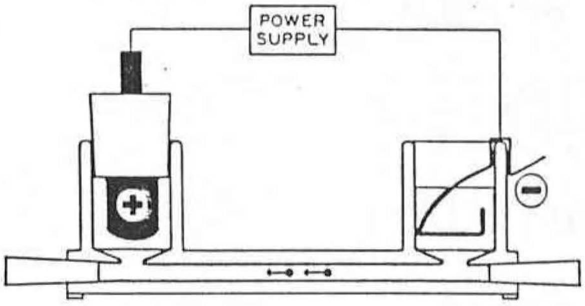
The Zeta Meter has been employed as a tool for assessing the stability of colloidal systems and emulsions. The duration of the curing process in an emulsion is dependent on the rate of adsorption of ions from the binder onto the surface of an oppositely charged aggregate particle. The index for this activity is called the Zeta Potential which is a measure of the difference in electrostatic charges (attractive and repulsive) of a system. The greater the difference in charges, the higher the degree of affinity of one particle (ion surface) to another.

The Zeta Potential for an emulsion-aggregate system is reflected in the magnitude of the difference in ionic charges between the asphalt and the surface of the aggregate. If the net charge is attractive the asphalt will adhere to the aggregate surface. If the net result is repulsive the bonding will be little more than superficial.

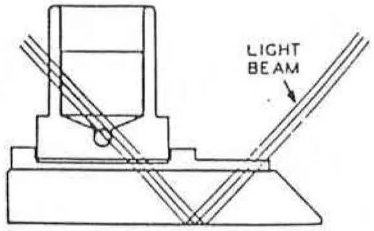
Zeta Potential measurements are made using a procedure called "microelectrophoresis". Using a set-up as shown in Figure 1, it was



MICROSCOPE AND ILLUMINATORS



SECTION THRU ELECTROPHORESIS CELL



MIRRORED CELL HOLDER

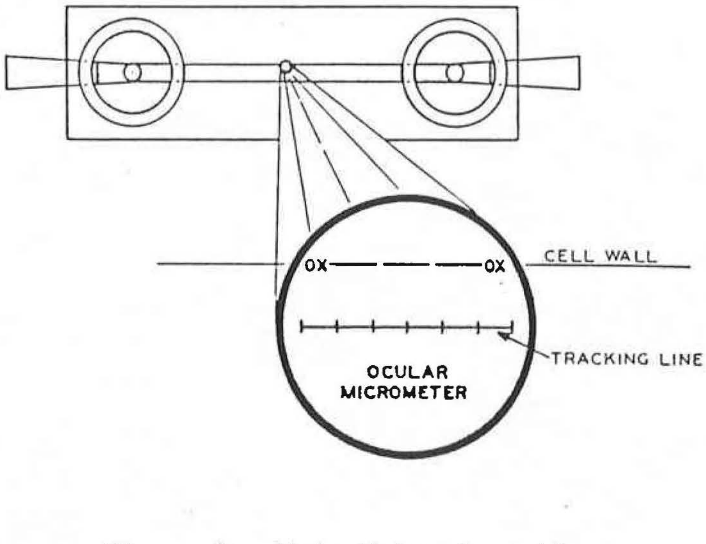


Figure 1. Zeta Meter Assembly.

hypothesized that if a sample of emulsion were placed in a quartz electrophoresis cell and a DC voltage applied, the relative affinity of the asphalt for the aggregate would be revealed by the velocity by which the asphalt ions moved toward the oppositely charged aggregate surface. This action is called "electrophoretic mobility". Velocity is measured by timing individual particles on a microscopic grid as they move across the tube.

Initial experiments using only the emulsion in the tube showed such movement. By charging the electrode potential, the corresponding increase or decrease in the velocity of asphalt ions was observed. However, when an attempt was made to utilize an aggregate particle as the electrode, all that was observed was unidirectional Brownian movement energized by the heat from the lamp on the quartz cell.

All attempts to produce an aggregate electrode were unsuccessful, and the use of this concept for this study had to be abandoned. A search of the literature uncovered no published references in which this device was used to assess cure activity in emulsion-aggregate systems.

DEVELOPMENT OF TTI COHESION TEST

A test method which is described in ASTM D3910-84 (11) as a cohesion test for determining the curing time of a slurry seal was investigated in this study as a method for determining the curing time of an emulsion chip seal. A schematic of this cohesion tester taken from ASTM D3910-84 is shown in Figure 2. The ASTM testing procedure involves preparing a slurry seal mat in the laboratory. After initial set of the slurry mat has occurred, the mat is placed beneath the pneumatically actuated rubber foot (one-inch diameter) of the cohesion tester, and a pressure is applied. The rubber foot is twisted by means of a hand torque tester or torque wrench which reads in inch-pounds or inch-ounces. The torque procedure is repeated at 15- to 30-minute intervals until the highest torque reading obtainable remains constant. An undisturbed site on the slurry pad is selected for each time-interval test. The time required to reach a constant maximum torque, or until the rubber foot rides freely over the slurry mat without any aggregate particles being dislodged, is recorded as the cure time.

This equipment was built by TTI for testing emulsion chip seals as specified in ASTM with one modification: the one-inch diameter rubber foot

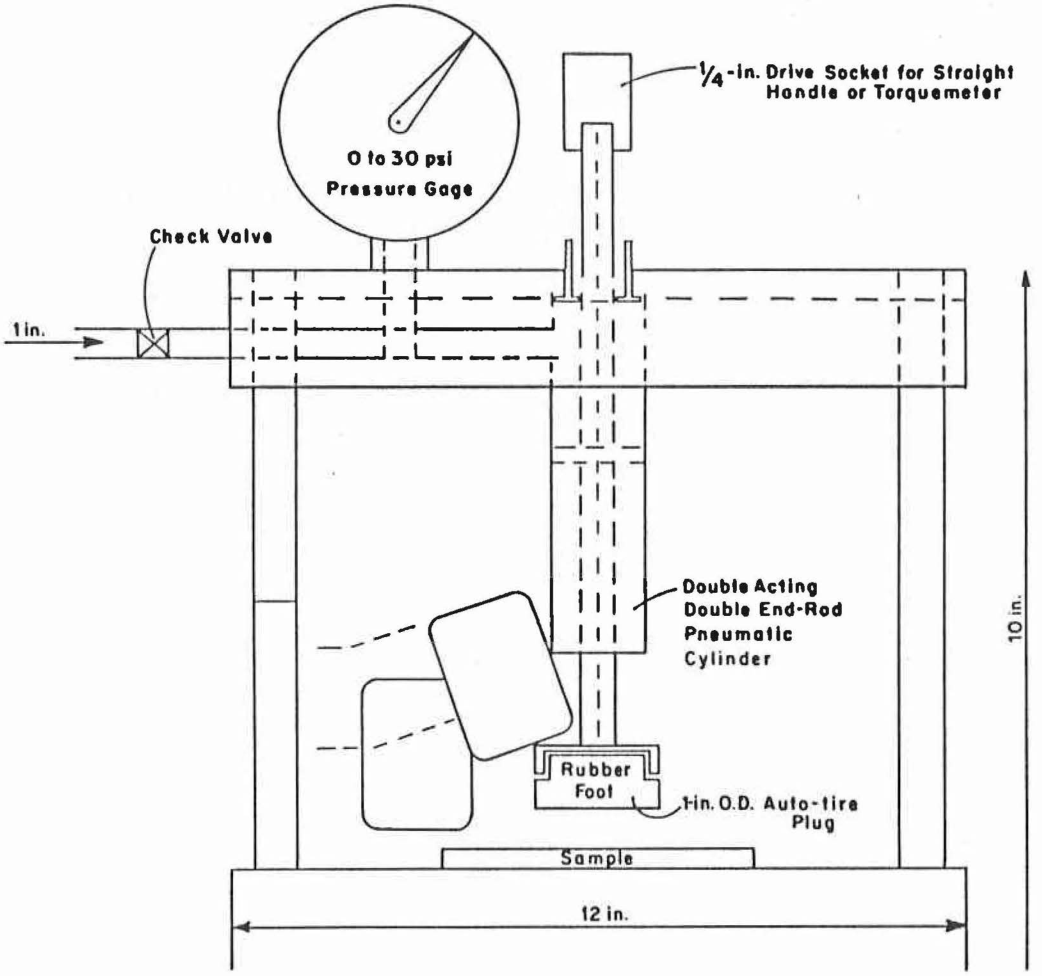


Figure 2. ASTM D3910 Cohesion Tester for Slurry Seals.

was replaced with a rubber foot three inches in diameter because the aggregate in a chip seal is much larger than that used in a slurry.

A thorough evaluation of the equipment using laboratory prepared chip seals proved that the torque wrench provided unreliable data. Because the torque wrench was turned manually, there was no control over the speed with which the wrench was turned or the angle through which it was turned, both of which affected the torque reading.

Due to the poor results obtained in the initial evaluation, further modifications to the equipment were made. The torque wrench was eliminated completely from the testing apparatus. A motor was installed on the equipment which would enable the rubber foot to be rotated at a constant speed. The motor was a Dayton brand, 6 RPM, 1/60 horsepower, shaded pole gearmotor with a maximum torque of 120 inch-pounds. This was later replaced with a 200 inch-pound shaded pole gearmotor, Dayton model number 3M327. A torque sensor was used to provide a measure of the torque. The torque sensor was designed and built in TTI's machine shop. It was made from 6061-T6 aluminum machined according to the specifications shown in Appendix A. The hollow portion of the aluminum piece was fitted with a strain-gage torque sensor. The strain-gage torque sensor is electrically connected to the motor which is connected to a signal conditioner and then to a strip-chart recorder. The output from the strip chart recorder provides a plot of the torque versus displacement of the rubber pad. The maximum torque value on the plot is taken as the torque reading for that particular test.

After a series of other minor revisions, the testing apparatus evolved into that shown in the photograph in Figure 3. The motor, which turns the rubber pad, is attached to the loading frame and is in line with the torque sensor and pneumatic cylinder. A schematic of the test apparatus is shown in Figure 4 with all of the component parts labeled. More detailed drawings of individual component parts are in Appendix A. A cost estimate to build the TTI Cohesion Tester is also shown in Appendix A.

Sample Preparation

One of the most difficult tasks in this study was to determine a method of sample preparation which would be somewhat standard for a range of different materials. Chip seal aggregates can vary in gradation and maximum

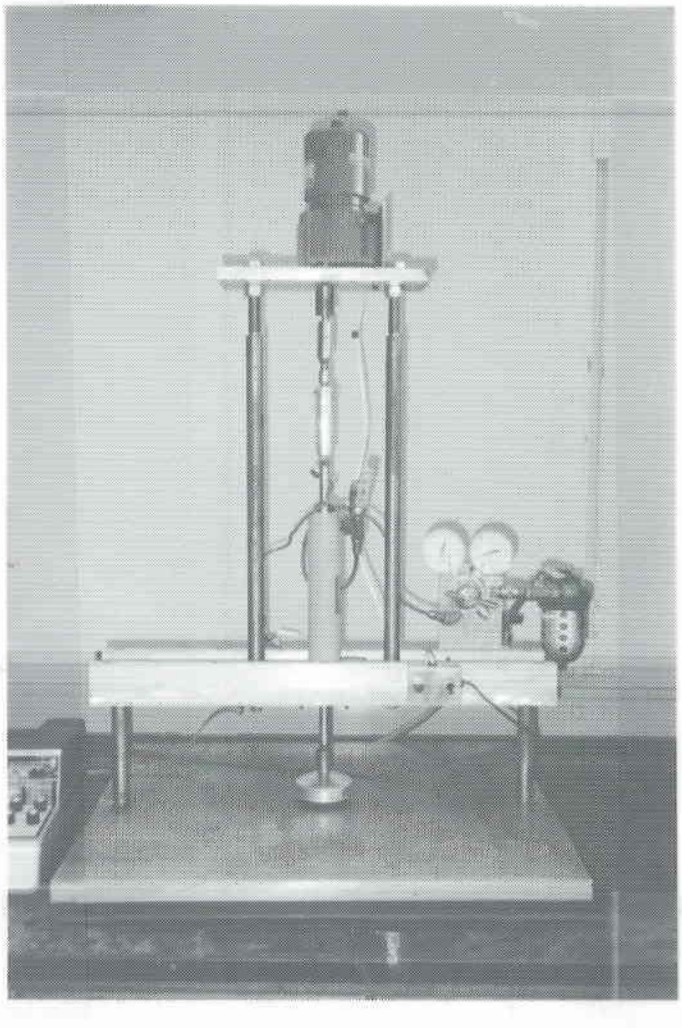


Figure 3. TTI Cohesion Tester.

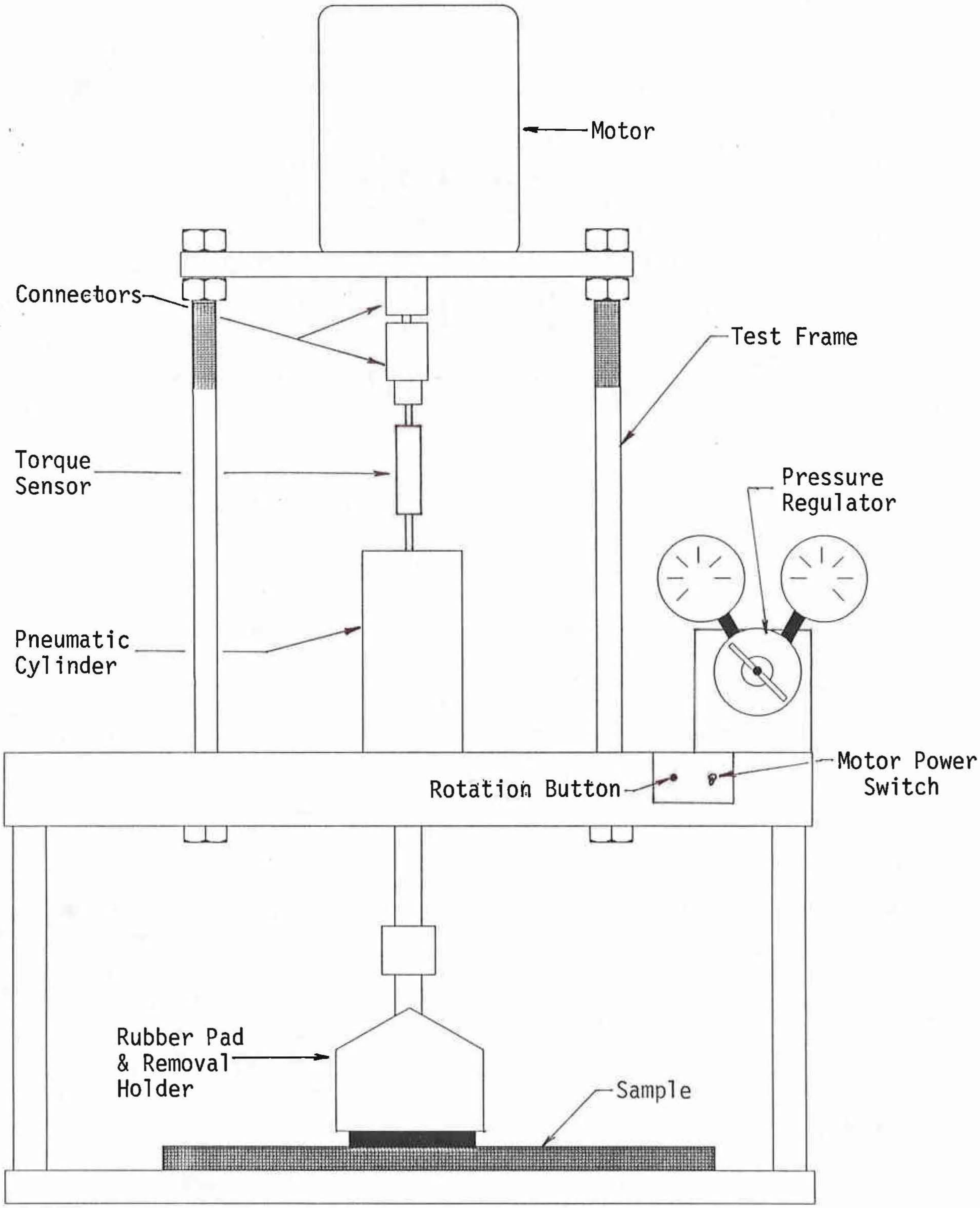


Figure 4. Schematic of TTI Cohesion Tester.

size, both of which would affect the results of the test. Another major factor which would affect test results is the quantity of emulsion used to make a sample.

After experimenting with a number of different techniques, a method was developed which provided some uniformity in sample preparation. Before testing, the aggregate should be sized to a one-size material. For a Texas Item 302, Grade 4 (12) chip seal aggregate which has the following gradation,

	Percent by Weight
Retained on 5/8" sieve.........	0
Retained on 1/2" sieve.........	0 - 2
Retained on 3/8" sieve.........	20 - 35
Retained on No. 4 sieve........	95 - 100
Retained on No. 10 sieve.......	99 - 100

the material should be sized as follows:

	Percent by Weight
Retained on 3/8" sieve..........	0
Retained on No. 4 sieve.........	100.

For a Texas Item 302, Grade 3 aggregate which has the following gradation,

	Percent by Weight
Retained on 3/4" sieve.........	0
Retained on 5/8" sieve.........	0 - 2
Retained on 1/2" sieve.........	20 - 35
Retained on 3/8" sieve.........	85 - 100
Retained on 1/4" sieve.........	95 - 100
Retained on No. 10 sieve.......	99 - 100

the aggregate should be sized as follows:

	Percent by Weight
Retained on 1/2" sieve..........	0
Retained on 3/8" sieve..........	100.

Not only does this provide for more uniformity in aggregate samples, it also allows for maximum contact area between the chip seal sample and the rubber pad.

Theoretically, the optimum aggregate quantity in a chip seal is such that the stone is lying in shoulder-to-shoulder contact in a one-stone thick layer. The aggregate quantity for this test should be determined by placing the aggregate in the empty sample pan at a quantity of 90 percent of that visually perceived to be optimum. The aggregate is placed at less than optimum so that there is some space between the aggregate. If the aggregate is placed too densely, excessive aggregate interlock will be measured as the pad is rotated on the surface rather than the cohesive properties of the binder. After the correct quantity of aggregate is determined, it is removed from the sample pan, placed in an oven and heated to 140°F. The sample pan used in these experiments was made from 16 gage steel of dimensions 14.5 inches by 20 inches with a 0.5-inch rim.

The emulsion and the pan should be heated to 140°F in an oven. The emulsion should be heated in a closed container to prevent loss of water. The correct quantity of emulsion must be determined on a trial-and-error basis. Emulsion should be poured into the pan, and the pan should be rotated to provide even distribution of the binder. The aggregate should be applied immediately and then rolled. Rolling was accomplished using a small hand roller with a rubber surface. Immediately after rolling, the thickness, or depth, of the binder should be measured. This can be accomplished by using a depth micrometer and taking several measurements between the stones. The binder depth should be approximately three millimeters. If not, a new sample should be made.

The sample should then be allowed to cure under heat lamps which have been placed such that the chip seal surface is approximately 120°F.

Testing Procedure

The sample should be placed in the apparatus underneath the rubber pad (Figures 5 and 6). An angle iron and "C" clamps are used to attach the sample pan to the testing frame. Air pressure should be turned on, and the required amount of air applied with the regulator. The data recorder should be turned on and calibration checked. The motor should be turned on by the switch and with the rotation button, the test begun. Once the chip seal has sheared and begins to turn with the pad, rotation should be stopped immediately. The value to be recorded is the highest point on the plot. Example plots are shown in Appendix A. Some experience is required to determine if the test was acceptable. Sometimes, the stones will crush or grind against each other causing erroneously high torque values. Slippage

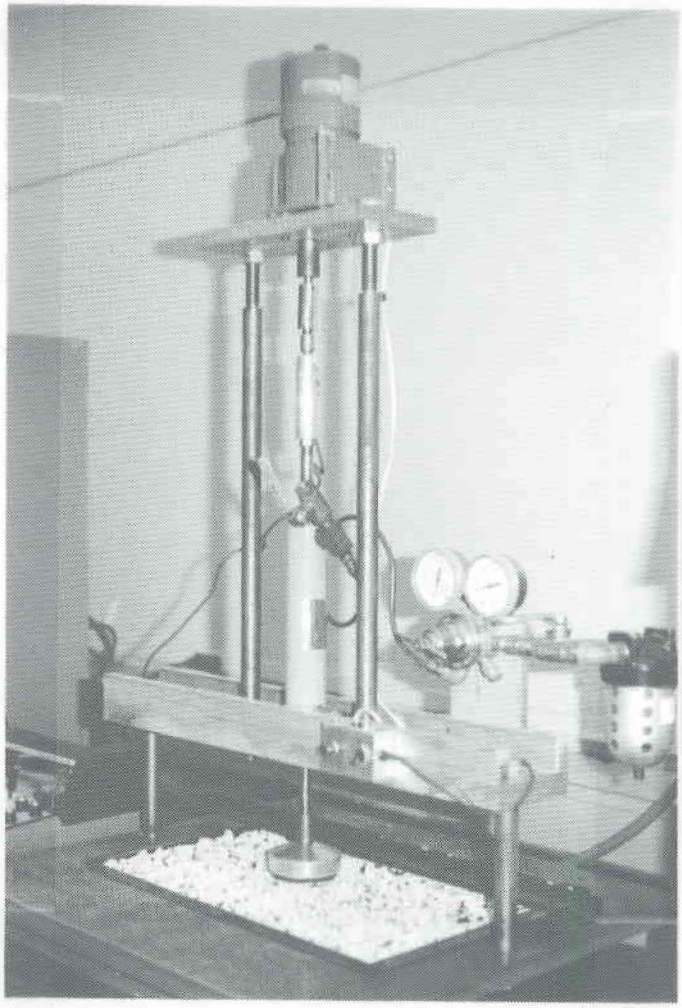


Figure 5. Cohesion Test In Progress.

Figure 6. Rubber Pad In-Place on Sample.

of the rubber pad along the aggregate surface can also occur providing erroneous data.

The test should be repeated at different time intervals throughout the curing process to adequately characterize the curing curves of the binder. Each time a test is run, the pan should be moved to provide a fresh testing surface on the same sample. The pan should be moved far enough such that the fresh surface is undisturbed by the used surface. After each test, the rubber pad surface should be cleaned. It can be removed as shown in Figure 7 for easy cleaning.

The amount of air pressure required to shear the chip seal surface increases as the sample cures. The following gage pressures are recommended:

1) 35 psi gage pressure at the beginning of the testing sequence until the torque value exceeds 35 inch-pounds,
2) 40 psi gage pressure until the torque value exceeds 45 inch-pounds, and
3) 45 psi gage pressure thereafter.

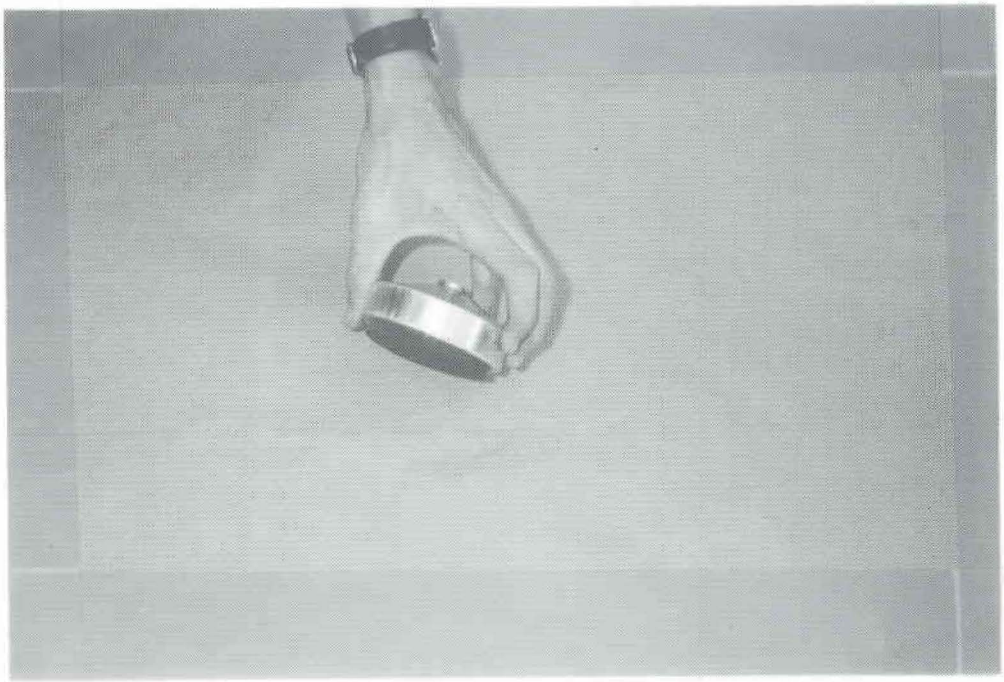


Figure 7. Removable Rubber Pad.

TTI COHESION TEST RESULTS

EVALUATION OF CHIP SEAL EMULSIONS

The Texas SDHPT, in general, uses two types of emulsions for chip seal construction: HFRS-2 and CRS-2. An experiment was designed utilizing a cohesion test apparatus developed under this project to determine curing time using these two emulsions and different aggregates. Four aggregates were chosen with different surface characteristics: limestone, river gravel, sandstone, and lightweight (expanded clay). The experimental design is shown in Figure 8. It is a full factorial experiment; therefore, all combinations of the above mentioned materials were tested. Two replicate tests were performed for each combination.

Material Properties

All emulsions were obtained directly from one manufacturer, Elf Asphalt. The HFRS-2 was obtained from their Baytown plant and the CRS-2 from Port Neches. Material properties of these emulsions are shown in Table 8.

Aggregate properties are shown in Table 9. All of the aggregates for these experiments were Item 302, Grade 4, which is the predominant grading used by the Department for chip seal construction. The grading specification for Grade 4 is as follows:

	Percent by Weight
Retained on 5/8" sieve.........	0
Retained on 1/2" sieve.........	0 - 2
Retained on 3/8" sieve.........	20 - 35
Retained on No. 4 sieve........	95 - 100
Retained on No. 10 sieve.......	99 - 100.

However, in order to minimize the effects of aggregate gradation on the cohesion test results, all four of the aggregates were sized to the following gradation prior to testing:

	Percent by Weight
Retained on 3/8" sieve..........	0
Retained on No. 4 sieve.........	100.

		Emulsion	
		CRS-2	HFRS-2
		Replicate 1 Replicate 2	Replicate 1 Replicate 2
		Replicate 1 Replicate 2	Replicate 1 Replicate 2
		Replicate 1 Replicate 2	Replicate 1 Replicate 2
		Replicate 1 Replicate 2	Replicate 1 Replicate 2

Figure 8. Experiment Design for Emulsion Chip Seal Cohesion Test.

Table 8. Properties of HFRS-2 and CRS-2 Emulsions.

Emulsion Grade:	**HFRS-2**	**CRS-2**
Properties		
Furol Viscosity at 122 F, sec	373	183
Residue by Distillation, %	69	66
Demulsibility, 35 cc of N/50 $CaCl_2$, %	57	-
Demulsibility, 35 ml. 0.8% sodium dioctyl sulfosuccinate, %	-	99
Tests on Residue:		
Penetration at 77°F	109	133
Ductility at 77°F	100+	100+

Table 9. Aggregate Properties for Grade 4 Limestone, River Gravel, Sandstone, and Lightweight.

Aggregate Type:	Limestone	River Gravel	Lightweight	Sandstone
Property				
Unit Weight by Rodding, lb/ft^3	84.1	94.2	52.4	93.6
Void Content by Rodding, %	43	41	38	41
Bulk Specific Gravity, dry	2.362	2.528	1.345	2.529
Absorption, %	3.9	1.1	15.7	1.9

Discussion of Results

The cohesion test was performed according to the experiment design shown in Figure 8. A chip seal sample was prepared in the laboratory according to the procedure discussed in the previous chapter and then allowed to cure. Testing was performed at different times throughout the curing process. In general, the cohesion test was performed on the samples at one-hour intervals for the first six hours following preparation and at 24 and 48 hours. The results were plotted on a graph as time (or age of sample in hours) versus maximum torque. Maximum torque is the maximum torque value acquired during one rotation of the rubber pad on the chip seal sample.

Test results for the experiment are shown in Figures 9 and 10. Each curve shown in these figures is an average of two curves produced from two replicate tests. The characteristic shape of all of the curves demonstrate that the chip seals gain strength (or cure) rapidly for the first six hours and then level off to a maximum value between 24 and 48 hours. The initial slopes of all of the curves shown in Figures 9 and 10 are approximately the same. Since the shape of all of the curves are about the same, indications are that all of the samples cured at about the same rate. However, the maximum torque values between samples obtained at 24 and 48 hours show greater differences between samples. This appears to be a result produced by the type of aggregate used rather than the emulsion curing rate. In other words, the curves shown in Figures 9 and 10 level off to different maximum torque values. However, these differences in overall maximum torque value are probably not related to the curing rate of the binder but may be related to the surface characteristics of the aggregate. This is perhaps better illustrated by plotting aggregate types together as shown in Figures 11 through 14. The maximum torque values at 48 hours are almost the same for the river gravel, lightweight and limestone aggregates. However, there is a slight difference in 48-hour values for the sandstone aggregate samples (Figure 14).

To normalize the effect of different aggregate types, selected parameters were extracted from the time versus torque curves to provide an indication of the rate of cure. These parameters are shown by an example curve in Figure 15. There are two parameters which provide an indication

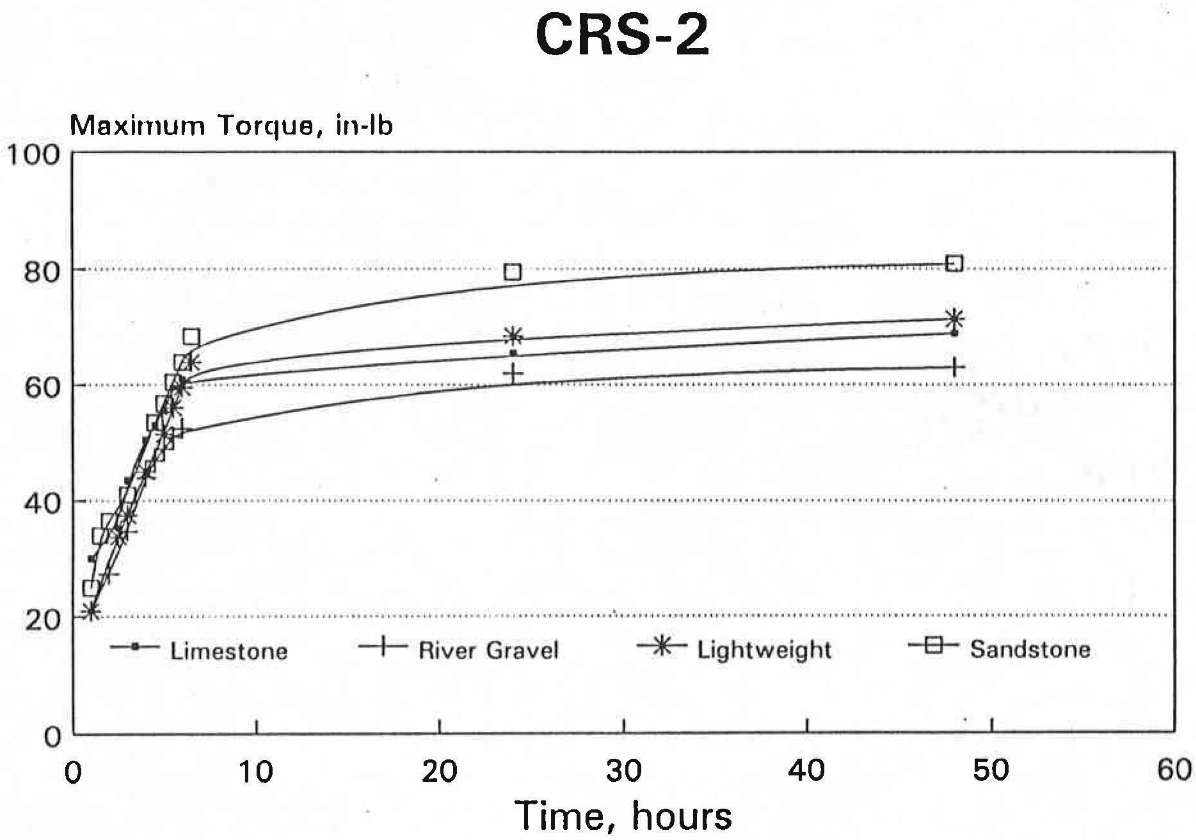


Figure 9. Cohesion Test Results for CRS-2 Emulsion Chip Seal Samples.

