The MICHIGAN TEST ROAD

FINAL REPORT on the DURABILITY PROJECT

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MICHIGAN
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JOHN C. MACKIE
COMMISSIONER

THE MICHIGAN TEST ROAD
DURABILITY PROJECT

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SYNOPSIS

Built in conjunction with the Design Project in 1940, the Durability Project of the Michigan Test Road was designed to study the effect of various factors on the durability of concrete in service. The study included both materials and operations, principally the following factors: 1) proportioning and grading of aggregates; 2) various types of additives, including plasticizers and air-entraining agents; 3) blends of portland with natural cement produced with and without a grinding aid; 4) limestone aggregates in various combinations and gradings; and 5) finishing and curing. Supplementary laboratory studies preceded and accompanied the construction and evaluation of the pavement. Also, several incidental studies were carried out in connection with the construction of the project and accelerated scaling tests were performed on all the various test areas during the first two winters after construction.

The most outstanding result of this study was the early verification of the beneficial effect of air entrainment on the durability of concrete, which led to the decision in 1943 to use air-entrained concrete in all Michigan pavements. Blending plain natural cement with portland cement improved scale resistance considerably, but the effect of the natural cement was magnified when beef tallow had been added as a grinding aid. The accelerated scaling tests indicated that for the mixtures used in this project limestone aggregates were conducive to scaling and that adding limestone dust tended to aggravate the condition rather than relieve it. In fact, the addition of fines in general produced no improvement in durability. Curing methods had little influence on ultimate durability, but the bituminous and transparent membranes caused undesirable temperature effects in the concrete. In the finishing study, brooming was moderately beneficial but not greatly superior to burlap finishing in its effect on resistance to scaling.

The relative performance of the various experimental sections of the pavement during the first 17 yr of service generally followed the pattern set in the early accelerated durability tests; the air-entrained concretes exceeded all others in durability and the sections with limestone aggregates were the first to require resurfacing.

CONTENTS

FIGURES


The Michigan Test Road
DESIGN PROJECT 10.1 MILES
DURABILITY PROJECT 7.7 MILES
TO CADILLAC
M 61
Marion
M 115
M 66
TO HOUGHTON LAKE
US 27
HARTWICK
MIDDLE
COUNTY
BRANCH
OSCEOLA
SYLVAN
FREEMAN
ORIENT
GARFIELD
SURREY
GRANT
US 10
OSCEOLA
CLARE
Farwell
Clare
CLARE
LANSING
DETROIT

FIGURE 1

THE MICHIGAN TEST ROAD
DURABILITY PROJECT

The performance of concrete in service cannot be predicted on the basis of laboratory studies alone, however valuable such studies may be in probing its attributes. The Durability Project was constructed to observe the influence of various factors on the durability of concrete in service and to afford a field laboratory for accelerated tests to determine the effect of each variable or factor on resistance to scaling.

The pavement was built in early fall of 1940 in conjunction with the Design Project in an investigational pavement now generally known as the Michigan Test Road. It is located on M 115 between US 10 and M 66 in Clare and Osceola Counties and consists of 17.8 mi of 22-ft concrete pavement, 10.1 mi of which constitute the Design Project and 7.7 mi the Durability Project (Fig. 1).

The purpose and scope of the program and a description of some of the exploratory laboratory studies preceding construction of the Durability Project were reported by Kushing (1, 2). A more comprehensive report on the entire project was published by the Michigan State Highway Department (3) as a separate bulletin shortly after the test road was built. A little later, Finney (4) reported the results of a laboratory investigation performed in conjunction with the durability study which dealt with the mechanism of scaling, chiefly the chemical aspect. In addition to these, five reports devoted exclusively to the Design Project have been issued (5, 6, 7, 8, 9), the last of which closed the project.

Like the Design Project, the Durability Project has been completely resurfaced with bituminous concrete -- the more severely scaled sections in 1951-1952, and the remainder in 1957. Therefore, this will be the final report on the Durability Project, and will include all observations for the 17-yr period prior to resurfacing.

In the following pages, the several phases of the project are first described in two sections entitled Description of the Project and Miscellaneous Project Information. After that, the factual information derived from the various studies is presented and discussed under the headings of Accelerated Scaling Tests, Laboratory Freezing and Thawing Tests of Field Specimens, Laboratory Tests of Pavement Cores, Incidental Studies, and Physical Condition of the Pavement.

DESCRIPTION OF THE PROJECT

The important general factors considered in the Durability Project were type and grading of aggregates, admixtures and air-entraining agents, cement blends, and finishing and curing methods. Supplementing the primary observations, several incidental studies were made which included mechanical analysis of the fresh concrete, setting time of concrete, pavement riding qualities, joint width changes, and periodic condition surveys.

In planning the project an effort was made to vary only one factor at a time. To do this the project was divided into eight test areas, designated Series 1 to 8. These are listed in Table 1, which also gives pertinent information on each test area. Each series is further subdivided into divisions and sections designated with letters and numerals respectively. In addition to Table 1, a schematic diagram of the Durability Project is presented in Fig. 2, showing the locations of the various test sections. A profile sketch is given in Fig. 3.

In the construction of the Durability Project, no special consideration was given to design or construction features except in those cases where such features were expressly planned as factors for study. All work was done in accordance with Michigan State Highway Department standard practice.

Joint width reference plugs were installed in most test sections, and thermocouples and Bouyoucos moisture cells were embedded at the top, middle, and bottom of the concrete slab at selected locations to study curing methods and joint width changes.

Throughout the entire project, the different concrete mixtures were observed visually to note their characteristics and appearance during mixing, placing, and finishing operations. In addition to these field observations, a great many test specimens were cast at the site for later laboratory study.

In describing the project, the various factors under study are classified functionally into the following groups: 1) Proportioning and Grading of Aggregates; 2) Proprietary Admixtures; 3) Air-Entraining Agents; 4) Calcium Chloride Admixture; 5) Natural Cement Blends; 6) Limestone Materials; 7) Standard Construction; 8) Finishing Methods; and 9) Curing Methods. Wherever applicable, this classification will be used throughout the remainder of this report in presenting data from the project.

Proportioning and Grading of Aggregates

Poorly graded aggregates are conducive to poor workability, segregation, difficult finishing, bleeding, and laitance. These properties contribute to inferior concrete with subsequent scaling and disintegration of the pavement surface. In an attempt to overcome these weaknesses, certain fines were added to increase the density and workability of the mix with a

TABLE I
SUMMARY OF TEST AREAS IN DURABILITY PROJECT

Series	Division	Station Beginning	Station End	Length, ft	Finish	Curing	Type of Standard Portland Cement	Admixture	b/b_o	Nomenclature Section Markers
1	A	358+50	370+50	1200	Burlap	Wetted Straw	Brand No. 1	None	0.76	1A
	B	370+50	382+50	1200	Broom	Wetted Straw	Brand No. 1	None	0.76	1A/1B
2	A	382+50	394+50	1200	Broom	Asph. Emulsion	Brand No. 1	None	0.76	1B/2A
3	A-1	394+50	395+70	120	Burlap	Asph. Emulsion initial curing[1]	Brand No. 1	None	0.76	2A/3A
	A-2	395+70	396+90	120	Burlap	Wetted Straw	Brand No. 1	None	0.76	
	A-3	396+90	398+10	120	Burlap	Paper with initial curing[1]	Brand No. 1	None	0.76	
	A-4	398+10	399+30	120	Burlap	Wetted Earth	Brand No. 1	None	0.76	
	A-5	399+30	400+50	120	Burlap	Ponding	Brand No. 1	None	0.76	
	A-6	400+50	401+70	120	Burlap	Double Burlap	Brand No. 1	None	0.76	
	A-7	401+70	402+90	120	Burlap	Paper	Brand No. 1	None	0.76	
	A-8	402+90	404+10	120	Burlap	2% $CaCl_2$ Admix.	Brand No. 1	None	0.76	
	A-9	404+10	405+30	120	Burlap	Membrane[2]	Brand No. 1	None	0.76	
4	A	405+30	412+50	720	Burlap	Wetted Earth	Brand No. 1	None	0.76	3A/4A
	A-1	412+50	413+70	120	Burlap	2% $CaCl_2$ Admix.	Brand No. 1	None	0.76	4A-1
	A	413+70	416+09	239	Burlap	Wetted Straw	Brand No. 1	None	0.76	
	B	416+09	422+07	598	Burlap	Wetted Straw	Brand No. 1	No. 1	0.76	4A/4B
	B	422+07	428+80	673	Burlap	Wetted Straw	Brand No. 1	No. 1	0.80	
	C	428+80	440+10	1130	Burlap	Wetted Straw	Brand No. 1	None	0.76	4B/4C
	D	440+10	446+10	600	Burlap	Wetted Straw	Brand No. 1	No. 2	0.76	4C/4D
	D	446+10	452+10	600	Burlap	Wetted Straw	Brand No. 1	No. 2	0.80	
	E	452+10	464+10	1200	Burlap	Wetted Straw	Brand No. 1	None	0.76	4D/4E
	F	464+10	466+50	240	Burlap	Wetted Straw	Brand No. 1	AEA No. 1	0.76	4E/4F
	F-1	466+50	467+70	120	Burlap	1% $CaCl_2$ Admix.	Brand No. 1	AEA No. 1	0.76	4F-1
	F	467+70	470+28	258	Burlap	Wetted Straw	Brand No. 1	AEA No. 1	0.76	
	F	470+28	476+10	582	Burlap	Wetted Straw	Brand No. 1	AEA No. 1	0.80	
	G	476+10	488+10	1200	Burlap	Wetted Straw	Brand No. 1	None	0.76	4F/4G
	H	488+10	494+10	600	Burlap	Wetted Straw	Brand No. 2	AEA No. 1	0.76	4G/4H
	H	494+10	499+55	545	Burlap	Wetted Straw	Brand No. 2	AEA No. 1	0.80	
	I	499+55	511+83	1228	Burlap	Wetted Straw	Brand No. 2	None	0.76	4H/4I
5	A	511+83	531+45	1962	Burlap	Wetted Straw	Brand No. 1	AEA No. 2[3]	0.76	4I/5A
	A	531+45	532+50	105	Burlap	Wetted Straw	Brand No. 1	AEA No. 2[3]	0.80	
	A-1	532+50	533+70	120	Burlap	1% $CaCl_2$ Admix.	Brand No. 1	AEA No. 2[3]	0.80	5A-1
	A	533+70	536+65	295	Burlap	Wetted Straw	Brand No. 1	AEA No. 2[3]	0.80	
	B	536+65	548+00	1135	Burlap	Wetted Straw	Brand No. 1	None	0.76	5A/5B
	C	548+00	566+09	1809	Burlap	Wetted Straw	Brand No. 2	AEA No. 2[3]	0.76	5B/5C
	C	566+09	572+58	649	Burlap	Wetted Straw	Brand No. 2	AEA No. 2[3]	0.80	
	D	572+58	584+80	1222	Burlap	Wetted Straw	Brand No. 2	None	0.76	5C/5D
6	A	584+80	590+75	595	Burlap	Wetted Straw	Brand No. 1	No grind. aid	0.76	5D/6A
	A	590+75	596+35	560	Burlap	Wetted Straw	blended nat. cement[4]	in nat. cem.	0.80	
	B	596+35	599+15	280	Burlap	Wetted Straw	Brand No. 1	None	0.76	6A/6B
	B	599+15	608+10	895	Burlap	Wetted Earth	Brand No. 1	None	0.76	
	C	608+10	614+00	590	Burlap	Wetted Earth	Brand No. 1	Beef tallow	0.76	6B/6C
	C	614+00	619+80	580	Burlap	Wetted Earth	blended nat. cement[4]	in natural cement[3]	0.80	
2	B	619+80	624+90	510	Broom	Cut-back Asph.	Brand No. 1	None	0.76	6C/2B
	1B-1	624+90	632+40	750	Broom	Wetted Earth	Brand No. 1	None	0.76	2B/1B-1
7	A	632+40	644+10	1170	Burlap	Wetted Earth	Brand No. 1	Silica Dust	0.76	1B-1/7A
	A	644+10	645+58	148	Burlap	Wetted Earth	Brand No. 1	Silica Dust	0.80	
	A	645+58	655+85	1027	Burlap	Wetted Straw	Brand No. 1	Silica Dust	0.80	
	B	655+85	668+04	1219	Burlap	Wetted Straw	Brand No. 1	None	0.76	7A/7B
	C	668+04	680+06	1202	Burlap	Wetted Straw	Brand No. 1	Limestone Dust	0.76	7B/7C
	C	680+06	691+75	1169	Burlap	Wetted Straw	Brand No. 1	Limestone Dust	0.80	
	D-11A[6]	691+75	692+10	35	Burlap	Wetted Straw	Brand No. 1	None	0.76	7C/7D 7C/11A
	D-11A	692+10	693+00	90	Burlap	Wetted Straw	Brand No. 1	None	0.76	
	D-11B	693+00	694+20	120	Burlap	Wetted Straw	Brand No. 1	None	0.76	11A/11B
	D-R.S.	694+20	694+30	10	Burlap	Wetted Straw	Brand No. 1	None	0.76	
	D-11C	694+30	697+92	362	Burlap	Wetted Straw	Brand No. 1	None	0.76	11B/11C
	D-R.S.	697+92	698+00	8	Burlap	Wetted Straw	Brand No. 1	None	0.76	
	D-11D	698+00	704+00	600	Burlap	Wetted Straw	Brand No. 1	None	0.76	11C/11D
	D-R.S.	704+00	704+18	18	Burlap	Wetted Straw	Brand No. 1	None	0.76	
	E	704+18	721+75	1757	Burlap	Wetted Straw	Brand No. 1	Modified Sand	0.76	11D/7E 7D/7E
	E	721+75	728+10	635	Burlap	Wetted Straw	Brand No. 1	Modified Sand	0.80	
	F-12A	728+10	728+28	18	Burlap	Wetted Straw	Brand No. 1	Modified Sand	0.80	7E/7F 7E/12A
	F-12A	728+28	729+00	72	Burlap	Wetted Straw	Brand No. 1	None	0.76	
	F-12B	729+00	730+20	120	Burlap	Wetted Straw	Brand No. 1	None	0.76	12A/12B
	F-R.S.	730+20	730+30	10	Burlap	Wetted Straw	Brand No. 1	None	0.76	
	F-12C	730+30	733+90	360	Burlap	Wetted Straw	Brand No. 1	None	0.76	12B/12C
	F-R.S.	733+90	734+00	10	Burlap	Wetted Straw	Brand No. 1	None	0.76	
	F-12D	734+00	736+42	242	Burlap	Wetted Straw	Brand No. 1	None	0.76	12C/12D
	F-R.S.	736+42	736+52	10	Burlap	Wetted Straw	Brand No. 1	None	0.76	
	F-12E	736+52	742+52	600	Burlap	Wetted Straw	Brand No. 1	None	0.76	12D/12E
	F-R.S.	742+52	742+62	10	Burlap	Wetted Straw	Brand No. 1	Limestone Dust[5]	0.76	
8	A	742+62	753+46	1084	Burlap	Wetted Straw	Brand No. 1	Limestone Dust[5]	0.76	12E/8A 7F/8A
	B	753+46	764+00	1054	Burlap	Wetted Straw	Brand No. 1	None[5]	0.76	8A/8B
		764+00								8B/S

(1) Initial curing consisted in placing damp burlap on concrete after finishing and removal the following morning prior to final curing operations.

(2) Transparent type with initial burlap curing.

(3) Interground with the cement.

(4) One sack of natural cement substituted for one sack of Portland cement per 6-bag batch.

(5) Limestone fine and coarse aggregates.

(6) Divisions D-11A to D-11D and F-12A to F-12E in Series 7 devoted to additional design studies incorporated in durability project because of insufficient space in design project.

R.S. - Expansion relief section.

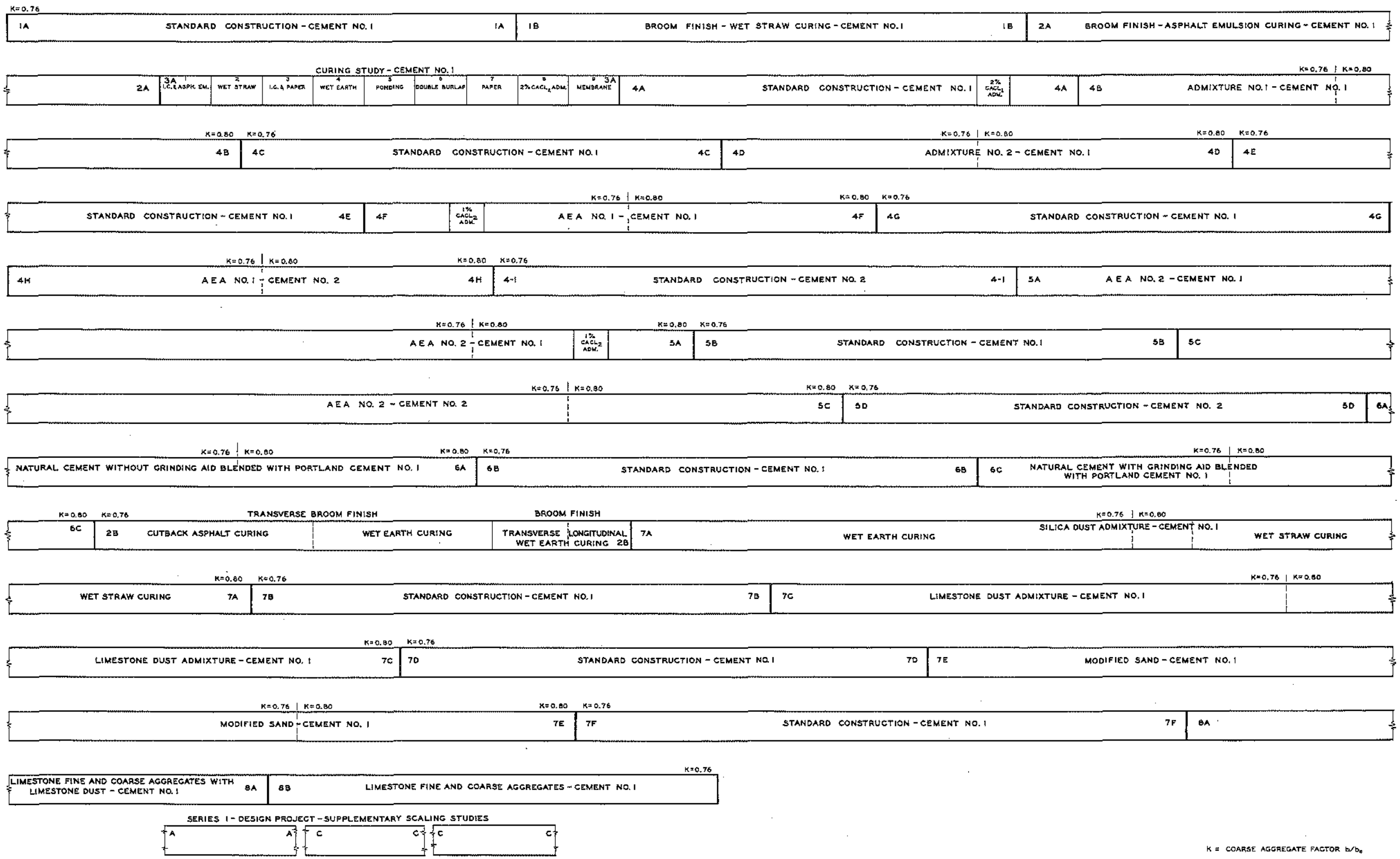


Figure 2. Schematic diagram of the Durability Project.

