D. Y. LEE
MAY 1977

Final Report
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LABORATORY STUDY OF SLURRY SEAL COATS

Highway Division,
Iowa Department of Transportation
HR-185

ERI Project 1263

Revised January 1978

ENGINEERING RESEARCH INSTITUTE
IOWA STATE UNIVERSITY
AMES, IOWA 50010 USA

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DEPARTMENT OF CIVIL ENGINEERING
ENGINEERING RESEARCH INSTITUTE
IOWA STATE UNIVERSITY AMES

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EXECUTIVE SUMMARY

Extensive programmed laboratory tests involving some 400 asphalt emulsion slurry seals (AESS) were conducted. Thirteen aggregates including nine Iowa sources, a quartzite, a synthetic aggregate (Haydite), a limestone stone from Nebraska, and a Chat aggregate from Kansas were tested in combination with four emulsions and two mineral fillers, resulting in a total of 40 material combinations. A number of meetings were held with the Iowa DOT engineers and 12 state highway departments that have had successful slurry seal experiences and records, and several slurry seal contractors and material and equipment suppliers were contacted. Asphalt emulsion slurry seal development, uses, characteristics, tests, and design methods were thoroughly reviewed in conjunction with Iowa's experiences through these meetings and discussions and through a literature search (covering some 140 articles and 12 state highway department specifications). The following is the summary of findings, conclusions, and recommendations:

1. Asphalt emulsion slurry seals, when properly designed and constructed, can improve the quality and extend the life of existing pavement surface, and their application can become a viable and economical pavement maintenance procedure, both preventive and corrective.

2. Although asphalt emulsion slurry seals have been used in the U.S. for more than 25 years and many thousands of miles of successful asphalt emulsion slurry seals have been built both in the U.S. and abroad, their design and construction are still an art rather than a science. Experiences with the slurry seal have been mixed; consistent

success in the construction and performance of the slurry seal, except in a few states, has not been achieved.

3. More than 40 material, slurry, and construction variables were identified that will affect the design, construction, and performance of an asphalt emulsion slurry seal.

4. The major reasons for the mixed experiences and lack of consistent success with AESS are believed to be:

- Too many variables that will affect the properties, design, construction and performance of an AESS.
- No standard design method and traffic and geographically-based design criteria.
- General lack of experiences, total process control and proper equipments on the part of some contractors.

5. Major material variables affecting slurry compatibility, mixing stability, slurry consistency, and wear resistance were identified as a result of the programmed laboratory testing. They are:

- Aggregate type and composition
- Aggregate gradation, amount, and type of fines
- Emulsion type and variability
- Prewet water content of aggregate
- Filler content
- Emulsion content

6. Although not all of the aggregates studied met current specifications, most of them could be made into a creamy, stable, homogeneous, free flowing slurry seal, with proper selections of emulsion type, emulsion content, prewet water content, and mineral filler type and content.

7. Not all of the slurries made with aggregates meeting sand equivalent and gradation specifications gave satisfactory abrasion and wear resistance. On the other hand, satisfactory slurries could be made with aggregate blends which failed to meet either sand equivalent or gradation specifications. These specification-performance (laboratory) inconsistencies point to the need for field study.

8. Based on laboratory results obtained in this study a number of recommendations are made with respect to Iowa slurry seal specifications.

9. Combining the basically sound Iowa slurry seal design procedure of 1975, laboratory results obtained from this project and experiences of other agencies and engineers, a laboratory asphalt emulsion slurry seal design procedure is recommended. The principal features of this procedure are:

- Estimate the theoretical residual asphalt requirement based on coating of an 8 μm film on aggregate surfaces.
- Establish the minimum asphalt (emulsion) content by the wet track abrasion test (WTAT) or shaker test.
- Establish the maximum asphalt (emulsion) content by sand adhesion value determined from the loaded wheel test or modified California rubber wheel test.

10. In order to establish design criteria and material specifications most suited for Iowa conditions of weather, traffic, and available aggregates, and to gain field experiences, a field test, as envisioned by the Iowa DOT engineers, is recommended. The proposed field test will consist of 32 sections of 500 ft each and will be constructed during the 1977 construction season by the Iowa DOT. The testing and

design of slurry seals for the test sections will be undertaken by Iowa State University. The selection of test site and the evaluation of construction procedures and slurry seal performance will be undertaken by Iowa DOT engineers.

11. It is expected that conclusions regarding the performance of slurry seals under Iowa conditions, the suitability of Iowa aggregates, and the performance-based design criteria will be made at the end of two to four years of field tests.

1. INTRODUCTION

A slurry seal is a mixture of asphalt emulsion, well-graded fine aggregate, water, and, often, mineral filler. When these ingredients are mixed in proper sequence and proportion, a creamy, homogeneous, and fluid mixture is formed. The slurry, because of its fluidity, can be spread in thin layers over an existing surface. After the setting and curing a thin, hard, dense asphalt surface results.

The slurry mixtures are normally produced by continuous mixers mounted on a truck chassis which also pull the box-type spreading units. Slurry mixtures are produced by cold-wet mixing processes in that aggregate, emulsified asphalt, and water are used. Break of the emulsion and setting and curing of the 1/8-in. to 1/2-in. thick surfacing evolves through chemical and/or mechanical action. Traffic can normally be placed on the cured seal coats after atmospheric exposure in anywhere from 1-8 hr depending on ambient conditions, material formulations and the nature of the ingredients (emulsion, aggregate, and mineral filler).

Slurry seals are used for pavement seal coats and crack fillers on airports, highways, streets, and parking lots. Generally, they are placed in lieu of cover aggregate seal coats and more expensive surface courses to restore and protect existing weathered and deteriorated pavements, and to improve skid resistance. More recently (Kari, 1977), slurry seals have been used over asphalt treated bases on low volume roads or in stage construction, as an interlocking layer for chip seals (Cape seals) and as wearing surfaces over recycled asphalt pavements.

The primary advantages of slurry seal coats are (1) low cost, (2) thin layer (no significant build-up at curbs, gutters, and manholes), (3) ease of application, (4) minimal equipment and manpower requirements, (5) low utilization of material and energy, (6) no loose aggregate problem associated with chip seals, and (7) construction speed. The primary disadvantages are (1) the probability of success being too dependent on the art of slurry sealing, (2) short service life, (3) lack of reliable design procedures and criteria, and (4) numerous construction constraints.

Experience in Iowa and other states indicates that alternatives are needed to cover aggregate seal coats and more expensive asphalt concrete overlays in order to protect or otherwise enhance pavement surfaces. Slurry seals have occasionally exhibited appropriate cost effectiveness and performance parameters. Unfortunately, except in a few states such as Kansas and Virginia, they have not been shown to be consistently satisfactory in that numerous difficulties and failures have occurred. These problems have prevented the slurry seals from becoming viable maintenance alternatives.

However, because this type of surface treatment occasionally has shown promise, it needs to be thoroughly studied and evaluated so that (1) usage can be expanded where appropriate and (2) the limitations can be properly identified.

2. OBJECTIVES

The overall objective of the proposed research is to review, evaluate, develop, and verify necessary information for successful design and application of emulsion slurry seals in Iowa. The research is to be conducted in two phases. The work reported here was addressed to Phase I of the study. The specific objectives are:

1. To provide a comprehensive literature search and digest on the material characteristics of, design procedures and criteria for, and field experiences with slurry seals.
2. To conduct a programmed laboratory study of slurry seal design procedures and criteria, testing and evaluation methods, and material and mixture characteristics.
3. To formulate tentative slurry seal laboratory design, testing and evaluation procedures, and recommendations on the desirability and design of field study.

3. REVIEW OF SLURRY SEAL DESIGN, APPLICATION, AND EXPERIENCES

A thorough literature search was conducted covering some 140 reports and articles and 12 highway department and other agency specifications. A number of meetings were held with Iowa DOT engineers. Twelve state highway departments, emulsion suppliers, slurry seal contractors and suppliers (including California, Kansas, Illinois, Kentucky, Louisiana, Virginia, Chevron, Inc., Armak Co., International Slurry Seals Association, Young Slurry Seal, Inc., Bitucote, and Benedict Slurry Seal) were contacted. Asphalt emulsion slurry seal developments, uses, characteristics, tests, and design procedures were reviewed in conjunction with Iowa's experiences through these meetings and discussions, and the literature search. Table 1 shows a compilation of material test procedures used by most major agencies that have had experiences with slurry seals. Table 2 is a documentation of Iowa's experiences. The following is a summary of these reviews:

3.1 Applications

Slurry seals have been used to improve and correct distresses of existing pavement surfaces on airport runways, highways, city streets, parking lots, and bridge decks. They have been used on both flexible and rigid pavement surfaces. The primary uses of slurry seals are (Barenberg et al., 1973; Godwin, 1975; Bradshaw, 1975):

- Crack sealing
- Surface sealing (to improve and protect the existing or new surface from oxidation, moisture and traffic wear)

Table 1. Summary of tests used by various agencies.

	Kansas	Virginia	Louisiana	Iowa	California	Proposed AASHTO	USAE	Chevron	Proposed ASTM (ISSA)	Young	Illinois	Kentucky
Aggregates												
• Gradation	X	X	X	X	X	X	X	X	X	X	X	X
• LA Abrasion			X	X		X				X		
• Soundness			X	X		X				X		
• Sand equivalent		X				X	X	X	X	X		X
• Sp. gr. and absorption	X[a]			X		X[a]	X		X	X[a]	X	
• Surface area by gradation	X					X	X			X	X	
• Surface area by CKE					X					X		
• % moisture vs. unit wt.										X		
• Washed sieve analysis	X			X						X		
• P.I.		X										X
• Void content		X										
• Insolubles												X
Emulsion												
• Viscosity	X	X	X	X	X	X		X		X	X	X
• Asphalt droplet size										X		
• Total residue	X	X	X	X	X	X		X		X	X	X
• Penetration of res.	X	X	X	X	X	X		X		X	X	X
• Particle charge	X	X	X	X	X	X		X		X	X	X
Slurry												
• Mixing test (compatibility)	X	X	X	X				X[b]		X		
• Stain setting test		X	X					X	X			
• Cure time (cohesion)									X			
• Penetration setting test								X[c]				
• Shaker durability	X[e]									X[d]		
• Consistency: funnel method		X					X		X	X	X	
cone method	X			X		X	X		X			
• Abrasion:												
WTAT 1/4"		X	X	X		X	X	X	X	X	X	
Rubberwheel, 1/4"					X							
Steel-wheel (knurled), 1/4"					X							
• Water resistance		X						X				
Standard Aggregate												
Ottawa sand					X							
Chat	X											
Granite agg. (Verdon, Va.)									X			

[a]By CKE
[b]Mechanical, Chevron P-4, P-7
[c]Chevron, P-8
[d]Steel balls
[e]Rubber balls

Table 2. Major Iowa experiences with emulsion asphalt slurry seals.

Specifications					Projects						
										Field Experiences[c]	
Date	Specs. No.	Emulsion	Aggregate	Mineral Fillers	Date	Co. (Project No.)	Aggregate	Emulsion	Lab Results	Construction	Performance
1966	602	SS-1h		• p.c.							
		(85-100 pen)	• Sand not exceeding 50%	• Limestone dust							
			• Sand equivalent not less than 35-45	• Fly ash							
			• 5-15% passing #200								
					1967	Pottaw. - Mills (MD-416-68-D4)	3/8 in. crushed stone blended with concrete sand	SS-1h		Low AC content, fine gradation, thin application	Fair. Short service life, premature wear and cracking.
					1969	Washington (Iowa 114S. Wellman)	Ferguson and 35% concrete sand	CQS-1h (Blakat)	Good	Good	Fair; premature wear.
1970	678	CSS-1h	• Crushed stone 50% + Natural sand 30% +	• Type I p.c. (2%)	1970	Davis (MD-529-68-D5)	Douds and sand	CSS-1h SS-1h	Mixed	• Mixed • Started with CSS-1h[a]	Surface failed with CSS-1h Good; after change of emulsion type
			• 6-14% passing #200								
			• Abrasion and soundness requirements								
			• 3/8 in. Dolomite and concrete sand	• Type I p.c. 1-2%	1971	Muscatine (MD-529-68-D5)	Moscow and 28-38% concrete sand	CSS-1h	Good	• Started with CSS-1h[b] Changed to SS-1h[b] • Poor	Very poor, flushed and slick, required heater treatment by maintenance
			• Crushed limestone and sand		1971	Delaware-Buchanan (Maint. U.S. 20)			NA		Satisfactory - high shrinkage
			• Crushed limestone and sand		1971	Jefferson (Maint. Ia. 78)			-	Strip seal (4') at centerline for cracking.	Fair, very susceptible to snowplow wear.
			• 3/8 in. Crushed limestone		1974	Adair (Maint. I-80)	Gilmore City, Fort Dodge Mine Formation	CSS-1h	NA	AC content too high for traffic volumes - wheel path strip seal over cracked areas.	Fair - flushed during hot weather and heavy traffic
			• 3/8 in. Crushed limestone and concrete sand		1974	Maint. Story Ia. 210	Ferguson stone	Blakat	NA	Segregation problems	Poor. Excessive wear.
1975		CSS-1h	• 100% crushed stone	• Type I p.c.	1975	Worth (MD-2165-69-D2)	Fertile	CSS-1h	Good	No major problems. Part of project redone because of rain damage.	Good; reflective cracking is evident due to old base.
			• Lithographic limestone excluded			Ia 337					
			• Lithographic limestone excluded	• Type I p.c.	1975	Cerro Gordo (MD-2165-69-D2) Iowa 107 Thornton to Meservey				No major problems.	
			• Crushed limestone and sand		1975	Monona (Maint. I-29 shoulders)				Maint. crack filling.	Satisfactory.
			• Crushed limestone and sand		1975	Pottaw - Harrison (Maint. I-29 shoulders)				Maint. crack filling.	Satisfactory
1976	793	CSS-1h	• 100% crushed stone	• Type I p.c.	1976	Franklin/Cerro Gordo (MP-2243-69-D2)	Garner	CSS-1h	Good	No major problems.	Good
		(85-100 pen)	• Lithographic limestone excluded								
			• 8-15% passing #200								
					1976	Adams-Taylor (MP-4444-69-D4)	Weeping Water, Nebraska	CSS-1h	Good	No major problems.	Good, except SN tests below average.

[a] Serious mixing, placing, setting problems, false break.

[b] Serious mixing placing, setting problems. Material bulked during placement.
Joint crack filling only.

[c] Rating - Poor, Fair, Good, Excellent } Four classes of performance used to classify behavior of slurry seals on roadway.
Satisfactory — Special uses.

Refer to Iowa Highway Research Board Report.

- Repair crazing, scaling, spalling, random cracking and "D" cracking in p.c. concrete pavement surfaces
- Improvement of skid resistance
- Temporary wear surface
- Improvement of the appearance of a surface.

3.2 Slurry Seal Users

Slurry seals have been used in the U.S. in at least a dozen states, notably Virginia, Kansas, Oklahoma, and Georgia, and many cities throughout the country. Larger users of slurry seal in foreign countries include Canada, the United Kingdom, France, South Africa, Spain, Mexico, Japan, Austria, and Switzerland.

3.3 Experiences and Problems

The following types of problems and failures have been encountered, both in Iowa and other states (Table 2):

- There are no standard, reliable design procedures and criteria. Certain laboratory tests and evaluations have led to erroneous conclusions with regard to slurry characteristics. On several occasions mixes were designed in the laboratory that could not be mixed and placed in the field.
- On several projects, what appeared to be acceptable slurry mixes were produced and placed, but the service lives were only a few months in duration. Traffic and weathering appeared to wear away the new surfacing inordinately considering the type and volume of traffic.
- Iowa experience has shown that several narrowly defined aggregate types, e.g., dolomitic limestone, can successfully be used in slurries. This precludes letting contracts for projects in areas where aggregates with different characteristics are encountered.

To summarize the problems commonly associated with slurry seals:

- Slurry design procedure
- Compatibility of material
- Segregation of mixture in the field (excess water)
- Surface streaking (oversized aggregate particles)
- Too slow a curing rate.

3.4 Materials

Aggregates: Most crushed stone is a good slurry aggregate. The key is that it must be, either siliceous or calcareous, clean. Experiences with sand have been mixed. Synthetic aggregates such as expanded clay and slag have been used successfully.

Emulsions: Both SS-1h and CSS-1h are used. In recent years quick-set emulsions (CQS-1h or QS-1h) have been developed. They have much shorter curing time but are more difficult to handle.

Mineral Fillers: Most commonly used fillers are Portland cement (Types I and III) and hydrated lime.

3.5 Tests and Procedures

As noted earlier there are currently no standard tests and procedures for slurry seal design (Table 1). Commonly required tests (and specifications) on aggregate are gradation and sand equivalent. Most agencies run some form of mixing (compatibility) test and consistency test on fresh slurry, and abrasion test (WTAT) on cured slurry.

4. PROGRAMMED LABORATORY TESTS

4.1 Materials

Thirteen aggregates (16 blends) and four asphalt emulsions were studied in this project (Table 3). Aggregates were obtained by the Iowa DOT and received in the early part of December 1976. Emulsions were obtained from Bitucote Products Co. between October 1976 and March 1977. These materials were selected jointly with Iowa DOT engineers in consideration of Iowa's past experiences, aggregate availability, and aggregates with known field performance records.

4.2 Experimental Design

Material combinations and levels of studies are shown in Table 3. These were established as a result of literature and experiences review and consultation with Iowa DOT engineers.

- Series 1 was a preliminary study using three aggregates (Garner, Haydite, and Weeping Water) and three emulsions in combination with a number of water contents and fillers to become familiar with the slurry mix characteristics through mixing, consistency, set, cure, water resistance, and wet track abrasion tests (WTAT). Rather extensive study on the shaker test was investigated, and a procedure for the major slurry study (Series 2) was established.

- Series 2 comprised the major part of this study. Thirteen aggregates were studied in combination with two gradings, four emulsions, three emulsion contents, and two mineral fillers. All slurries were tested for mixing stability, set, cure, WTAT, and shaker durability.

- Series 3 was a study on loaded wheel tests (LWT) and California abrasion tests on three aggregates and two emulsions at four emulsion levels.

Table 3. Slurry seal material combinations and levels of study.

Series (Level of Study)[a]	Aggregate															
	1A	1B	2	3	5A	5B	6	7	8	9	10	11D	11F	12A	12B	13
	Garner	Garner	Garner	Ferguson	Conklin	Lithographic	Concrete Sand	Garner	Quartzite	Haydite	Chat	Dolomite	Dolomite	Dallas	Dickinson	Weeping Water
	L_1C[b]	L_1C_1	L_1F	L_2C	L_3	$L_3 + S$	S + FA	$L_1 + S$	Q	H	C	DC	DF	G_1	G_2	L_4
CSS-1h(85)	1,2	2	2	2,3,4	2	2	2,3	2	2	1,2	2	2	2	2,3	2	2
SS-1h	1,2	2	2	2	–	2	2	2	–	2	–	2	2	2	2	1,2
CQS-1h	–	2[c]	–	2*	2*	–	2*	–	2*	1	2*	–	2*	2*	–	–
CSS-1h(40)	–	–	–	2,4	–	–	3	–	–	–	–	2	–	–	–	–

[a]Series 1 (Study level 1): 3 aggregate x 2 emulsion
- Consistency / set / cure / water resistance
- Wet track abrasion test, 3/8 in.
- Shaker durability

Series 2 (Study level 2): 16 aggregates (gradings) x 4 emulsions x 3 emulsion levels
- Mixing and compatibility
- Consistency (cone / funnel)
- Set / cure (cohesion / stain) / curing rate)
- Wet track abrasion test (WTAT), 3/8 in.
- Shaker durability

Series 3 (Study level 3): 3 aggregates x 2 emulsions
- Loaded wheel test
- Abrasion by rubber wheels (California 355-A)
- Abrasion by knurled steel wheels (California 355-C)

Series 4 (Study level 4): 2 aggregates x 2 emulsions x 3 emulsion levels
- Thickness effects on WTAT
- Sand equivalent effects on WTAT
- Percent passing #200 and passing #325 on WTAT
- Compaction effects on WTAT
- Low temperature WTAT

[b]L = Crushed Limestone; FA = Fly Ash; S = Concrete Sand; C = Coarse Grading; F = Fine Grading; G = Gravel; D = Dolomite

[c]Mixing, compatibility, and curing rate only.

- Series 4 was a series of tests designed to study WTAT as affected by slurry thickness, sand equivalent, percent fines, compaction, test temperature, and its repeatability. Two aggregates and two emulsions were used at three emulsion levels.

4.3 Methods and Procedures

Several promising design and testing procedures were evaluated. These included the ISSA procedure using the wet track abrasion test (ISSA, 1975; Kari and Coyne, 1964), the surface area and absorption method (Young, 1973; Harper *et al*., 1965), the California method and its modifications (1967, 1971), the Iowa DOT tentative slurry seal design procedure (1975), and the newly proposed Standard Recommended Practice for Design, Testing and Construction of Slurry Seals under consideration in ASTM Committee D-4 (1976). The "shaker" or "bouncing ball" method developed by the Kansas Highway Department (Delp, 1976; Fiock and McAtee, 1972) and the use of a loaded wheel tester (Benedict, 1975) in testing slurry seal were also studied. Consideration was given in all cases to modifying procedures where deficiencies were noted or where conditions were not suited for Iowa.

5. RESULTS AND DISCUSSIONS

5.1. Aggregates and Emulsions

Results of tests on aggregates are given in Table 4. The Iowa DOT Materials Laboratory supplied data on wet sieve analysis, L. A. Abrasion, soundness, sand equivalent, specific gravity and absorption, P.1 and pH. The Bituminous Research Laboratory, Iowa State University, conducted dry sieve analysis, passing #325 by washing, sand equivalent, centrifugl kerosene equivalent (CKE), voids content (Virginia VTM-5, Appendix A), and chemical analysis by the EDTA titration method. Mr. Jack Dybalski of Armack Co. kindly determined Zeta potential and specific surface on - #325 of five aggregates (Garner, Ferguson, Quartzite, Moscow, and Weeping Water). The Zeta potentials for the four calcareous aggregates ranged from -14 to -20 mV, and that for quartzite was -32 mV. The specific surface by nitrogen adsorption ranged from 0.47 m^2/g for Moscow dolomite to 3.16 m^2/g for Garner. The specific surface for quartzite could not be determined by this method. From chemical analysis it can be seen that the aggregates covered a wide range of materials from limestone (Conklin, Weeping Water, Ferguson, Garner) dolomite (Moscow), to siliceous Chat, Haydite, and quartzite. However, the pH values of the aggregates were in a narrow range between 7.4 for Chat and 9.3 for Ferguson.

Compared with Iowa and ISSA specifications, seven of the blends did not meet gradation requirements for all the sieves, Garner limestone did not meet the sand equivalent requirement of 45, and Conklin limestone did not meet the Iowa freeze and thaw requirement. Results

Table 4. Characteristics of aggregates studied.

Aggregate No. ISU	1 - (L_1C)		1 - (L_1C_1)		2 - (L_1F)		3 - (L_2C)		5 (L_3)		6 (S)		7 (L_1C+S)	
DOT	770		770		770		750		15		752		770 + 752	
Type	Limestone		Limestone		Limestone		Limestone		Limestone		Concrete Sand		Limestone	
Source	Garner		Garner		Garner		Ferguson		Conklin		Hallet		+ Concrete Sand	
Used as	100%		90% 770 10% -100 of 770		- #8 of 770		- #4 of 750		- #4 of 15		90% 752 10% fly ash		70% 770 30% 752	
Gradation % passing	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
1/2 in.	100	100	100	100	100	100	100	100	100	100	100	100	100	100
3/8 in.	100	100	100	100	100	100	100	100	100	100	100	100	100	100
No. 4	92	92	93	93	100	100	100	100	100	100	97	98	93	93
No. 8	66	70	69	73	100	100	56	52	60	58	80	88	69	67
No. 16	47	46	52	50	71	66	34	25	40	39	65	71	51	52
No. 30	35	28	42	34	53	40	27	17	32	29	46	50	37	33
No. 50	26	15	33	23	39	21	22	13	26	24	19	18	21	14
No. 100	19	9	27	16	29	13	18	10	21	19	10	10	13	7
No. 200	14	4	20	8	21	6	15	7	18	15	9	9	10	4
No. 325	9.0		15.6		12.9		6.0		16.2		7.6		5.9	
Sp. Surface of - 325 m2/gm	3.16		--		--		1.45		--		--		--	
Specific Gravity,	2.812		2.812		2.812		2.712		2.662		2.667[c]		2.777[c]	
Sand Equivalent	31[a]		28		30		53[a]		57[a]		98[a]		51[c]	
L.A. Abrasion loss, %	23		23		23		33		23		--		--	
CKE, %	3.7		4.8		4.3		4.25		4.75		2.7		2.95	
Absorption, %	0.34		0.34		0.34		1.30		1.32		0.22		--	
F & T[b], %	4.1		4.1		4.1		3.5		32.0		--		--	
Voids, % #16	54		54		54		53		52		47[h]		51	
#30	56		56		56		55		53		47		52	
#50	57		57		57		54		54		47		53	
Ave.	55.7		55.7		55.7		54		53		47		52	
Total Agg. as received	47		47		47		47		39.4		41		43.3	
pH	8.7		8.7		8.7		9.3		8.4		8.0		--	
Liquid Limit	16		16		16		15		16		N.P.		N.P.	
Plastic Limit	15		15		15		13		14		N.P.		N.P.	
Plasticity Index	1		1		1		2		2		N.P.		N.P.	
Chemical Composition											#752	#768	#770	#752
$CaCO_3$, %	57.7		57.7		57.7		63.2		91.3		27.5	21.5	57.7	27.5
$MgCO_3$, %	31.3		31.3		31.3		27.8		5.8		10.3	3.9	31.3	10.3
Insolubles, %	7.4		7.4		7.4		3.9		1.6		53.3	50.1	7.4	53.3
Specifications	Ia	ISSA	Ia	ISSA	Ia	ISSA	Ia	ISSA	Ia	ISSA	Ia	ISSA	Ia	ISSA
Comparison[g]	Yes	No	No	Yes	No	No	Yes	No	No	No	No	Yes	Yes	No

Aggregate No. ISU	8 (Q)		9 (H)		10 (C)		11 (D)		11 (F)		12 (A)		12 (B)		13	
DOT	765 + 767		--		60		757		757		780		779		722	
Type	Quartzite		Haydite		Chat		Dolomite		Dolomite		Gravel		Gravel		Limestone	
Source	Dell Rapids		Missouri		Kansas		Moscow		Moscow		Dallas		Dickinson		Weeping Water, Neb.	
Used as	60% 765 40% 767		100%		100%		- #4 of 757		- #8 of 757		- #4 of 780		- #4 of 779		100% 722	
Gradation % passing	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
1/2 in.	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
3/8 in.	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
No. 4	92	86	100	100	88	88	100	100	100	100	100	100	100	100	87	90
No. 8	79	73	92	87	55	58	71	69	100	100	70	68	69	66	62	75
No. 16	65	56	57	51	29	30	50	40	71	59	51	48	50	44	42	54
No. 30	54	46	34	30	18	18	38	27	55	39	39	35	37	31	31	40
No. 50	33	29	22	19	13	13	31	19	44	28	30	26	28	22	23	20
No. 100	16	15	15	12	9	8	23	14	33	20	23	17	21	15	18	13
No. 200	8	8	12	8	6	4	18	9	25	14	17	11	15	10	16	9
No. 325	6.3		5.3		5.9		11.7		17.3		9.4		11.0		13.9	
Sp. Surface of - 325 m2/gm	--		--		--		0.47		--		--		--		1.98	
Specific Gravity,	2.649[c]		1.77		2.621		2.793		2.793		2.714		2.739		2.687	
Sand Equivalent	81[c]		87		77		54		54		48		74		46	
L.A. Abrasion loss, %	23		19		--		30		30		26		23		--	
CKE, %	2.5		6.25		2.1		3.65		3.45		4.45		3.5		4.5	
Absorption, %	0.18[c]		14.4		1.32		1.11		1.11		1.42		0.38		0.50	
F & T[b], %	0.2[c]		0.97[d]		--		3.0		3.0		3.5		4.0		--	
Voids, % #16	55[c]		56		54		55		55		54		54		52	
#30	54[c]		56		55		55		55		55		54		53	
#50	53[c]		55		55		55		55		55		56		54	
Ave.	54[c]		55		55		55		55		55		55		53	
Total Agg. as received	41[c]		44.6		42		43		43		41[e]		45[f]		48	
pH	8.1[c]		--		7.4		8.4		8.4		8.7		8.6		8.3	
Liquid Limit	N.P.		N.P.		N.P.		15		15		17		17		15	
Plastic Limit	N.P.		N.P.		N.P.		14		14		16		15		12	
Plasticity Index	N.P.		N.P.		N.P.		1		1		1		2		3	
Chemical Composition																
$CaCO_3$, %	0.0		0.0		1.5		36.1		36.1		14.0		6.0		82.0	
$MgCO_3$, %	0.0		1.2		6.2		60.1		60.1		15.5		4.3		6.9	
Insolubles, %	97.3		97.1		87.5		1.0		1.0		64.5		62.1		6.4	
Specifications	Ia	ISSA	Ia	ISSA	Ia	ISSA	Ia	ISSA	Ia	ISSA	Ia	ISSA	Ia	ISSA	Ia	ISSA
Comparison[g]	No	Yes	No	Yes	No	No	No	No	No	No	No	No	Yes	Yes	No	Yes

[a]SE run on total aggregate
[b]% psg. No. 8 after 16 cycles F & T, water-alcohol solution
[c]Weighted avg.
[d]Freeze-thaw, 25 cycles
[e]on - 3/8 in.
[f]on - #8
[g]Yes: meets gradation specs; No: Does not meet gradation specs
[h]For concrete sand (752)

of tests on asphalt emulsions are given in Table 5. Some settlement occurred in CSS-1h (Iowa) as evidenced by the low viscosity at 77 °F and low asphalt residue content. Special efforts had to be made to stir the settlement back into suspension for this particular emulsion.