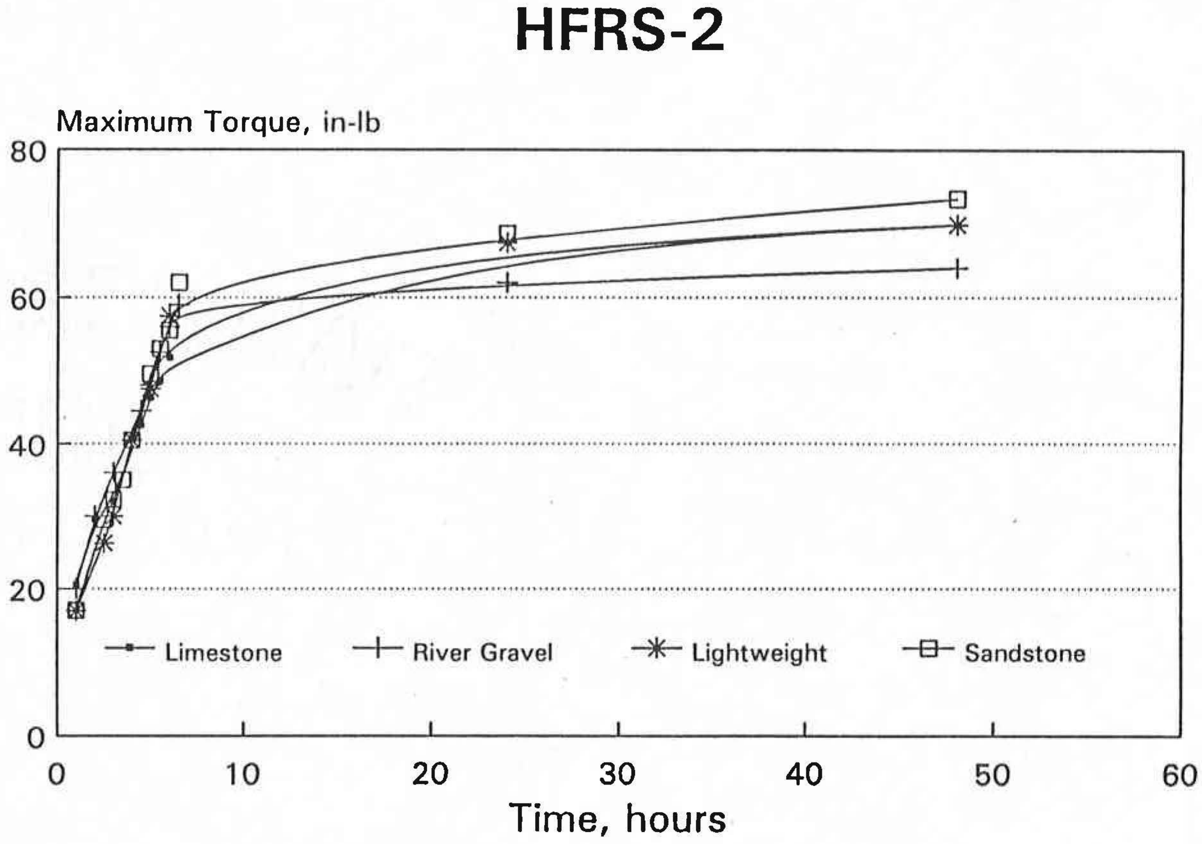


Figure 10. Cohesion Test Results for HFRS-2 Emulsion Chip Seal Samples.

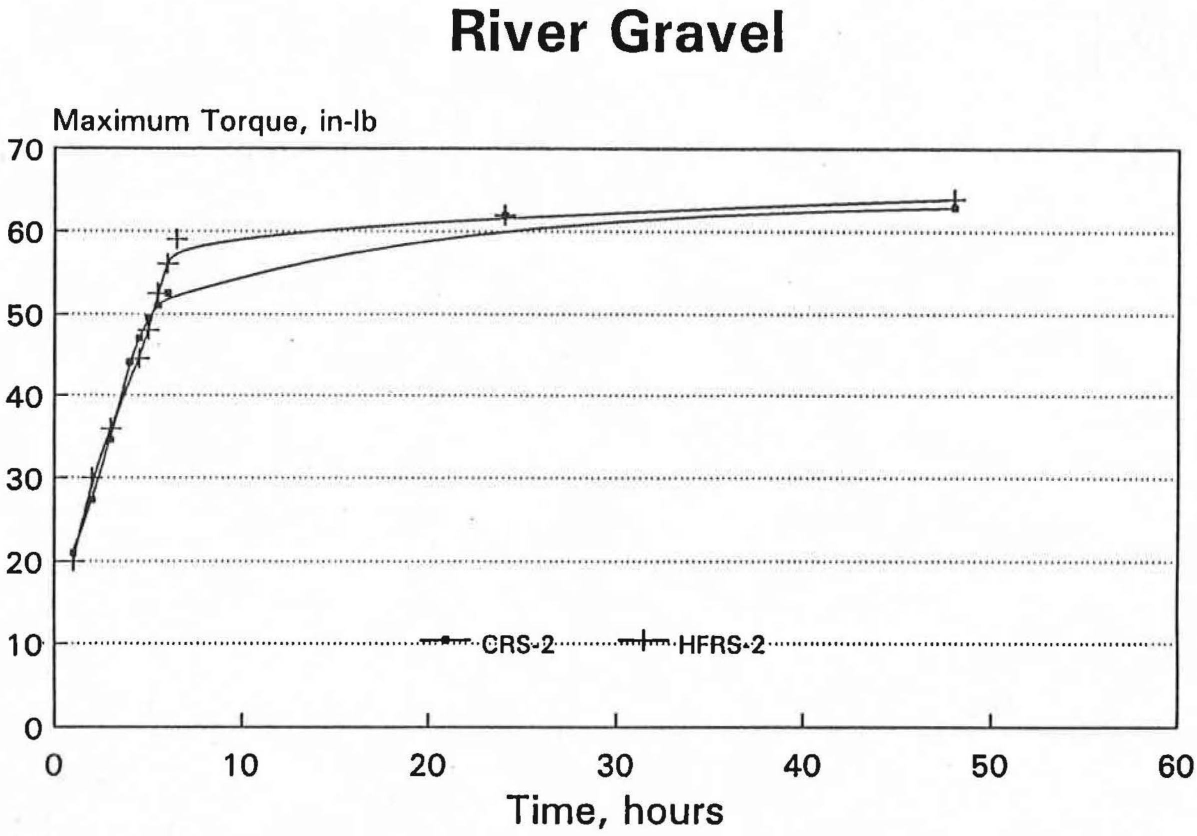


Figure 11. Cohesion Test Results for Chip Seal Sample Made with River Gravel.

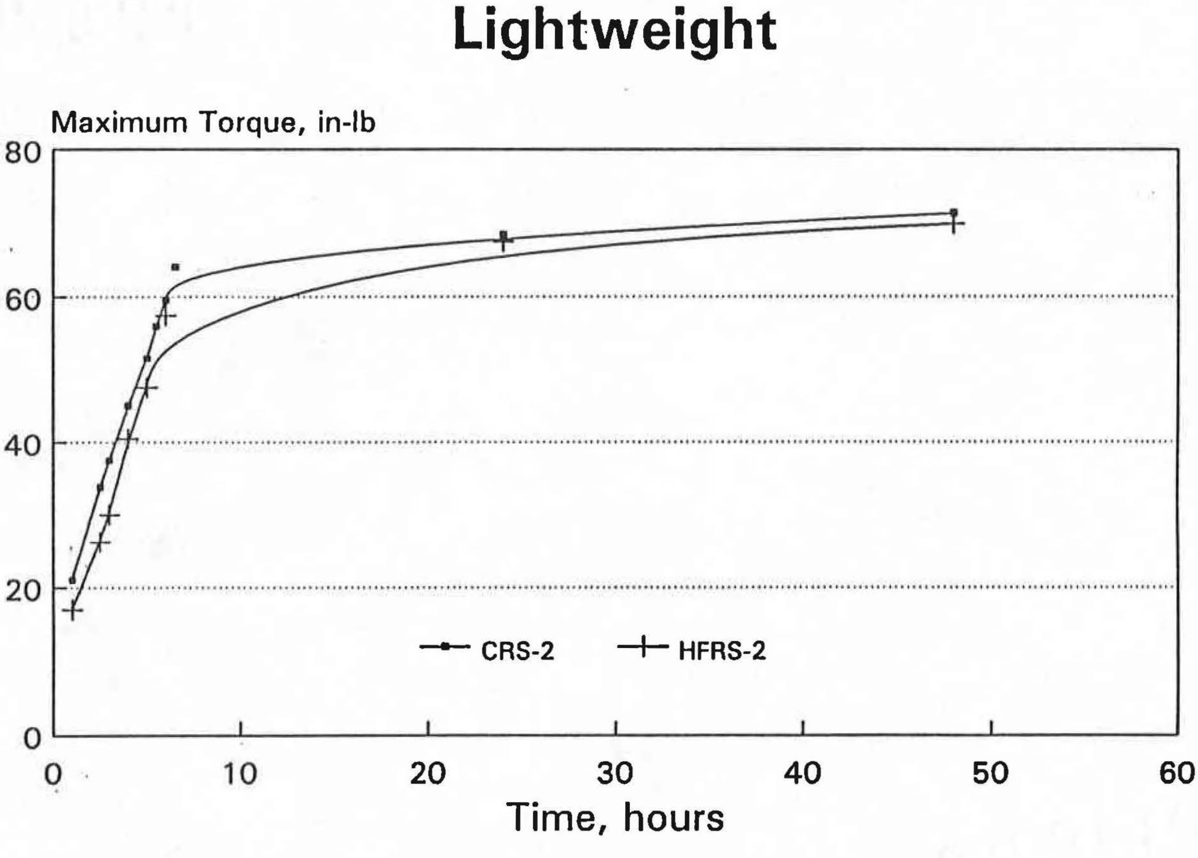


Figure 12. Cohesion Test Results for Chip Seal Samples Made with Lightweight Aggregate.

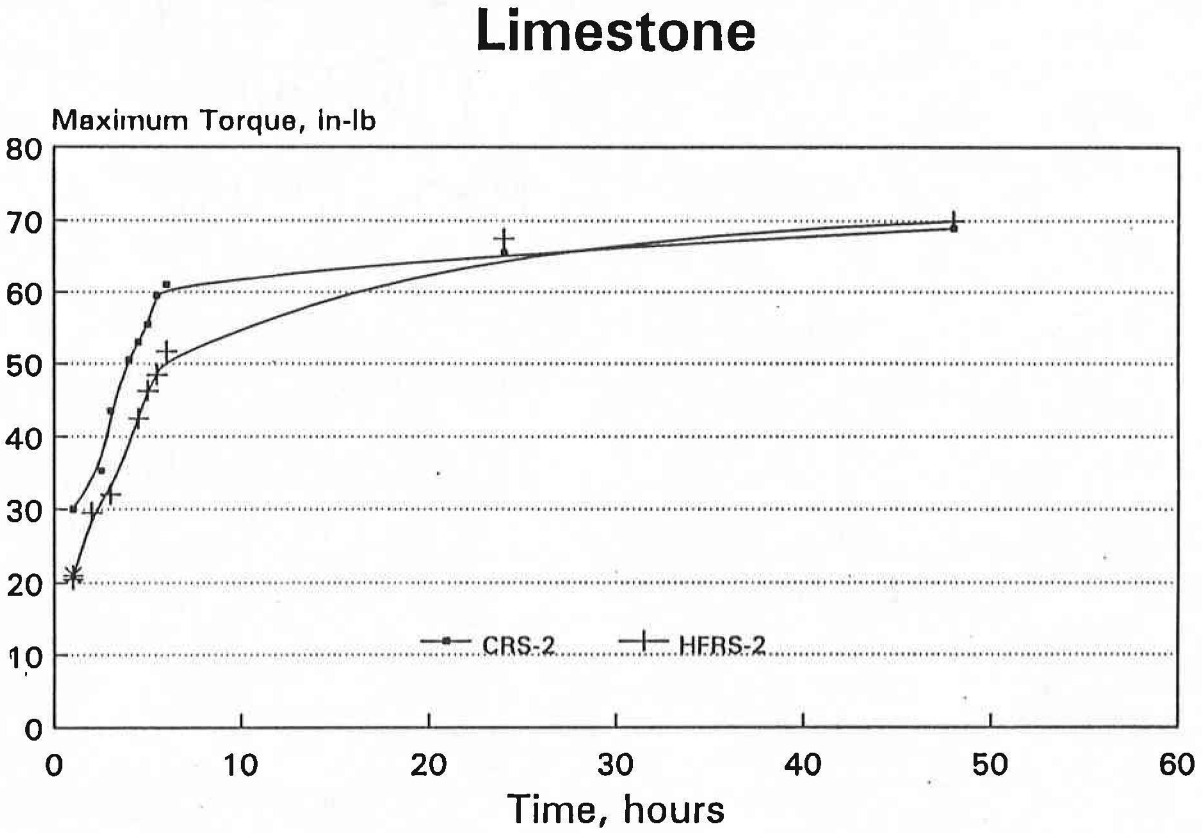


Figure 13. Cohesion Test Results for Chip Seal Samples Made with Limestone Aggregate.

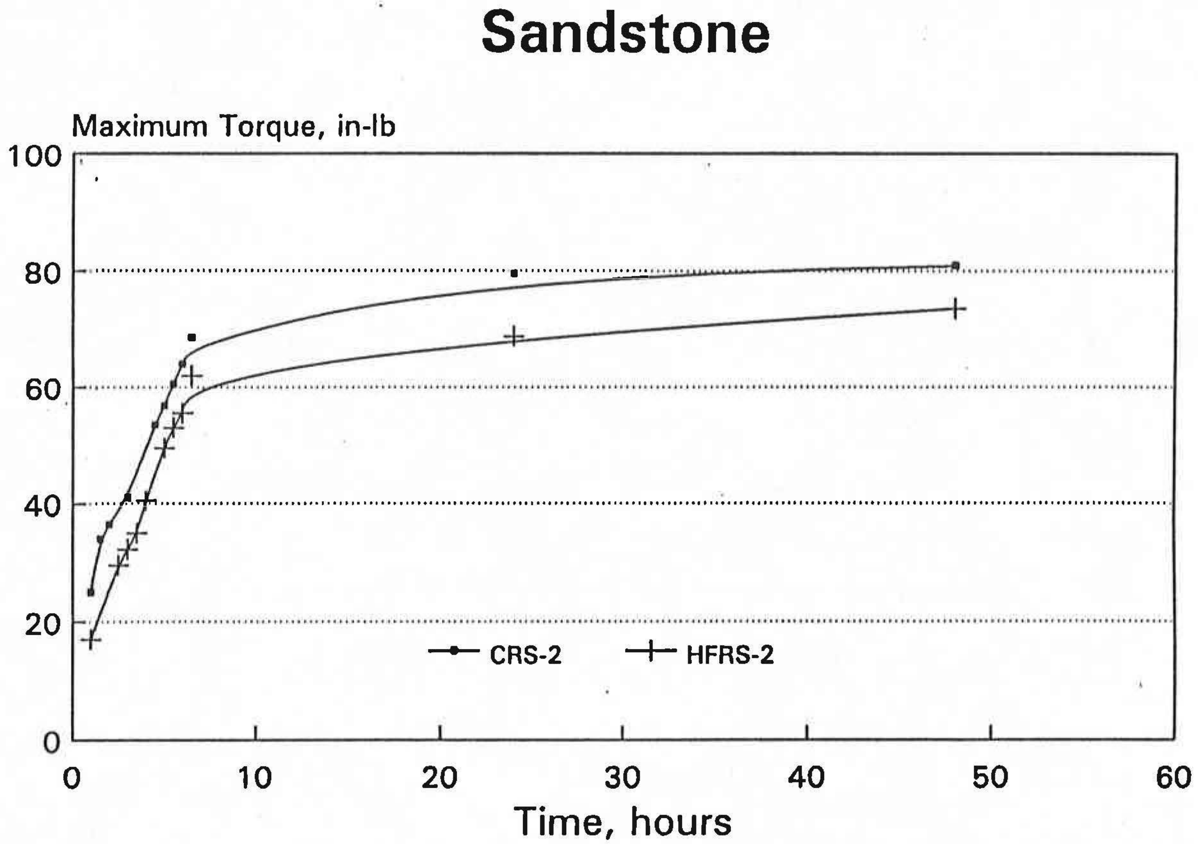


Figure 14. Cohesion Test Results for Chip Seal Samples Made with Sandstone Aggregate.

EXAMPLE COHESION TEST CURVE

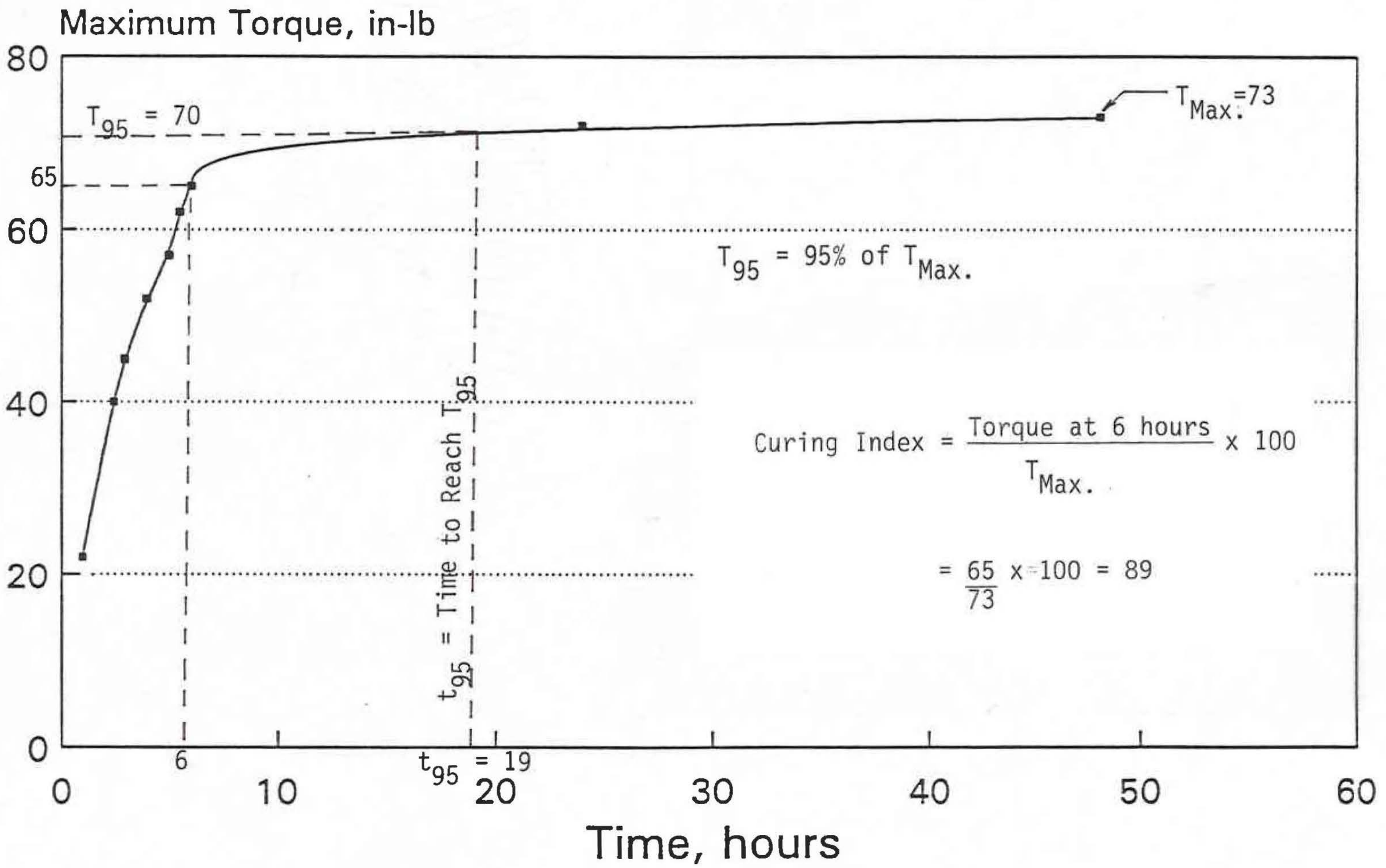


Figure 15. Example Curve for TTI Cohesion Test.

of the rate of cure: t_{95} and Curing Index. The t_{95} value is the time it takes to reach 95 percent of the maximum attainable torque. The testing process should continue until the time versus torque curve levels off. In the example (Figure 15), the final maximum torque value is 73. Ninety-five percent of this value is 70 which is shown as T_{95}. This translates to a time of 19 hours to reach 95 percent of the maximum torque or t_{95}.

The Curing Index shown in Figure 15 is a term given to the percentage of cure occurring at six hours. It is calculated by dividing the torque value at six hours by the final maximum torque value and multiplying by 100 percent. The curing curves for all of the samples tested throughout this study, whether the curing rate was fast or slow, exhibited an abrupt change in direction at about six to seven hours. The six-hour value was therefore taken to be a critical point.

The Curing Index for each of the samples is shown in Figure 16. Each bar represents an average of two replicate tests. Individual data points are shown in Appendix B, Figures B1 through B8. Average Curing Index values ranged from 75 to 89. A statistical analysis using analysis of variance techniques (ANOVA) was performed on the Curing Index responses and indicated that there was no significant difference between the two emulsions or between the four different aggregates. The statistical analysis is presented in Appendix C.

The time required to reach 95 percent of the maximum attainable torque, or t_{95}, is shown in Figure 17. The average t_{95} values ranged from 19 to 35 hours. A statistical analysis of the t_{95} responses, shown in Appendix C, indicated that there was no significant difference between the two emulsions or between the four different aggregates.

EVALUATION OF WET (SSD) AGGREGATE

The fact that there was no significant difference in the curing rates of the materials in the previous experiment as measured by t_{95} and Curing Index is not surprising since both emulsions studied were classified as rapid-setting emulsions. However, the previous experiment failed to reveal whether the test procedure could detect differences in curing rates. Therefore, using the same two emulsions, limestone and sandstone, as in the

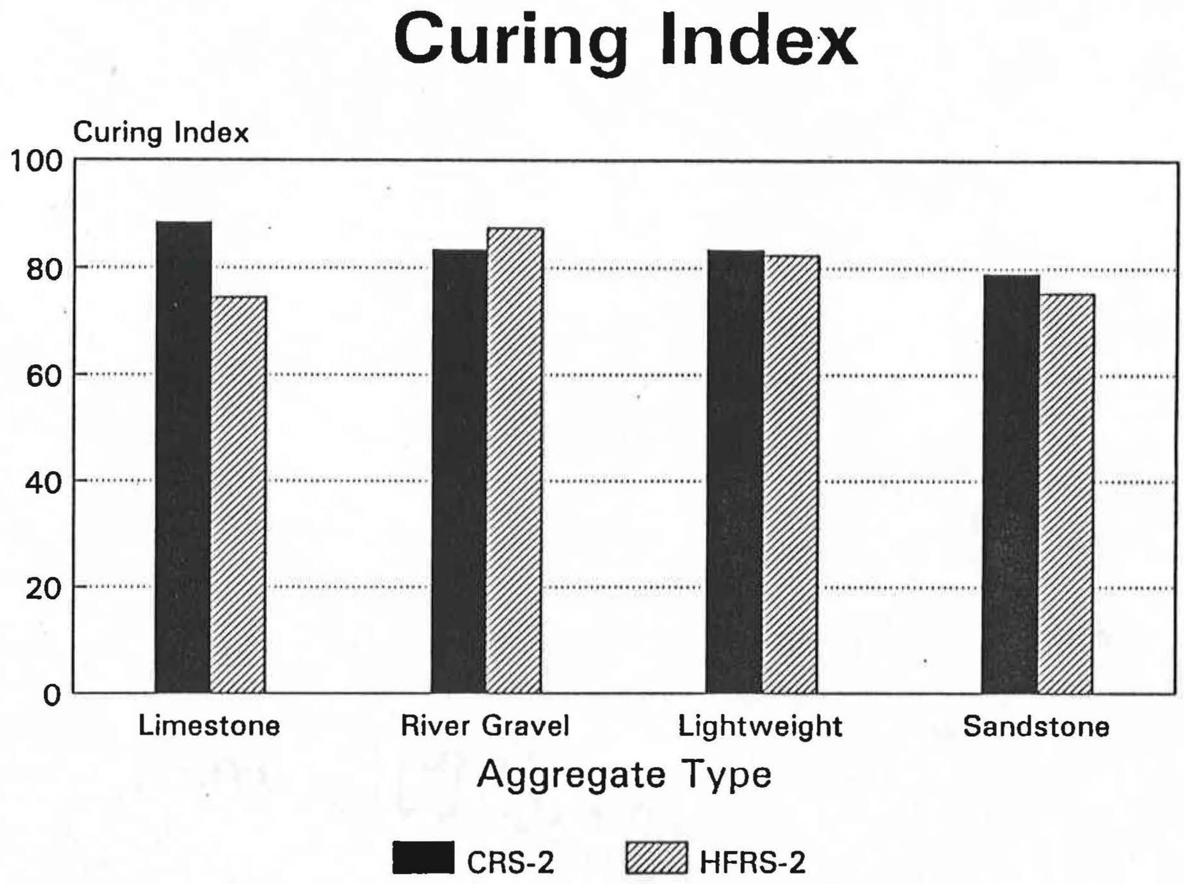


Figure 16. Curing Index for CRS-2 and HFRS-2 Emulsion Chip Seals.

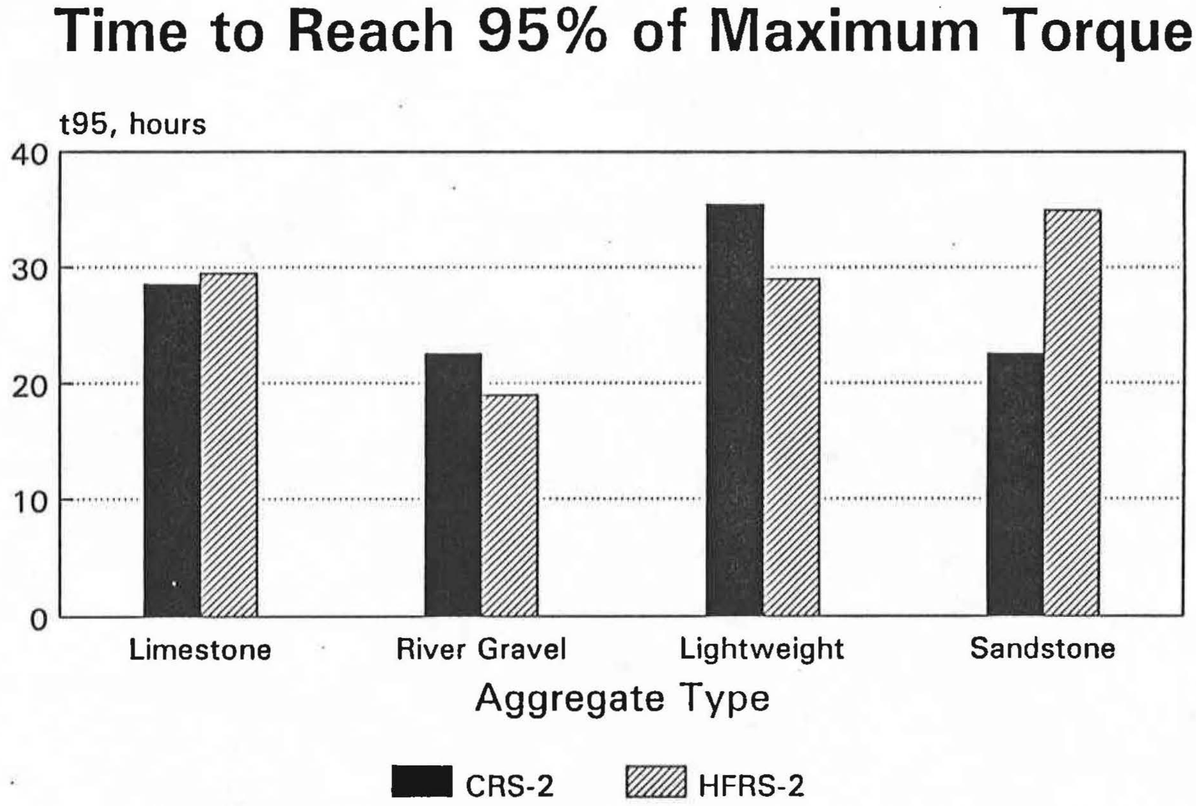


Figure 17. Time to Reach 95 Percent of Maximum Torque for CRS-2 and HFRS-2 Emulsion Chip Seals.

previous experiment, another experiment was performed. This time, the aggregate was at a saturated, surface-dried (SSD) condition, as opposed to dry, at the time the chip seal samples were fabricated. It was expected that the saturated condition of the aggregate would reduce the curing time of the laboratory chip seal. A factorial experiment was performed without replication using two types of emulsions and two types of saturated aggregates.

Discussion of Results

The results of these tests are shown in Figures 18 through 21. Each figure contains the test results of the SSD aggregate sample compared with the corresponding dry aggregate sample from the previous experiment. The curing rate for most of the dry aggregate chip seal samples began to level off between 24 and 48 hours; however, the curing rate had not leveled off on the SSD aggregate samples even at 72 hours. Even though the curing rate had not leveled off, testing on the SSD aggregate samples did not continue beyond 72 hours because there was no available, undisturbed area on the chip seal samples for further testing. It was assumed that the sample would have cured to a maximum value at least equivalent to the dry sample. Refer to Appendix B, Figures B9 through B12, for a complete exhibit of all of the data.

The Curing Indices for both the dry and SSD aggregate samples are shown in Figure 22. While the dry aggregate samples had Curing Indices ranging from 75 to 89, the wet aggregate samples had Curing Indices ranging from 61 to 68. In other words, the dry aggregate samples reached from 75 to 89 percent of their total cure in six hours, and the SSD aggregate samples reached only 61 to 68 percent of their assumed total cure in six hours.