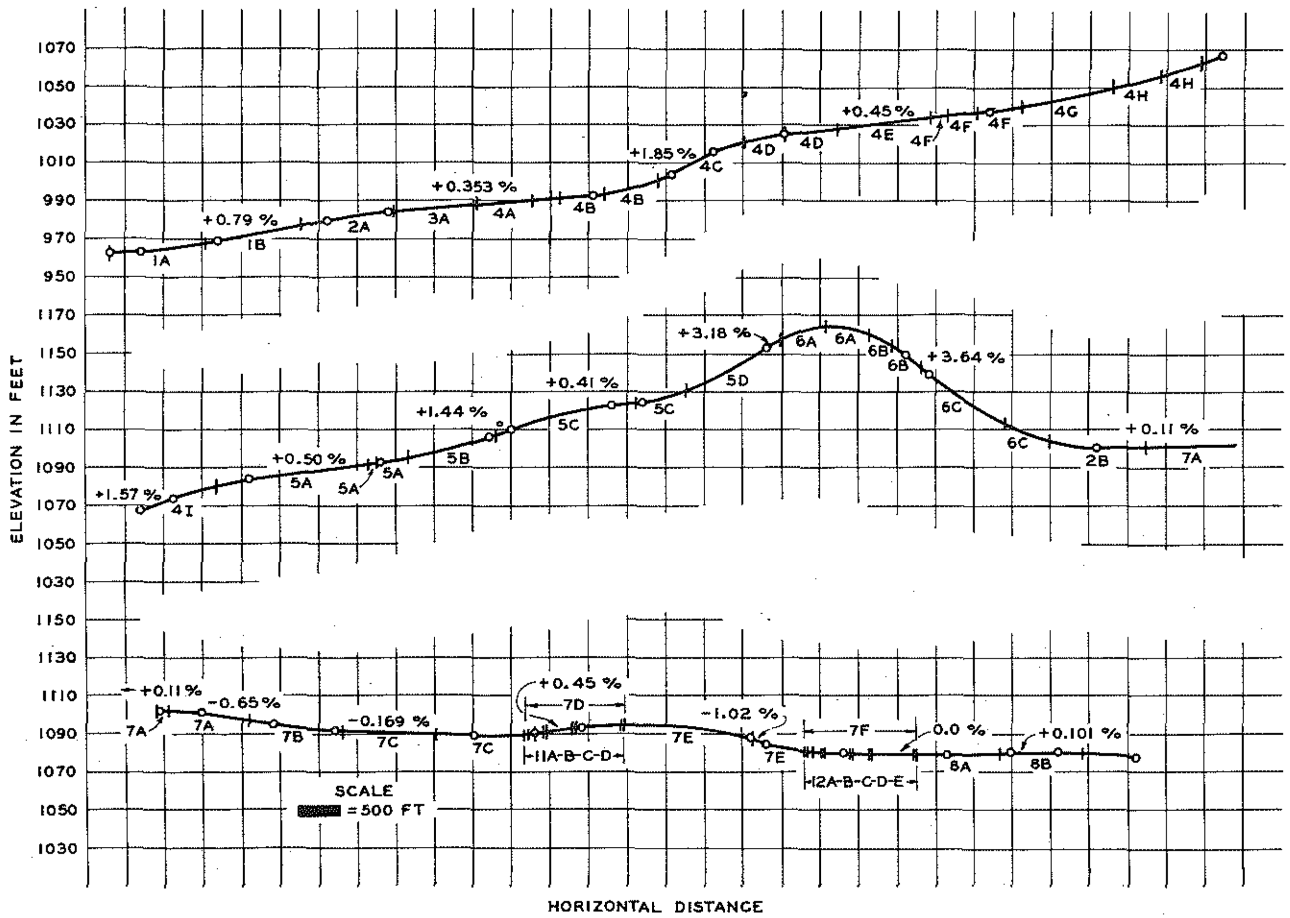


Figure 3. Profile of the Durability Project.

possible resultant reduction of scaling. The fines included natural sand and two kinds of mineral filler, silica dust and limestone dust. These materials were considered to be inert, acting wholly as a physical addition to produce a workable and presumably more durable concrete.

Natural Sand. In modifying the sand grading, an attempt was made to approach ideal gradation and still be conservative as to cost. A study of the general characteristics of available concrete aggregates meeting Michigan State Highway Department 1940 specifications showed the desirability of improving the gradation of the Fine Aggregate 2NS, particularly by modifying the amount of material passing the Nos. 50, 100, and 200 sieves. Consequently in Section 7E special fine sand obtained from a local natural deposit was blended with the batch materials at the rate of 175 lb per cu yd of concrete. The combined mixture of fine aggregates was designated Modified Sand 2NS.

Mineral Fillers. Another phase of the grading improvement study included two types of mineral filler which were added to the concrete to provide additional fines. These materials were silica dust and limestone dust meeting Michigan State Highway Department gradation requirements for Mineral Filler 3MF. They were added to each batch in the amount of 85 lb per cu yd of concrete. The quantity to be added was determined from laboratory analysis, taking into consideration the amount of fines in the fine aggregate, the fineness of the portland cement, and the gradation of the mineral filler. Silica dust was used in Section 7A and limestone dust in Section 7C.

Proprietary Admixtures

Materials selected were two well-known commercial products designated here as Admixtures No. 1 and No. 2. Both were used with Cement No. 1 in two different concrete mix designs for each admixture.

Admixture No. 1. This material was a patented plasticizing agent containing ferric alumina silicate and other ingredients. Two lb per sack of cement were added to the dry batch at the mixer as recommended by the manufacturer. Admixture No. 1 was used in Section 4B of the Durability Project.

Admixture No. 2. This admixture was another type of plasticizing agent containing an organic oxy-acid as the active ingredient. The organic oxy-acid was combined with an inert filler as a carrier to ensure uniform distribution of the active ingredient throughout the concrete. Admixture

No. 2 was added to the dry batch at the mixer in the amount of 1 lb per sack of cement as recommended by the manufacturer and was used in Section 4D.

Air-Entraining Agents

The air-entraining agents included a wetting agent added to the batch at the mixer and a resin interground with the cement at the mill. These agents were designated AEA No. 1 and AEA No. 2 respectively, and each was used in two different mix designs with each of two brands of cement. Preliminary tests were performed to determine the amount of each necessary to produce 3 to 5 percent air in the fresh concrete, measured at that time by a drop in weight of approximately 4 to 6 lb per cu ft.

AEA No. 1. This material was a patented wetting agent manufactured for industrial use. It contained sodium lauryl sulfate as the active ingredient and could be obtained in paste or flake form. Sufficient agent was added to the mix to produce a drop in weight from that of the standard mix of 4 to 6 lb per cu ft of concrete of a specified consistency and cement content. It was found that for the particular materials used in this project, 0.06 lb of agent in paste form per bbl of cement reduced weight approximately 5 lb per cu ft.

The paste was dissolved in water to form a solution of known concentration. The required amount of the solution per batch of concrete was added to the dry materials at the skip. AEA No. 1 was used in Sections 4F and 4H.

AEA No. 2. The raw or un-neutralized resin was ground with the clinker at the mill to produce air-entraining portland cement. For the materials used here a resin content of about 0.15 lb per bbl of cement produced the required 4 to 6 lb drop in weight. It was required that air-entraining cements be milled from the same clinkers used by their respective producers in manufacturing the two standard portland cements. Specifications also required that the manufacturers of these cements furnish acceptable evidence that they had had previous experience in producing air-entraining portland cement in quantity, and that the standard and special cements would be uniform in quality, fineness, and chemical composition. Cements with AEA No. 2 were used in Sections 5A and 5C.

Calcium Chloride Admixture

It is common practice to add calcium chloride to concrete mixtures during cold weather construction to accelerate strength gain and prevent frost damage. Consequently, calcium chloride was added to the mix for 120 ft in Sections 4A, 4F, and 5A, not only to determine its effect as a curing agent, but also to observe its effect on the physical characteristics of standard concrete and concrete containing the two types of air-entraining agents. The calcium chloride in flake form was added to the dry batch at the mixer skip in the amounts shown in Table 1.

Natural Cement Blends

Two natural cements of the same brand were used, one manufactured with and the other without the use of a grinding aid. Each was blended with Cement No. 1 in two different mix designs.

The natural cement without grinding aid was manufactured in accordance with Standard Specification for Natural Cement, ASTM Designation: C 10-37. The second natural cement was manufactured under the same requirements, except that beef tallow was used as a grinding aid. No requirements were placed upon the grinding aid itself because the natural cement with grinding aid had been a standard product of the manufacturer.

The portland-natural cement was blended on the basis of 1 sack (75 lb) of natural cement to 5 sacks of portland cement. The cement content, including both portland and natural cement, was 5.5 sacks (1.375 bbl) per cu yd of concrete as specified for the entire project. Section 6A contained the blended natural cement without grinding aid and Section 6C the natural cement with grinding aid.

Limestone Materials

In addition to the studies of aggregates and additives previously described, a portion of the Durability Project was set aside for study of limestone aggregates with and without added fines.

The use of manufactured limestone sand as a fine aggregate in concrete construction has been in disfavor not only in Michigan but also in some other states where this material is available. At the time this road was built, the main objections to its use in concrete were reduced workability, excessive bleeding, difficult finishing, and a tendency toward excessive surface scaling. In recent years many limestones have also shown a marked tendency to polish under traffic and become dangerously slippery.

Two test areas were constructed entirely of concrete containing crushed fine and coarse limestone aggregates to study the stone sand problem under controlled conditions. The first, Section 8A, contained limestone coarse aggregate and stone sand with limestone dust added as a possible method of improving the characteristics of the mixture. Limestone dust was added at the rate of 85 lb per cu yd of concrete, amounting to about 2 percent of the total mix. For comparative study, a second test area, Section 8B, was established containing limestone fine and coarse aggregates but no added limestone dust. Both sections were constructed and cured in the same way.

Standard Construction

Sections containing two different brands of cement in the standard mixture, constructed in accordance with Department specifications, were interspersed throughout the project for two purposes: 1) to indicate possible effects of cement brand on durability; and 2) to provide reference sections for comparison with adjacent or nearby sections of non-standard construction containing the same brand of cement. Locations of these sections are given in Table 1.

Finishing Methods

The brooming of concrete surfaces with stiff brooms as a final finishing operation has been used by some highway engineers to reduce the amount of fine superficial material and to provide a non-skid surface. Others have contended that this method aggravates scaling by providing grooves for the collection of salt solutions. Because of this difference of opinion it was felt that a study should be made of burlap finishing and brooming to obtain comparative data on the two methods.

Two different factors were involved in the studies: 1) burlap finish versus broom finish under standard curing conditions with wetted coverings; and 2) burlap finish versus broom finish with curing by two types of bituminous membrane.

The bituminous membranes were asphalt emulsion and cutback asphalt. The cutback asphalt was applied immediately after finishing operations; the asphalt emulsion was applied after initial curing with burlap.

Sections 1A and 1B, and 2A and 2B were devoted to this study of finishing methods.

Curing Methods

Past evaluations of concrete curing methods had been based largely on strength tests, with very little data available on relative effect on durability. Therefore, a study of curing methods under actual field conditions was included in the program. In this study, observations and measurements were made to evaluate the influence of the various curing methods on durability, especially with regard to scaling, and determine the effect of these methods on thermal and moisture conditions within the slab. Also it was particularly desired to compare a transparent membrane-forming compound with conventional wet curing methods in use at the time.

The curing methods selected were asphalt emulsion, cutback asphalt, wetted straw, wetted earth, ponding, double burlap, paper curing with and without initial burlap curing, calcium chloride integrally mixed, and a transparent membrane with initial burlap curing. Series 3 was set up for the principal curing study, although additional comparisons more limited in scope can be found in other areas of the project.

MISCELLANEOUS PROJECT INFORMATION

During and after construction, various data were collected on factors which directly or indirectly influence pavement behavior. The following information on pavement design, concrete mixtures, soils, and traffic and climatological conditions provides a useful background for appraising performance of the various experimental sections and the pavement as a whole.

Pavement Design

The pavement was constructed in accordance with the Michigan State Highway Department 1940 plans and specifications. Significant features were:

Pavement laid in full width construction.
Pavement width: 22 ft.
Cross-section: 9-7-9 in.
Expansion joints spaced at 120 ft.
Contraction joints (weakened-plane type) spaced at 60 ft.
Hinge or warping joints spaced at 30 ft.
Expansion joints 1 in. wide, using premolded fiber filler and sealed with asphalt, SOA.

Steel mesh reinforcement: 60 lb per 100 sq ft.

Longitudinal joint at center (weakened-plane type) with 1/2- by 40-in. round tie bars spaced at 48 in.

Load transfer:

At expansion joints, Translode Angle Unit with continuous base.

At contraction joints, 3/4- by 15-in. dowels spaced at 15 in.

Concrete Mixtures

Two different brands of Type I cement and two corresponding air entraining cements of the same brands were used, but Cement No. 1 in the standard mix was prescribed for all sections where the factor under study was constructional in nature. The standard mix design for the two cements was modified as necessary to suit the requirements of the various factors included for study.

Mix Design. Concrete mixtures were designed by the mortar voids method as provided in Michigan specifications. Except for the mixtures containing limestone fine and coarse aggregates, concrete mixtures with two coarse aggregate factors, b/b_o, of 0.76 and 0.80 respectively, were used for all sections containing admixtures. The coarse aggregate factor, b/b_o, is the ratio of the absolute volume of coarse aggregate per unit volume of concrete to the absolute volume of coarse aggregate per unit volume of dry, bulk coarse aggregate. In effect it can be considered the bulk volume of loose coarse aggregate per unit volume of concrete. In the Michigan method of design, b_o refers to dry loose volume rather than dry rodded volume of coarse aggregate. Basic concrete proportioning data for the different mixes are summarized in Table 12 (App. A).

Materials. The two brands of cement are designated Cements Nos. 1 and 2; physical and chemical properties are listed in Table 13 (App. A).

Specifications required that the air-entraining cement with interground resin conform to the standard specifications for Portland Cement, Type I, ASTM Designation C 150, with the following exceptions and additions:

> The cement shall be ground with 0.15 lb (±20 percent) of pulverized resin per barrel, which shall be uniformly added to the clinker at the time of grinding. The specific surface as determined in accordance with ASTM C 115-28T shall not be less than 1750 nor more than 2100 square centimeters per gram.

Specification requirements for the resin are given in Table 14 (App. A).

The natural fine and coarse aggregates were obtained from a Michigan commercial gravel producer and had the physical properties summarized in Tables 15 and 16 (App. A). In accordance with standard Michigan practice, the coarse aggregate was separated into two gradings, 4A and 10A, equal amounts of each being used in the batch. The grading of the natural sand which was blended with the fine aggregate to form a modified mixture is also given in Table 15.

The limestone aggregates conformed to Michigan requirements for Coarse Aggregates 4A and 10A, and Stone Sand 2SS; the mineral fillers, silica dust and limestone dust, were furnished under the specifications for Mineral Filler 3MF. The characteristics of these materials are shown in Tables 17 and 18 (App. A).

General Soil Conditions

The subbase and subgrade soils were of several different types common to the locality: Plainfield sand, Rubicon sand, Nester loam, Coloma sand, Roselawn sand, Bergland clay loam, and Newton sand. In general these soils were ideal for subgrade and subbase purposes, except in an area between Stations 463+00 and 578+00 where it was necessary to construct a 12-in. sand subbase on the existing subgrade.

The sandy soils (Plainfield, Rubicon, Coloma, and Roselawn) possess in common the characteristics of low water-retaining ability, incoherence, and susceptibility to wind erosion when exposed. These soils required no constructed subbase. On the other hand, Newton sand, Bergland clay loam, and Nester loam have poor drainage characteristics and required construction of a free-draining sand subbase. Locations of the various soil types, and cut and fill areas, are shown in Fig. 4.

Immediately before placing the concrete, moisture and density tests were made on subbase and subgrade soils at locations throughout the project. The samples were taken at 9- and 18-in. depths representing subbase and subgrade respectively. Data from these observations are given in Table 19 (App. A), and indicate in a general way the variations in moisture and natural densities which might be encountered in normal construction. The physical characteristics of the sand subbase are presented in Table 20 (App. A).

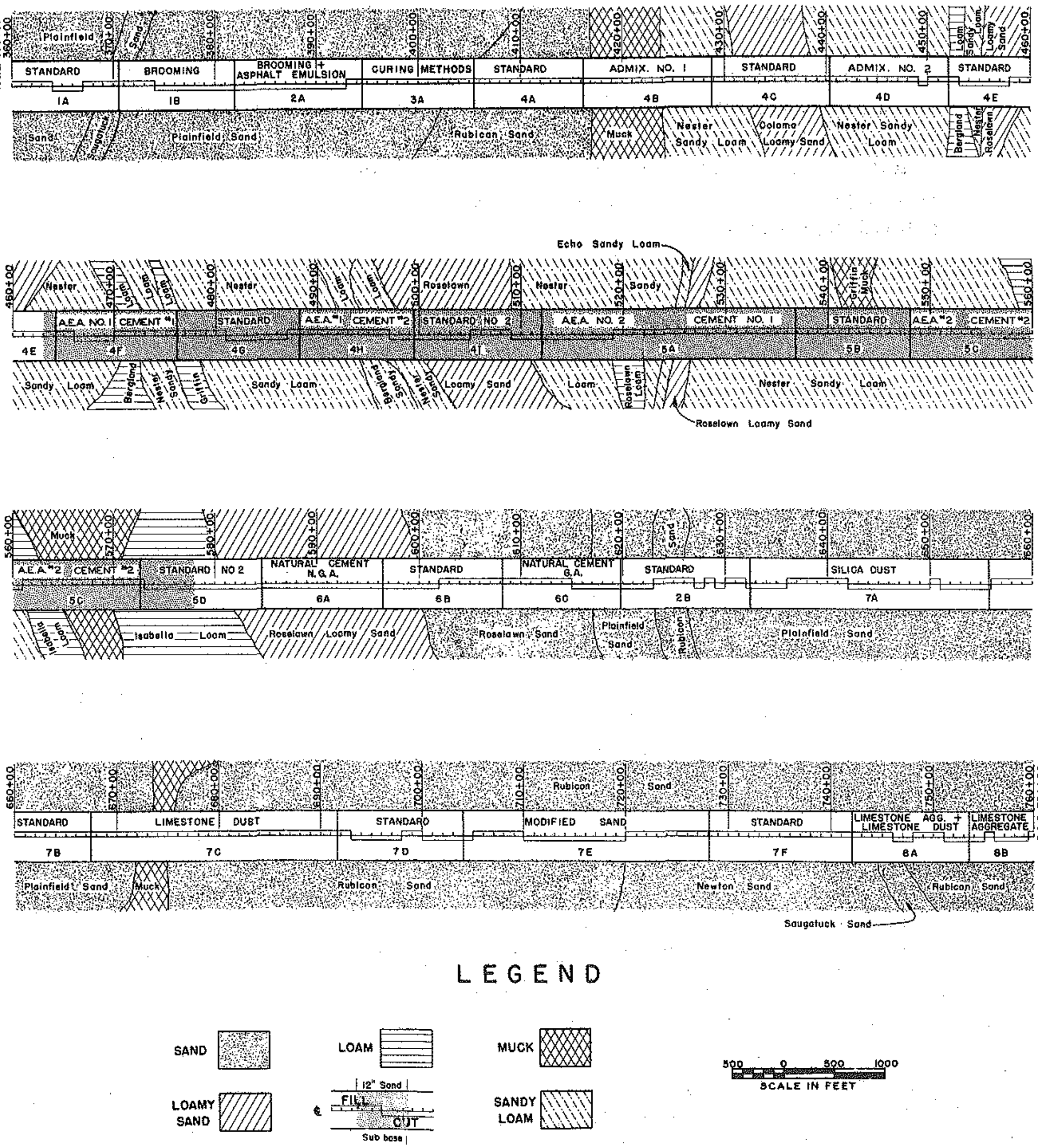


Figure 4. Soil types and earthwork operations.

Traffic Characteristics

Automatic recording equipment was installed on the Test Road to obtain a continuous daily record of traffic flow. In addition to the daily traffic counts, classification surveys were made periodically. During these surveys the axle loads, axle spacings, and frequency of the various types of commercial vehicles were recorded. Wheel loads were obtained by means of portable loadometers from which axle loads were determined.

Annual average daily traffic flow from 1941 to 1957 is shown in Table 21 (App. B) and Fig. 5. Except for the war years (1942-45), total traffic increased slightly each year. Commercial traffic generally increased at a rather uniform rate throughout the 17 yr and by the end of this period had about doubled. The average monthly totals for passenger and commercial vehicles given in Fig. 6 illustrate the seasonal pattern of total traffic flow over the project.

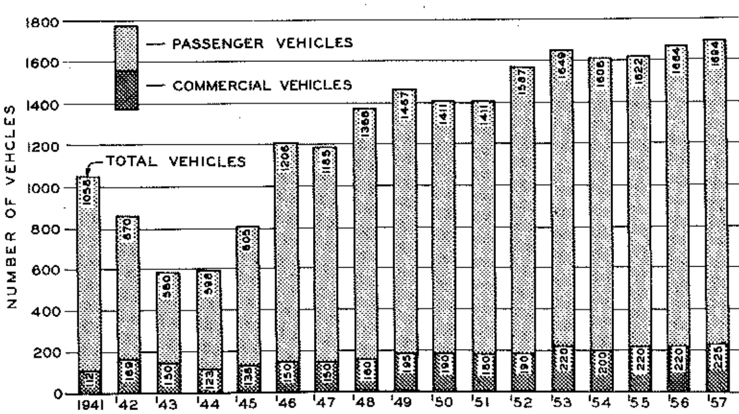
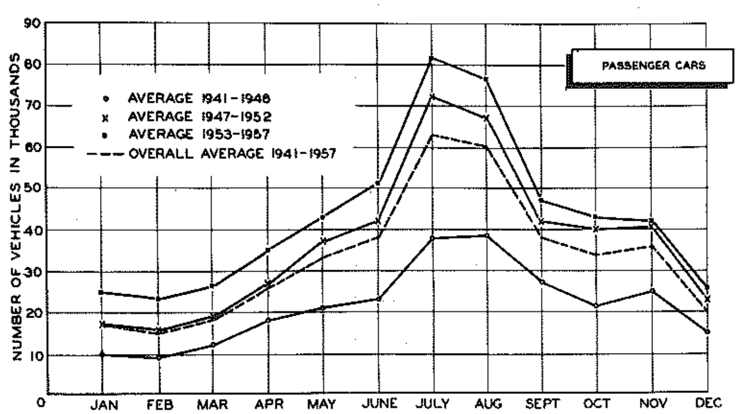
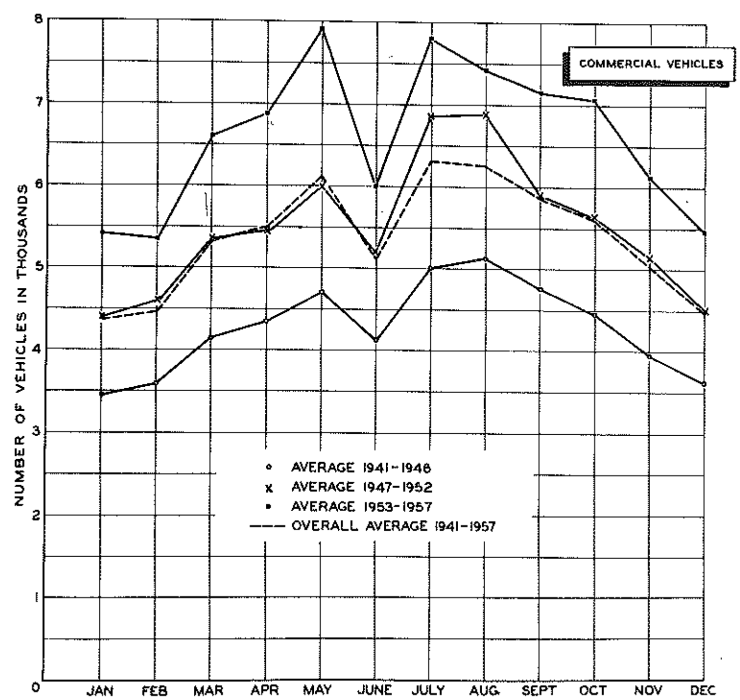


Figure 5. Average daily traffic.

