77

HIGHWAY QUALITY CONTROL PROGRAM
Statistical Parameters

Progress Report on a Highway Planning and Research Project
Conducted in Cooperation With
The U. S. Department of Commerce--Bureau of Public Roads

Research Laboratory Division
Office of Testing and Research
Research Project 63 G-123
Research Report No. R-572

State of Michigan
Department of State Highways
Lansing, March 1966

INTRODUCTION

This report has been prepared to summarize statistical analyses that have been conducted on various highway materials and construction procedures. This summary is in accordance with a Bureau of Public Roads memorandum from F. B. Farrell, Bureau of Public Roads Regional Engineer, to Division Engineers in Indiana, Michigan, and Wisconsin on January 13, 1966, titled "Statistical Parameters - Quality Control Program." The information gathered to date on Phases I and II of the Department's H. P. R. program on Highway Quality Control has been screened to present all available data requested in this memorandum.

The data in this report arise from two sources: 1) random sampling of past field construction records of job control testing, and 2) a statistically designed experiment on field testing of aggregate gradation conducted to determine, if possible, specific causes for testing variation. For the first set of data, it was possible to obtain only the following statistical parameters requested in the Bureau's memorandum: the number of test measurements, the arithmetic mean and overall variance, and the overall standard deviation. Thus, specific causes for variation cannot be assigned. For the second set of data, deriving from the experimental program, some information was available on sampling and testing variance due to different inspectors and different equipment (screening sieves). However, the experimental design was not set up to differentiate between material and experimental variance. In every case, the specification requirements are illustrated or discussed along with the data, and, therefore, the separate transmittal of specifications suggested in the Bureau's memorandum is deemed unnecessary.

CONTENTS

Aggregate Gradation--Records Survey 1

Fineness Modulus 15

Flexural Strength of Concrete Beams 19

Thickness of Concrete Pavements 24

Air Content of Fresh Pavement Concrete 26

Moisture and Density of Aggregate Base Course and
Sand Subbase 28

Aggregate Gradation--Field Experiment .34
Experimental Procedure 35
Selection of Samples 37
Aggregate Passing 3/8-in. Sieve 40
Aggregate Passing No. 10 Sieve 44
Aggregate Passing No. 200 Sieve 50
Control Charts for 22A Aggregate 54
Results of the Field Experiment 57

AGGREGATE GRADATION--RECORDS SURVEY

The chief sources of information were daily job control records of aggregate field testing covering the period 1959 through 1961. About 120 highway projects were classified by finding, counting, and identifying daily records; types of aggregate; and producers. The types of aggregate materials involved in this study were limestone, gravel, and slag. Detailed analysis of the data established proper sampling procedures and the computations required for appropriate statistical evaluation.

It should be noted that the data analyzed and shown in Table 1 did not include the percents passing for all sieve size requirements of the specifications, but did include representative sieve sizes for each aggregate. In addition, it should be noted that Table 1 consists exclusively of data from accepted batches of material. The 4A, 6A, 6AA, and 10A aggregates are used for coarse aggregate in portland cement concrete for either pavements or structures; the 9A aggregate for bituminous base and binder courses; 20A for bituminous aggregate surface course; 22A for aggregate base and surface courses, aggregate shoulders, and aggregate resurfacing; 23A for aggregate shoulders and aggregate approaches; 24A for selected subbase; 25A for bituminous concrete wearing course; 26B for bituminous non-skid surface treatment; and 2NS sand for portland cement concrete. These materials were produced in accordance with then current Michigan specifications; however, in the 1965 edition of the Michigan Standard Specifications, certain revisions were made which changed the requirements for some of these aggregates, and two classifications (10A and 26B) no longer exist.

Since the Table 1 data consisted only of results from accepted batches, a study was subsequently made to determine the proportion of accepted-to-rejected material, and how the inclusion of data from the rejected material would influence the overall distribution. Aggregate type 22A was selected for this study since from experience it was noted that this type generally has a larger proportionate amount of rejected material than other aggregate types. Data from 11 projects were studied with the results summarized in Table 2. Approximately 3.7 percent of the material tested was rejected for one or more deviations from specification requirements. For the 104 rejected results, 42 (or 40.4 percent) failed to pass No. 10 sieve within requirements, 22 (or 21.1 percent) failed to meet requirements on loss by washing, (No. 200 sieve), 8 (or 7.7 percent) failed to meet 3/8-in. sieve requirements, while 16 (or 15.4 percent) failed to meet the requirements for more than one sieve, and 16 (or 15.4 percent) failed for other reasons than gradation requirements.

TABLE 1
SUMMARY OF GRADATION TESTS ON ACCEPTED MATERIAL OF DIFFERENT AGGREGATE TYPES

Material and Producer	Item	Type 4A — Sieve Size and Spec. Limits, % — 2-1/2 in. 100	2 in. 95-100	1-1/2 in. 65-90	1 in. 10-40	1/2 in. 0-20	3/8 in. 0-5	Loss by Washing 0.8 % max.
Gravel Producer A (300 Tests)	Avg. Gradation,%			77.8	22.2	2.2	1.1	
	Std. Deviation,%			8.0	8.1	1.8	1.0	
	% of Tests:							
	Within Specs., %			95.3	97.0	100.0	99.3	
	Above,%			0.7	2.0	0.0	0.7	
	Below,%			4.0	1.0	0.0	0.0	
Gravel Producer B (300 Tests)	Avg. Gradation,%			80.6	26.1	3.7	1.4	
	Std. Deviation,%			7.0	7.0	3.7	1.5	
	% of Tests:							
	Within Specs., %			97.6	95.7	100.0	96.7	
	Above,%			1.7	3.3	0.0	3.3	
	Below,%			0.7	1.0	0.0	0.0	
Gravel Producer C (300 Tests)	Avg. Gradation,%	Not Analyzed	Not Analyzed	74.7	23.8	0.7		Not Analyzed
	Std. Deviation,%			6.4	8.1	1.1		
	% of Tests:							
	Within Specs., %			96.0	98.0	100.0	100.0	
	Above,%			1.0	1.7	0.0	0.0	
	Below,%			3.0	0.3	0.0	0.0	
Gravel Producer D (300 Tests)	Avg. Gradation,%			75.5	29.8	5.2	1.9	
	Std. Deviation,%			7.9	8.8	3.8	1.7	
	% of Tests:							
	Within Specs., %			92.3	93.0	99.7	94.3	
	Above,%			1.7	7.0	0.3	5.7	
	Below,%			6.0	0.0	0.0	0.0	
Gravel Producer E (300 Tests)	Avg. Gradation,%			80.2	22.9	5.1	2.4	
	Std. Deviation,%			7.1	7.0	4.2	2.1	
	% of Tests:							
	Within Specs., %			95.0	97.4	99.0	92.3	
	Above,%			3.3	2.3	1.0	7.7	
	Below,%			1.7	0.3	0.0	0.0	

Material and Producer	Item	Type 4A (Cont.) — Sieve Size and Spec. Limits, % — 2-1/2 in. 100	2 in. 95-100	1-1/2 in. 65-90	1 in. 10-40	1/2 in. 0-20	3/8 in. 0-5	Loss by Washing 1.5 % max.
Stone Producer F (300 Tests)	Avg. Gradation,%			74.0	28.7	1.0	0.7	
	Std. Deviation,%			5.9	6.2	0.9	0.6	
	% of Tests:							
	Within Specs., %			99.7	99.7	100.0	100.0	
	Above,%			0.0	0.3	0.0	0.0	
	Below,%			0.3	0.0	0.0	0.0	
Stone Producer G (300 Tests)	Avg. Gradation,%			77.2	25.9	3.2	1.7	
	Std. Deviation,%			7.6	8.6	4.6	1.7	
	% of Tests:							
	Within Specs., %			97.0	96.7	100.0	95.0	
	Above,%			0.7	2.3	0.0	5.0	
	Below,%	Not Analyzed	Not Analyzed	2.3	1.0	0.0	0.0	Not Analyzed
Stone Producer H (300 Tests)	Avg. Gradation,%			77.4	19.6	2.9	1.7	
	Std. Deviation,%			7.2	7.3	2.6	2.5	
	% of Tests:							
	Within Specs., %			94.7	95.4	100.0	94.0	
	Above,%			2.0	0.3	0.0	6.0	
	Below,%			3.3	4.3	0.0	0.0	
Slag Producer I (300 Tests)	Avg. Gradation,%			76.1	21.8	1.9	1.3	
	Std. Deviation,%			7.0	4.7	1.2	0.8	
	% of Tests:							
	Within Specs., %			96.3	99.7	100.0	100.0	
	Above,%			0.0	0.0	0.0	0.0	
	Below,%			3.7	0.3	0.0	0.0	

NOTE: Method of sampling was by proportional allocation of daily job control records of materials which were accepted. Sizes of samples as indicated in first column for each material and producer. Current Specifications (1965 Edition) are different than those shown, as follows:

4A--Unchanged	9A--Changed	22A--Changed Somewhat	25A--Changed Significantly
6A--Changed	10A--No Longer Exists	23A--Changed Slightly	26B--No Longer Exists
6AA--Changed	20A--Changed	24A--Changed	2NS--Unchanged

TABLE 1 (cont.)
SUMMARY OF GRADATION TESTS ON ACCEPTED MATERIAL OF DIFFERENT AGGREGATE TYPES

Material and Producer	Item	Type 6A: Sieve Size and Spec. Limits, % 2-1/2 in. 100	2 in. 95-100	1-1/2 in. 90-100	1 in. 60-90	1/2 in. 25-55	No. 4 0-8	Loss by Washing 0.8 % max.
Gravel Producer A (300 Tests)	Avg. Gradation,%			99.8	77.3	37.3	0.9	
	Std. Deviation,%			0.7	6.3	6.9	0.7	
	% of Tests:							
	Within Specs., %			100.0	99.3	99.3	100.0	
	Above,%			0.0	0.7	0.0	0.0	
	Below,%			0.0	0.0	0.7	0.0	
Gravel Producer U (226 Tests)	Avg. Gradation,%	Not Analyzed	Not Analyzed	99.9	79.1	34.5	0.8	Not Analyzed
	Std. Deviation,%			0.4	6.4	7.1	0.8	
	% of Tests:							
	Within Specs., %			100.0	99.1	95.6	100.0	
	Above,%			0.0	0.9	0.9	0.0	
	Below,%			0.0	0.0	3.5	0.0	
Gravel Producer V (222 Tests)	Avg. Gradation,%			98.6	72.4	33.7	2.5	
	Std. Deviation,%			1.6	7.5	7.4	1.6	
	% of Tests:							
	Within Specs., %			100.0	96.8	94.6	100.0	
	Above,%			0.0	0.9	0.0	0.0	
	Below,%			0.0	2.3	5.4	0.0	

Material and Producer	Item	Type 6AA: Sieve Size and Spec. Limits, % 1-1/2 in. 100	1 in. 95-100	1/2 in. 30-60	No. 4 0-8	Loss by Washing 0.8 % max.
Gravel Producer S (89 Tests)	Avg. Gradation,%	Not Analyzed	99.9	47.4	3.5	Not Analyzed
	Std. Deviation,%		0.5	6.3	1.6	
	% of Tests:					
	Within Specs., %		100.0	98.9	100.0	
	Above,%		0.0	1.1	0.0	
	Below,%		0.0	0.0	0.0	

Material and Producer	Item	Type 9A: Sieve Size and Spec. Limits, % 1-1/4 in. 100	3/4 in. 45-65	3/8 in. 0-25	No. 4 0-10	Loss by Washing 3 % max.
Crushed Gravel Producer A (147 Tests)	Avg. Gradation,%		54.8	4.5	1.0	
	Std. Deviation,%		5.5	3.1	0.6	
	% of Tests:					
	Within Specs., %		97.9	100.0	100.0	
	Above,%		0.7	0.0	0.0	
	Below,%		1.4	0.0	0.0	
Stone Producer H (108 Tests)	Avg. Gradation,%	Not Analyzed	51.6	8.3	3.0	Not Analyzed
	Std. Deviation,%		6.3	4.7	1.8	
	% of Tests:					
	Within Specs., %		90.7	100.0	100.0	
	Above,%		1.9	0.0	0.0	
	Below,%		7.4	0.0	0.0	
Crushed Gravel Producer T (80 Tests)	Avg. Gradation,%		52.7	3.0	1.6	
	Std. Deviation,%		5.5	1.9	1.0	
	% of Tests:					
	Within Specs., %		95.0	100.0	100.0	
	Above,%		0.0	0.0	0.0	
	Below,%		5.0	0.0	0.0	

TABLE 1 (cont.)
SUMMARY OF GRADATION TESTS ON ACCEPTED MATERIAL OF DIFFERENT AGGREGATE TYPES

Material and Producer	Item	Type 10A				
		Sieve Size and Spec. Limits, %				Loss by Washing 0.8 % max.
		1-1/2 in. 100	1 in. 95-100	1/2 in. 35-65	No. 4 0-8	
Gravel Producer A (300 Tests)	Avg. Gradation,%	Not Analyzed	98.6	47.8	0.9	Not Analyzed
	Std. Deviation,%		1.6	8.3	0.8	
	% of Tests:					
	Within Specs., %		98.7	96.3	100.0	
	Above,%		0.0	1.0	0.0	
	Below,%		1.3	2.7	0.0	
Gravel Producer B (300 Tests)	Avg. Gradation,%		99.2	50.5	2.2	
	Std. Deviation,%		1.3	7.5	2.2	
	% of Tests:					
	Within Specs., %		99.7	98.3	98.3	
	Above,%		0.0	0.7	1.7	
	Below,%		0.3	1.0	0.0	
Gravel Producer C (300 Tests)	Avg. Gradation,%		99.6	50.3	3.2	
	Std. Deviation,%		1.0	8.1	2.4	
	% of Tests:					
	Within Specs., %		99.7	96.3	98.3	
	Above,%		0.0	2.0	1.7	
	Below,%		0.3	1.7	0.0	
Gravel Producer D (300 Tests)	Avg. Gradation,%		97.9	46.4	1.8	
	Std. Deviation,%		1.7	7.4	1.8	
	% of Tests:					
	Within Specs., %		96.3	96.7	100.0	
	Above,%		0.0	0.3	0.0	
	Below,%		3.7	3.0	0.0	
Gravel Producer E (300 Tests)	Avg. Gradation,%		99.0	47.2		
	Std. Deviation,%		1.7	8.4		
	% of Tests:					
	Within Specs., %		97.0	93.4	100.0	
	Above,%		0.0	1.3	0.0	
	Below,%		3.0	5.3	0.0	

Material and Producer	Item	Type 10A (Cont.)				
		Sieve Size and Spec. Limits, %				Loss by Washing 1.5 % max.
		1-1/2 in. 100	1 in. 95-100	1/2 in. 35-65	No. 4 0-8	
Stone Producer F (219 Tests)	Avg. Gradation,%	Not Analyzed	99.99	44.4	2.2	Not Analyzed
	Std. Deviation,%		0.1	7.5	1.7	
	% of Tests:					
	Within Specs., %		100.0	100.0	98.6	
	Above,%		0.0	0.0	1.4	
	Below,%		0.0	0.0	0.0	
Stone Producer G (300 Tests)	Avg. Gradation,%		99.5	47.5	3.4	
	Std. Deviation,%		1.1	8.3	1.9	
	% of Tests:					
	Within Specs., %		99.7	95.7	98.0	
	Above,%		0.0	0.0	2.0	
	Below,%		0.3	4.3	0.0	
Slag Producer I (271 Tests)	Avg. Gradation,%		98.7	45.5		
	Std. Deviation,%		1.2	6.7		
	% of Tests:					
	Within Specs., %		99.6	98.2	99.6	
	Above,%		0.0	0.0	0.4	
	Below,%		0.4	1.8	0.0	

TABLE 1 (cont.)
SUMMARY OF GRADATION TESTS ON ACCEPTED MATERIAL OF DIFFERENT AGGREGATE TYPES

Material and Producer	Item	Type 20A					
		Sieve Size and Spec. Limits, %					Loss by Washing 0-5 %
		3/4 in. 100	3/8 in. 60-80	No. 10 40-50	No. 40 15-30	No. 200 0-5	
Gravel Producer K (140 Tests)	Avg. Gradation,%	Not Analyzed	75.0	44.2	22.6	3.1	Not Analyzed
	Std. Deviation,%		4.7	3.0	3.7	0.7	
	% of Tests:						
	Within Specs., %		90.0	73.6	98.6	99.3	
	Above,%		10.0	10.7	1.4	0.7	
	Below,%		0.0	15.7	0.0	0.0	
Gravel Producer N (172 Tests)	Avg. Gradation,%		77.9	43.7	17.1	4.1	
	Std. Deviation,%		2.5	3.3	2.6	0.6	
	% of Tests:						
	Within Specs., %		87.8	90.7	93.0	95.3	
	Above,%		12.2	8.1	0.0	4.7	
	Below,%		0.0	1.2	7.0	0.0	
Gravel Producer O (193 Tests)	Avg. Gradation,%		77.0	43.5	17.8	4.1	
	Std. Deviation,%		3.0	3.8	2.6	0.6	
	% of Tests:						
	Within Specs., %		91.7	85.5	96.4	96.4	
	Above,%		8.3	3.1	0.0	3.6	
	Below,%		0.0	11.4	3.6	0.0	

Material and Producer	Item	Type 22A				
		Sieve Size and Spec. Limits, %				Loss by Washing 3-7 %
		1 in. 100	3/4 in. 90-100	3/8 in. 65-85	No. 10 30-45	
Gravel Producer C (300 Tests)	Avg. Gradation,%	Not Analyzed	96.5	71.7	40.8	Not Analyzed
	Std. Deviation,%		2.1	4.5	4.3	
	% of Tests:					
	Within Specs., %		100.0	94.7	87.3	
	Above,%		0.0	0.0	11.7	
	Below,%		0.0	5.3	1.0	
Gravel Producer J (300 Tests)	Avg. Gradation,%		95.5	72.8	39.6	
	Std. Deviation,%		2.6	4.6	3.7	
	% of Tests:					
	Within Specs., %		98.0	97.0	92.4	
	Above,%		0.0	0.0	7.3	
	Below,%		2.0	3.0	0.3	
Gravel Producer M (300 Tests)	Avg. Gradation,%		96.2	70.6	40.1	
	Std. Deviation,%		2.7	4.7	4.0	
	% of Tests:					
	Within Specs., %		99.7	95.3	92.7	
	Above,%		0.0	0.0	7.3	
	Below,%		0.3	4.7	0.0	
Gravel Producer P (300 Tests)	Avg. Gradation,%		97.3	71.8	38.3	
	Std. Deviation,%		2.2	5.4	5.1	
	% of Tests:					
	Within Specs., %		100.0	91.7	91.7	
	Above,%		0.0	0.3	4.3	
	Below,%		0.0	8.0	4.0	
Gravel Producer R (300 Tests)	Avg. Gradation,%		98.0	70.4	38.9	
	Std. Deviation,%		2.2	4.5	4.1	
	% of Tests:					
	Within Specs., %		100.0	93.3	96.0	
	Above,%		0.0	0.0	3.0	
	Below,%		0.0	6.7	1.0	