The times to reach 95 percent of the maximum attainable torque, or t_{95}, for both the dry and SSD aggregate samples are shown in Figure 23. The dry aggregate samples shown here reached 95 percent of their maximum torque in 24 to 35 hours while the wet aggregate samples did not reach 95 percent of their assumed maximum torque until 56 to 122 hours. In Figure 23, it also

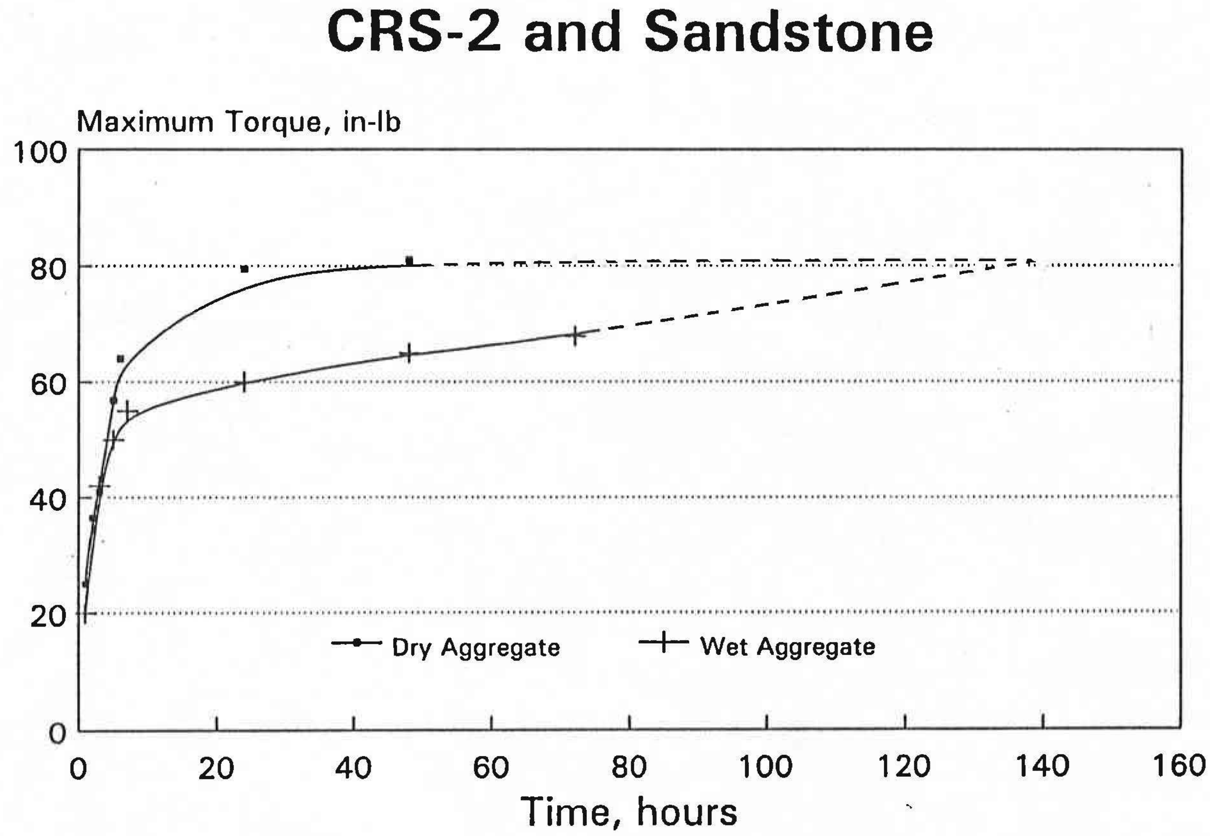


Figure 18. Cohesion Test Results Comparing Dry and Wet (SSD) Sandstone, CRS-2 Emulsion Chip Seal Samples.

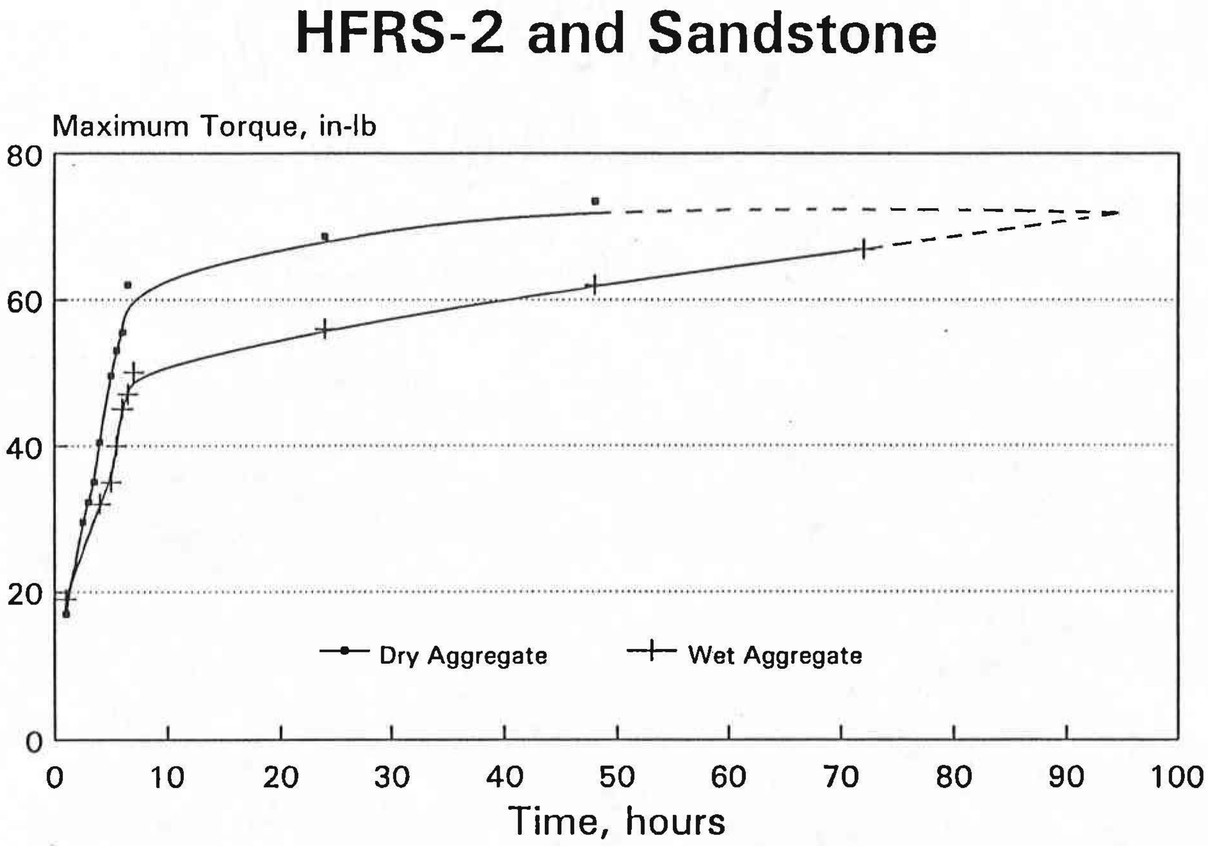


Figure 19. Cohesion Test Results Comparing Dry and Wet (SSD) Sandstone, CRS-2 Emulsion Chip Seal Samples.

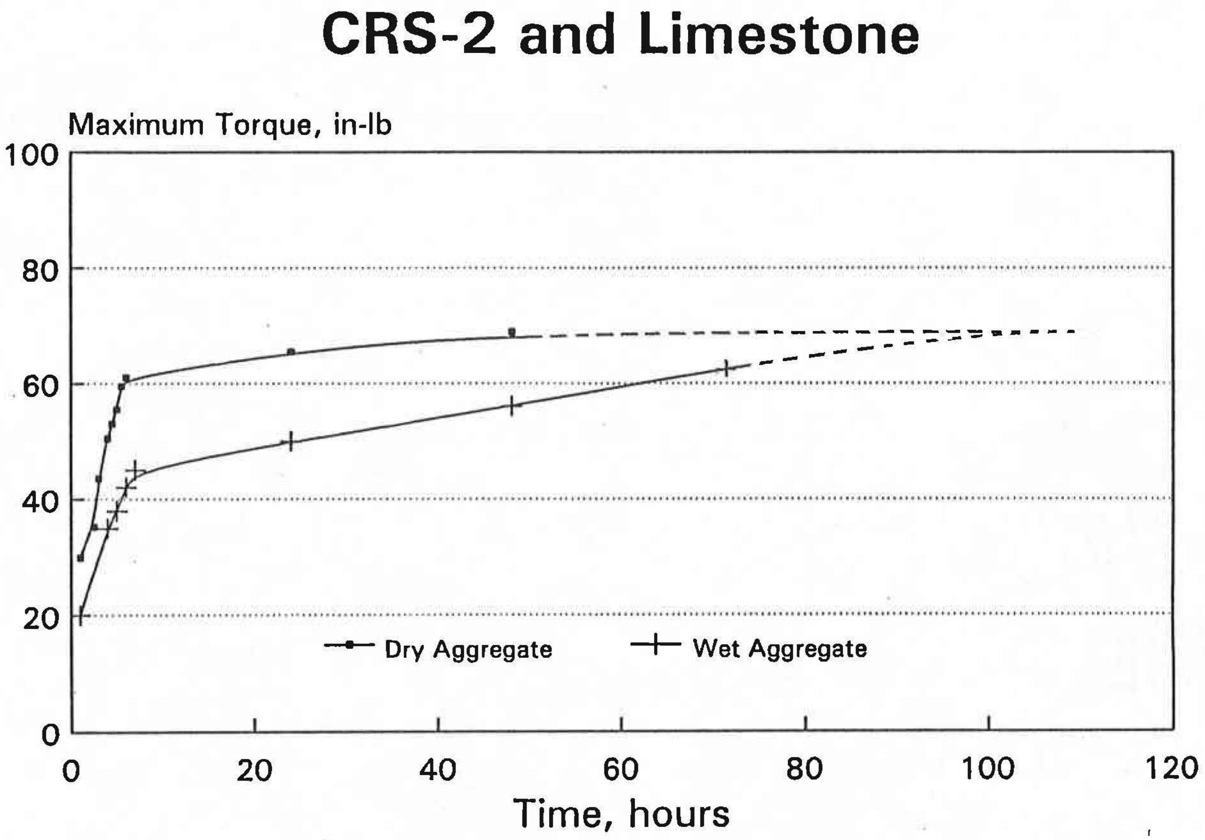


Figure 20. Cohesion Test Results Comparing Dry and Wet (SSD) Limestone, CRS-2 Emulsion Chip Seals.

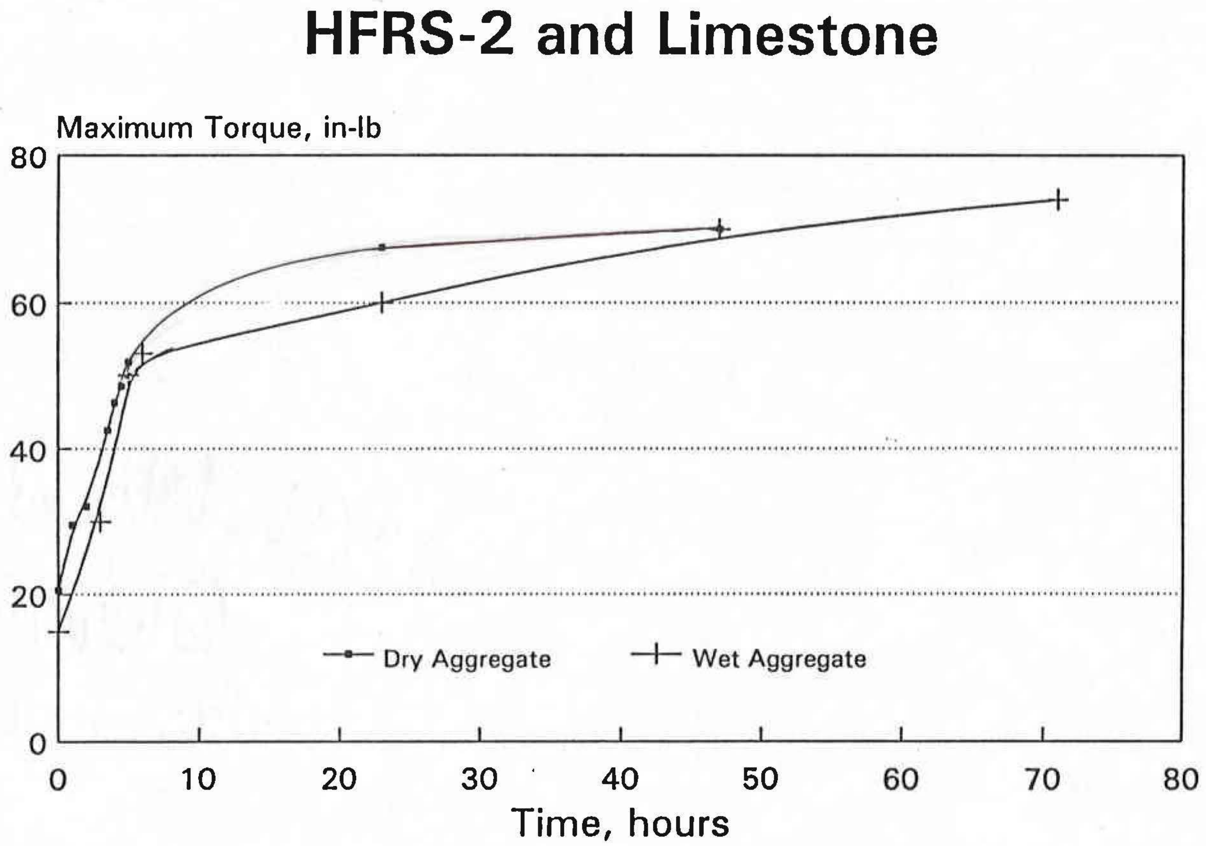


Figure 21. Cohesion Test Results Comparing Dry and Wet (SSD) Limestone, HFRS-2 Emulsion Chip Seals.

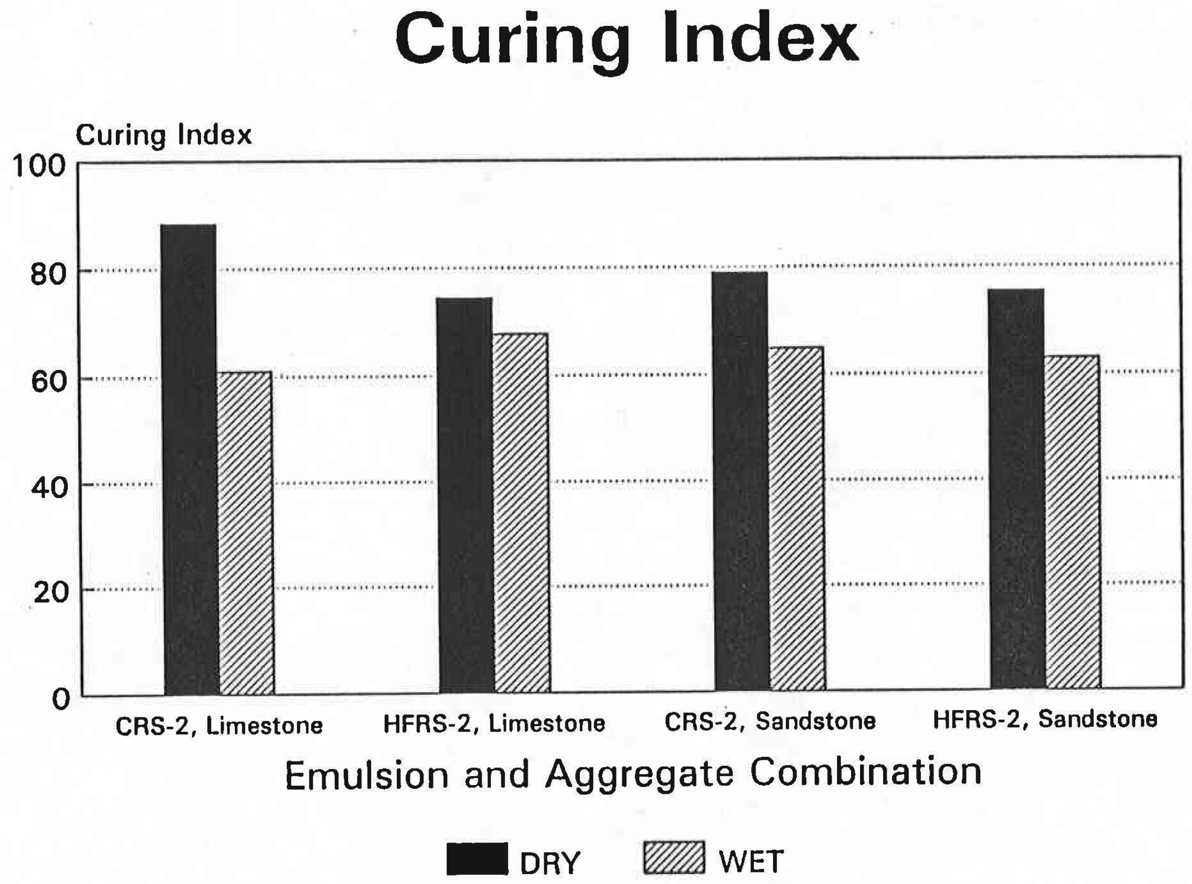


Figure 22. Curing Index Comparing Dry and Wet (SSD) Aggregate Chip Seals.

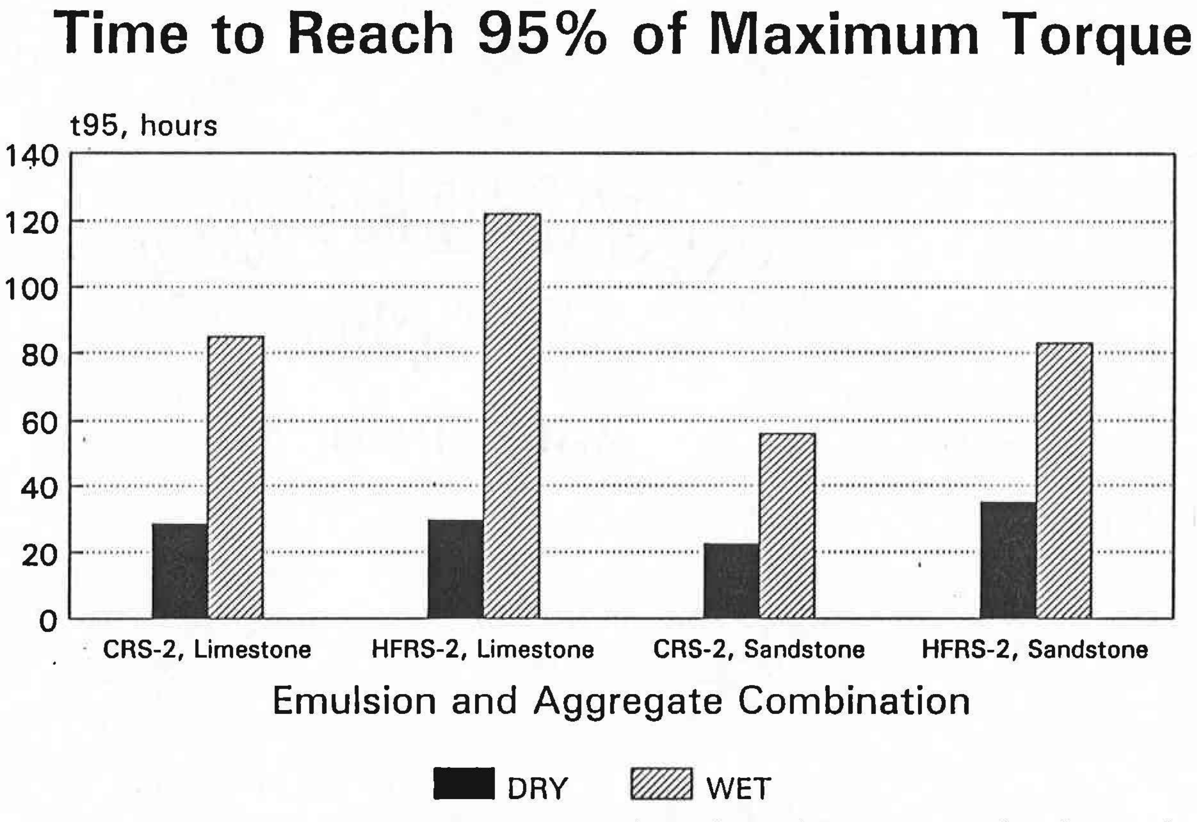


Figure 23. Time to Reach 95 Percent of Maximum Torque Comparing Dry and Wet (SSD) Aggregate Chip Seals.

appears that the test is showing sensitivity to both emulsion type and aggregate type for the SSD aggregate samples. Both limestone samples had higher t_{95} values than both of the sandstone samples. Both of the HFRS-2 samples had higher t_{95} values than both of the CRS-2 samples.

EVALUATION OF OTHER EMULSIONS

A limited number of other emulsions were tested to compare with the previous tests. A CRS-2 from a different source than the previous CRS-2 was tested. This sample was obtained from Elf Asphalt at the Lubbock plant and is designated as "CRS-2(Lubbock)" to differentiate it from the previous CRS-2 sample. An RS-2 and MS-1 from the Lubbock plant were also tested. A CRS-2p obtained from Elf Asphalt's Mt. Pleasant plant was evaluated. The "p" designates the addition of a polymer. Test properties for these emulsions are shown in Table 10.

Aggregates used previously were used for these tests. These aggregate samples were oven-dried.

Discussion of Results

All of the data for these tests are presented in Appendix B, Figures B13 through B16. The CRS-2(Lubbock) and CRS-2p samples were prepared using the sandstone aggregate and compared with the previous CRS-2 sample. The cohesion test results for these three samples are shown in Figure 24. The two CRS-2 samples from different sources have almost identical curves. The CRS-2p sample appears to cure at about the same rate as the other two samples but has a higher torque value at all times. This higher torque value may be an effect of the polymer.

The MS-1 and RS-2 emulsions were tested with the limestone aggregate. The cohesion test curves are presented in Appendix B, Figures B15 and B16. The Curing Index and t_{95} values are shown in Figures 25 and 26 and are compared with the HFRS-2/dry limestone and CRS-2/dry limestone samples from the previous experiment. The RS-2 emulsion had a Curing Index of 79 and a t_{95} value of 33 hours. This falls within the range of values for all of the other rapid-setting emulsions which were tested in this study which is an indication of the repeatability of the test. Two replicate tests were

Table 10. Emulsion Material Properties for CRS-2(Lubbock), RS-2, MS-1, and CRS-2p.

Emulsion Grade:	**CRS-2(Lubbock)**	**RS-2**	**MS-1**	**CRS-2p**
Properties				
Furol Viscosity at 122°F, sec	271	159		305
Furol Viscosity at 77°F, sec			32	
Residue by Distillation, %	67	70	64	69
Demulsibility, 35 ml of N/50 $CaCl_2$, %		61		
Demulsibility, 35 ml 0.8% sodium dioctyl sulfosuccinate, %	73			81
Tests on Residue:				
Penetration at 77°F	120	123	133	81
Ductility at 77°F	NA	NA	NA	67

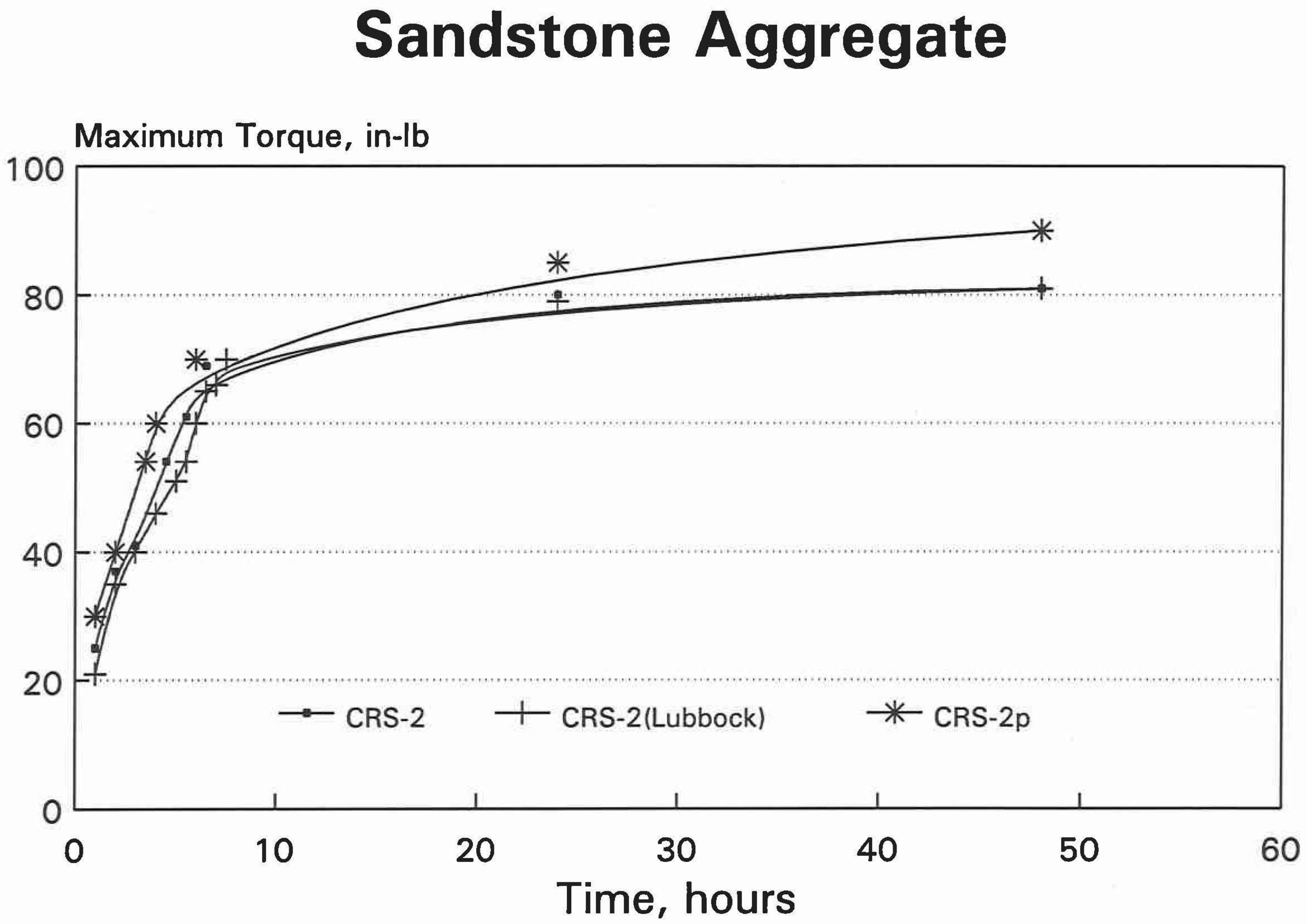


Figure 24. Cohesion Test Results for CRS-2(Port Neches), CRS-2(Lubbock), and CRS-2p.

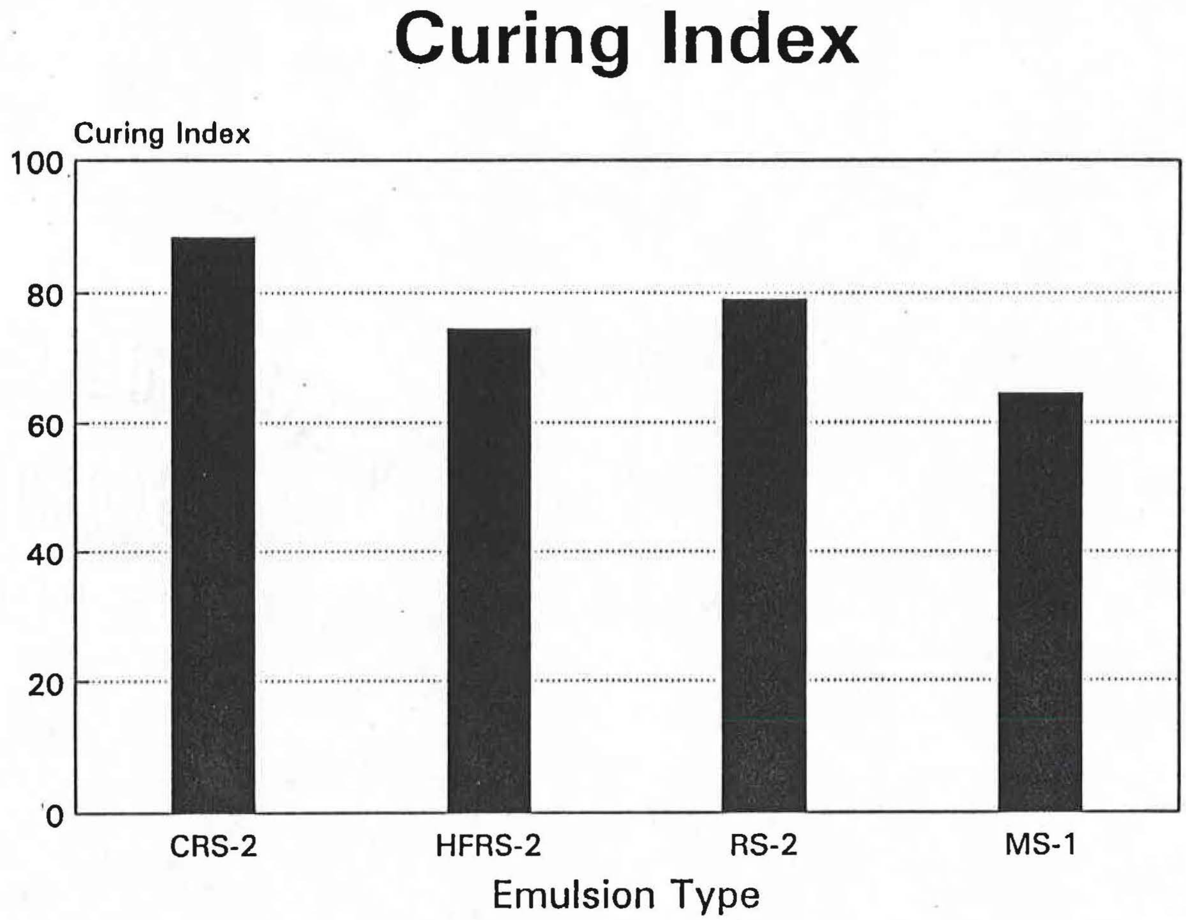


Figure 25. Curing Index for CRS-2, HFRS-2, RS-2 and MS-1 Samples Made with Sandstone Aggregate.