Figure 6. Average monthly traffic.





Average wheel load distribution is shown in Table 22 (App. B) and axle load frequency averaged for the 17 yr in Fig. 7. For comparison, a similar curve is shown for 1955 commercial traffic on a heavily traveled interstate route, US 24, 8 mi south of Monroe, Michigan.

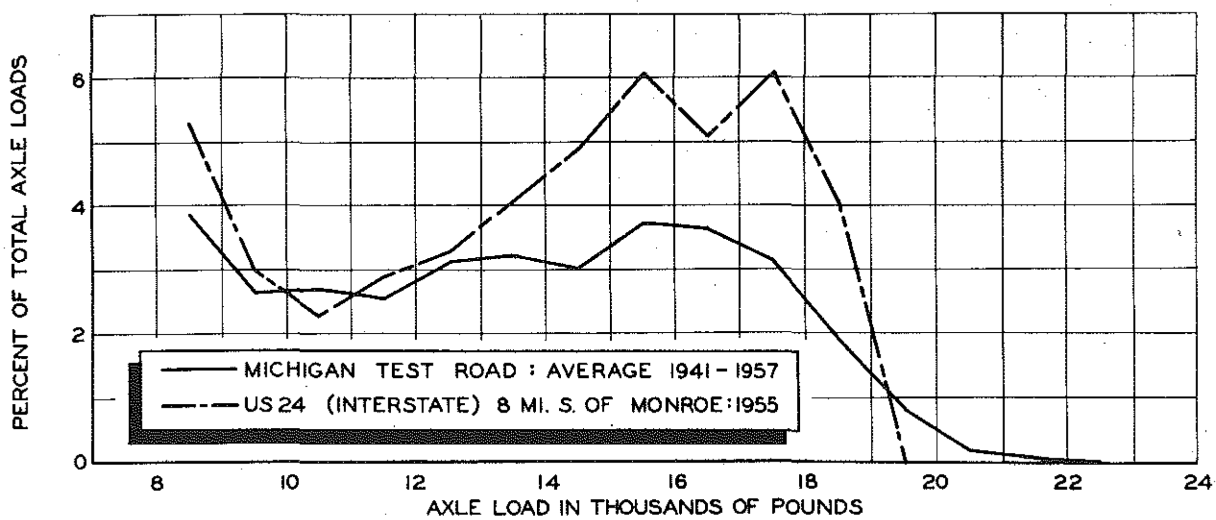


Figure 7. Axle load frequency.

Climatological Data

Average daily air temperature variation from 1941 to 1957 and average daily air temperatures for the same period are shown in Fig. 8. Daily variations in temperature were considerably less in winter than in summer. Daily range in winter varied from 4 to 39 deg F, with an average of about 17 deg. During summer, daily range of air temperature varied from a low of 9 deg to a high of 45 deg, with an average of about 27 deg. Average daily temperature varied from 20 F in winter to 67 F in summer, a total average annual change of 47 deg.

Total annual precipitation (1941-57) is given in Fig. 9. Average annual rainfall for the 17-yr period was 31.92 in. and departure of yearly totals from this average was relatively small, indicating fairly uniform moisture conditions through the life of the project.

The normal freezing index for the area is approximately 1,050 degree days. Freezing index is defined as the difference in degree days between the maximum and minimum points on the curve obtained by plotting accumulated degree days against time from summer to summer. Degree days are obtained by subtracting the mean temperature for each day from 32 F.

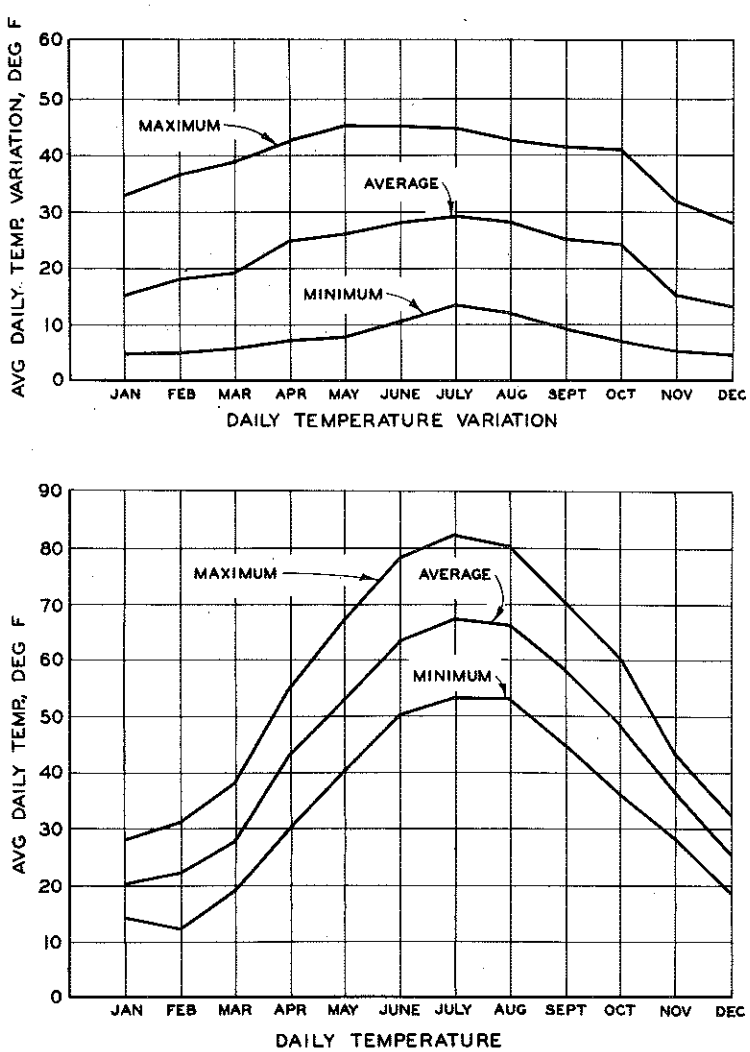


Figure 8.
Air temperature record.

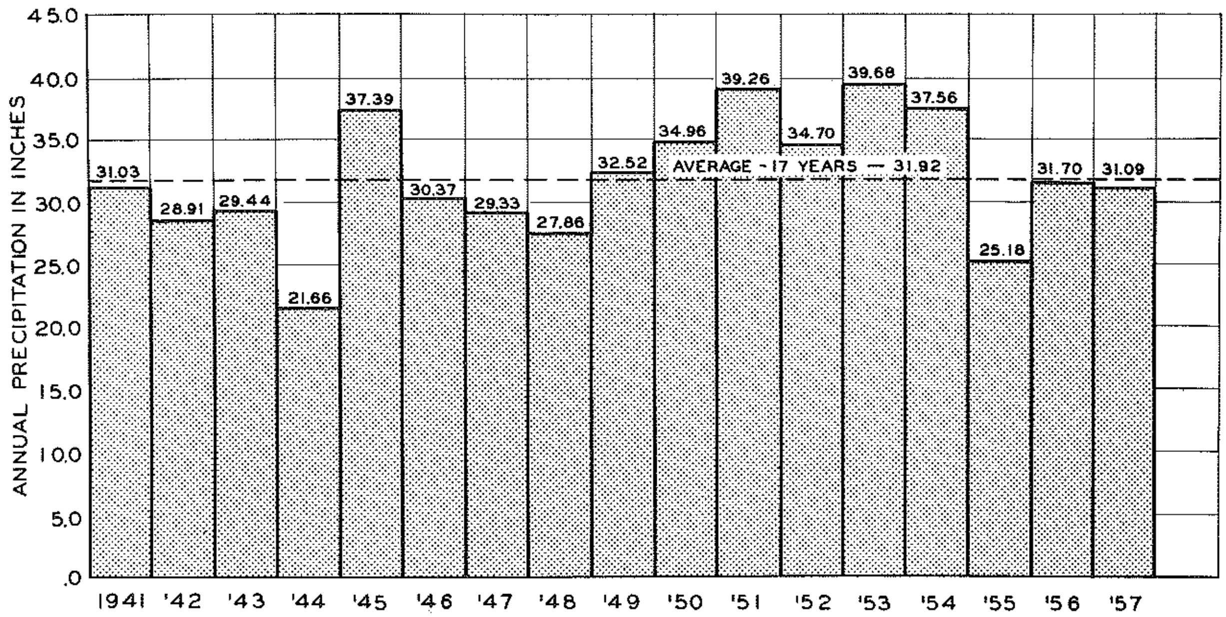


Figure 9. Annual precipitation.

ACCELERATED SCALING TESTS

The accelerated scaling studies were originally planned to continue for several years to determine the possible effect of age on scale resistance. Therefore, no de-icing chemicals were applied for winter maintenance until all scaling tests were completed. However, after the first two winters the results on the age effect were so inconclusive and the effect of the various other factors so clear that continuation seemed unnecessary and the tests were stopped.

Later, in the winter of 1944-45 when the pavement was a little over 4 yr old, additional scaling tests to determine only the effect of age were conducted on two sections of standard construction in conjunction with similar tests on neighboring pavements ranging in age from 5 to 9 yr. The results of this independent but related study did indicate a definite relation between age and resistance to scaling, the 4-yr-old Test Road sections showing marked improvement over the younger concrete tested previously, and the other pavements 6 or more yr old remaining unscaled throughout the tests.

The scope of the accelerated scaling studies is illustrated in the schematic diagram of Fig. 10, showing the pavement sections embodying the various factors under observation and the approximate location of each test panel.

Test Methods

For the scaling study, pavement sections 120 ft long representing each of the various concrete mixtures and construction features were chosen to provide sufficient area for a succession of accelerated tests. In each section, two panels 3 ft wide and 12 ft long were established along the east edge of the pavement. Safety precautions were maintained day and night to warn motorists of the presence of the test areas. A typical view of a test area in operation is shown in Fig. 11.

Originally two test methods, A and B, were employed to determine resistance of the various pavement sections to calcium chloride attack.

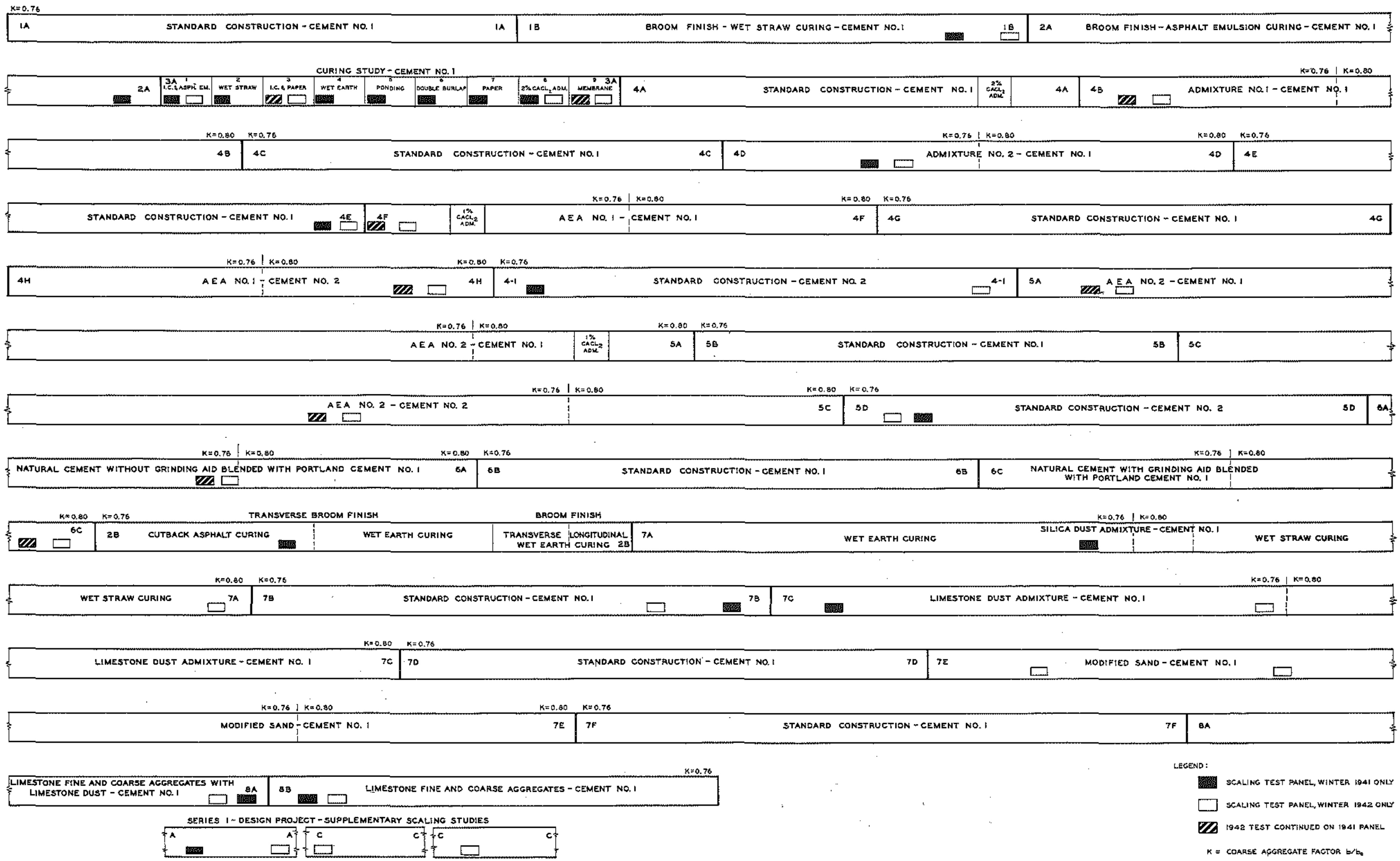


Figure 10. Location of panels for accelerated scaling tests.

In Method A, a 10-percent solution of calcium chloride of 1/4-in. minimum depth was applied and allowed to remain in place 5 days. Then the solution was removed, the panel flushed, and covered with water 1/4-in. deep. After the water had frozen, the ice was melted by applying 5 lb of flake calcium chloride per area. When the ice had melted sufficiently, the slush was removed, the surface flushed, and the test area allowed to rest one day before beginning the next cycle. Method A was discontinued after the first winter because Method B was found to be more severe and more easily controlled.

In Method B, water was applied to the test area and allowed to freeze overnight. The following morning the ice was melted by distributing 5 lb of flake calcium chloride over the area. When the ice had melted sufficiently, the slush was removed and the surface flushed. Fresh water was applied and the freezing and thawing cycle repeated. On the basis of the quantity of melted ice in each test area, 5 lb of calcium chloride would be sufficient to produce a 10-percent solution.

At the end of each freezing and thawing cycle, the amount of scale developed during the cycle was determined visually after superimposing over the test area a steel mesh grid with openings 12 in. square. In this way the amount of scaled surface could be estimated quickly and accurately. Each area was photographed at the end of the test.

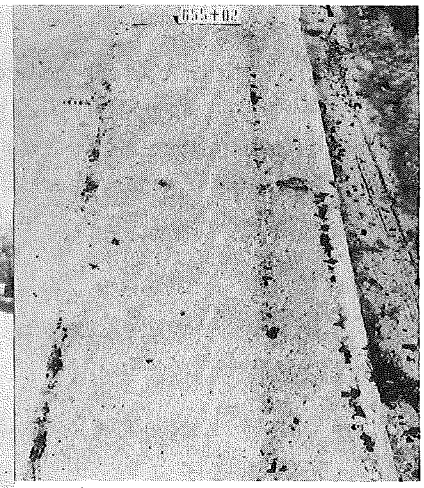
During the first series of scaling studies (1940-41), two test panels were established for each factor studied. One was subjected to Method A and the other to Method B. In the next winter (1941-42), Method B was used on those areas tested in 1940-41 where it seemed advisable to continue the treatment and on new areas established to correlate age with scale resistance.

Test Results

A classified summary of data obtained from the scaling tests is given in Table 23 (App. B) and Fig. 12. The condition of typical panels at the end of the accelerated tests is shown in Fig. 11. In discussing these results the various factors are compared both individually and collectively in the group classifications given previously.

Proportioning and Grading. Adding mineral fillers such as silica dust, limestone dust, and other fines with a preponderance of material passing the No. 200 sieve, was not a satisfactory method for improving scale resistance of concrete pavements (Fig. 12). However, on the basis of the data from these tests, silica dust proved to be the most beneficial of the three materials tried, and limestone dust the least.

Test area in operation



Silica Dust, 33 cycles

Modified Sand, 12 cycles

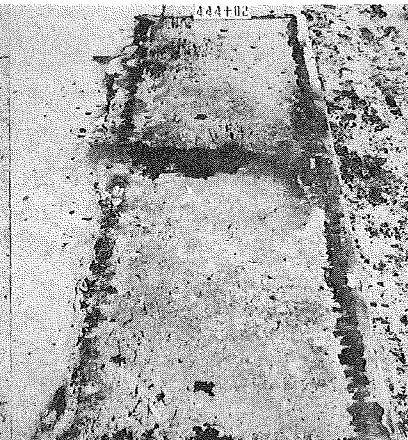
Broom Finish, 23 cycles

Limestone Aggregate with Limestone Dust, 22 cycles

Limestone Dust, 8 cycles

Figure 11. Condition of typical panels at end of accelerated scaling test.

Admixture No. 1, 93 cycles



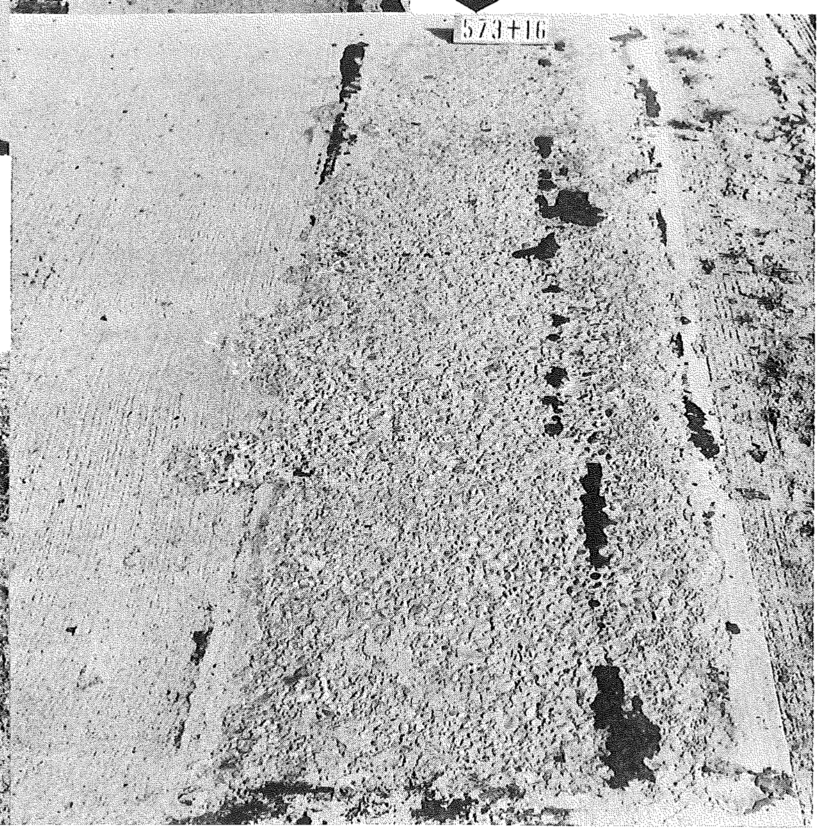
Admixture No. 2, 61 cycles

AEA No. 2, 94 cycles

AEA No. 1, 93 cycles

Natural Cement blend, no grinding aid, 90 cycles

Standard Concrete Brand No. 2 Cement, 32 cycles



Natural Cement blend with grinding aid, 94 cycles

Figure 11. Condition of typical panels at end of accelerated scaling test (continued).