5.2 Preliminary Tests (Series 1)

Three aggregates (Weeping Water limestone and Haydite and Ottawa sand) were used in conjunction with three emulsions to become familiar with the mixing, consistency, cohesion, funnel flow, shaker, and wet track abrasion tests and to finalize some of the test procedures to be followed in Series 2.

A number of equipment items were fabricated at the ERI Machine Shop. These included shaker tester sample retainers (Photo 1), a WTAT set-up (Photo 2) and hose cutting device, a cohesion tester, and various contact adopters (Photo 3). A loaded wheel tester was rented from Benedict Slurry Seal, Inc., of Dayton, Ohio (Photo 4). In addition, a California rubber wheel abrader and a California knurled wheel abrader were made for use with a modified Hobart C-100 which can drive the abrader at 63 rpm (Photo 5).

A significant development in the early stages of this project was the adoption of a standard Gilson shaker for the slurry wear/durability test using 4-in. diameter cans. Because the capability of testing a large number of specimens and the general availability of this basic equipment in most highway laboratories, this test, when correlated with either WTAT and/or field test results, can be readily adopted as a routine slurry design/control test by most laboratories.

Table 5. Properties of emulsified asphalts.

	CSS - 1 h	SS - 1 h	CQS - 1 h	CSS - 1 h (40)
Viscosity, SSF, @ 77 °F	14.8	31.1	21.5	23.1
Wt./Gal. lbs.	8.41	8.49	8.29	8.39
Solubility in trichloroethylene	99.76	99.71	99.67	--
Asphalt content, % by Wt.	56.1	64.6	63.5	62
Penetration of residue, - 77/100/5	81	52	65	69
Particle charge test	Positive	Negative	Positive	Positive
Viscosity of residue @ 140 °F, p.	--	4040	2030	1870
@ 275 °F, cs	--	659	359	384
pH	--	9.9	5.4	4.9

Photo 1. Shaker durability test.

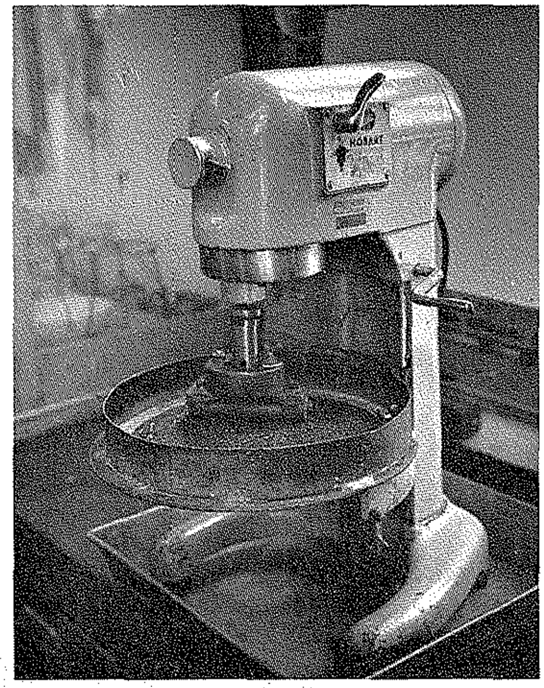

Photo 2. Chevron WTAT: rubber hose.

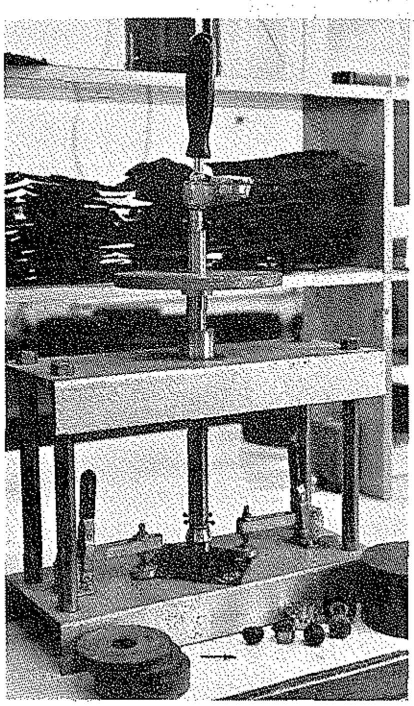

Photo 3. Cohesion tester.

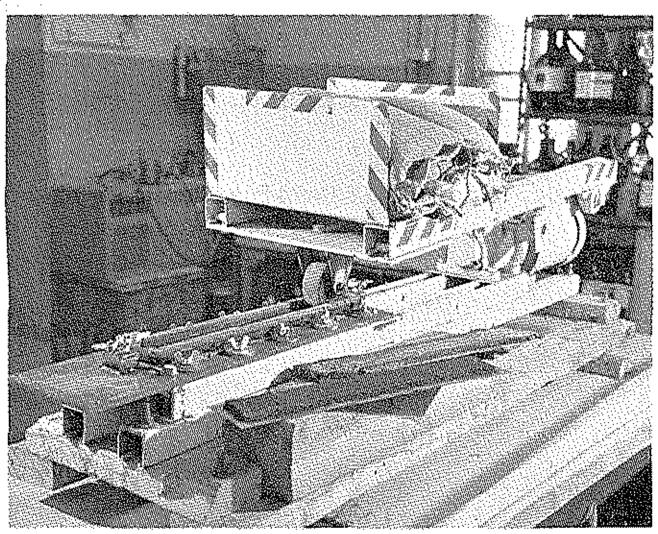

Photo 4. Loaded wheel tester with sand frame in position. Specimens before and after test are shown in foreground.

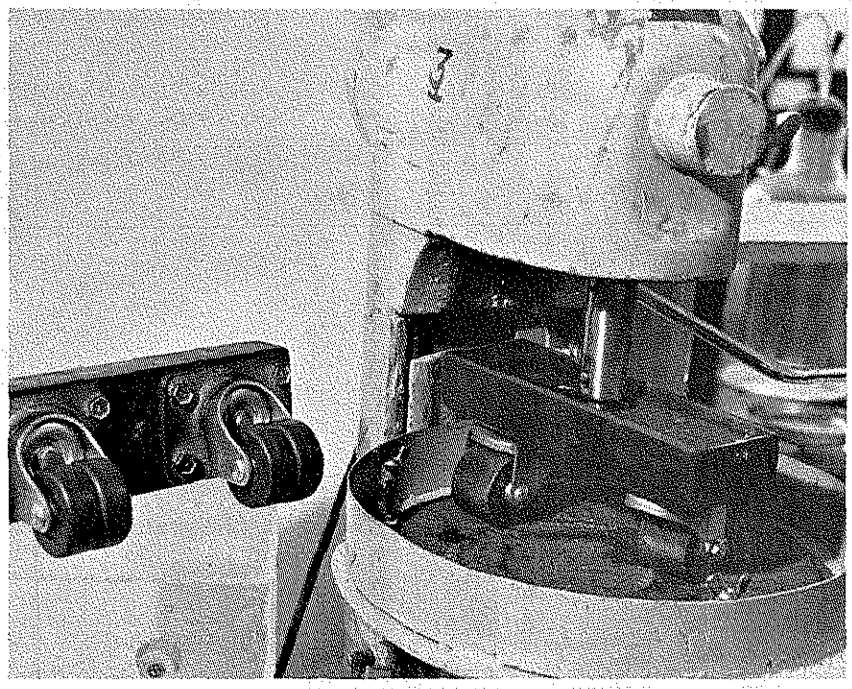

Photo 5. California WTAT with knurled wheels in test position and rubber wheel abrading head on the left.

After a considerable number of exploratory trials, varying shaking time, quantity of sand and water, number, type, and size of balls (four to eight 1-1/8-in., 60 durometer Buna S rubber balls, four to eighteen 1/2-in. steel balls, four to eight 3/4-in. steel balls), and treatment of specimens, the following operating conditions were adopted (Appendix B):

- Slurry specimen thickness: 1/4 in.
- Slurry treatment before each shaking: 90 min in a freezer at -10 °F.
- Shaking with 50 g ice water (35 ± 2 °F) and 50 g ASTM C 190 sand.
- Two shaking periods of 30 min each, weight loss determined after each shaking.

It is believed that this procedure can produce more repeatable results in less time than other conditions and is sensitive to changes in a wide range of slurry compositions. Figures 1-3 show the results of shaker tests over a range of emulsion contents and operating conditions.

Experiments with set time by paper stain/blot method, cure time by cohesion test (Appendix D), and penetration test with modified grease penetration cone, funnel flow test, and water resistance were less successful. The paper stain test was found to be too dependent on subjective judgment; the penetration test, funnel flow test, and water resistance test were not repeatable. It was concluded that these tests need to be modified and/or refined.

The cohesion test was tried on many specimens under loading conditions with various contact adopters. Weights varying between

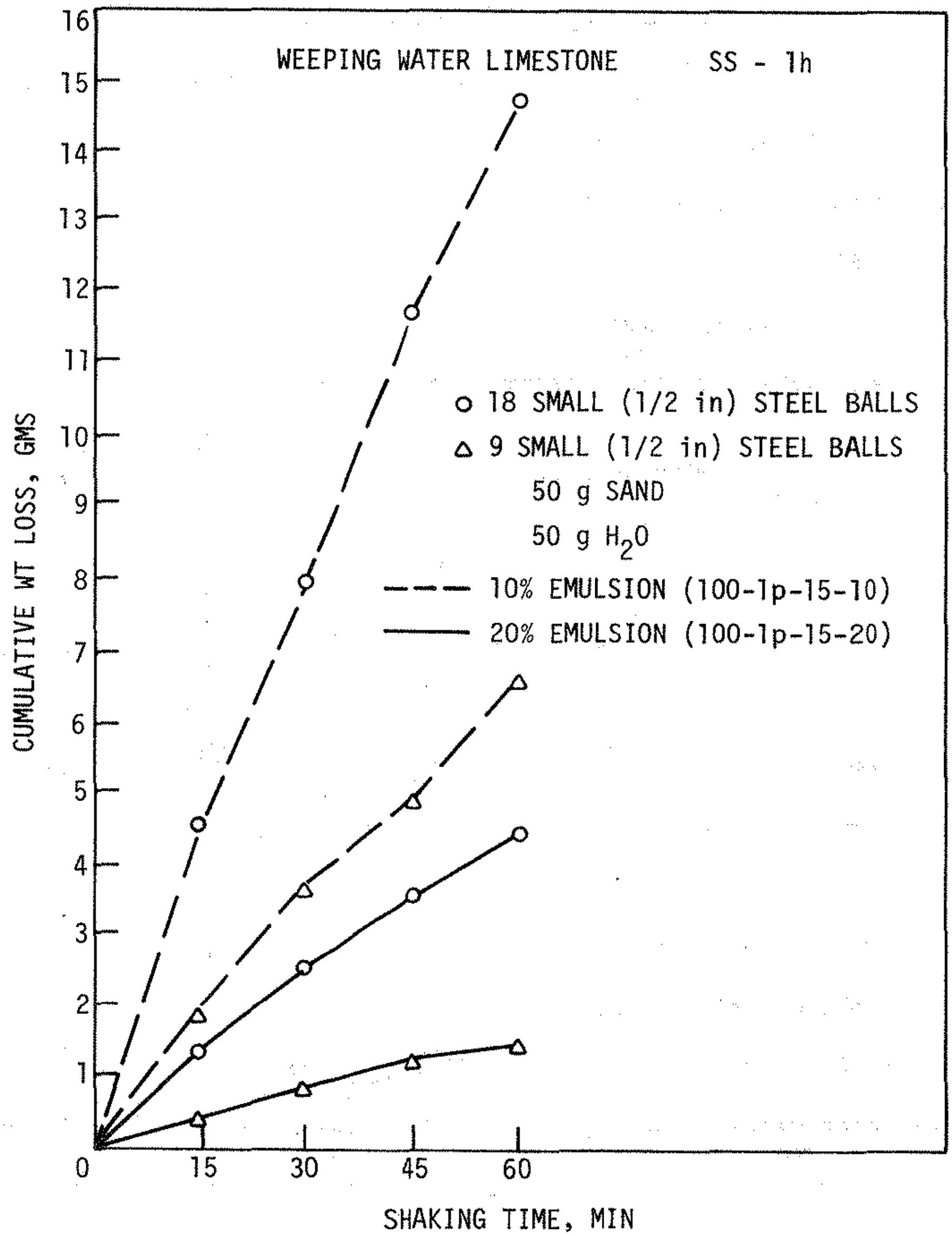

Fig. 1. Shaker test, 9 vs 18 small steel balls (Weeping Water/SS-1h).

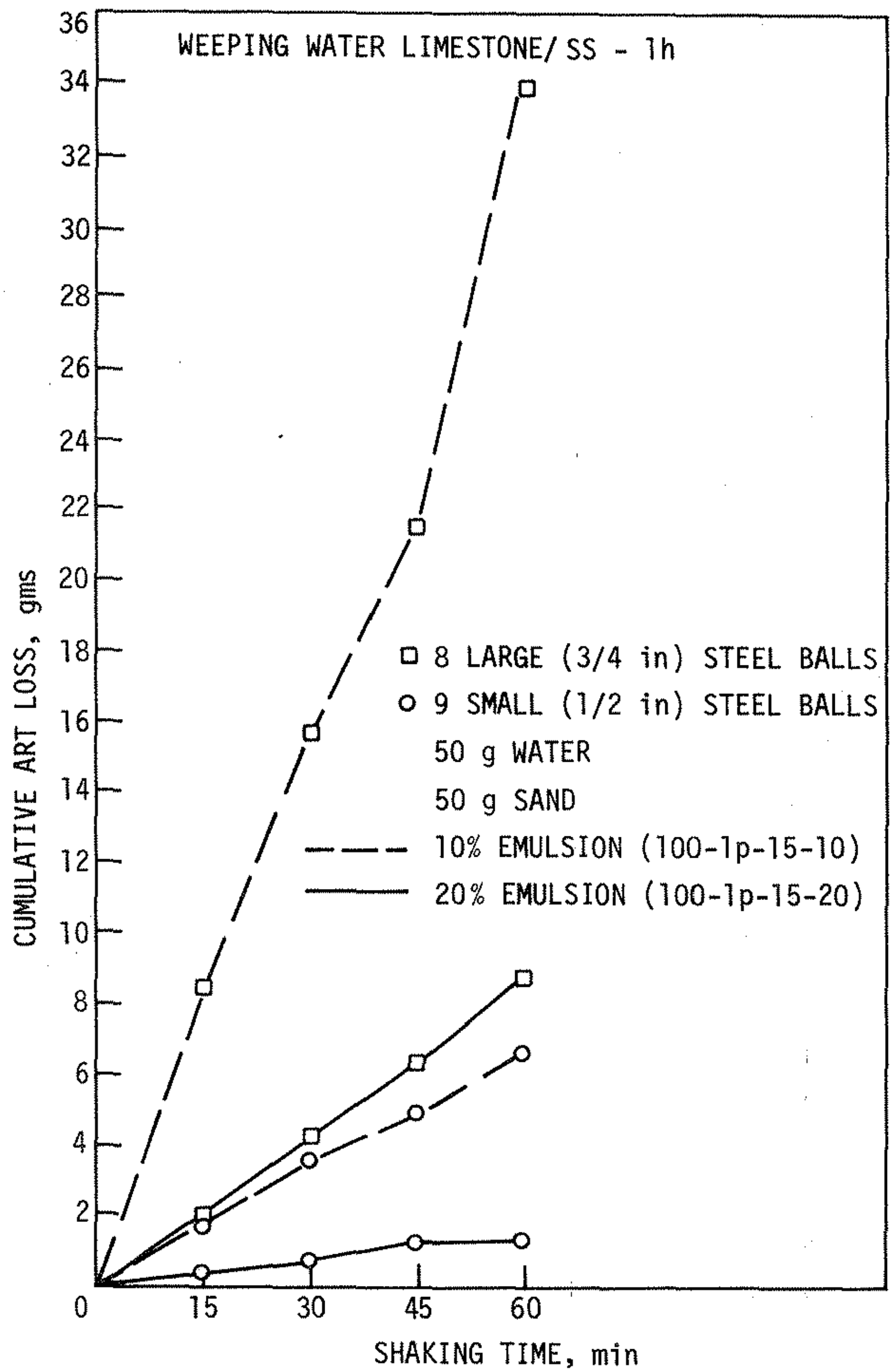

Fig. 2. Shaker test, eight large vs nine small balls (Weeping Water/ SS-1h).

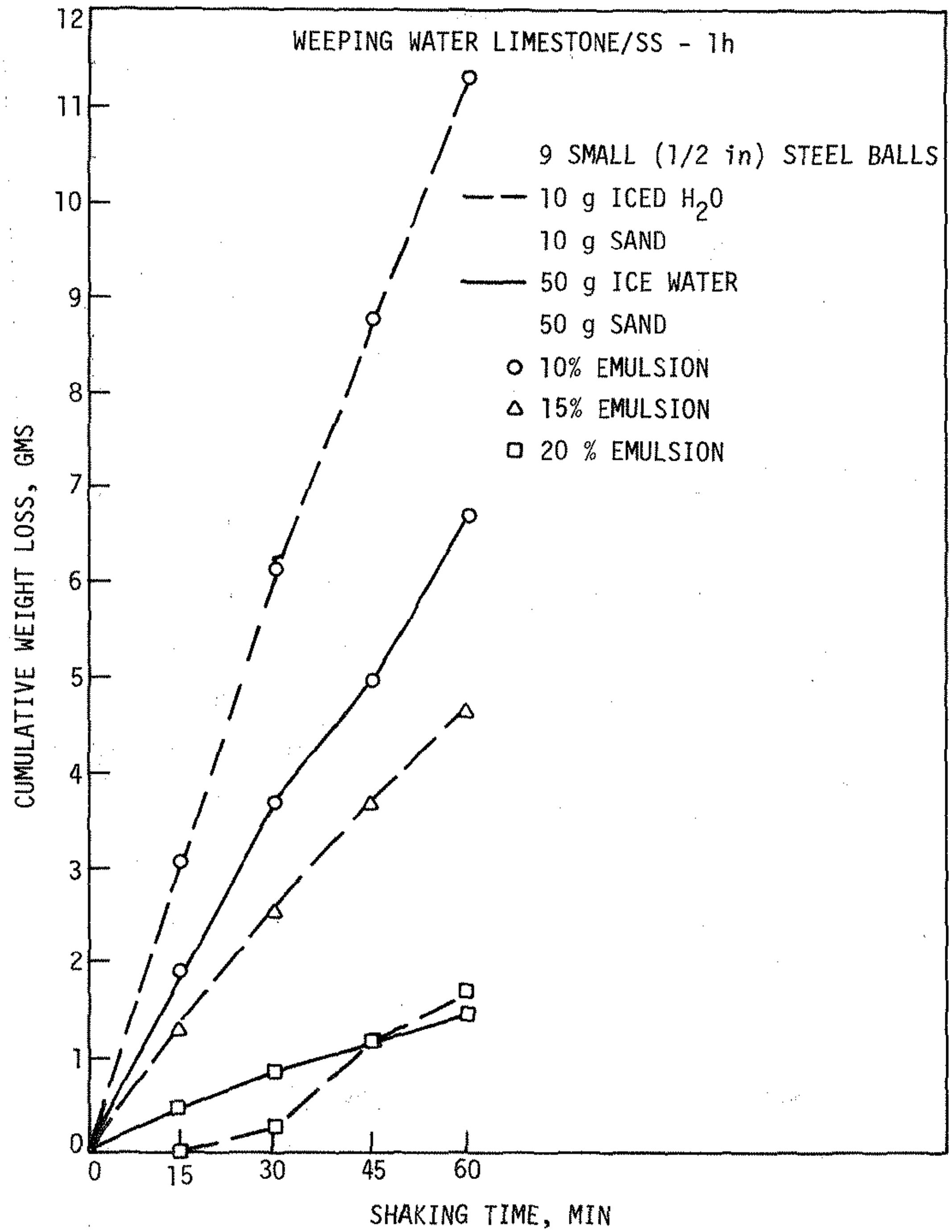

Fig. 3. Effects of water and sand on shaker test (Weeping Water/SS-1h).

4.4 and 29 lbs were tried with four adopters of different contact faces (flat hard rubber, spherical hard rubber, abrasive-coated face, and portable Torvane soil shear device). No meaningful and repeatable torque versus time measurements could be obtained. Although this approach to determining cure time seemed sound, the operating conditions and/or contact adopter need to be refined. Curing (weight loss vs time) curves of some 1/4-in. slurry pads were determined and seemed to indicate curing characteristics of slurries. It was determined that two 1/4-in. x 4-in. diameter slurry pads would be made; one would be used to determine cohesion versus time curve with a 20-lb weight on a 1-1/8-in. 60 durometer rubber ball, and the second one would be used to determine the percent weight loss versus time curve. An alternative to the cohesion (torque) test would be a simple cohesion/tensile strength test such as Hveem cohesiometer. It is recommended that such an approach to curing rate be evaluated in Phase II (field test) of this project.

Microscopic examinations of slurry at various curing times were also tried. Although stages of break, set, and coating of particles could be observed, they could not be quantified. However, this approach also holds potential and should be further explored in Phase II.

5.3 Slurry Characteristics of Major Material Combinations (Series 2)

This was the major emphasis of the laboratory phase of the slurry test, consisting of 16 aggregates (grading) and three emulsions (31 aggregate/emulsion combinations, each at three emulsion content levels). In all a total of 400 mixing/consistency tests, 90 cohesion/curing tests, and 260 WTAT and 170 shaker tests were conducted.

The general procedure of slurry preparation and testing for each aggregate/emulsion combination was as follows:

a. Estimate the theoretical residue (emulsion) requirement (Et) based on surface area/absorption method for an 8-μm coating (Appendix E, p. (81).

b. Run cup mixing test on a 100-g aggregate sample using the calculated emulsion requirement (Et) to estimate optimum prewet water content, filler requirement, and mixing time. Adjust emulsion content for added filler and note the mixing characteristics (such as creaminess, stiffening, separation, coating, foaming, etc.). (Appendix E, p. 82).

c. Determine optimum mix-water content for three levels of emulsion content of 0.8 Et, 1.00 Et, and 1.2 Et for 2.5-cm cone consistency (Appendix E, p. 83).

d. Run cohesion and weight loss tests versus time at 0.8 Et, 1.0 Et, and 1.2 Et at corresponding water content at 2-3 cm flow.

e. Run shaker test on duplicate samples and WTAT on triplicate samples on cured slurries at 0.8 Et, 1.0 Et, and 1.2 Et.

The results of the slurry composition and properties of these 85 slurries [except those for CSS-1h (40-90 pen)] are tabulated in Table 6.

5.3.1 <u>Mixing, Compatibility and Curing</u>

The key to good slurry, both for placement and service durability, is that the ingredients are compatible and can be made into a creamy,

Table 6. Compositions and properties of slurry mixes (Series II).

Aggregate	Garner 1A(L_1C)			Garner 1B(L_1C_1)			Garner 2(L_1F)			Ferguson 3(L_2C)			Conklin Lithographic 5A(L_3)			Conklin Lithographic 5B(L_3 + S)		
ISU #																		
DOT #	770			90% 770 10% (-#100 of 770)			-#8 of 770			-#4 of 750			-#4 of 15			50% -#4 of 15; 50% Concrete Sand		
Slurry Composition																		
% Aggregate	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
% Filler/Type	1/P.C.	1/P.C.	1/P.C.	2/P.C.	2/P.C.	2/P.C.	1/P.C.	1/P.C.	1/P.C.	1/H.L.	1/H.L.	1/H.L.	4/P.C.	4/P.C.	4/P.C.	2/P.C.	2/P.C.	2/P.C.
													.3/E-11	.3/E-11	.3/E-11	1.5/E-11	1.5/E-11	1.5/E-11
% H_2O	23	23	20	21	21	21	21	21	22	26	24	22	15	10	10	7	7	6
% Emulsion, CSS-1h	10	12	14	14	17	21	13	16	19	10	12	14	19	23	27	13	16	19
Cone Flow, cm	4	3.2	2	3	3.5	3	2.7	3	3.2	2.5	2.9	2	3.9	2.9	2	3	3.3	3.4
Shaker Test[a]																		
Loss after 30 min, g	30.6	23.9	12.9	6.5	5.2	5.2	13.4	9.7	8.4	1.3	1.8	2.8	0	0	5.6	13.2	3.5	0
Loss after 60 min, g	50.2	48.4	17.6	11.8	7.4	6.7	24.8	15.7	19.6	3.1	3.4	4.3	0	0	12.7	20.4	4.5	0
WTAT[b]																		
Loss, g/ft^2	860	441	210	261	172	102	378	168	212	62	38	46	185	93	129	629	100	110
Slurry Composition																		
% Aggregate	100	100	100	100	100	100	100	100	100	100	100	100	--	--	--	100	100	--
% Filler/Type	0	0	0	0	0	0	0	0	0	0	0	0	--	--	--	3/H.L.	3/H.L.	--
% H_2O	17	16	13	16	14	14	16	15	14	14	11	9	--	--	--	8	7	--
% Emulsion, SS-1h	9	11	13	12	15	19	12	15	18	9	11	13	--	--	--	14	17	--
Cone Flow, cm	2.5	3.8	4	3	2.2	2.4	2.2	3	3.2	1.9	2.9	2	--	--	--	1.9	4	--
Shaker Test[a]																		
Loss after 30 min, g	12.6	6.2	5.1	7.2	5.2	4.9	13.1	9.9	6.6	7.0	3.7	3.5	--	--	--	2.3	.7	--
Loss after 60 min, g	21.7	10.1	7.7	12.8	8.0	7.4	23.6	17.1	10.1	11.9	5.4	5.6	--	--	--	3.8	--	--
WTAT[b]																		
Loss, g/ft^2	202	100	78	139	99	64	208	141	90	144	73	47	--	--	--	23	8	--

[a]Sample frozen 90 min, shake with 50 g water at 30 °F, 50 g ASTM C190 sand and 9-1/2 inch steel balls; average of duplicate sample.