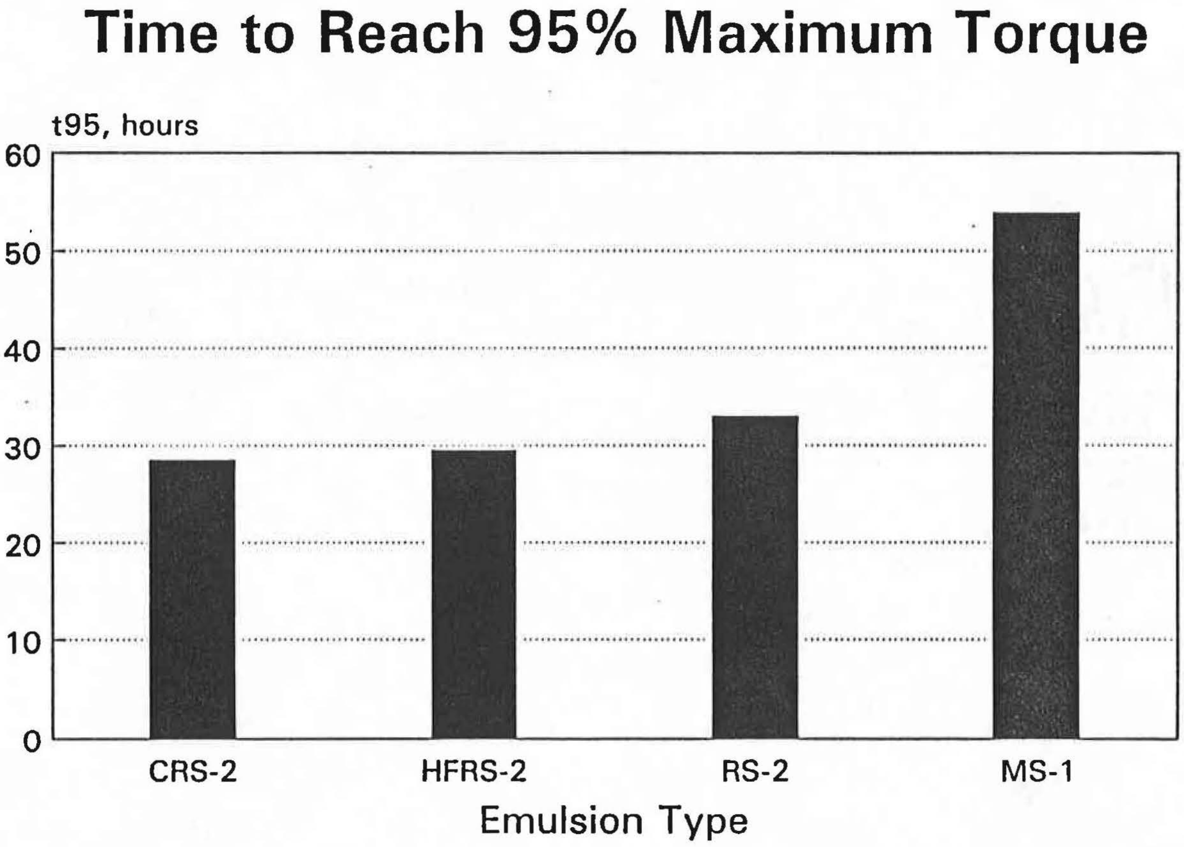


Figure 26. Time to Reach 95 Percent Maximum Torque for CRS-2, HFRS-2, RS-2 and MS-1 Samples Made with Sandstone Aggregate.

performed using the MS-1 and limestone. The average Curing Index for the MS-1 was 65, and the t_{95} value was 54 hours.

VIALET AND SLIDING PLATE VISCOSITY TESTS

EVALUATION OF VIALET TEST

The Vialet test has been used to provide information on the following (7):

1. Appropriateness of aggregate design quantities,
2. Resistance of aggregate to an impact force over several time intervals, and
3. Rate of set of binder.

Stroup-Gardiner, et. al. (7) developed correlations for field observations for 18 field test sections placed with various types of emulsions and concurrent laboratory Vialet testing. Some of the conclusions in this study (7) are as follows:

1. Problems with excess aggregate can be identified with the 5- or 24-hour initial invert Vialet test,
2. Problems with aggregate pick up on rollers during construction are related to the 10-minute impact Vialet test results showing less than 30 percent material retained,
3. Problems with surface damage with early brooming are indicated by the 3-minute impact Vialet test results of less than 60 percent material retained,
4. Field sections showing good performance after one month under low-volume traffic conditions generally have 24-hour impact Vialet test results of greater than 80 percent material retained.

The Vialet test was evaluated in this study to determine its effectiveness providing an indication of the curing rate for laboratory emulsion chip seals. It was also evaluated to provide a correlation to the Cohesion Test.

Test Procedure

The testing method used for the Vialet test in this study was the same as that used by Stroup-Gardiner et. al. (7) except that the sample was rolled with a hand-held rubber roller rather than a weighted tire. The material types and quantities were also different. The test uses a 0.25-inch steel plate, seven by seven inches square as a sample preparation medium. A 0.25-inch rim prevents binder runoff. A force is imparted to an inverted chip seal sample by means of dropping a steel ball, two inches in diameter, from a height of 18 inches.

Prior to sample preparation, both the plates and emulsions were preheated to 140°F. Emulsion was applied at an application rate of 0.35 gallons per square yard. The plate was rotated until the binder was evenly distributed over the surface. Aggregate was applied at a rate of 90 percent of the design quantity which was the amount used in the Cohesion Test. The sample was then rolled using a hand-held rubber roller.

A total of 15 samples were prepared. Three samples were tested at 10-minute, 30-minute, 2-hour, 5-hour, and 24-hour intervals. A separate set of three samples was prepared for each time interval. All samples were allowed to cure at 77°F (plus or minus 5°F) and a relative humidity of less than 50 percent. A photograph of a prepared sample is shown in Figure 27.

An initial weight of the sample and the plate was obtained, then the specimen was inverted in the test apparatus for ten seconds and a second weight was taken. However, no stone loss occurred as a result of the initial invert in this study. This is probably because none of the samples in this study had any excess aggregate. The plate was then immediately reinverted in the apparatus, and a steel ball dropped in the center of the plate three times within a ten-second period. A final weight was then taken and percent material retained after impact was calculated.

Experiment Design

The materials used in this experiment were from the same group of materials used for the Cohesion Test experiments described in the previous chapter. Three emulsions were used in this experiment: HFRS-2, CRS-2, and CRS-2p. The aggregates were river gravel and limestone. These aggregates were of the same gradation as those used for the cohesion test:

0 percent by weight retained on the 3/8" sieve,
100 percent by weight retained on the No. 4 sieve.

Two replicates tests of each combination of materials were performed. The experiment design is shown in Figure 28.

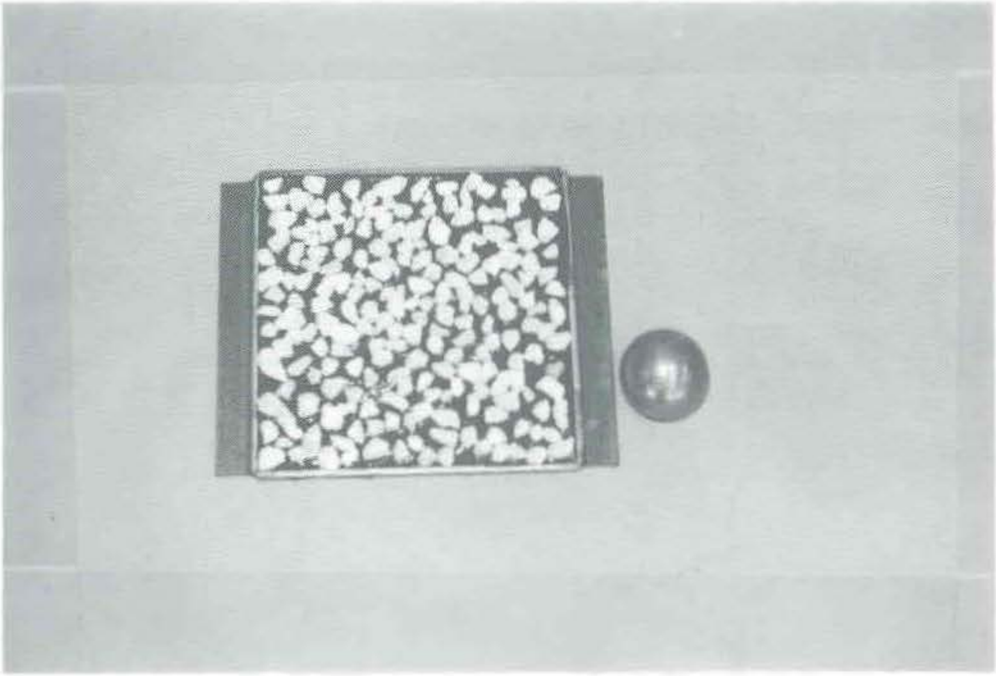


Figure 27. Prepared Vialet Sample.

		Emulsion		
		HFRS-2	CRS-2	CRS-2p
		Replicate 1	Replicate 1	Replicate 1
		Replicate 2	Replicate 2	Replicate 2
		Replicate 1	Replicate 1	Replicate 1
		Replicate 2	Replicate 2	Replicate 2

Figure 28. Vialet Test Laboratory Experiment Design.

Discussion of Results

All of the results for this experiment are tabulated in Tables 11 through 16. Figure 29 shows the results obtained with the HFRS-2 emulsion. Each bar represents an average of two replicate tests. From this figure, there appears to be no difference between the limestone and the river gravel samples. There is also very little difference in the results at 10-minutes as compared to the 24-hour results. Retention rates at 10 minutes were about 90 percent and at 24 hours about 98 percent. Figures 30 and 31 compare the CRS-2 emulsion to the CRS-2p using limestone and river gravel aggregates. The CRS-2p samples had 99 percent retention rates even at 10-minutes. The CRS-2 samples, however, also had high retention rates at 10-minutes of 93 percent.

A statistical analysis on the above experiment which is presented in Appendix C revealed that there was a statistical difference between the CRS-2 and CRS-2p at the 10-minute and 30-minute time intervals. However, the HFRS-2 and CRS-2 were not significantly different at these time intervals, and all three emulsions were not significantly different at the 2-hour, 5-hour and 24-hour time intervals.

The Vialet test as conducted in this experiment did not provide any indication of the curing rate of the binders; therefore, the results could not be used to develop a correlation to the Cohesion Test. These results also did not compare well at all to the results obtained by Stroup-Gardiner et. al. (7) where the material retained at the 10-minute interval ranged from 7 to 64 percent. This may be due to the fact that the aggregate used in the TTI study had been cut to a one-size fraction. If a standard Grade 4 had been used which contained some larger stones, these larger stones would have had a smaller embedment depth and would likely have been dislodged at the 10-minute and 30-minute time intervals. Also the aggregate in the TTI study was placed at 90 percent of optimum; therefore, there was no excess aggregate which could contribute to a low retention rate.

EVALUATION OF SLIDING PLATE MICROVISCOSITY TEST

As an emulsion chip seal begins to cure, the viscosity of that emulsion will increase with time. Therefore, if the viscosity of that emulsion could

Table 11. Vialet Test Results After Impact for HFRS-2 and Limestone.

Test Time	Percent Material Retained									
	Replicate 1					Replicate 2				
	Sample No. 1	Sample No. 2	Sample No. 3	Mean	S.D.	Sample No. 1	Sample No. 2	Sample No. 3	Mean	S.D.
10 min.	91.0	90.2	80.3	87.2	6.0	91.6	93.0	91.9	92.2	0.7
30 min.	93.2	85.1	83.1	87.1	5.3	85.2	90.9	92.0	89.4	3.7
2 hr.	89.9	95.8	88.8	91.5	3.8	97.0	96.2	96.7	96.6	0.4
5 hr.	95.9	96.2	96.7	96.3	0.4	97.8	98.7	99.6	98.7	0.9
24 hr.	95.5	96.3	95.8	95.9	0.4	98.0	100.0	99.1	99.0	1.0

Table 12. Vialet Test Results After Impact for HFRS-2 and River Gravel.

Test Time	Percent Material Retained									
	Replicate 1					Replicate 2				
	Sample No. 1	Sample No. 2	Sample No. 3	Mean	S.D.	Sample No. 1	Sample No. 2	Sample No. 3	Mean	S.D.
10 min.	88.4	93.2	89.8	90.5	2.5	96.4	95.6	97.0	96.3	0.7
30 min.	95.7	93.6	95.6	95.0	1.2	89.7	93.6	94.0	92.4	2.4
2 hr.	89.5	93.9	86.9	90.1	3.5	92.3	90.4	91.2	91.3	1.0
5 hr.	93.9	92.7	97.9	94.8	2.7	99.0	96.4	96.5	97.3	1.5

Table 13. Vialet Test Results After Impact for CRS-2 and Limestone.

Test Time	Percent Material Retained									
	Replicate 1					Replicate 2				
	Sample No.			Mean	S.D.	Sample No.			Mean	S.D.
	1	2	3			1	2	3		
10 min.	99.4	98.8	93.1	93.1	3.5	90.0	87.1	96.2	91.1	4.6
30 min	91.8	86.4	95.4	91.2	4.5	75.9	80.8	80.9	79.2	2.9
2 hr.	98.6	98.9	96.8	98.1	1.1	95.0	93.1	93.6	93.9	1.0
5 hr.	98.7	100.0	100.0	99.6	0.8	99.6	99.5	99.4	99.5	0.1
24 hr.	99.1	97.8	99.6	98.8	0.9	100.0	100.0	100.0	100.0	0.0

Table 14. Vialet Test Results After Impact for CRS-2 and River Gravel.

Test Time	Percent Material Retained									
	Replicate 1					Replicate 2				
	Sample No.			Mean	S.D.	Sample No.			Mean	S.D.
	1	2	3			1	2	3		
10 min.	93.4	96.0	94.0	94.5	1.4	90.4	88.4	95.0	91.3	3.4
30 min.	76.5	85.9	89.3	83.9	6.6	87.0	90.0	98.1	91.7	5.7
2 hr.	65.6	76.1	75.1	72.3	5.8	97.3	97.6	94.1	96.3	1.9
5 hr.	100.0	100.0	100.0	100.0	0.0	98.6	97.4	99.1	98.4	0.9
24 hr.	99.6	98.0	99.0	98.9	0.8	99.5	99.9	99.6	99.7	0.2

Table 15. Vialet Test Results After Impact for CRS-2p and Limestone.

Test Time	Percent Material Retained									
	Replicate 1					Replicate 2				
	Sample No. 1	2	3	Mean	S.D.	Sample No. 1	2	3	Mean	S.D.
10 min.	99.6	99.3	99.3	99.4	0.2	96.2	98.6	98.9	97.9	1.5
30 min.	99.1	98.7	98.3	98.7	0.4	96.6	95.0	96.8	96.1	1.0
2 hr.	98.6	98.4	99.0	98.7	0.3	96.6	98.2	93.5	96.1	2.4
5 hr.	99.1	99.8	99.0	99.3	0.4	99.5	97.4	97.1	98.0	1.3
24 hr.	100.0	99.9	99.7	99.9	0.2	99.3	99.7	99.3	99.4	0.2

Table 16. Vialet Test Results After Impact for CRS-2p and River Gravel.

Test Time	Percent Material Retained									
	Replicate 1					Replicate 2				
	Sample No. 1	2	3	Mean	S.D.	Sample No. 1	2	3	Mean	S.D.
10 min.	99.3	99.0	99.2	99.2	0.2	99.2	99.0	99.5	99.2	0.3
30 min.	97.9	99.2	98.4	98.5	0.7	98.2	96.0	98.0	97.4	1.2
2 hr.	98.1	98.7	99.1	98.6	0.5	98.9	95.9	96.6	97.1	1.6
5 hr.	100.0	99.9	99.0	99.6	0.6	96.6	97.7	97.0	97.1	0.6
24 hr.	100.0	100.0	99.8	99.9	0.1	99.9	99.0	99.9	99.6	0.5

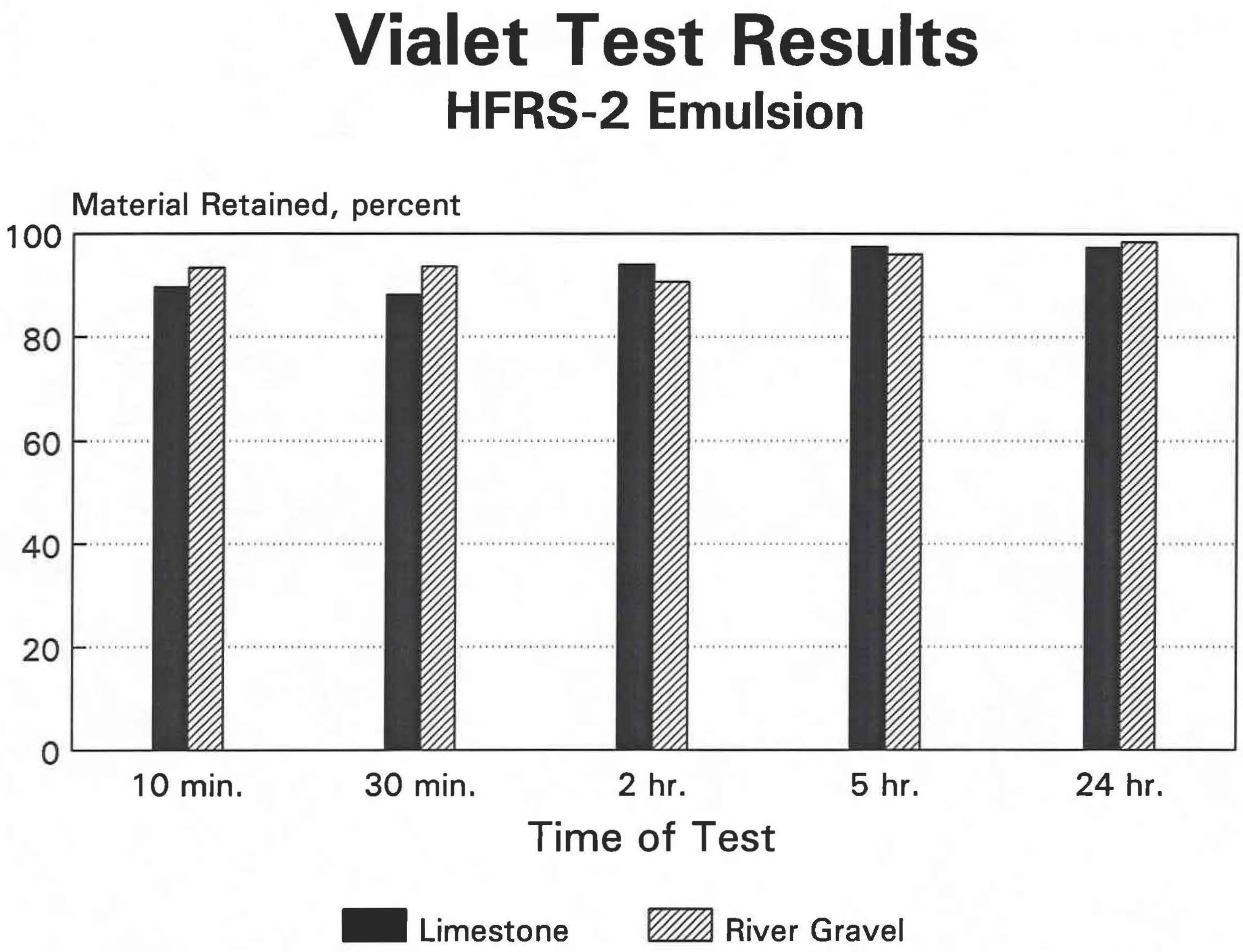


Figure 29. Vialet Test Results for HFRS-2 Emulsion Samples.

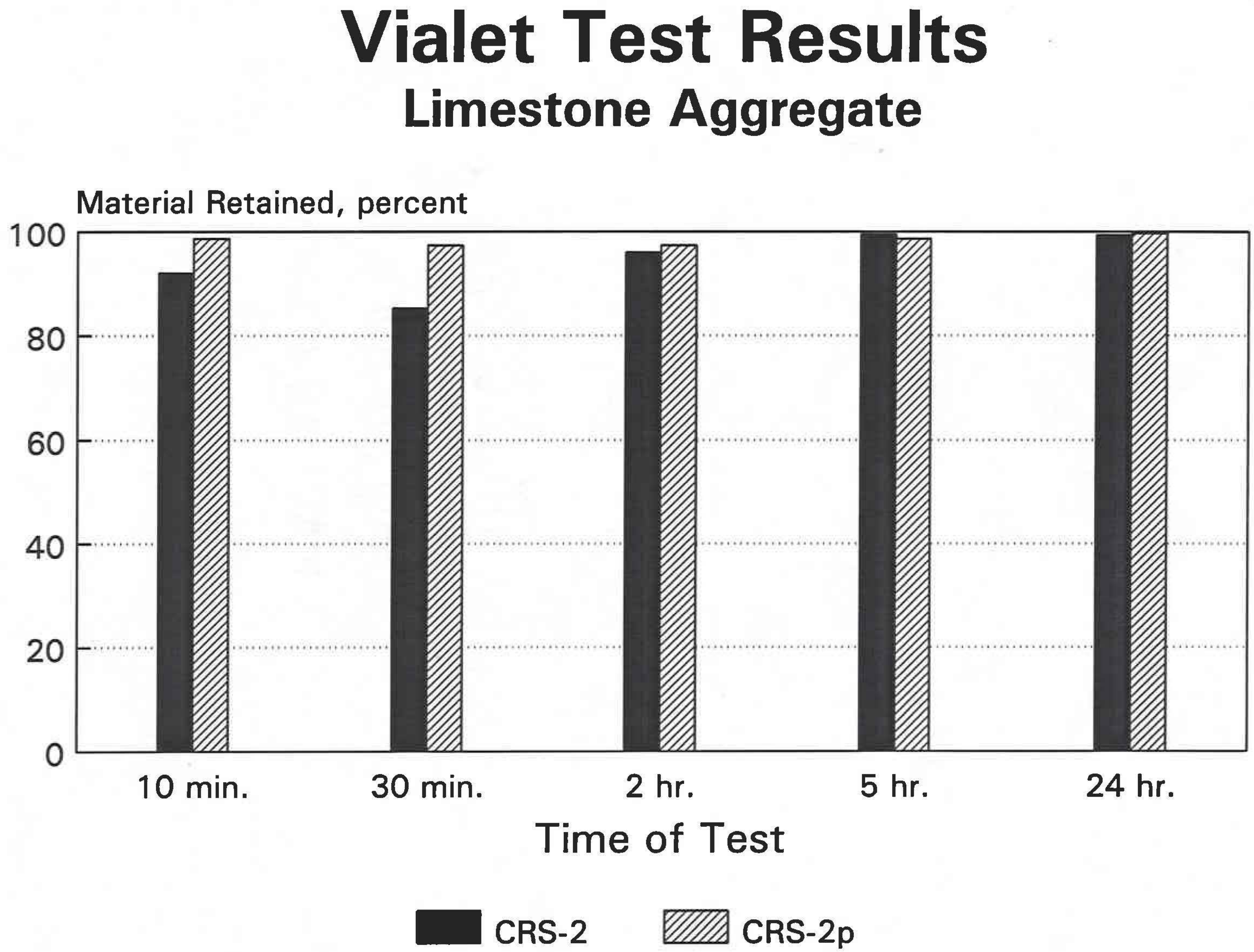


Figure 30. Vialet Test Results for CRS-2 and CRS-2p Samples Made with Limestone Aggregate.

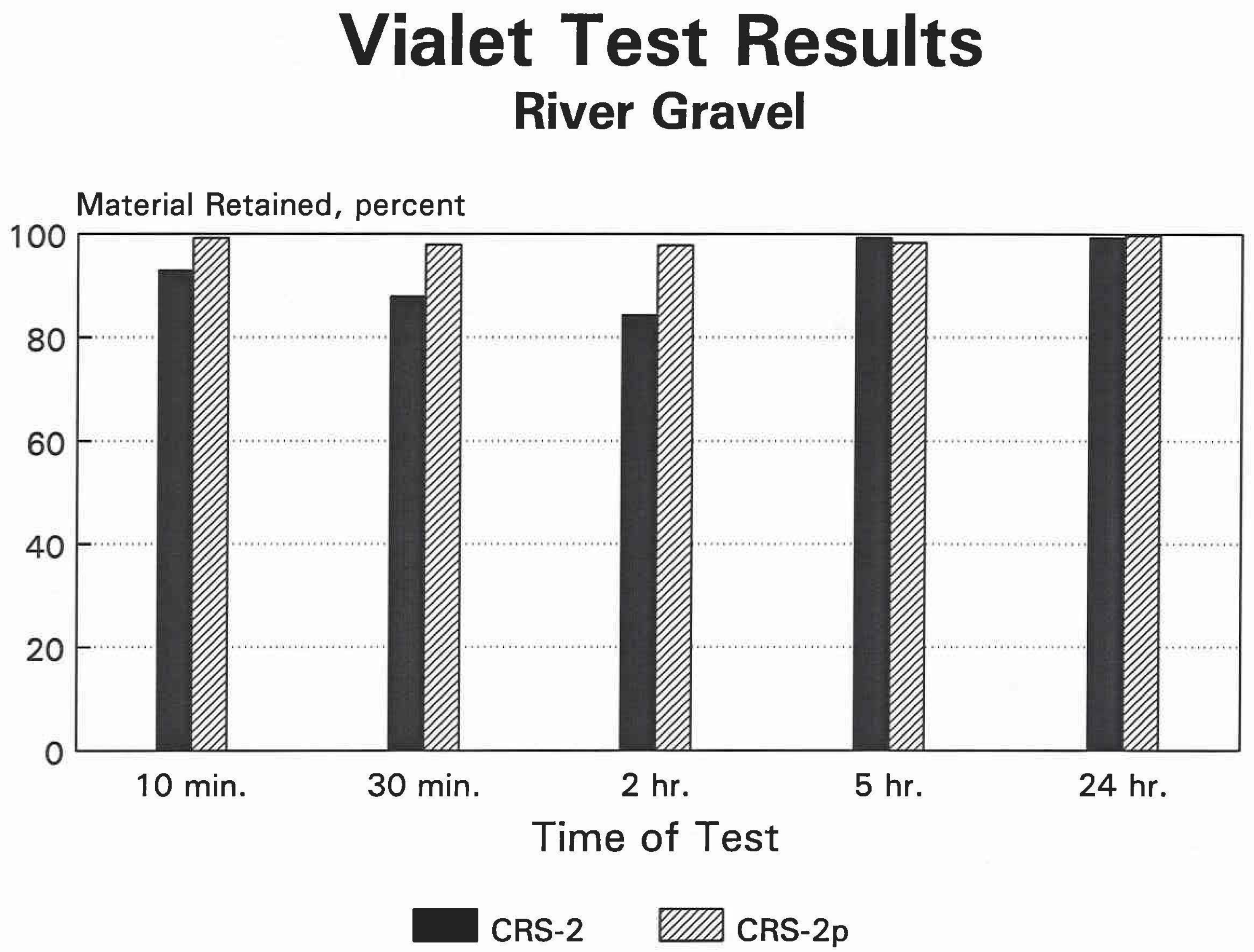


Figure 31. Vialet Test Results for CRS-2 and CRS-2p Samples Made with River Gravel Aggregate.

be monitored with time, it would provide an indication of the curing rate of the binder. This viscosity was measured in this study using the Sliding Plate Microviscometer (ASTM D3570-77) (13).

Testing Procedure

An asphalt emulsion chip seal was made in the laboratory in a six-inch diameter pan. Two replicate samples were tested of CRS-2 and limestone. The chip seal was allowed to cure under heat lamps such that the temperature of the chip seal surface was 120°F. Throughout the curing process, tiny samples of binder were taken from between the stones and tested using the Sliding Plate Microviscometer.

A film of binder, 50 μm thick, was placed between two matched glass plates. One of a pair of the plates was clamped to the viscometer frame and the other to a device for adding the load. Five different loadings were used and the displacement rate recorded for the movable plate. Data developed permitted calculation of viscosity. The test was performed at 77°F.

Discussion of Results

The results of these tests are shown in Figure 32. As expected, the viscosity of the binder increases with time. However, there seems to be some variability in the data as is shown in Figure 32.

Time did not permit a thorough investigation of this test as a suitable method for determining the curing rate of emulsions; however, the data indicate that the test procedure may have the potential to indicate curing rate of emulsions.

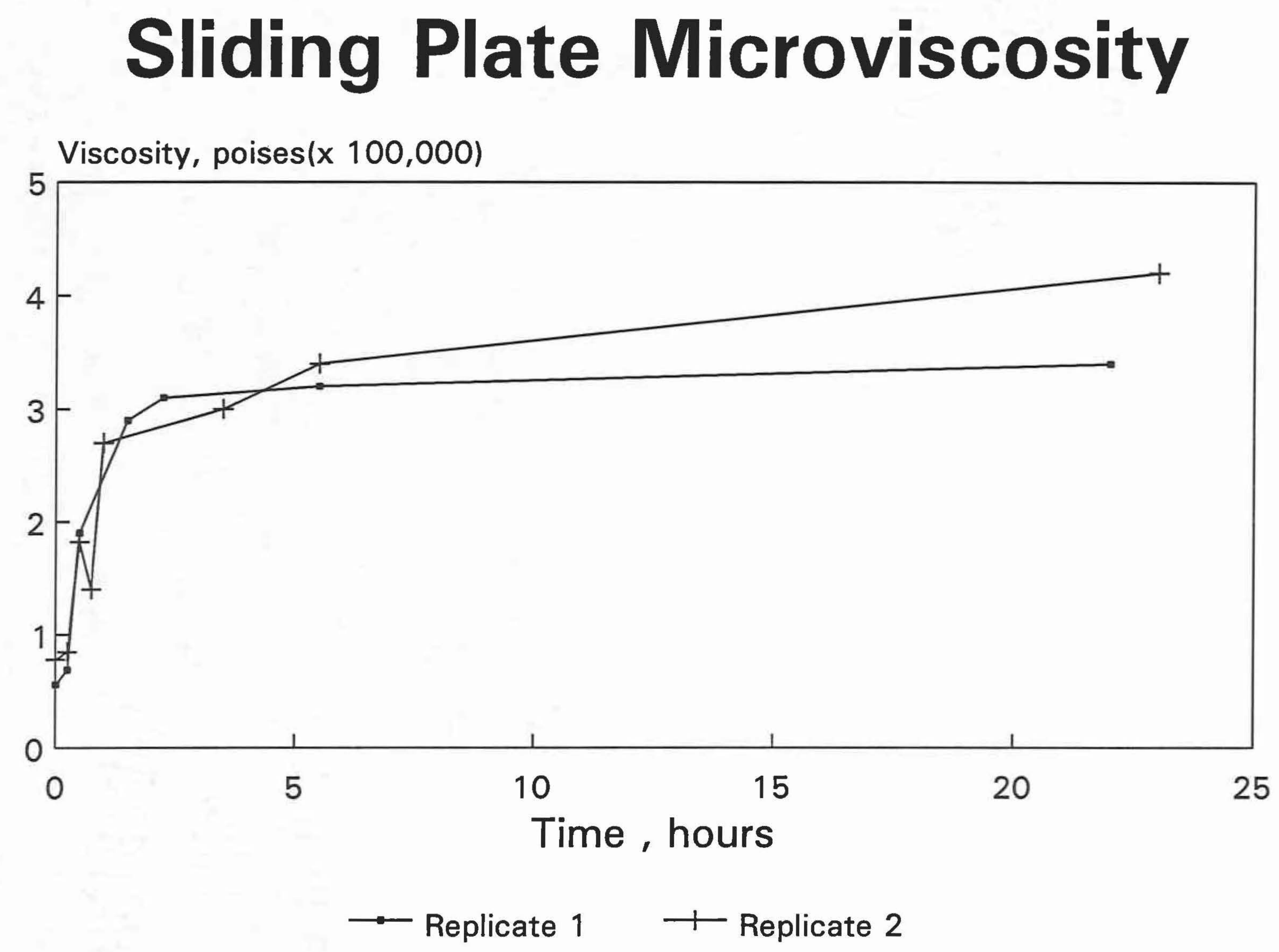


Figure 32. Sliding Plate Microviscosity Results for CRS-2/Limestone Chip Seal Samples.

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10. "Pavement Evaluation", Phase I. Pavement Evaluation Equipment-Federal Highway Administration Final Report No. FHWA-RD-75-78, Contract No. DOT-FH-8264.