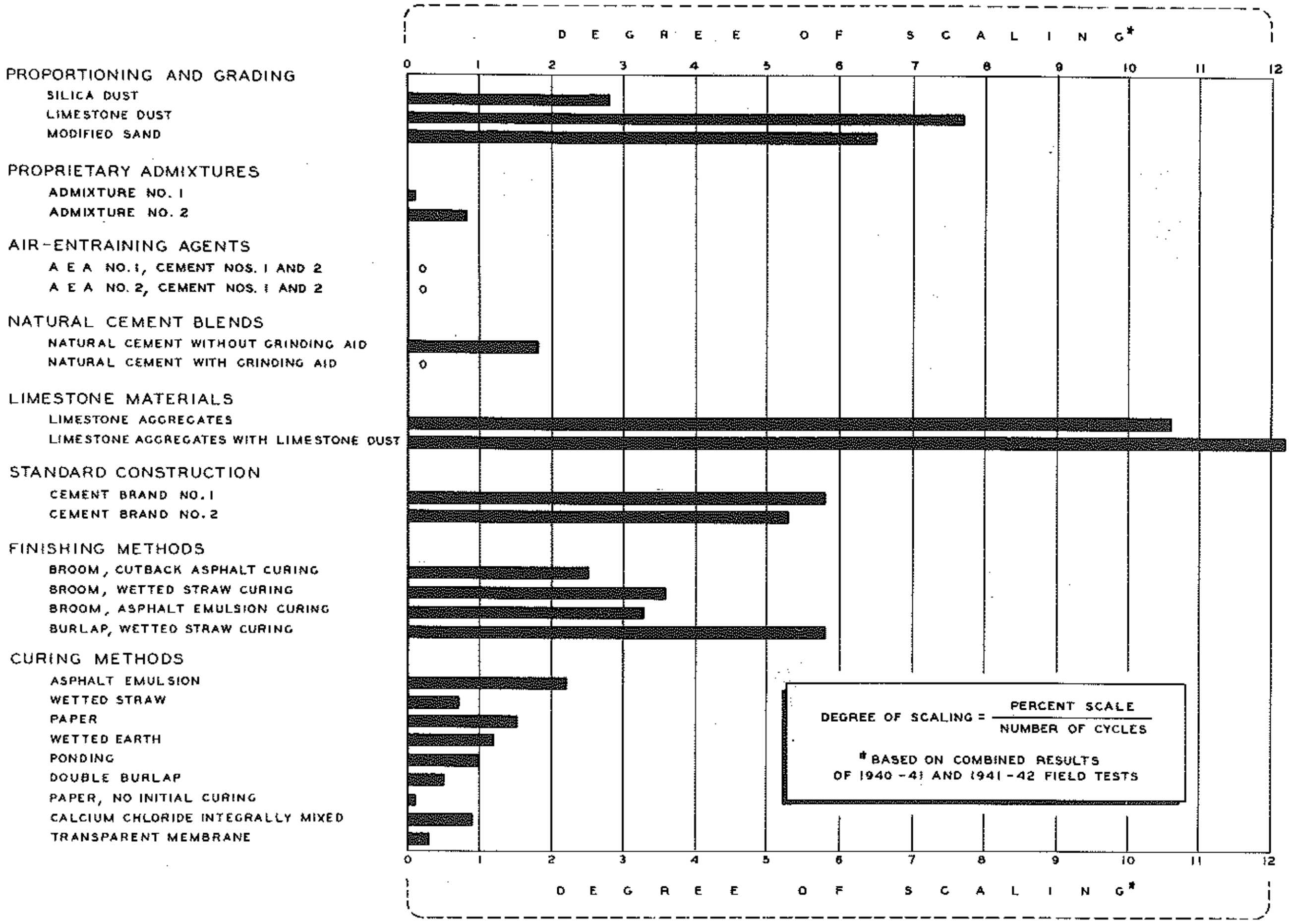


Figure 12. Scaling of experimental pavement sections in accelerated test.

Proprietary Admixtures. Of the two materials in this category Admixture No. 1 gave good results, two different panels showing only 6 percent scale in 93 cycles and 8 percent in 61 cycles, but Admixture No. 2 was less effective, the area developing 56 percent scale in 61 cycles. Both admixtures were much more effective than the mineral fillers in improving scale resistance, but less so than the air-entraining agents.

Air-Entraining Agents. Both of the air-entraining agents were outstanding in their ability to prevent scaling. The same result was achieved by both methods of air entrainment with both brands of cement. The beneficial effect of entrained air on the durability of concrete is now a well-established fact, but the results of these early tests strongly influenced the decision in 1943 to use air-entrained concrete in all Michigan pavements.

Natural Cement Blends. Concrete containing natural cement blended with portland scaled less than concrete with portland cement alone (Fig. 12). Moreover, in the section containing natural cement with a grinding aid no scaling was observed in the entire 2-yr test. Entrainment of air by the grinding aid was probably the most important element contributing to the scale resistance of this concrete.

Limestone Materials. Limestone aggregates were conducive to scaling and adding limestone dust to such mixtures tended to aggravate the condition rather than relieve it. Surface appearance at the end of the test may be seen in Fig. 11.

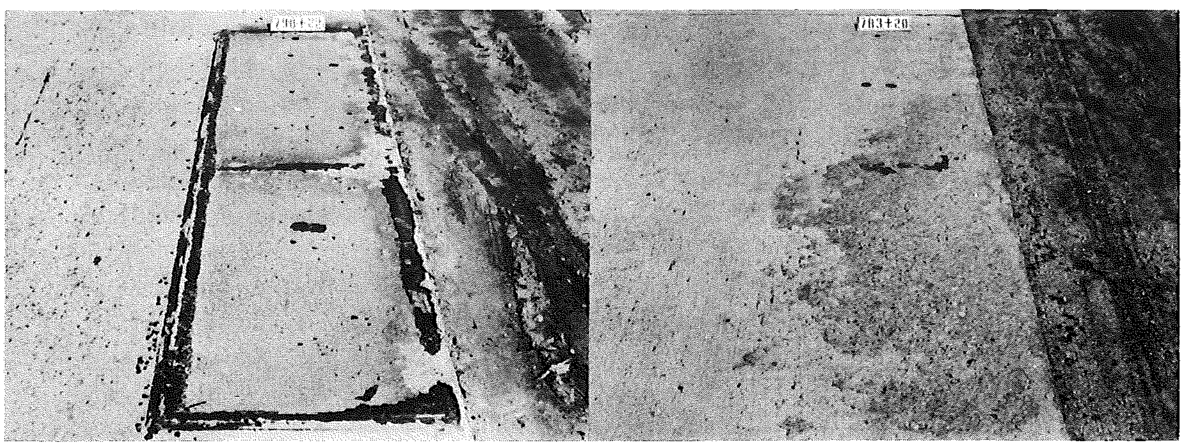
Standard Construction. The relative scale resisting properties of the two different cements are also shown in Fig. 12. In this instance there was little difference in the effects of the two brands on the scale resistance of their respective concretes. All panels of standard construction scaled over their entire surfaces after relatively few cycles of the accelerated test. A panel on concrete containing Cement No. 2 is shown in Fig. 11.

Finishing Methods. Finishing methods on standard concrete did not have a pronounced influence on durability in these tests (Fig. 12). Brooming apparently produced a more resistant surface than burlap finishing, but the difference was not marked. Furthermore, no significant advantage was gained by substituting bituminous membrane curing for standard curing methods on broomed concrete. However, cutback asphalt curing seemed to produce better results than asphalt emulsion. This result may have been due to the fact that the cutback was applied immediately after completion of finishing operations instead of after initial burlap curing. The final surface condition of a test panel on broomed concrete with standard wet straw curing is also shown in Fig. 11 for comparison with burlap finished concrete.

Curing Methods. Because of the many uncontrollable variables in field curing experiments it is difficult to determine the effect of various curing methods on concrete durability. Weather and the time of day when concrete is placed particularly tend to mask differences in behavior directly traceable to methods of curing. This is illustrated in the present instance by the fact that a slow rain started to fall when the paver was about halfway through the curing section and operations were suspended at 3 p.m. Almost the only conclusion which can be drawn from these tests is that the weather and extra care prompted by the emphasis on curing apparently benefited all subdivisions of the curing section compared to other sections of standard construction. Waterproof paper and transparent membrane seemed to benefit most from these conditions (Fig. 12). Other aspects and results of the curing study are presented and discussed more fully later in this report.

Rain-Marked Surface. In conjunction with the regular scaling studies, extra panels were installed on the Design Project to compare sections of pavement with and without a rain-marked surface. The panels were subjected to the same accelerated freezing and thawing tests as those on the Durability Project. Test results are included in Table 23 (App. B), and Fig. 13 illustrates the condition of the two panels at the end of the test. Cement No. 2 was used throughout the Design Project.

The rain-marked panel showed a much higher resistance to scaling than the panels on unmarked concrete. This interesting result was not entirely unexpected, the same effect having been observed previously in other pavements built with non-air-entrained concrete.



Rain-marked concrete, 61 cycles | Unmarked concrete, 9 cycles

Figure 13. Effect of rain marking of resistance to scaling.

LABORATORY FREEZING AND THAWING TESTS OF FIELD SPECIMENS

During construction of the pavement, samples of concrete from the various special sections were molded into beams for laboratory examination in conjunction with the scaling studies. These beams were subsequently subjected to accelerated tests to determine relative resistance to freezing and thawing as an indication of inherent durability. Progressive deterioration was measured by change in the value of Young's modulus found by the sonic method.

Preparation of Specimens

The concrete field specimens were molded into 3- by 6- by 15-in. beams. A series of cylindrical beams, 4 in. in diameter and 16 in. long, were also cast for comparison with the rectangular beams (Fig. 14). Specimens were rodded in two layers, struck off, and finished in the manner specified for standard concrete flexural specimens. The beams were cured in the field for 7 days in the same way as the concrete in the completed pavement. After the 7-day curing period, the beams were taken to the laboratory and stored in a moist room until time to begin the tests.

Two series of beams were subjected to freezing and thawing after moist storage for 5 mo and 1 yr respectively. All the cylindrical beams were included in the tests of the 5-mo beams. In addition, the specimens were tested for flexural and compressive strength at the termination of the freezing and thawing cycles.

Test Methods

The specimens were placed in specially designed rubber containers having a wall thickness of 3/16-in. Sufficient water was added to the containers to cover the specimens to a depth of 1/4-in. The ratio of water to concrete by weight was approximately 0. 11. The number of containers in any one freezing compartment and the quantity of liquid in the freezing bath were adjusted so that when the compartment was fully charged, the level of the freezing liquid was approximately equal to that of the water in the containers.

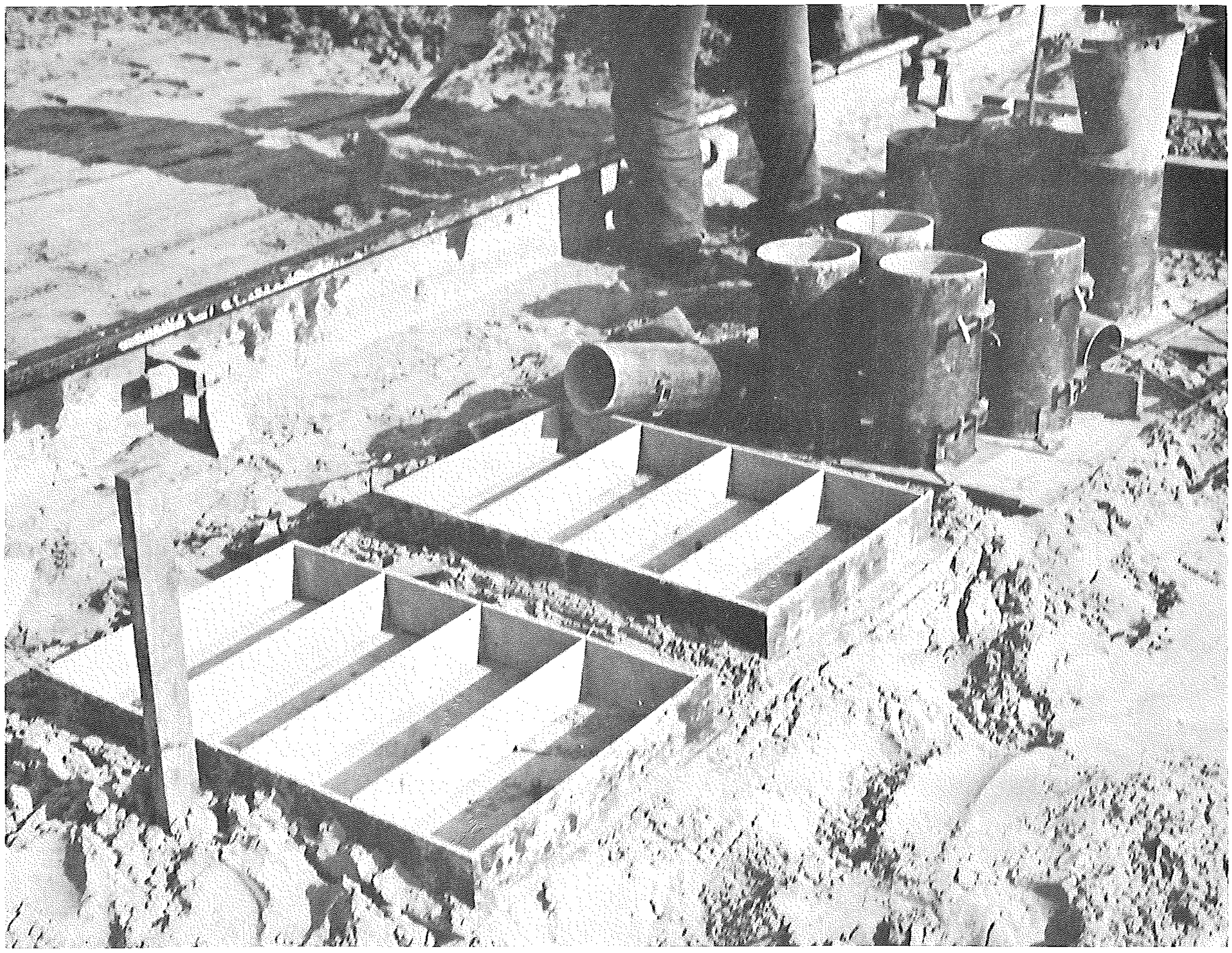


Figure 14. Steel molds ready for casting field specimens.

The freezing liquid was glycerin diluted with water. The rubber containers holding two specimens each were placed in the freezing compartment so that all sides of the containers were in contact with the freezing liquid and circulation of the liquid would not be impeded. A charge in each of two freezing compartments consisted of approximately 18 beams. Such a charge constituted about 75 percent of full load capacity of the freezing unit.

<u>Freezing and Thawing Cycle.</u> The specimens were placed in the freezing chamber in the afternoon, allowed to freeze overnight, and thawed the next morning. This procedure constituted a freezing and thawing cycle.

At the beginning of the cycle, the temperature of the freezing liquid was -20±2 F, rising to a maximum of 20 F under full load. The temperature upon removal of the specimens was approximately -10 F.

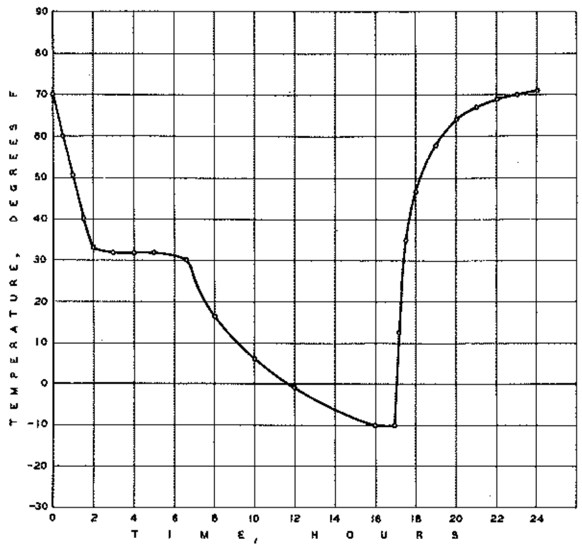


Figure 15. Freezing and thawing temperature cycle.

At the end of the freezing period, the containers were removed from the refrigerator and placed in a water bath at 90 to 100 F until the ice around the specimens melted completely. The water was then drained from the containers, the specimens turned end for end in the containers, and fresh tap water at approximately 80 F added to the proper level, after which the specimens were allowed to reach equilibrium in air at a room temperature of 75 F. Complete thawing required about 6 hr. The characteristics of this freezing and thawing cycle are illustrated in Fig. 15.

Method of Measuring Deterioration. At the beginning of the first freezing and thawing cycle, and at intervals of five cycles thereafter, the specimens were surface dried and tested for fundamental frequency by the dynamic, or sonic, method. Freezing and thawing were continued until the beams failed and had to be removed, or until the reduction in elastic modulus from the initial value had reached at least 90 percent. Upon termination of the freezing and thawing cycles, the intact specimens were tested in flexure to determine the corresponding decrease in modulus of rupture. The two pieces from the flexural test were then cut into 3-in. cubes for compressive tests.

Test Results

Freezing and thawing data are summarized in Table 24 (App. B) and presented graphically in Fig. 16. The table shows the average disintegration rate for the various concrete mixtures and the number of cycles required to reach both a 50- and 90-percent reduction in modulus. The

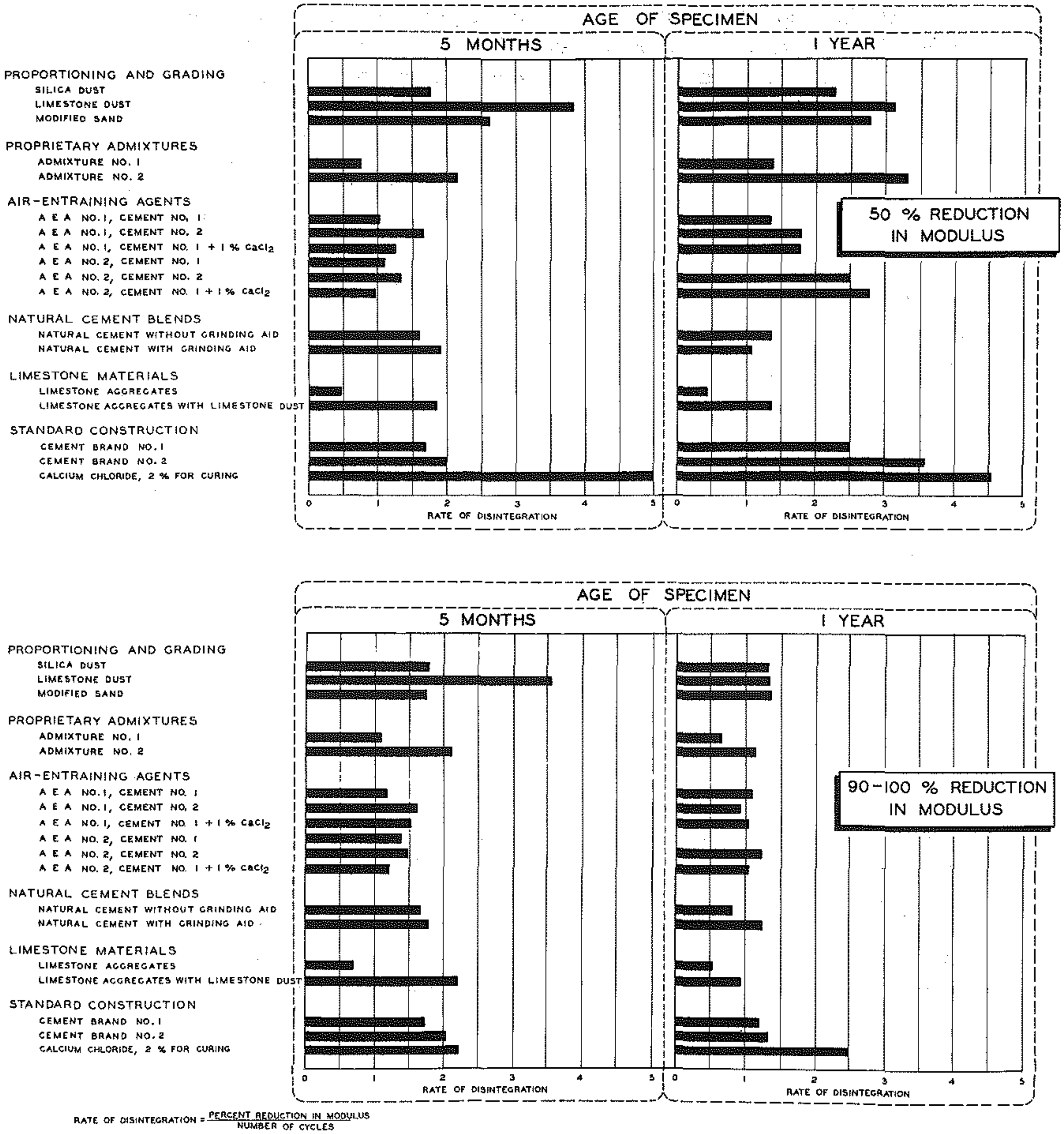


Figure 16. Rate of disintegration of field molded specimens by freezing and thawing in water.

table includes data for the rectangular beams only; the cylindrical specimens proved unsatisfactory for freezing and thawing studies and results for this group are not included. It should be pointed out here that many of the rectangular beams in this test failed prematurely by fracture because the maximum size of coarse aggregate in the field molded specimens was only slightly less than the smallest dimension of the beam. Consequently, the indicated differences in durability of the various mixtures are neither as clear-cut nor as significant as they would have been with thicker specimens or a smaller size of coarse aggregate in the concrete.

Proportioning and Grading. The concrete mixture containing limestone dust had a higher disintegration rate than mixtures containing either silica dust or natural fines. However, the rate of disintegration of all three mixtures was greater than that of standard concrete containing Cement No. 1.

Proprietary Admixtures. Of the two materials in this category, Admixture No. 1 performed better in this test and mixtures containing it were considerably superior to standard concrete. On the other hand, mixes containing Admixture No. 2 were no better than standard concrete, indicating a reversal of the results from the accelerated scaling study which showed a definitely beneficial effect for this admixture.