[b]Average of 3 samples; sample abraded 5 min in 77 °F water with a rubber hose.

Table 6. (Continued)

Aggregate	Concrete Sand and Fly Ash			Garner and Concrete Sand			Quartzite			Handite			Chat			Moscow Dolomite		
ISU #	6(S)			$7(L_1C + S)$			8(Q)			9(H)			10(C)			11(D)		
DOT #	90% 752 10% 768			70% 770 30% 752			60% 765 40% 767			--			10			-4 of 757		
Slurry Composition																		
% Aggregate	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
% Filler/Type	1/P.C.	1/P.C.	1/P.C.	1/H.L.	1/H.L.	1/H.L.	1/P.C.	1/P.C.	1/P.C.	1/H.L.	1/H.L.	1/H.L.	2p	2p	2p	1/H.L.	1/H.L.	1/H.L.
% H_2O	17	15	12	23	23	21	13	12	12	60	60	60	15	14	14	22	24	24
% Emulsion, CSS-1h	12	15	18	9	11	12	13	16	19	24	26	28	11	16	21	13	16	19
Cone Flow, cm	5	4	3	3.5	3.5	2	3	4	3.5	3	3.5	1.5	1.5	2.2	3	2.5	3	1.5
Shaker Test[a]																		
Loss after 30 min, g	1.8	2.2	3.0	8.2	7.4	8.7	10.6	4.1	2.9	1.0	4.8	1.4	7.4	1.7	0.4	1.9	0.8	1.9
Loss after 60 min, g	2.7	3.3	4.3	16.2	13.2	13.5	16.8	6.3	4.3	0.9	5.6	2.9	11.9	2.6	0.2	3.8	1.0	2.9
WTAT[b]																		
Loss, g/ft^2	37	36	28	344	156	248	175	171	185	152	164	135	315	163	33	77	39	85
Slurry Composition																		
% Aggregate	100	--	--	100	100	100	--	--	--	100	100	--	--	--	--	100	100	100
% Filler/Type	1/H.L.	--	--	0	0	0	--	--	--	1/P.C.	1/P.C.	--	--	--	--	0	0	0
% H_2O	10	--	--	14	13	10	--	--	--	9	6	--	--	--	--	11	9	7
% Emulsion, SS-1h	12	--	--	8	10	12	--	--	--	34	42	--	--	--	--	12	15	18
Cone Flows, cm	3.7	--	--	2	2.5	2	--	--	--	3.2	4.5	--	--	--	--	2.2	4	5
Shaker Test[a]																		
Loss after 30 min, g	0.7	--	--	12.1	4.4	5.8	--	--	--	0	0	--	--	--	--	4.7	3.7	2.5
Loss after 60 min, g	1.5	--	--	21.2	9.4	8.8	--	--	--	0	0	--	--	--	--	7.4	6.0	3.8
WTAT[b]																		
Loss, g/ft^2	0	--	--	83	46	85	--	--	--	51	28	--	--	--	--	63	30	52

[a]Sample frozen 90 min, shake with 50 g water at 30 °F, 50 g ASTM C190 sand and 9-1/2 inch steel balls; average of duplicate sample.

[b]Average of 3 samples; sample abraded 5 min in 77 °F water with a rubber hose.

Table 6. (Continued)

Aggregate	Moscow Dolomite			Dallas Gravel			Dickinson Gravel			Weeping Water		
ISU #	11(F)			12(A)			12(B)			13		
DOT #	-8 of 757			-4 of 780			-4 of 779			722		
Slurry Composition												
% Aggregate	100	100	100	100	100	100	100	100	100	100	100	100
% Filler/Type	1/H.L.	1/H.L.	1/H.L.	2/H.L.	2/H.L.	2/H.L.	1/H.L.	1/H.L.	1/H.L.	1/H.L.	1/H.L.	1/H.L.
% H_2O	30	26	24	26	33	37	27	30	32	25	27	29
% Emulsion, CSS-1h	18	22	26	20	23	27	14	22	26	13	16	21
Cone Flow, cm	4.5	2.8	3.2	2	3.2	3.2	2.8	2.5	3	1.9	2.7	1.8
Shaker Test[a]												
Loss after 30 min, g	5.6	3.4	2.5	0	0.8	0	3.7	1.4	0.6	3.8	2.3	0.2
Loss after 60 min, g	8.4	5.6	4.5	0.7	1.5	0	5.8	2.2	1.1	6.9	4.4	0.9
WTAT[b]												
Loss, g/ft^2	112	84	57	46	37	62	116	41	31	102	69	33
Slurry Composition												
% Aggregate	100	100	100	100	100	100	--	100	--	--	100	--
% Filler/Type	0	0	0	0	0	0	--	1/H.L.	--	--	0	--
% H_2O	13	9	7	13	10	9.5	--	10	--	--	12	--
% Emulsion, SS-1h	17	21	25	18	23	27	--	22	--	--	15	--
Cone Flow, cm	2	3.2	4	3.2	2.5	2.7	--	--	--	--	2.2	--
Shaker Test[a]												
Loss after 30 min, g	7.5	4.7	4.1	4.7	3.5	2.9	--	0.8	--	--	4.8	--
Loss after 60 min, g	10.2	6.9	1.6	7.9	5.2	4.9	--	1.2	--	--	8.1	--
WTAT[b]												
Loss, g/ft^2	85	47	67	51	36	35	--	33	--	--	70	--

[a] Sample frozen 90 min, shake with 50 g water at 30 °F, 50 g ASTM C190 sand and 9-1/2 inch steel balls; average of duplicate sample.

[b] Average of 3 samples; sample abraded 5 min in 77 °F water with a rubber hose.

fluid, homogeneous, and stable slurry. The following discussion concerns this aspect of results:

- Except for Garner limestone and Conklin lithographic limestone, all the other aggregates could be made into slurries with CSS-1h at proper pre-wet water content and type and amount of filler. Redicote E-11 was needed for a satisfactory slurry with Conklin/CSS-1h combination. The cured Garner/CSS-1h specimen had spotty appearances, indicating that the emulsion might have been broken during mixing, resulting in an uneven coating. This result may be due to the high specific surface of Garner (3.16 m^2/g) and the high percent of Conklin passing No. 325 sieve. The cured Conklin/CSS-1h slurries with Redicote E-11 and with 2% hydrated lime as additives are compared in Photo 6.

- Although no satisfactory slurry could be made with SS-1h and three siliceous aggregates (quartzite, Haydite, and Chat), SS-1h was much easier to work with than CSS-1h. In most cases, filler was not required. In contrast, CSS-1h is more touchy, and the proper prewet water content and some type of filler is required. Again, there were difficulties in making Garner/SS-1h and Conklin/SS-1h slurries. The differences in appearance of cured Quartzite slurries made with CSS-1h, SS-1h and CQS-1h emulsions are shown in Photo 7.

- There was a general trend of increasing cohesion (torque) and then leveling off with time for all slurries, but the test was not repeatable.

- Curing (drying) curves for some of the slurries are shown in Fig. 4. Although CQS-1h slurries showed quick-set characteristics as indicated by points of inflection occurring at shorter cure time, no significant differences could be observed between SS-1h and CSS-1h. In all cases constant weight could be reached (at 77 °F and 50% humidity) within 24 hr. However, the attainment of constant weight may not indicate that the slurry is cured in the sense that aggregate particles are coated and cohesion (bond) is established between bitumen and aggregate. This was evidenced by breaking the slurry after one day and after four days as shown in Photo 8. Photo 9 shows the initial cured (right half of specimen 10 and left half of specimen 12) and final cured (left half of specimen 10 and right half of specimen 12) slurries of Chat and Haydite with CSS-1h. A possible alternative for determining cure time for traffic control is to determine total moisture content in the slurry at various curing times instead of moisture loss, and to establish, either in the laboratory or in the field, the maximum moisture content that can be tolerated by slurries made with different types of emulsions in order for them to resist traffic load.

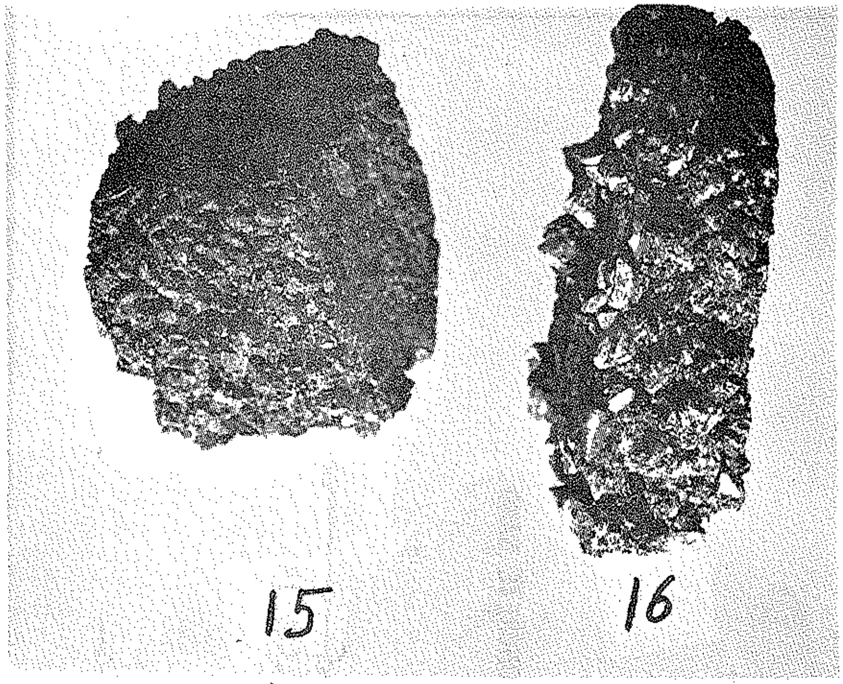

Photo 6. Cured Conklin/CSS-1h slurries with 0.2% Redicote E-11 (15) and with 2% hydrated lime (16).

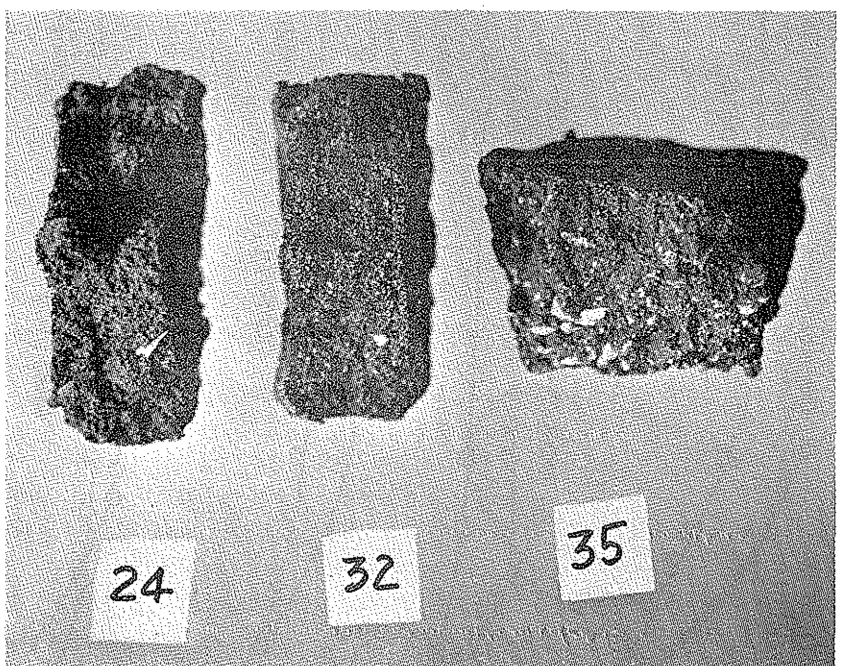

Photo 7. Cured quartzite slurries made with CSS-1h (24), SS-1h (32) and CQS-1h (35).

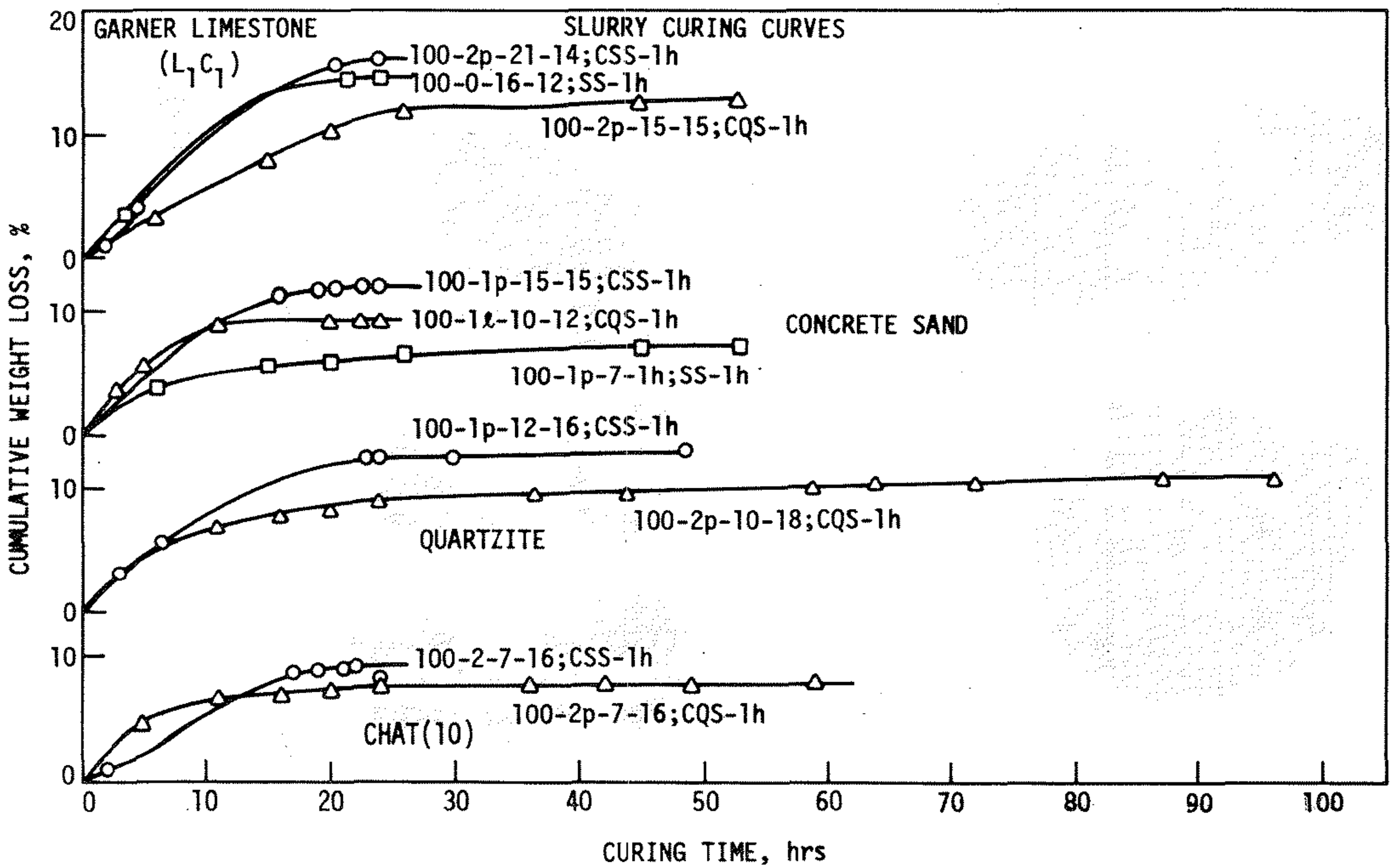

Fig. 4. Typical slurry curing curves.

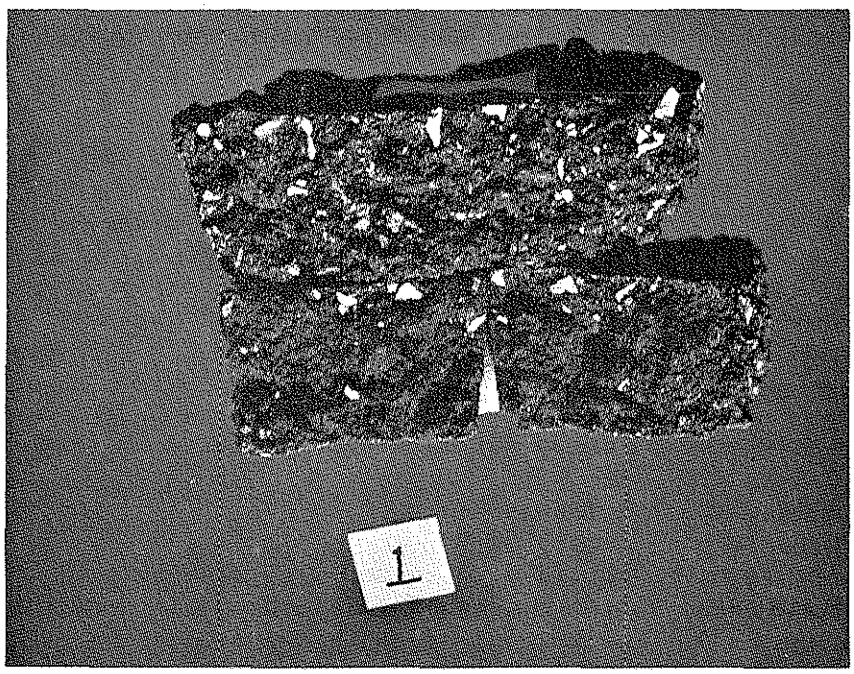

Photo 8. Conklin limestone/CSS-1h; one-day cure (top) and four-day cure (bottom).

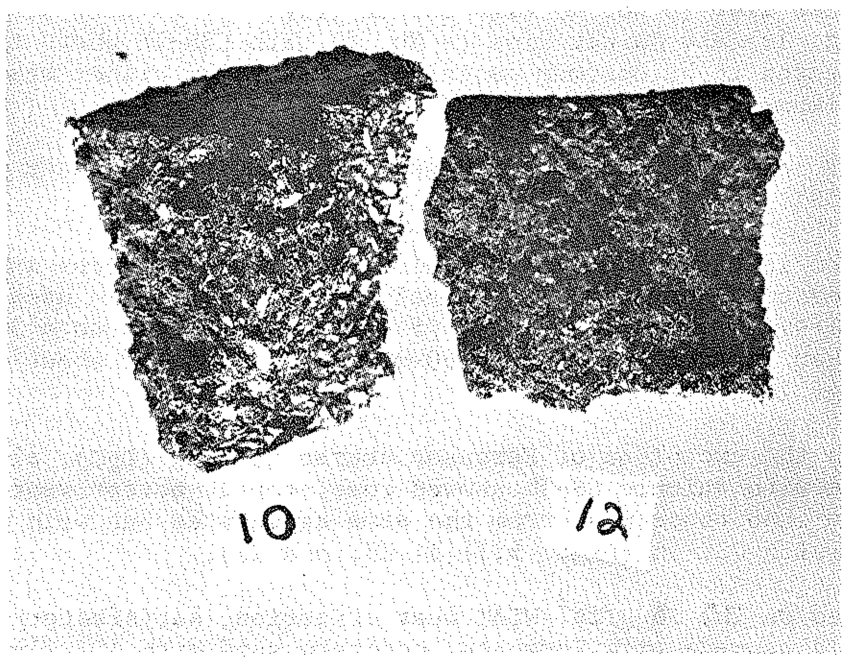

Photo 9. Initial (1-day) and final (4-day) breaking faces of Chat (10) and Haydite (12) with CSS-1h.

- The importance of pre-wet water content when working with CSS-1h is shown in Photos 10 and 11. In both cases, although total mixing water and emulsion contents were the same, insufficient prewet water content resulted in premature breakage of the emulsion and poor slurries.

- Although either portland cement or lime can be used in making stable slurry, for some aggregates, especially when in combination with CSS-1h, hydrated lime resulted in better slurries. Photo 12 shows the differences in appearance of cured Ferguson/CSS-1h slurries containing no filler, 1% portland cement and 1% hydrated lime.

5.3.2 Mechanical Properties of Cured Slurries

Wear resistance of cured slurries was evaluated by shaker test and WTAT. Major observations are:

- Shaker loss, in general, increases with shaking time and decreases with emulsion content; neither relationship is consistently linear (Figs. 5-13). The exceptions to this statement were Conklin limestone with CSS-1h (Fig. 8) and concrete sand plus fly ash with CSS-1h (Fig. 10), where shaker loss increased with increasing emulsion content, and Garner limestone with concrete sand (Fig. 7), Dallas fine (- No. 4) with CSS-1h (Fig. 9), Haydite with CSS-1h (Fig. 10) and Garner fine (- No. 8) with CSS-1h where there appeared to be optimum emulsion contents for either maximum or minimum loss.

- WTAT loss, in general, decreases with emulsion content (Figs. 14-18).

- There is significant correlation between shaker loss and WTAT based on linear regression analyses. The commonly used slurry seal WTAT wear criterion of 75 g/ft^2 corresponds to a 30-min shaker loss of 2.7 g and a 60-min shaker loss of about 4.0 g (Fig. 19).

- With the exception of Ferguson coarse grading (L_2C), slurries made with anionic SS-1h showed consistently better wear resistance than those made from the same aggregates but with cationic emulsion CSS-1h (Figs. 5,11,14,15, and 17).

- Based on the 75 g/ft^2 WTAT wear criterion, satisfactory slurries could be made with Ferguson, concrete sand with 10% fly ash, Haydite, Chat, and Moscow dolomite, both gravels and Weeping Water limestone, but not with Garner, Conklin, lithographic limestone, and quartzite.

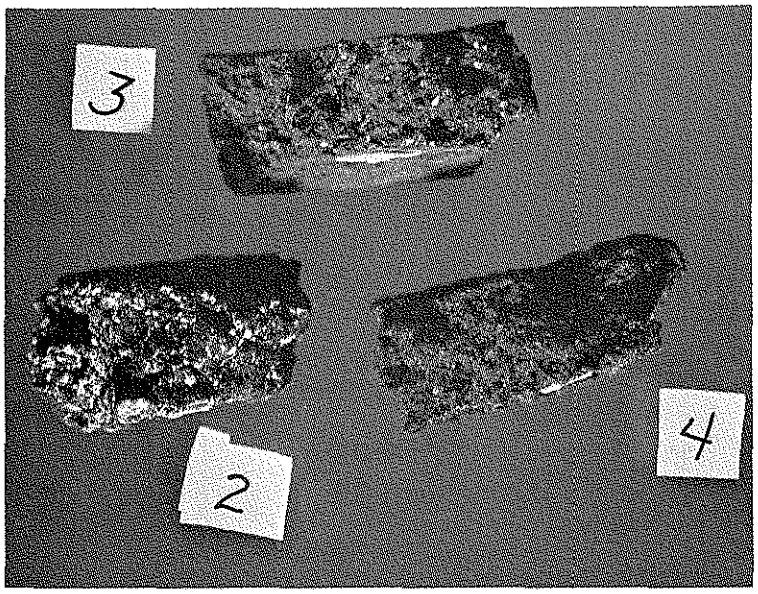

Photo 10. Weeping Water limestone/CSS-1h.
2: Insufficient prewet water content (13%)
3: Opt. prewet water content (20%) and 1% p.c.
4: Opt. prewet water content (17%) and 1% lime.

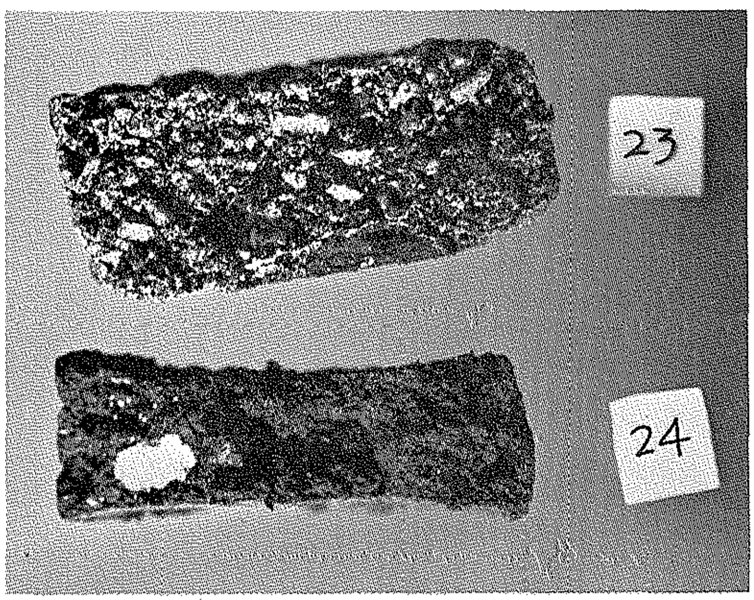

Photo 11. Quartzite/CSS-1h
Effects of preset water content in adequate water content (top) and adequate water content (bottom).

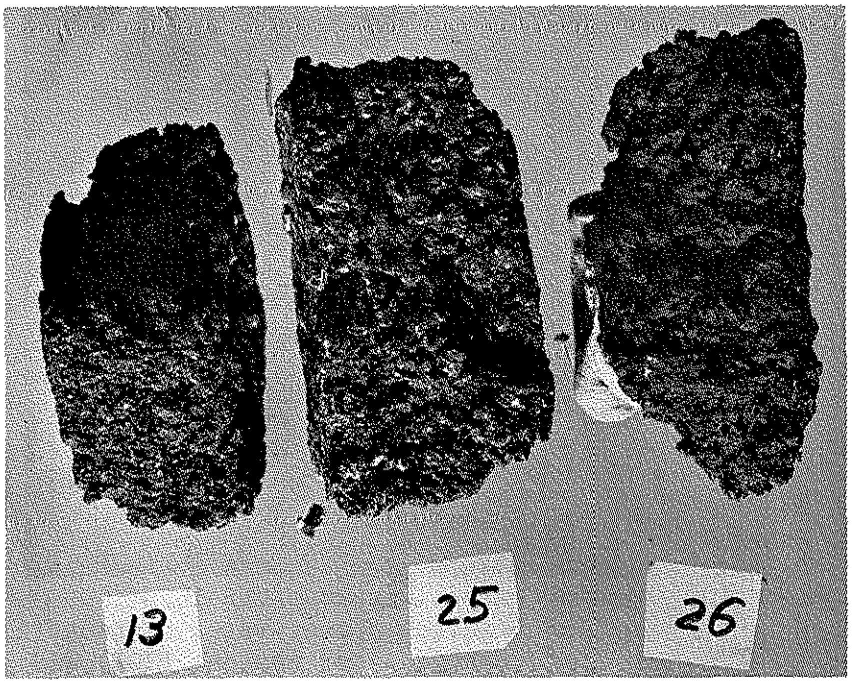

Photo 12. Effects of filler type on the cured slurries made with Ferguson limestone and CSS-1h: No filler (13), 1% portland cement (25) and 1% hydrated lime (26).