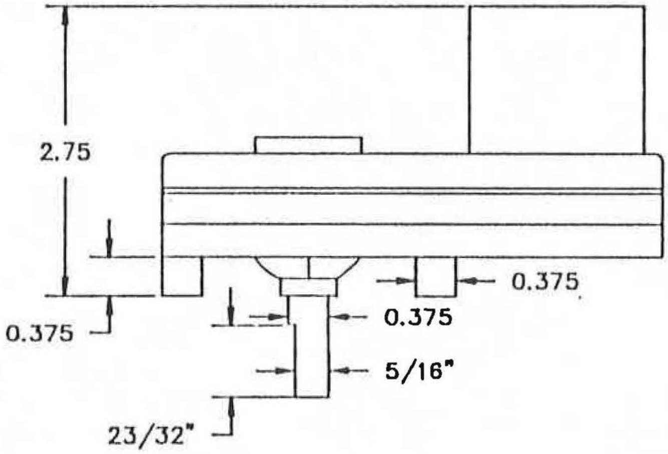
11. Annual Book of ASTM Standards, "Standard Practices for Design, Testing, and Construction of Slurry Seal," Test Designation ASTM D3910-84,1 American Society for Testing and Materials, 1990.

12. "Standard Specifications for Construction of Highways, Streets and Bridges," Texas State Department of Highways and Public Transportation, 1982.

13. Annual Book of ASTM Standards, "Standard Test Method for Viscosity of Materials with a Sliding Plate Microviscometer," Test Designation ASTM D 3570-77, American Society for Testing and Materials, 1977.

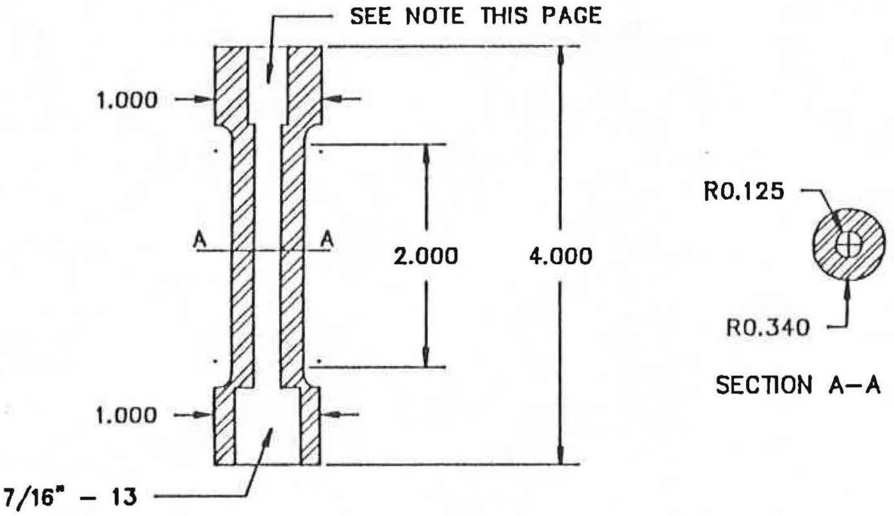
APPENDIX A

DETAILS OF TTI COHESION TEST APPARATUS



MANUFACTURER: DAYTON
MODEL: 3M104
SPEED: 6 RPM
MAX TORQUE: 120 IN-LB
INPUT POWER: 1/60 HP
115 VOLTS
60 HZ
1.65 AMPS

MOTOR

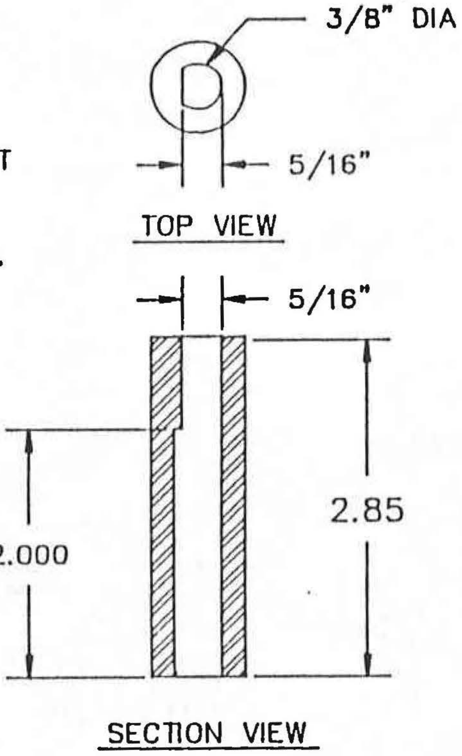


NOTES:
1. ALL DIMENSIONS SHOWN MUST BE MAINTAINED.
2. ALL DIMINSIONS NOT SHOWN DEPEND UPON CONNECTIONS.
3. UNITS ARE IN INCHES.
4. ALUMINUM 6061-T6.

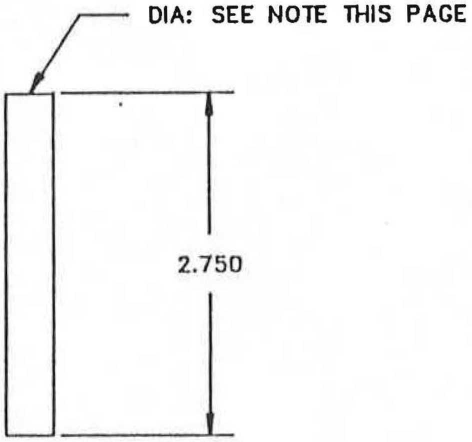
TORQUE SENSOR

NOTES:

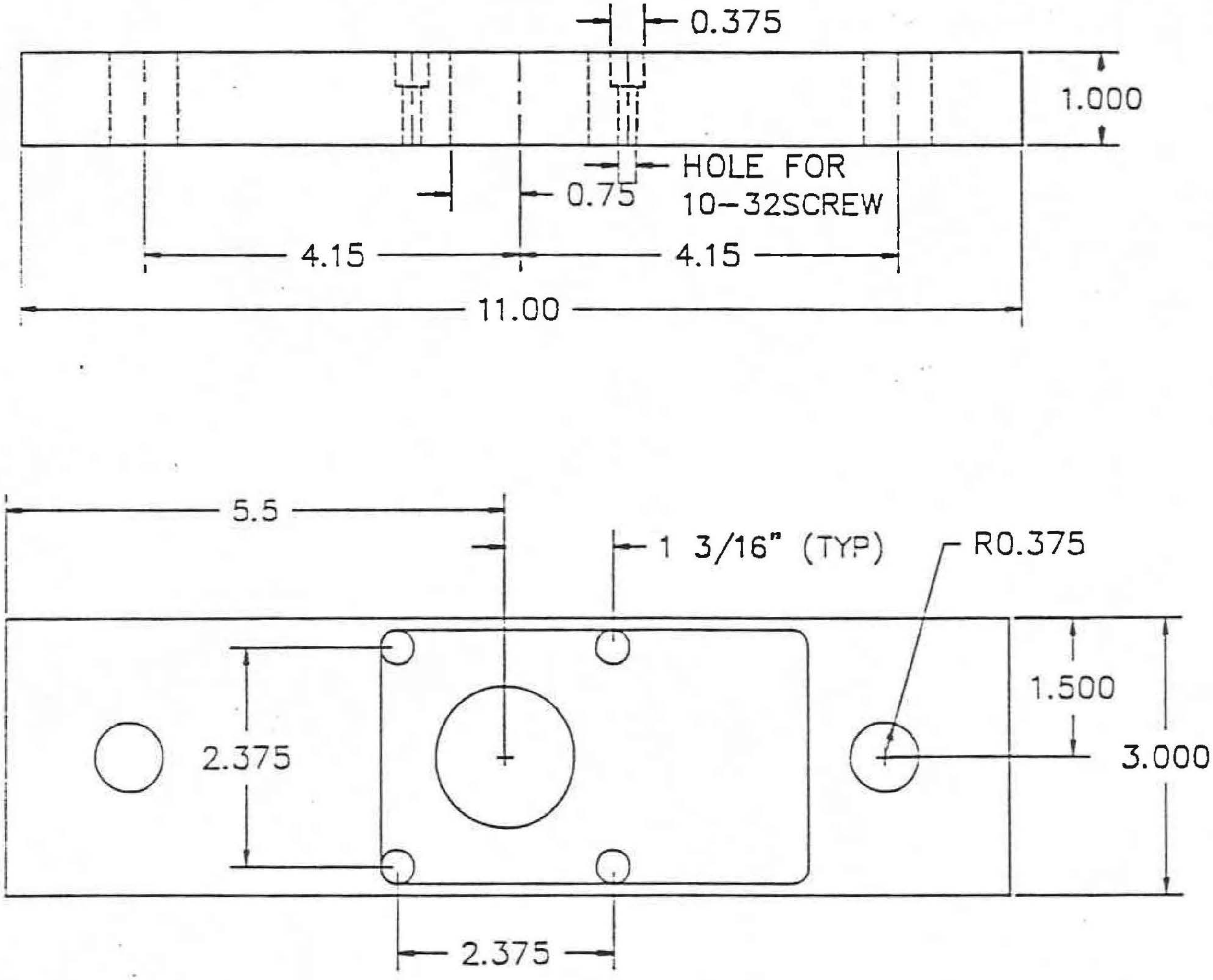
1. ALL DIMENSIONS SHOWN MUST BE MAINTAINED.
2. ALL DIMINSIONS NOT SHOWN DEPEND UPON CONNECTIONS.
3. UNITS ARE IN INCHES.
4. ALUMINUM 6061-T6.



FEMALE CONNECTOR

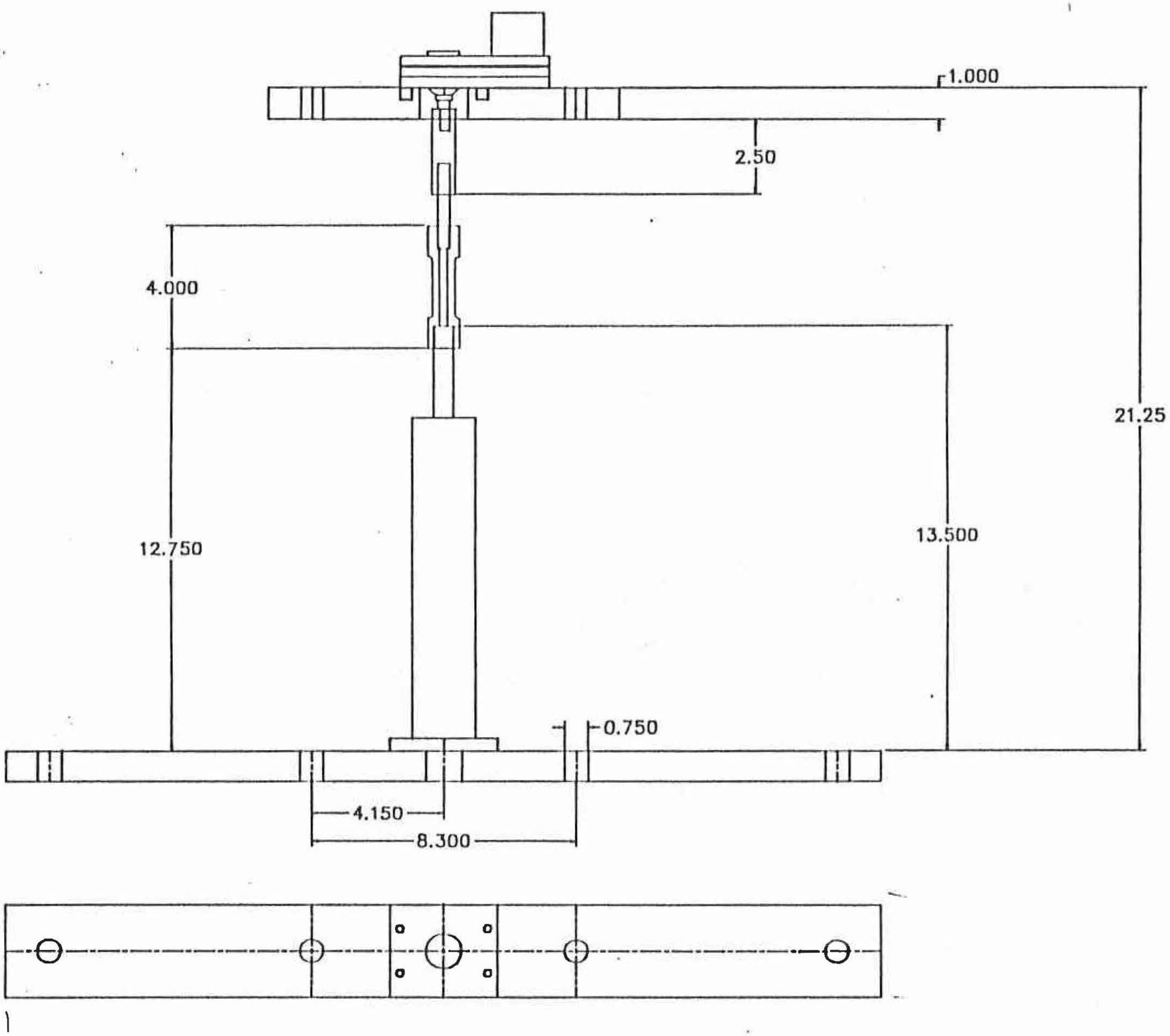


MALE CONNECTOR



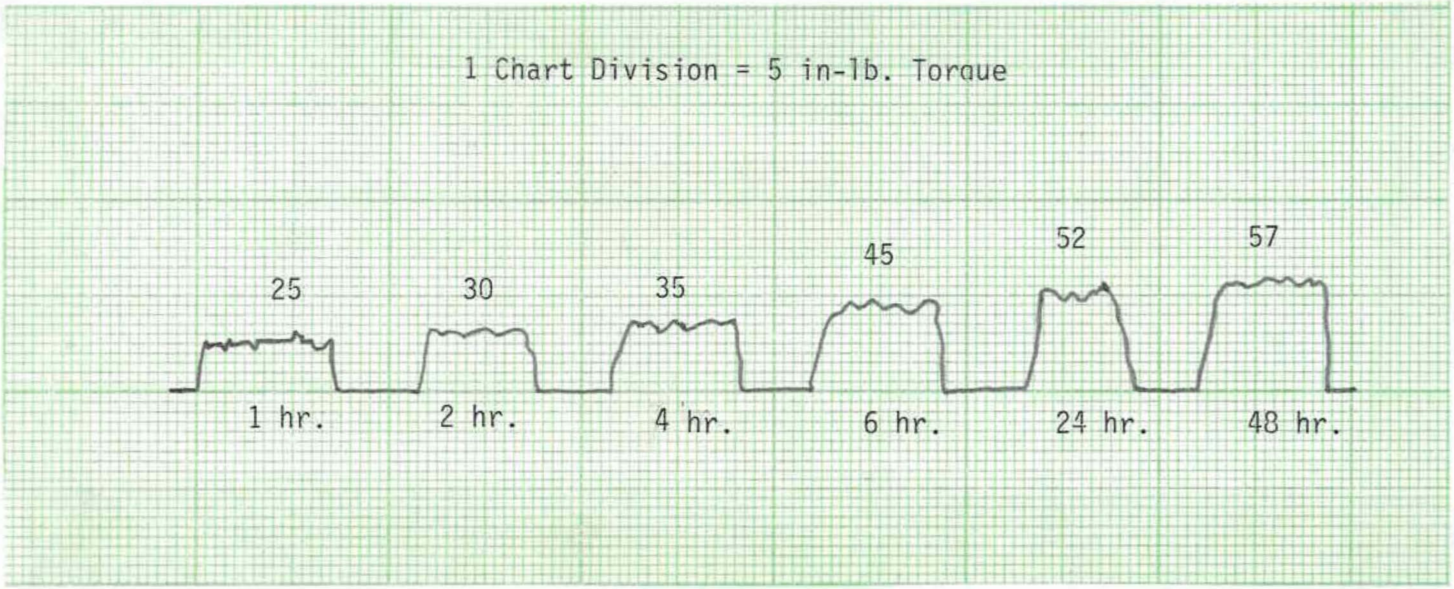
NOTES:
1. MOUNT GEARMOTOR TO FLAT SURFAC
   USING (4) 10–32 SCREWS.
2. USE ALUM 6061–T6.
3. ALL WORK DIMENSIONS SHALL BE
   MEASURED FROM CENTERLINE.

METAL PLATE FOR MOUNTING GEARMOTOR


1.000
2.50
4.000
21.25
13.500
12.750
0.750
4.150
8.300

COST ESTIMATE FOR COHESION TESTER

ITEM		COST
General Parts		$ 715.00
Regulator		150.00
Air Filter		90.00
Pneumatic Cylinder		100.00
Torque Motor		130.00
Calibration Box		600.00
Transducer		250.00
Plotter		925.00
Machining	30 hr. @ &50/hr.	1500.00
	Total	$4460.00



EXAMPLE PRINTOUT FROM STRIP-CHART RECORDER
FOR COHESION TEST

APPENDIX B

COHESION TEST DATA

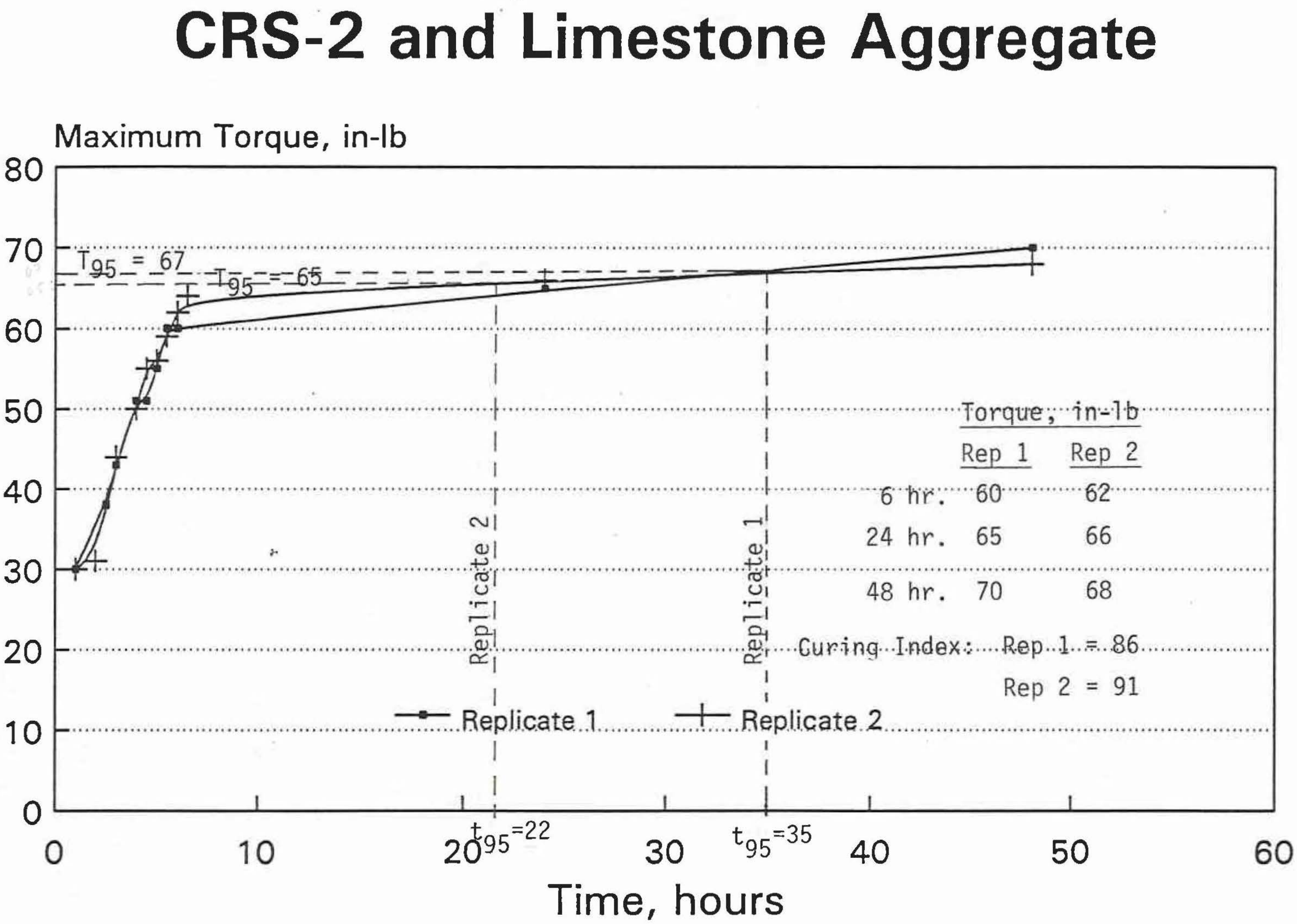


Figure B1. Cohesion Test Results for CRS-2 Emulsion and Limestone Aggregate.

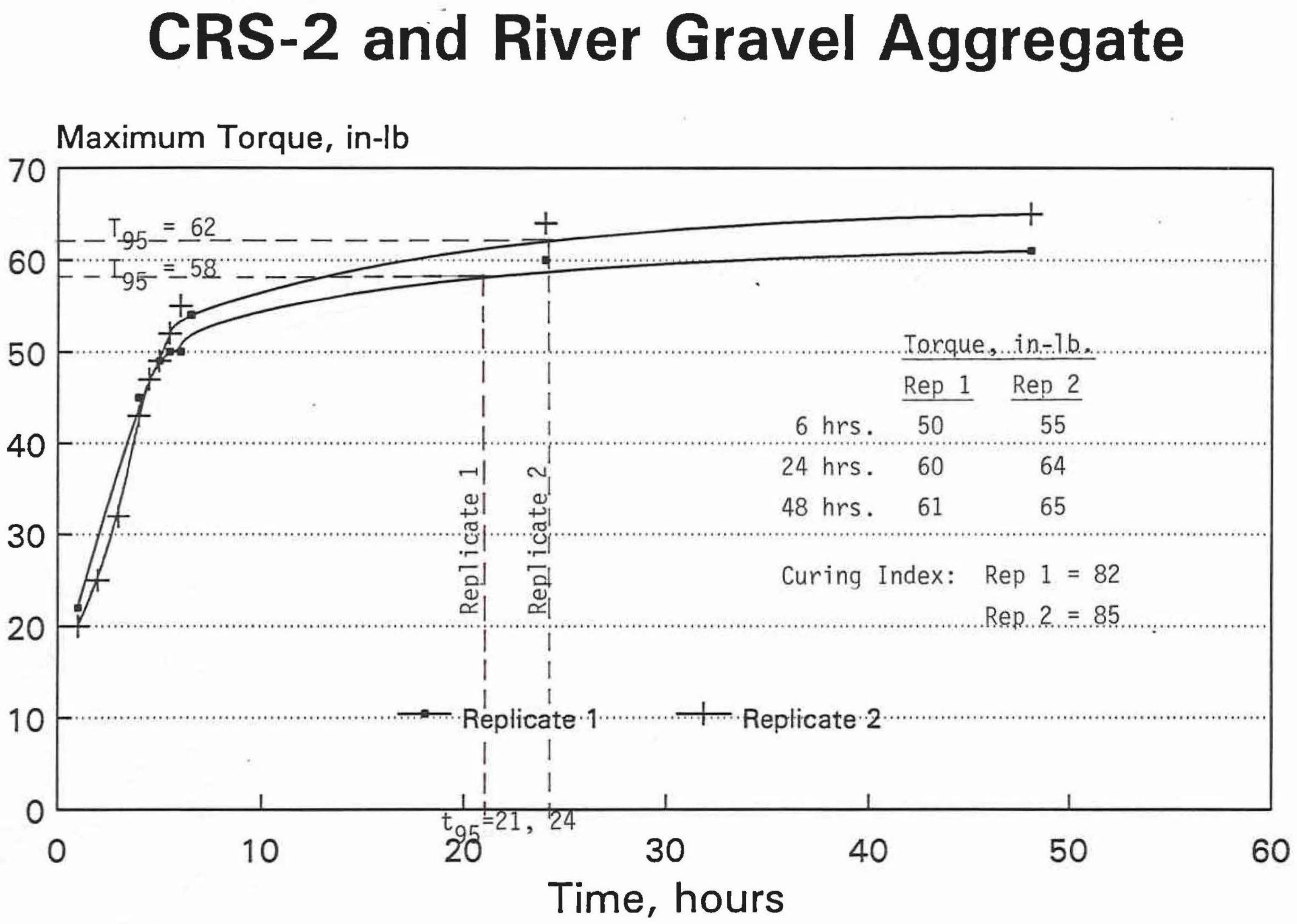
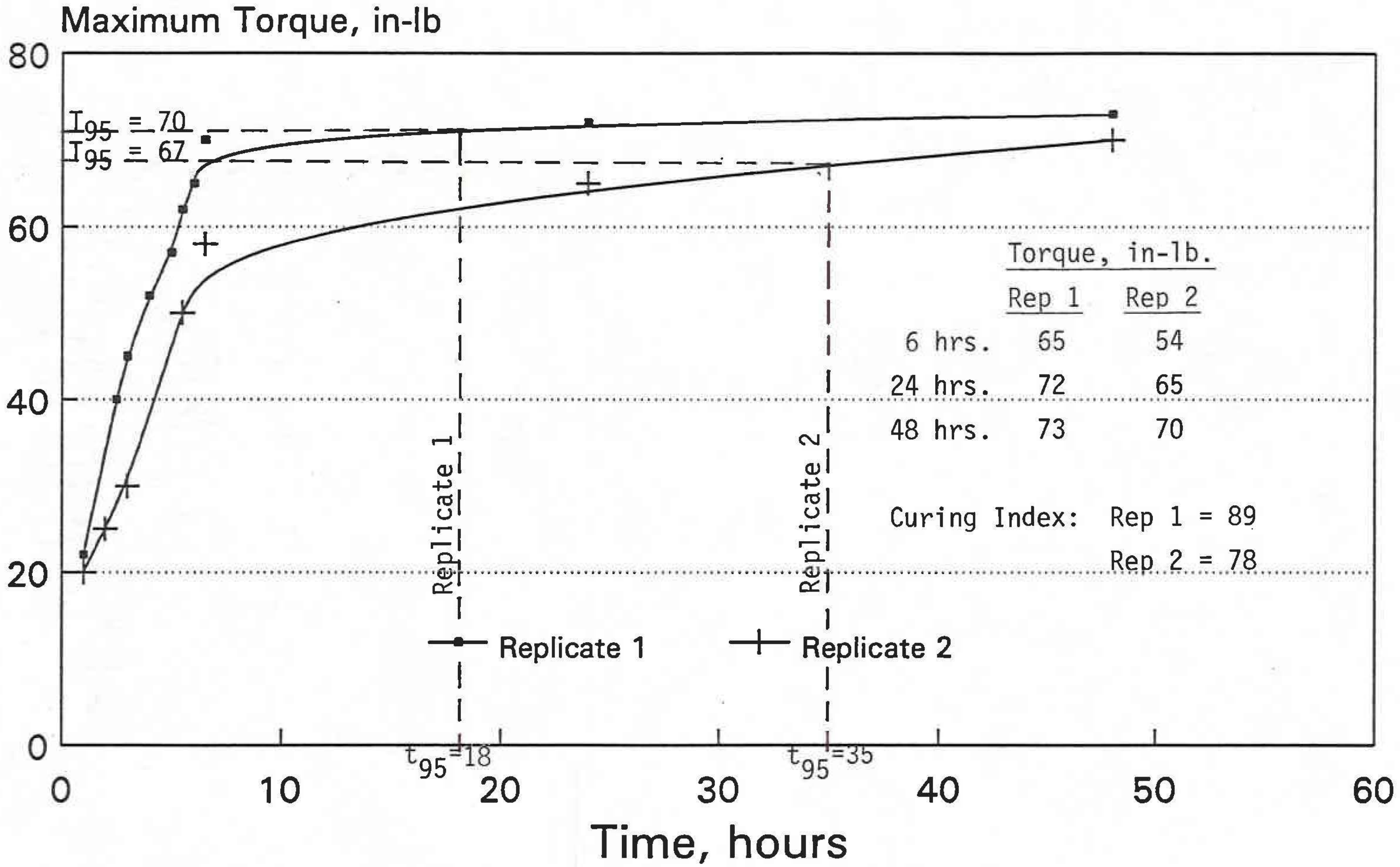


Figure B2. Cohesion Test Results for CRS-2 Emulsion and River Gravel Aggregate.

CRS-2 and Lightweight Aggregate



	Torque, in-lb.	
	Rep 1	Rep 2
6 hrs.	65	54
24 hrs.	72	65
48 hrs.	73	70

Curing Index: Rep 1 = 89
Rep 2 = 78

Figure B3. Cohesion Test Results for CRS-2 Emulsion and Lightweight Aggregate.

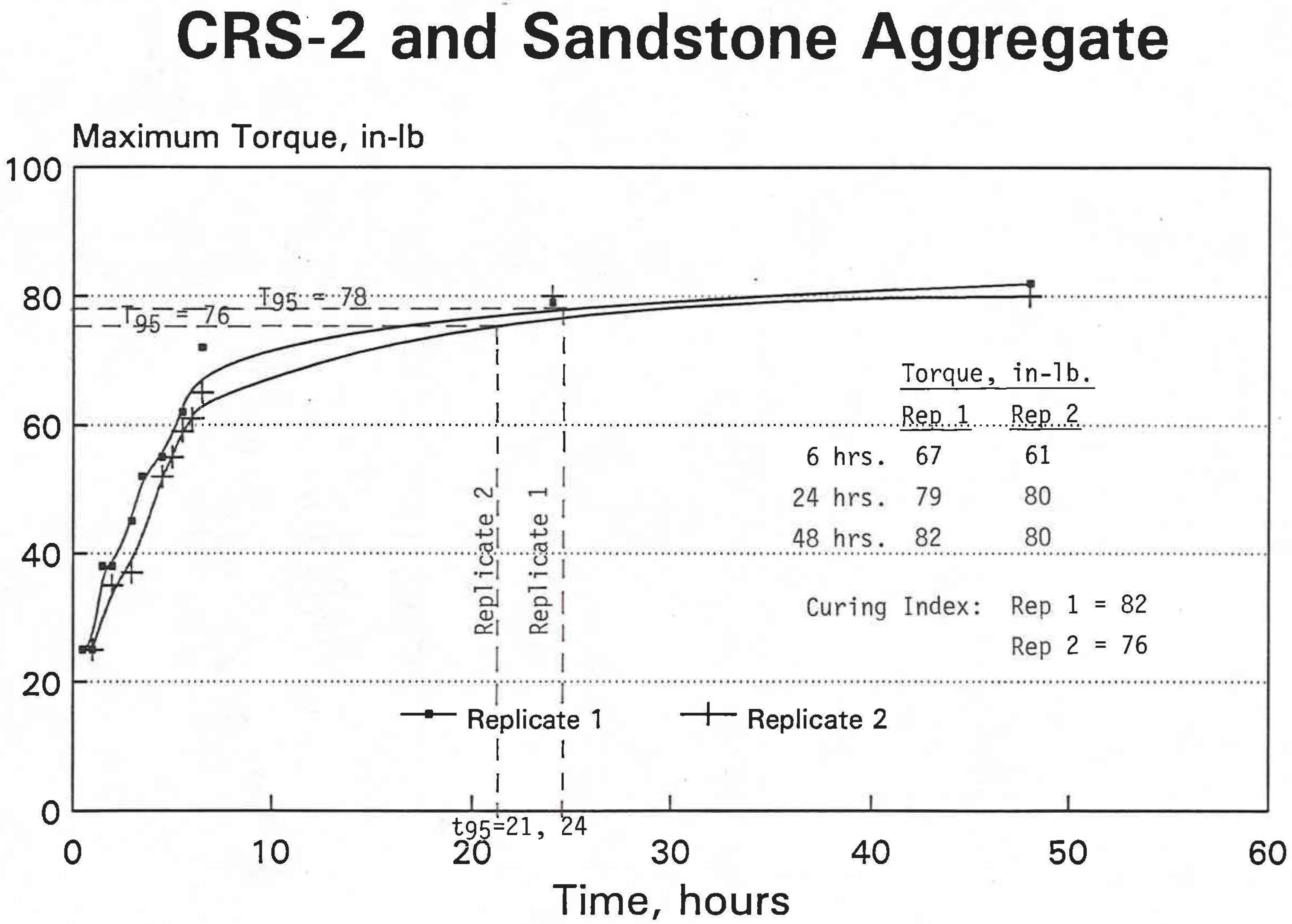


Figure B4. Cohesion Test Results for CRS-2 Emulsion and Sandstone Aggregate.