Air-Entraining Agents. Both air-entraining agents materially enhanced durability, although the margin of superiority over the standard mixtures was less than would normally be expected. The 1-percent calcium chloride addition had no noticeable adverse effect on the durability of air-entraining mixtures containing either agent.

Natural Cement Blends. In general, mixtures containing natural cement without beef tallow as a grinding aid exhibited greater durability than those with it. Again, this result was the opposite of that from the accelerated scaling tests.

Limestone Materials. Concrete containing limestone aggregates possessed outstanding ability to resist disintegration by freezing and thawing in this test (Table 24, App. B). Adding limestone dust to the mixtures containing limestone aggregates was definitely harmful, however, resulting in a marked reduction of durability.

Standard Construction. Concrete containing Cement No. 2 was slightly less resistant than that with Cement No. 1, but the difference was not significant.

Adding 2 percent of calcium chloride to the standard concrete mixture reduced resistance to freezing and thawing. Here again the results from this test did not agree with those from the accelerated scaling study.

Physical Properties of Tested Beams

After completion of the freezing and thawing cycles, the beams were tested for flexural and compressive strength. The third-point method of loading was used to determine flexural strength, and the two segments from each broken beam were then cut into 3-in. cubes, capped with plaster of paris, and broken in compression.

Data from these tests are given in Table 2. The values for percent loss of flexural strength were computed from the average 28-day flexural strengths of standard 6- by 8- by 36-in. field specimens cast from the same concrete used to make the sonic beams. Similarly, the values for percent loss in compressive strength are based on the average compressive strength of 6- by 12-in. field cylinders cured for 28 days.

The data show in general that the various admixtures had no harmful effects on the concrete (Table 2). However, the fact that many specimens failed prematurely in the freeze and thaw test is plainly manifested in the results of these strength tests which show an abnormally low ratio of loss in compressive strength to loss in flexural strength and dynamic modulus. This is especially true in the case of the air-entrained concretes, including the blend of natural cement containing a grinding aid.

Discussion

As mentioned earlier, this freezing and thawing study was undertaken to furnish additional information on the relative all-round durability of the various mixtures, with particular reference to general deterioration from freezing and thawing as opposed to surface scaling. Unfortunately, the specimens were made in a way now known to be conducive to premature failure in some instances. In spite of inconsistencies thus engendered, however, the accelerated scaling test and the laboratory freezing and thawing test evidently were evaluating quite different qualities of the concrete and produced correspondingly different results.

Unquestionably the accelerated scaling test was the more significant of the two. Strength tests of cores taken from the 10-yr-old pavement almost invariably indicated a considerable gain in compressive strength over the 28-day and 20-mo values, demonstrating that no general structural deterioration from freezing and thawing had occurred in any of the pavement sections. During this same interval, scaling had progressed so far in the two sections containing limestone aggregates that they had to be resurfaced in 1951 and 1952. Other sections of non-air-entrained concrete continued to scale progressively until the remainder of the project was resurfaced in 1957.

Another reason for the lack of correlation of the laboratory freezing and thawing test with either the accelerated scaling test or subsequent

TABLE 2
SUMMARY OF TEST DATA ON MOLDED SPECIMENS

Factor Studied	Original Dynamic Modulus psi	Loss, Percent		
		Dynamic Modulus	Flexural Strength	Compressive Strength
Proportioning and Grading				
Silica Dust	6.7×10^6	92	77	35
Limestone Dust	6.5	93	75	40
Modified Sand	6.8	95	86	40
Proprietary Admixtures				
Admixture No. 1	6.5	93	67	26
Admixture No. 2	7.1	85	86	53
Air-Entraining Agents				
AEA No. 1, Cement No. 1	5.8	94	64	10
AEA No. 1, Cement No. 2	5.9	93	71	14
AEA No. 1, Cement No. 1, + 1% $CaCl_2$	5.8	83	72	36
AEA No. 2, Cement No. 1	5.7	98	67	51
AEA No. 2, Cement No. 2	6.9	94	73	31
AEA No. 2, Cement No. 1, + 1% $CaCl_2$	5.2	95	84	0
Natural Cement Blends				
Without Grinding Aid	6.7	96	67	21
With Grinding Aid	6.1	93	76	7
Limestone Materials				
Limestone Aggregates	6.1	89	68	42
Limestone Agg. with Limestone Dust	5.9	93	67	56
Standard Construction				
Cement Brand No. 1	6.0	94	92	40
Cement Brand No. 2	6.4	94	81	54
$CaCl_2$, 2% for Curing	6.3	94	88	47

surface scaling is the fact that surface characteristics due to the construction operations of placing and finishing were not carried over at all in the molded specimens. In pavement concrete, differences in basic durability of the various mixtures were probably less significant than differences in surface vulnerability created by the effects of construction operations on mixtures composed of different materials and having different physical characteristics.

LABORATORY TESTS OF PAVEMENT CORES

In addition to the accelerated scaling studies and the freezing and thawing tests of molded field specimens, a laboratory study was also made to compare the durability of pavement cores from the various experimental sections. The core study had three objectives: 1) to gather additional data of significance in evaluating the factors under consideration; 2) to observe the relative durability of concrete at the top and bottom of the pavement slab; and 3) to determine the relative merits of freezing and thawing concrete in a calcium chloride solution and in tap water. Besides the freezing and thawing tests, specific gravity, absorption, and permeability were also determined to relate these properties to durability.

The cores were taken 4 mo after completion of pouring operations in conjunction with the Department's routine coring procedure for checking pavement thickness. Because of the large number of test areas sampled, only one core from each area was included in the freezing and thawing test. Companion cores from the same test areas were used to check pavement thickness and determine compressive strength. At the time of the tests the concrete was 21 mo old.

Freezing and Thawing Tests

Each core was cut transversely into three sections approximately 2 in. thick, representing the top, middle, and bottom of the pavement. The top and bottom sections were further divided into two equal segments. One segment from the top and bottom of each core was reserved for freezing and thawing in a 10-percent calcium chloride solution; the remaining segments from the same cores were frozen and thawed in tap water for comparison. The middle section was retained for absorption and permeability tests.

Test Procedure. The freezing and thawing cycle and equipment were the same as those used for the sonic beams described previously. Specimens subjected to the calcium chloride treatment were kept in the solution during the entire freezing and thawing cycle. The solution was checked for concentration after each five cycles and thoroughly agitated at the beginning of each freezing period.

At the end of each five or ten cycles the specimens were removed from the rubber containers, wiped off, and visually examined for evidence of surface scaling and failure of bond between mortar and aggregate. The visual inspection was supplemented by noting the sound or ring when the specimen was struck lightly with a hammer. The test was continued to the point where the specimen either had totally disintegrated or could be broken apart easily by light tapping with a hammer.

Results and Discussion. The freezing and thawing cycles necessary for complete disintegration (100-percent failure) of each specimen are summarized in Tables 3 and 4 together with specific gravity values for the top and bottom core segments. Disintegration rates are shown in Figure 17.

Because specimen size and shape did not permit exact measurement of deterioration by the sonic method, only a qualitative rather than a quantitative evaluation of the various factors was possible. Nevertheless there were several well-defined indications bearing on the three objectives of the test.

First, the concretes containing purposefully entrained air were the most resistant to disintegration from freezing and thawing either in tap water or calcium chloride solution. Concretes made with Admixture No. 1, Air-entraining Agents Nos. 1 and 2, and natural cement with grinding aid are in this category. None of the other mixtures showed improvement over standard concrete in this test.

Another significant finding was that, except for the air-entrained concretes, the core tops were less durable than the bottoms (Fig. 17). This was true for either method of freezing and thawing. In nearly all cases, cores from the air-entrained concretes, including those containing Admixture No. 1 and natural cement with grinding aid, exhibited practically equal durability of top and bottom sections. In 1940, W. C. Hansen (10) reported a comprehensive study of pavement cores from non-air-entrained concretes in which he found that surface scaling was associated with a lack of uniformity of the concrete from top to bottom of the slab. At that

TABLE 3
SUMMARY OF CORE DURABILITY STUDY
Freezing and Thawing in Water

Factor Studied	Core No.	Cement Brand	b/b_o	Cycles for Disintegration			Specific Gravity		
				Top	Bottom	% Var.	Top	Bottom	Var.
Proportioning & Grading									
Silica Dust	241A	1	0.76	135	135	0	2.47	2.50	-.03
Silica Dust	242	1	0.80	90	135	-33	2.46	2.49	-.03
Limestone Dust	246	1	0.80	135	200	-33	2.46	2.48	-.02
Modified Sand	250	1	0.80	50	60	-17	2.48	2.51	-.03
Proprietary Admixtures									
Admixture No. 1	215	1	0.80	200	155	+29	2.44	2.51	-.07
Admixture No. 2	217A	1	0.76	135	190	-29	2.49	2.51	-.02
Admixture No. 2	218	1	0.80	135	135	0	2.54	2.47	+.07
Air-Entraining Agents									
AEA No. 1	220	1	0.80	205	205	0	2.46	2.46	.00
AEA No. 1	223	2	0.80	110	200	-45	2.48	2.46	+.02
AEA No. 2	225A	1	0.76	175	170	+ 3	2.41	2.41	.00
AEA No. 2	227	1	0.80	200	200	0	2.41	2.39	+.02
AEA No. 2	229A	2	0.76	205	200	+ 3	2.48	2.49	-.01
AEA No. 2	230	2	0.80	215	200	+ 8	2.46	2.50	-.04
Natural Cement Blends									
Nat. Cem. without Grind. Aid	234	1	0.80	135	145	- 7	2.46	2.52	-.06
Nat. Cem. with Grind. Aid	237	1	0.80	195	120	+63	2.44	2.44	.00
Limestone Materials									
Limestone Aggregates	255	1	0.76	135	205	-34	2.44	2.45	-.01
Limestone Agg. with Limestone Dust	253	1	0.76	50	155	-68	2.44	2.50	-.06
Standard Construction									
Cement Brand No. 1	228	1	0.76	120	135	-11	2.48	2.50	-.02
Cement Brand No. 1	243	1	0.76	120	195	-38	2.46	2.52	-.06
Cement Brand No. 1	247	1	0.76	135	170	-21	2.47	2.51	-.04
Cement Brand No. 1	251	1	0.76	135	200	-33	----	----	----
Cement Brand No. 2	224	2	0.76	80	110	-27	2.48	2.53	-.05
Cement Brand No. 2	232	2	0.76	70	135	-48	2.50	2.51	-.01
Finishing Methods									
Broom, Asph. Emulsion Curing	204	1	0.76	110	135	-19	2.49	2.50	-.01
Curing Methods									
Asphalt Emulsion	205	1	0.76	80	200	-60	2.47	2.49	-.02
Wetted Straw	206	1	0.76	60	155	-61	2.47	2.51	-.04
Paper with Initial Curing	207	1	0.76	155	155	0	2.50	2.52	-.02
Wetted Earth	208	1	0.76	60	135	-56	2.47	2.52	-.05
Ponding	209	1	0.76	70	170	-59	2.47	2.48	-.01
Double Burlap	210	1	0.76	80	50	+60	2.48	2.43	+.05
Paper, No Initial Curing	211	1	0.76	100	185	-46	2.49	2.50	-.01
Membrane with Initial Curing	213	1	0.76	110	80	+38	2.48	2.48	.00

TABLE 4

SUMMARY OF CORE DURABILITY STUDY

Freezing and Thawing in 10-Percent $CaCl_2$ Solution

Factor Studied	Core No.	Cement Brand	b/b_o	Cycles for Disintegration			Specific Gravity		
				Top	Bottom	% Var.	Top	Bottom	Var.
Proportioning and Grading									
Silica Dust	241A	1	0.76	75	100	-25	2.44	2.49	-.05
Silica Dust	242	1	0.80	55	130	-58	2.45	2.47	-.02
Limestone Dust	246	1	0.80	50	70	-29	2.46	2.48	-.02
Modified Sand	250	1	0.80	20	25	-20	2.47	2.54	-.07
Proprietary Admixtures									
Admixture No. 1	215	1	0.80	186	176	+ 6	2.42	2.52	-.10
Admixture No. 2	217A	1	0.76	60	65	- 8	2.51	2.51	.00
Admixture No. 2	218	1	0.80	95	55	+73	2.54	2.50	+.04
Air-Entraining Agents									
AEA No. 1	220	1	0.80	140	206	-32	2.43	2.46	-.03
AEA No. 1	223	2	0.80	55	130	-58	2.51	2.45	+.06
AEA No. 2	225A	1	0.76	145	186	-22	2.38	2.46	-.08
AEA No. 2	227	1	0.80	186	165	+13	2.37	2.43	-.06
AEA No. 2	229A	2	0.76	130	165	-21	2.48	2.48	.00
AEA No. 2	230	2	0.80	130	145	-10	2.45	2.44	+.01
Natural Cement Blends									
Nat. Cem. without Grind. Aid	234	1	0.80	75	165	-55	2.46	2.49	-.03
Nat. Cem. with Grind. Aid	237	1	0.80	186	201	- 7	2.41	2.45	-.04
Limestone Materials									
Limestone Aggregates	255	1	0.76	60	186	-68	2.43	2.47	-.04
Limestone Agg. with Limestone Dust	253	1	0.76	35	105	-67	2.43	2.49	-.06
Standard Construction									
Cement Brand No. 1	228	1	0.76	45	65	-31	2.49	2.50	-.01
Cement Brand No. 1	243	1	0.76	35	78	-55	2.44	2.48	-.04
Cement Brand No. 1	247	1	0.76	55	176	-69	2.47	2.49	-.02
Cement Brand No. 1	251	1	0.76	45	155	-71	2.48	2.48	.00
Cement Brand No. 2	224	2	0.76	50	35	+43	2.52	2.53	-.01
Cement Brand No. 2	232	2	0.76	45	70	-36	2.48	2.51	-.03
Finishing Methods									
Broom, Asph. Emulsion Curing	204	1	0.76	60	100	-40	2.49	2.50	-.01
Curing Methods									
Asphalt Emulsion	205	1	0.76	50	155	-68	2.47	2.49	-.02
Wetted Straw	206	1	0.76	50	110	-55	2.47	2.52	-.05
Paper with Initial Curing	207	1	0.76	60	155	-61	2.50	2.52	-.02
Wetted Earth	208	1	0.76	35	110	-68	2.47	2.52	-.05
Ponding	209	1	0.76	50	85	-41	2.47	2.48	-.01
Double Burlap	210	1	0.76	50	25	+100	2.48	2.43	+.05
Paper, No Initial Curing	211	1	0.76	75	110	-32	2.49	2.50	-.01
Membrane with Initial Curing	213	1	0.76	45	130	-65	2.48	2.48	.00

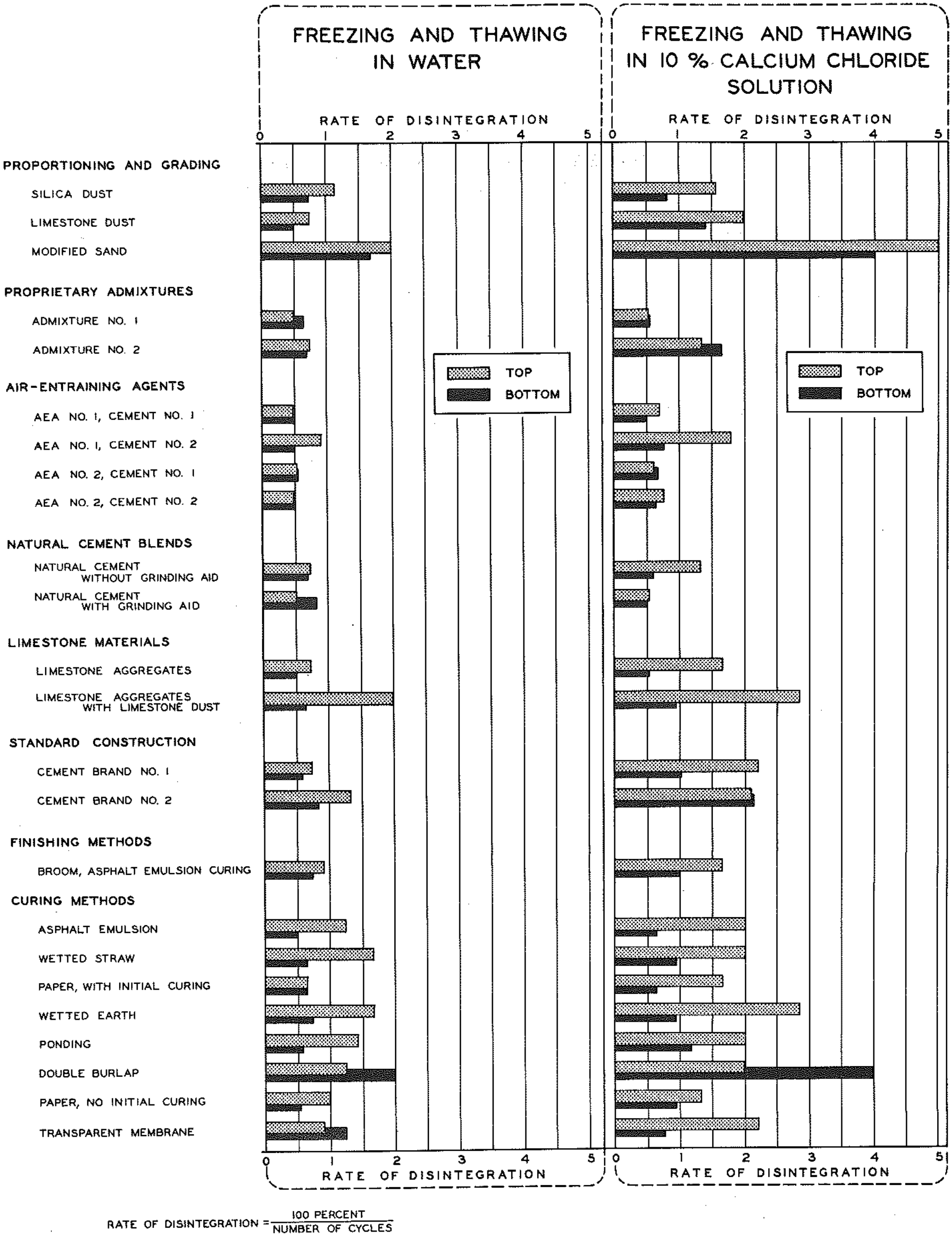
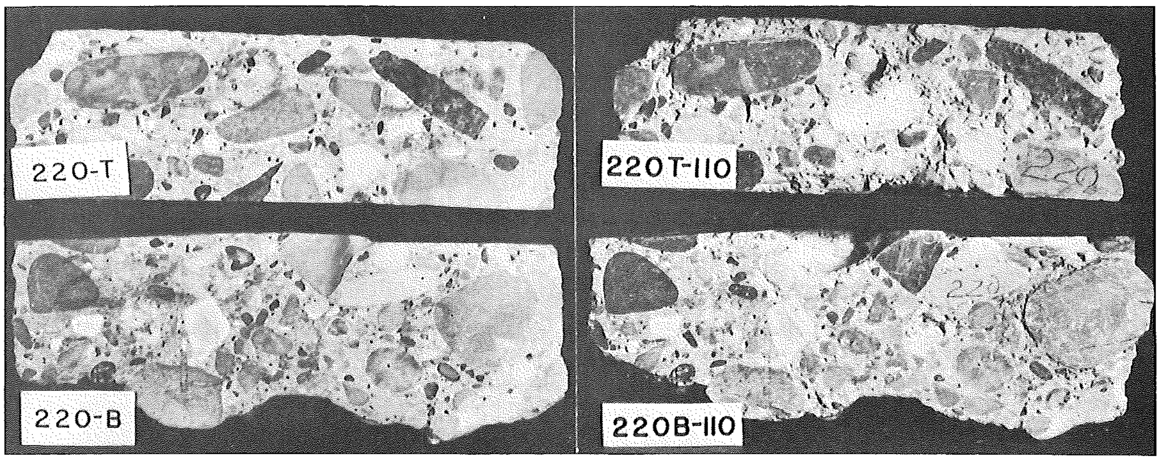


Figure 17. Rate of disintegration of core specimens by freezing and thawing.

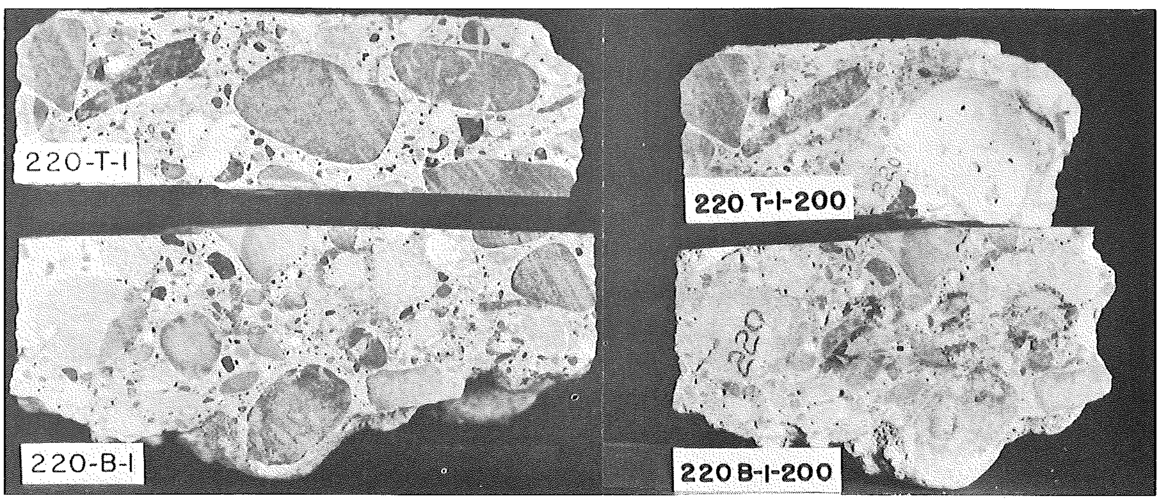
time air entrainment had not come into general use and he attributed the lack of durability of the top portion to bleeding and segregation resulting from placing and finishing high-slump mixtures. Measurements of specific gravity and absorption supported this view. From the study of cores from the Durability Project, it seems probable that the increased resistance of the air-entrained concretes to surface scaling was due in part to the greater uniformity brought about by a reduction of bleeding and segregation, as well as the effect of the air bubbles themselves on frost resistance explained in recent years by Powers and others (11-16).