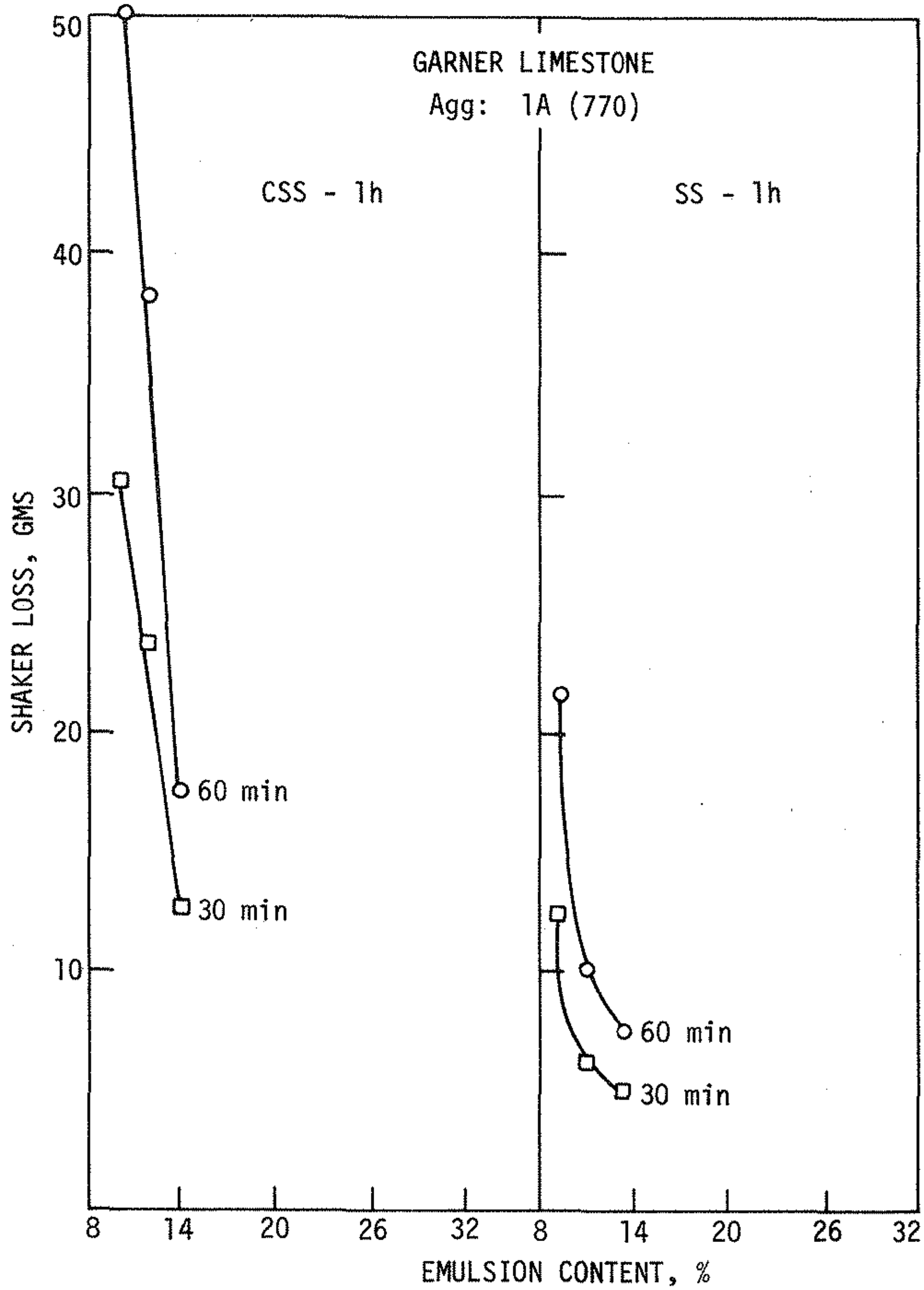

Fig. 5. Shaker loss vs emulsion content, Garner limestone.

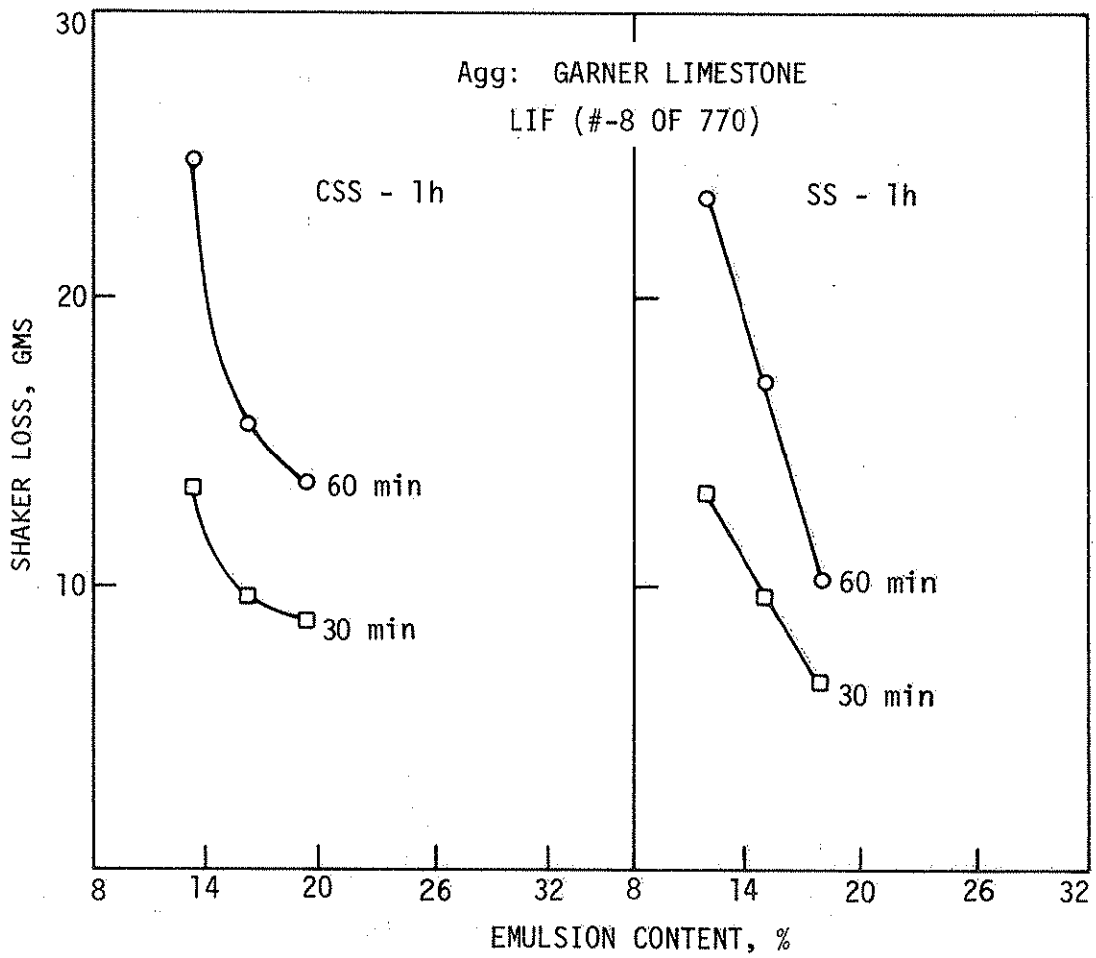

Fig. 6. Shaker loss vs emulsion content, Garner fine (L_1F).

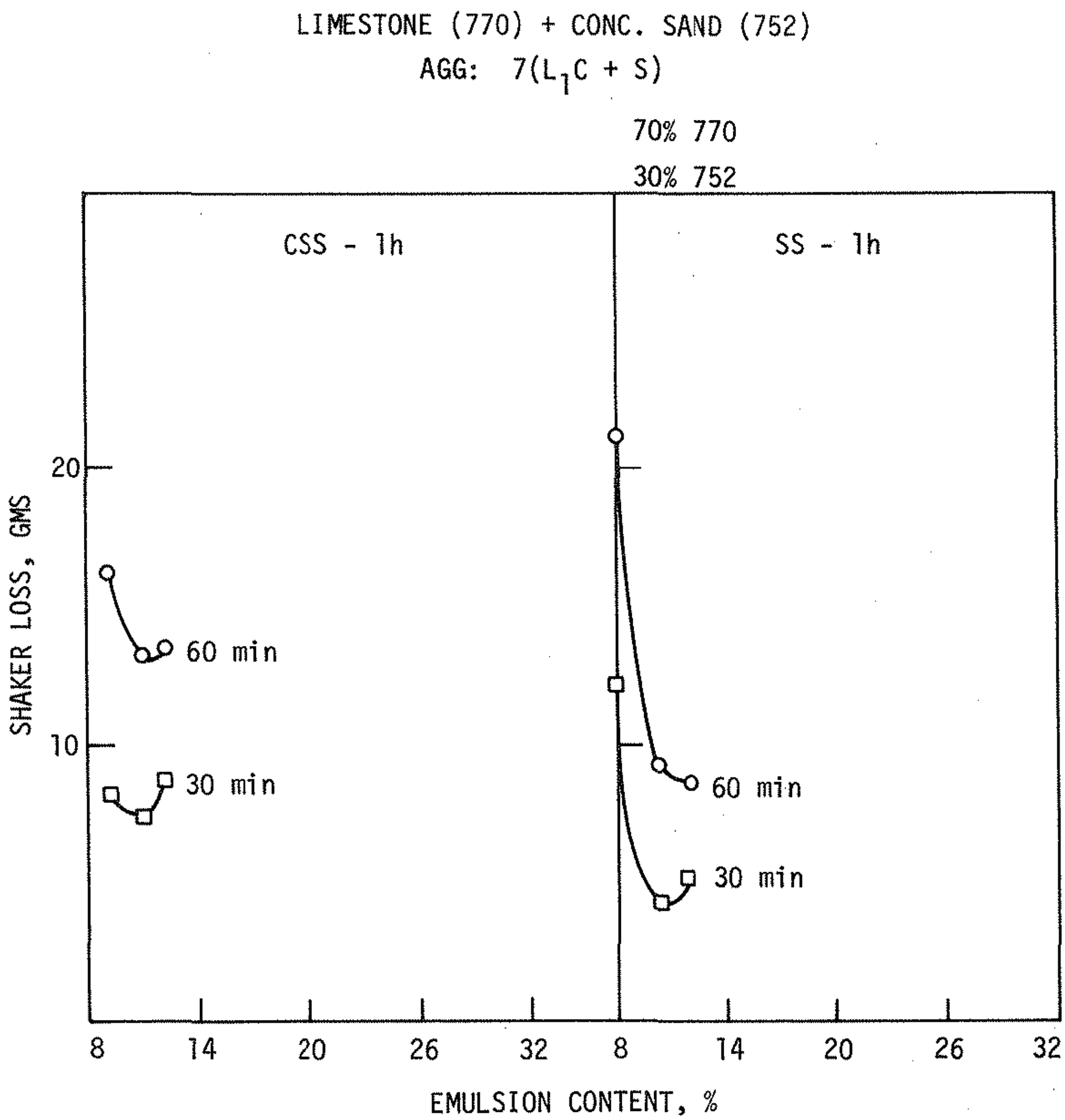

Fig. 7. Shaker loss vs emulsion content, Garner plus concrete sand ($L_1C + S$).

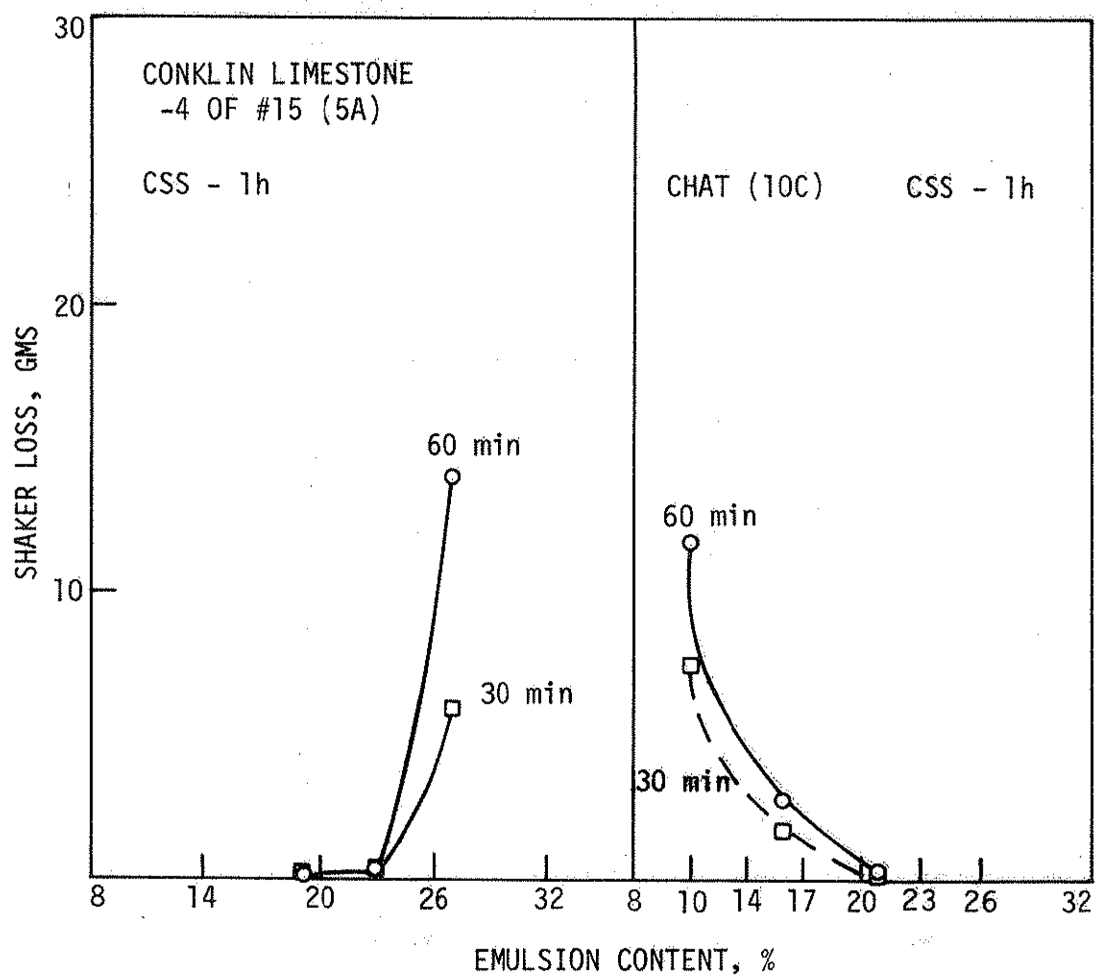

Fig. 8. Shaker loss vs emulsion content, Conklin limestone.

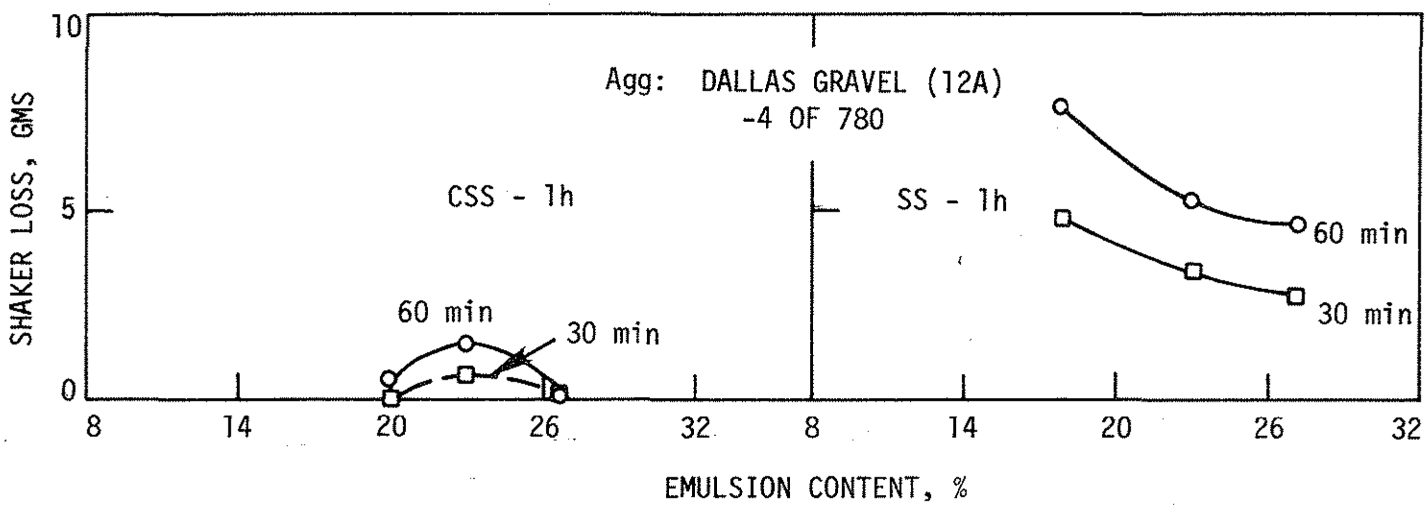

Fig. 9. Shaker loss vs emulsion content, Dallas gravel.

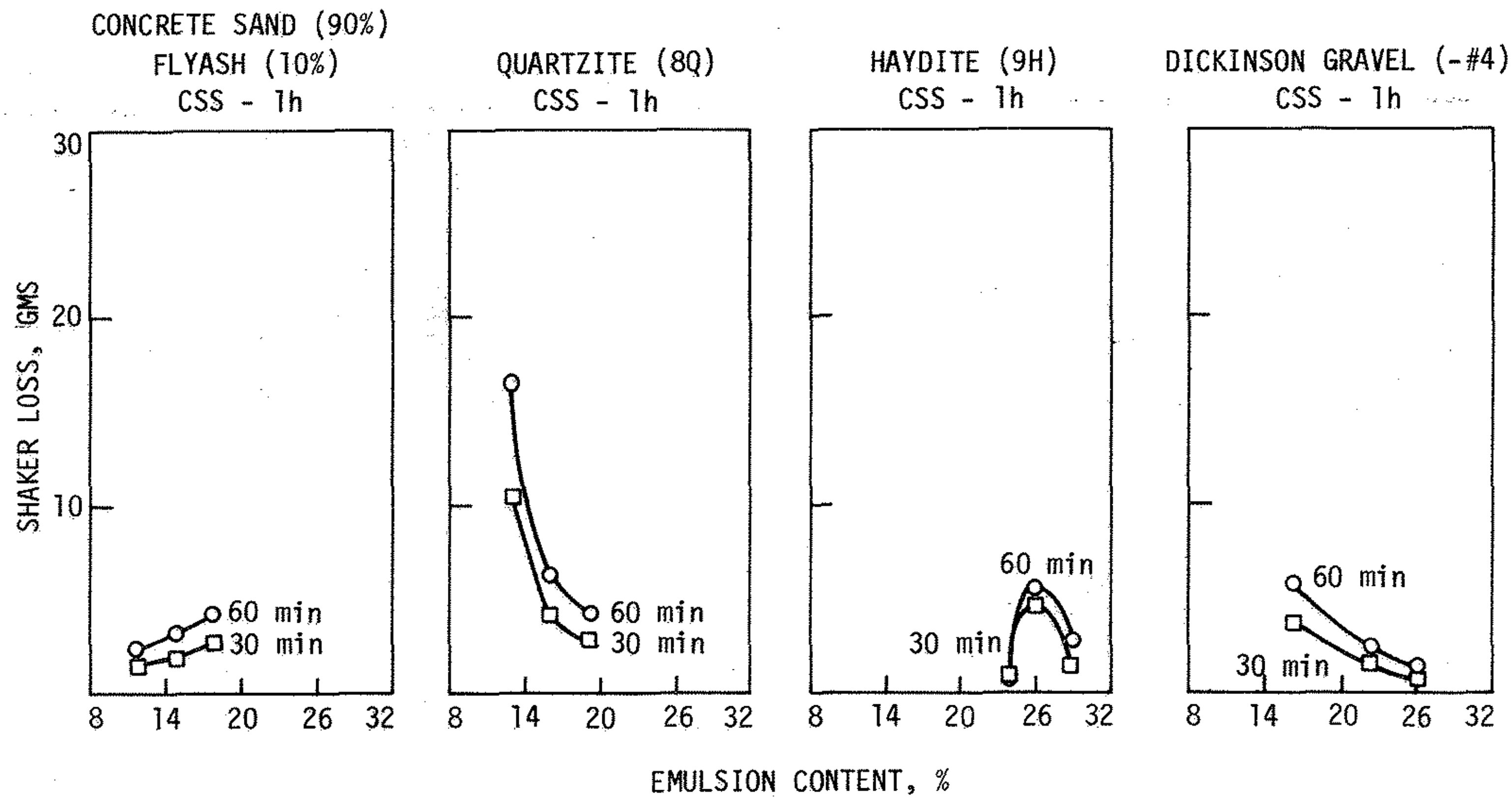

Fig. 10. Shaker loss vs emulsion content, concrete sand/Flyash, quartzite, Haydite and Dickinson gravel.

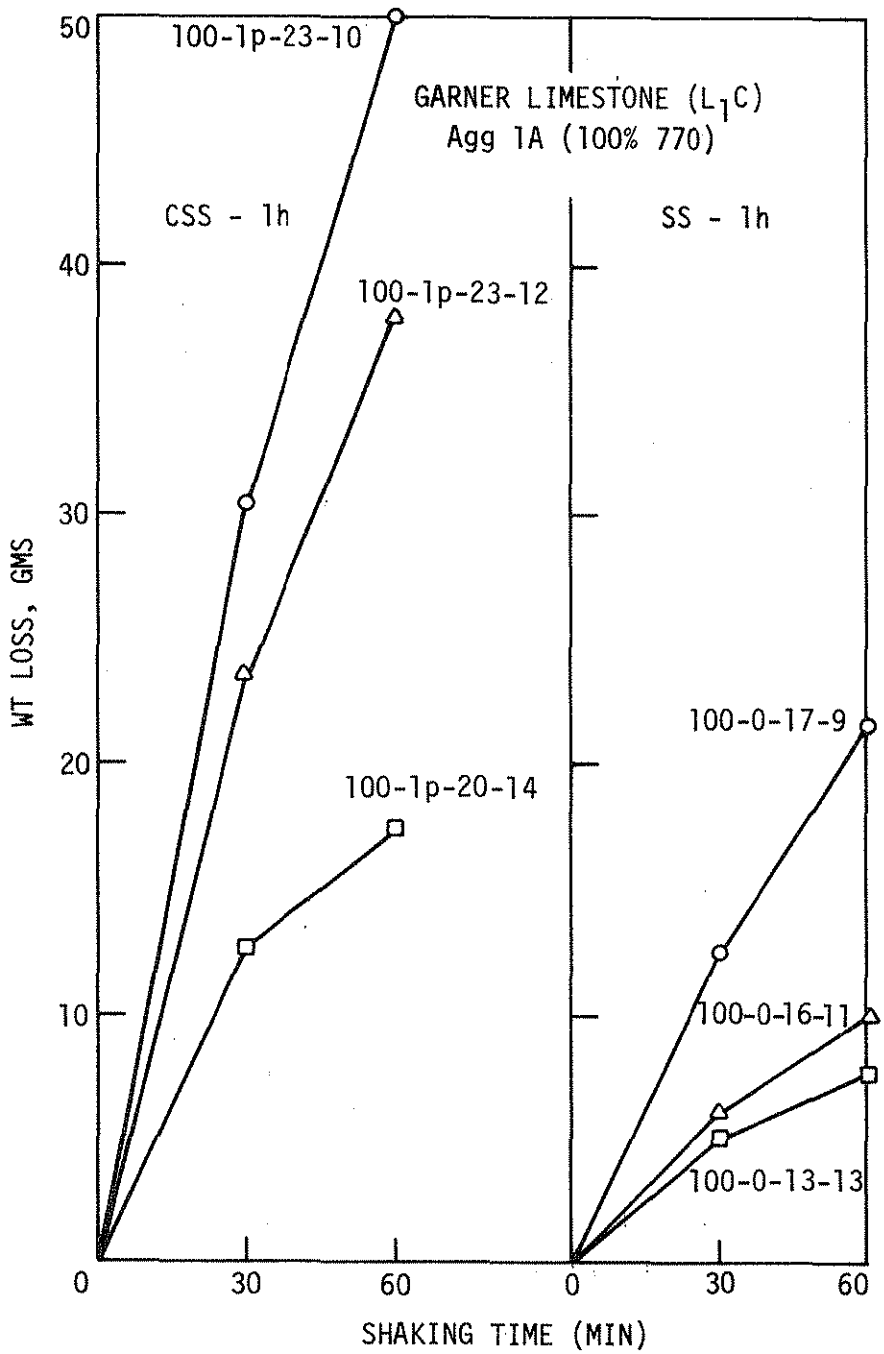

Fig. 11. Shaker loss vs shaking time, Garner limestone (L_1C).

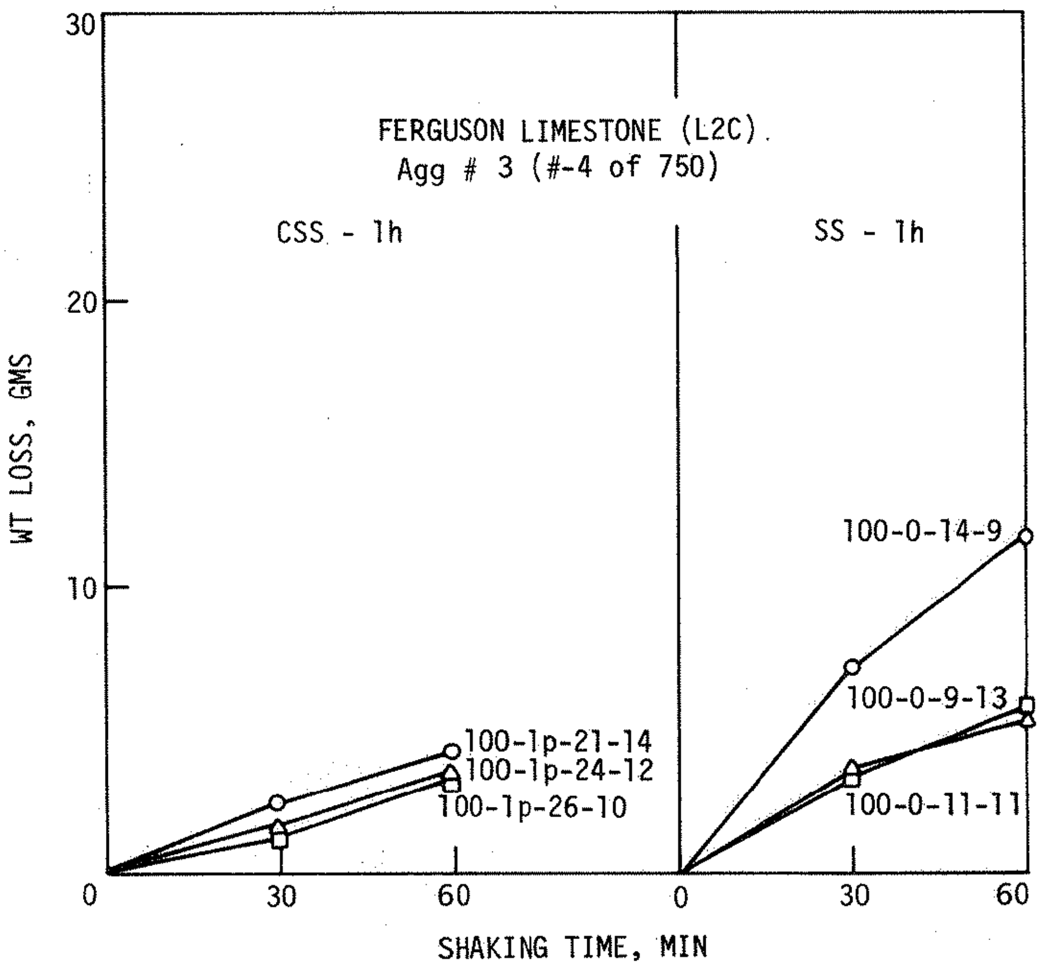

Fig. 12. Shaker loss vs shaking time, Ferguson limestone (L_2C).