TABLE 1 (cont.)
SUMMARY OF GRADATION TESTS ON ACCEPTED MATERIAL OF DIFFERENT AGGREGATE TYPES

Material and Producer	Item	Type 23A: Sieve Size and Spec. Limits, %: 1 in. 100	3/8 in. 60-85	No. 10 25-50	Loss by Washing 7-15 %
Gravel Producer C (282 Tests)	Avg. Gradation,%		73.3	41.2	
	Std. Deviation,%		5.7	7.5	
	% of Tests:				
	Within Specs., %		98.6	90.0	
	Above,%		0.0	8.9	
	Below,%		1.4	1.1	
Gravel Producer J (300 Tests)	Avg. Gradation,%	Not Analyzed	74.8	46.3	Not Analyzed
	Std. Deviation,%		4.4	4.4	
	% of Tests:				
	Within Specs., %		99.7	86.0	
	Above,%		0.3	14.0	
	Below,%		0.0	0.0	
Gravel Producer L (300 Tests)	Avg. Gradation,%		78.2	43.5	
	Std. Deviation,%		4.9	6.1	
	% of Tests:				
	Within Specs., %		93.3	86.0	
	Above,%		6.7	14.0	
	Below,%		0.0	0.0	

Material and Producer	Item	Type 24A: Sieve Size and Spec. Limits, %: 1 in. 100	3/8 in. 60-85	No. 10 30-50	Loss by Washing 3-7 %
Gravel Producer J (300 Tests)	Avg. Gradation,%		75.2	43.6	
	Std. Deviation,%		4.9	4.0	
	% of Tests:				
	Within Specs., %		99.4	95.7	
	Above,%		0.3	4.3	
	Below,%		0.3	0.0	
Gravel Producer K (300 Tests)	Avg. Gradation,%	Not Analyzed	74.5	44.3	Not Analyzed
	Std. Deviation,%		6.1	5.3	
	% of Tests:				
	Within Specs., %		98.0	90.3	
	Above,%		2.0	9.0	
	Below,%		0.0	0.7	
Gravel Producer M (300 Tests)	Avg. Gradation,%		68.6	41.4	
	Std. Deviation,%		5.2	5.5	
	% of Tests:				
	Within Specs., %		98.3	96.0	
	Above,%		0.0	2.3	
	Below,%		1.7	1.7	

Material and Producer	Item	Type 25A: Sieve Size and Spec. Limits, %: 5/8 in. 100	1/2 in. 90-100	3/8 in. 50-80	No. 4 10-25	No. 10 0-10	Loss by Washing 3 % max.
Crushed Gravel Producer A (300 Tests)	Avg. Gradation,%		96.6	60.9	16.2	4.0	
	Std. Deviation,%		1.8	6.7	3.6	1.5	
	% of Tests:						
	Within Specs., %		99.7	98.0	99.4	100.0	
	Above,%		0.0	0.0	0.3	0.0	
	Below,%		0.3	2.0	0.3	0.0	
Stone Producer G (133 Tests)	Avg. Gradation,%	Not Analyzed	94.6	68.3	14.0	2.6	Not Analyzed
	Std. Deviation,%		2.2	6.2	3.3	1.1	
	% of Tests:						
	Within Specs., %		98.5	99.2	96.2	100.0	
	Above,%		0.0	0.0	0.0	0.0	
	Below,%		1.5	0.8	3.8	0.0	
Stone Producer Q (248 Tests)	Avg. Gradation,%		92.5	61.5	14.7	2.5	
	Std. Deviation,%		2.1	6.1	3.2	1.0	
	% of Tests:						
	Within Specs., %		97.6	99.2	98.8	100.0	
	Above,%		0.0	0.0	0.0	0.0	
	Below,%		2.4	0.8	1.2	0.0	

TABLE 1 (cont.)
SUMMARY OF GRADATION TESTS ON ACCEPTED MATERIAL OF DIFFERENT AGGREGATE TYPES

Material and Producer	Item	Type 26B					
		Sieve Size and Spec. Limits, %					Loss by Washing 3 % max.
		5/8 in. 100	1/2 in. 90-100	3/8 in. 60-85	No. 4 10-35	No. 10 0-10	
Gravel Producer A (157 Tests)	Avg. Gradation,%	Not Analyzed	97.7	70.9	17.0	2.1	Not Analyzed
	Std. Deviation,%		1.6	7.7	4.5	1.3	
	% of Tests:						
	Within Specs., %		100.0	92.4	97.5	100.0	
	Above,%		0.0	0.6	0.0	0.0	
	Below,%		0.0	7.0	2.5	0.0	
Gravel Producer B (131 Tests)	Avg. Gradation,%	Not Analyzed	97.5	72.7	20.2	4.9	Not Analyzed
	Std. Deviation,%		1.4	8.2	5.9	2.5	
	% of Tests:						
	Within Specs., %		100.0	97.7	99.2	95.4	
	Above,%		0.0	0.0	0.8	4.6	
	Below,%		0.0	2.3	0.0	0.0	
Gravel Producer C (163 Tests)	Avg. Gradation,%	Not Analyzed	97.2	75.3	22.6	1.8	Not Analyzed
	Std. Deviation,%		1.9	7.4	6.3	1.9	
	% of Tests:						
	Within Specs., %		100.0	90.1	98.2	100.0	
	Above,%		0.0	7.4	1.2	0.0	
	Below,%		0.0	2.5	0.6	0.0	

Material and Producer	Item	Type 2NS							
		Sieve Size and Spec. Limits, %							Loss by Washing 3 % max.
		3/8 in. 100	No. 4 95-100	No. 8 66-95	No. 16 35-75	No. 30 20-55	No. 50 10-30	No. 100 0-10	
Sand Producer A (300 Tests)	Avg. Gradation,%	Not Analyzed	Not Analyzed	86.4	69.3	Not Analyzed	18.0	2.6	Not Analyzed
	Std. Deviation,%			3.0	3.2		3.5	1.2	
	% of Tests:								
	Within Specs., %			100.0	99.0		100.0	100.0	
	Above,%			0.0	1.0		0.0	0.0	
	Below,%			0.0	0.0		0.0	0.0	
Sand Producer B (300 Tests)	Avg. Gradation,%	Not Analyzed	Not Analyzed	86.3	61.9	Not Analyzed	16.1	3.2	Not Analyzed
	Std. Deviation,%			4.3	3.5		3.2	0.9	
	% of Tests:								
	Within Specs., %			100.0	100.0		99.0	100.0	
	Above,%			0.0	0.0		0.0	0.0	
	Below,%			0.0	0.0		1.0	0.0	
Sand Producer C (300 Tests)	Avg. Gradation,%	Not Analyzed	Not Analyzed	80.6	65.9	Not Analyzed	13.5	2.7	Not Analyzed
	Std. Deviation,%			3.4	6.3		3.4	0.9	
	% of Tests:								
	Within Specs., %			100.0	100.0		98.7	100.0	
	Above,%			0.0	0.0		0.3	0.0	
	Below,%			0.0	0.0		1.0	0.0	
Sand Producer D (300 Tests)	Avg. Gradation,%	Not Analyzed	Not Analyzed	80.7	66.1	Not Analyzed	13.3	3.2	Not Analyzed
	Std. Deviation,%			2.8	3.2		2.8	1.2	
	% of Tests:								
	Within Specs., %			100.0	100.0		98.3	100.0	
	Above,%			0.0	0.0		0.0	0.0	
	Below,%			0.0	0.0		1.7	0.0	
Sand Producer E (300 Tests)	Avg. Gradation,%	Not Analyzed	Not Analyzed	89.6	69.4	Not Analyzed	18.6	3.3	Not Analyzed
	Std. Deviation,%			2.5	3.4		2.9	0.8	
	% of Tests:								
	Within Specs., %			100.0	99.0		100.0	100.0	
	Above,%			0.0	1.0		0.0	0.0	
	Below,%			0.0	0.0		0.0	0.0	

TABLE 2
SUMMARY OF ACCEPTED AND REJECTED
22A AGGREGATE BATCHES

Project	Number of Test Results		
	Total	Accepted	Rejected
1	311	307	4
2	319	306	13
3	338	319	19
4	313	313	0
5	245	210	35
6	136	136	0
7	79	79	0
8	207	202	5
9	169	166	3
10	461	454	7
11	246	228	18
	2824	2720	104

Figures 1, 2, and 3 show the effect of rejected material on frequency distributions of percents passing the 3/4- and 3/8-in., and No. 10 sieves, respectively.

Although tests were studied for 104 lots of 150 tons each of rejected material (out of 2824 lots), the plotting of the distribution of percents passing certain sieves was confined to 60 samples selected at random from the 104. This reduction was made to maintain the approximate proportions of accepted and rejected material. The three graphs show that inclusion of rejected material in the statistical analysis at the rate of approximately 3.7 percent, as encountered for 22A aggregate, would not significantly alter the averages or standard deviations given in Table 1. Thus, for at least this one case the overall distribution is not significantly changed by this inclusion of rejected material.

Figure 4 shows the distribution of non-conforming tests by type of aggregate, producer, and various sieve sizes for gravel, stone, and slag. The non-conforming tests shown are those only within the population of accepted material--that is, the same data given in Table 1. For 4A aggregate and 2NS sand, the distribution of the percents passing is indicated for various sieve sizes. For 4A aggregate (Figure 5), the distribution of percent passing the 1/2- and 3/8-in. sieves tends to be close to the lower specification limit. For 2NS sand (Figure 5), the distribution of percents passing the Nos. 8 and 16 sieves bunch toward the upper specification limit, for the No. 50 it is pretty well centered, but for the No. 100 sieve the results definitely bunch toward the lower specification limit of zero. Table 1 illustrates the inherent distribution characteristics within the specification limits for the other type aggregates.

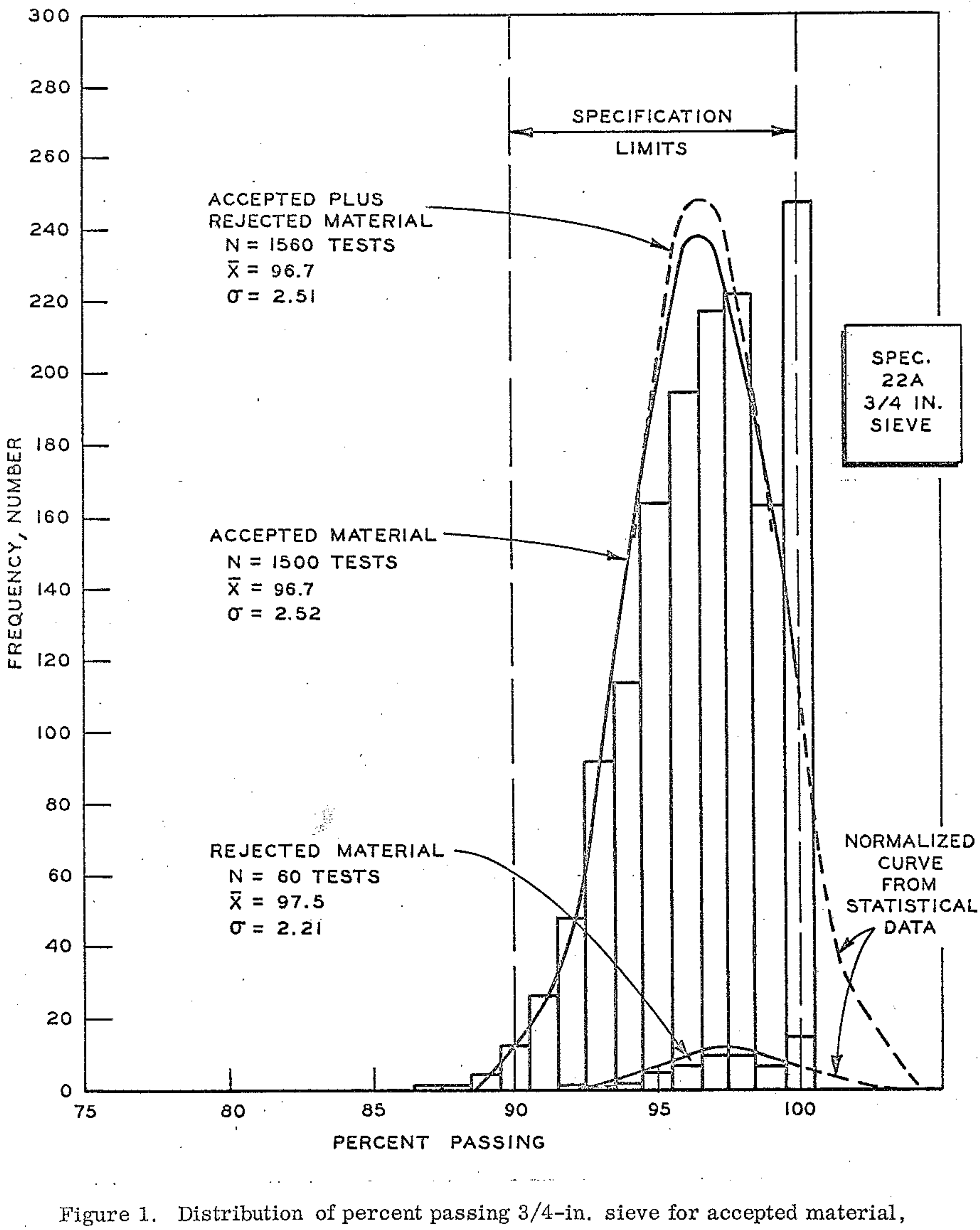


Figure 1. Distribution of percent passing 3/4-in. sieve for accepted material, rejected material, and the combination for 22A aggregate.

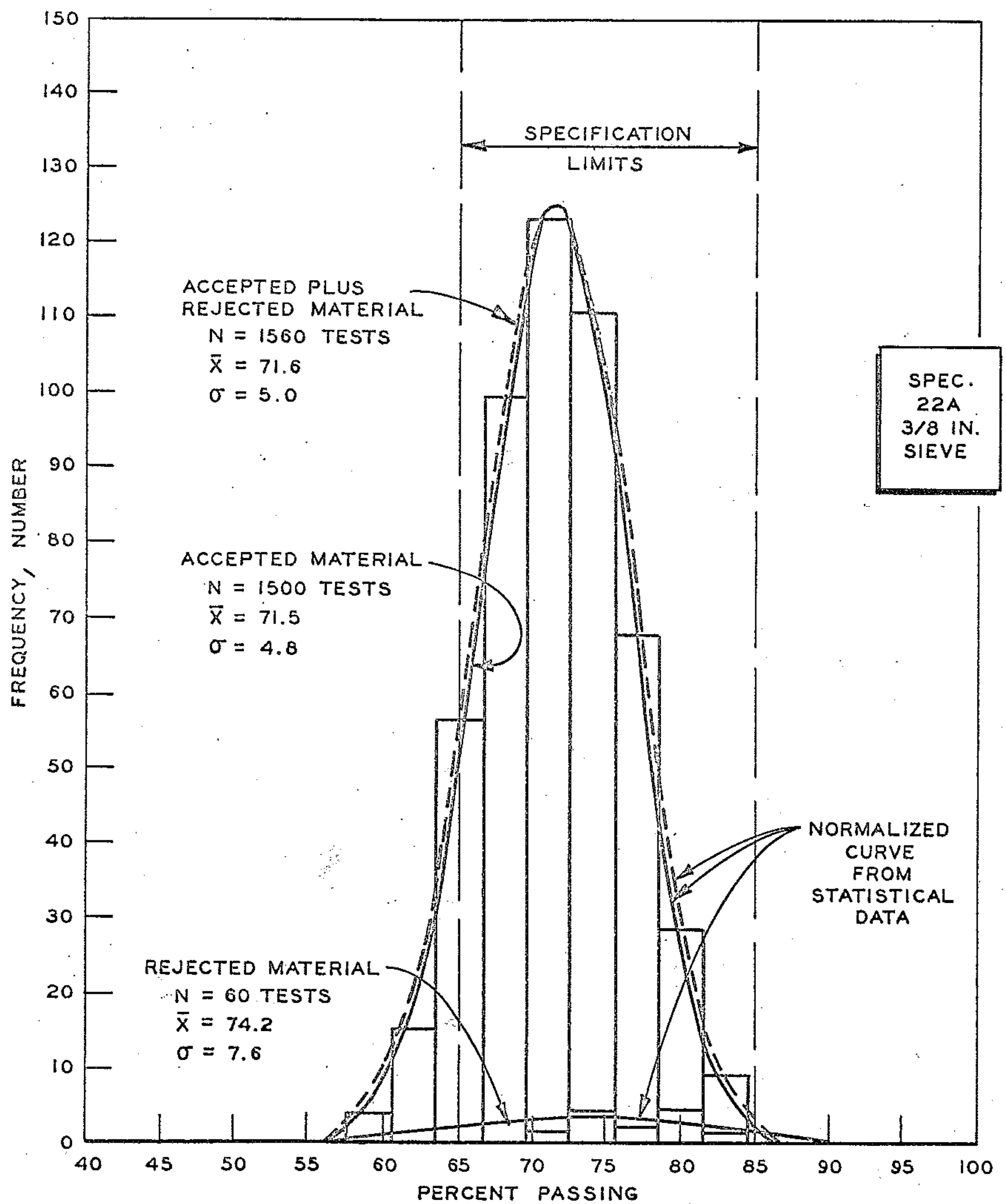


Figure 2. Distribution of percent passing 3/8-in. sieve for accepted material, rejected material, and the combination for 22A aggregate.