The results shown in Fig. 17 also indicate that the less durable concretes deteriorated much more rapidly in the calcium chloride brine than in water. For the air-entrained concretes the difference in the rate of disintegration in water and in brine was considerably less, indicating that freezing and thawing in the salt solution tended to accentuate intrinsic differences in durability of the various mixtures. Even the air-entrained concretes, however, seemed to break down differently in the two freezing media. Those frozen in brine were characterized by a progressive crumbling of the mortar, while those frozen in water failed by a general structural breakdown, as illustrated in Fig. 18. The two sets of specimens are opposite halves of the top and bottom slices of a core from the section containing AEA No. 1. The pair at the top of the figure was frozen in a 10-percent calcium chloride solution and the pair at the bottom in plain water. The difference in behavior shown in these photographs was also noted for all the other specimens in various degrees.

A recent study by Verbeck and Klieger (15) has confirmed the earlier discovery by Arnfelt (17) that relatively dilute solutions (2 to 4 percent) of calcium chloride are more destructive than either more concentrated ones or plain water during freezing and thawing. From the fact that they were able to produce comparable scaling with organic antifreezing agents such as urea and ethyl alcohol, the same authors (15) also conclude that the mechanism of scaling is primarily physical rather than chemical. Their results, however, show a sharp rise in destructive effect of the 16-percent $CaCl_2$ solution over those of lower concentration on both air-entrained and non-air-entrained concretes after about 75 cycles of freezing and thawing. A similar rise did not occur when sodium chloride, urea, and ethyl alcohol were used as de-icing agents. Furthermore, in our own laboratory, thin plates of mortar and concrete have spontaneously disintegrated in a few weeks when stored continuously in a 30-percent calcium chloride solution at room temperature. That there is a chemical as well as a physical action seems certain (4, 18). Apparently more study is needed to explain the effect of chemical de-icers on both the constituents and the structure of concrete during freezing and thawing.



Core No. 220 before and after 110 cycles
in 10-percent calcium chloride solution



Core No. 220 before and after 200 cycles in water

Figure 18. Effects of freezing and thawing
in calcium chloride solution and in water.

Results from the various accelerated tests are compared with actual pavement performance in Table 5. Whatever the mechanism of attack may be, the rate of disintegration of the core tops in calcium chloride solution paralleled fairly closely the rate of scaling of the various mixtures in the accelerated scaling tests and the subsequent performance of the pavement itself. Results of freezing and thawing the cores in water were not as closely related to actual performance. On the whole, freezing and thawing in calcium chloride solution proved to be a more significant and discriminating test than freezing and thawing in water.

Specific Gravity

Bulk specific gravity, saturated basis, was determined by the procedure given in ASTM Method C 127 for coarse aggregate, except that the specimens were saturated by immersion in water for at least 48 hr. Specific gravity values for the core segments subjected to the freezing and thawing tests were given in Tables 3 and 4. A complete summary may be found in Table 25 (App. B).

Referring again to Tables 3 and 4, there is evidently a significant relation between density and durability of the non-air-entrained concretes--the higher the specific gravity, the greater the durability. With few exceptions, bottom segments having specific gravities higher than the corresponding top segments showed greater resistance to freezing and thawing. This is true for either method of freezing and thawing.

In the case of concretes containing air-entraining agents, whose effectiveness depends on the formation of small, well-distributed air voids, the situation was reversed, with the less dense segments showing greater durability.

Absorption

The standard procedure for determining absorption was modified in these tests to give information on the rates of both absorption and drying as well as total amounts of water gained and lost. Specimens for the test were the center sections of the same cores represented in the freezing and thawing study. These core sections had reached an air dry-moisture equilibrium after storage for 2 yr in the laboratory atmosphere. After initial weighing they were dried at a temperature of 230 F until the moisture loss became less than 0.1 percent per day. At the end of the drying period, the specimens were immediately immersed in distilled water at 70-75 F and surface-dry weights recorded at intervals of 1/2, 1, 3, 6,

TABLE 5
COMPARISON OF ACCELERATED TEST RESULTS WITH PAVEMENT PERFORMANCE

Factor Studied	Rate of Disintegration[1]					Degree of Scaling[2]	Percent Scale.
	Pavement Cores				5 Mo. Beams		
	Freeze & Thaw in Water		Freeze & Thaw in 10% $CaCl_2$		Freeze & Thaw In Water 90-100% Reduction	Accelerated Scaling Tests	Pavement 1955
	Top	Bottom	Top	Bottom			
Proportioning and Grading							
Silica Dust	1.13	0.74	1.58	0.89	1.79	2.7	6
Limestone Dust	0.74	0.50	2.00	1.43	3.57	7.7	6
Modified Sand	2.00	1.67	5.00	4.00	1.75	6.5	38
Proprietary Admixtures							
Admixture No. 1	0.50	0.65	0.54	0.57	1.10	0.1	0
Admixture No. 2	0.74	0.69	1.36	1.68	2.13	0.8	0
Air-Entraining Agents							
AEA No. 1, Cement No. 1	0.49	0.49	0.71	0.49	1.19	0.0	0
AEA No. 1, Cement No. 2	0.91	0.50	1.82	0.77	1.61	0.0	0
AEA No. 2, Cement No. 1	0.54	0.55	0.62	0.58	1.37	0.0	0
AEA No. 2, Cement No. 2	0.48	0.50	0.77	0.65	1.49	0.0	0
Natural Cement Blends							
Nat. Cem. without Grind. Aid	0.74	0.69	1.33	0.61	1.67	1.8	1
Nat. Cem. with Grind. Aid	0.51	0.83	0.54	0.50	1.79	0.0	0
Limestone Materials							
Limestone Aggregates	0.74	0.49	1.67	0.54	0.70	10.6	70[3]
Limestone Agg. with Limestone Dust	2.00	0.65	2.86	0.95	2.22	12.2	90[4]
Standard Construction							
Cement Brand No. 1	0.79	0.57	2.22	1.03	1.72	5.8	8
Cement Brand No. 2	1.33	0.83	2.11	2.15	2.04	5.3	6
Finishing Methods							
Broom, Cutback Asph. Curing						2.5	1
Broom, Wetted Straw Curing						3.6	4
Broom, Asph. Emulsion Curing	0.91	0.74	1.67	1.00		3.3	2
Burlap, Wetted Straw Curing						5.8	8
Curing Methods							
Asphalt Emulsion	1.25	0.50	2.00	0.65		2.2	10
Wetted Straw	1.67	0.65	2.00	0.95		0.7	7
Paper, with Initial Curing	0.65	0.65	1.67	0.65		1.5	8
Wetted Earth	1.67	0.74	2.86	0.95		1.2	10
Ponding	1.43	0.59	2.00	1.18		1.0	9
Double Burlap	1.25	2.00	2.00	4.00		0.5	10
Paper, No Initial Curing	1.00	0.54	1.33	0.95		0.1	3
$CaCl_2$, Integrally Mixed						0.9	9
Transparent Membrane	0.91	1.25	2.22	0.77		0.3	8

(1) Rate of Disintegration = $\frac{\text{Percent Reduction}}{\text{Number of Cycles}}$

(2) Degree of Scaling = $\frac{\text{Percent Scale}}{\text{Number of Cycles}}$

(3) Condition in 1950, Resurfaced in 1952

(4) Condition in 1950, Resurfaced in 1951

12, 24, and 96 hr from the beginning of the saturation period. At 96 hr the absorption was practically complete, less than 0.2 percent of moisture being taken up after the first 24 hr.

A summary of the data is presented in Table 26 (App. B) and in Fig. 19. The rate of change of moisture content during the drying period is expressed as percent of the original moisture lost per hour for successive intervals from the initial air-dried to the oven-dried condition. Similarly, the average absorption rate during each interval from the oven-dried to the saturated state is expressed as percent of the total absorption per hour.

Although the results show a fairly general relationship between absorption and resistance to freezing and thawing in water, the test did not give a reliable indication of durability. The concretes containing added fines, such as silica dust, limestone dust, and modified sand, had the highest absorption and proved to be the poorest in the freezing and thawing test. On the other hand, it is quite evident that the remarkable durability of concretes containing air-entraining agents did not depend on their absorption characteristics. Numerous examples among the test specimens show that standard concrete mixtures with absorption values equal to or less than those of the air-entrained concretes failed to match the latter in resistance to freezing and thawing in water. The presence of chlorides during the freezing and thawing treatment makes the relationship more complex by introducing additional chemical and physical phenomena into the process.

In some instances the behavior of the specimens during the drying period sheds additional light on the physical characteristics of the concrete that probably affect its durability. From Table 26 (App. B) it is evident that there was a considerable variation among the different concrete specimens in the amount of water present in the air-dry condition. In general, those specimens with the lower initial moisture content gave up this moisture at a noticeably greater rate during the early stages of the drying period. This difference in behavior was not always reflected in the values obtained for total absorption. For example, in the first group of specimens, which represent the proportioning and grading phase of the study, it may be noticed that while the total absorption covers a range of only 4.26 to 4.42 percent by weight, there was a wide difference in initial moisture content and rate at which these specimens lost weight during the first 6 hr of drying. During this period the modified sand specimen, with only 1.44 percent of initial moisture, lost nearly 75 percent of the total originally present, while the silica dust specimen with

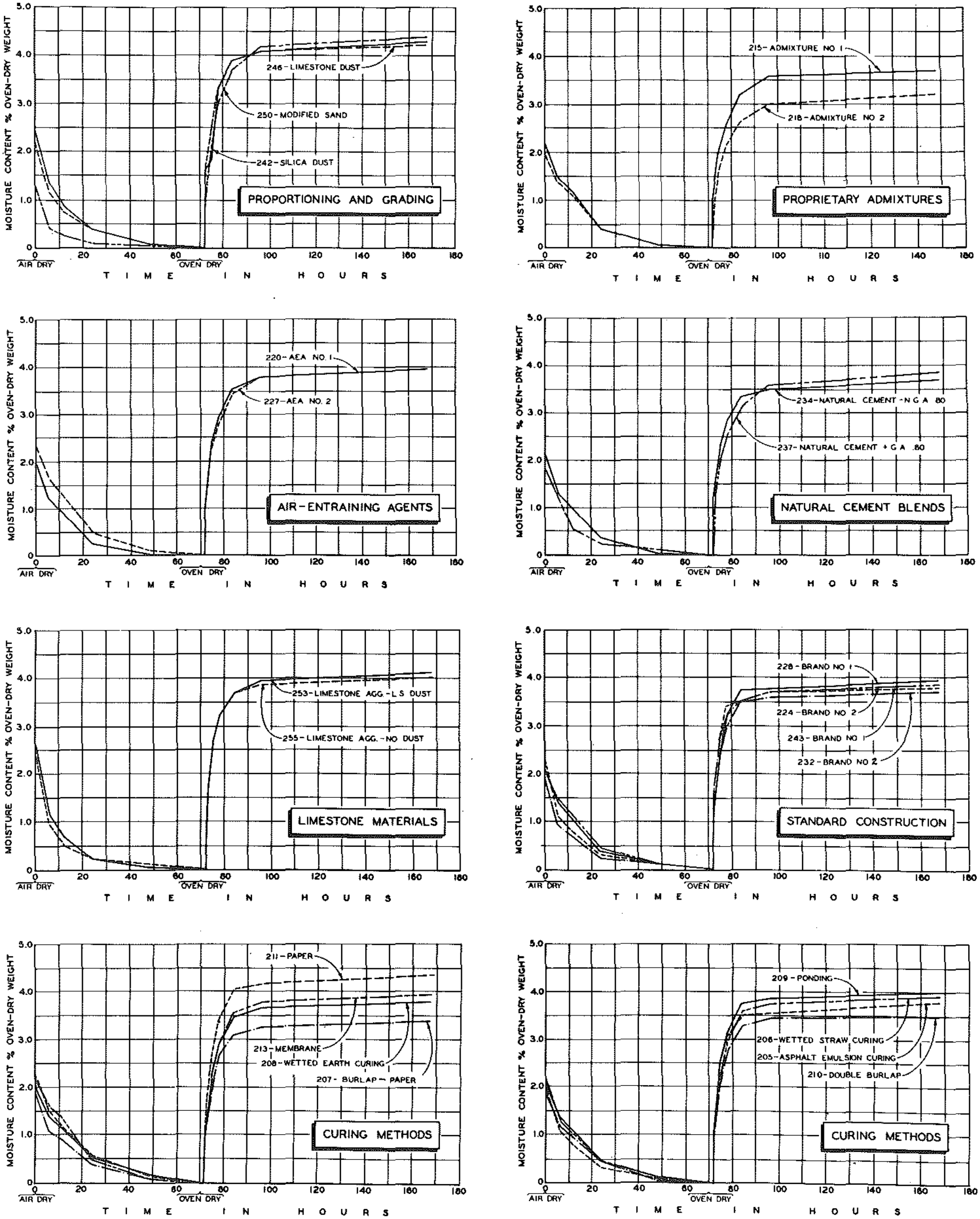


Figure 19. Rate of absorption of pavement cores.

2.45 percent gave up only slightly more than 45 percent of its moisture during the same period.

At the time the tests were performed it seemed reasonable that differences such as these would indicate the relative porosity or permeability of the various concrete mixtures, and perhaps point the way to some further application of this test to the analysis and interpretation of durability phenomena. Since that time, tests similar in principle but much more precise and refined in technique have thrown considerable light on the structure and properties of portland cement paste, mortar, and concrete, and their relation to durability. The works of Powers and Brownyard (13), Pickett (19), Verbeck and Klieger (15, 16), Blaine, Hunt and Tomes (20), and others (21, 22) are examples of the useful and practical application of the principles of mechanics, thermodynamics, and physical chemistry to study of the properties and behavior of concrete.

Permeability

As a further aid in interpreting the results of the durability study an attempt was made to determine the relative permeability of 15 core sections used in the absorption study. The procedure was similar to one used by Dunagan (23) and was limited to the measurement of water passage by capillarity and evaporation, no attempt being made to evaluate a permeability coefficient for viscous flow or vapor diffusion.

The center sections, which were 2-1/2 to 3 in. thick and about 5-3/4 in. in diameter, were first sealed in metal collars with the top surface flush with the upper rim of the collar. The disks were supported on the bottom by cutting four strips in the collar up to the lower face of the core and bending the strips inward at right angles. Core and collar were then placed in flat, water-tight metal containers with a circular opening cut in the top to receive the collar in a snug fit. The joint between collar and container was then soldered, the pan filled with water to the level of the inlet which was then closed by means of a screw plug, and the entire assembly sealed at all joints with three coats of orange shellac. In a complete assembly, the lower face of the core was in direct contact with the water in the pan (Fig. 20). After initial weighing, the specimens were placed in a cabinet maintained at 90 to 100 F and 40 to 45 percent relative humidity, with a fan to maintain a more rapid and uniform rate of evaporation from the core surfaces. Moisture loss was measured by daily weighings to the nearest gram for 40 days.

Results of the study, presented in Table 27 (App. B) and Fig. 21, show only a rough correlation with those of the durability tests. Again it must be admitted that the method used here was crude compared to more recent techniques devised to study pore structure. Moreover, permeability is a much more elusive property to define and evaluate than absorptivity and, like absorptivity, is influenced by many factors. For further discussion of the significance of concrete properties related to pore structure, the reader is referred to an excellent treatment of this subject by Verbeck (24).

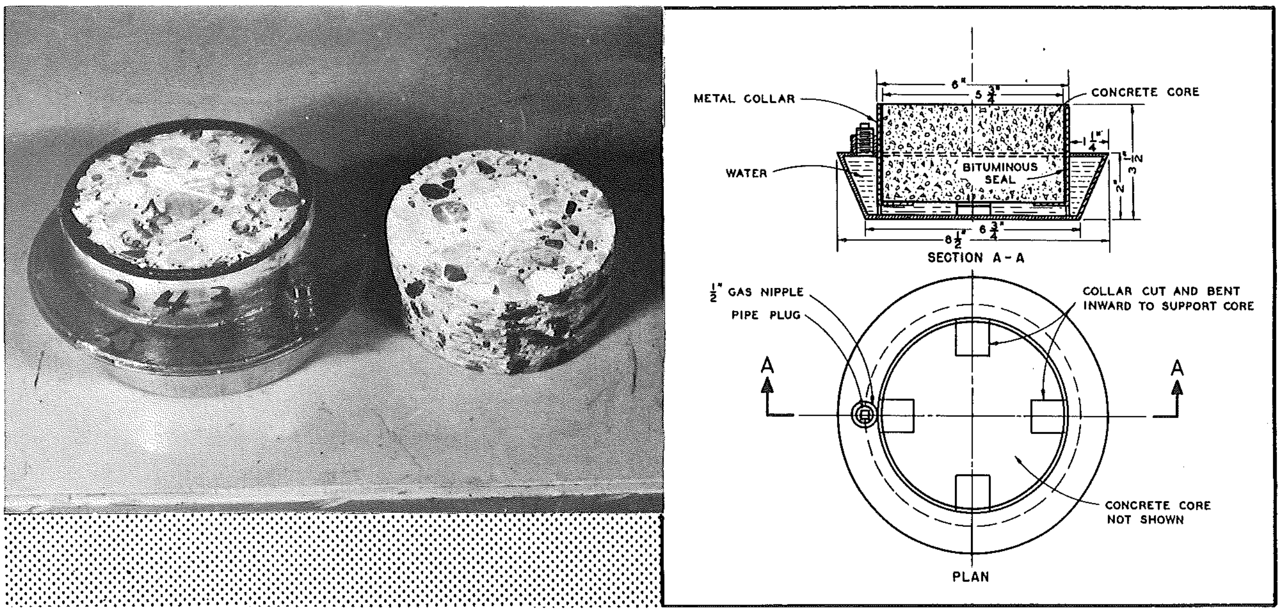


Figure 20. Permeability assembly.

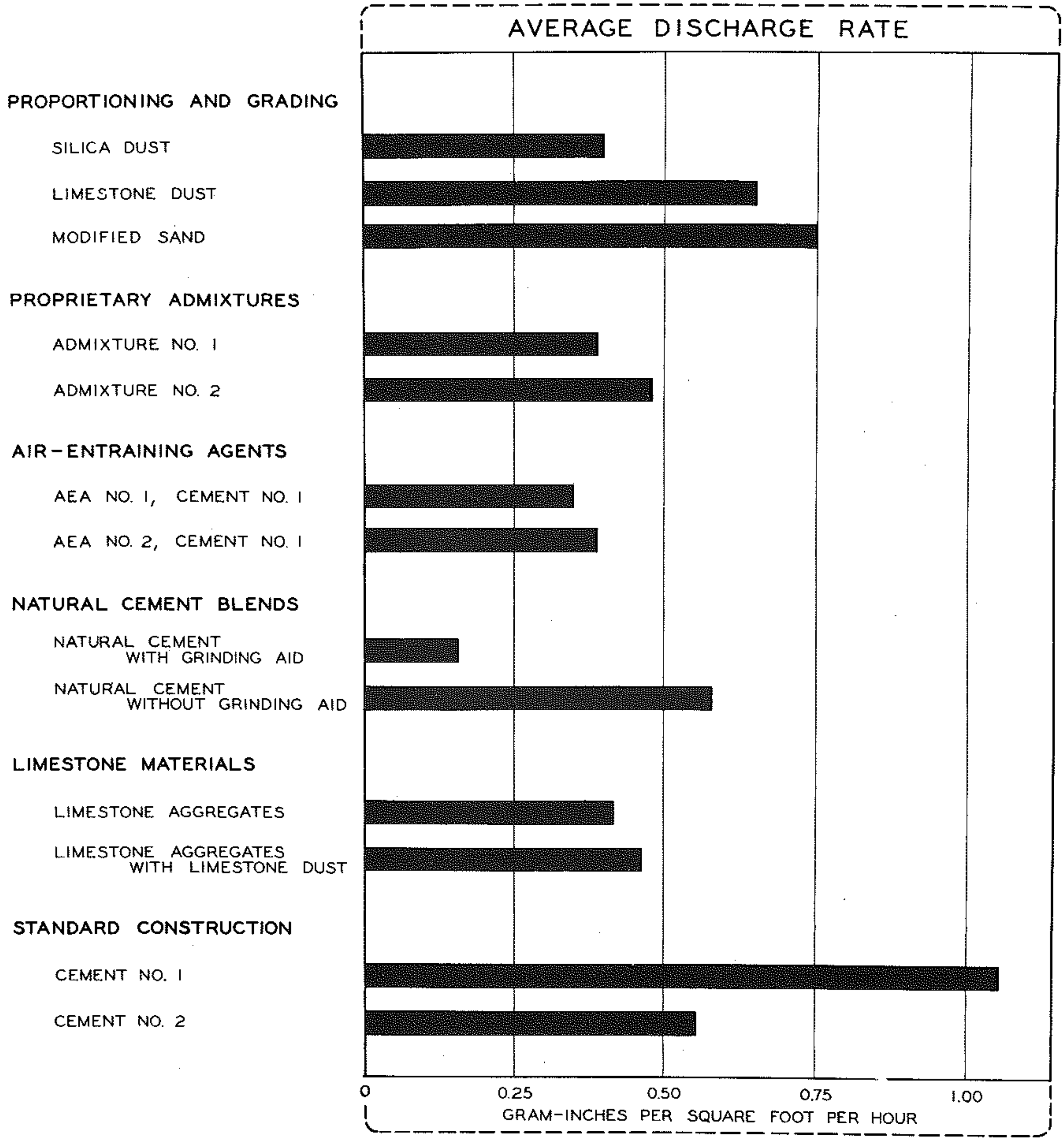


Figure 21. Rate of water passage through core sections.