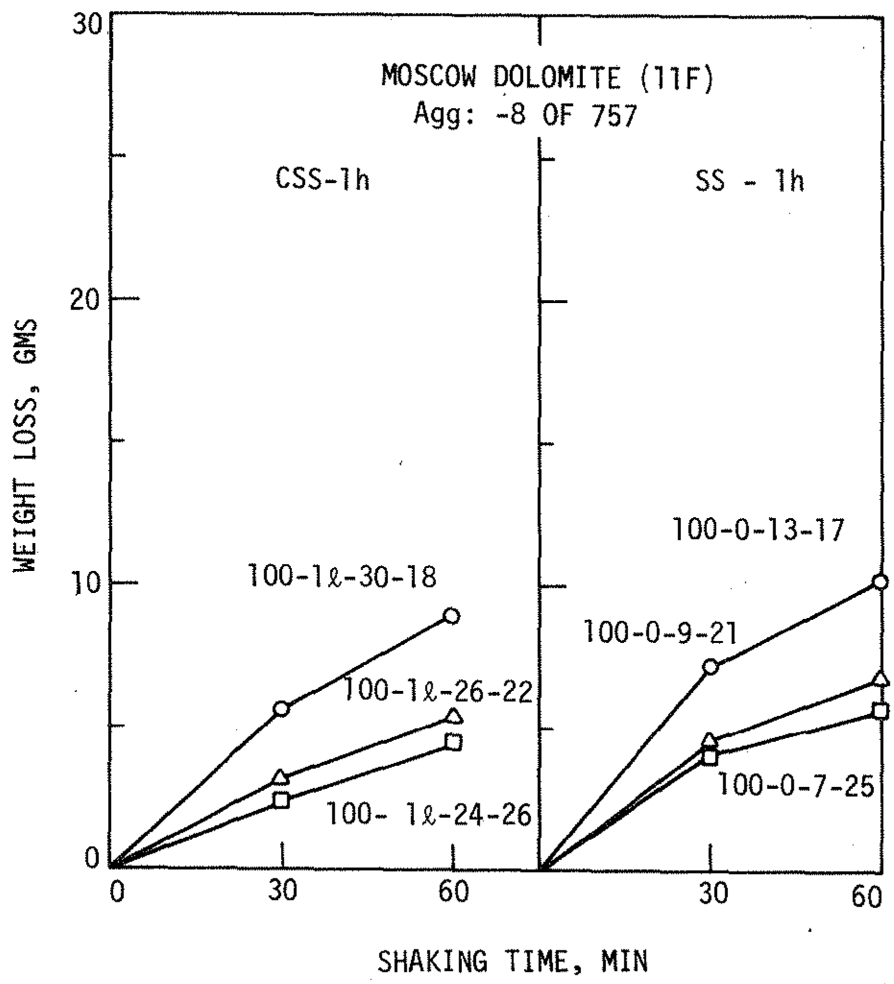

Fig. 13. Shaker loss vs shaking time, Moscow dolomite (L_1F).

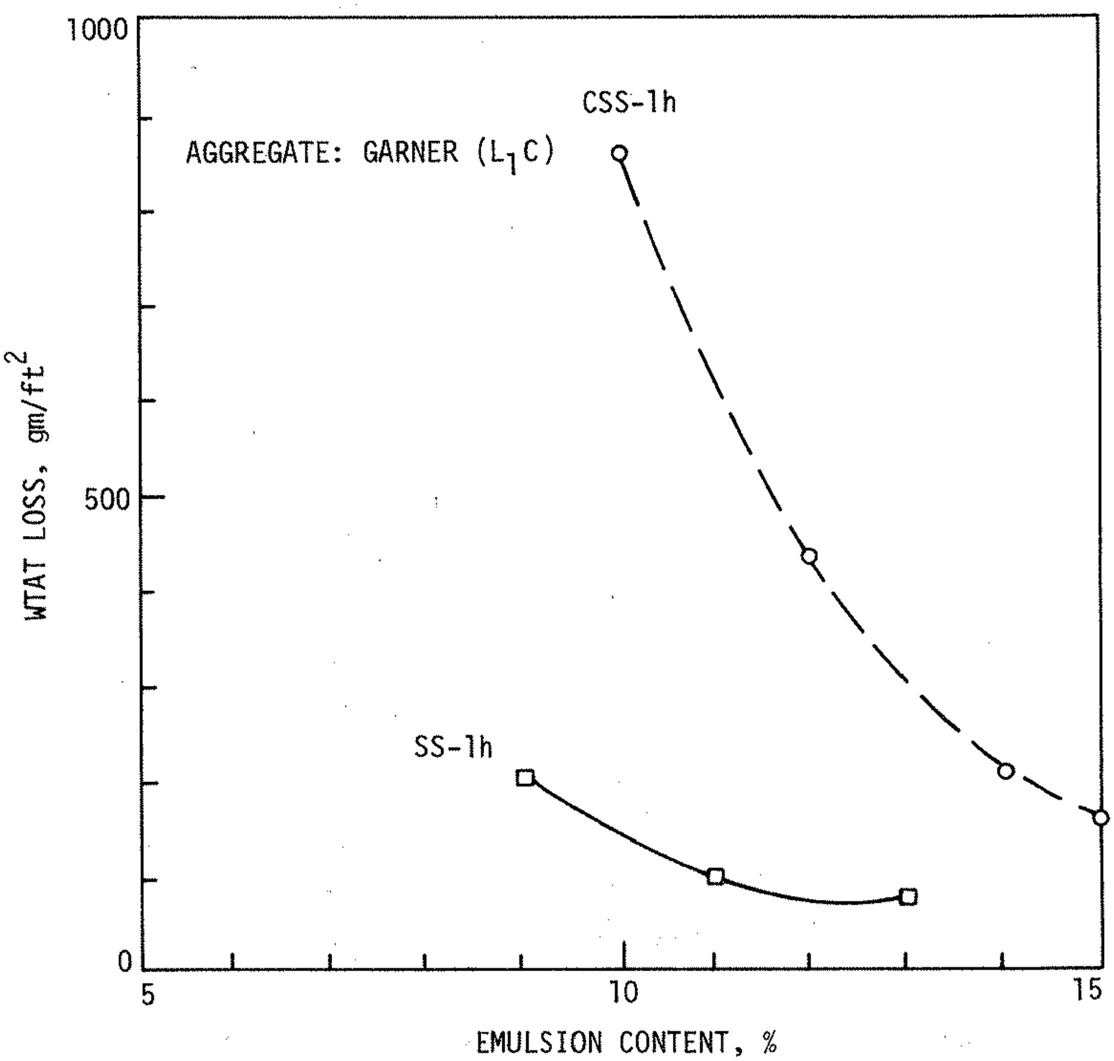

Fig. 14. WTAT loss vs emulsion content, Garner limestone (L_1C).

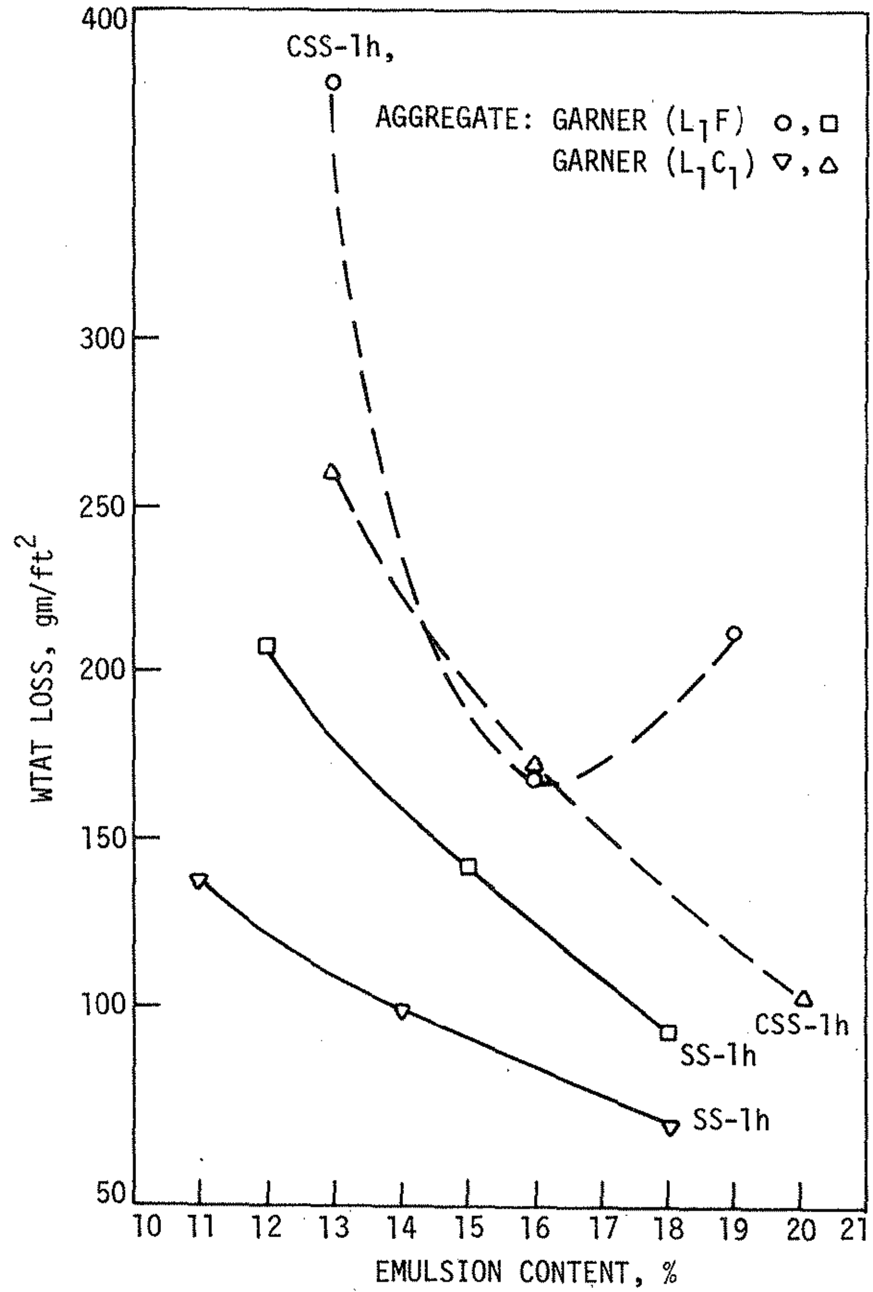

Fig. 15. WTAT loss vs emulsion content, Garner limestone (L_1F and L_1C_1).

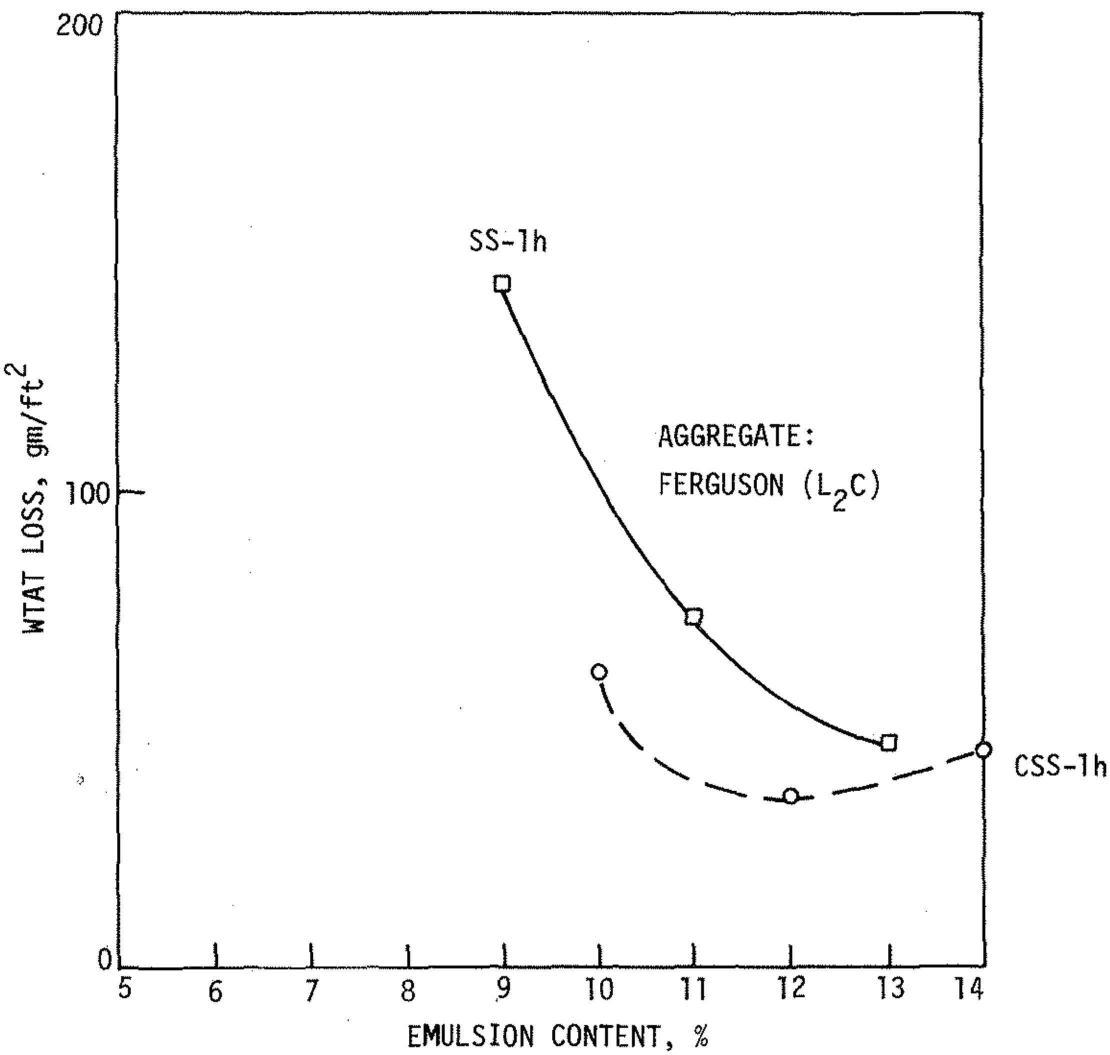

Fig. 16. WTAT loss vs emulsion content, Ferguson limestone (L_2C).

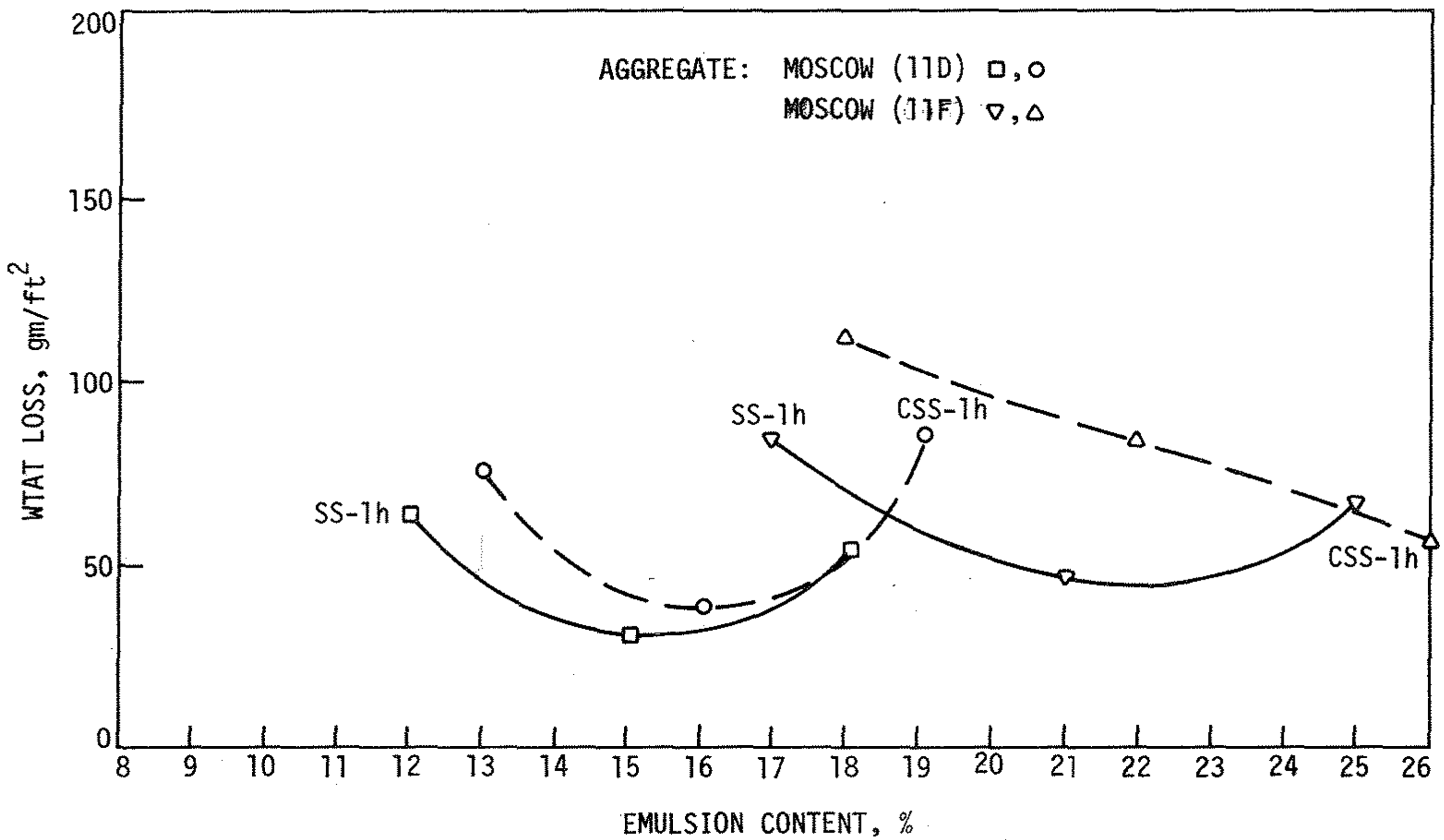

Fig. 17. WTAT loss vs emulsion content, Moscow (L_1D and L_1F).

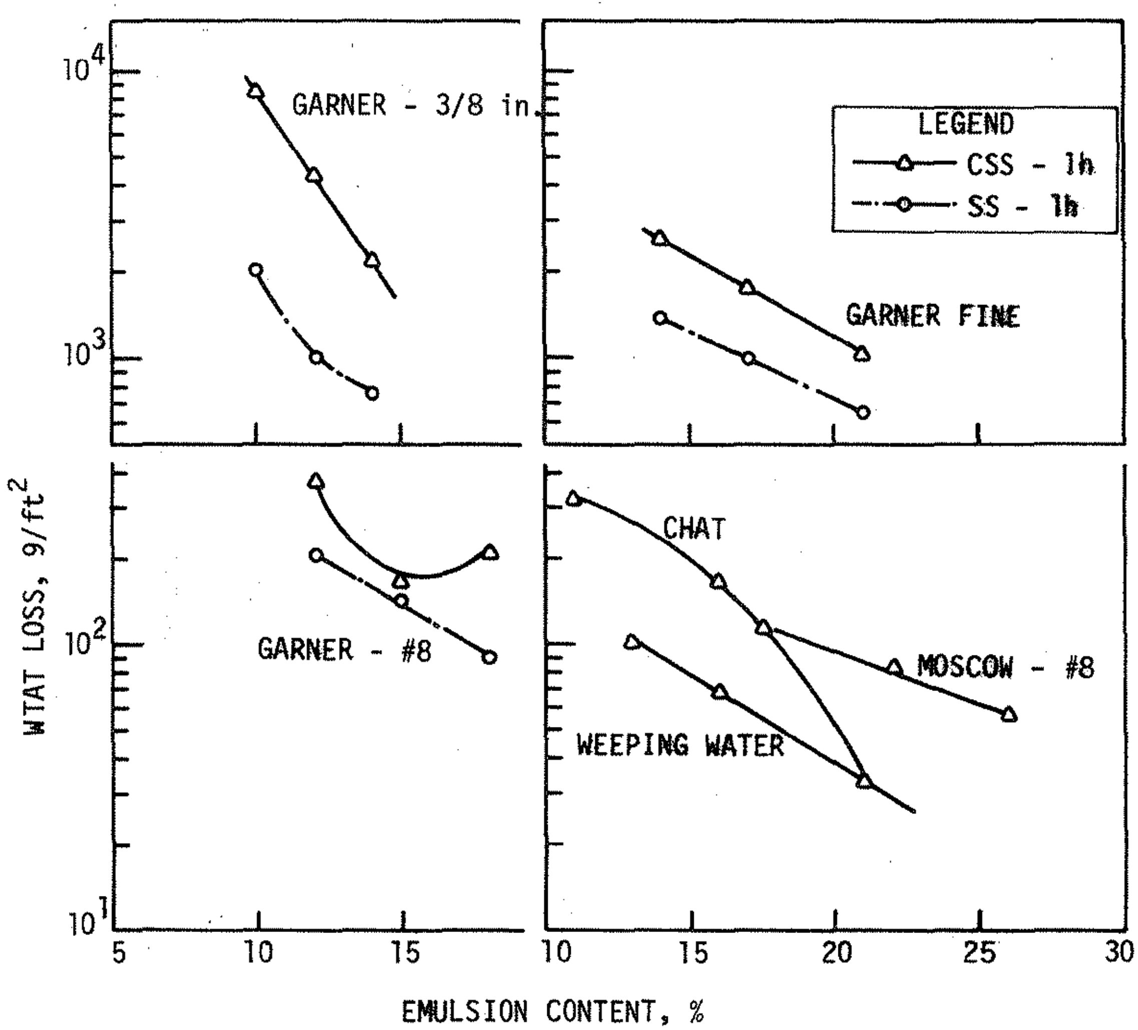

Fig. 18. Log WTAT loss vs emulsion content.

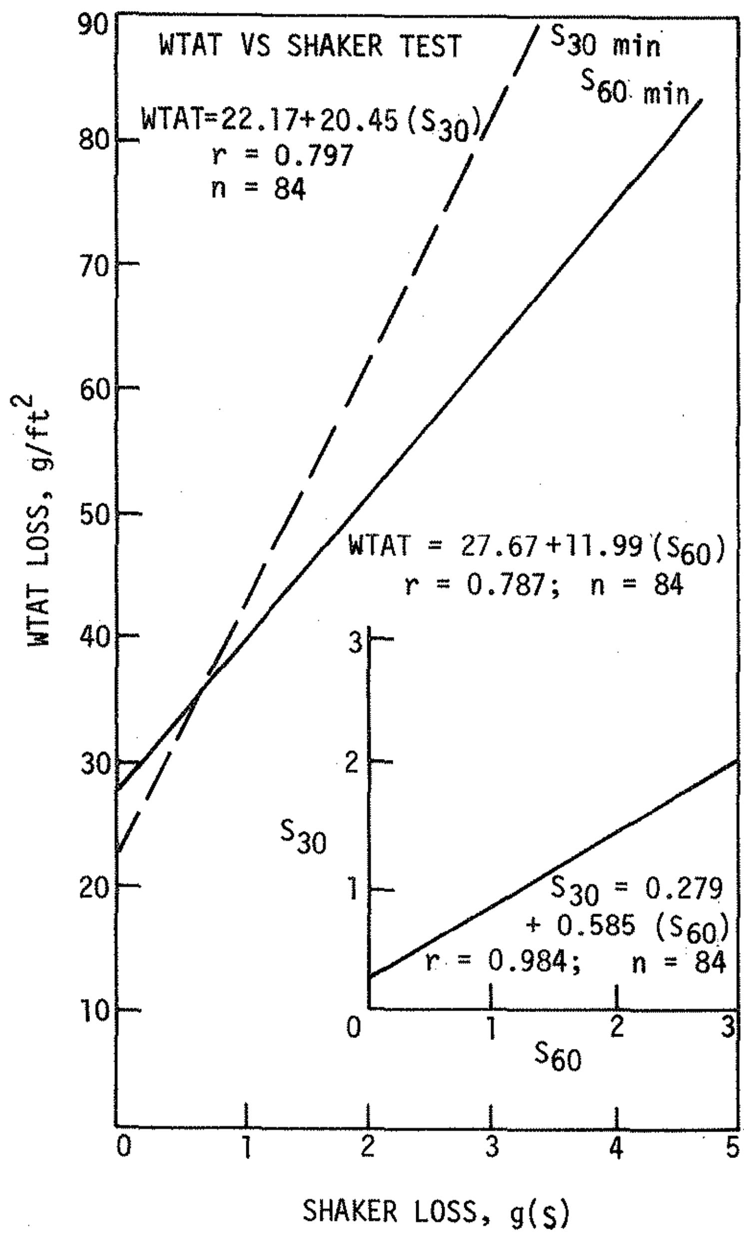

Fig. 19. WTAT vs shaker test and shaker loss at 30 min vs loss at 60 min.

- Blending of low wear resistant Garner and Conklin with concrete sand (30-50%) improved the WTAT and shaker results, especially when used with anionic SS-1h.

- Within gradation specification limits, increasing fines improved the wear resistance of cured slurries (e.g., Garner L_1C versus Garner L_1C_1). However, no appreciable difference was observed between slurry wear resistances of coarse and fine gradings made with the same aggregates and the same emulsions.

- No significant wear difference was observed between slurries made with higher penetration (81 pen) Iowa specification CSS-1h and lower penetration (69 pen) standard CSS-1h (Fig. 20).

- Due to either inadequacy in current specifications or inadequacy in WTAT criteria, only four (concrete sand plus fly ash, Haydite, Dickinson gravel, and Weeping Water) of the 16 aggregate blends meeting both gradation (either Iowa or ISSA) specifications and sand equivalent of 45+ also resulted in slurries meeting WTAT criterion. Five (Ferguson, Chat, Moscow coarse, Moscow fine, and Dallas gravel) aggregate blends met only the sand equivalent requirement (not gradation specifications) but resulted in slurries meeting WTAT criterion. Garner limestone blended with 30% concrete sand and quartzite met both sand equivalent and gradation specifications, but slurries failed to meet WTAT requirement. The three Garner blends failed to meet the sand equivalent requirement, and their slurries failed to meet WTAT criterion. Conklin lithographic limestone met the sand equivalent requirement, but the WTAT loss of the slurries was too high. These inconsistencies point to the need for field study.

5.4 Loaded Wheel Tests (Series 3)

The loaded wheel tester (LWT) was developed by Benedict (1975) to simulate traffic load on the slurry seal in the laboratory. In his own work compaction curves were drawn by a profilograph, tackiness points were detected, and sand adhesion measurements were made of the excess asphalt extruded to the specimen surface. It was found that the compaction curves, tack points, and sand adhesion values were related to the asphalt content and the number of LWT cycles.