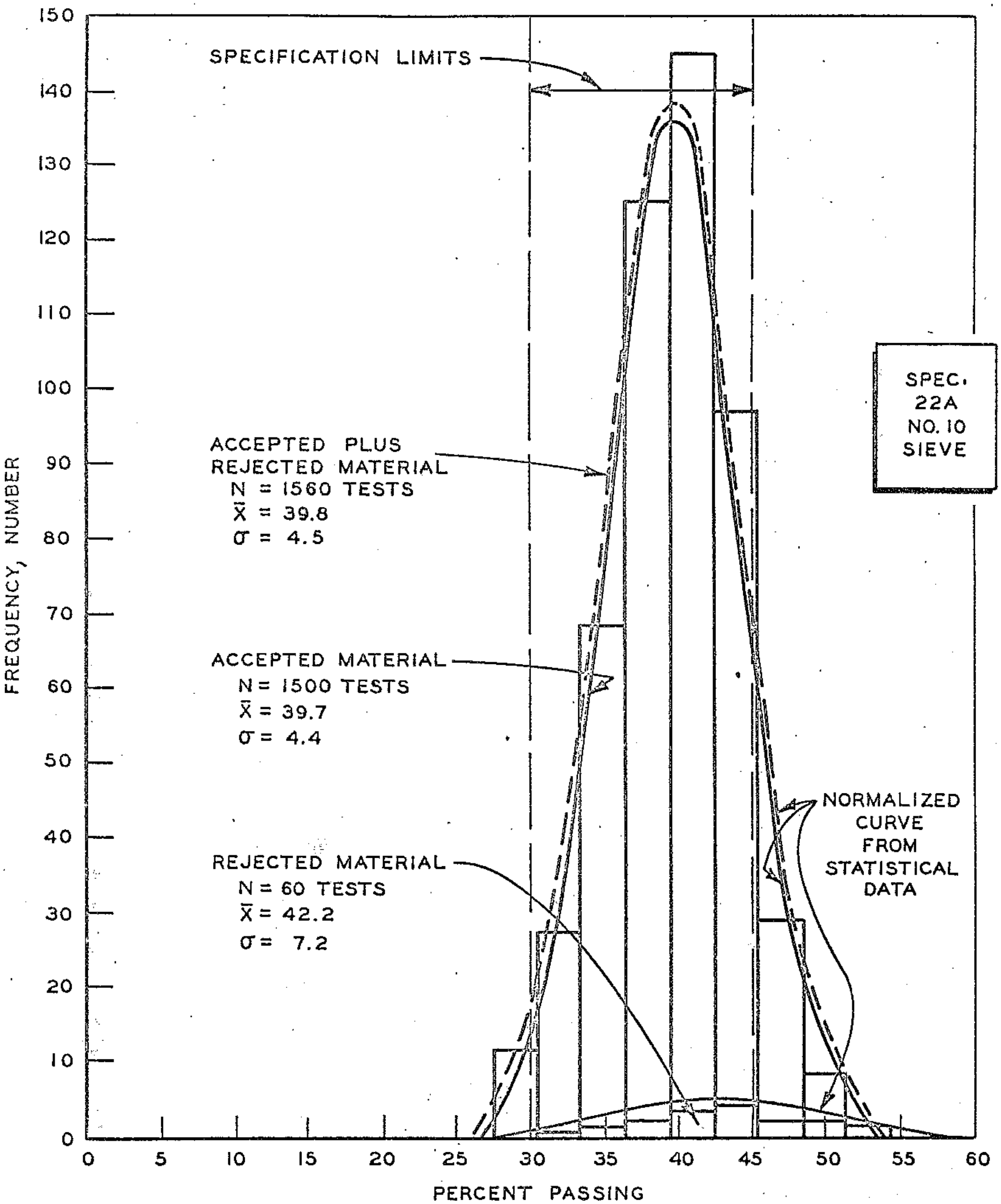


Figure 3. Distribution of percent passing No. 10 sieve for accepted material, rejected material,and the combination for 22A aggregate.

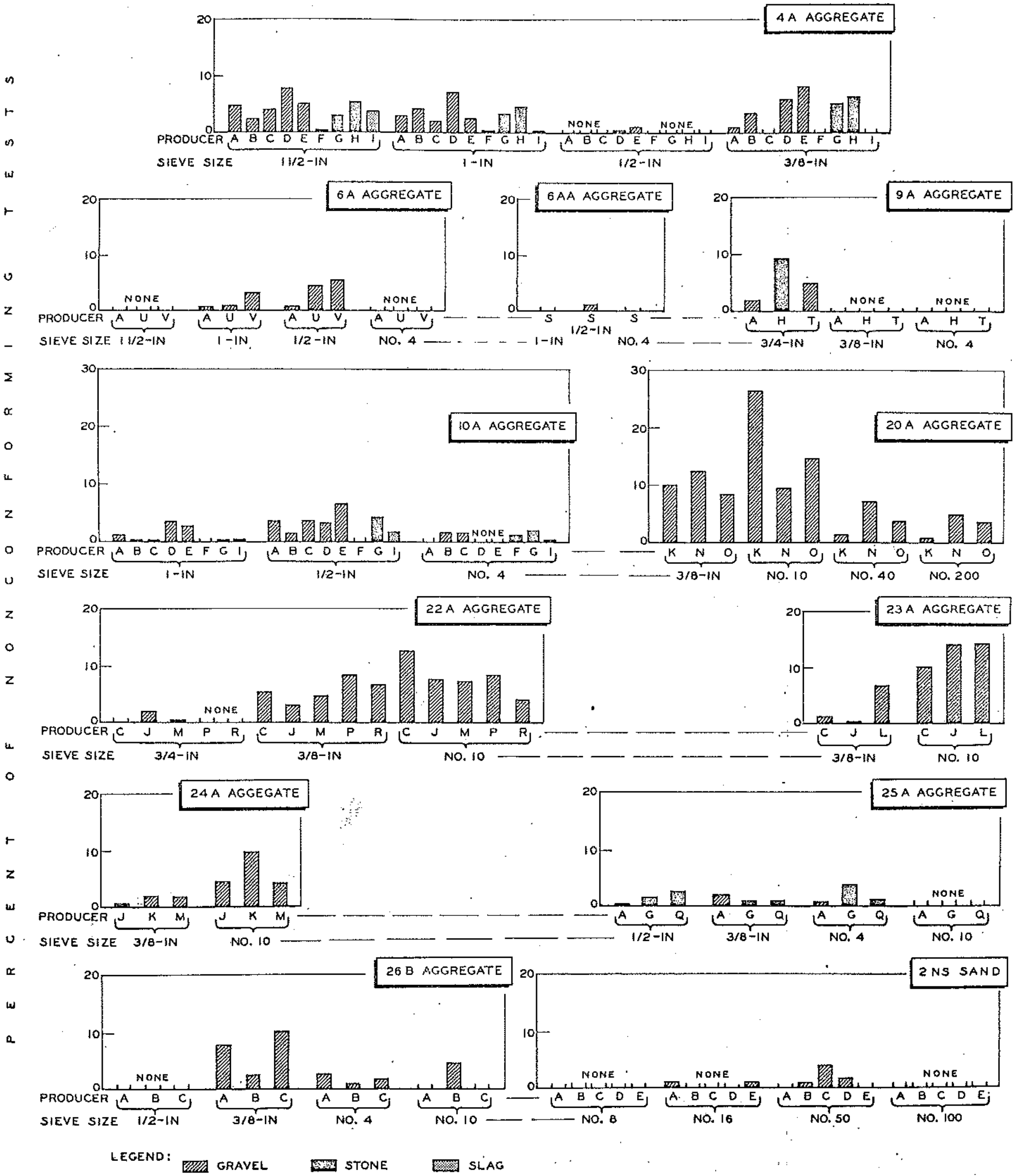
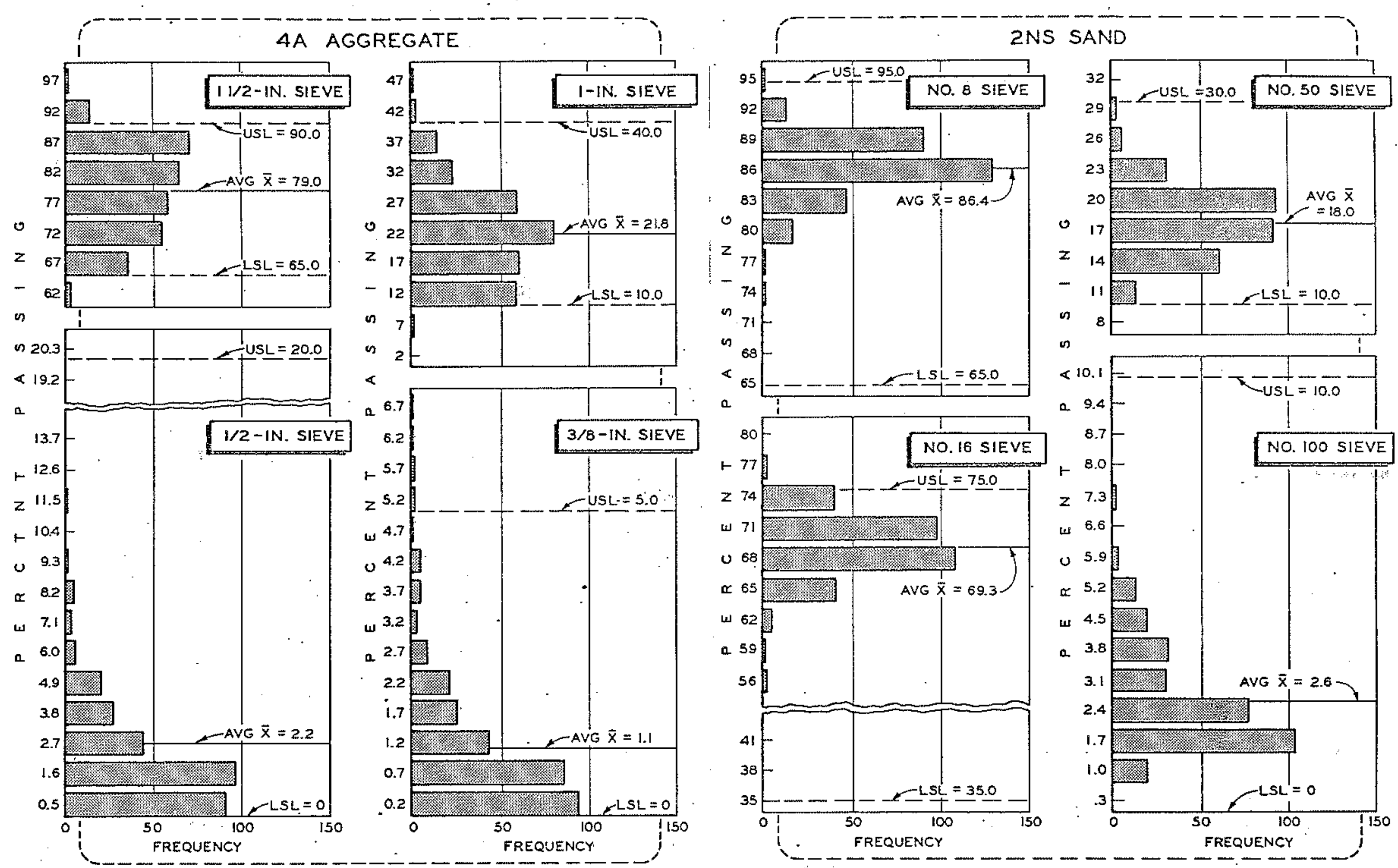


Figure 4. Variability of fractions defective (nonconforming tests) among aggregate producers for materials passing various sieve sizes.



USL = UPPER SPECIFICATION LIMIT
LSL = LOWER SPECIFICATION LIMIT

Figure 5. Histograms for 4A aggregate and 2NS sand.

FINENESS MODULUS

Fineness modulus of either fine or coarse aggregate is a measure of the degree of uniformity of its grading. It is used as an index of coarseness or fineness--the higher the modulus, the coarser the aggregate. In Michigan, fineness modulus is computed only for sand, by adding the cumulative percentages by weight of the material retained on the 3/8 in., Nos. 4, 8, 16, 30, 50, and 100 sieves, and dividing the sum by 100. The base fineness modulus for each pit is determined from the average of a continued period of production of acceptable fine aggregate. The specifications for gradation of fine aggregate (2NS sand) require control of grading so that the fineness modulus of representative samples should not vary more than $\pm$ 0.20 from the average fineness modulus of all samples previously taken from the same source.

From daily records of aggregate field testing, covering the period of 1962 through 1963, ten projects were sampled at random to study relative variability of the fineness modulus of 2NS sand. Approximately 20 samples of 2NS gradings were randomly selected from each of the ten to compute the modulus according to specifications. The results of these computations are summarized in Table 3.

In addition, Fig. 6 shows several daily fineness modulus averages on natural (2NS) sand, plotted in chronological order. These samples were all taken from one belt. Starting with Report No. 9, a base modulus of 3.06 was established using the running average of the first six tests, with limits of $\pm$ 0.20 (indicated by the darker shading at center). The average of the entire group is 2.98. However, a clear downward trend is evident after Report No. 13 and again after Report No. 14, with the material becoming progressively finer through Report No. 23; production was stopped for the winter after Report No. 25. Of interest here is the wide variation in daily results from a given pit.

Corresponding information from a different pit is shown in Fig. 7 for samples taken from one stockpile. Considerably more uniformity is evident here. A base of 2.81 was established from results of the first 13 reports, which were taken prior to the tests graphed in Fig. 7.

TABLE 3
SUMMARY OF TEST RESULTS ON FINENESS MODULUS FOR GRADATION OF 2NS SAND

Project No. and Date	Number of Tests	Fineness Modulus	
		Average	Standard Deviation
47014, C6 (11-15-61 to 9-6-62)	20	2.85	0.11
33084, C5 (1-25-62 to 8-29-62)	20	2.87	0.11
63081E, C10 (4-20-62 to 10-11-62)	13	2.79	0.10
81074, C1 (5-23-62 to 10-18-62)	24	2.94	0.11
63173, C4 (6-27-62 to 7-18-62)	20	2.83	0.06
47013, C8 7-17-62 to 10-1-62)	21	3.26	0.32
49025, C18 (10-5-62 to 8-19-63)	20	2.89	0.27
47065, C1 (10-13-62 to 10-18-62)	20	3.31	0.12
41027A, C (10-18-62 to 6-3-63)	20	2.88	0.08
63101A, C1 (10-19-62 to 7-2-63)	22	3.44	0.09

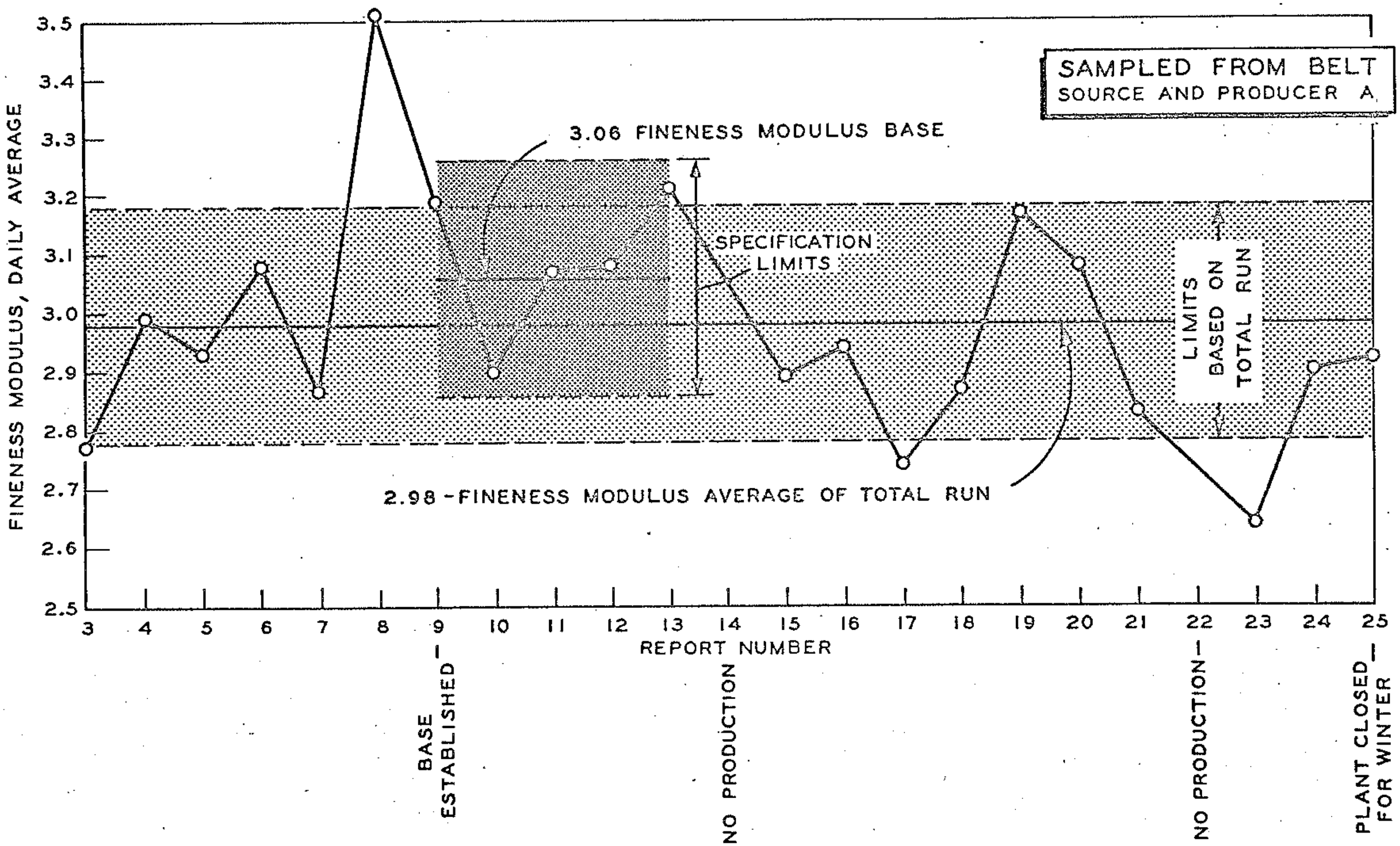


Figure 6. Fineness modulus for natural (2NS) sand sampled from belt.