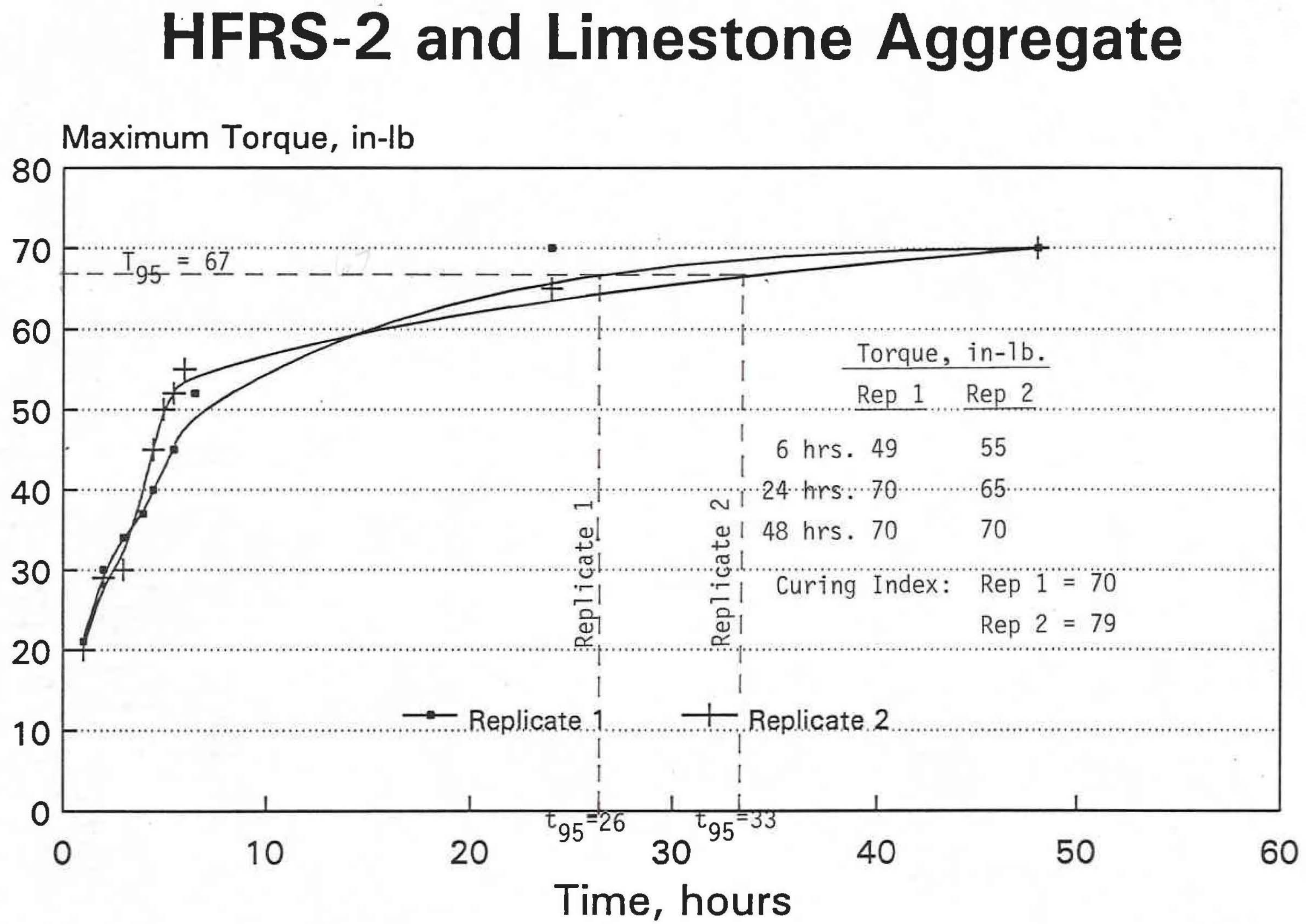
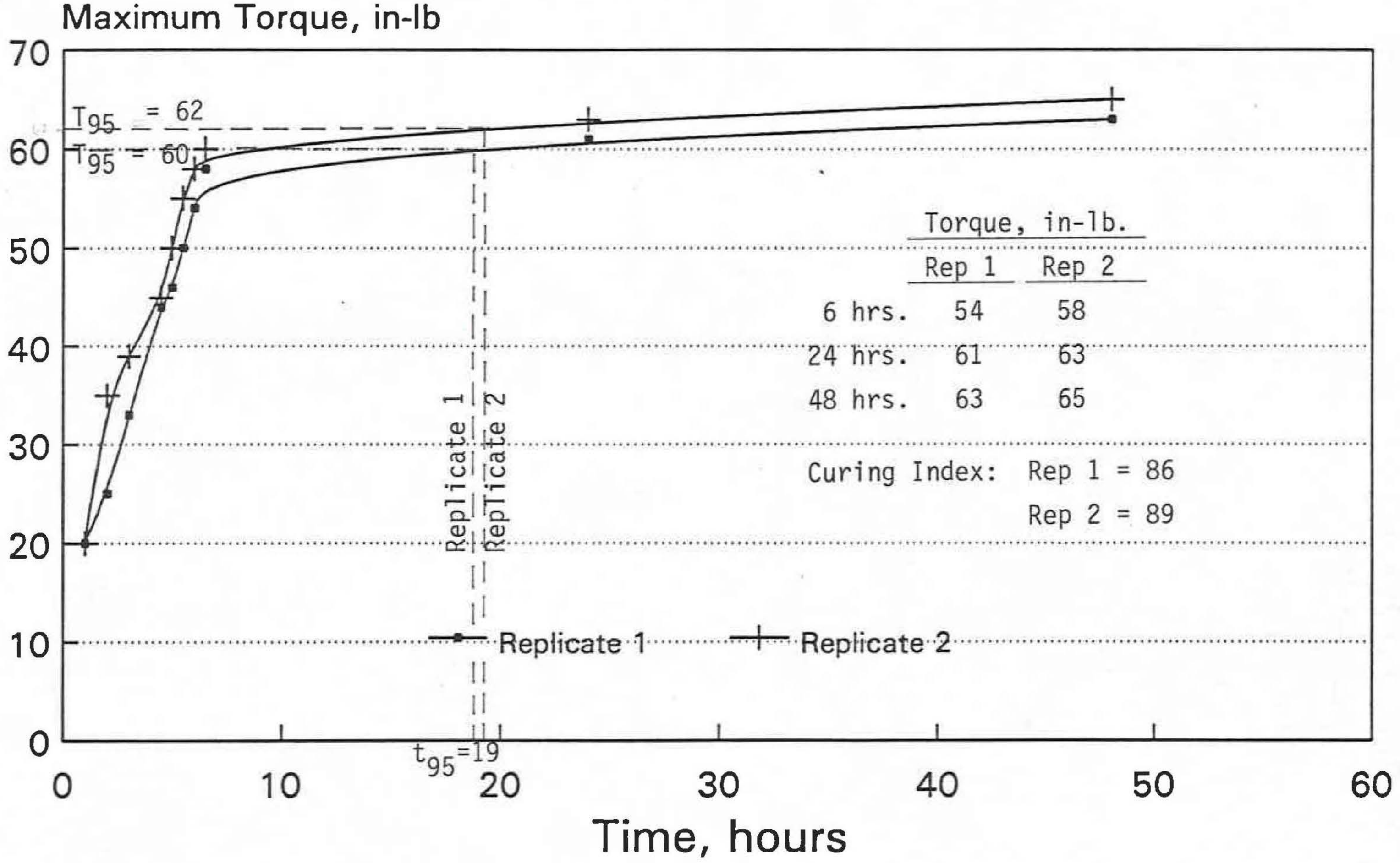


Figure B5. Cohesion Test Results for HFRS-2 Emulsion and Limestone Aggregate.

HFRS-2 and River Gravel Aggregate



	Torque, in-lb.	
	Rep 1	Rep 2
6 hrs.	54	58
24 hrs.	61	63
48 hrs.	63	65

Curing Index: Rep 1 = 86
Rep 2 = 89

Figure B6. Cohesion Test Results for HFRS-2 Emulsion and River Gravel Aggregate.

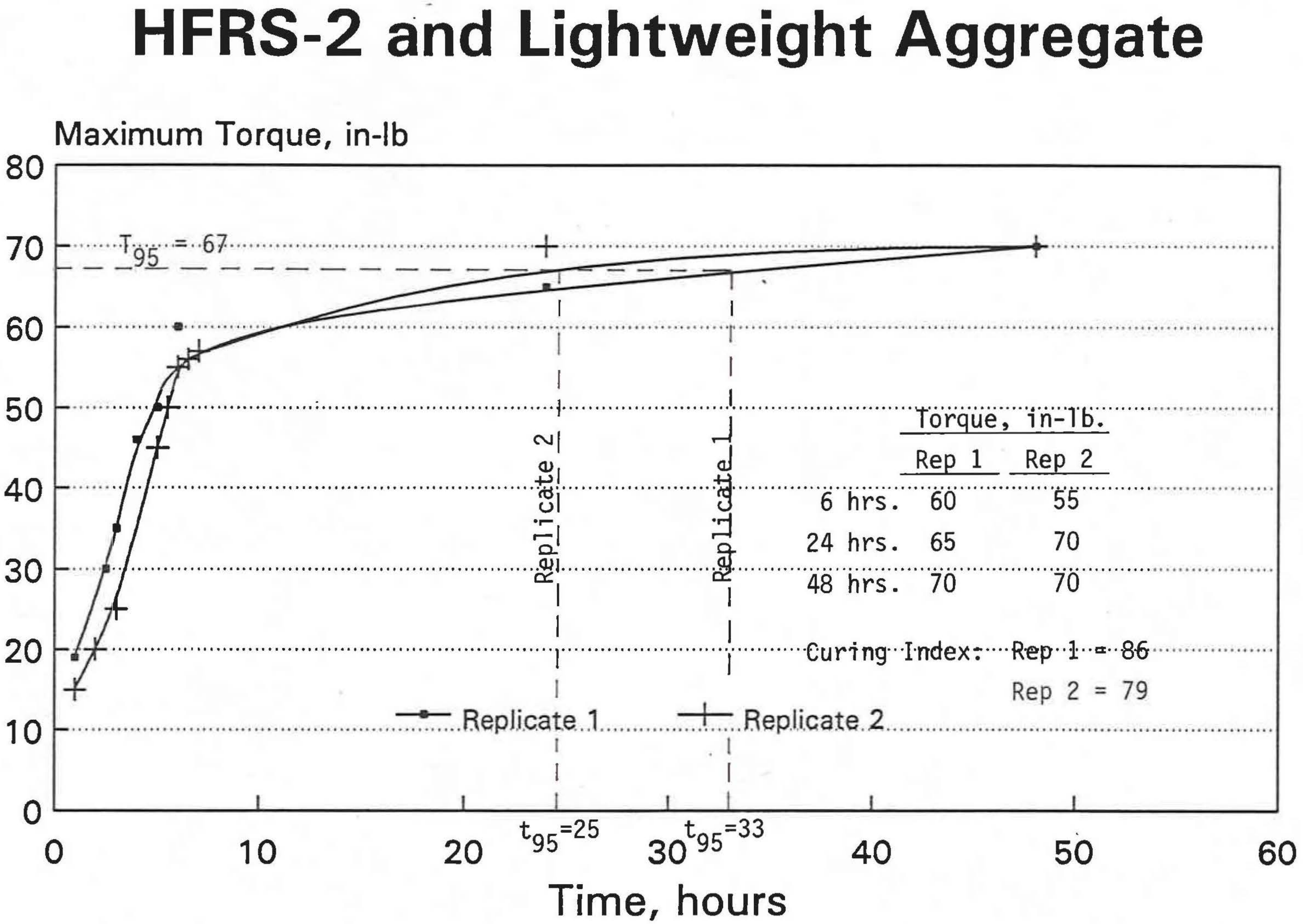
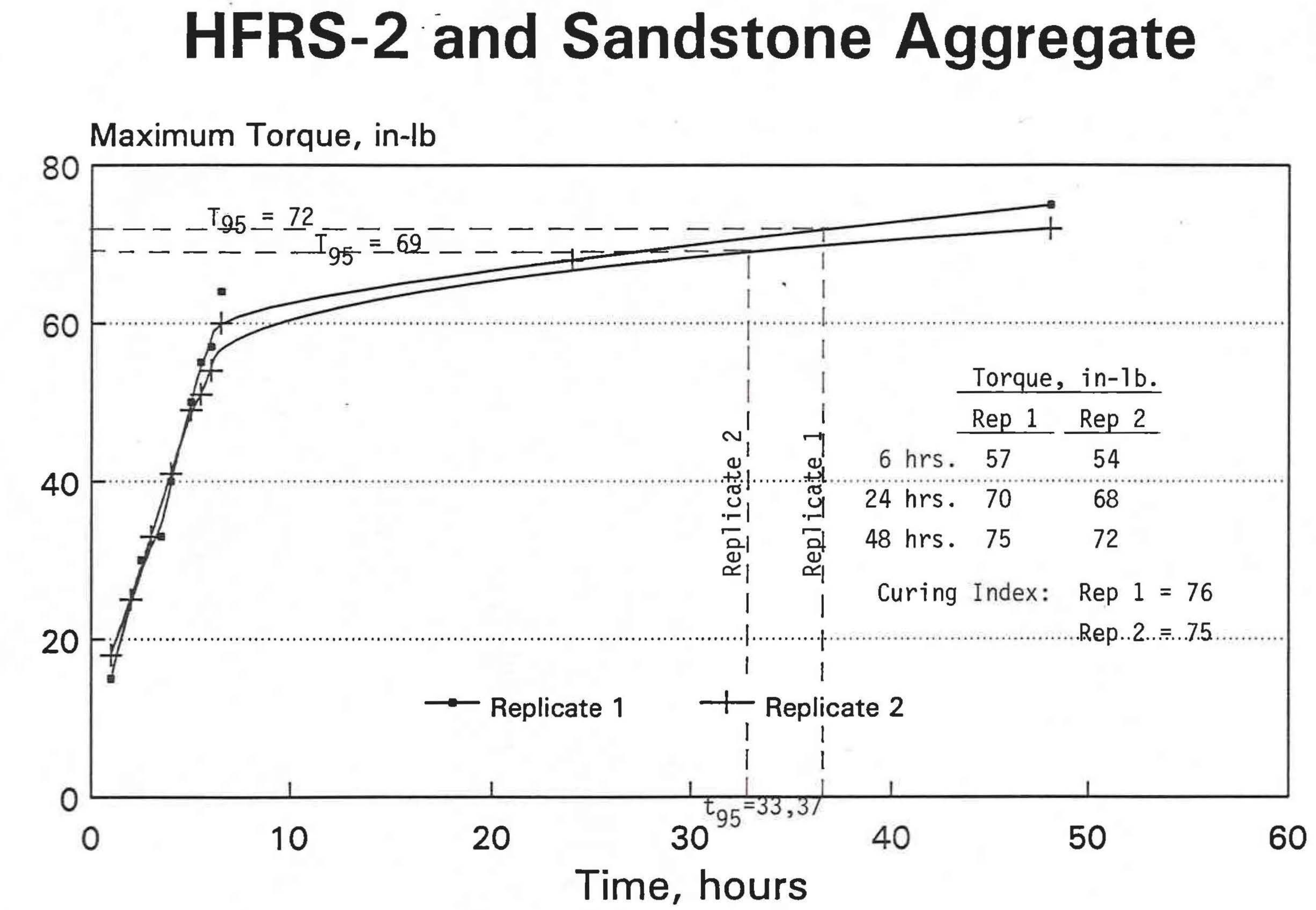


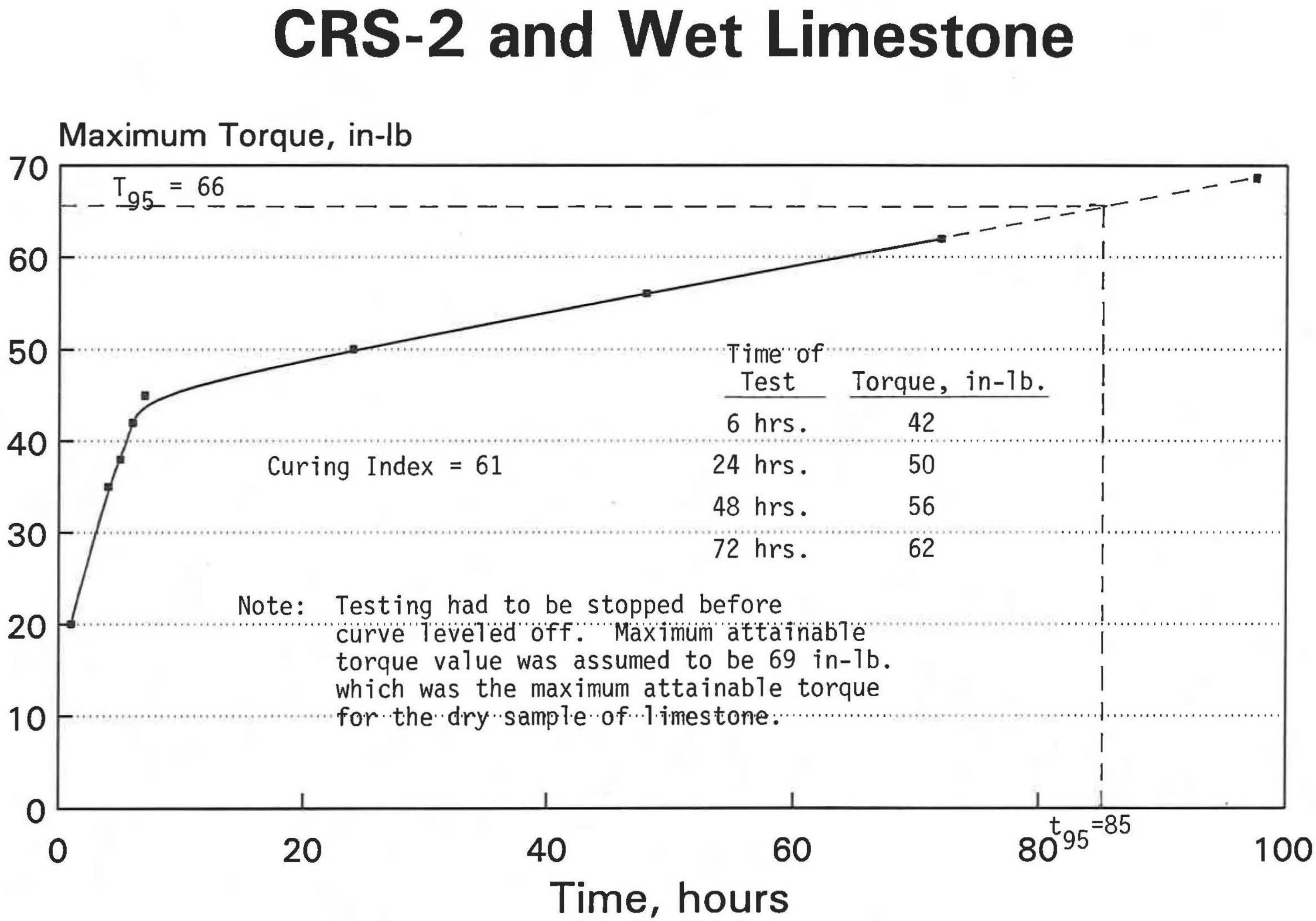
Figure B7. Cohesion Test Results for HFRS-2 Emulsion and Lightweight Aggregate.



	Torque, in-lb.	
	Rep 1	Rep 2
6 hrs.	57	54
24 hrs.	70	68
48 hrs.	75	72

Curing Index: Rep 1 = 76
Rep 2 = 75

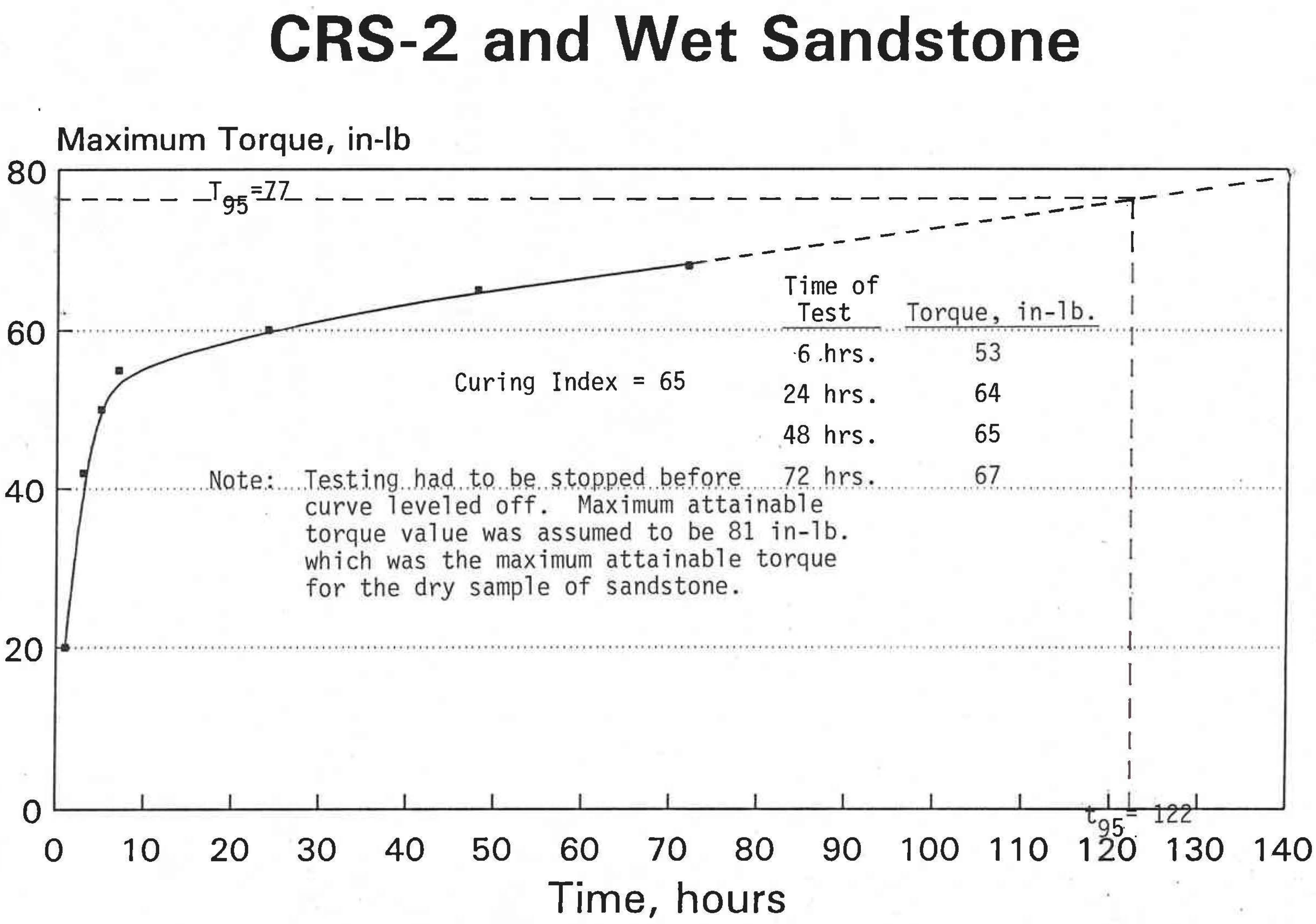
Figure B8. Cohesion Test Results for HFRS-2 Emulsion and Sandstone Aggregate.



Time of Test	Torque, in-lb.
6 hrs.	42
24 hrs.	50
48 hrs.	56
72 hrs.	62

Note: Testing had to be stopped before curve leveled off. Maximum attainable torque value was assumed to be 69 in-lb. which was the maximum attainable torque for the dry sample of limestone.

Figure B9. Cohesion Test Results for CRS-2 Emulsion and Wet (SSD) Limestone Aggregate.

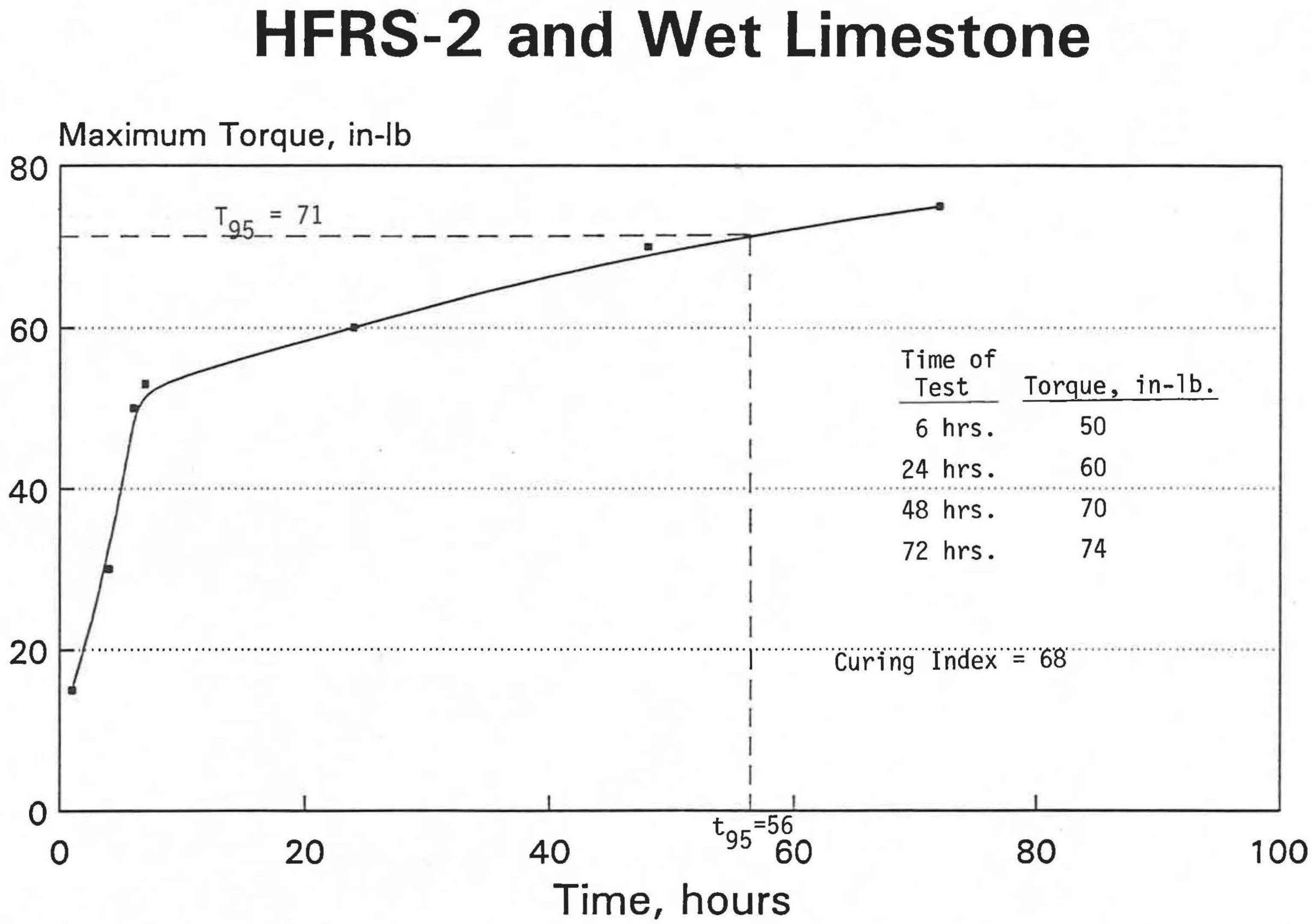


Curing Index = 65

Time of Test	Torque, in-lb.
6 hrs.	53
24 hrs.	64
48 hrs.	65
72 hrs.	67

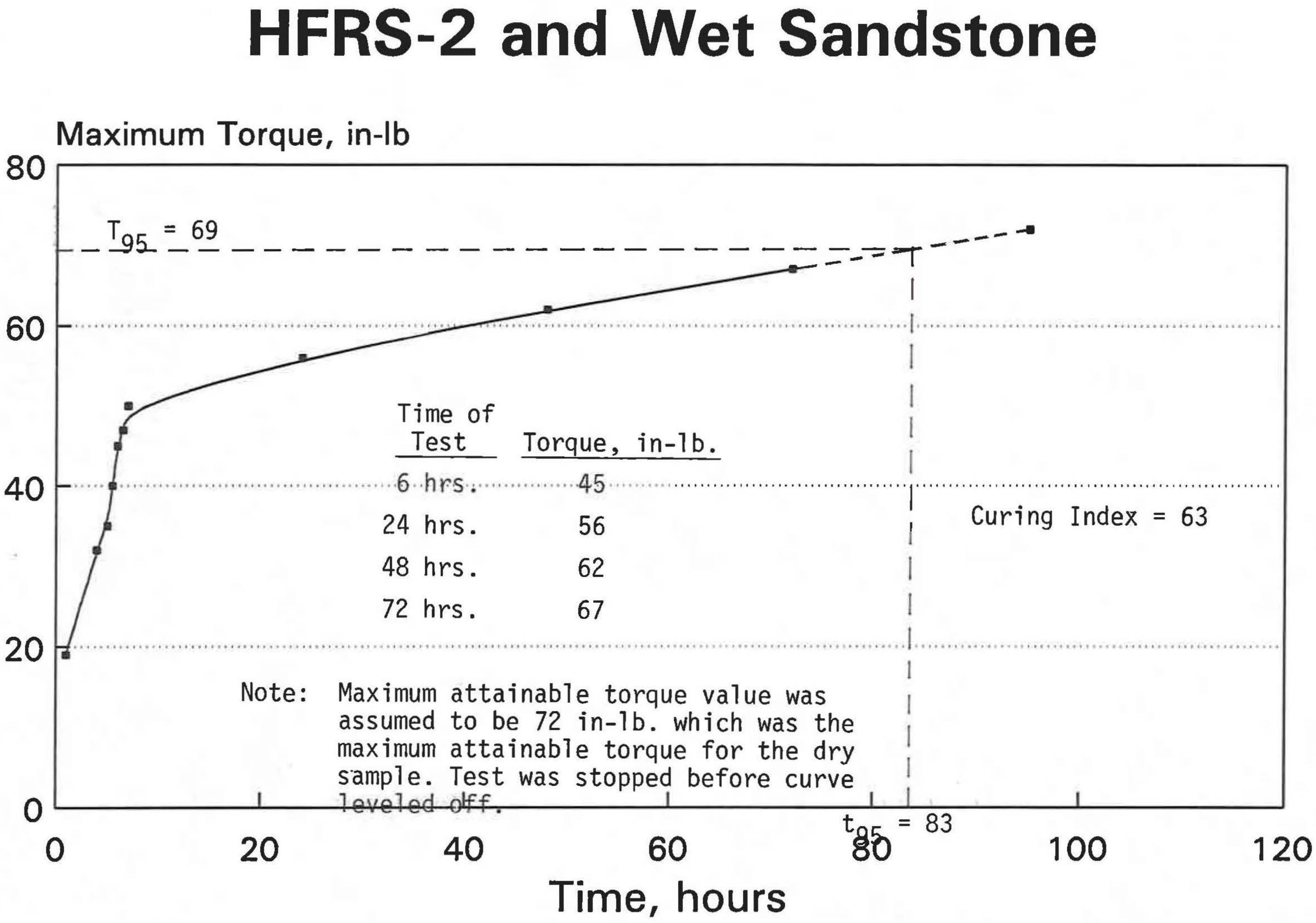
Note: Testing had to be stopped before curve leveled off. Maximum attainable torque value was assumed to be 81 in-lb. which was the maximum attainable torque for the dry sample of sandstone.