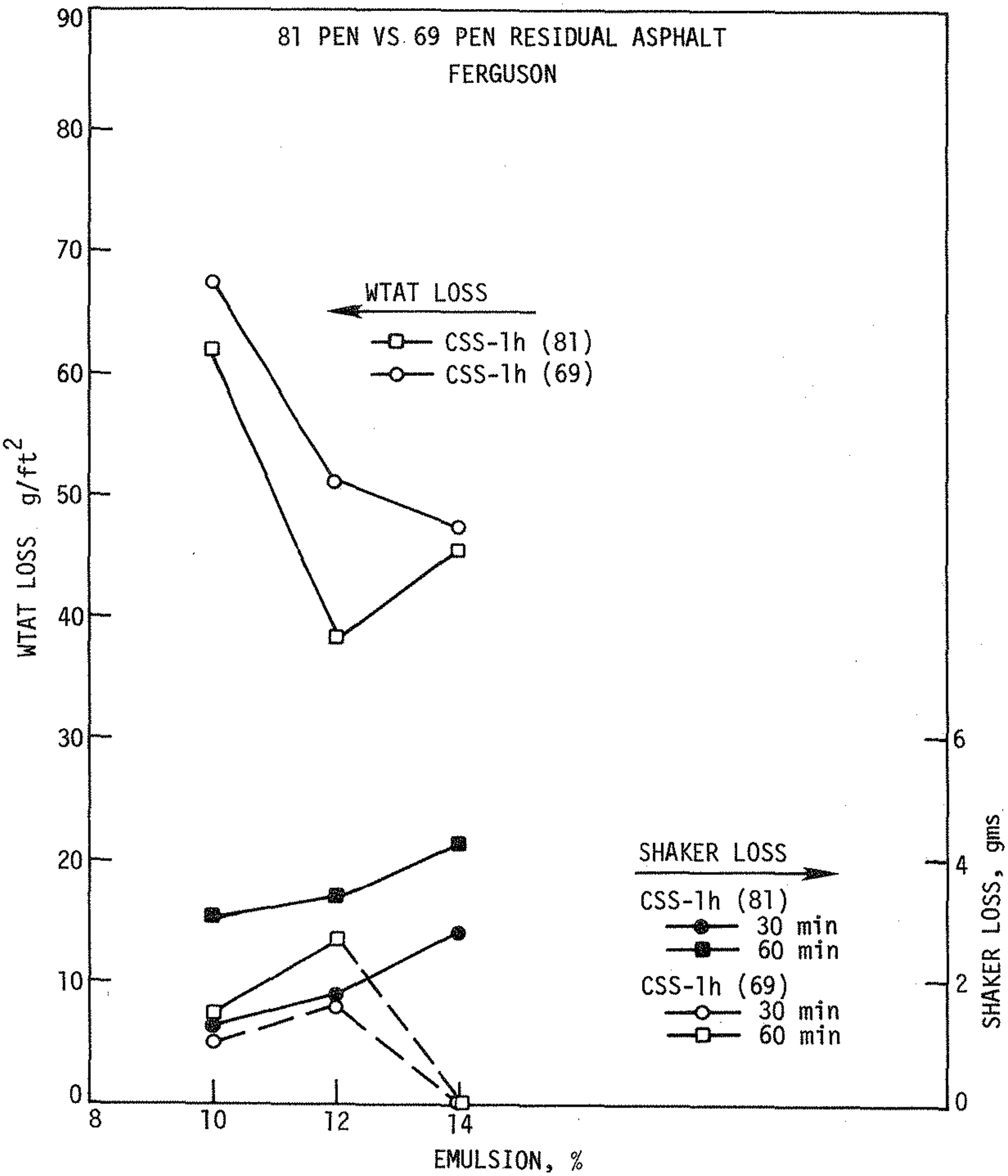

Fig. 20. Effect of base asphalt hardness on WTAT and shaker loss.

There is good indication that the tack point and sand adhesion value can be a measure of the upper limit of asphalt content the slurry can contain without the danger of flushing and bleeding.

Six series of slurries made with six aggregate blends and cationic emulsions, each at four to six emulsion levels, were tested with the LWT following the procedure described in Appendix F. Compaction curve by profilograph was not measured because of the difficulties in interpreting the results. Tack points and sand adhesion values after 1000 cycles under total load of 125 lbs were determined. The sand adhesion values versus emulsion content curves are shown in Figs. 21-23. There is a general trend of increased sand adhesion with increasing emulsion content, except for Haydite and Dickinson gravel, where sand adhesion values dropped beyond certain emulsion contents (Fig. 23).

Limited tests were tried with sand adhesion determination on slurries compacted by California rubber wheels. Sand adhesion values were determined, after 30 min traffic compaction by loaded California rubber wheels (1800 revolutions), by compaction of 180 $^{\circ}$F sand for 5 min. The results on two series of slurry mixes were shown in Figs. 21 and 23. Similar sand adhesion values were obtained at slightly higher emulsion contents. These results have shown that, because of the general availability of mechanical mixers in most laboratories and the larger areas afforded by the specimens, it has the potential of replacing the more specialized LWT for design of slurry seals.

Because of the potential of the loaded wheel test in establishing the maximum allowable asphalt content in a slurry, this test should be further investigated in Phase II of this project. Loaded wheel test

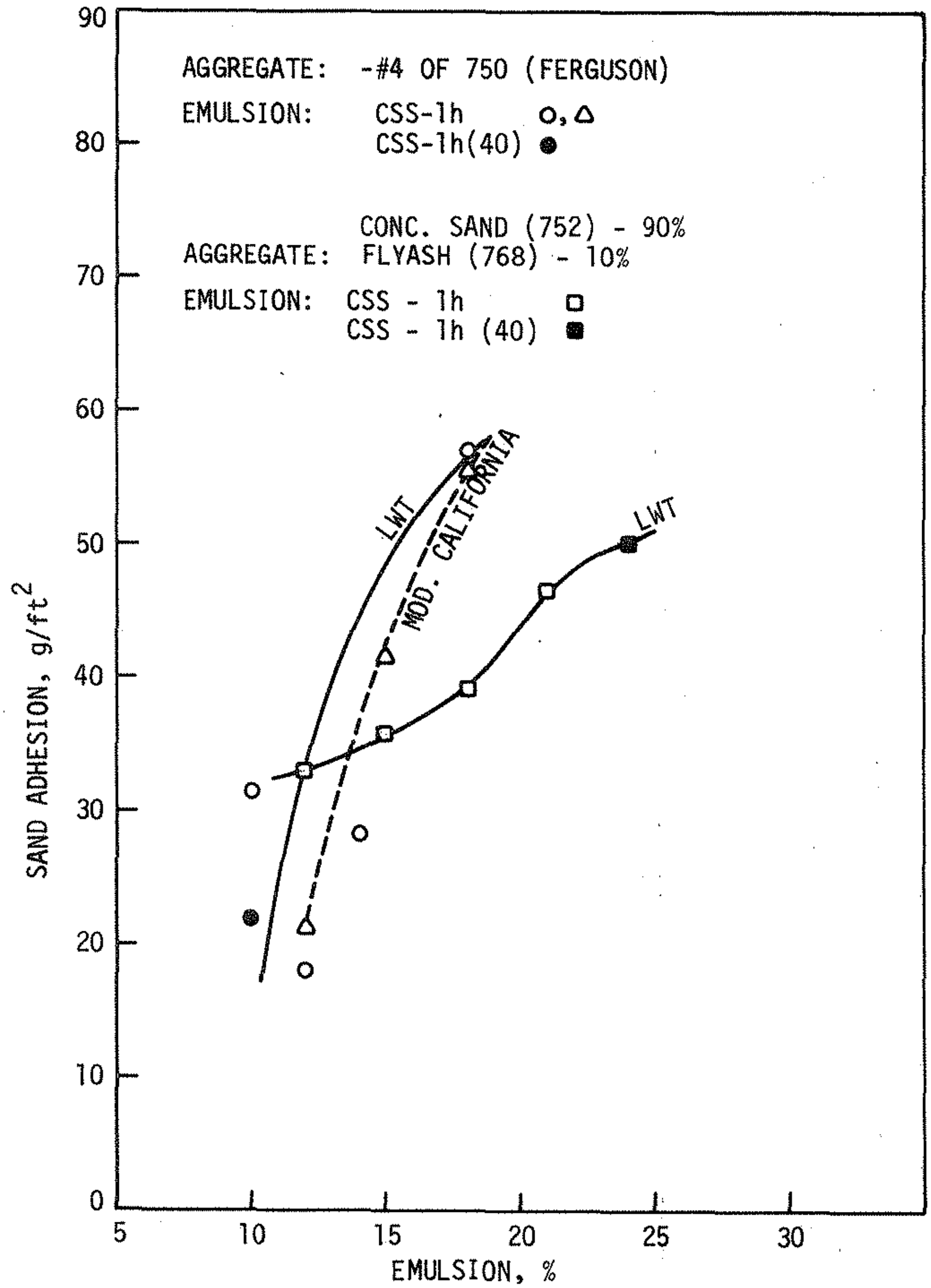

Fig. 21. LWT sand adhesion vs emulsion content (Ferguson and concrete sand).

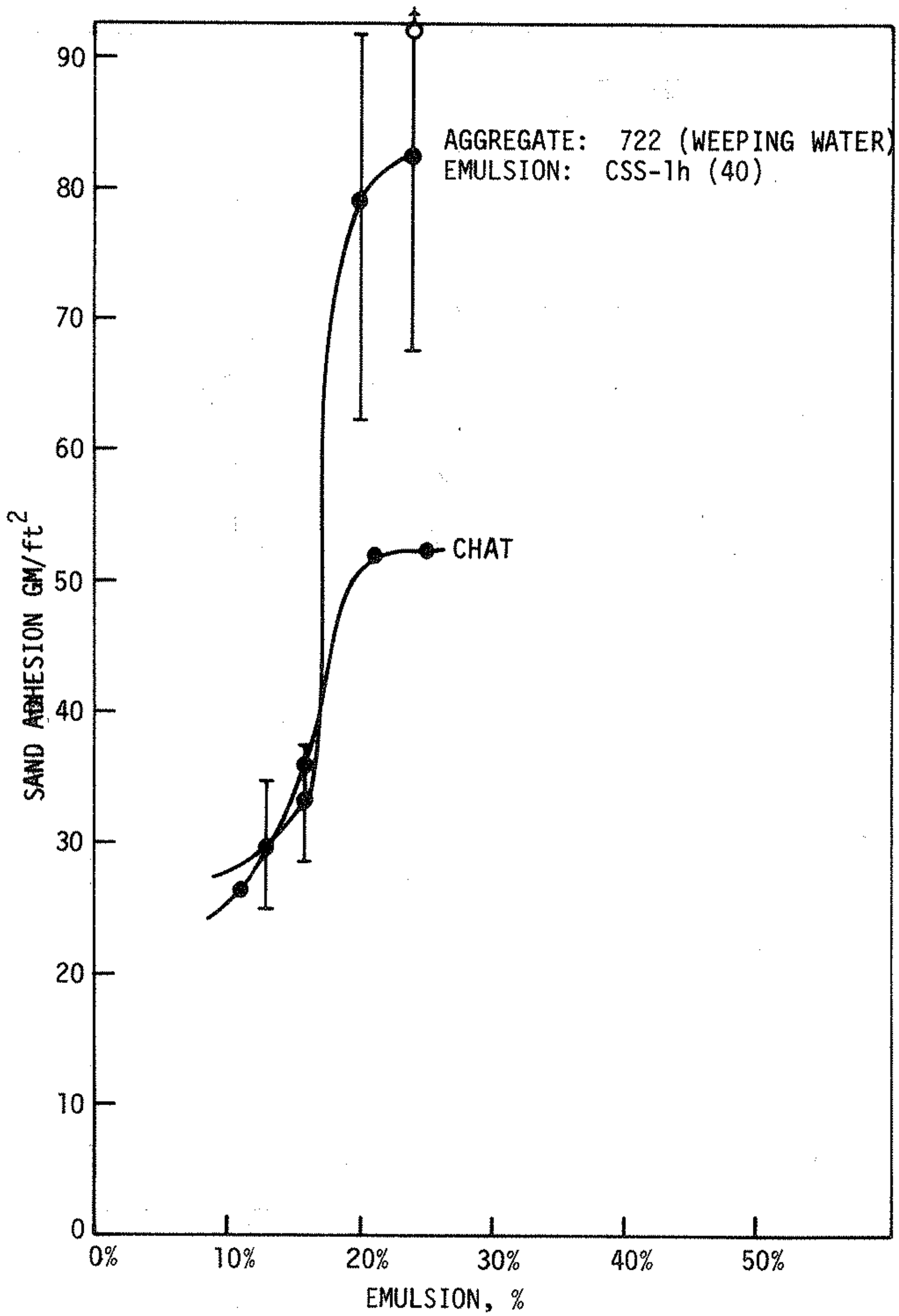

Fig. 22. LWT sand adhesion vs emulsion content, Weeping Water and chat.

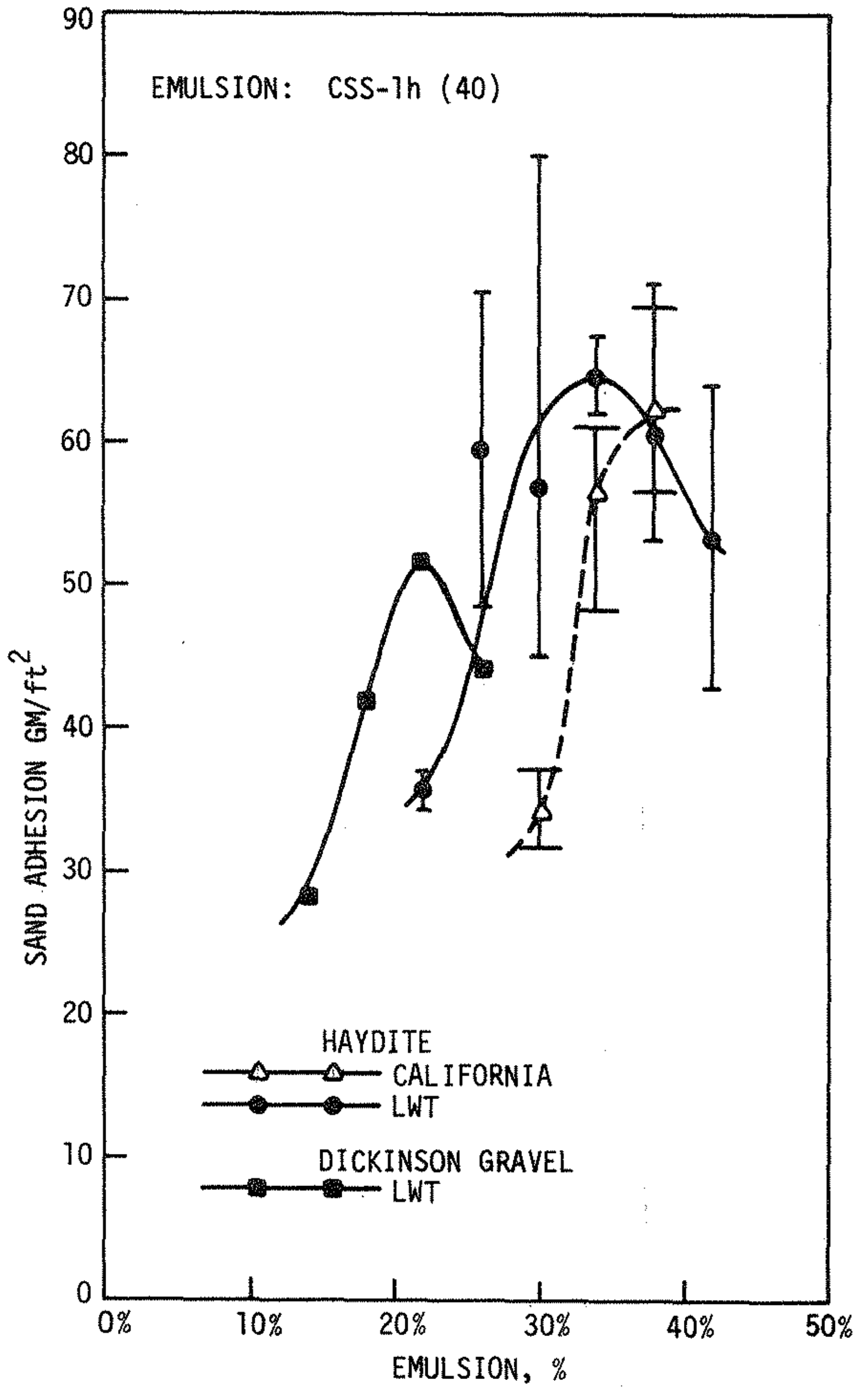

Fig. 23. LWT sand adhesion vs emulsion content, Haydite and Dickinson gravel.

and field correlations should be made with respect to sand adhesion limit at different levels of traffic.

The results of tack points determined in conjunction with loaded wheel tests were plotted in Fig. 24. Although the tack point shows the relative sensitivity of the aggregate to change in emulsion content or the susceptibility to flushing, the repeatability is poor. Both sand adhesion and tack point determinations need refinement.

5.5 Special Studies

Five series of special studies were conducted using Ferguson limestone (- #4) and two cationic emulsions on (a) effect of fines (or sand equivalent and - #325) on WTAT, (b) effect of slurry thickness on WTAT, (c) effect of compaction on slurry WTAT, (d) effect of testing temperature on WTAT, and (e) WTAT repeatability. A total of 81 WTAT specimens were tested.

To determine the effect of fines on WTAT, various percentages of Garner fines passing a 200 sieve were added to Ferguson (L_2C) passing No. 4 sieve, and slurries were made at the theoretical emulsion level (Et) and 20% either side of Et (0.8 Et and 1.2 Et). The results are presented in Fig. 25. The improvement in wear resistance due to increases in fines and asphalt content is evident.

Figure 26 shows the effect of slurry seal specimen thickness from 1/4-3/8 in. on WTAT results. WTAT results are dependent on slurry thickness: increases in thickness reduce WTAT loss.

To determine the effect of slurry compaction on WTAT loss, six specimens were prepared at each of three emulsion levels. Half of the

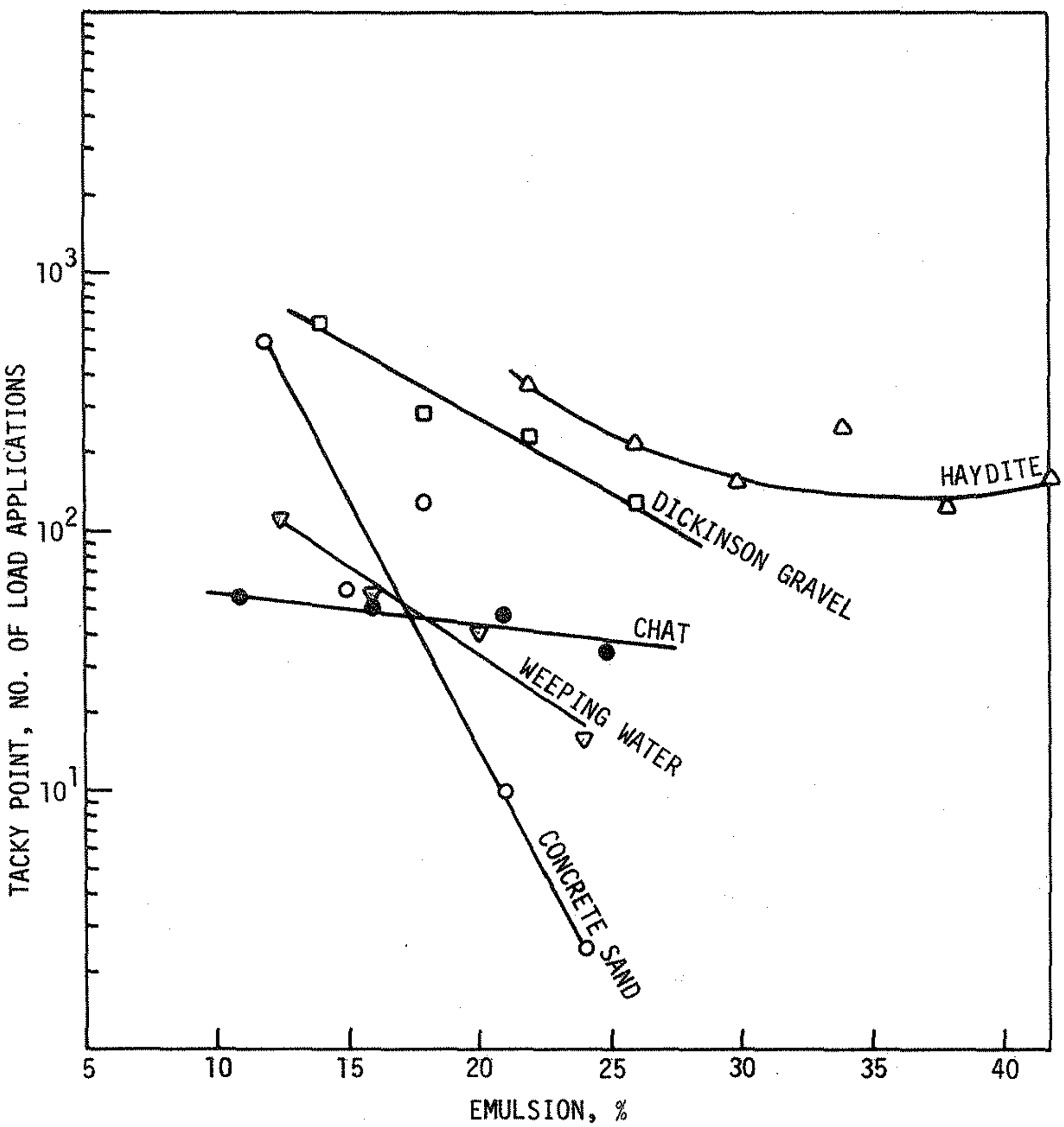

Fig. 24. Tacky point vs emulsion content.

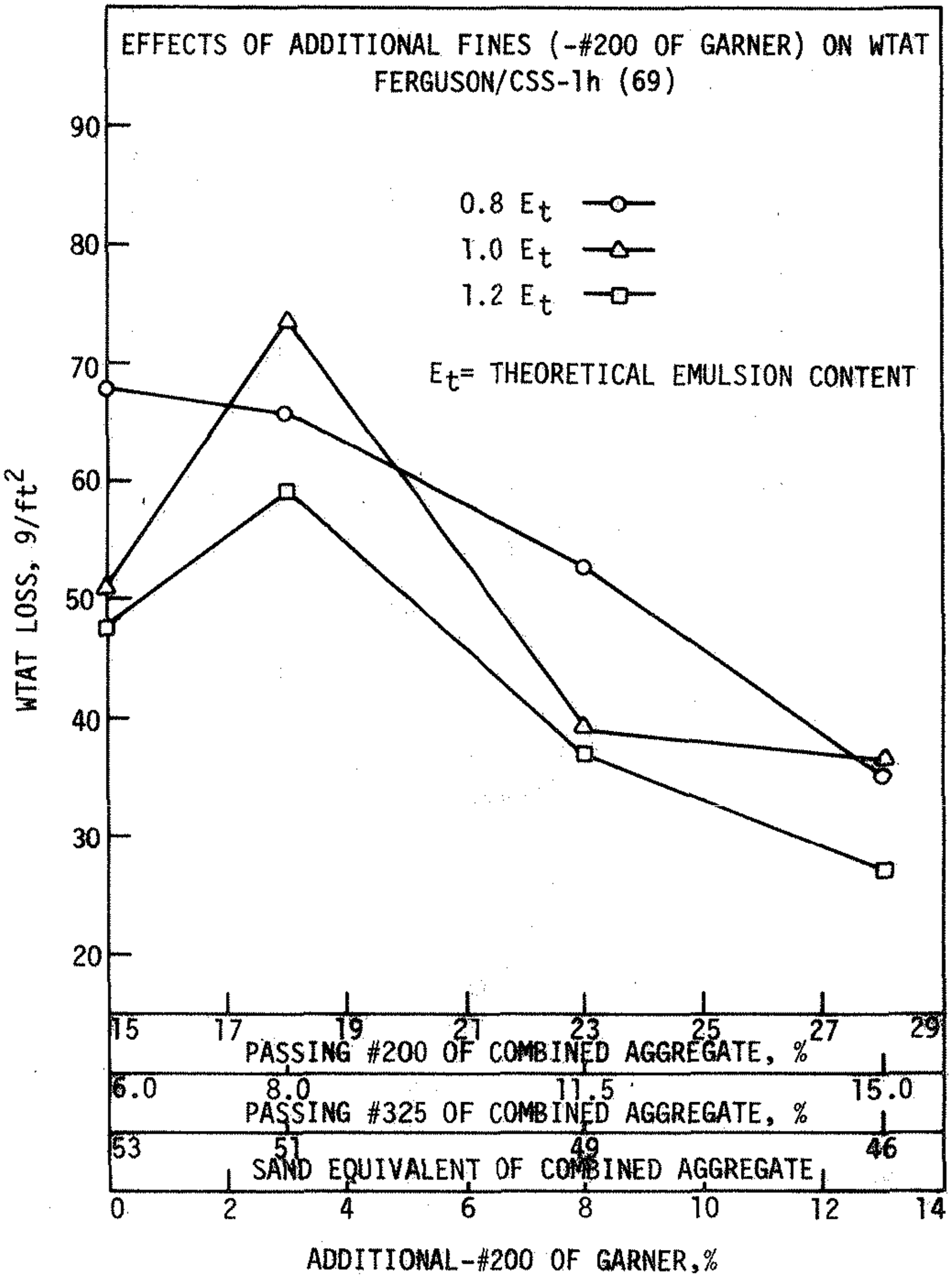

Fig. 25. Effects of additional fines (- #200), percent passing #200, percent passing #325, and sand equivalent on WTAT (Ferguson/CSS-1h). E_t = theoretical emulsion content.

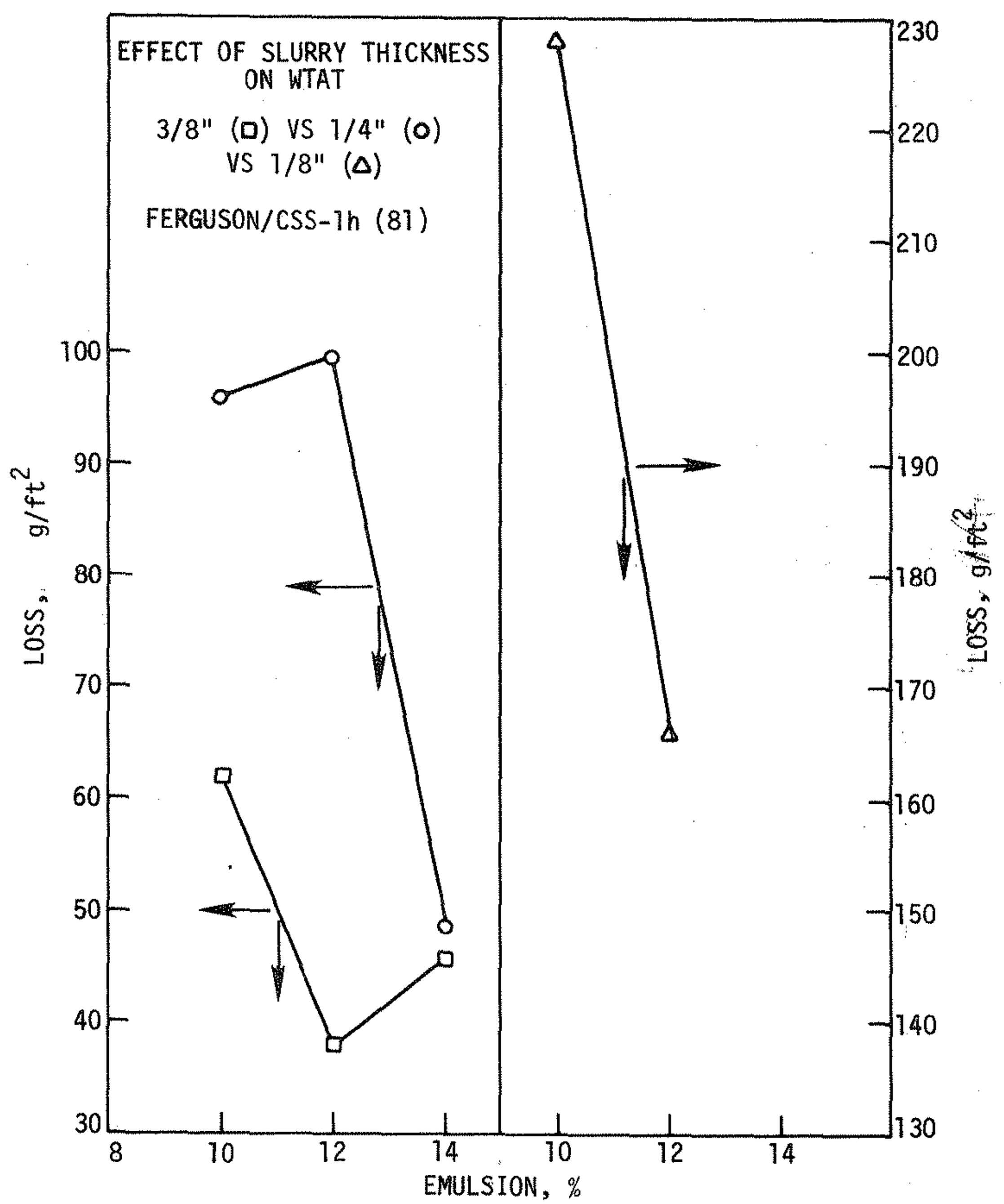

Fig. 26. Effect of slurry thickness of WTAT, Ferguson/CSS-1h (81).

specimens were tested following standard procedure, and half of the specimens were compacted 10 times at 50 psi pressure before testing. Results clearly show the improved wear resistance of compaction, especially at higher emulsion content levels (Fig. 27).