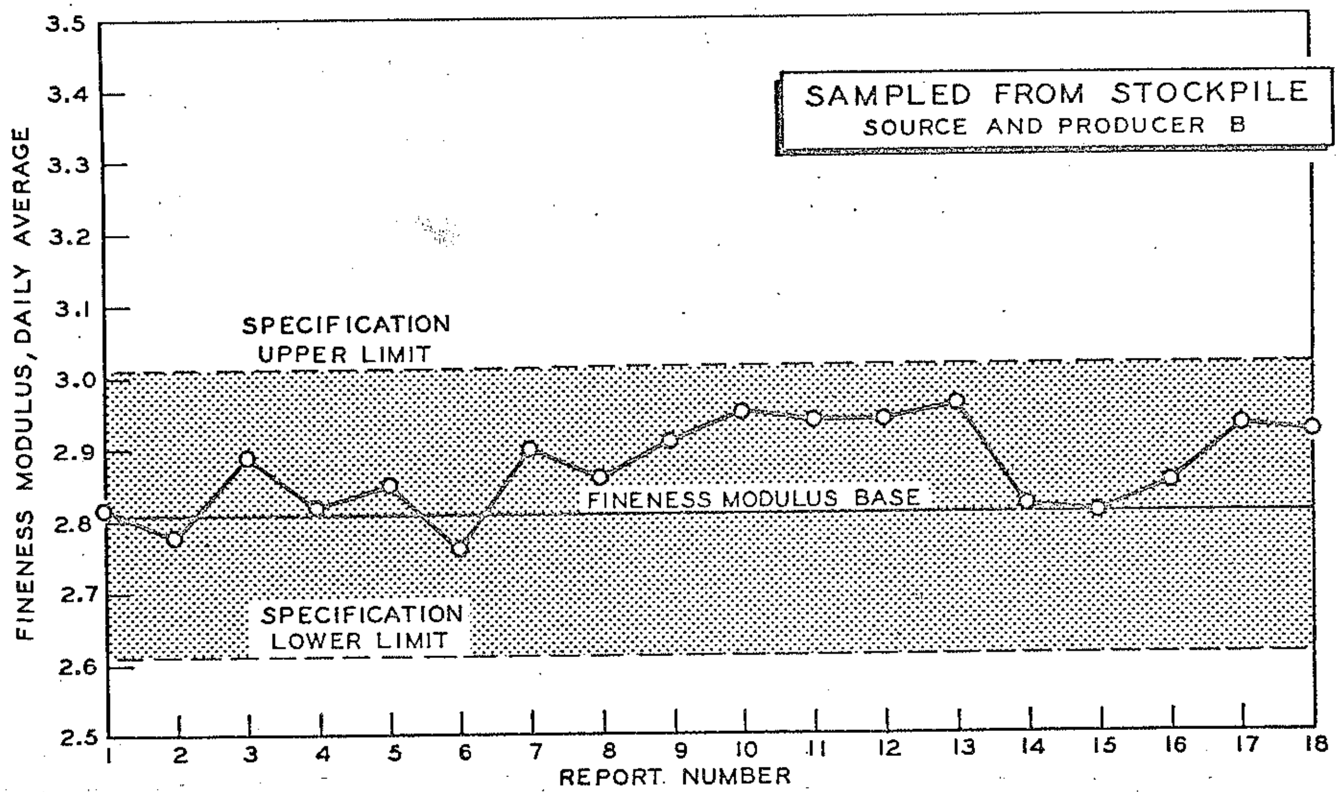


Figure 7. Fineness modulus for natural (2NS) sand sampled from stockpile.

FLEXURAL STRENGTH OF CONCRETE BEAMS

Flexural strength of concrete beams was studied from field records of all 1959-1961 Michigan projects using Grade A concrete for both pavement and bridge construction. Hundreds of field tests found in project files were condensed on special form sheets and punched on data cards for computer processing. Frequency distributions were grouped and analyzed for both road and bridge concrete beam specimens 7, 14, and 28 days old. The analysis involved computing the mean value or sample average $\bar{X}$, the sampling variability or standard deviation S, and the relative variability or coefficient of variation V. The relative variability here was computed by the expression

$$V = 100 \frac{S}{\bar{X}} \qquad (1)$$

which is useful for indicating the degree of uniformity in flexural strength tests on concrete beam specimens. From these computations the percentage of tests below the specified minimum limits (fraction defective) was estimated. The estimated values were checked against actual defective values found from the cumulative frequency distributions.

The results covering approximately three years of construction work under varying weather conditions are summarized in Table 4 for both pavement and bridge projects. Variations in strength within single beams were computed by multiplying the average range of several groups of two breaks per beam by a constant of 0.8865, as given in the literature. Results are summarized in Table 5 for both pavement and bridge projects. For this table, within-test relative variation V_1 was computed as follows:

$$V_1 = 100 \frac{S_1}{\bar{X}} \text{ and } S_1 = \frac{\bar{R}}{d_2} \qquad (2)$$

where

S_1 = within-test standard deviation,

$1/d_2$ = 0.8865 from statistical tables,

$\bar{R}$ = average range of groups of two breaks per beam, and

$\bar{X}$ = average strength.

According to present specifications for flexural strength (modulus of rupture), the steel molds in which the beams are cast are nominally 6 by 6 by 36 in. A set of four beams is made on alternate days when

TABLE 4
SUMMARY OF FLEXURAL STRENGTH TESTS ON 1959-61 CONCRETE BEAM SPECIMENS

			Item	Individual Values			Average Values of Two Breaks per Beams			Minimum Values Within Two Breaks per Beam		
				Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall
Pavement Concrete	Cement Factor = 5.5 sacks per cu yd	7-day Tests	Number of tests	713	1904	701	354	942	345	354	942	345
			Average strength, psi	654.9	652.7	644.8	655.3	653.3	645.2	632.7	631.9	619.6
			Relative variation, percent	12.9	13.9	15.5	11.9	13.1	14.7	12.0	13.2	15.3
			Percent less than 550 psi	8.0	9.0	16.5	6.5	7.0	15.0	11.0	11.0	22.0
		14-day Tests	Number of tests	601	1604	596	300	792	294	300	792	294
			Average strength, psi	749.3	750.4	740.6	749.6	751.2	741.7	726.9	729.3	714.6
			Relative variation, percent	12.3	18.1	15.5	11.6	17.7	14.7	12.2	17.8	15.5
			Percent less than 600 psi	3.0	5.5	11.5	2.5	4.5	10.0	6.5	9.0	15.0

			Item	Individual Values				Average Values of Two Breaks per Beam				Minimum Values Within Two Breaks per Beam			
				Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
Bridge Concrete	Cement Factor = 5.9 sacks per cu yd	7-Day Tests	Number of tests	635	778	474	181	317	388	236	89	317	388	236	89
			Average strength, psi	654.1	661.7	620.7	590.9	654.3	661.7	620.1	593.0	633.4	639.5	600.5	565.7
			Relative variation, percent	13.8	15.0	14.2	25.2	13.1	14.3	13.2	24.1	13.4	14.2	13.5	25.0
			Percent less than 550 psi	11	10	19	34	11	9	21	28	16	14	27	42
		28-Day Tests	Number of tests	608	742	467	156	304	371	233	78	304	371	233	78
			Average strength, psi	814.2	802.0	777.7	726.3	814.2	802.0	777.9	727.0	793.4	778.1	754.6	700.3
			Relative variation, percent	13.3	13.8	13.6	17.2	12.8	13.2	13.0	16.4	13.0	13.5	13.4	16.6
			Percent less than 650 psi	5	6	10	20	5	5	9	19	8	9	13	25
	Cement Factor = 5.5 sacks per cu yd	7-Day Tests	Number of tests	294	459	262	153	147	221	130	76	147	221	130	76
			Average strength, psi	614.8	626.8	591.9	571.4	615.1	628.8	591.8	570.4	592.9	607.1	572.4	549.3
			Relative variation, percent	15.2	13.8	15.9	23.5	14.3	13.1	15.3	23.0	14.1	13.5	15.6	23.3
			Percent less than 550 psi	23	18	29	37	21	13	26	39	28	22	34	50
		28-Day Tests	Number of tests	283	462	252	174	141	231	126	87	141	231	126	87
			Average strength, psi	795.9	762.5	756.6	709.2	796.6	762.5	756.6	709.2	771.6	741.1	734.2	684.6
			Relative variation, percent	13.6	13.6	13.8	16.4	12.9	13.1	13.2	15.6	13.3	13.3	13.5	16.2
			Percent less than 650 psi	9	15	16	28	6	13	15	25	12	19	19	33

NOTE: There are normally two breaks per beam. In this survey, an occasional report gave only one break, or only one was legible, resulting in slight discrepancies between columns. Results are presented in this way so that the reader may select the information of interest.

TABLE 5
WITHIN-TEST RELATIVE VARIATIONS FOR FLEXURAL STRENGTH
1959-61 Concrete Beam Specimens

			Item	Spring	Summer	Fall	Winter
Pavement Concrete	Cement Factor = 5.5 sacks per cu yd	7-Day Tests	Number of tests	100	100	100	---
			Avg. strength, psi	655.3	653.3	645.3	---
			Average range, psi	42.5	38.4	51.8	---
			Relative variation, percent	5.7	5.2	7.1	---
		14-Day Tests	Number of tests	100	100	100	---
			Average strength, psi	749.6	751.2	741.7	---
			Average range, psi	44.0	46.5	58.4	---
			Relative variation, percent	5.2	5.5	7.0	---
Bridge Concrete	Cement Factor = 5.9 sacks per cu yd	7-Day Tests	Number of tests	100	100	100	89
			Average strength, psi	654.3	661.7	620.1	593.0
			Average range, psi	39.9	39.9	39.8	54.3
			Relative variation, percent	5.4	5.3	5.7	8.1
		28-Day Tests	Number of tests	100	100	100	100
			Average strength, psi	814.2	802.0	777.9	727.0
			Average range, psi	37.4	45.9	39.7	51.4
			Relative variation, percent	4.1	5.1	4.5	6.3
	Cement Factor = 5.5 sacks per cu yd	7-Day Tests	Number of tests	100	100	100	76
			Average strength, psi	615.1	628.8	591.8	570.4
			Average range, psi	46.0	39.8	42.7	41.0
			Relative variation, percent	6.6	5.6	6.4	6.4
		28-Day Tests	Number of tests	100	100	100	100
			Average strength, psi	796.6	762.5	756.6	709.2
			Average range, psi	49.0	47.4	46.1	48.6
			Relative variation, percent	5.5	5.5	5.4	6.1

pavement is placed; for concrete structures, one set of beams is made from the first concrete pour at the job site, and a set for each succeeding 200 cu yd poured. For pavements, two beams are tested at 7 and 14 days, and for bridges, two beams are tested at 7 and 28 days. Michigan uses the cantilever type of loading, with two breaks per beam.

The minimum values (lower acceptance limits) required for flexural strength when concrete specimens are properly cured under moist conditions at 60 to 80 F are 550 psi at 7 days, 600 psi at 14 days, and 650 psi at 28 days for cement factors of 5.5 or 5.9 sacks per cu yd of concrete.

Two facts were noted in connection with the resulting frequency distributions. First, the grouped data from both pavements and bridges followed closely symmetrical distributions. Second, the grouped data reflected the influence of seasonal testing conditions. This can be explained in terms of fluctuations of relative variation for individual and average values of two breaks per beam as shown in Table 4. Values for percent of nonconforming tests, for example, were significantly higher in fall than in spring for pavement projects and higher in winter than in spring for bridge projects, as shown in Fig. 8. Some generalizations may be made from Tables 4 and 5 regarding effects of the flexural strength average, the relative variation, and the specified lower acceptance limits required in flexural strength tests:

1. Strength tests for pavement concrete in seasons other than spring, with approximately the same average value but greater relative variation than those recorded in spring, show a greater proportion of values falling below the lower limit.

2. Fluctuations in relative variations within single beams reflect the influence of seasonal curing conditions.

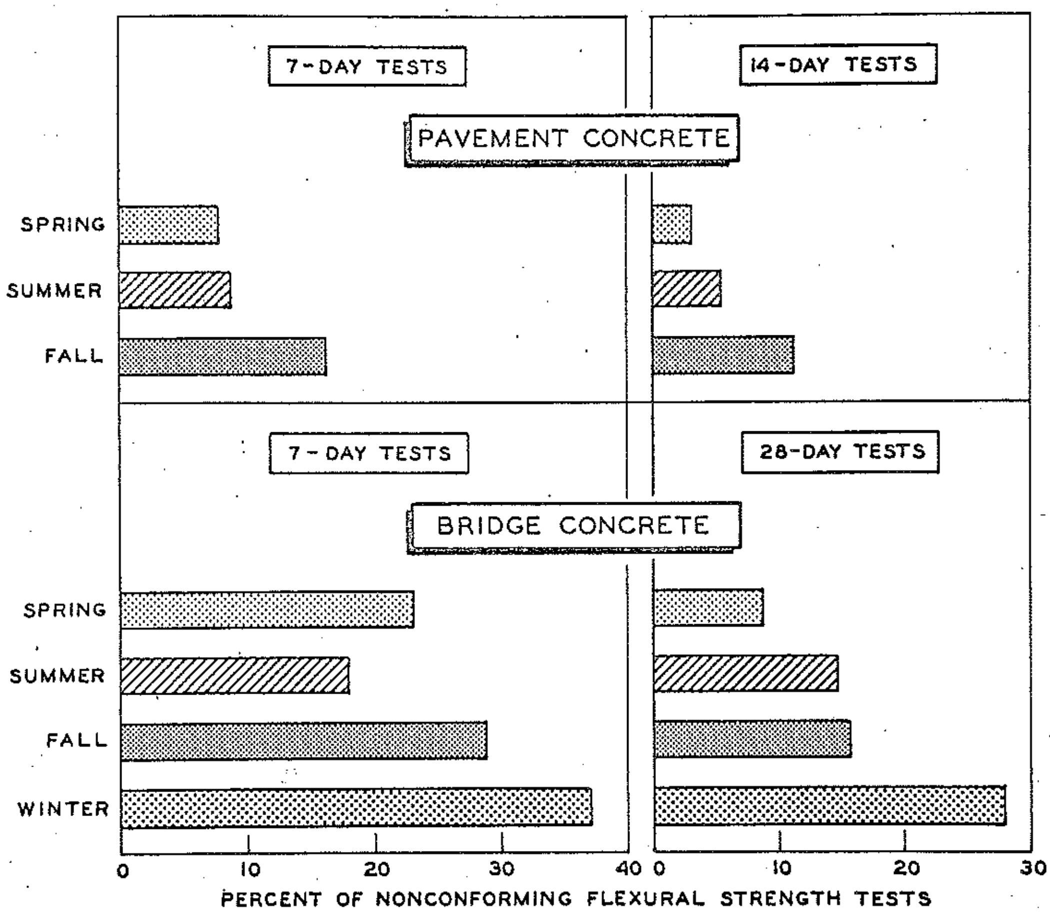


Figure 8. Flexural strength of concrete beams, reflecting influence of seasonal testing conditions on field results.

THICKNESS OF CONCRETE PAVEMENTS

The study of thickness of portland cement concrete pavements was based on 15 projects sampled at random from field records covering the period 1959-1961. From these data, 656 tests were grouped and analyzed to estimate standard statistical parameters as well as the percentage of tests outside the specified limits. Specifications require that thickness of the completed pavement be controlled so that the average depth of each concrete core should not be more than 1/2-in. under the design thickness. One core is taken at random from each 1000-ft length of pour in accord with plan stationing. The depth of each core is found using a depth-gage from the center of the upper end of the specimen and from eight other points equally spaced around the center. The individual measurements are recorded to the nearest 0.05 in., and the average of these nine measurements expressed to the nearest 0.10 in. is considered the core depth.

The frequency distribution of measured pavement thickness as obtained from the average depth of each of 656 concrete cores is shown in Figure 9. While the nominal pavement thickness in 9 in., the average depth measured was 9.2 in. and one standard deviation was $\pm$ 0.28 in. The distribution is quite symmetrical and approximates a normal distribution. Only two cores out of 656 were below the minimum specification depth of 8.5 in., or approximately 0.3 percent.

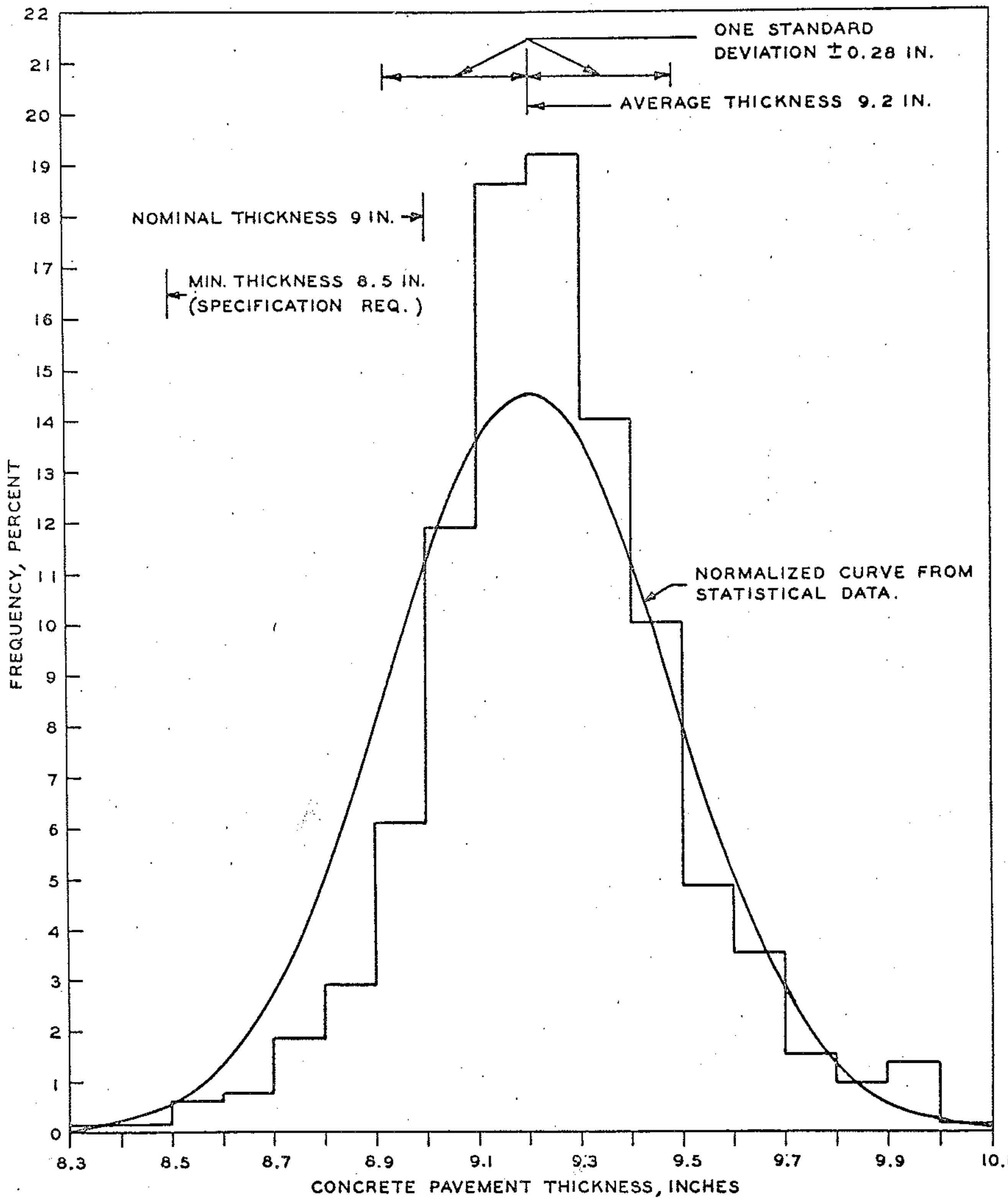


Figure 9. Frequency distribution of concrete pavement thickness: 1959-61.