Figure B10. Cohesion Test Results for CRS-2 Emulsion and Wet (SSD) Sandstone Aggregate.



Time of Test	Torque, in-lb.
6 hrs.	50
24 hrs.	60
48 hrs.	70
72 hrs.	74

Figure B11. Cohesion Test Results for HFRS-2 Emulsion and Wet (SSD) Limestone Aggregate.



Time of Test	Torque, in-lb.
6 hrs.	45
24 hrs.	56
48 hrs.	62
72 hrs.	67

Note: Maximum attainable torque value was assumed to be 72 in-lb. which was the maximum attainable torque for the dry sample. Test was stopped before curve leveled off.

Figure B12. Cohesion Test Results for HFRS-2 Emulsion and Wet (SSD) Sandstone Aggregate.

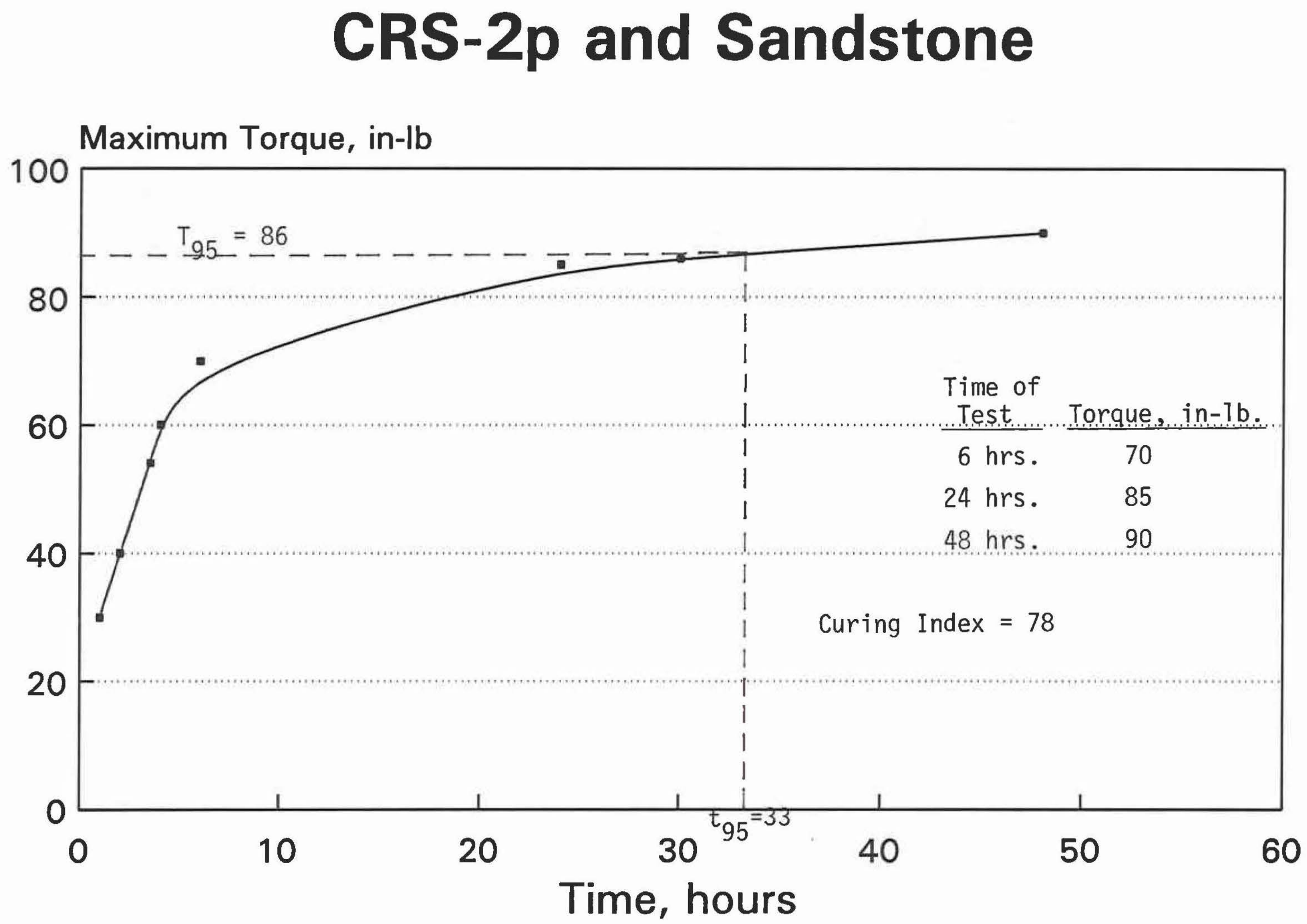
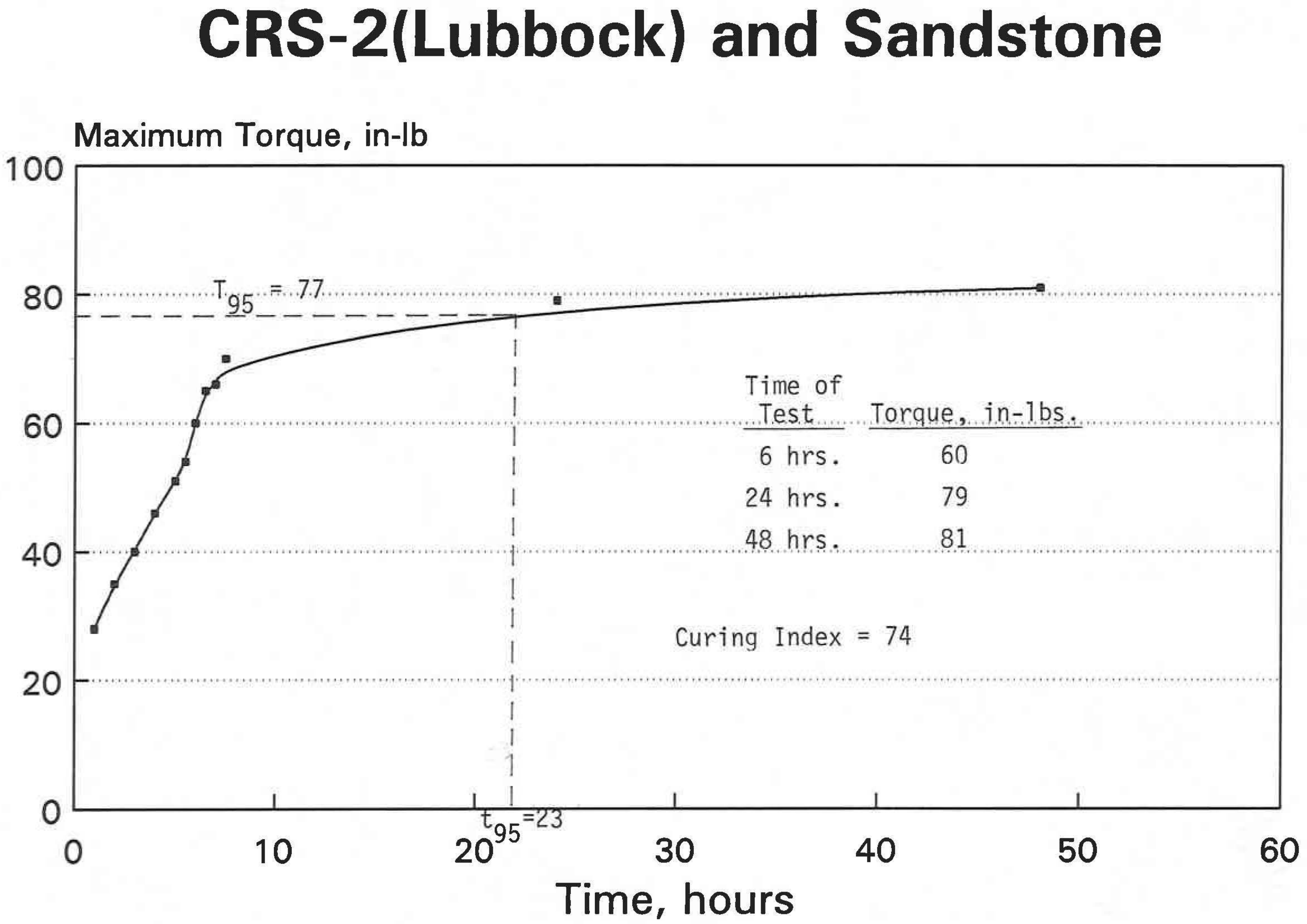
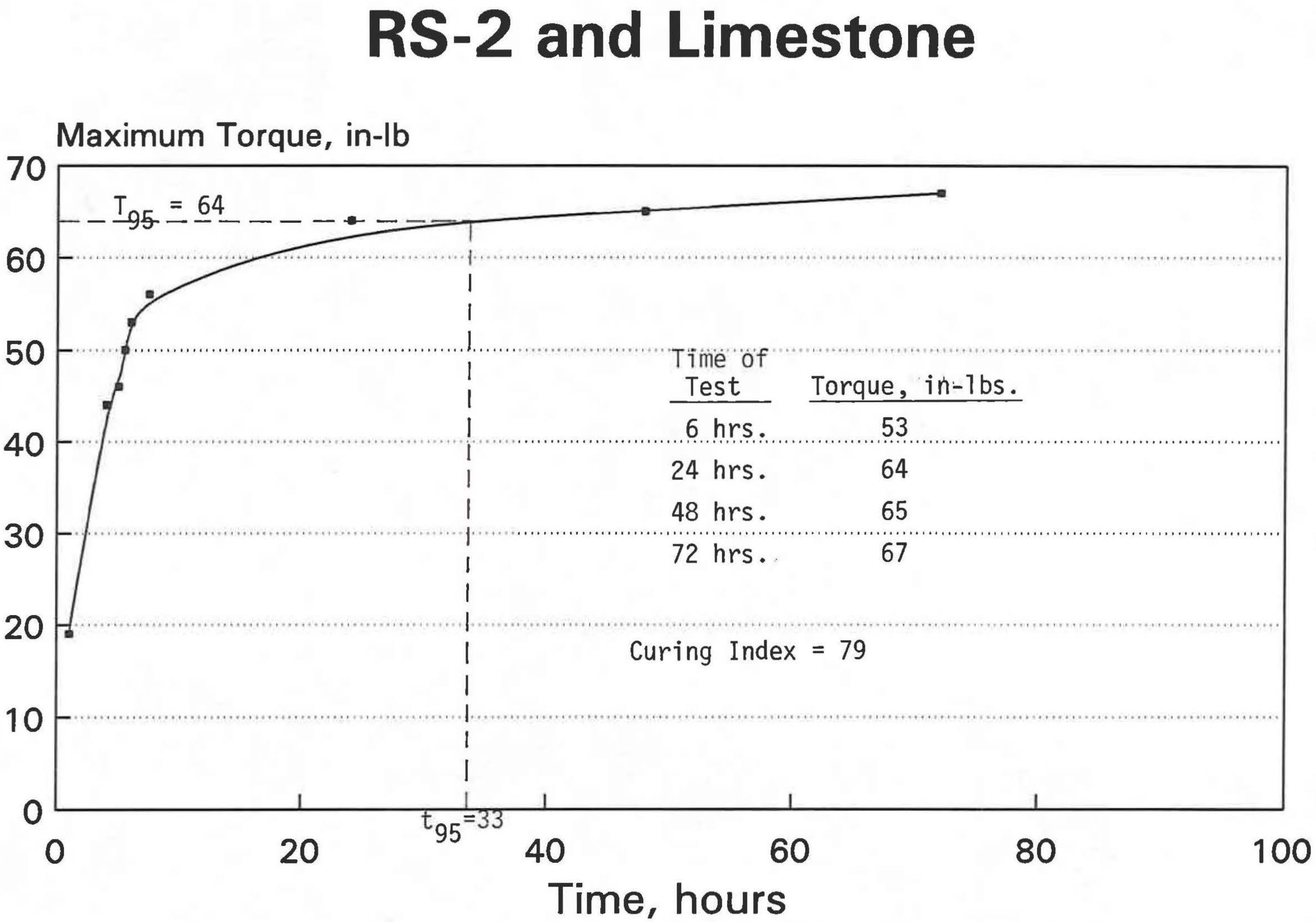


Figure B13. Cohesion Test Results for CRS-2p Emulsion and Sandstone Aggregate.



Time of Test	Torque, in-lbs.
6 hrs.	60
24 hrs.	79
48 hrs.	81

Figure B14. Cohesion Test Results for CRS-2 (Lubbock) Emulsion and Sandstone Aggregate.



Time of Test	Torque, in-lbs.
6 hrs.	53
24 hrs.	64
48 hrs.	65
72 hrs.	67

Curing Index = 79

Figure B15. Cohesion Test Results for RS-2 Emulsion and Limestone Aggregate.

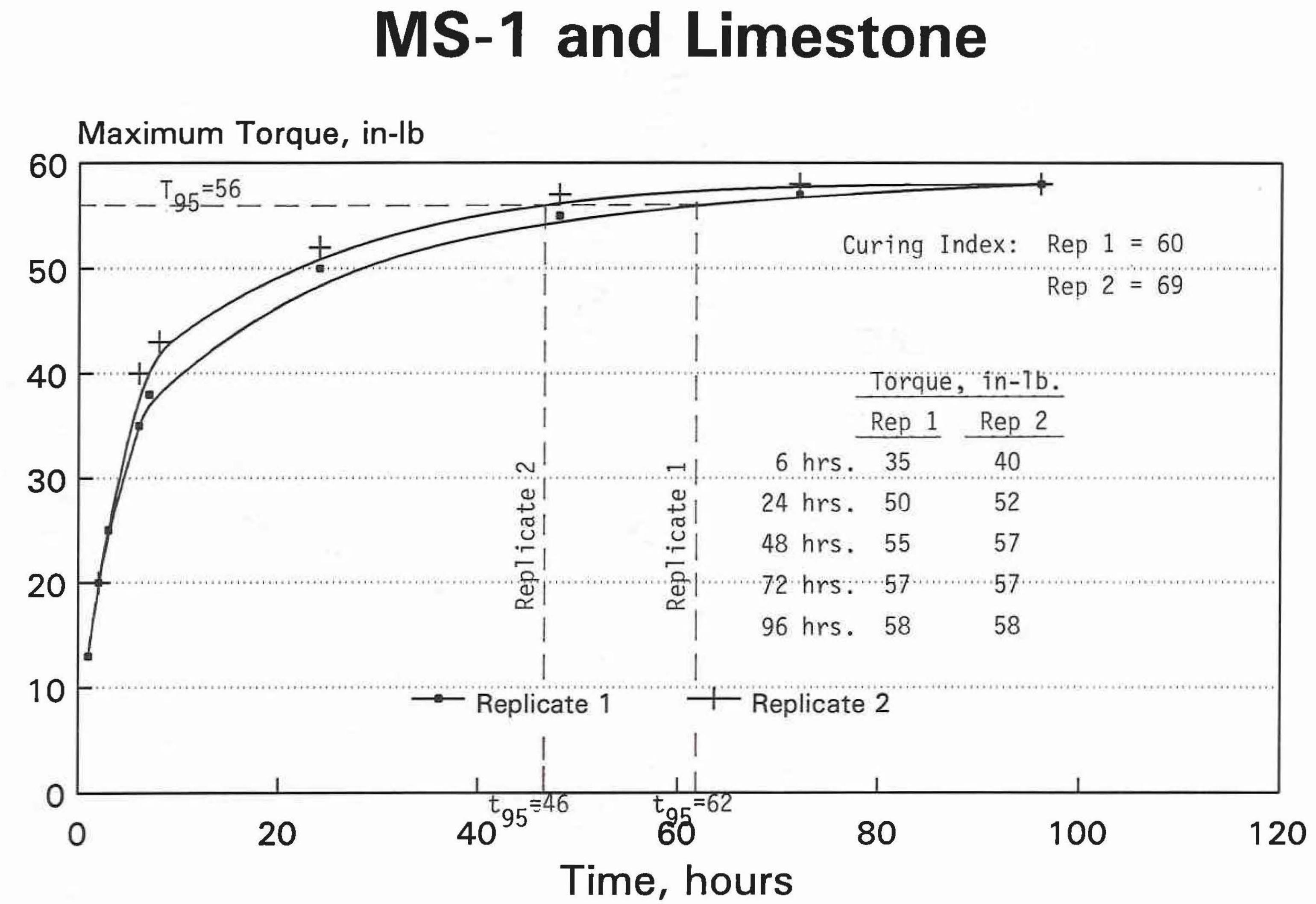


Figure B16. Cohesion Test Results for MS-1 Emulsion and Limestone Aggregate.

APPENDIX C

STATISTICAL ANALYSES OF DATA

```
                       Analysis of Variance for Torque6
--------------------------------------------------------------------------------
Source of variation    Sum of Squares   d.f.   Mean square   F-ratio   Sig. level
--------------------------------------------------------------------------------
MAIN EFFECTS               133.50000      4     33.375000     1.963      .1934
  EMULSION                  64.00000      1     64.000000     3.765      .0883
  AGGREGATE                 69.50000      3     23.166667     1.363      .3219

2-FACTOR INTERACTIONS      105.50000      3     35.166667     2.069      .1829
  EMULSION  AGGREGATE      105.50000      3     35.166667     2.069      .1829

RESIDUAL                   136.00000      8     17.000000

TOTAL (CORR.)              375.00000     15
--------------------------------------------------------------------------------
0 missing values have been excluded.


                Multiple range analysis for Torque6 by EMULSION
--------------------------------------------------------------------------------
Method: 95 Percent Scheffe
Level      Count         Average    Homogeneous Groups
--------------------------------------------------------------------------------
HFRS-2        8       55.250000     *
CRS-2         8       59.250000     *
--------------------------------------------------------------------------------


                Multiple range analysis for Torque6 by AGGREGATE
--------------------------------------------------------------------------------
Method: 95 Percent Scheffe
Level      Count         Average    Homogeneous Groups
--------------------------------------------------------------------------------
River Gr      4       54.250000     *
Limeston      4       56.500000     *
Lightwei      4       58.500000     *
Sandston      4       59.750000     *
--------------------------------------------------------------------------------
```

Table C1. Analysis of Variance and Multiple Range Tests for Cohesion Test Torque Values at 6 Hours.

```
                      Analysis of Variance for Torque24
--------------------------------------------------------------------------------
Source of variation    Sum of Squares   d.f.    Mean square   F-ratio   Sig. level
--------------------------------------------------------------------------------
MAIN EFFECTS                330.25000     4       82.56250     10.568       .0028
  EMULSION                   22.56250     1       22.56250      2.888       .1277
  AGGREGATE                 307.68750     3      102.56250     13.128       .0019

2-FACTOR INTERACTIONS       92.687500     3      30.895833      3.955       .0532
  EMULSION  AGGREGATE       92.687500     3      30.895833      3.955       .0532

RESIDUAL                    62.500000     8      7.8125000

TOTAL (CORR.)               485.43750    15
--------------------------------------------------------------------------------
0 missing values have been excluded.


               Multiple range analysis for Torque24 by EMULSION
--------------------------------------------------------------------------------
Method: 95 Percent Scheffe
Level     Count        Average   Homogeneous Groups
--------------------------------------------------------------------------------
HFRS-2        8      66.500000   *
CRS-2         8      68.875000   *
--------------------------------------------------------------------------------


              Multiple range analysis for Torque24 by AGGREGATE
--------------------------------------------------------------------------------
Method: 95 Percent Scheffe
Level     Count        Average   Homogeneous Groups
--------------------------------------------------------------------------------
River Gr      4      62.000000   *
Limeston      4      66.500000   *
Lightwei      4      68.000000   **
Sandston      4      74.250000    *
--------------------------------------------------------------------------------
```

Table C2. Analysis of Variance and Multiple Range Tests for Cohesion Test Torque Values at 24 Hours.

```
                     Analysis of Variance for Torque48
--------------------------------------------------------------------------------
Source of variation   Sum of Squares   d.f.   Mean square   F-ratio   Sig. level
--------------------------------------------------------------------------------
MAIN EFFECTS               393.75000      4      98.43750    34.239       .0000
  EMULSION                  12.25000      1      12.25000     4.261       .0729
  AGGREGATE                381.50000      3     127.16667    44.232       .0000

2-FACTOR INTERACTIONS      48.250000      3     16.083333     5.594       .0230
  EMULSION  AGGREGATE      48.250000      3     16.083333     5.594       .0230

RESIDUAL                   23.000000      8     2.8750000

TOTAL (CORR.)              465.00000     15
--------------------------------------------------------------------------------
0 missing values have been excluded.
```

```
              Multiple range analysis for Torque48 by EMULSION
--------------------------------------------------------------------------------
Method: 95 Percent Scheffe
Level     Count       Average   Homogeneous Groups
--------------------------------------------------------------------------------
HFRS-2        8     69.375000   *
CRS-2         8     71.125000   *
--------------------------------------------------------------------------------
```

```
             Multiple range analysis for Torque48 by AGGREGATE
--------------------------------------------------------------------------------
Method: 95 Percent Scheffe
Level     Count       Average   Homogeneous Groups
--------------------------------------------------------------------------------
River Gr      4     63.500000   *
Limeston      4     69.500000    *
Lightwei      4     70.750000    *
Sandston      4     77.250000     *
--------------------------------------------------------------------------------
```

Table C3. Analysis of Variance and Multiple Range Tests for Cohesion Test Torque Values at 48 Hours.

```
                      Analysis of Variance for CureIndex
--------------------------------------------------------------------------------
Source of variation    Sum of Squares    d.f.    Mean square    F-ratio    Sig. level
--------------------------------------------------------------------------------
MAIN EFFECTS                196.25000       4      49.062500      2.372        .1389
  EMULSION                   52.56250       1      52.562500      2.541        .1496
  AGGREGATE                 143.68750       3      47.895833      2.315        .1523

2-FACTOR INTERACTIONS       172.68750       3      57.562500      2.782        .1099
  EMULSION  AGGREGATE       172.68750       3      57.562500      2.782        .1099

RESIDUAL                    165.50000       8      20.687500

TOTAL (CORR.)               534.43750      15
--------------------------------------------------------------------------------
0 missing values have been excluded.


               Multiple range analysis for CureIndex by EMULSION
--------------------------------------------------------------------------------
Method: 95 Percent Scheffe
Level      Count        Average    Homogeneous Groups
--------------------------------------------------------------------------------
HFRS-2         8      80.000000    *
CRS-2          8      83.625000    *
--------------------------------------------------------------------------------


               Multiple range analysis for CureIndex by AGGREGATE
--------------------------------------------------------------------------------
Method: 95 Percent Scheffe
Level      Count        Average    Homogeneous Groups
--------------------------------------------------------------------------------
Sandston       4      77.250000    *
Limeston       4      81.500000    *
Lightwei       4      83.000000    *
River Gr       4      85.500000    *
--------------------------------------------------------------------------------
```

Table C4. Analysis of Variance and Multiple Range Tests for Cohesion Test Curing Index Values.

```
                      Analysis of Variance for t95
--------------------------------------------------------------------------------
Source of variation   Sum of Squares   d.f.   Mean square   F-ratio   Sig. level
--------------------------------------------------------------------------------
MAIN EFFECTS              222.75000      4     55.687500     1.473      .2966
  EMULSION                 39.06250      1     39.062500     1.033      .3392
  AGGREGATE               183.68750      3     61.229167     1.619      .2601

2-FACTOR INTERACTIONS     136.68750      3     45.562500     1.205      .3684
  EMULSION  AGGREGATE     136.68750      3     45.562500     1.205      .3684

RESIDUAL                  302.50000      8     37.812500

TOTAL (CORR.)             661.93750     15
--------------------------------------------------------------------------------
0 missing values have been excluded.
```

```
                 Multiple range analysis for t95 by EMULSION
--------------------------------------------------------------------------------
Method: 95 Percent Scheffe
Level     Count        Average   Homogeneous Groups
--------------------------------------------------------------------------------
CRS-2         8      25.000000   *
HFRS-2        8      28.125000   *
--------------------------------------------------------------------------------
```

```
                 Multiple range analysis for t95 by AGGREGATE
--------------------------------------------------------------------------------
Method: 95 Percent Scheffe
Level     Count        Average   Homogeneous Groups
--------------------------------------------------------------------------------
River Gr      4      20.750000   *
Lightwei      4      27.750000   *
Sandston      4      28.750000   *
Limeston      4      29.000000   *
--------------------------------------------------------------------------------
```

Table C5. Analysi of Variance and Multiple Range Tests for Cohesion Test t_{95} Values.

```
                         Analysis of Variance for T95
--------------------------------------------------------------------------------
Source of variation   Sum of Squares   d.f.   Mean square   F-ratio   Sig. level
--------------------------------------------------------------------------------
MAIN EFFECTS               363.25000      4      90.81250    31.587       .0001
  EMULSION                   9.00000      1       9.00000     3.130       .1148
  AGGREGATE                354.25000      3     118.08333    41.072       .0000

2-FACTOR INTERACTIONS      37.500000      3     12.500000     4.348       .0428
  EMULSION  AGGREGATE      37.500000      3     12.500000     4.348       .0428

RESIDUAL                   23.000000      8     2.8750000

TOTAL (CORR.)              423.75000     15
--------------------------------------------------------------------------------
0 missing values have been excluded.
```

```
                  Multiple range analysis for T95 by EMULSION
--------------------------------------------------------------------------------
Method: 95 Percent Scheffe
Level     Count        Average   Homogeneous Groups
--------------------------------------------------------------------------------
HFRS-2        8      66.375000   *
CRS-2         8      67.875000   *
--------------------------------------------------------------------------------
```

```
                  Multiple range analysis for T95 by AGGREGATE
--------------------------------------------------------------------------------
Method: 95 Percent Scheffe
Level     Count        Average   Homogeneous Groups
--------------------------------------------------------------------------------
River Gr      4      60.500000   *
Limeston      4      66.500000    *
Lightwei      4      67.750000    *
Sandston      4      73.750000     *
--------------------------------------------------------------------------------
```

Table C6. Analysis of Variance and Multiple Range Tests for Cohesion Test T_{95} Values.

```
                      Analysis of Variance for TENmin
--------------------------------------------------------------------------------
Source of variation   Sum of Squares   d.f.   Mean square   F-ratio   Sig. level
--------------------------------------------------------------------------------
MAIN EFFECTS               137.26583      3     45.755278     7.308        .0199
  emulsion                 128.76500      2     64.382500    10.283        .0115
  Aggregate                  8.50083      1      8.500833     1.358        .2881

2-FACTOR INTERACTIONS      6.1316667      2     3.0658333      .490        .6353
  emulsion  Aggregate      6.1316667      2     3.0658333      .490        .6353

RESIDUAL                   37.565000      6     6.2608333

TOTAL (CORR.)              180.96250     11
--------------------------------------------------------------------------------
0 missing values have been excluded.
```

```
                 Multiple range analysis for TENmin by emulsion
--------------------------------------------------------------------------------
Method: 95 Percent Scheffe
Level     Count         Average   Homogeneous Groups
--------------------------------------------------------------------------------
HFRS-2        4       91.550000   *
CRS-2         4       92.500000   **
CRS-2p        4       98.925000    *
--------------------------------------------------------------------------------
```

```
                Multiple range analysis for TENmin by Aggregate
--------------------------------------------------------------------------------
Method: 95 Percent Scheffe
Level     Count         Average   Homogeneous Groups
--------------------------------------------------------------------------------
Limeston      6       93.483333   *
River Gr      6       95.166667   *
--------------------------------------------------------------------------------
```

Table C7. Analysis of Variance and Multiple Range Tests for Vialet Test Ten-Minute Values.

Table C8. Analysis of Variance and Multiple Range Tests for Vialet Test 30-Minute Values.

```
                         Analysis of Variance for THIRTYmin
--------------------------------------------------------------------------------
Source of variation    Sum of Squares   d.f.   Mean square    F-ratio    Sig. level
--------------------------------------------------------------------------------
MAIN EFFECTS                277.71500      3      92.57167      4.940       .0463
  emulsion                  253.06167      2     126.53083      6.753       .0291
  Aggregate                  24.65333      1      24.65333      1.316       .2950

2-FACTOR INTERACTIONS       12.111667      2     6.0558333       .323       .7357
  emulsion  Aggregate       12.111667      2     6.0558333       .323       .7357

RESIDUAL                    112.43000      6     18.738333

TOTAL (CORR.)               402.25667     11
--------------------------------------------------------------------------------
0 missing values have been excluded.
```

```
               Multiple range analysis for THIRTYmin by emulsion
--------------------------------------------------------------------------------
Method: 95 Percent Scheffe
Level     Count        Average   Homogeneous Groups
--------------------------------------------------------------------------------
CRS-2         4      86.500000   *
HFRS-2        4      90.975000   *
CRS-2p        4      97.675000   *
--------------------------------------------------------------------------------
```

```
               Multiple range analysis for THIRTYmin by Aggregate
--------------------------------------------------------------------------------
Method: 95 Percent Scheffe
Level     Count        Average   Homogeneous Groups
--------------------------------------------------------------------------------
Limeston      6      90.283333   *
River Gr      6      93.150000   *
--------------------------------------------------------------------------------
```

```
               Multiple range analysis for THIRTYmin by emulsion
--------------------------------------------------------------------------------
Method: 95 Percent Tukey HSD Intervals
Level     Count        Average   Homogeneous Groups
--------------------------------------------------------------------------------
CRS-2         4      86.500000   *
HFRS-2        4      90.975000   **
CRS-2p        4      97.675000    *
--------------------------------------------------------------------------------
```

```
                           Analysis of Variance for TWOhour
--------------------------------------------------------------------------------
Source of variation     Sum of Squares     d.f.     Mean square     F-ratio    Sig. level
--------------------------------------------------------------------------------
MAIN EFFECTS                 188.90500        3       62.968333       1.199         .3871
  emulsion                   117.85167        2       58.925833       1.122         .3855
  Aggregate                   71.05333        1       71.053333       1.353         .2889

2-FACTOR INTERACTIONS         77.261667       2       38.630833        .736         .5179
  emulsion   Aggregate        77.261667       2       38.630833        .736         .5179

RESIDUAL                     315.05000        6       52.508333

TOTAL (CORR.)                581.21667       11
--------------------------------------------------------------------------------
0 missing values have been excluded.
```

Table C9. Analysis of Variance for Vialet Test Two-Hour Values.

```
                          Analysis of Variance for FIVEhour
--------------------------------------------------------------------------------
Source of variation     Sum of Squares     d.f.     Mean square     F-ratio    Sig. level
--------------------------------------------------------------------------------
MAIN EFFECTS                 15.471667        3       5.1572222       2.748         .1350
  emulsion                   14.001667        2       7.0008333       3.730         .0886
  Aggregate                   1.470000        1       1.4700000        .783         .4193

2-FACTOR INTERACTIONS          .8450000       2        .4225000        .225         .8049
  emulsion   Aggregate         .8450000       2        .4225000        .225         .8049

RESIDUAL                     11.260000        6       1.8766667

TOTAL (CORR.)                27.576667       11
--------------------------------------------------------------------------------
0 missing values have been excluded.
```

Table C10. Analysis of Variance for Vialet Test Five-Hour Values.

```
                      Analysis of Variance for TWENTYFOUR
--------------------------------------------------------------------------------
Source of variation    Sum of Squares    d.f.    Mean square    F-ratio    Sig. level
--------------------------------------------------------------------------------
MAIN EFFECTS                7.1933333       3      2.3977778      1.489       .3096
  emulsion                  6.8600000       2      3.4300000      2.130       .1999
  Aggregate                  .3333333       1       .3333333       .207       .6698

2-FACTOR INTERACTIONS        .6866667       2       .3433333       .213       .8138
  emulsion  Aggregate        .6866667       2       .3433333       .213       .8138

RESIDUAL                    9.6600000       6      1.6100000

TOTAL (CORR.)               17.540000      11
--------------------------------------------------------------------------------
0 missing values have been excluded.
```

Table C11. Analysis of Variance for Vialet Test 24-Hour Values.