It was thought that wear loss might be affected by slurry temperature, especially at low temperatures. A series of specimens were prepared and tested for WTAT at 32-35 ^{o}F after conditioning in a freezer (-15 ^{o}F) for 90 min. Results were compared with identical specimens tested at standard (77 ^{o}F) condition (Fig. 28). Unfortunately, no definite trend could be observed from this comparison.

To determine the repeatability of WTAT, a set of eight identical slurry specimens were made of Ferguson (- #4) and 12% CSS-1h (40). The mean was 80.8 g/ft^2, the standard deviation was 15.3, and the coefficient of variation of 19%. The coefficient of variation of most WTAT triplicate samples was between 10-20% with a low of 1% and a high of 44%.

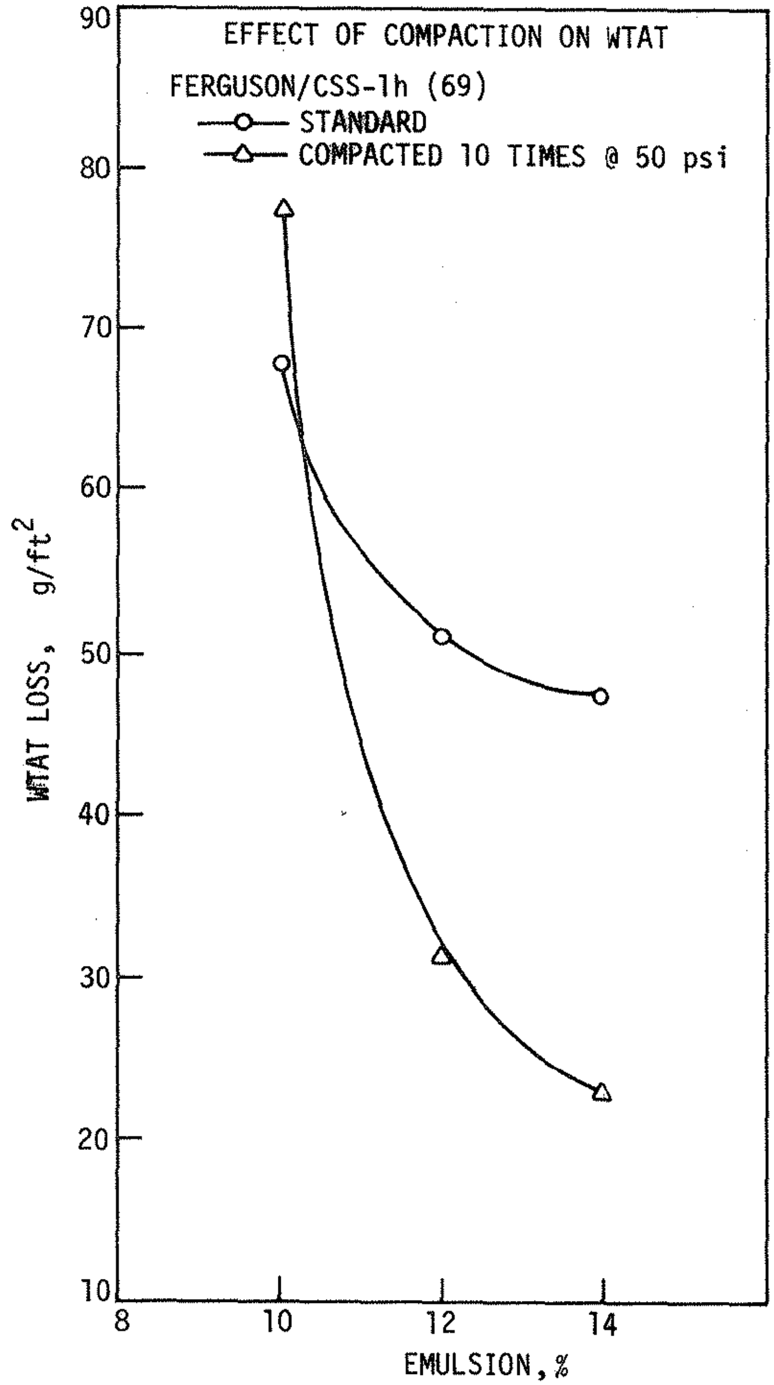

Fig. 27. Effect of compaction on WTAT, Ferguson/CSS-1h (81).

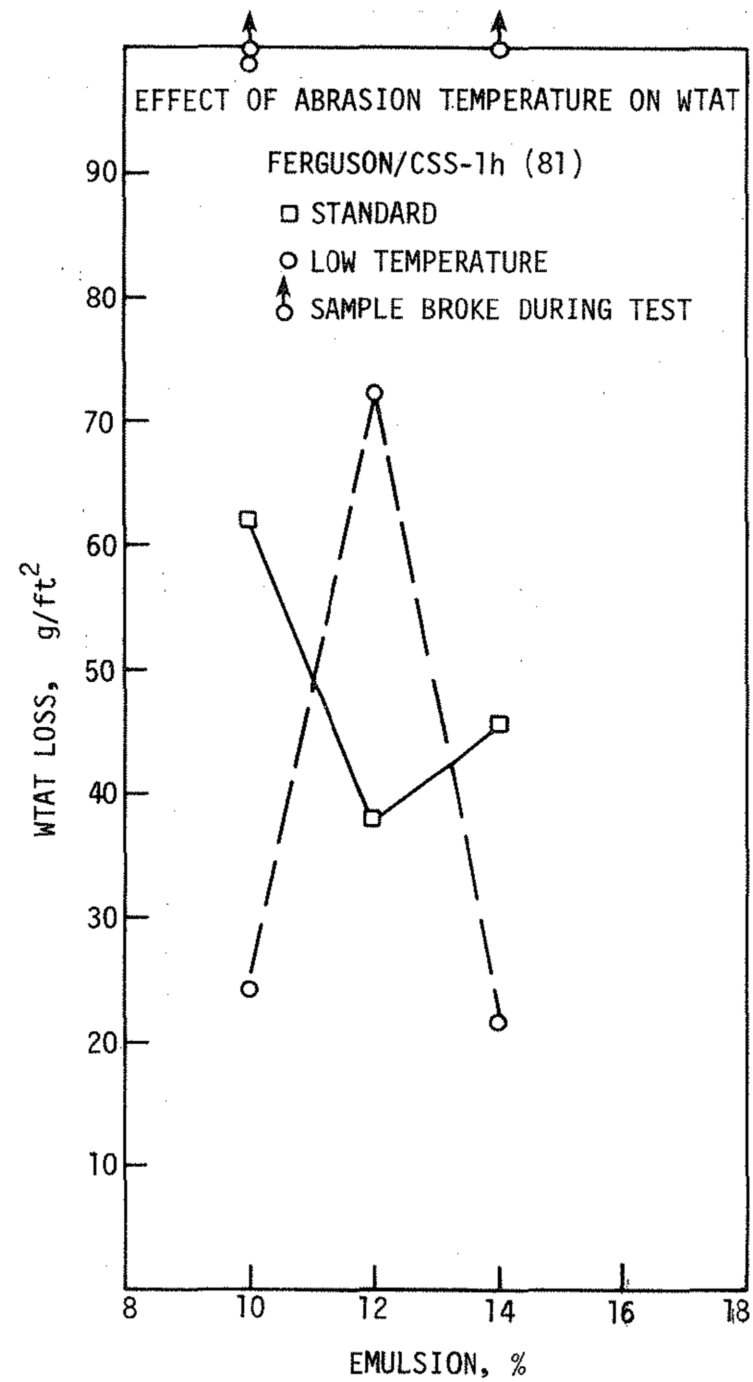

Fig. 28. Effect of abrasion temperature on WTAT, Ferguson/CSS-1h (81).

6. TENTATIVE SLURRY SEAL DESIGN PROCEDURE

Based on literature provided by other agencies, (especially Virginia, 1976, and Benedict, 1977), on experiences gained in this project, and on the Iowa DOT tentative slurry design procedure (1975), which is basically a sound procedure, the following tentative slurry seal design procedure is recommended (see flow chart in Appendix G).

1. Evaluation and Selection of Materials:
    a. Determine aggregates properties
        1. Durability records
        2. Mineral/chemical composition
        3. Gradation (washed)
        4. L.A. Abrasion
        5. Soundness
        6. P.I. (3-)
        7. Voids (Virginia VTM-5) (47+)
        8. Sand equivalent (45+)
    b. Obtain aggregate design parameters
        1. Surface area calculated from gradation
        2. Specific gravity
        3. Centrifuge kerosene equivalent (CKE)
    c. Determine emulsion properties
        1. Viscosity of emulsion
        2. Percent residue
        3. Penetration and viscosity of residue
        4. pH

5. Particle charge

6. Particle size distribution (Young's method)

d. Emulsion design parameters

1. Particle charge

2. Percent residue

2. Estimate the theoretical residue asphalt requirement for an 8-μm film coating of the calculated aggregate surface area and convert to theoretical emulsion content Et (see Appendix E).

3. Estimate the optimum prewet water/filler/additive requirements by cup mixing test (100 g aggregate) for a creamy, homogeneous, fluid and stable slurry. (Adjust Et for added filler). Minimum mixing time should be 2 min at 75-80 °F.

4. Determine the optimum mix water content for a cone flow of 2-3 cm. Start with Et and the minimum prewet water content and filler content. Adjust filler content if required.

5. Prepare slurry mixes for:

   a. Set time by paper stain method* for a 1/4-in. to 3/8-in. specimen at field temperatures.

   b. Curing time by cohesion test* and/or curing cure* and/or tensile strength* at field temperatures.

   c. WTAT† (at least triplicate samples) or shaker test† (triplicate samples).

   d. LWT† (triplicate samples) or modified California rubber wheel sand adhesion*† or ISU traffic simulator sand adhesion.*†

---

*Method needs to be refined.

†Criterion needs to be established by field-laboratory correlation studies.

6. Repeat Steps 3-5 for 0.8 Et and 1.2 Et.

7. Plot WTAT (shaker) loss and sand adhesion versus percent emulsion (or residual asphalt content) curves to determine the optimum asphalt (emulsion) content (Fig. 29).

As a general guide for mix adjustments during the slurry seal design process, a cause-effect (problem) check list is prepared and shown in Table 7. This table is only concerned with laboratory design process, it may be modified to include field problems in the future.

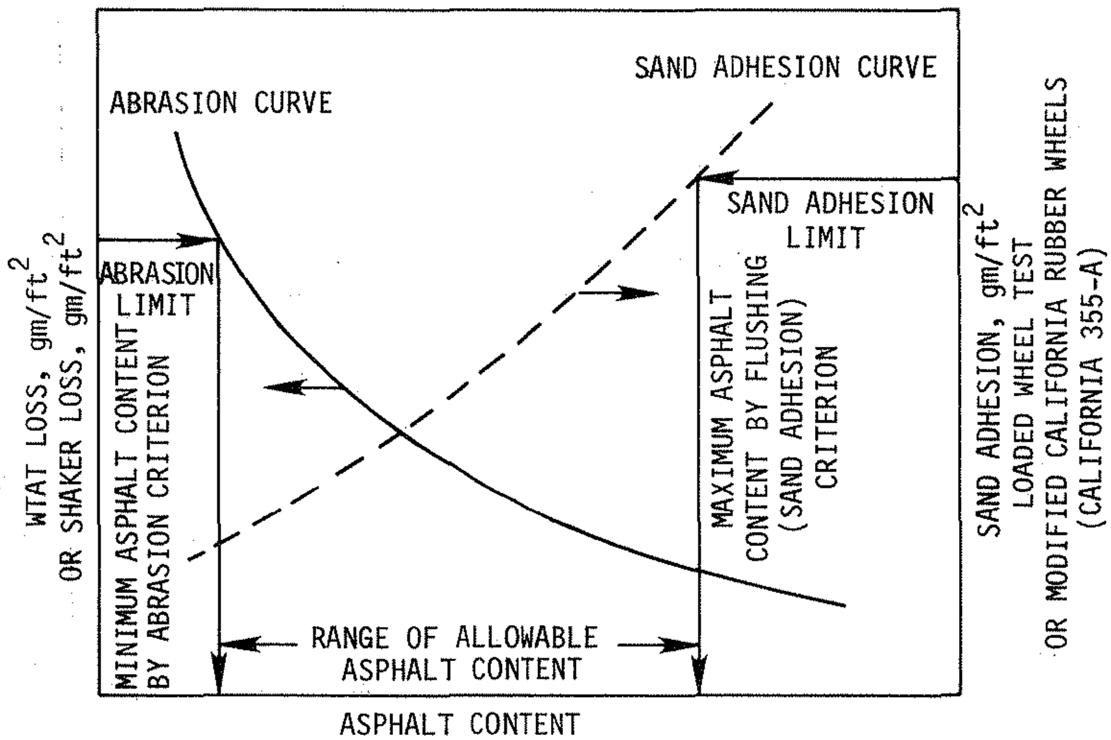

Fig. 29. Graphical determination of optimum emulsion content.

Table 7. Possible causes for major slurry seal problems.

PROBLEMS MAY BE ENCOUNTERED IN SLURRY	FACTORS OR PROBABLE CAUSES: HIGH CLAY (LOW SAND EQUIVALENT)-AGG.	HIGH FINES (-#200) IN AGGREGATE	LOW FINES IN AGGREGATE	EXCESS PREWET WATER IN AGGREGATE	INSUFFICIENT PREWET WATER IN AGGREGATE	EXCESS EMULSION (BINDER) IN SLURRY	INSUFFICIENT EMULSION IN SLURRY	EXCESS WATER IN SLURRY	INSUFFICIENT WATER IN SLURRY	EXCESS FILLER IN SLURRY	INSUFFICIENT FILLER IN SLURRY	SURFACE AREA OF AGGREGATE HIGH	POOR QUALITY AGGREGATE	LOW VOIDS CONTENT IN AGGREGATE	AGG/EMULSION INCOMPATIBLE	PARTICLE SIZE DISTRIBUTION OF EMULSION	MIXING TEMPERATURE TOO HIGH	EXCESS REDICOTE E-11
PREMATURE BREAK OF THE SLURRY (INSTABILITY)	X	X			X		X				X	X			X	X	X	
FALSE SLURRY								X			X				X			
SLOW BREAK			X	X		X		X		X								
SLOW CURE OR DRYING	X		X	X		X		X		X								X
TOO RAPID DRYING		X			X				X		X						X	
HIGH FLOW (RUNNING & WET)				X		X		X										
TOO LOW FLOW (STIFF)	X	X			X		X		X	X		X						
SEPARATION OR SEGREGATION			X	X				X			X				X			
FOAMING				X				X		X					X			X
FLOATING (FATTING UP) OF BINDER			X	X		X		X			X			X				
FORMATION OF FISSURES UPON DRYING	X	X										X						
HIGH SAND ADHESION			X			X												
HIGH WTAT OR SHAKER LOSS	X				X		X				X	X	X		X			
BROWN COLORING OF CURED SLURRY	X						X					X			X			
CURED SLURRY TOO BRITTLE		X					X											

7. SUMMARY AND CONCLUSIONS

Extensive programmed laboratory tests involving some 400 asphalt emulsion slurry seals (AESS) were conducted. Thirteen aggregates including nine Iowa sources, a quartzite, a synthetic aggregate (Haydite), a limestone stone from Nebraska, and a Chat aggregate from Kansas were tested in combination with four emulsions and two mineral fillers, resulting in a total of 40 material combinations. A number of meetings were held with the Iowa DOT engineers; 12 state highway departments that have had successful slurry seal experiences and records, and several slurry seal contractors and material and equipment suppliers were contacted. Asphalt emulsion slurry seal development, uses, characteristics, tests, and design methods were thoroughly reviewed in conjunction with Iowa's experiences through these meetings and discussions and through a literature search (covering some 140 articles and 12 state highway department specifications). The following are the summary of findings, conclusions, and recommendations:

1. Asphalt emulsion slurry seals, when properly designed and constructed, can improve the quality and extend the life of existing pavement surface and can become a viable and economical pavement maintenance procedure, both preventive and corrective.

2. Although asphalt emulsion slurry seals have been used in the U.S. for more than 25 years and many thousands of miles of successful asphalt emulsion slurry seals have been built both in the U.S. and abroad, their design and construction is still an art rather than a science. Experiences with the slurry seal have been mixed; consistent

success in the construction and performance of the slurry seal, except in a few states, has not been achieved.

3. The major reasons for the mixed experiences and lack of consistent success with AESS are believed to be:

- Too many variables that will affect the properties, design, construction and performance of an AESS.
- No standard design method and traffic and geographically-based design criteria.
- General lack of experiences, total process control and proper equipments on the part of some contractors.

4. Major material variables affecting slurry compatibility, mixing stability, slurry consistency and wear resistance were identified as a result of the programmed laboratory testing. They are:

- Aggregate type and composition
- Aggregate gradation, amount, and type of fines
- Emulsion type and variability
- Prewet water content of aggregate
- Filler content
- Emulsion content.

5. Although not all of the aggregates studied met current specifications, most of them could be made into a creamy, stable, homogeneous, free flowing slurry seal, with proper selections of emulsion type, emulsion content, prewet water content, and mineral filler type and content.

6. Not all of the slurries made with aggregates meeting sand equivalent and gradation specifications gave satisfactory abrasion and wear resistance. On the other hand, satisfactory slurries could be made with

aggregate blends which failed to meet either sand equivalent or gradation specifications. These specification-performance (laboratory) inconsistencies point to the need for field study.

7. Poor overall characteristics of slurries made with Garner aggregate and its low sand equivalent value indicate that the sand equivalent requirement should, perhaps, be included in specifications for slurry seal aggregates.

8. Poor overall characteristics of Conklin slurries shows the wisdom of Iowa specifications in excluding lithographic limestone.

9. Although anionic emulsion SS-1h is not included in current Iowa specifications, mainly due to its slow curing rate, it is by far the easiest emulsion to work with and often resulted in slurries with better overall qualities. Considerations should be given to permitting the use of SS-1h and thus making more aggregates suitable for slurry seal work.

10. The single most important factor in making successful slurries with cationic CSS-1h is the pre-wet water content. It is recommended that pre-wet water content be specified in field applications.

11. A Gilson shaker durability test was developed. Once correlated with WTAT and/or field test results, this test has the potential of being readily used as a routine slurry design/control test by most laboratories.

12. Combining the basically sound Iowa slurry seal design procedure of 1975, laboratory results obtained from this project, and experiences of other agencies and engineers, a laboratory asphalt emulsion slurry

seal design process is recommended. The principal features of this procedure are:

- Estimate the theoretical residual asphalt requirement based on coating of an 8-μm film on aggregate surfaces.
- Establish the minimum asphalt (emulsion) content by the wet track abrasion test (WTAT) or the shaker test.
- Establish the maximum asphalt (emulsion) content by the sand adhesion value determined from loaded wheel test or modified California rubber wheel test.

13. In order to establish design criteria and material specifications most suited for Iowa conditions of weather, traffic, and available aggregates, and to gain field experiences, a field test, as envisioned by Iowa DOT engineers, is recommended.

14. It is expected that conclusions regarding the performance of slurry seals under Iowa conditions, the suitability of Iowa aggregates, and the performance-based design criteria will be made at the end of two to four years of field tests.

8. FIELD PERFORMANCE AND EVALUATION OF SLURRY SEALS

8.1 Objectives

Since the first extensive uses of asphalt emulsion slurry seals in California in 1955, many miles of slurry seals have been applied in both the U.S. and abroad using a wide range of materials on many types of surfaces for various purposes with varying degrees of success.

There has been ample evidence to indicate that when properly designed and constructed the asphalt slurry seal can effectively seal cracks and improve the surface quality (e.g., skid resistance) of airport and highway pavements to restore and/or protect existing weathered and deteriorating pavements.

In view of the problems of energy, environment, and economy, there is good reason to believe that emphasis in maintaining and protecting our enormous investment in the existing highway system and in upgrading safety standards will be continued. The ability of asphalt emulsion slurry seal to reduce one of the major causes of highway pavement deterioration due to entrapped water under pavements and to improve skid resistance will make it one of the most attractive maintenance alternatives.

However, while many miles of successful asphalt slurry seals have been constructed, mainly through experiences in the art, in the U.S. (e.g., in Kansas, Virginia, Georgia, and Oklahoma), experiences in Iowa and other states have shown that consistent success of slurry seal application in the field has been difficult to obtain and that field experiences often do not reflect laboratory results.

The programmed laboratory testing on 40 material combinations has shown that:

- Although not all of the aggregates studied met current specifications, nearly all of them can be made into a creamy, stable, homogeneous, free flowing slurry seal, with proper selections of emulsion type, emulsion content, prewet water content, and mineral filler type and content.
- Not all of the slurries made with aggregates meeting specifications gave satisfactory abrasion and wear resistance.
- Although anionic emulsion SS-1h is not included in current Iowa specifications, mainly due to its slow curing rate, it is by far the easiest emulsion to work with and often resulted in slurries with better overall qualities.

To test these findings, to determine limitations of some materials and applicability of other materials in slurry seals, to correlate laboratory tests with field performances, and to establish material specifications and design criteria for Iowa conditions of weather, traffic, and materials a field performance and evaluation is recommended.

8.2 Test Program

The proposed slurry seal field test factorial arrangement is shown in Fig. 30. The test program will consist of thirty-two 500 ft x 12 ft sections at a site to be selected by the Iowa DOT engineers. The variables and their respective levels are as follows:

Factor	Variables	Levels
Aggregate type	Garner limestone, Ferguson limestone; Moscow dolomite; quartzite; concrete sand; Dallas gravel; Dickinson gravel; and Haydite (expanded clay)	7
Gradation	Fine; Coarse	2

Fig. 30. Proposed slurry seal field test factorial arrangement.

AGGREGATE			GARNER								FERGUSON				QUARTZITE				CONCRETE SAND AND FLY ASH				MOSCOW DOLOMITE				GRAVEL				HAYDITE				
GRADATION(a)			FINE				COARSE				FINE		COARSE		FINE		COARSE		FINE		COARSE		FINE		COARSE		DALLAS COARSE		DIKINSON COARSE		FINE		COARSE		
SAND EQUIVALENT			40-		60+		40-		60+		40-	60+	40-	60+	40-	60+	40-	60+	40-	60+	40-	60+	40-	60+	40-	60+	40-	60+	40-	60+	40-	60+	40-	60+	
FILLER TYPE(b)			P	L	P	L	P	L	P	L	P	P	P	P	P	P	P	P	P	P	P	P	L	L	L	L	L	L	L	L	P	P	P	P	L
EMULSION	EMULSION CONTENT(c)	FLOW, cm																																	
CSS-1h (IOWA)	0.8 E_a	2-3										▨		▨																					
		4-5																																	
	1.0 E_t	2-3					▨	▨	▨	▨		▨		▨				▨				▨		▨		▨	▨			▨				▨	▨
		4-5										▨		▨																					
	1.2 E_l	2-3										▨		▨																					
		4-5																																	
CSS-1h (40-90)	0.8 E_a	2-3												▨																					
		4-5																																	
	1.0 E_t	2-3												▨				▨																	
		4-5																																	
	1.2 E_l	2-3												▨																					
		4-5																																	
SS-1h	0.8 E_a	2-3												▨																					
		4-5																																	
	1.0 E_t	2-3												▨												▨				▨				▨	▨
		4-5																																	
	1.2 E_l	2-3												▨																					
		4-5																																	

▨ INDICATE TREATMENT COMBINATIONS TO BE TESTED

(a) FINE: FINE SIDE OF IOWA SPECS; COARSE: COARSE SIDE OF IOWA SPECS

(b) P: TYPE 1 PORTLAND CEMENT; L: HYDRATED LIME

(c) EMULSION CONTENT: E_t: THEORETICAL EMULSION CONTENT BASED ON U.S. ARMY SURFACE AREA METHOD AND 8 μm FILM
E_l: HIGHEST EMULSION CONTENT DETERMINED BY LOADED WHEEL TESTER;
E_a: LOWEST EMULSION CONTENT DETERMINED BY WTAT

Factor	Variables	Levels
Sand equivalent	40-; 60+	2
Emulsion type	CSS-1h (85-100 pen) CSS-1h (40-90 pen) SS-1h	3
Emulsion content	80% Theoretical Emulsion Content 100% Theoretical Emulsion Content 120% Theoretical Emulsion Content	3
Filler type	Type 1 Portland Cement; hydrated lime	2
Slurry consistency	2-3 cm cone flow; 4-5 cm cone flow	2

This recommended factorial arrangement will allow testing and comparison of slurry seals in terms of:

- Field versus laboratory behavior with respect to mixing stability, set and cure time, wear resistance (durability), and flushing (bleeding) susceptibility under traffic.
- Poor laboratory results in Phase 1 on aggregates that meet Iowa specifications.
- Good laboratory results in Phase 1 on aggregates that do not meet Iowa specifications.
- Coarse versus fine graded slurry seals.
- High versus low sand equivalent aggregates.
- Portland cement versus hydrated lime as fillers.
- Normal versus high flow (low consistency) slurry seals.
- Soft versus hard base asphalt emulsions.
- Cationic versus anionic emulsions.
- Field performance versus emulsion content.
- Feasibility of using fly ash in slurry seal.

Preferably the test site is an existing high traffic volume (10,000 VPD +) four-lane asphalt surfaced highway because traffic control is easier, and performance results can be obtained quicker. The existing pavement should be structurally sound to simplify slurry seal performance evaluation. Although not essential, the test site should be located relatively close to Ames so participating researchers from the Iowa DOT and ISU can easily make frequent visits.

8.3 Scope of the Test Program

The proposed test program will consist of the following tasks:

1. Site selection (Iowa DOT engineers)
2. Site (existing pavement) condition survey (DOT and ISU)
    a. Surface conditions:
        - Surface texture and absorptivity
        - Cracks
        - Skid resistance
        - Surface irregularities
    b. Surface geometry: crown, transverse and longitudinal grades, etc.
    c. Subsurface condition: base, subbase and subgrade moisture contents, etc.
    d. Photographic documentation.
3. Material testing and slurry seal design (ISU)
    a. Aggregates: Tests will include:

        Chemical/mineral analysis, gradation (dry and wet), sand equivalent, voids, L.A. abrasion, freeze, and thaw, CKE, specific gravity and absorption, pH, Zeta potential, and plasticity.

b. Emulsions: Tests will include:

Viscosity, residue content, particle size distribution, particle change, pH, viscosity, and penetration of residue.

c. Slurry seals: Tests will include:

Mixing stability, time of set, curing rate, water resistance, shaker durability, wet track abrasion test and loaded wheel sand adhesion test.