AIR CONTENT OF FRESH PAVEMENT CONCRETE

Analysis of field data dealing with air content of fresh pavement concrete was based on 60 projects sampled at random from files covering the period 1959-1961. From the selected projects, 4065 tests were grouped and analyzed to estimate important characteristics of the data, such as the degree of normality, average, and standard deviation of the test results. Michigan requires an average air content between 4 and 7 percent for concrete pavement. Periodic tests for air content of freshly mixed concrete are made at the job site by the standard pressure meter method.

As shown in Figure 10, the frequency distribution shows acceptable normality for this condition of symmetrical control limits, and the average of 5.65 percent is very close to the midpoint of the specification (5.5 percent). Slightly over 90 percent of the tests fall within the specification limit, with 2.9 percent below and 6.3 percent above the lower and upper limits, respectively.

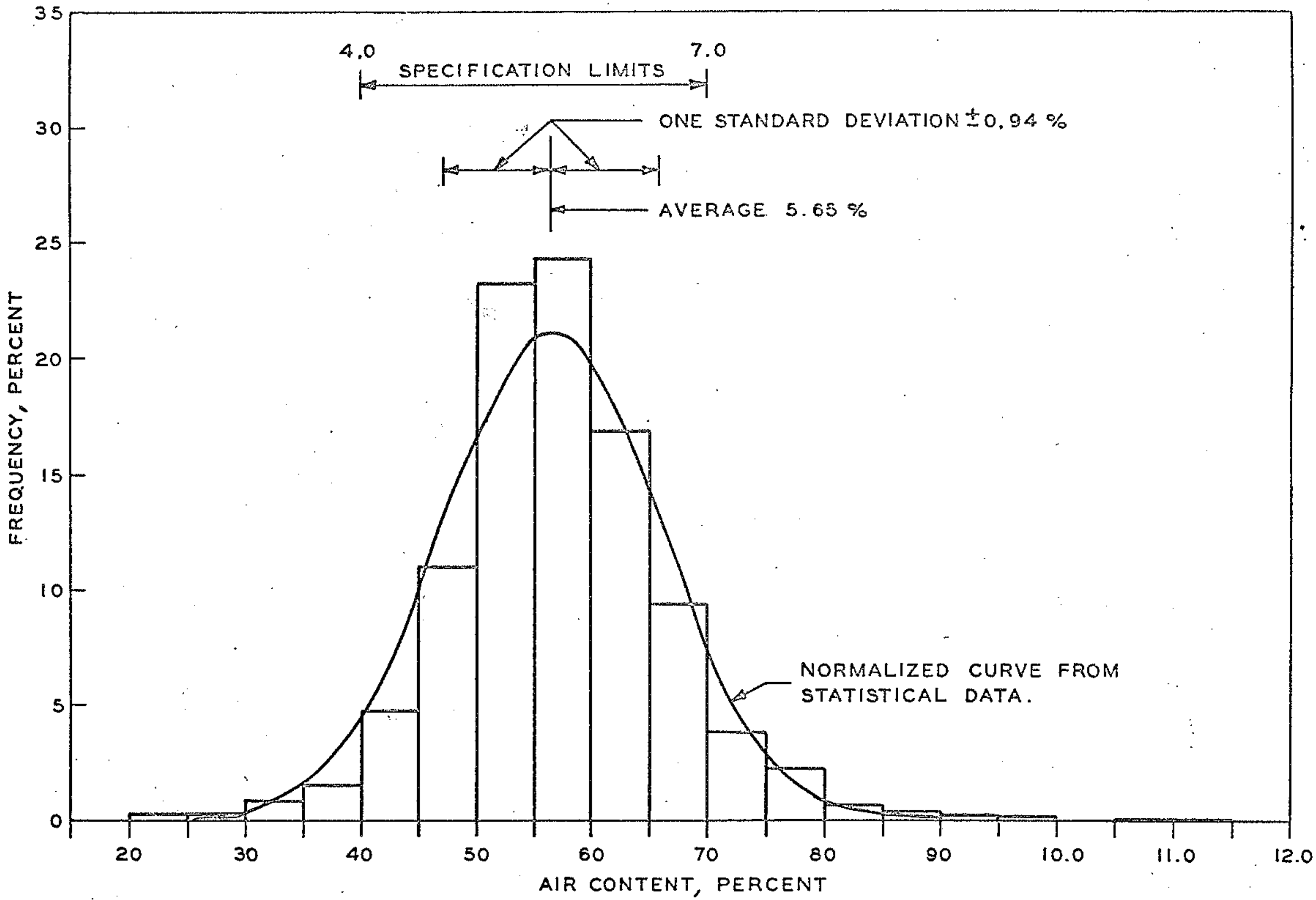


Figure 10. Frequency distribution of concrete pavement air content: 1959-61

MOISTURE AND DENSITY OF AGGREGATE BASE COURSE AND SAND SUBBASE

Field data dealing with moisture content and density of subbase for pavements were analyzed, covering the 1961 and 1962 construction periods on the basis of 132 projects sampled at random from the files. In Figure 11, frequency distributions of moisture content for aggregate base course and sand subbase are shown. For the former, the average moisture content is 5.1 and for the latter 6.3 percent, while standard deviations are $\pm$ 1.6 and $\pm$ 2.6 percent, respectively. In both cases, a slightly unsymmetrical distribution may be noted with the long tail always at the higher end of the moisture content.

For aggregate base course and sand subbase, the Michigan Cone Test is used to obtain the maximum unit weight of the material and the Rainhart test is used routinely to determine actual density of the material as placed and compacted on the grade. Department specifications require a minimum of 100 percent of the maximum unit weight for aggregate base course and 95 percent for sand subbase. Routine inspection procedure calls for testing at locations giving evidence of being the least compacted. If the test indicates that the compaction does not meet the particular specification requirement (95 or 100 percent of the maximum unit weight) then further compaction of the area is required and a second test is made.

It should be noted that the frequency distributions shown in Figure 12 for aggregate base course and sand subbase are only for final or accepted tests--that is, tests meeting the specification and representing accepted compacted areas. The average density values for 1961 and 1962 construction seasons were nearly identical, being 102.2 and 102.1 percent, respectively, for 1961 and 1962 aggregate base course, and 98.2 and 98.4 percent for sand subbase for 1961 and 1962. Standard deviations for sand subbase were nearly identical in 1961 and 1962, being 2.16 and 2.14 percent. However, the standard deviation for aggregate base course increased from 2.05 percent in 1961 to 2.62 percent in 1962. Both materials and each year of construction presented frequency distributions with the long tail at the high end of the compaction range.

The preceding data were based on accepted tests only, and therefore, for a more complete picture of the total density distributions likely to be experienced, some additional density data were analyzed from a 1965 construction project near Lansing. On this project, 502 initial density measurements were made on the clay embankment, with 143 being below

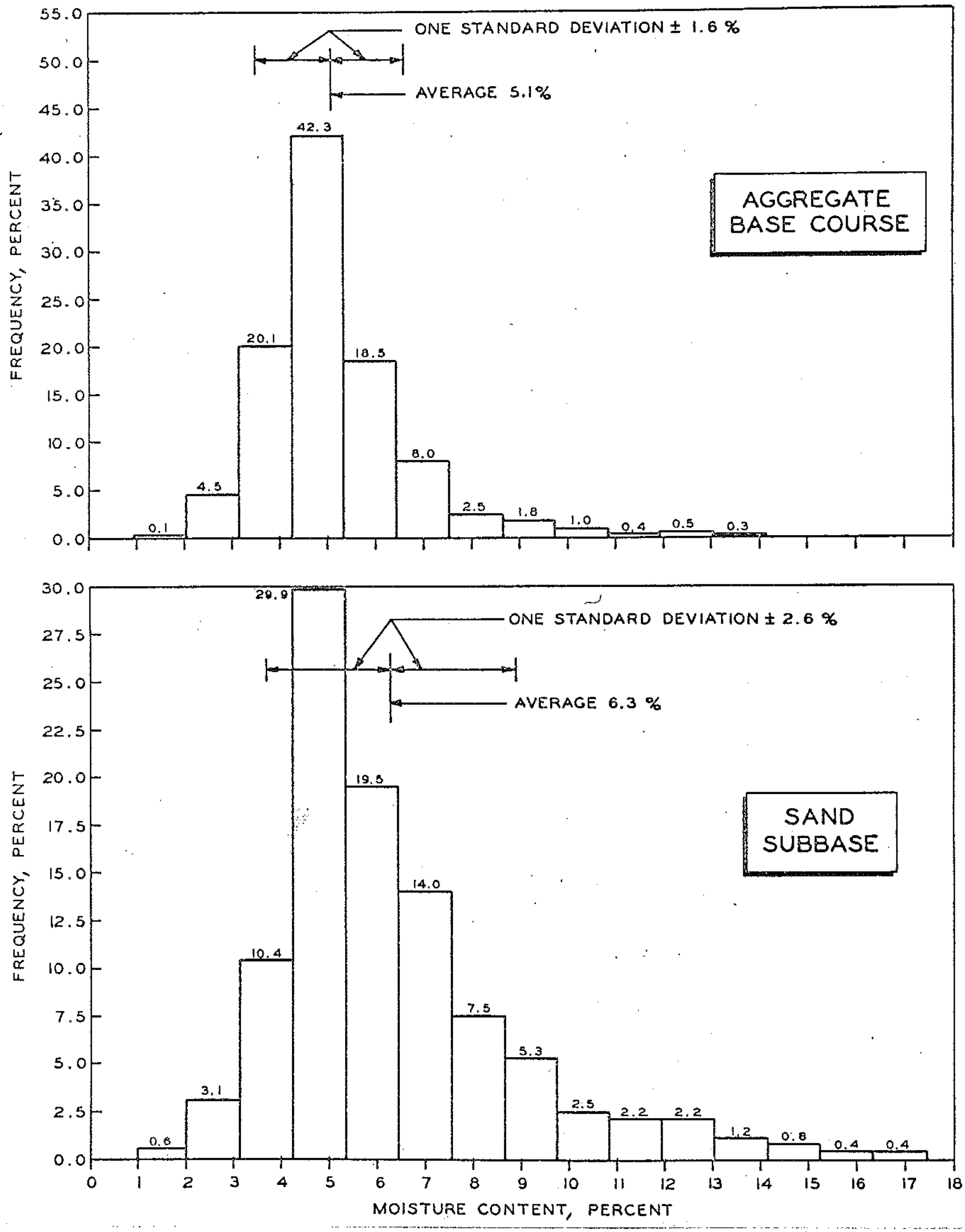
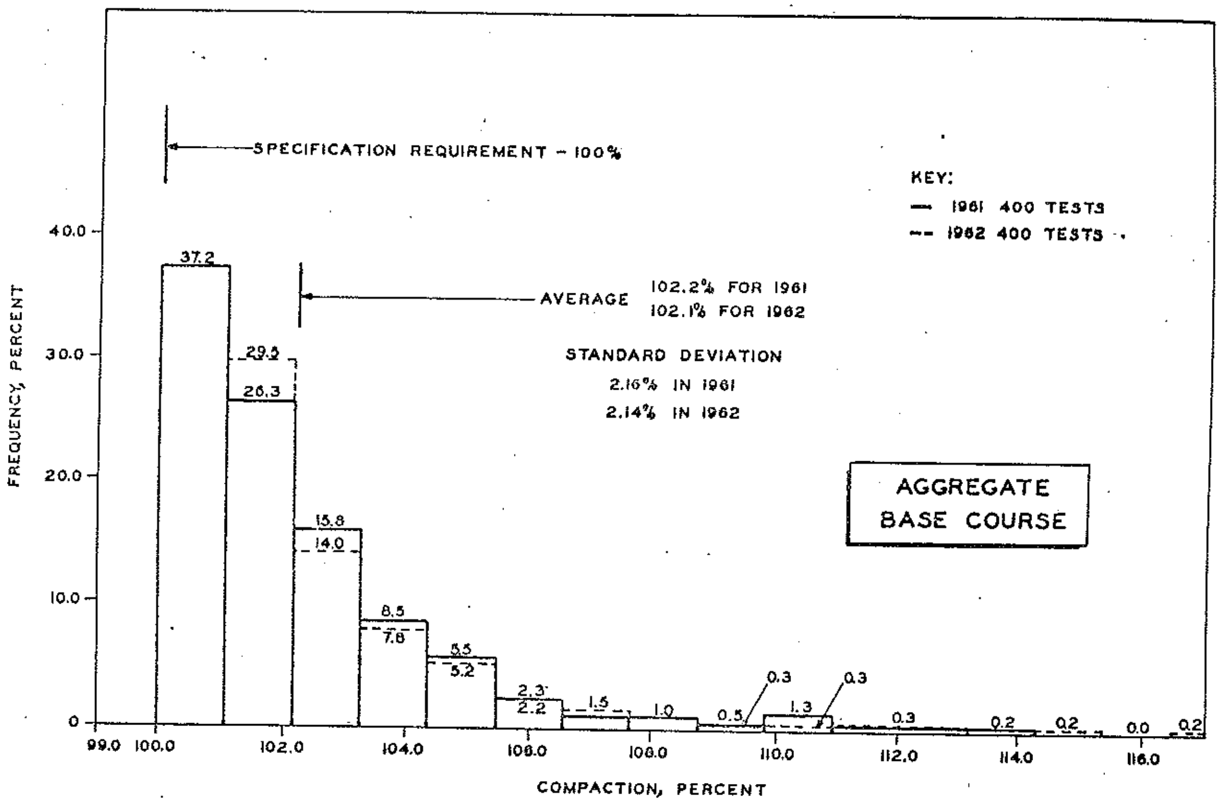


Figure 11. Frequency distributions of moisture content for aggregate base course (802 tests) and sand subbase (800 tests).



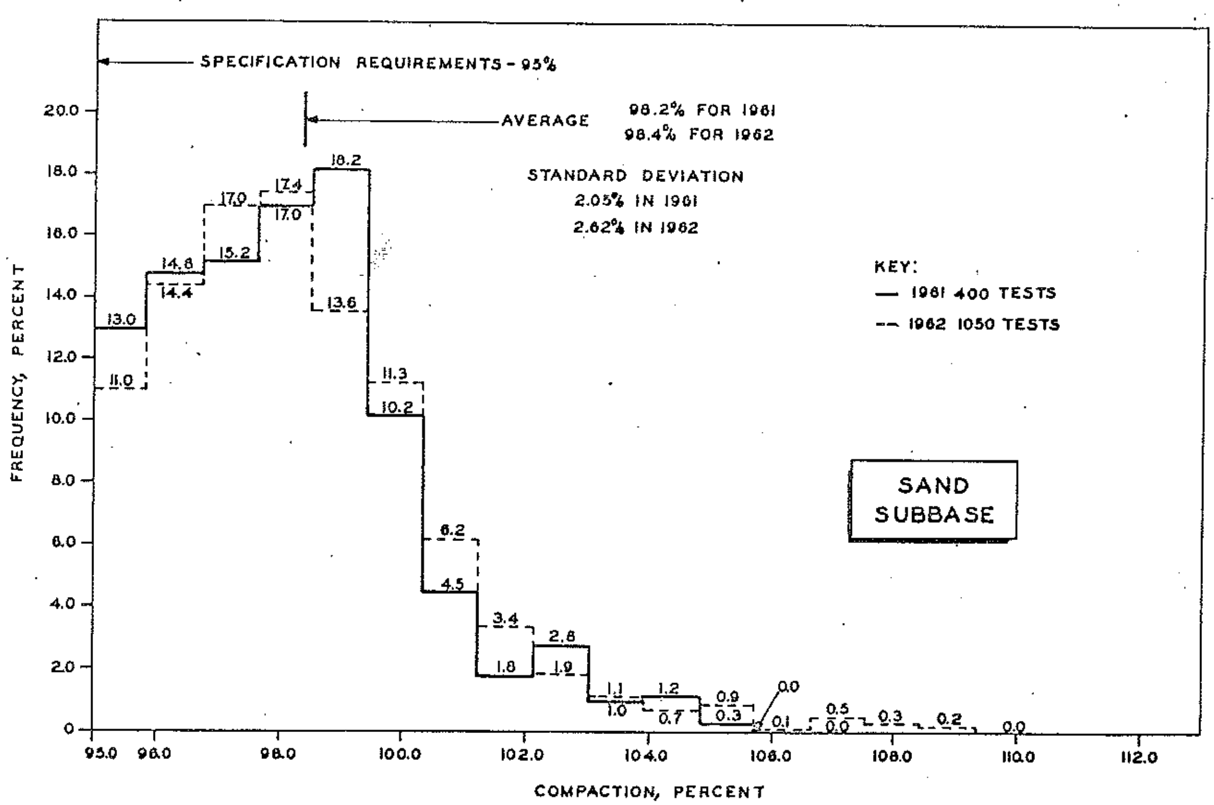


Figure 12. Frequency distributions of percent compaction for aggregate base course and sand subbase, for final or accepted tests only.

the 95-percent density requirement and 359 tests acceptable (95 percent or greater). This density distribution is illustrated in Figure 13. For all grade areas represented by unacceptable test results, additional compaction was required until further testing indicated that the grade was compacted to the minimum 95 percent of maximum unit weight. Figure 13 also illustrates similar density distributions of initial test results for selected subbase and sand subbase. For selected subbase, 2.9 percent were initially unacceptable, and for sand subbase 3.05 percent.