APPENDIX D

"The Duomorph - An In-Situ Viscoelastic Characterization Transducer"

The Duomorph – An In-Situ Viscoelastic Characterization Transducer

D. Saylak, J. S. Noel and **R. Boggess,** USA

ABSTRACT

This paper describes a device which can be used to measure rate-dependent properties of materials in both laboratory and field environments. The Duomorph has been designed for use either on the surface or embedded in materials with moduli ranging from 10 to 10^6 psi. Construction and operating details are presented along with graphical solutions to permit rapid reduction of field data into elastic and viscous components of the complex modulus. The potential for extending the use of the Duomorph to monitoring cure cycles, and aging of filled and unfilled polymeric systems is also discussed.

ZUSAMMENFASSUNG

Dieser Artikel beschreibt eine Anlage die gebraucht kan werden zum messen Gang-Abhangiger Eigenschaften von Material im Laborator sowie in praktische Umweltbedingungen. Der Duomorph ist entworfen geworden zum gebrauch entweder auf der Oberflache oder innerhalb Material, mit Modulus Reichen von 10 bis zu 10^6 psi. Konstruktion und Betriebsdaten werden vorgestellt zusammen mit Graphische Loesungen die schnelle reduktion erlauben von praktische Messwerte zu Elastische und Viskoese Daempfung Komponenten des Komplex Modulus. Das Potential zur Erweiterung der Anwendung des Duomorph zum Registrieren des Haerten und Vergueten von auffgefuellte und nicht auffgefuellte Polymern wird im Betrag genommen.

ABREGE

Cet article decrit un mecanisme qui peut etre utilise pour mesurer le taux des proprietes dependentes des materiaux dans un mileu de laboratoire aussi bien dans des milieux environants. Le Duomorph a ete concu pour usage ou bien dans la surface ou a l interieur des materiaux avec des modules rangeant de 10 a 10^6 psi. Les details de structure et de fonctionnement sont presentes avec des solutions diagrammees a fin de permettre la reduction rapide de donnees pratiques dans des composants d elasticite et de viscosite du module complexe. Le potential pour itendre l usage du Duomorph comme moniteurs des cycles de cure et d affaibbissement progessif de systems polymeriques remplis et vides, est egalement decrit.

1. Introduction

Often it is necessary to monitor physical or structural changes which are occuring in a material after it has been in service. Sometimes this can be accomplished by taking samples during fabrication and storing them in simulated environments for periodic testing at some later date. This form of surveillence testing gives rise to the question "is the separately stored sample representative of the material in the field?". If there is a gross difference anticipated, field samplings must be taken.

In the case of polymeric systems, changes in a material's structural integrity are usually associated with changes in stiffness since this parameter provides an index of its current deformation and load carrying capability. This is especially true in evaluating performance ratings for asphaltic concrete highways although similar treatments have been employed for solid propellants [2], fine-grained soils, rubbers and plastics.

Two approaches most commonly used to generate stiffness data on asphalt pavements are by coring and deflection measurements. The former procedure entails the drilling of a cylindrical core which can be taken back to the laboratory for testing. The laboratory procedure for determining the dynamic stiffness, also called the Resilient Modulus M_R, was developed by Schmidt [3]. This test is carried out by means of measuring the resultant strain produced by a high rate pressure pulse delivered diametrically to a cylindrical specimen. In the former, deflections are measured by means of truck mounted devices which apply a programmed load through a ram pushing downward on the surface. Either geophones or LVDT's [4] are used to monitor the shape of the resulting deflection basin.

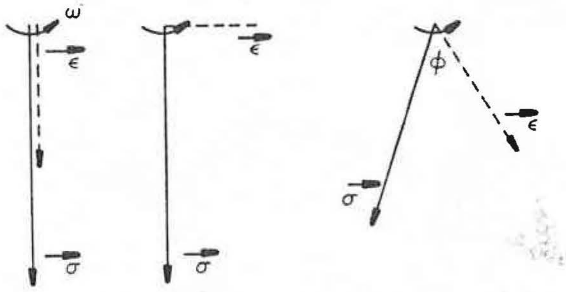
The single valued stiffnesses generated by the above methods are sufficient for use in elastic layered pavement analysis computer codes [5] but were found to be incapable of satisfying the input requirements of recently developed viscoelastic programs [6].

Both of the approaches mentioned above are currently being altered to provide a more complete characterization of the rate-dependent properties of the pavement material. The device to be described presents a technique to generate the viscoelastic characterization required by the new computer codes. It should be noted that although the data presented was taken on asphaltic concrete samples, the techniques and data reduction methods discussed below can be extended to other polymeric materials.

2. Viscoelastic Response

The viscoelastic properties which can be determined by the Duomorph include; complex modulus (E^*), its associated elastic (E') and viscous (E'') components and loss tangent ($\tan \phi$). These two parameters are determined under dynamic conditions (i.e. where the stress or strain loadings are oscillatory functions). The resulting parameters measured using such perturbations are functions of frequency rather than time.

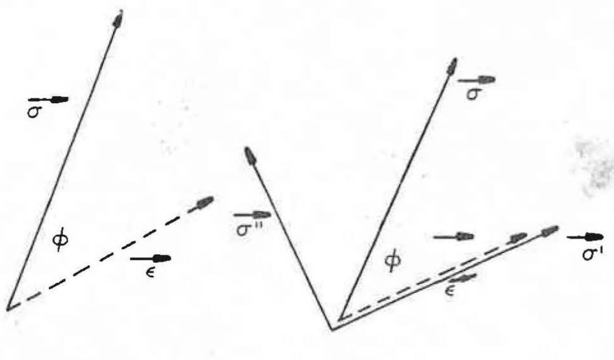
If a material is subjected to a sinusoidal stress loading function its strain response will reflect the nature of its mechanical properties. If the stress and resulting strain are in phase with each other (i.e. phase angle $\phi = 0$; independent of frequency and elaspsed time) the material's behavior is categorized as elastic. If on the other hand the strain is 90^0 out of phase with stress, the material is considered to be viscous. For phase angles in the range of $0^0 < \phi < 90^0$ the material is characterized as viscoelastic, the degree of which is assessed by the magnitude of ϕ. These three classifications are depicted below.



Elastic $\phi = 0$ Viscous $\phi = 90^0$ Viscoelastic $0 < \phi < 90^0$

Now consider a sample of viscoelastic material subjected to a sinusoidal stress. The stress and its strain response at any time can be represented using the technique of rotating vectors. In the figure given below, the magnitude of the stress vector $\vec{\sigma}$ represents the maximum of the stress applied to the sample which is being loaded at a frequency, ω. It is obvious from the figure that the two vectors do not coincide. The strain lags the stress by the angle ϕ which is also called the loss or lag angle.

The absolute modulus of the material $|E|$ is defined as the magnitude of the stress vector divided by the magnitude of the strain vector. Quite often it is convenient to separate the viscoelastic response into "in-phase' (elastic) and "out-of-phase" (viscous) components. This is done as shown below.



Here the projection of $\vec{\sigma}$ onto $\vec{\varepsilon}$ yields $\vec{\sigma}'$ the component of σ in phase with the strain while the projection of $\vec{\sigma}$ on the axis perpendicular to $\vec{\varepsilon}$ yields $\vec{\sigma}''$, the component out of phase with strain. The elastic and viscous moduli, E' and E'' respectively, and the loss tangent, $\tan \phi$, can be computed as follows:

$$E' = \frac{\sigma'}{\varepsilon} \qquad E'' = \frac{\sigma''}{\varepsilon} \tag{1}$$

$$\tan \phi = \frac{\sigma''}{\sigma'} = \frac{E''}{E'} \tag{2}$$

$$E^* = E' + iE'' \tag{3}$$

In the last expression, the viscoelastic modulus has been shown in its complex form where the out of phase component, E'', is made the imaginary part and E' the real part of E^*.

The values of E' have a direct relation to the degree of cross linking in a polymer which in turn gives the material its elastic characteristics. If the material ages or experiences changes in its cross link density this will result in a change in the magnitude of E'. The values of E'' reflect any changes in polymer chain structure brought about by chain scission, hydrolysis, plasticizer migration, etc. Since both types of activity can be occurring simultaneously during the life of the material the change in magnitude of the loss tangent with time can be an indication of the primary mechanisms involved. Hence changes in these properties represent convenient parameters for monitoring aging in polymeric systems.

3. The Duomorph - Design and Operation

The Duomorph sensor consists of two radially expanding piezoelectric (PZT) ceramic crystals bonded together into a circular bending plate. When excited by an electric field the plate is distorted into a parabolic surface due to the radial expansion and/or contraction of the crystals. As the polarity of the excitation is cycled the disc goes into reversed bendings. Figure 1 shows the general arrangement of the sensor.

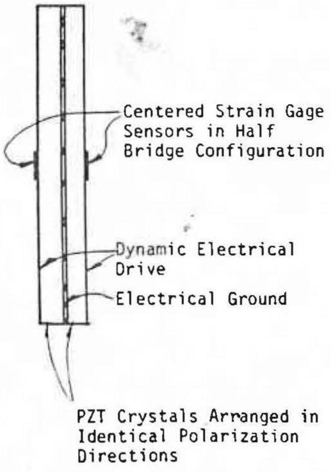


Fig. 1. Duomorph Sensor

The two PZT elements are bonded together using an epoxy adhesive. Strain gages cemented to each face of the sensor form a bridge which can measure very small bending strains. If the device is to be used on hard surfaces or in hostile environments a thin layer of epoxy should be applied to the sensor surface to protect the delicate strain gages.

The sensor must be tightly coupled to the specimen so that all forces and motion are transferred into the material being tested. This can be done either by totally embedding the sensor into a material or by forcing it onto a surface with sufficient pressure to insure good contact. For the surface-mounted sensor to function properly the surface must be smooth since surface irregularities or debris will adversely affect the performance of the Duomorph.

The Duomorph sensor is sensitive to a modulus range of 1 decade; e.g. 700 MPa to 7000 MPa (10^5 psi to 10^6 psi). This means that a Duomorph must be sized for a particular range of modulus. For wide ranges of E more than one sensor may be required. Since the mechanical properties of the ceramic material remain nearly constant, designing a Duomorph of the proper stiffness is only a matter of selecting the proper thickness-to-diameter ratio.

The transducer is made by embedding the Duomorph sensor in the surface of a mass of low modulus (≈ 300 psi) silicone rubber which is contained in an aluminum cylinder. The diameter of the cylinder should be large enough to minimize end effects. The silicone rubber distributes the pressure uniformly over the surface of the sensor and holds it firmly against the material to be tested. A schematic drawing showing the components which make up the transducer is shown in Figure 2.

The Duomorph sensor used in the work discussed in this paper was designed for use on asphaltic concrete. These materials can have moduli ranging from 700 to 7000 MPa (10^5 to 10^6 psi) depending on the type of ingredients used in the concrete, its temperature or rate of loading.

It was found that in order to get deflections in asphalt large enough for satisfactory measurement, a driving voltage of ± 250V is desirable. Because of the capacitive nature of the Duomorph sensor, the power required for driving increases with frequency. A schematic of the Duomorph circuitry is shown in Figure 3.

Early in the developmental program it was found that a very large error was introduced into the strain gage signal by capacitive coupling of the excitation voltage. Due to the bridge arrangement and the fact that the two outer surfaces were oppositely charged, an error signal was coupled into the strain gage bridge. This error signal was in phase with the expected output signal. Two corrective actions were taken to eliminate this annoyance. A symmetrical configuration was adopted. This configuration allowed the outer surfaces to be kept always at the same potential, thus eliminating any capacitively-coupled signal. The other corrective measure was the use of AC excitation to the bridge.

The amplifier used has a band pass of 2500 Hz and is capable of resolving strain of less than 1.5 μ-in/in., with typical signal strain levels of 200 μ-in/in.

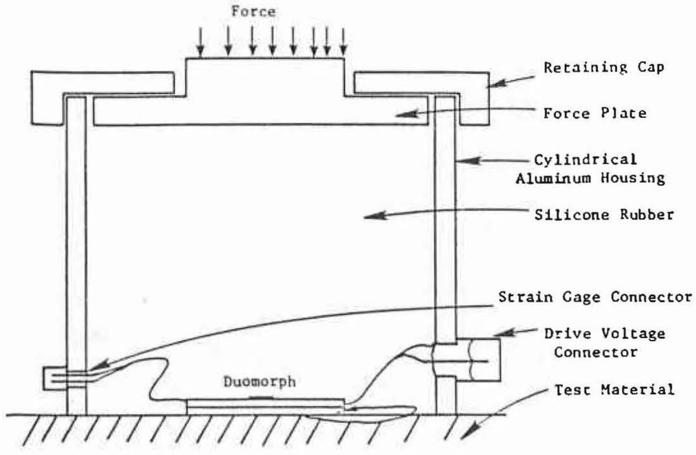


Fig. 2. Assembly for surface measurements

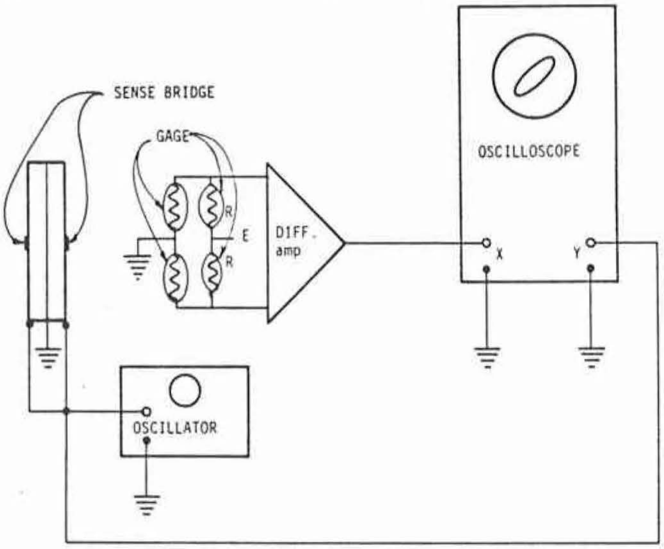


Fig. 3. Schematic diagram of Duomorph test apparatus

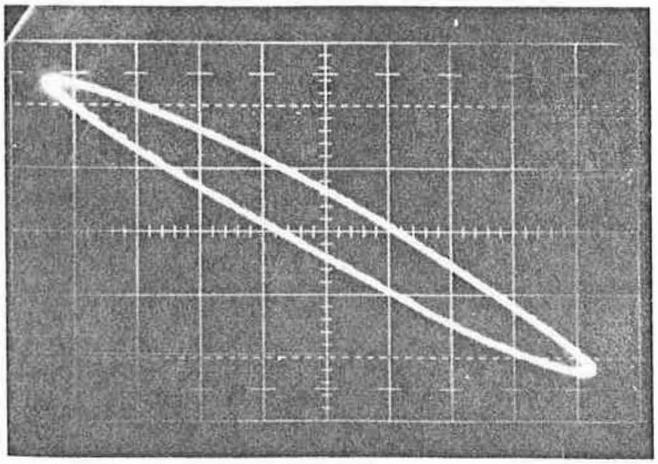


Fig. 4. A typical Lisajous plot

4. Data Reduction

The method for reducing the Duomorph output to find the dynamic properties of viscoelastic materials relies on the results of an analysis published by Schapery in 1976 (see Reference 7). Typically the driving voltage and the output of the strain gages are both fed into an oscilloscope which displays them on the cathode ray tube as the ordinate and abcissa, respectively. An example of such a plot, conventionally referred to as a Lisajous curve, shown in Figure 4. The elliptical shape is characteristic for viscoelastic materials wherein the slope and area are related to stiffness and the inherent damping characteristics of the material.

If the strain is exactly in phase with the voltage, as would be the case for elastic behavior, the ellipse would degenerate into a single sloping line. On the other hand, if the strain is 90° out of phase with the voltage, the area enclosed by the ellipse becomes a maximum.

From a material standpoint it is necessary to interpret the ordinate and abscissa in units that can be related to machanical properties of the material being tested. The abscissa can be simply calibrated into strain units by using the conventional application of a known shunt resistance to the strain gage bridge in conjunction with the gage factor. Thus the abscissa can be directly interpreted as the strain on the surface of the disc.

The interpretation of the driving voltage is more difficult, and is circumvented by using a ratio of driving voltage in air to that against the material. When viewed in this manner the driving voltage can be considered to be linearly related to the equivalent line moment which if uniformly distributed around the periphery of the sensor would force the same shape changes. In practice one should use the same driving voltage for establishing the shape of the ellipses in air (one for each frequency) as when in contact with, V_o the material being tested, V_c.

If the driving voltages are the same then the ratio of the total strain excursion with the sensor in contact with the specimen, ε_c, to the total strain excursion in air, ε_o, yields to a number reflecting the degree of restraint caused by the sample material. If the driving voltages are different, the ratio must be modified by the ratio of the driving voltage, thusly

$$\frac{M_c}{M_o} = \frac{\varepsilon_c}{\varepsilon_o}\frac{V_o}{V_c} \qquad (4)$$

The numerical value of this ratio is entered as the ordinate of Figure 5 which when transposed to the abscissa yields M' a parameter which relates the gage and material stiffnesses.

Knowing M' it is next necessary to deduce the loss tangent, tan ϕ. This can best be done using the relationship

$$-\text{Sin}\ \theta = \frac{1}{2}\left(\frac{V_1}{V_2} + \frac{H_1}{H_2}\right) \qquad (5)$$

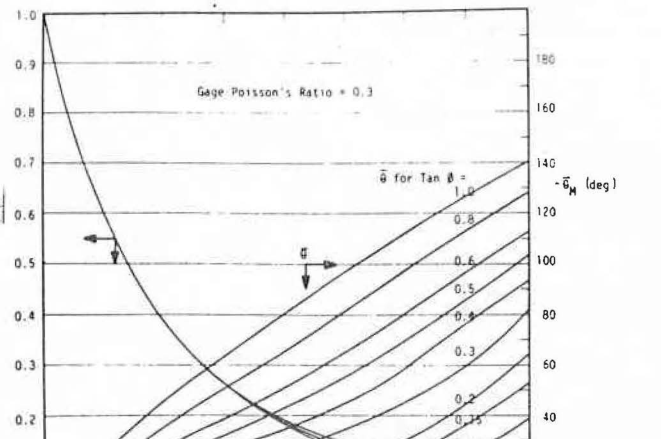
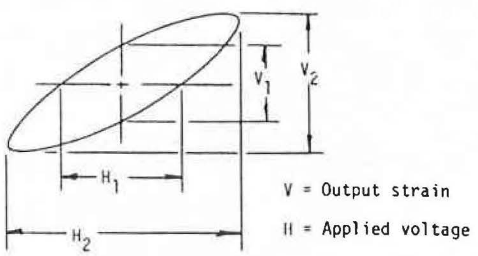


Fig. 5. Curves for reducing the output of the Duomorph to the real and loss tangent components of the dynamic modulus



$$-\text{Sin}\ \theta_M = \frac{1}{2}\left(\frac{V_1}{V_2} + \frac{H_1}{H_2}\right) \qquad \frac{M_c}{M_o} = \frac{V_2\ (\text{material})}{V_2\ (\text{air})}$$

Fig. 6. Graphical determination of bending moment ratio and θ_M from Duomorph output

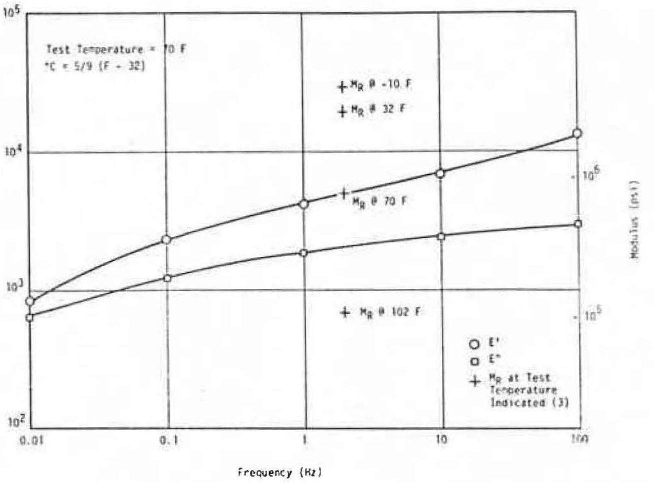


Fig. 7. Comparison of complex modulus and resilient modulus data from asphaltic concrete samples of Texas Farm Road 493

where the values of V_1, V_2, H_1 and H_2 are measured from the Lisajous curve as shown in Figure 6. If θ is determined at each frequency, both in air, θ_o, and when pressed against the material being tested, θ_c then θ_m is determined by

$$-\theta_m = -(\theta_o - \theta_c) \qquad (6)$$

This value is used to enter the right hand scale of Figure 5.

Once the point defined by the coordinates (M',θ_m) is found the appropriate family of curves yields tan ϕ.

The real part of the modulus of the asphalt can be computed using the equation

$$E' = \frac{8}{3}(1-\nu^2)M'\ \frac{E_s h_s^3}{12a_s^3\ (1-\nu_s^2)} \qquad (7)$$

where the subscript s indicates that the thickness, h, the radius, a, and Poisson's ratio ν apply to the sensor. And finally E" is computed using

$$E'' = E'\ \tan\phi \qquad (8)$$

For viscoelastic materials the complex modulus is a function of the frequency. So both E' and E" must be determined for discrete frequencies and plotted as shown in Figure 7. These data were generated on samples taken from two asphaltic pavements in Texas.

Figure 7 shows the real and imaginary moduli of an asphaltic concrete pavement material cored from Texas Farm-to-Market Road 493. All tests were performed in the laboratory at 70°F and reflect the type of behavior that can be expected of asphalt. The real part of the modulus, E', increases linearly on the log-log plot versus frequency. The imaginary part of the modulus, E", also increased over the range of frequencies tested. The rate dependence shown indicates the material's behavior over this frequency range is viscoelastic.

The Resilient Modulus, M_R, data generated at different temperatures are also shown on the graphs. These points are plotted at 2Hz which corresponds to the width of the pressure pulse used in the resilient modulus test [3]. Since M_R is an elastic modulus its value should be expected to correspond to E' at the same temperature and loading rate. The good agreement between M_R and the E' at 70°F and 2Hz is readily apparent.

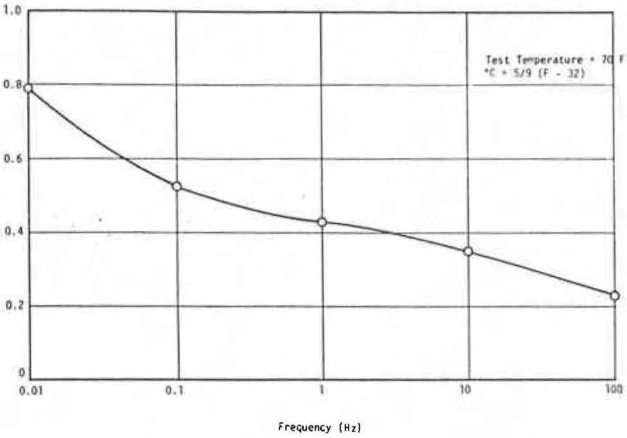


Fig. 8. Loss tangent vs. frequency data from asphaltic concrete samples of Texas Farm Road 493

Figure 8 shows the relationship between loss tangent and frequency. The reduction in tan ϕ with frequency is characteristic of viscoelastic behavior. As the frequency continues to increase the viscous component will vanish and tan ϕ will approach zero.

5. Conclusions

This work has demonstrated that the Duomorph may be used as a sensitive device for obtaining the dynamic moduli and loss tangents of asphalt pavements. The test equipment is compact, portable and convenient to set up and use in the field. The necessary data can be collected rapidly and nondestructively so that the extraneous effects of handling and sample preparation are minimal.

The results cover a range of practical frequencies (loading rates) characteristic of those induced by automobile and truck traffic.

The graphical solutions provide a means of rapidly reducing field data to the real and imaginary modulus components. Such rapid reduction capability makes it possible to compare data in the field and make on-the-spot test checks if necessary.

The numerical values of the moduli measured with the Duomorph compared favorably with those measured using the Resilient Modulus Test, the routine test for dynamic modulus used by highway engineers. This adds to the confidence that can be placed in results and provides encouragement for further applications using the device. Work is now in progress to extend the use of the Duomorph to other materials such as fiber reinforced composites. In this sense the device will be used to monitor structural changes during cure from which the basis for optimizing process variables can be established.

6. References

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[2] Briar, H. P. and Bills, K. W., Jr., "Development of an In-Situ Transmitter for Solid Rocket Propellant Surveillence", Final Report in Air Force Contract No. F04611-71-C-0044, AFRPL-TR 72-93, December, 1972.

[3] Schmidt, R. J., "A Practical Method of Measuring Resilient Modulus of Asphalt-Treated Mixes", Highway Research Record, No. 404, Highway Research Board, 1972, pp 22-32.

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[6] Moavenzadeh, F., Sasson, J. E., Findakly, H. K. and Brademeyer, B., "Synthesis for a Rational Design of Flexible Pavements", Part III, Operating Instruction and Program Documentation Research Report R74-26, Massachusetts Institute of Technology, Department of Civil Engineering, February, 1974.

[7] Briar, H. P., Bills, K. W., Jr. and Schapery, R. A., Design and Test of the Operational In-Situ Gage for Solid Propellants Surveillance, Final Report in Air Force Contract No. F04611-73-C-0040, June, 1976.

APPENDIX E

FIELD DATA COLLECTED AT TEST SITES

Location

District 14 County Bastrop Highway US290

Mile Post or Station Limits: From FM2336 To FM 2104

Evaluated by: G. Teetes, K. Weese

Lane Both

Preconstruction

Type of Surface on Old Roadway Gr.3 Chip Seal

Condition of Old Surface:

Rutting

Raveling

Flushing Slight

Corrugations

Alligator Cracking

Longitudinal Cracking

Transverse Cracking

Patching

Deflection: Mean – Std. Deviation Range No.

Road Roughness: Mean – Std. Deviation Range No.

Skid Number: Mean – Std. Deviation Range No.

Surface Texture: Outer Wheel path 0.58 Between wheel path

Inner wheel path Centerline

Traffic: ADT Per Lane 7400 % Trucks 15 Eq. 18 Kips per lane –

Design

Type of Asphalt HFRS-2p

Type of Aggregate Gr.4/Gr. 3 Source of Aggregate ~~Texas Crushed Stone~~ and Streetman

Construction

Asphalt Shot: 0.28/0.38 gsy

Temperature of Shot: 140 °F

Aggregate Quantity: 120/92 sy/cy

Climatic Conditions: Temperature 92

Rainfall: Day Before Construction None

Day of Construction None

Day After Construction None

2 Days After Construction None

Date(s) of Construction: 6/27/88

Performance

Date	Overall	Aggregate Retention	Bleeding	Aggregate Embedment
6/88	Good	95%	0	35
7/88	Good	95%	0	40

Laboratory Vialet Test Results(Gr 4)

Time	% Ret.
10 min	20
30 min	75
2 hr.	98
5 hr.	98
24 hr.	98

Location

District 14
County Williamson
Highway SH29
Mile Post or Station Limits: From SH95 To I35
Evaluated by K. Weese, G. Teetes
Lane Both

Preconstruction

Type of Surface on Old Roadway Chip seal

Condition of Old Surface:
Rutting
Raveling
Flushing slight
Corrugations
Alligator Cracking
Longitudinal Cracking
Transverse Cracking
Patching

Deflection: Mean - Std. Deviation Range No.
Road Roughness: Mean - Std. Deviation Range No.
Skid Number: Mean - Std. Deviation Range No.
Surface Texture: Outer Wheel path 0.60 Between wheel path
Inner wheel path Centerline
Traffic: ADT Per Lane 2000 % Trucks 8 Eq. 18 Kips per lane

Design

Type of Asphalt HFRS-2p
Type of Aggregate Gr 4/ Gr 3
Source of Aggregate Texas Crushed Stone

Construction

Asphalt Shot: 0.28/0.36 gsy
Temperature of Shot: 138 °F
Aggregate Quantity: 116/85 sy/cy
Climatic Conditions: Temperature 94
Rainfall: Day Before Construction None
Day of Construction None
Day After Construction None
2 Days After Construction None

Date(s) of Construction: 7/6/88

Performance

Date	Overall	Aggregate Retention	Bleeding	Aggregate Embedment
7/88	Good	95%	5%	40%
8/88	Good	90%	10%	55%

Laboratory Vialet Test Results (Gr 4)

Time	% Ret.
10 min	18
30 min	73
2 hr	96
5 hr	98
24 hr	99

Location

District 23

County Eastland

Highway I20 Feeder

Mile Post or Station Limits: From US 80 To North 1 mile

Evaluated by Cindy Estakhri

Lane WB

Preconstruction

Type of Surface on Old Roadway asphalt concrete

Condition of Old Surface:

Rutting

Raveling

Flushing

Corrugations

Alligator Cracking

Longitudinal Cracking

Transverse Cracking slight

Patching

Deflection: Mean - Std. Deviation Range No.

Road Roughness: Mean - Std. Deviation Range No.

Skid Number: Mean - Std. Deviation Range No.

Surface Texture: Outer Wheel path 0.89 Between wheel path

Inner wheel path Centerline

Traffic: ADT Per Lane 1000 % Trucks Eq. 18 Kips per lane

Design

Type of Asphalt HFRS-2

Type of Aggregate Gr 4 Ltweight Source of Aggregate Ranger

Construction

Asphalt Shot: 0.35 gsy

Temperature of Shot: 135 °F

Aggregate Quantity: 135 sy/cy

Climatic Conditions: Temperature 98

Rainfall: Day Before Construction None

Day of Construction None

Day After Construction None

2 Days After Construction None

Date(s) of Construction: 8/87

Performance

Date	Overall	Aggregate Retention	Bleeding	Aggregate Embedment
8/87	Good	95%	20%	45%
8/88	Fair	95	35	70%

Laboratory Vialet Test Results

Time	% Ret.
10 min.	18
30 min.	60
2 hr.	95
5 hr.	98
24 hr.	98