INCIDENTAL STUDIES

In conjunction with the durability studies just described, various observations and additional tests were made to provide data useful in evaluating the different elements of the project. These incidental studies included physical characteristics of the fresh concrete, mechanical analysis of fresh concrete, setting time of concrete, strength and elastic modulus, curing, pavement roughness, and concrete volume changes.

Physical Characteristics of Fresh Concrete

During paving operations all of the various mixtures were observed to note such characteristics as consistency, workability, segregation, bleeding, and ease of finishing. Slump cone tests were made at intervals to check consistency. The specified slump for this project was 1 to 3 in. Slump cone readings are given in Table 28 (App. B), arranged as an ungrouped frequency distribution of values in increments of 1/4 in. A grouped frequency distribution in 1/2-in. cells is shown in Fig. 22. These data indicate that slump varied from 0 to 5-1/4 in. with more than 90 percent of the values falling within specification limits.

Even with fresh concretes of the same consistency as measured by the slump test there were marked differences in the way the various mixtures reacted to placing and finishing operations. For example, certain mixtures tended to bleed excessively, others were harsh and hard to work, while still others were buttery and easily finished. Since these qualities affect scale resistance of the hardened concrete, the characteristics of the various mixtures will be described in some detail.

Proportioning and Grading. Adding mineral fillers, silica dust, limestone dust, and natural fines produced mixtures more plastic than standard concrete yet possessing excellent workability. A typical example of the unusual plasticity of a concrete mix with added fines is shown in Fig. 23. Finishing and surface characteristics of the three concrete mixtures were similar. Very little bleeding was observed. When bleeding did occur, it was confined to local areas and probably due to variations in water content of the mix. The added fines produced a thin layer of buttery mortar which gave a fine texture to the surface but varied considerably in consistency depending on water content.

While fines contribute greatly to workability and good placement, it was discovered in preliminary tests that the mortar content could be decreased when certain admixtures were used and still maintain good workability and satisfactory finishing characteristics. During construction this observation was verified. Mixtures containing added fines suffered no noticeable reduction in workability when the coarse aggregate ratio, b/b_o, was increased from 0.76 to 0.80. Mixtures containing air-entraining agents and the proprietary admixtures began to appear slightly harsh when the coarse aggregate content was increased, but workability and finishing were still satisfactory. It will be seen later that changing the coarse aggregate ratio did not consistently affect either strength or durability.

Proprietary Admixtures. Admixture No. 1 had a different effect on the fresh concrete mixture than either the added fines or the air-entraining agents. The mix was decidedly gelatinous, with a high resistance to dis-

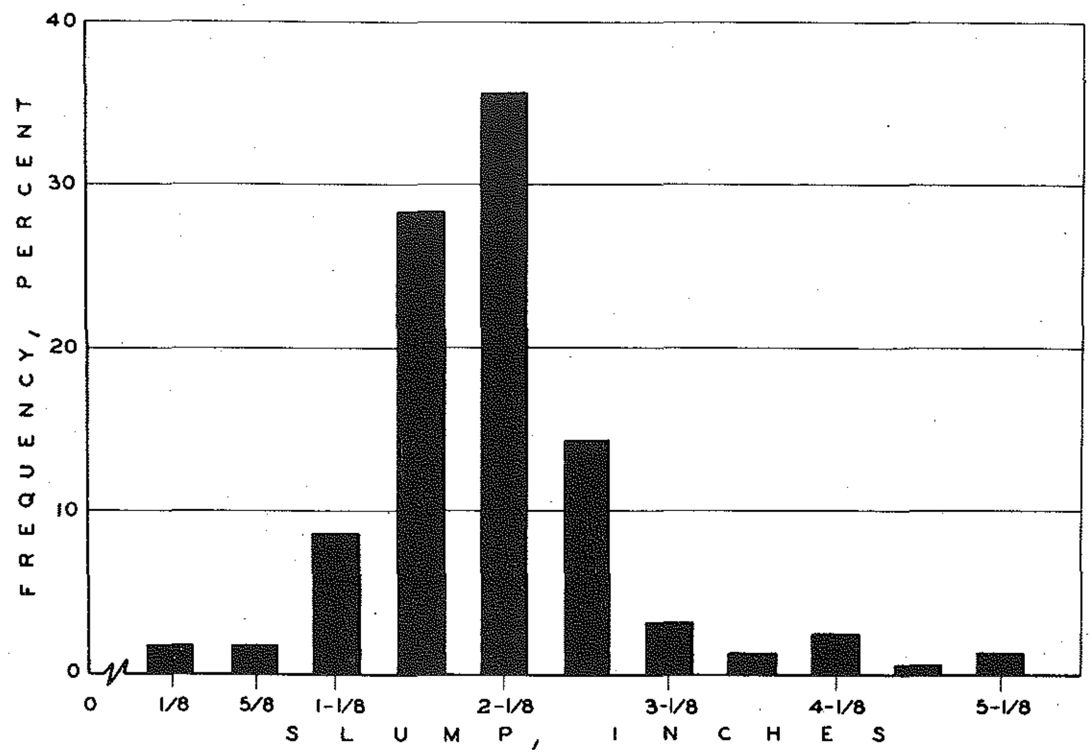


Figure 22. Grouped frequency distribution of slump values.

Figure 23. Typical appearance of concrete containing added fines.

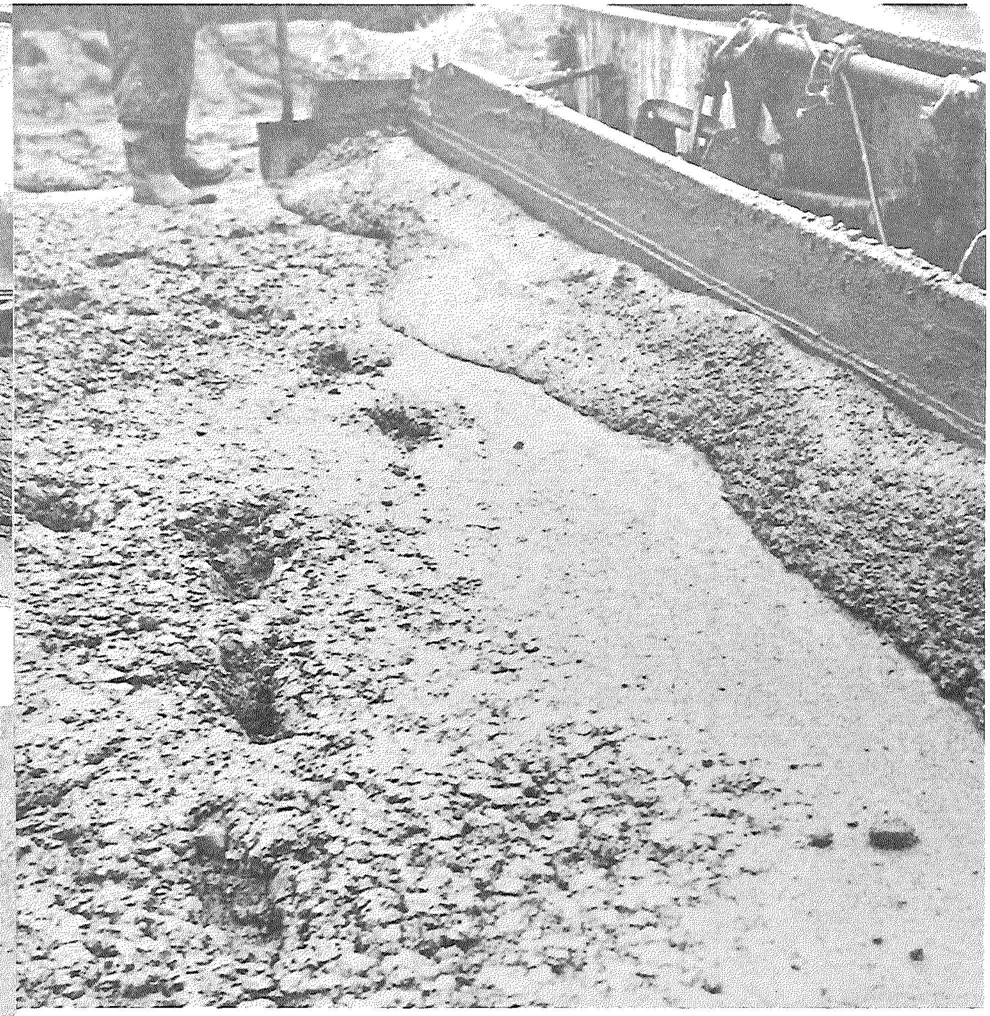


Figure 24. Typical appearance of air-entrained concrete.

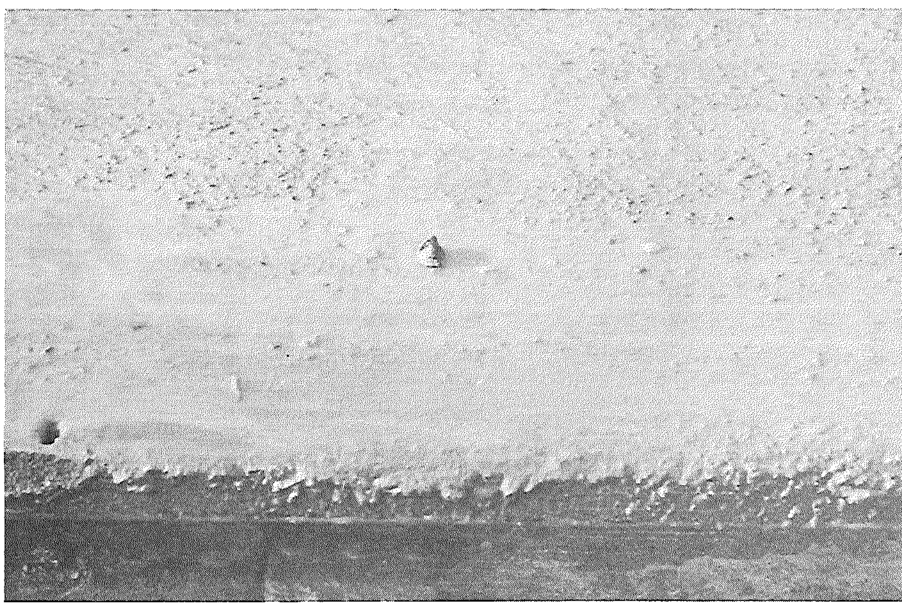


Figure 25. Bleeding of concrete containing limestone fine and coarse aggregates.

placement and a tendency to be sticky. This caused difficult finishing at times, especially in the operations of longitudinal floating, installing joints, and leveling depressions in the surface. Some bleeding occurred in the form of small boils. Air temperatures when this section was poured ranged from 46 to 66 F. At an air temperature of 50 F the concrete was unusually slow in setting, delaying removal of the forms the next day.

Concrete containing Admixture No. 2 acted in much the same way except that workability and finishing characteristics were somewhat better. The mixture was dense and, although not rubbery, it could not be worked by mechanical equipment if the slump fell below 1-1/2 in. The most noticeable characteristic of this admixture was the production of a false initial set within an hour after placing. At times this prevented proper straightedging and floating of the surface. Occasionally it was necessary to sprinkle water on the surface in order to complete finishing operations. Some bleeding occurred in this section, also in the form of small boils.

Air-Entraining Agents. The two air-entraining agents produced mixtures similar in plasticity and workability. No bleeding or laitance appeared and the workability and finishing qualities were much better than those of standard concrete. Mixtures with AEA No. 1 seemed easier to finish than those with AEA No. 2, the latter becoming somewhat sticky at times even though the finishing equipment was steel shod. Fig. 24 shows the general appearance of air-entrained concrete during screeding.

Air contents of the mixtures as determined by drop in weight are shown in Table 6. The mix design for these two materials was based on a drop in weight of 4 to 6 lb. Air contents thus determined did not take

TABLE 6
AIR CONTENT OF AIR-ENTRAINED MIXTURES

Mixture	Cement Brand No. 1			Cement Brand No. 2		
	Unit Wt., pcf	Drop in Wt., pcf	% Air	Unit Wt., pcf	Drop in Wt., pcf	% Air
Standard	152.1	---	---	152.4	---	---
AEA No. 1	148.2	3.9	2.6	148.7	3.7	2.4
AEA No. 2	147.7	4.4	2.9	150.6	1.8	1.2

Unit weights determined at an average slump of 2 in.

into account the air content of the standard mix which would normally amount to 1 to 1.5 percent. Adding this air volume brings the total air content of the air-entrained mixtures to around 4 percent, except in the case of the mixture containing AEA No. 2 with Cement No. 2 which had less than 3 percent air. Apparently this relatively low air content had no adverse effect on durability, as sections of this concrete performed fully as well as those with higher air contents.

Natural Cement Blends. Blends of natural cement, both with and without the grinding aid, produced mixtures of good workability. Mixtures containing natural cement without the grinding aid showed evidence of bleeding and laitance but had good finishing qualities. Concrete containing natural cement with the grinding aid was entirely free from bleeding and laitance and had finishing characteristics similar to those of the air-entrained mixtures.

Natural cement with the grinding aid produced a drop in weight of 3/4 lb per cu ft, and natural cement with no grinding aid a drop of 0.4 lb per cu ft. These weight differences indicate air contents of about 2.2 and 0.3 percent respectively, above that of the standard mix. Undoubtedly the air entraining effect of the grinding aid was responsible for the outstanding scale resistance of concrete containing this cement.

Limestone Materials. Concrete mixtures made with limestone fine and coarse aggregates, both with and without the addition of limestone dust, exhibited poor workability and finishing characteristics. Extensive bleeding and laitance were noted in the concrete containing only the limestone aggregate (Fig. 25). Adding limestone dust improved the workability considerably but had little effect on bleeding. The extensive and premature scaling of these sections can be attributed largely to the creation of a weak physical structure during the setting and early hardening period as a result of excessive bleeding and formation of laitance.

Mechanical Analysis of Fresh Concrete

To supplement the qualitative observations of physical characteristics, mechanical analysis of the fresh concrete mixture was performed as a quantitative check on proportions and uniformity. Specifically, it was desired to do three things: 1) compare actual proportions with design quantities; 2) determine uniformity of proportions from top to bottom of the slab as a measure of the degree of bleeding and segregation; and 3) compare the uniformity of the fresh concrete before and after passage of the longitudinal finishing machine.

Test Method. The method was one developed by Dunagan (25) using the buoyancy principle. Samples of about 8 lb were taken, generally in duplicate, at several locations in each test area approximately 3 ft from the slab edge. Samples from the top of the slab were taken from the surface to a depth considerably above the steel; those from the middle included material from just above and below the steel; bottom samples were from the portion just below the steel to material in contact with the subgrade. Samples for "before" and "after" determinations were taken from the surface at the same station immediately before and after passage of the longitudinal float.

Results and Discussion. Average proportions of concrete constituents are given in Table 7 along with design values for comparison. All of the results show satisfactory agreement with the design values, within the limitations of the test. More than half the observed values agree very closely, which indicates little or no selective effect of construction operations on proportions of the various mixtures.

Results of the tests for segregation are shown in Table 8. About the only conclusion that can be drawn from this test is that bleeding occurred in practically all mixtures. However, the test was not sufficiently discriminating to give quantitative differences for comparison.

A comparison of proportions before and after passage of the longitudinal float is presented in Table 9. Here again the results indicate that any effects which the operation may have had on vertical distribution of the constituents were not great enough to be distinguishable by this test.

In all three of the above studies the method did not have the accuracy originally expected, probably due largely to the number and size of samples tested. To obtain more accurate and consistent results, it was apparent afterward that individual samples would have to weigh at least 25 lb and that at least two such samples should be taken for each determination. Several other sources of error discussed by the author (25) may have affected the results in spite of the meticulous attention to detail with which the tests were performed.

Setting Time of Concrete

At selected locations setting time was measured by the Burggraf penetrometer to see what effect the various admixtures might have on the timing of finishing operations. The tests were made under uncontrolled

TABLE 7
COMPARISON OF ACTUAL MIX PROPORTIONS WITH DESIGN VALUES

Factor Studied	Cement Brand	b/b_o	Ratio by Weight: Water: Cement			Parts by Weight: Fine Aggregate			Parts by Weight: Coarse Aggregate		
			Design	Actual	% Diff.	Design	Actual	% Diff.	Design	Actual	% Diff.
Proportioning and Grading											
Silica Dust	1	.76	0.569	0.573	+ 0.8	2.29	2.40	+ 4.8	4.08	4.13	+ 1.2
Silica Dust	1	.80	0.557	0.574	+ 3.1	2.22	2.42	+ 9.0	4.18	4.34	+ 3.9
Limestone Dust	1	.76	0.570	0.563	- 1.2	2.32	2.62	+12.9	4.07	3.84	- 5.5
Limestone Dust	1	.80	0.560	0.625	+11.7	2.26	2.68	+18.6	4.19	4.09	- 2.3
Modified Sand	1	.76	0.566	0.613	+ 8.4	2.31	2.36	+ 2.1	4.07	4.39	+ 7.9
Modified Sand	1	.80	0.547	0.588	+ 7.5	2.16	2.13	- 1.4	4.30	4.50	+ 4.7
Proprietary Admixtures											
Admixture No. 1	1	.76	0.505	0.452	-10.5	2.32	2.10	- 9.5	4.07	3.70	- 9.1
Admixture No. 1	1	.80	0.470	0.458	- 2.6	2.19	2.15	- 1.8	4.30	4.04	- 6.1
Admixture No. 2	1	.76	0.525	0.459	-12.6	2.36	2.22	- 5.9	4.08	3.93	- 3.7
Admixture No. 2	1	.80	0.505	0.463	- 8.3	2.21	2.16	- 2.3	4.30	4.28	- 0.5
Air-Entraining Agents											
AEA No. 1	1	.76	0.530	0.485	- 8.5	2.29	2.13	- 7.0	4.08	4.20	+ 2.9
AEA No. 1	1	.80	0.510	0.478	- 6.3	2.13	2.03	- 4.7	4.30	4.01	- 6.7
AEA No. 1	2	.76	0.529	0.556	+ 5.1	2.30	2.35	+ 2.2	4.08	4.18	+ 2.5
AEA No. 1	2	.80	0.510	0.515	+ 1.0	2.16	2.17	+ 0.5	4.31	4.19	- 2.8
AEA No. 2	1	.76	0.528	0.557	+ 5.5	2.32	2.49	+ 7.3	4.07	3.68	- 9.6
AEA No. 2	1	.80	0.518	0.566	+ 9.3	2.24	2.27	+ 1.3	4.19	3.75	-10.5
AEA No. 2	2	.76	0.528	0.558	+ 5.7	2.33	2.38	+ 2.1	4.07	4.20	+ 3.2
Natural Cement Blends											
Natural Cement Without Grinding Aid	1	.76	0.570	0.532	- 6.7	2.27	2.29	+ 0.9	4.08	4.04	- 0.9
Natural Cement with Grinding Aid	1	.76	0.569	0.615	+ 8.1	2.21	2.50	+12.9	4.08	4.55	+11.5
Limestone Materials											
Limestone Aggregates	1	.76	0.538	0.526	- 2.2	2.59	2.34	- 9.5	3.58	3.11	-13.1
Limestone Agg. with Limestone Dust	1	.76	0.571	0.573	+ 0.4	2.55	2.54	- 0.2	3.58	3.20	-10.5
Standard Construction											
Cement Brand No. 1	1	.76	0.523	0.496	- 5.0	2.37	2.25	- 4.9	4.07	3.89	- 4.3
Cement Brand No. 2	2	.76	0.525	0.514	- 2.1	2.40	2.35	- 2.4	4.07	4.09	+ 0.6