On this same project some random density tests were made of the selected subbase and sand subbase on grades already accepted on the basis of standard sampling and testing procedures. Figure 14 illustrates that the density distribution for accepted selected subbase varied from 90.8 to 103.8 percent of maximum unit weight, with approximately 20 percent of the random tests falling below the minimum requirement of 95-percent compaction. A similar distribution of random tests from previously accepted sand subbase grade is also illustrated in Figure 14, where approximately 34 percent of the test results were below the specification requirement of 95 percent of the maximum unit weight.

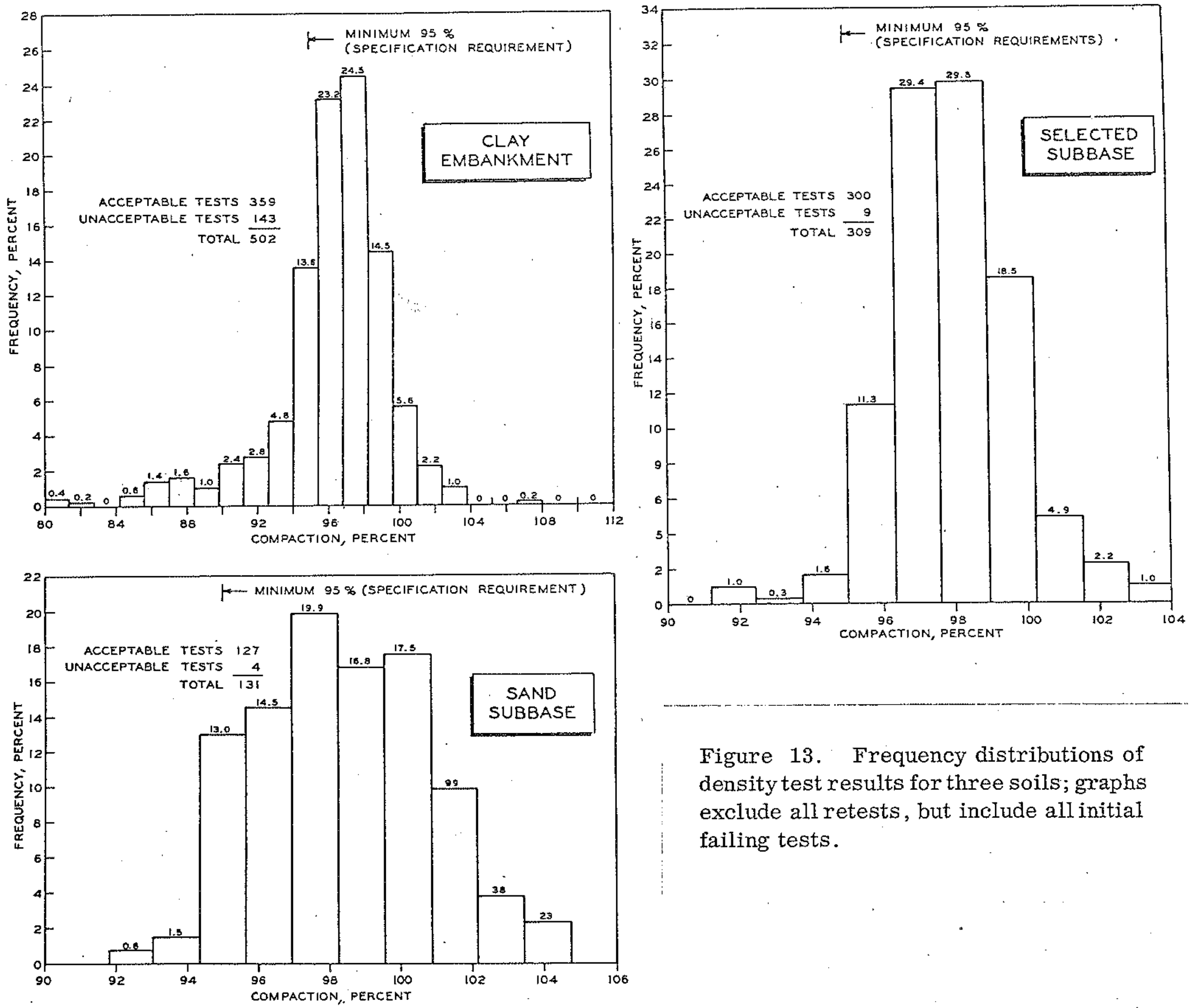


Figure 13. Frequency distributions of density test results for three soils; graphs exclude all retests, but include all initial failing tests.

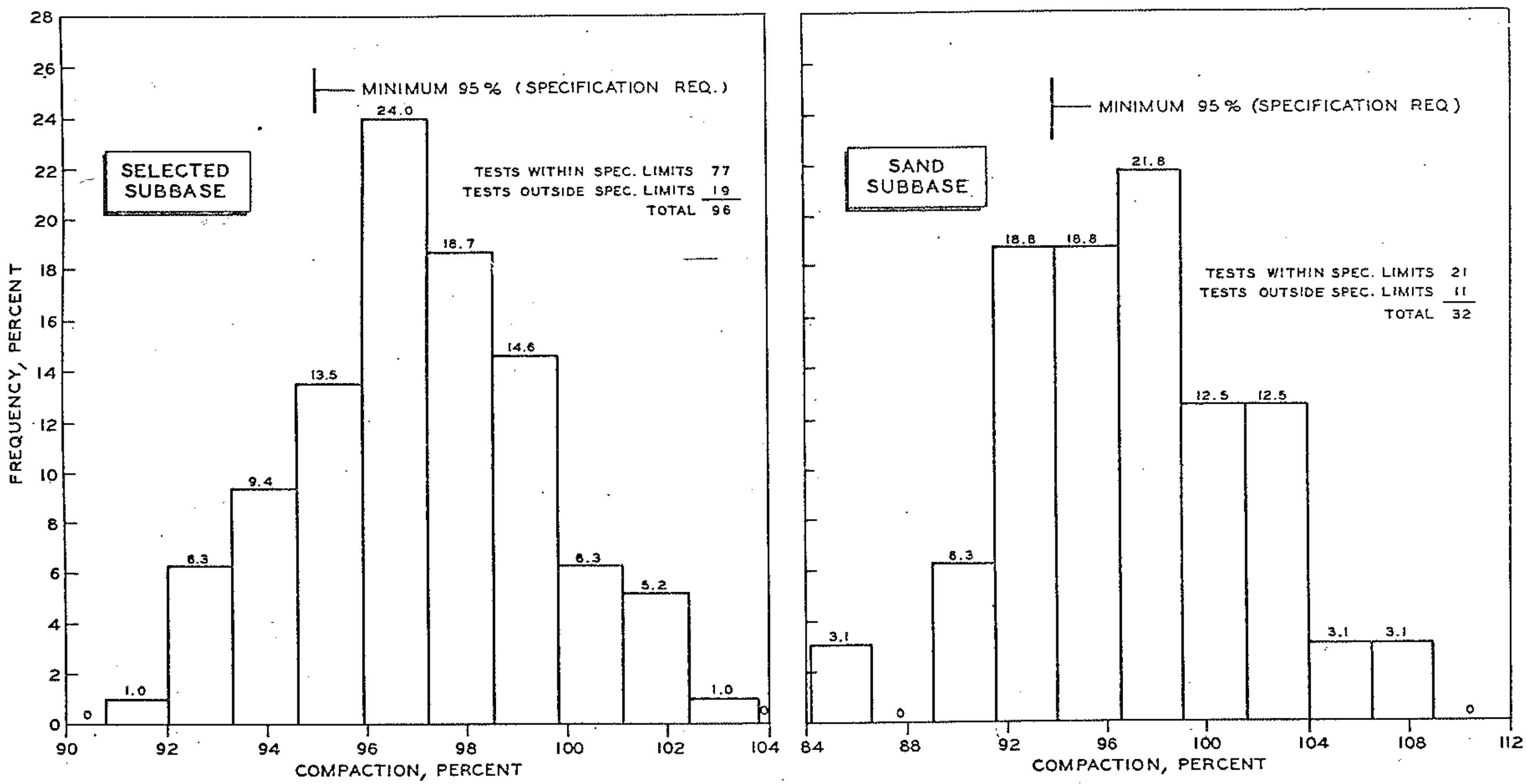


Figure 14. Frequency distributions of density test results for accepted aggregate base course and sand subbase.

AGGREGATE GRADATION--FIELD EXPERIMENT

The field records survey for aggregate gradation indicated that sampling and testing procedures now in use for acceptance or rejection of such materials allow many possibilities for introduction of deviations.

A field experiment was carefully planned to determine what part aggregate inspectors, screening sieves, and sampling methods play in the uniformity of gradation results. This required an experimental design which may be discussed in terms of the following mathematical equation:

$$X = G + I + M + S + IM + IS + MS + IMS + E \qquad (3)$$

where

X = an individual test,
G = the overall mean,
I, M, S = effects due to inspectors, sampling methods, and screening kits, respectively,
IM, IS, MS, IMS = effects due to various interactions, and
E = random error.

Based on this model and other algebraic identities the following variances may be determined:

V_t = overall variance of the gradation results
V_1 = variance attributable to different aggregate inspectors
V_2 = variance attributable to different screening sieves
V_3 = variance attributable to different sampling procedures
V_4 = variance attributable to inherent material and experimental deviations

In planning the experimental work, consideration was given to the availability of manpower and testing equipment, and the type and location of aggregate materials being produced, thus largely limiting the experiment to a fixed statistical model.

The experiment was expected to indicate:

1. Whether aggregate inspectors require further training in sampling and testing of aggregate materials.
2. Whether testing equipment requires periodic calibration or more careful maintenance.

3. Whether improved precision is feasible in gradation analysis.
4. Whether significant interactions (i.e., combined effects produced by several factors, exceeding the total of their individual effects) are occurring in the experimental work.

Experimental Procedure

A portable plant was selected, producing 22A aggregate for base and surface courses near Maple Rapids, Michigan. For this type of material the 1963 specifications required the following grading limits:

Sieve Size	Percent Passing (cumulative)
1-in.	100
3/4-in.	90 to 100
3/8-in.	65 to 85
No. 10	30 to 45
No. 200*	3 to 10

* i.e., loss by washing

The experimental design required three aggregate inspectors selected from a number of well-trained personnel from different locations, and three screening kits also selected from sieves available from the Testing Laboratory Division.

Each of the three aggregate inspectors used each screening kit equally often, and sampled and tested 60 samples for about four weeks of aggregate production. During the course of the experiment, a regular aggregate inspector informed testing personnel as to the status of the material being produced. The specifications require as a standard one complete gradation analysis for each 150 tons of coarse aggregate. Four or five tests per day cover the production from an average gravel plant. The regular inspector takes a representative sample by sampling from different areas of the stock-pile and combining into a composite sample of about 100 lb of aggregate material. The composite or average sample is then reduced by quartering to a size suitable for testing for loss by washing (or passing No. 200) and sieve analysis. These field operations are illustrated by flow chart in Figure 15.

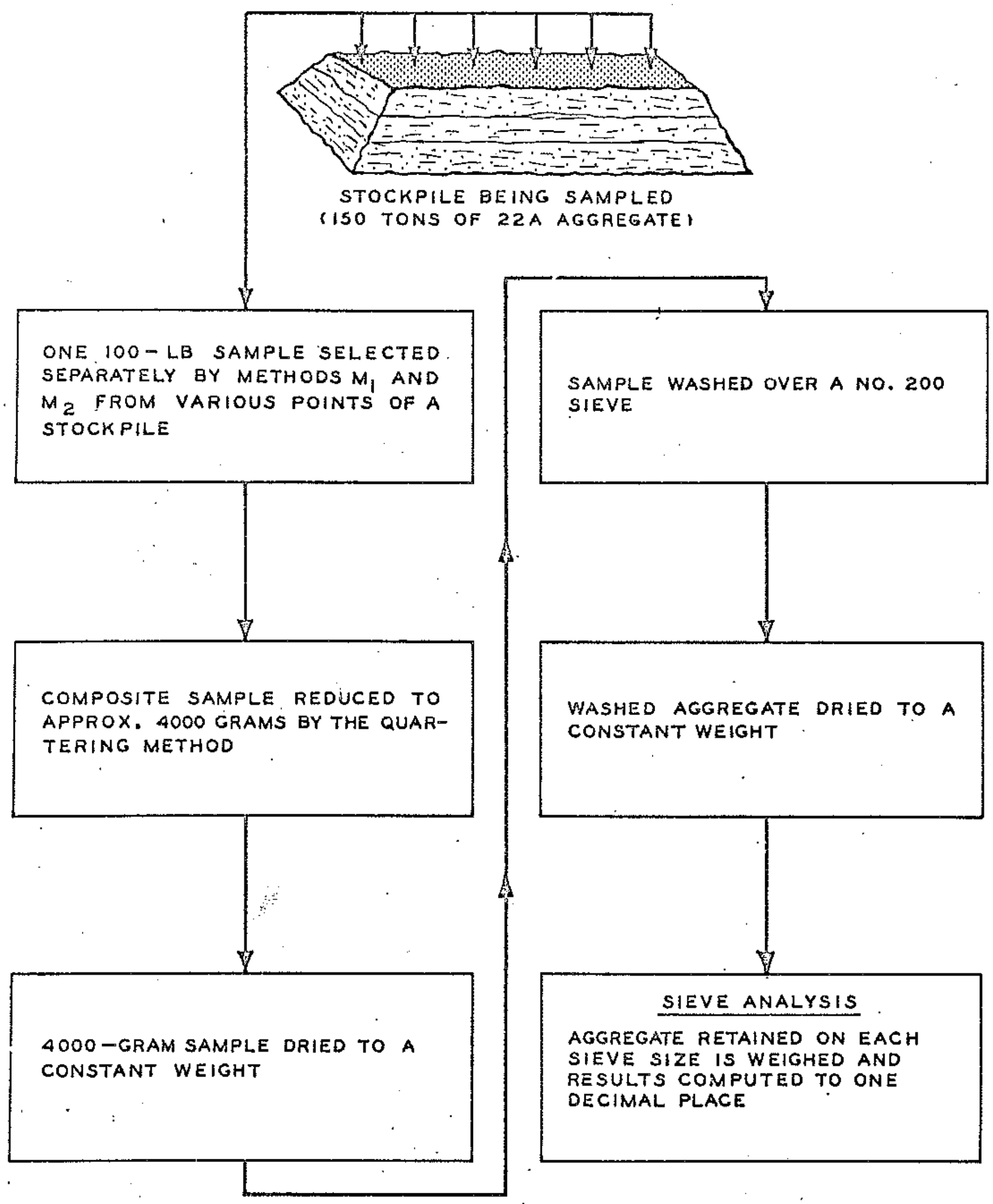


Figure 15. Flow chart for sampling and screening coarse aggregates.

In addition, the three inspectors performing the experimental testing obtained their samples from the same stockpile tested by the regular inspector. Both groups of inspectors took their samples prior to any additional production being placed on the stockpile. The inspectors performing the experimental testing obtained their samples by the standard sampling procedure (shown schematically in Figure 16) and also by selected random sampling so that each sampling location from the stockpile would have an equal likelihood of being included in the composite samples. A random sampling pattern involving ten locations is also shown in Figure 16. Values for length X and width Y of the stockpile were computed from a table listing random numbers in decimal fractions and on actual stockpile dimensions of 150 by 24 ft. In both cases, the dotted lines show paths followed by the inspectors over the sampling areas.

Thus, two different sampling methods were included as part of the experimental design. To avoid unnecessary delay during the field testing, necessary space, equipment, and materials were furnished in a mobile-laboratory truck parked near the project site. The experiment was conducted on accepted 22A aggregate without interference with the regular inspector's duties nor with aggregate plant operations. After following the sampling and testing procedures outlined in the design, the selected inspectors recorded their field observations on special form sheets. At the bottom of this form, coding letters were provided for the inspector's name, testing equipment used, location of the material being sampled, the time of sampling, and the date. Then the data were punched on cards for computer processing.

Selection of Samples

Cost, labor, facilities, and time available all limited the sample size to 10 gradation tests for each combination of inspector-screening kit-sampling method, as shown in Figure 17, where

M_1 = regular or standard method of sampling,

M_2 = random method of sampling,

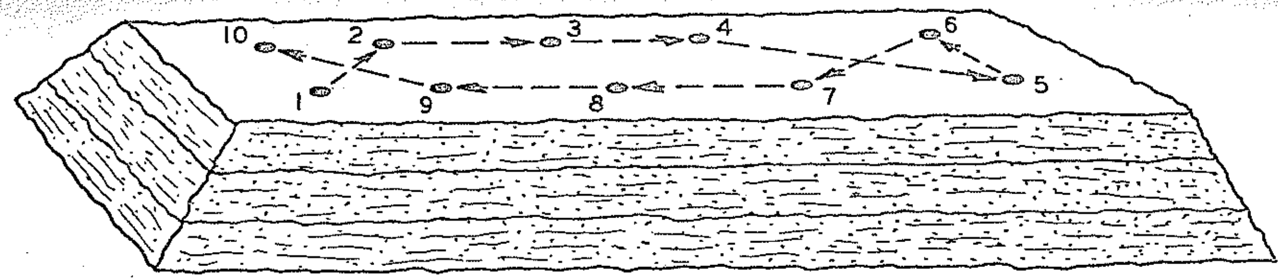
I_1, I_2, I_3 = three aggregate inspectors chosen at random from a large group,

S_1, S_2, S_3 = three screening kits, also chosen from several that were available, and

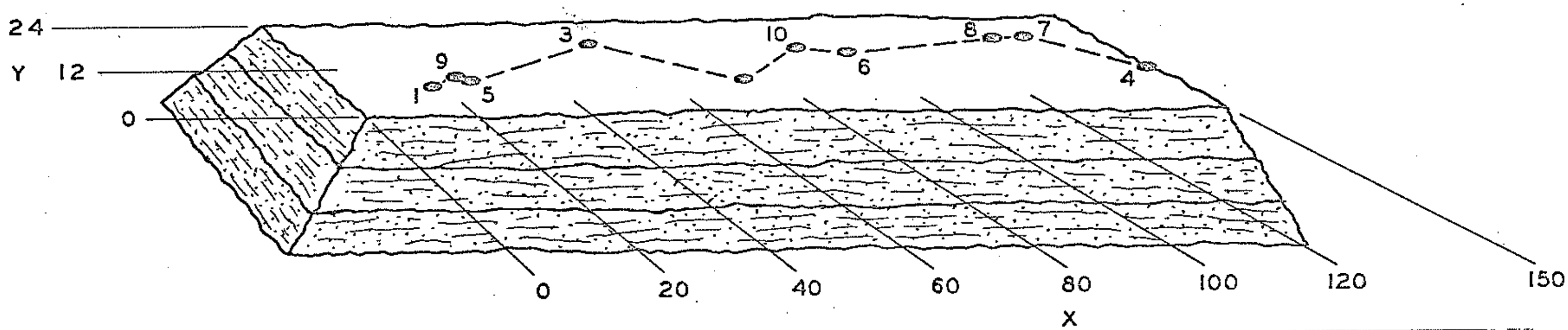
n = 10 gradation analyses per cell.