4. Construction of the slurry seal test sections (Iowa DOT)

5. Performance evaluation (Iowa DOT)

a. During construction: the following will be tested, observed and recorded:

- Slurry uniformity
- Extraction
- Crack filling
- Slurry stability, separation, and foaming
- Rate of cure
- Aggregate moisture versus unit weight
- Slurry consistency
- Surface preparation
- Temperature, humidity, wind velocity, etc.

b. At three-month intervals, the following will be tested, observed and documented:

- Uniformity of the slurry seals
- Sanding, tearing, or scuffing
- Extraction test
- Permeability
- Skid resistance
- Crack sealing
- Adhesion to existing pavement
- Flushing/bleeding
- Subsurface moisture conditions
- Traffic counts

6. Reports (Iowa DOT and ISU): It is expected that three reports will be prepared during the program:

- Report No. 1 will be prepared by ISU three months after the construction of the test sections. It will cover the laboratory tests and evaluation of the materials and slurry seals.
- Report No. 2 will be prepared by Iowa DOT six months after the construction of the test sections. It will document the slurry behavior and problems during construction.
- Report No. 3 will be prepared jointly by Iowa DOT and ISU on performance evaluation and laboratory correlation as affected by the factors included in the field test factorial arrangements. As end products, it also will

include a slurry seal test and design manual, a set of performance-based specifications, and a set of slurry seal construction and inspection guides.

8.4 Program Schedule

It is recommended that the test sections be constructed by September 15, 1977, field performance tests continue to be conducted for two years, and the final report be due by December 31, 1979.

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Appreciation is also extended to the various highway departments and agencies listed in Table 1 for supplying specifications and other information on slurry seals.

The following individuals contributed to this investigation: Ruth Abatzoglou, Ken Dedecker, and K. Y. Wong.

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APPENDIX A

Virginia Test Method for Determining Percent Voids in Stone Sand

Designation: VTM-5

1. Scope

This method covers the procedures to be used in determining the average percent voids present in manufactured stone sand and is therefore a method for controlling particle shape.

2. Apparatus

The apparatus required shall consist of the following:

a. Standard set of fine aggregate sieves containing a No. 8, No. 16, No. 30, and No. 50 sieve.

b. Set of balances.

c. Metal cylindrical cup calibrated for weight and volume and having approximately a height of 5.5 inches and a diameter of 2 inches.

d. A metal frame with a base 6 inches square and a height of 10 3/4 inches with an opening in the top capable of supporting a funnel which when suspended, will have its base one inch above the cup when the cup is placed on the base. The bottom opening of the funnel will have a diameter of one inch. The base will be fitted with lugs that are so placed that they will center the cup directly below the funnel.

e. Small glass plate approximately 2 inches square.

f. Steel straight edge approximately 12 inches long.

3. Procedure

The sample is sieved until ample material of the No. 16, No. 30, and No. 50 sizes is present to fill the cup to overflowing. This will usually require at least three sievings.

Each size is introduced separately into the funnel of the apparatus with the glass plate being held firmly against the bottom of the funnel. When the funnel is full, the glass plate is withdrawn and the material allowed to flow freely into the cup.

The cup is then struck off with the straightedge, being careful not to jar the container and thus pack the material.

Three separate weighings of each size are made and the average weight determined.

The specific gravity of the material, determined previously according to AASHO T 84, is multiplied by the volume of the cup to obtain a theoretical solid weight.

This computed value is compared to the weight obtained by weighing the material and the percentage is the percent solids present. This is subtracted from 100 to obtain the percent voids.

The percent voids obtained from the three sizes is averaged and reported as the percent voids of the total sample.

APPENDIX B

Shaker Test Procedure

Apparatus (See Photo 1)

1. The Gilson Mechanical Screen Shaker:

   a. Motor: 1078 rpm

   b. Vibration Amplitude: 0.5 in.

2. Two Gilson screen trays; each can hold 12 open-top cans size 4 1/16 in. x 4 11/16 in. and each tray has a 1/4-in. thick steel cover. On one side of the cover, there are 12 circular rubber gaskets. The diameter of these gaskets is about 1/8 in. greater than that of the cans.
3. 24 open-top cans (No. 401 x 411, 4 1/16 in. O.D. x 4 11/16 in.)
4. 1/2-in. diameter steel balls.
5. ASTM C190 silica sand

Procedure

1. Pour enough freshly mixed slurry in tared cans to make a slurry 1/4 in. thick as cast. Gently tap the bottom of can against a flat surface to bring the slurry to level.
2. Cure the specimen in can at 140 ^{o}F for 24 hr., cool, and weigh.
3. Put specimen and can in a freezer (at -10 ^{o}F) for 90 min.
4. After 90 min., remove and add 50 g of C190 sand, 50 g of ice water (at 33-35 ^{o}F), and nine 1/2-in. steel balls to each can. Position cans with specimens on the sample tray and retainer and cover the top of each can with a piece of plastic paper and then with the steel cover plate.

5. Tighten the cover with the wing screws provided.
6. Mount and fix trays onto the Gilson shaker.

   Shake for 30 min.
7. Remove cans from the shaker.
8. Remove the steel balls and wash out sand abraded materials.
9. Oven dry the specimen at 140 ^{o}F to constant weight and weigh.
10. The weight difference from the original weight is calculated and reported as shaker loss at 30 min (grams or grams per square foot).
11. Repeat 3-9 for 60 min shaker loss in grams or grams per square foot.

APPENDIX C

Wet Track Abrasion Test

1. Scope

1.1 This method of test covers measurement of the wearing qualities of slurry seal under wet abrasion conditions.

2. Summary of Method

2.1 A slurry mixture of fine graded aggregate, asphalt emulsion and water is prepared to a homogeneous flowing consistency. The slurry is formed into a disc by pouring in the circular opening of a template resting on a larger circlet of heavy smooth roll roofing.

2.2 After removal of the template the disc specimen is dried to constant weight at 140 ^{o}F. The cured slurry is placed in a water bath for one hour, then mechanically abraded under water with a rubber hose for 5 min. The abraded specimen is washed free of debris, dried at 140 ^{o}F and weighed. The loss in weight expressed as grams per square foot is reported as the wear value (WTAT loss).

3. Apparatus

3.1 A Hobart C-100 planetary type mechanical stirrer equipped with a 5-lb weighted rubber hose holding device (abrasion head) with about 1/2 in. of free up-and-down movement in the shaft sleeve (See Photo 2).

3.2 Heavy flat bottom metal pan, approximately 13-in. diameter with 2-in. vertical side walls having three equi-spaced screw clamps capable of securing 11-1/4-in. diameter specimen to bottom of pan.

3.3 Supply of 11-1/4-in. diameter discs cut from smooth 50- to 60-lb weight roll roofing.

3.4 Circular template 1/4 in. to 3/8 in. thick with an 11-in. diameter circular opening.

3.5 Reinforced rubber hose equivalent to U.S. Rubber Company P-290 with a 3/4-in. inside diameter and about 1/4-in. wall thickness. The hose shall be cut into 5-in. lengths and drilled with two paired 3/8-in. holes aligned on 4-in. centers.

3.6 Wooden prop block or equivalent for supporting platform assembly into position during testing.

4. Procedure for Preparation of Test Specimen

4.1 Mix about 800 g of slurry.

4.2 Place the template over the 11-1/4-in. diameter disc of roofing felt and hold the template down with quick snap clamps. Immediately pour the slurry onto the roofing disc.

4.3 Squeegee the slurry level with the top of the template with a minimum of manipulation. Scrape off excess material and discard.

4.4 Remove the template, place the molded specimen in the 140 ^{o}F oven, and dry to constant weight.

5. Wet Track Abrasion Test

5.1 Remove the dried specimen from the 140 ^{o}F oven, allow it to cool to room temperature, and weigh.

5.2 After weighing, place the specimen in the 77 ^{o}F water bath for 60-75 min.

5.3 Remove the specimen from the water bath and place in the 13-in. diameter flat bottom pan. Secure the specimen to the pan bottom by tightening the three wing-nuts and screws.

5.4 Completely cover the specimen with at least a 1/4-in. depth of water (temperature 77 ^{o}F).

5.5 Secure the pan containing the specimen on the platform of the Hobart C-100 machine. Lock the rubber hose abrasion head on the shaft of the Hobart machine. Elevate the platform of the Hobart machine until the rubber hose bears on the surface of the specimen. Use the prop block to support the platform assembly during testing.

5.6 Switch to the low speed of the Hobart machine (approximately 144 shaft rpm at 62 turns of the planetary). Operate the machine for exactly 5 min running time. (Note: Install a fresh section of hose after completion of each test.) It is permissible to rotate the hose 1/4 turn after each test run and obtain a fresh section for the next specimen.

5.7 Remove the specimen from the pan after the abrasion cycle and wash off debris. Place the washed test specimen in the 140 ^{o}F oven and dry to constant weight.

5.8 The dried specimen is removed from the 140 ^{o}F oven, allowed to reach room temperature, and weighed. The difference between this weight and the weight obtained in Section 5.1 is multiplied by 3.06 to express the loss in grams per square foot (wear value).

APPENDIX D

Abridged Testing Procedures for Consistency, Set Time and Cure Time of Emulsion Asphalt Slurry Seal

1. Cone Consistency Test

1.1 The cone is used to determine the amount of water required to form a stable, workable mixture. This test used the sand adsorption cone described in ASTM C-128 or AASHTO T-84 and a base flow scale. The Cone is a hollow 20-gage metal frustrum, 2.9 in. high with 1.5-in. top and 3.5-in. bottom diameters. The flow scale has seven concentric circles inscribed on an industrial tile or metal sheet or paper in one centimeter increasing radii from the circle formed by the large end of the cone.

1.2 Several trial mixtures are made using 400 g of combined aggregate at ambient temperature, optimum emulsion, and varied water contents. The cone is centered on the flow scale, and after 30 sec of thorough mixing the cone is loosely filled, struck off, and immediately removed with a smooth vertical motion. The outflow of the slurry is measured at four points 90° apart, averaged, and recorded as " ________ cm flow @ ________% added mix water."

1.3 Optimum is considered as 2.5 cm radial flow with limits of 2.0 cm to 3.0 cm and reproducibility of ± 0.25 cm. Design work should be performed on all the actual project materials and should simulate field conditions of temperature and stockpile moisture expected.

2. Set Time

2.1 This method of test is used to determine the time required for the slurry mat to reach initial set (resistance to paper blot).

2.2 The slurry mix or mixtures that provide the desired consistency shall be repeated to determine their setting chracteristics. A mix passing the consistency test is poured onto a 6 in. X 6 in. asphalt felt pad and screeded to a 1/4-in. thickness. At the end of 15 min., at 77 ± 3 ^{o}F and 50 ± 5% relative humidity, a paper towel or tissue is lightly pressed or blotted on the slurry surface. If no brown stain is transferred to the paper, the slurry is considered set. If a brown stain does appear, repeat the blot procedure at 15 min intervals. Record and report time required to obtain a stain-free blot as the set time.

3. Cure Time

3.1 Total cure of a slurry mat is obtained when complete cohesion between asphalt coated aggregate particles occurs. A cohesion testing device is used to measure cure time.

3.2 A slurry mix of optimum design obtained from use of the consistency test is screeded onto a roofing felt pad to a thickness not exceeding the height of the largest aggregate fragment present in the mix. A 4-in. diameter template is used to obtain uniform thickness of the slurry mat.

3.3 After "set" of the slurry mat has occurred, the mat is placed beneath the weighted rubber foot (1-in. diameter) of the Cohesion Tester (see Photo 3). The rubber foot is twisted by means of a hand torque tester. The torque procedure is repeated at 15-30 min intervals until the highest torque reading obtainable remains constant. An undisturbed site on the slurry pad should be selected for each time-interval test. The time required to reach a constant optimum torque is recorded as the cure time.

APPENDIX E

Data Sheets for Slurry Seal Design, Mixing, and Setting Tests, Consistency and Cure Test

Form 185-1
11/20/76

Bituminous Research Laboratory
Iowa State University

Design of Slury Seals

Project HR-185
Date ______
Emulsion: SS-1H ✓ CSS-1H (40) ___
CQS-1H ___ CSS-1H(100) ___
Calculated by RA
Sp. Gr. of Emulsion (SGE) 1.020
Residue Ashpalt Content in Emulsion (R) 65 %
Aggregate : -#4 of Dickinson Gr. (779) (12B)
Apparent Sp. Gr. (ASG) 2.739
ISSA seal type: Type 1 (fine) ___ ; Type II (General) ✓
Surface area of aggregate (SA): ___

Sieve size	percent passing	x	Surface Area Factor	=	Surface Area ft^2/lb. Aggregate
3/8 in.	*100		0.02		2.00
No. 4	100		0.02		2.00
No. 8	69		0.04		2.76
No. 16	50		0.08		4.00
No. 30	37		0.14		5.18
No. 50	28		0.30		8.40
No. 100	21		0.60		12.60
No. 200	15		1.60		24.00
			Total SA	=	60.99

Corrected SA, (CSA) = SA x $\frac{2.65}{ASG}$ = 59.11 ft^2 / lb aggregate

	(0.8E)	(1.0E)	(1.2E)	
Film thickness (t) =	7 μ	8 μ	9 μ	10 μ
Kerosene absorption (KA), % =	___	3.5	___	___

Total bitumen required, gm/100 gm agg.

= (CSA) x (t)x (SGE) x (0.0205) + (KA)

___	13.39	___	___

Emulsion required,* gm/100 gm agg.

$$= \frac{(BR) \times (100)}{(R)} =$$ ___ 20.60 ___ ___

Ill. E = (2.00 + SA) × 0.33 16.62 20.77 24.92

ISSA recommended medium emulsion content
Fine (Type 1) = 20 gm/100 gm dry aggregate
General (Type II) = 16 gm/100 gm dry aggregate

*Increase emulsion required by 1 percent for every additional p.c. or hydrated lime added to the aggregate

Form 185-2
11/20/76

Bituminous Research Laboratory
Iowa State University

Slury Seal Mixing and Setting Tests

Project ________________ Date ______________
Temperature _________°F. Operator ____________
Relative Humidity _________% p.c. Type 1___ II___
Aggregate________________ Emulsion______________
Sand Equivalent (SE)_______
Calculated emulsion content, gm/100 gm dry aggregate = ______________________

Trial No.	____	____	____	____	____	____
Aggregate, gm (oven dry/ air dry)	____	____	____	____	____	____
P.C. / Hydrated lime, gm	____	____	____	____	____	____
Water, gm	____	____	____	____	____	____
Emulsion*, gm	____	____	____	____	____	____
Mixing time, min.	____	____	____	____	____	____
Mixing characterics;						
Free flowing and creamy	____	____	____	____	____	____
Balling or stiffening (premature braking)	____	____	____	____	____	____
Separation/coating	____	____	____	____	____	____
Foaming /bubbles	____	____	____	____	____	____
Set time ; Clock time,	____	____	____	____	____	____
Paper blot and displacement 15 min.	____	____	____	____	____	____
30 min.	____	____	____	____	____	____
60 min.	____	____	____	____	____	____
24 hrs.	____	____	____	____	____	____
Water resistance						
30 min.	____	____	____	____	____	____
60 min.	____	____	____	____	____	____

*Increase emulsion content by 1 gm for every additional gram of p.c. or hydrated lime added to the aggregate.

Form 185-3
12/2/76

Bituminous Research Laboratory
Iowa State University

Consistency & Cure Test

Project: ______________ Date ____________
Temperature: __________ °F Operator ____________
Relative Humidity ______ % p.c. Type 1 ___ Type II ___
Aggregate ______________ Emulsion: __________ gm.

Mix Number:	____	____	____	____	____
Aggregate, gm.	____	____	____	____	____
p.c. / Hydrated lime, gm.	____	____	____	____	____
Water, gm.	____	____	____	____	____
Emulsion*, gm.	____	____	____	____	____
Cone flow, cm.	____	____	____	____	____
Funnel flow, sec.	____	____	____	____	____

Cohesion; weight __________, foot# _____, torque inch-lb.

clock-time	____	____	____	____	____
1/2 hr.	____	____	____	____	____
1 hr.	____	____	____	____	____
4 hrs.	____	____	____	____	____
24 hrs.	____	____	____	____	____

Torvane; shear head# _____, Depth _____ in.

Clock-time	____	____	____	____	____
1/2 hr.	____	____	____	____	____
1 hr.	____	____	____	____	____
4 hrs.	____	____	____	____	____
24 hrs.	____	____	____	____	____

*Increase emulsion required by 1 percent for every additional p.c. or hydrated lime added to the aggregate

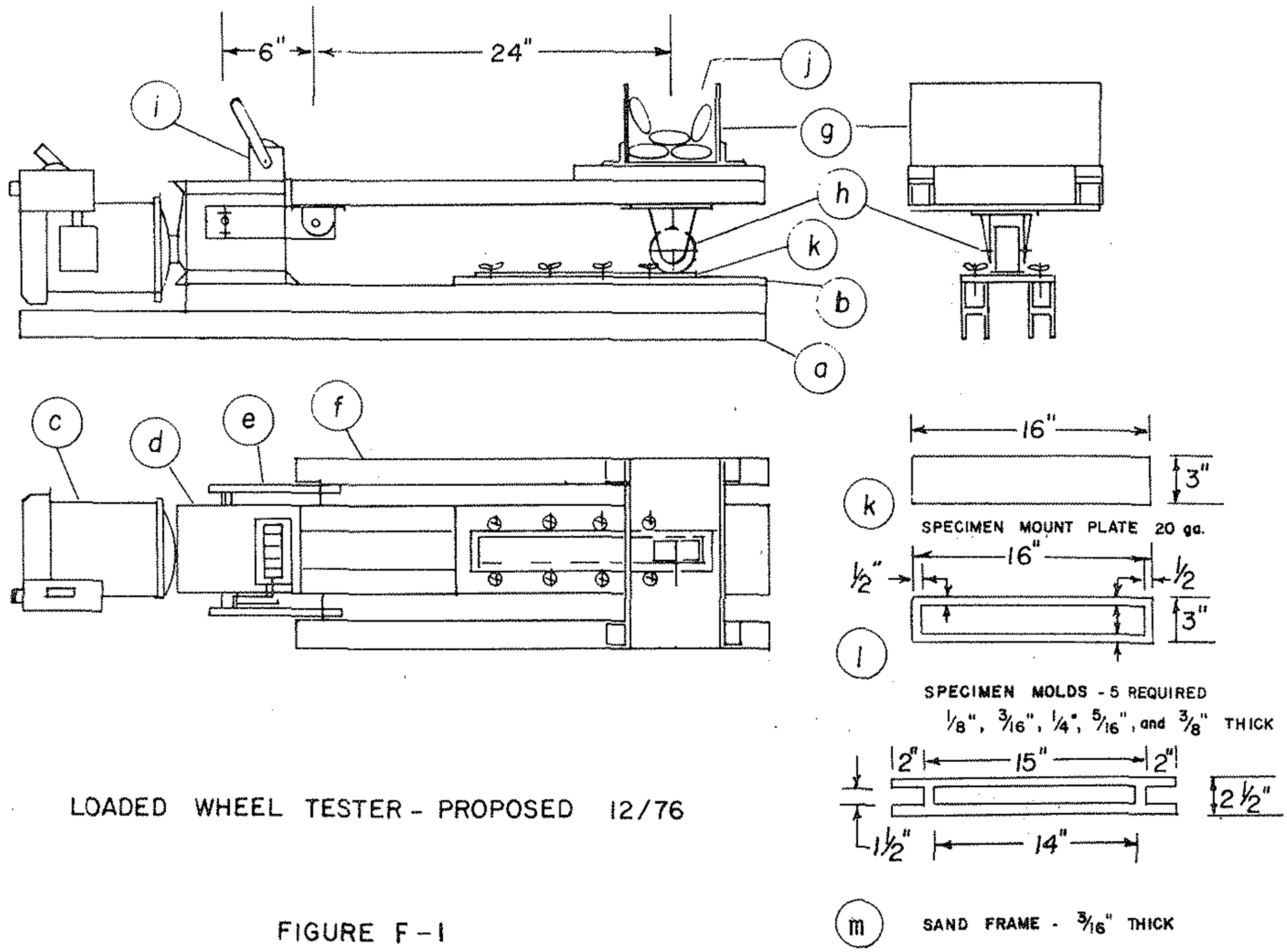
APPENDIX F

Loaded Wheel and Sand Adhesion Test

1. Prepare sufficient slurry seal mix to fill the molds. Mixing should proceed rapidly and thoroughly so that the specimen is cast 30 sec after the addition of the emulsion.
2. The selected mold is centered over a previously weighed specimen mounting plate and uniformly over-filled with the mixture. Using a horizontal sawing motion with the strike-off bar held in a vertical position, the specimen is struck off level with the specimen frame. When the specimen has set sufficiently to prevent displacement, the mold is removed. The specimen is dried for a minimum of 12 hrs to constant weight in a 140 ^oF oven. The specimen is removed from the oven and cooled to room temperature.
3. The specimen is then placed on the mounting plate firmly against the locating pins and clamped in position with the clamp washers and wing nuts provided.
4. The wheel is inspected, thoroughly cleaned with evaporative solvent and water, and then placed on the specimen; the weight box is then loaded to the desired weight (125 lb).
5. The counter is returned to zero, and compaction is started. The cycles per minutes should be 44.
6. At some point during the compaction, an audible tackiness and visible shine may be noted. At this point, sufficient water to prevent adhesion of the specimen to the wheel must be added from the wash bottle. (With certain aggregates, it may become necessary

to liberally flush the wheel path with water to prevent abraded fines from impacting the specimen.) Notation of the revolutions required to reach the tack point is made.

7. After 1000 cycles, the machine is stopped and unloaded, and the specimen is washed of loose particles and dried at 140 ^{o}F to constant weight.
8. The dried weight of the specimen is noted, and the specimen is mounted on the mounting plate in its original position. The sand frame is centered over the specimen, with the foam rubber against the specimen and secured to prevent loss of sand. Hot ASTM C 109 sand (180 ^{o}F) is uniformly spread in to fill the sand mold, the wheel is immediately loaded on the specimen, and 100 cycles are complete.
9. All loose sand is removed, and the specimen is removed and weighed. The increase in weight due to sand adhesion is noted.



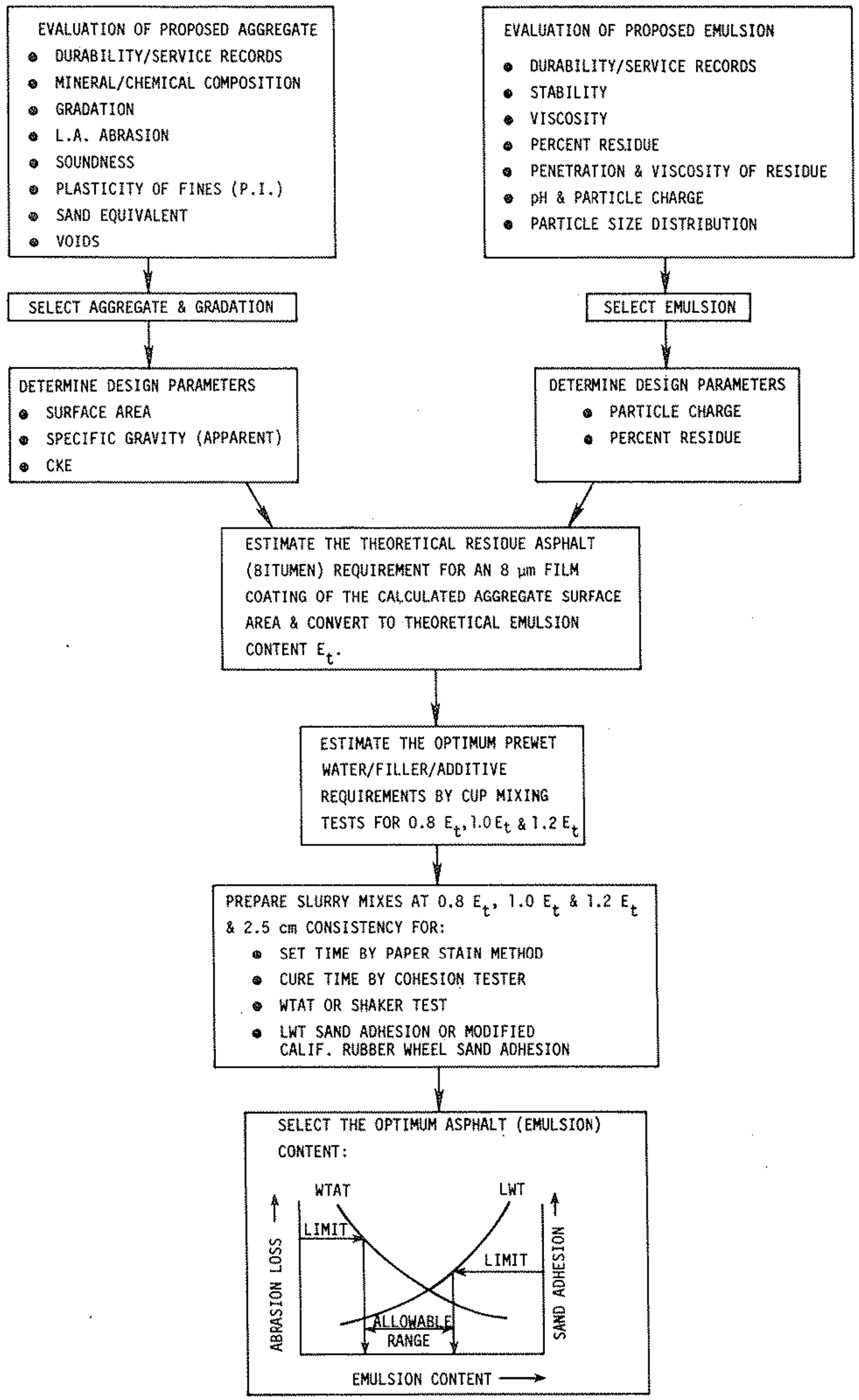
LOADED WHEEL TESTER - PROPOSED 12/76

FIGURE F-1

a. FRAME OF ADJUSTABLE STEEL CHANNEL
b. MOUNTING PLATE FOR SPECIMENS
c. 1/3 hp, 1750 rpm FLANGED MOTOR
d. 40:1 HORIZONTAL DOUBLE OUTPUT SHAFT GEAR REDUCER
e. DRIVE CRANKS, 6-in. RADIUS
f. DRIVEN CONNECTING ARMS OF ADJUSTABLE, STEEL CHANNEL
g. WEIGHT BOX, CENTRALLY ADJUSTABLE OVER THE WHEEL
h. BASSICK #180 CASTER ASSEMBLY WITH 3-in. DIAMETER x 1 in. RUBBER TIRE MOUNTED AT A HORIZONTAL DISTANCE OF 24 in. BETWEEN DRIVE AND CASTER AXLES. (OTHER WHEELS MAY BE USED)
i. RESETABLE REVOLUTION COUNTER
j. 5-25 lb BAGS OF #7 OR #8 LEAD SHOT
k. SPECIMEN MOUNTING PLATES, 20 GAGE GALVANIZED STEEL x 3 in. x 16 in. DEBURRED
l. SPECIMEN MOLDS VARIOUSLY .125, .188, .250, .313, and .375 in. THICK x 3 in. x 16 in. OUTSIDE and 2 in. x 15 in. INSIDE DIMENSIONS
m. STEEL SAND FRAME, .188 in. x 2.5 in. x 15 in. OUTSIDE AND 1.5 in. x 14 in. INSIDE DIMENSIONS, COMPLETELY LINED ON ONE SIDE WITH 1/2 in. x 1/2 in. ADHESIVE-BACKED FOAM RUBBER INSULATION

APPENDIX G

Slurry Seal Design Flow Chart



APPENDIX H

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BITUMINOUS EMULSION SLURRY SEALS

HR-185

June 1977

Compiled by

D. Y. Lee

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