Survey records covering 22A aggregate indicate that for a randomized survey sample size of 10 gradation tests, a 20-percent risk of failing to detect genuine changes in the average value passing the 3/8-in. sieve was tolerated, with a 5-percent chance of erroneously recording nonexistent changes.

ONE STANDARD SAMPLING PROCEDURE CURRENTLY IN USE



RANDOM SAMPLING PROCEDURE



RANDOM SAMPLING RECORD

PROJECT NO.	63 G-123
SAMPLE NO.	21
DATE	7-8-64
TIME	11:00 AM
MATERIAL	Base & Surface Agg.
SPECIFICATION	22A
PRODUCER	A4
INSPECTOR	I_2
KIT	S_1
DESTINATION	Stockpile (150' x 24')

LOCATIONS, FT		
SPOT	X	Y
1	18	7
2	74	8
3	55	18
4	150	11
5	26	9
6	100	14
7	139	19
8	131	19
9	23	10
10	91	16

Figure 16. Comparison of standard and random sampling procedures.

	M_1			M_2		
	I_1	I_2	I_3	I_1	I_2	I_3
S_1	n	n	n	n	n	n
S_2	n	n	n	n	n	n
S_3	n	n	n	n	n	n

Figure 17. Experimental design involving three main factors: sampling methods, aggregate inspectors, and screening sieves.

On the other hand, for the same sample size, the risks of missing genuine changes in the average values passing Nos. 10 and 200 were close to 5 and 12 percent, respectively, with a probable error of 5 percent in recording nonexistent changes.

The experimental results are summarized below separately for each of the three sieve sizes involved. In all cases, extensive use was made of analysis of variance, a statistical technique for estimating how much of the total variation in gradation results can be significantly attributed to aggregate inspectors, screening sieves, sampling methods, or their interactions. The remaining variation due to other relatively non-significant causes is classed as residual variation, made up of inherent material and experimental variation.

Aggregate Passing 3/8-in. Sieve

The results of the analysis of variance (Table 6) indicate that the main effects of both M and I are highly significant--at the 1-percent level--but that there is no significant effect due to S. The results also show that the interaction MIS is significant at the 5-percent level. The possibility that this interaction might really occur is questionable since the 3/8-in. sieves seemed identical in physical appearance before and after cleaning in the field. On the other hand, the results may be interpreted better in terms of main effects M and I as summarized in Table 7 and shown graphically in Figure 18. All three inspectors obtained higher values when using the regular sampling method, but Inspector I_3 was fairly stable with both methods, since he showed the smallest deviation from the grand average of 70.13 percent passing. This is reasonable because I_3 was the most experienced inspector of the three involved in the experiment.

Thus, inspectors and methods of sampling independently affected the gradation results passing the 3/8-in. sieve. A possible explanation for obtaining a lower average with a random sampling method is that a more representative sample can be expected by using this method as compared to regular sampling. Statistical theory states that a randomized sampling procedure increases the likelihood of getting samples representative of the lot, thus reducing or eliminating sampling as a source of bias. The investigation indicates that the bias is more likely to be on the higher side of the average when the standard sampling procedure is used. On the other hand, since both main factors M and I proved to be highly significant, interest would then center on how much of the overall variation in gradation results is due to discrepancy between the sampling methods and how much is due to discrepancy among different inspectors. An analysis of components of variance gave an estimated value of 6 percent of the total variance

TABLE 6
TABLE OF ANALYSIS OF VARIANCE FOR PASSING 3/8 IN. SIEVE

Nature of effect	Source of Variance	Sum of Squares	Degrees of Freedom	Variance Estimate	F	F Tests	
						F 0.05	F 0.01
Main Factors	M	162.64	1	162.64	15.00**	3.90	6.81
	I	106.64	2	53.32	4.92**	3.06	4.75
	S	21.20	2	10.60	0.98	3.06	4.75
Interactions Among Factors	MI	60.23	2	30.11	2.78	3.06	4.75
	MS	28.14	2	14.07	1.30	3.06	4.75
	IS	76.96	4	19.24	1.77	2.43	3.45
	MIS	124.96	4	31.24	2.88*	2.43	3.45
Replication	Residual	1756.14	162	10.84			
	Total	2336.92	179	13.06			

Legend:
- ** Significant at the 1 and 5-percent levels (highly significant)
- * Significant at the 5-percent level
- M Sampling Methods
- I Aggregate Inspectors
- S Screening Kits

NOTE: Deviations are significant when they are large enough to make the assumption of equal performance unlikely. They are significant when the number in the "F" column is larger than the corresponding number in the "F 0.05" subcolumn, and highly significant when larger than the corresponding number in the "F 0.01" subcolumn.

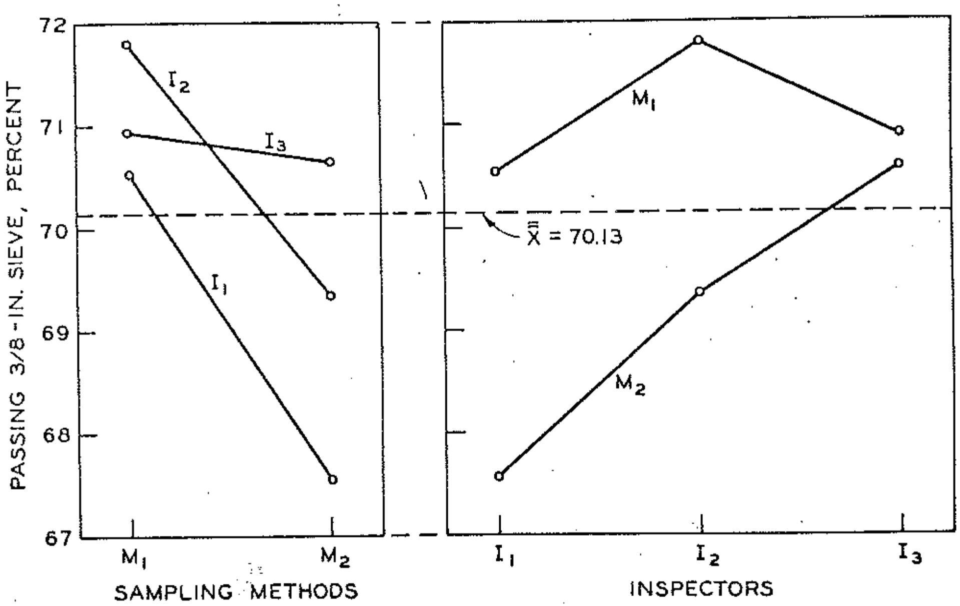


Figure 18. Significant variations due to sampling methods as well as inspectors.

TABLE 7
SUMMARY OF GRADATION TESTS
ON 22A AGGREGATE PASSING 3/8-IN. SIEVE

Inspector	Item	Regular Method of Sampling, M_1	Random Method of Sampling, M_2
I_1	No. of Tests	30	30
	Avg. Gradation, %	70.52	67.57
	Std. Deviation, %	3.42	3.52
I_2	No. of Tests	30	30
	Avg. Gradation, %	71.79	69.33
	Std. Deviation, %	2.82	3.41
I_3	No. of Tests	30	30
	Avg. Gradation, %	70.92	70.63
	Std. Deviation	3.09	4.00
Total and Average	No. of Tests	90	90
	Avg. Gradation, %	71.08	69.17
	Std. Deviation, %	3.13	3.83

attributable to sampling methods, and about 4 percent attributable to different inspectors. The remaining 90 percent of the total variance was due to residual variations including inherent material variation and experimental variations. Assuming that discrepancies of sampling methods and by inspectors could be eliminated or reduced by teaching better sampling procedures or developing more rigorous training programs, these estimated values indicate that much could be gained by such action.

Aggregate Passing No. 10 Sieve

The results of the analysis of variance (Table 8) indicate that the presence of interaction effects is significant enough to reduce the accuracy of the main effect comparisons. Here, the analysis must be supplemented by a detailed examination of the nature of such interactions. The combined influence (interaction) of inspectors with screening kits, significantly affecting the gradation results, is shown in Table 9 and Figure 19. Some combinations of the two factors (inspectors and screening kits) were better or worse than would be expected under existing conditions. Thus, from Figure 19, it appears that each inspector found a different kit that gave results with smallest deviation from the grand average of 43.20 percent passing. In fact, for better results, screening kit S_1 could have been assigned to inspector I_2, kit S_2 to inspector I_3, and kit S_3 to inspector I_1. However, under existing conditions, little could be gained by taking the trouble of assigning particular screening kits to particular inspectors.

Possible reasons for such interactions might include: a) the inspector's practice of rearranging aggregate particles retained on the No. 10 sieve so they may pass; b) inspector's fatigue caused by shaking aggregate test samples by hand under field operating conditions; c) serious discrepancies in sieve openings over the same screening area caused by improper care of testing kits as used in the field.

On the other hand, the difference between the two sampling methods M_1 and M_2 was of sufficient magnitude in some cases to be of practical importance. As shown in Table 10 and Figure 20, relative performance of aggregate inspectors was not consistent for all kits, particularly when the two sampling methods are compared. For example, the best combinations were $I_1\ M_1\ S_1$, $I_2\ M_2\ S_1$, $I_1\ M_2\ S_2$, and $I_2\ M_2\ S_3$ because these were closest to the grand average of 43.20 percent.

When interactions are significant, the standard procedure for analyzing the components of variance is carried out for each factor separately. The results are as follows:

TABLE 8

TABLE OF ANALYSIS OF VARIANCE FOR PASSING NO. 10 SIEVE

Nature of effect	Source of Variance	Sum of Squares	Degrees of Freedom	Variance Estimate	F	F Tests	
						F 0.05	F 0.01
Main Factors	M	97.98	1	97.98	10.67**	3.90	6.81
	I	39.10	2	19.55	2.12	3.06	4.75
	S	14.06	2	7.03	0.77	3.06	4.75
Interactions Among Factors	MI	25.29	2	12.64	1.38	3.06	4.75
	MS	3.61	2	1.80	0.20	3.06	4.75
	IS	280.20	4	70.05	7.63**	2.43	3.45
	MIS	98.81	4	24.70	2.69*	2.43	3.45
Replication	Residual	1487.32	162	9.18			
	Total	2046.36	179	11.43			

Legend:
- ** Significant at the 1 and 5-percent levels (highly significant)
- * Significant at the 5-percent level
- M Sampling Methods
- I Aggregate Inspectors
- S Screening Kits

TABLE 9
SUMMARY OF GRADATION TESTS
ON 22A AGGREGATE PASSING NO. 10 SIEVE

Inspector	Items	Screening Kits		
		S_1	S_2	S_3
I_1	No. of Tests	20	20	20
	Avg. Gradation, %	41.27	43.88	42.55
	Std. Deviation, %	3.72	3.21	3.03
I_2	No. of Tests	20	20	20
	Avg. Gradation, %	43.96	41.91	45.09
	Std. Deviation, %	2.52	4.12	3.08
I_3	No. of Tests	20	20	20
	Avg. Gradation, %	45.40	42.79	42.07
	Std. Deviation, %	2.01	3.10	3.22
Total and Average	No. of Tests	60	60	60
	Avg. Gradation, %	43.54	42.86	43.23
	Std. Deviation, %	3.28	3.54	3.34

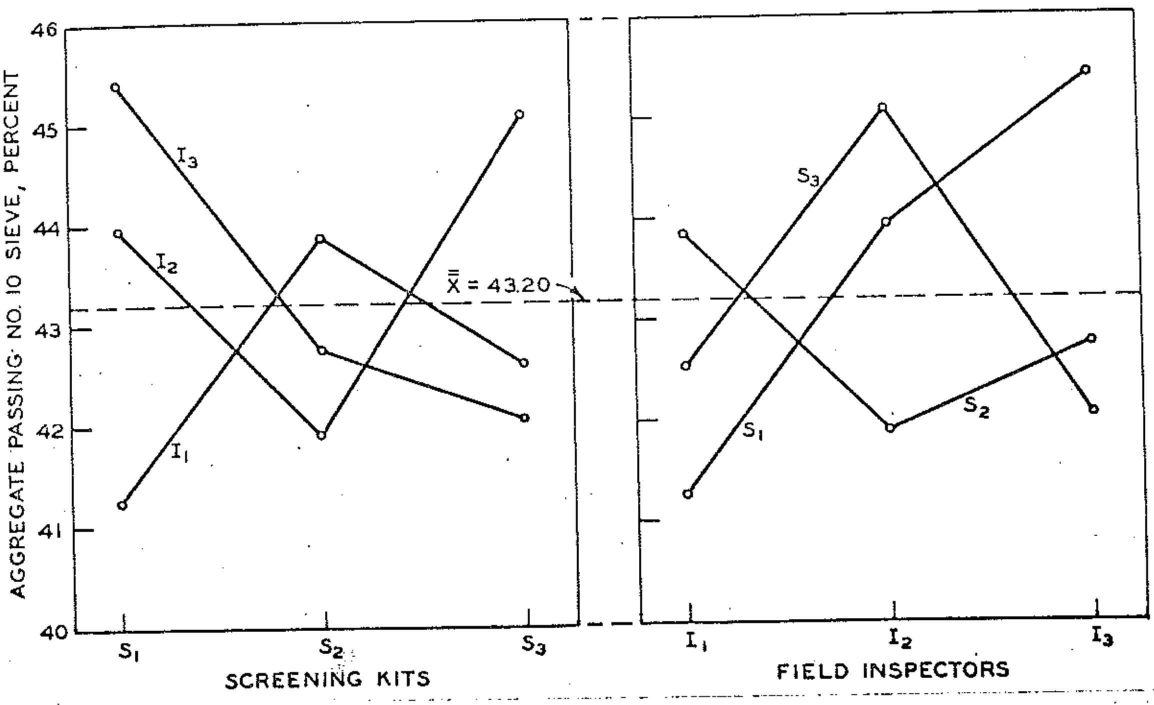


Figure 19. Combined influence (or interaction) of two factors (screening kits-inspectors) affecting gradation results.

TABLE 10
SUMMARY OF GRADATION TESTS
ON 22A AGGREGATE PASSING NO. 10 SIEVE,
USING TWO SAMPLING METHODS

Sampling Methods	Inspector	Item	Screening Kits		
			S_1	S_2	S_3
Regular Sampling Method M_1	I_1	No. of Tests	10	10	10
		Avg. Gradation, %	43.27	43.97	43.68
		Std. Deviation, %	3.50	3.43	2.97
	I_2	No. of Tests	10	10	10
		Avg. Gradation, %	44.47	42.20	47.05
		Std. Deviation, %	2.46	3.62	1.78
	I_3	No. of Tests	10	10	10
		Avg. Gradation, %	45.31	44.02	41.56
		Std. Deviation, %	2.12	1.81	3.56
Random Sampling Method M_2	I_1	No. of Tests	10	10	10
		Avg. Gradation, %	39.27	43.78	41.42
		Std. Deviation, %	2.84	3.16	2.79
	I_2	No. of Tests	10	10	10
		Avg. Gradation, %	43.44	41.62	43.12
		Std. Deviation, %	2.61	4.74	2.88
	I_3	No. of Tests	10	10	10
		Avg. Gradation, %	45.48	41.55	42.57
		Std. Deviation, %	2.00	3.68	2.93

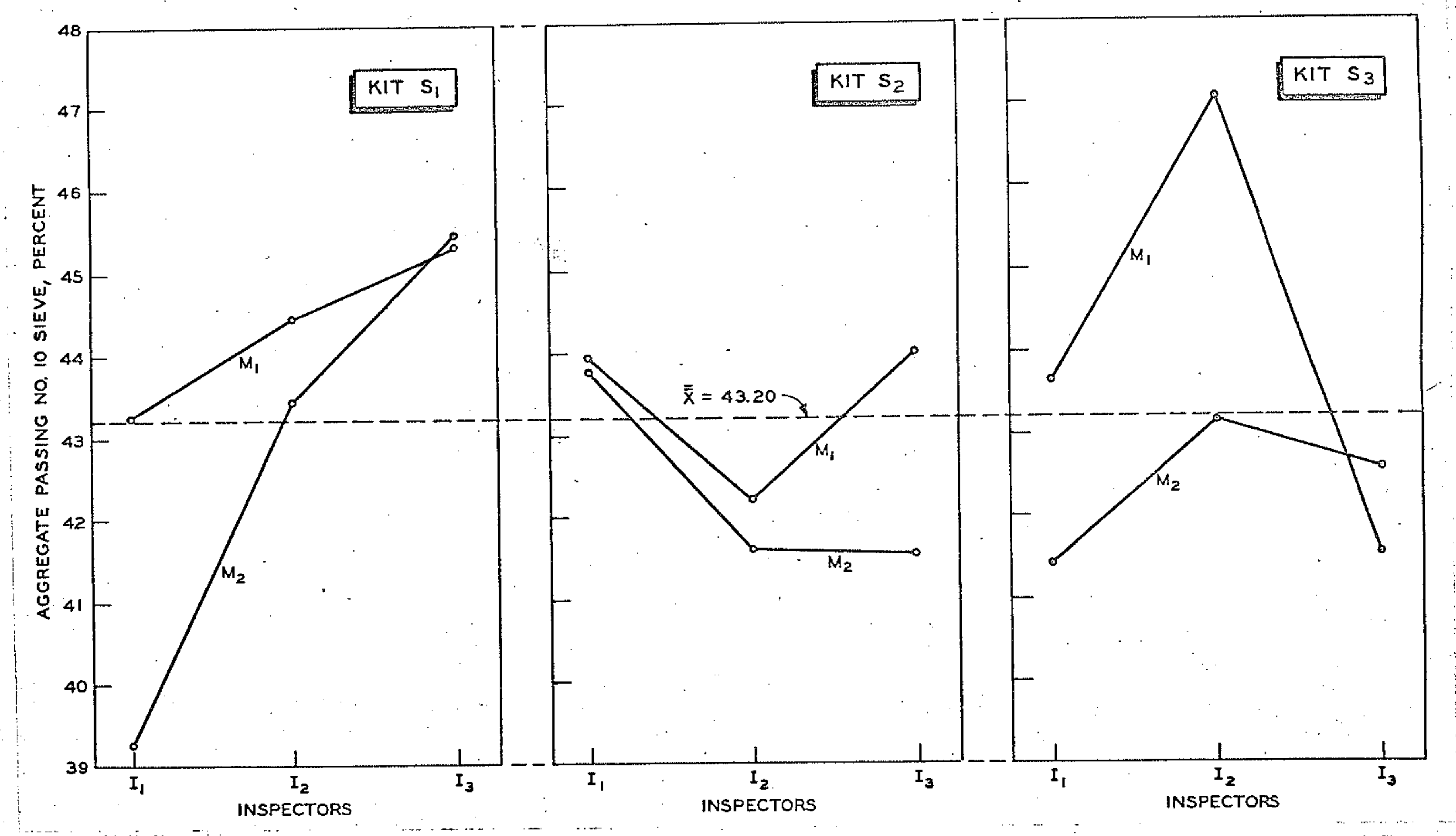


Figure 20. Relative performance of aggregate inspectors for individual kits and different sampling methods.

Source of Variance	Inspectors		
	I_1	I_2	I_3
Sampling Methods, percent	8	6	--
Screening Kits, percent	7	11	18
Residual Deviations, percent	85	83	82
Total	100	100	100

For example, Inspector I_1, always using the same calibrated kit and always sampling and testing in the same manner, might get gradation results with a constant bias, but the total variance of individual readings would be reduced by 15 percent. On the other hand, Inspector I_3, being the most experienced, by always using the same calibrated kit might reduce the total variance by 18 percent. These estimated values would indicate how much might be gained by better calibration of screening kits or remedial training of aggregate inspectors selected for this experiment.

Aggregate Passing No. 200 Sieve

The analysis of variance (Table 11) indicates that highly significant interactions occurred between inspectors and kits during the experimental work. In fact, the combination of these two factors markedly affected the uniformity of gradation results as shown in Table 12 and Figure 21. The interpretation of these interrelated factors is somewhat similar to the results for material passing the No. 10 sieve. For example, it appears that some particular combinations (such as S_2 I_2, S_1 I_2, and S_2 I_3 or S_3 I_3) were better than others under experimental conditions. These interactions might occur for two principal reasons:

1. The difficulty in obtaining uniform effective sieve openings after the No. 200 mesh has been normally used in field work.

2. Variation among individual inspectors in their procedure of agitating and washing an aggregate test sample over a No. 200 sieve.

TABLE 11

TABLE OF ANALYSIS OF VARIANCE FOR PASSING NO. 200 SIEVE

Nature of Effect	Source of Variance	Sum of Squares	Degrees of Freedom	Variance Estimate	F	F Tests	
						F 0.05	F 0.01
Main Factors	M	2.45	1	2.45	2.21	3.90	6.81
	I	6.77	2	3.39	3.05	3.06	4.75
	S	0.26	2	0.13	0.12	3.06	4.75
Interactions Among Factors	MI	0.02	2	0.01	0.01	3.06	4.75
	MS	5.57	2	2.79	2.51	3.06	4.75
	IS	62.35	4	15.59	14.04**	2.43	3.45
	MIS	2.95	4	0.74	0.67	2.43	3.45
Replication	Residual	179.82	162	1.11			
	Total	260.19	179	1.45			

Legend:
- ** Significant at the 1 and 5 percent levels (highly significant)
- M Sampling Methods
- I Aggregate Inspectors
- S Screening Kits

TABLE 12
SUMMARY OF GRADATION TESTS
ON 22A AGGREGATE PASSING NO. 200 SIEVE

Inspector	Items	Screening Kits		
		S_1	S_2	S_3
I_1	No. of Tests	20	20	20
	Avg. Gradation, %	7.58	9.07	7.93
	Std. Deviation, %	1.08	0.91	1.33
I_2	No. of Tests	20	20	20
	Avg. Gradation, %	8.28	8.34	9.38
	Std. Deviation, %	1.06	1.38	0.73
I_3	No. of Tests	20	20	20
	Avg. Gradation, %	9.27	7.99	7.92
	Std. Deviation, %	0.72	1.11	0.98
Total and Average	No. of Tests	60	60	60
	Avg. Gradation, %	8.37	8.46	8.41
	Std. Deviation, %	1.18	1.22	1.24

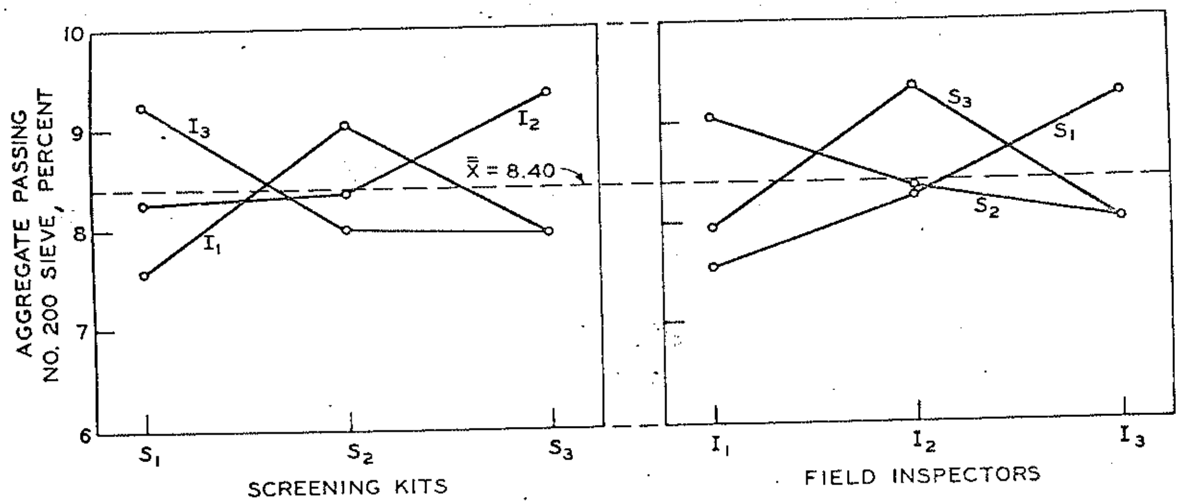


Figure 21. Combination of two factors (screening kits-inspectors) affecting uniformity of results.

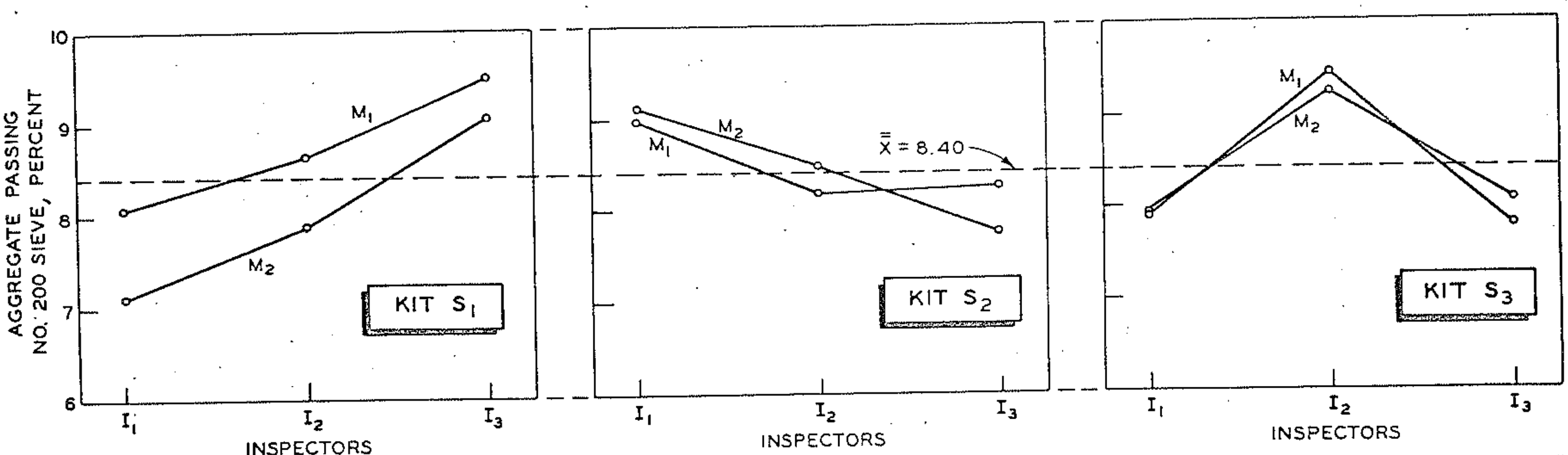


Figure 22. Interactions in various situations.

The nature of these interactions may be examined in detail in Table 13 and Figure 22 for each separate kit. Here, the best combinations were I_2 M_2 S_2, I_3 M_1 S_2, and I_2 M_1 S_1, because they were closest to the grand average of 8.40 percent passing the No. 200 sieve. In addition, these situations reveal that variations in sampling procedures were not significant, and thus such variations could be expected under typical field conditions.

Since interactions were significant in this case, the procedure for analyzing the components of variance are exactly the same as for aggregate passing the No. 10 sieve. The results are as follows:

Source of Variance	Inspectors		
	I_1	I_2	I_3
Sampling Methods, percent	--	--	--
Screening Kits, percent	23	15	28
Experimental Deviations, percent	77	85	72
Total	100	100	100

These estimated values would indicate how much more precision in gradation results might be attained by training inspectors to work alike, or by more careful calibration and maintenance of testing sieves.

Control Charts for 22A Aggregate

For detecting process variation during continuous production of 22A aggregate, control charts for a regular inspector and three inspectors who worked under experimental conditions are shown in Figure 23. The regular inspector and the inspectors performing the experiment obtained their samples at the same time from the same stockpile. Since the No. 10 sieve occasionally causes trouble to producers, this sieve was selected to illustrate relative performance of the inspectors in relation to acceptability of the material. The control charts show daily average results passing the No. 10 sieve during 11 consecutive days of acceptable aggregate production. These charts disclose the following:

1. Daily average values fell consistently above the specification mean. In addition, all four charts show an increasing trend, suggesting that production conditions were changing and that an investigation of production problems might well be justified at this point.

TABLE 13
SUMMARY OF GRADATION TESTS
ON 22A AGGREGATE PASSING NO. 200 SIEVE,
USING TWO SAMPLING METHODS

Sampling Methods	Inspector	Item	Screening Kits		
			S_1	S_2	S_3
Regular Sampling Method M_1	I_1	No. of Tests	10	10	10
		Avg. Gradation, %	8.06	8.99	7.90
		Std. Deviation, %	1.06	0.76	1.30
	I_2	No. of Tests	10	10	10
		Avg. Gradation, %	8.66	8.18	9.46
		Std. Deviation, %	1.28	0.88	0.62
	I_3	No. of Tests	10	10	10
		Avg. Gradation, %	9.49	8.24	7.79
		Std. Deviation, %	0.76	0.93	0.85
Random Sampling Method M_2	I_1	No. of Tests	10	10	10
		Avg. Gradation, %	7.09	9.14	7.95
		Std. Deviation, %	0.91	1.07	1.44
	I_2	No. of Tests	10	10	10
		Avg. Gradation, %	7.89	8.49	9.29
		Std. Deviation, %	0.63	1.79	0.85
	I_3	No. of Tests	10	10	10
		Avg. Gradation, %	9.04	7.74	8.04
		Std. Deviation, %	0.64	1.26	1.13

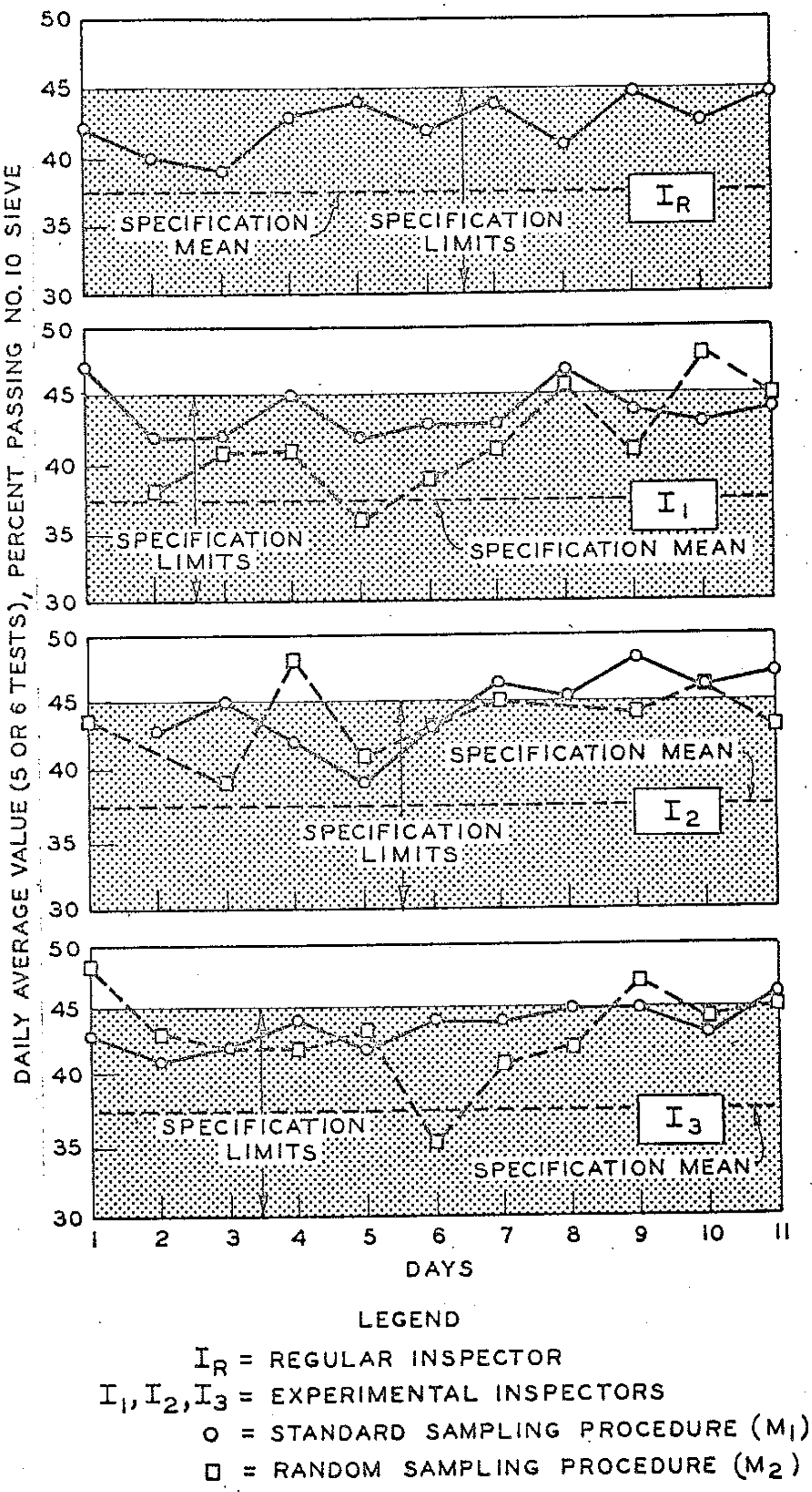


Figure 23. Relative performance of aggregate inspectors using standard and random sampling methods.

2. Because of this increasing trend, Inspectors I_1, I_2, and I_3 probably would have rejected about 20, 40, and 10 percent, respectively, of the total aggregate material already accepted by the regular inspector I_R. Here, definite decision rules might be desirable regarding the acceptability of material whenever successive average values show increasing or decreasing trends on the same side of the specified mean.

3. In general, lower average values were obtained with the random sampling method than with the standard procedure. Furthermore, the difference between the two sampling methods was remarkably consistent for Inspector I_1. This finding supports the results of the analysis of variance, as previously explained.

Results of the Field Experiment

Briefly, the results of the field study are as follows:

1. Inspectors and methods of sampling independently affected gradation results passing the 3/8-in. sieve. An analysis of components of variance gave an estimated value of 4 percent of the total variance attributable to different inspectors, 6 percent attributable to sampling methods, and the remaining 90 percent attributable to inherent material and experimental deviations.

2. The test data on passing No. 10 sieve showed the presence of significant interaction effects among the main factors involved in the experiment. Analysis of components of variance was carried out for each inspector separately with the following results:

a. Variance due to different ways of selecting the sample ranged from 0 to 8 percent.

b. Variance due to different screening sieves ranged from 7 to 18 percent.

c. The remaining variance of 85 percent is attributable to inherent material and experimental deviations.

3. Similarly, the test data on passing the No. 200 sieve were affected by significant interactions between inspectors and kits during the experimental work. Analysis of components of variance was carried out for each inspector separately with the following results:

a. Variance due to different screening kits covered 15 to 28 percent.

b. Variance due to inherent material and experimental deviations was 72 to 85 percent.

c. Variations in sampling procedures were not significant.

4. Control charts for 22A aggregate disclosed at least four significant features not covered by current conventional records-keeping methods, but nevertheless important in an efficient sampling acceptance procedure:

a. Daily average values fell consistently above the specified mean.

b. Daily average results showed a gradual upward trend.

c. Test inspectors would have reached different decisions on acceptance or rejection of the material already accepted by the regular inspector.

d. In general, higher values were obtained with the standard method of sampling than with the random sampling procedure. Also, Inspector I_1 appeared to maintain a consistent difference between the two sampling methods.