TABLE 8
MIX PROPORTIONS AT TOP AND BOTTOM OF PAVEMENT

Factor Studied	Cement Brand	b/b_o	Water, lb/sack cement			Fine Aggregate, parts by weight				Coarse Aggregate, parts by weight			
			Top	Bottom	% Var.	Design	Top	Bottom	% Var.	Design	Top	Bottom	% Var.
Proportioning and Grading													
Silica Dust	1	.76	55.3	53.6	+ 3.2	2.29	2.39	2.41	- 0.8	4.08	3.43	4.48	- 1.1
Silica Dust	1	.80	55.9	51.4	+ 8.8	2.22	2.41	2.45	- 1.6	4.18	4.44	4.29	+ 5.8
Limestone Dust	1	.76	54.3	52.0	+ 4.4	2.32	2.59	2.55	+ 1.6	4.07	3.69	3.90	- 5.4
Limestone Dust	1	.80	59.3	58.2	+ 1.9	2.26	2.66	2.69	- 1.1	4.19	4.20	3.96	+ 6.1
Modified Sand	1	.76	60.9	53.0	+14.9	2.31	2.45	2.29	+ 7.0	4.08	4.07	4.72	-13.8
Modified Sand	1	.80	54.3	55.4	- 2.0	2.16	2.04	2.20	- 7.3	4.30	4.53	4.65	- 2.6
Proprietary Admixtures													
Admixture No. 1	1	.76	44.0	40.1	+ 9.7	2.32	2.13	2.07	+ 2.9	4.07	3.57	3.83	- 6.8
Admixture No. 1	1	.80	45.4	42.6	+ 6.6	2.19	2.15	2.16	- 0.5	4.30	4.35	3.84	+13.5
Admixture No. 2	1	.76	43.4	45.4	- 4.4	2.36	2.21	2.28	- 3.1	4.08	3.64	4.82	- 3.7
Admixture No. 2	1	.80	44.5	42.6	+ 4.5	2.21	2.10	2.19	- 4.1	4.30	4.10	4.21	- 2.6
Air-Entraining Agents													
AEA No. 1	1	.76	43.3	42.6	+ 1.6	2.29	2.12	2.03	+ 4.4	4.08	3.67	4.72	- 1.1
AEA No. 1	1	.80	47.4	43.6	+ 8.7	2.13	2.04	2.03	+ 0.5	4.30	4.31	4.06	+ 6.2
AEA No. 1	2	.76	52.5	51.2	+ 2.5	2.30	2.35	2.26	+ 4.0	4.08	4.06	4.40	- 7.7
AEA No. 1	2	.80	48.1	46.2	+ 4.1	2.16	2.15	2.17	- 0.9	4.31	4.05	4.09	- 1.0
AEA No. 2	1	.76	54.6	50.3	+ 8.5	2.32	2.49	2.53	- 1.6	4.07	3.54	3.71	- 4.6
AEA No. 2	1	.80	51.7	54.8	- 5.7	2.24	2.30	2.30	0.0	4.19	3.72	3.77	- 1.3
AEA No. 2	2	.76	51.2	50.1	+ 2.2	2.33	2.35	2.41	- 2.5	4.07	3.70	4.40	-15.9
Natural Cement Blends													
Natural Cement without Grinding Aid	1	76	52.8	47.7	+10.7	2.27	2.33	2.29	+ 1.7	4.08	4.15	4.10	+ 1.2
Natural Cement with Grinding Aid	1	.76	58.3	55.1	+ 5.8	2.21	2.51	2.50	+ 0.4	4.08	4.67	4.38	+ 6.6
Limestone Materials													
Limestone Aggregates	1	.76	48.2	48.9	- 1.4	2.59	2.31	2.39	- 3.3	3.58	2.96	3.22	- 8.1
Limestone Agg. with Limestone Dust	1	.76	55.1	50.1	+10.0	2.55	2.58	2.47	+ 4.4	3.58	3.53	3.09	+18.1
Standard Construction													
Cement Brand No. 1	1	.76	47.7	45.4	+ 5.1	2.37	2.25	2.24	+ 0.5	4.07	3.89	3.94	- 1.3
Cement Brand No. 2	2	.76	49.6	46.6	+ 6.4	2.42	2.37	2.41	- 1.6	4.06	3.86	4.37	-11.7

TABLE 9
EFFECT OF LONGITUDINAL FLOAT ON VERTICAL DISTRIBUTION OF CONCRETE CONSTITUENTS

Factor Studied	Cement Brand	b/b_o	Water, lb/sack cement			Fine Agg., parts by weight			Coarse Agg., parts by weight		
			Before	After	% Variation	Before	After	% Variation	Before	After	% Variation
Proportioning and Grading											
Silica Dust	1	.76	53.0	57.7	+ 8.8	2.38	2.41	+ 1.26	3.55	3.32	- 6.48
Silica Dust	1	.80	54.9	57.0	+ 3.8	2.35	2.48	+ 1.27	4.78	4.10	-14.22
Limestone Dust	1	.76	53.6	55.0	+ 2.6	2.64	2.55	- 3.41	3.85	3.54	- 8.04
Modified Sand	1	.76	60.2	61.6	+ 2.3	2.47	2.41	- 2.43	3.91	4.24	+18.70
Modified Sand	1	.80	49.5	59.1	+19.4	1.99	2.08	+ 4.53	4.19	4.87	+16.22
Proprietary Admixtures											
Admixture No. 1	1	.76	42.5	45.6	+ 7.3	2.12	2.14	+ 0.94	3.32	3.82	+15.05
Admixture No. 1	1	.80	47.1	43.6	- 9.5	2.18	2.12	- 2.75	4.26	4.44	+ 4.22
Admixture No. 2	1	.76	43.1	43.7	+ 1.4	2.16	2.26	+ 4.62	3.69	3.59	- 2.71
Air-Entraining Agents											
AEA No. 1	1	.76	47.2	45.5	- 3.6	2.16	2.08	- 3.70	4.00	3.35	-16.22
AEA No. 1	2	.76	----	52.5	-----	2.39	2.32	- 2.92	4.21	3.92	- 6.88
AEA No. 1	2	.80	49.3	46.9	- 4.9	2.16	2.14	- 0.93	4.08	4.02	- 1.47
AEA No. 2	1	.76	56.1	53.1	- 5.3	2.60	2.38	- 8.46	3.78	3.31	-12.42
AEA No. 2	2	.76	53.6	50.0	- 6.7	2.43	2.30	- 5.36	3.82	3.58	- 6.28
Natural Cement Blends											
Natural Cement without Grinding Aid	1	.76	50.5	55.2	+ 9.3	2.21	2.44	+10.4	4.30	4.15	- 3.49
Natural Cement with Grinding Aid	1	.76	57.2	59.5	+ 4.0	2.48	2.55	+ 3.10	4.64	4.71	+ 1.51
Limestone Aggregates											
Limestone Aggregates	1	.76	50.4	46.0	- 8.7	2.32	2.31	- 0.43	2.82	3.10	+10.00
Limestone Agg. with Limestone Dust	1	.76	53.2	56.9	+ 6.9	2.63	2.53	- 3.80	3.46	3.60	+ 4.05
Standard Construction											
Cement Brand No. 1	1	.76	46.6	48.6	+ 4.3	2.26	2.23	- 1.33	3.86	3.92	+ 1.55
Cement Brand No. 2	2	.76	51.1	48.1	- 5.9	2.42	2.32	- 4.13	3.96	3.75	- 5.31

atmospheric conditions using the apparatus shown in Fig. 26. The penetrometer consisted essentially of a steel cone mounted so that the apex could be depressed a measured distance below the surface of the fresh mortar. The pressure required to depress the cone 1/4 in. was measured by a spring scale supporting the specimen as shown in the figure. Specimens were prepared by filling the pan with mortar obtained by passing the fresh concrete through a 1/4-in. sieve. A load of 20 oz for 1/4-in. penetration was taken to indicate the point of minimum stiffening for starting hand finishing operations. In practice the tests were continued until the weight for the required penetration reached a value of 15 lb or more.

Results of the tests are shown in Table 29 (App. B) and Fig. 27. In spite of variability induced by differences in air temperature and humidity, there are two well defined indications in these results. First, both air-entraining agents prolonged the setting time of mixtures containing Cement No. 1. No explanation is offered for this effect other than to call attention to the data in Table 13 (App. A) which show that both the initial and final setting times of Cement No. 1 with interground AEA No. 2 were considerably longer than those of the plain cement. During construction, however, there was no noticeable delay attributable to this cause. The second effect was the action of the 1-percent calcium chloride addition in bringing the setting times of both air-entrained mixtures back to normal. In addition to these two effects, adding limestone dust and natural fines also appeared to prolong setting time, but not excessively.

Strength and Elastic Modulus

Throughout the project cylinders and beams were cast for compressive and flexural tests to determine the effect of the various factors on strength and to check the strengths of both standard and special mixtures against specification requirements. Besides the regular strength test specimens, a considerable number of the 3- by 6- by 15-in. beams molded for the laboratory durability tests remained after the tests were started. These smaller beams were kept in the moist room for 10 yr and then tested for dynamic modulus of elasticity and flexural strength.

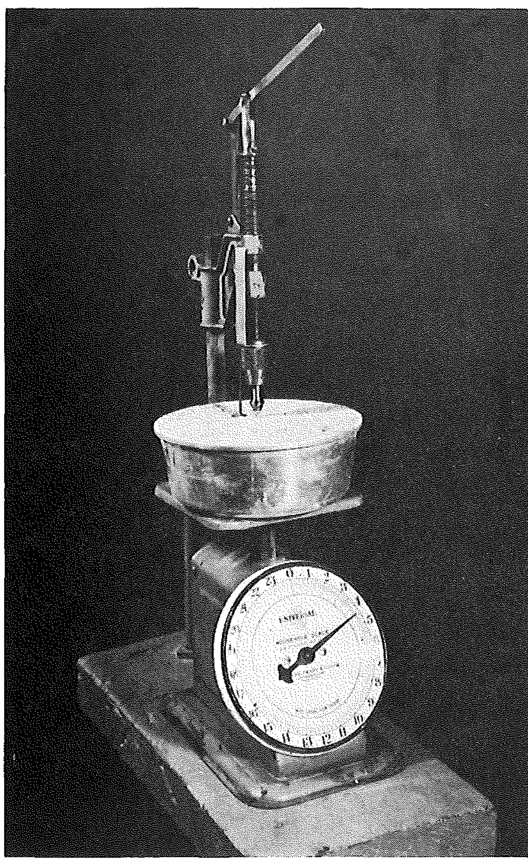
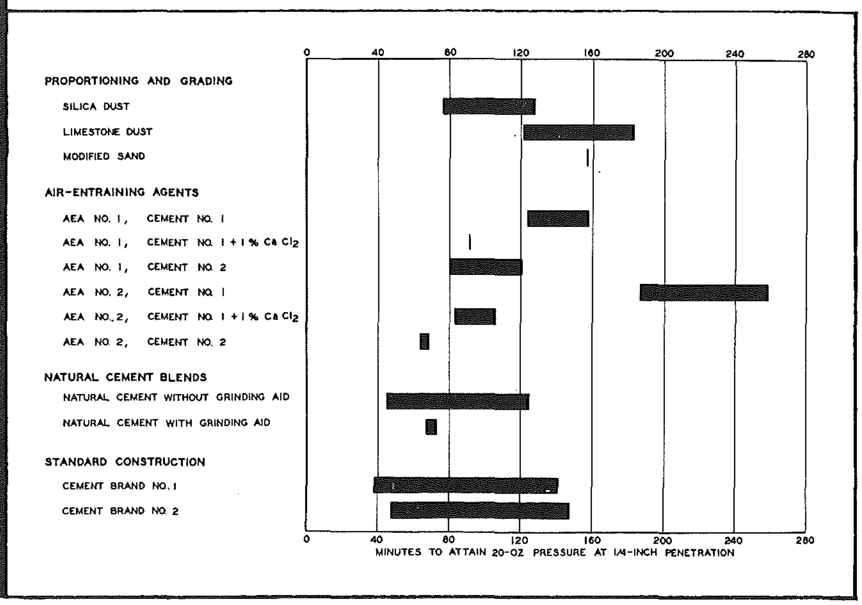


Figure 26. Burggraf penetrometer.

Figure 27. Setting time of concrete.



In addition to the molded specimens, cores were taken shortly after the pavement was finished for a routine check on compressive strength and pavement thickness. Ten years later the pavement was again cored to obtain further information on strength gain for correlation with performance, and to determine air content of the hardened concrete by the camera lucida method. Finally, Swiss hammer readings were taken in 1956 at the core locations and converted to compressive and flexural strength values.

Data on strength are not as complete as planned owing to unforeseen difficulties in casting and handling field specimens during construction. At times the test areas were poured in such rapid succession that personnel and the supply of specimen molds were not sufficient to cast all of the specimens desired. The number of available specimens was reduced still further by occasional faulty molding and breakage in subsequent handling. Nevertheless enough tests were made to satisfy minimum requirements of the study.

Compressive Strength. Standard 6- by 12-in. cylinders were cured 3 to 4 days in the field before being taken to the laboratory. All specimens except those containing 2-percent calcium chloride were stored in the moist room until tested. Compression tests were made in accordance with ASTM Method C39-39.

A condensed summary of average 7- and 28-day compressive strengths is given in Table 30 (App. B) along with the results obtained from the two sets of cores and the Swiss hammer tests. Strengths of the field-molded specimens are shown in Fig. 28. Compressive strengths of all mixtures were well above the specification requirement of 2500 psi at 28 days. However, strength reduction due to air-entrainment was plainly evident, some mixtures having less than 80 percent of the strength of standard mixtures. Adding 1 percent calcium chloride to the mixture containing the two air-entraining agents lowered the strength still further. Concretes containing the other admixtures generally exhibited strengths equal to or greater than those of the standard mix. Admixture No. 2 in particular consistently produced noticeably higher strengths at all ages. Table 10 gives values of air content, 10-yr strengths, and extent of pavement scaling in 1955 for the various mixtures to show the relation of air content to strength and durability.

Flexural Strength. Standard modulus of rupture beams 6- by 8-in. in cross-section were cast in two lengths, 24 in. and 36 in. These beams were cured in the same way as the pavement they represented, and broken

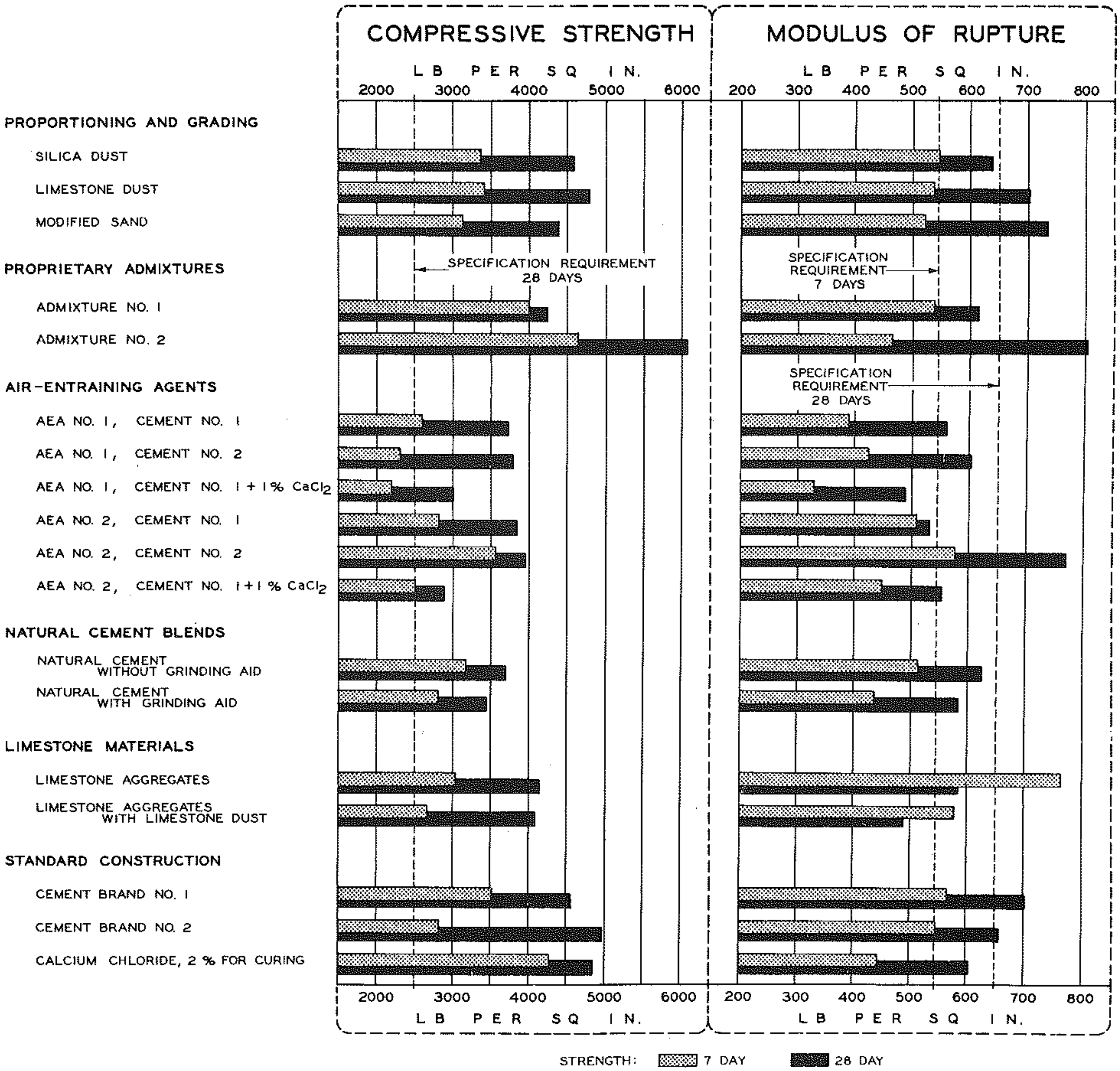


Figure 28. Compressive and flexural strengths of field-molded specimens.

at 7 and 28 days. Some were tested by third-point loading according to ASTM Method C78-39. The remainder were broken by the cantilever method using a machine designed by the Michigan State Highway Department. Specification values were based on results obtained with the Department's beam breaker which was found to give values about 20 percent higher than those obtained by third-point loading in these tests.

TABLE 10

AIR CONTENT IN RELATION TO STRENGTH AND DURABILITY

Factor Studied	Percent Air 10-Yr Cores (1)	Compressive Strength, 10-Yr Cores psi	Percent of Standard No. 1	Flexural Strength, 10-Yr Beams psi	Percent Scale Pavement 1955
Proportioning and Grading					
Silica Dust	2.0	7450	128	842	6
Limestone Dust	1.4	6580	114	935	6
Modified Sand	1.0	6800	117	---	38
Proprietary Admixtures					
Admixture No. 1	4.0	4900	85	828	0
Admixture No. 2	1.3	7350	127	828	0
Air-Entraining Agents					
AEA No. 1, Cement No. 1	3.7	5600	97	797	0
AEA No. 1, Cement No. 2	4.0	5800	100	707	0
AEA No. 2, Cement No. 1	5.7	3850	66	---	0
AEA No. 2, Cement No. 2	2.3	5100	88	---	0
Natural Cement Blends					
Nat. Cement without Grinding Aid	1.6	6650	115	---	1
Nat. Cement with Grinding Aid	2.8	5200	90	723	0
Limestone Materials					
Limestone Aggregates	1.4	7200	124	---	70(2)
Limestone Agg. with Limestone Dust	1.0	5600	97	929	90(2)
Standard Construction					
Cement Brand No. 1	1.5	5800	100	904	8
Cement Brand No. 2	1.9	7300	126	---	8

(1) Camera lucida method

(2) Condition in 1950. Resurfaced in 1951-1952

Flexural test results are summarized in the same way as those from the compressive tests, and are shown in Table 31 (App. B) and Fig. 28. Values given in the table are the average for two breaks of each specimen, and only the results from third-point loading are included. Comparison of flexural and compressive test data shows that the former were influenced by the various factors in the same general way as the latter but not to the same extent. In the case of the air-entrained concretes, this observation agrees with subsequent experience in the use of air-entraining agents.

Modulus of Elasticity. Data on modulus of elasticity at 28 days and 10 yr are listed in Table 32 (App. B). Determinations were made on the 3- by 6- by 15-in. beams by the sonic method and on the pavement cores by compression at a load of 2000 psi. The dynamic values are, of course, higher than the secant moduli since the former are determined at no load. The data in the table show that the dynamic modulus of all mixtures increased appreciably over the 10-yr period but less than either flexural or compressive strength. Also, mixtures containing the air-entraining agents and natural cements seem to have slightly lower moduli than the others but the data are not sufficient to establish this point.

Effect of Coarse Aggregate Ratio on Strength. As mentioned earlier, two different coarse aggregate ratios, b/b_0, were used in the design of mixtures containing the various additions. Compressive and flexural strengths of these mixtures are given in Table 33 (App. B). Increasing b/b_0 from 0.76 to 0.80 did not seriously affect workability and had no consistent effect on strength. The 1955 condition survey of the pavement further revealed no significant difference in effect on scale resistance. For this reason, tabulations of results have been simplified throughout this report by combining data from both test areas containing the same admixture or air-entraining agent into a single value for the basic mixture.

Curing Study

The purpose and scope of the curing study were given earlier in this report. Briefly, the principal objectives were: 1) to evaluate the influence of the various curing methods on durability, especially with regard to scaling; and 2) to determine the effect of these methods on thermal and moisture gradients in the slab. The relative performance of a transparent membrane curing compound was also of particular interest. Results of the durability phase of the curing study were presented and discussed earlier in connection with the various accelerated tests performed on the pavement and in the laboratory. The present account is concerned chiefly with thermal and moisture effects.

Series 3 was set up for the curing study and consisted of nine sections 120 ft long, one each for the following methods:

1. Asphalt emulsion applied at the rate of 1/20 gal per sq yd after initial burlap curing.
2. Wetted straw at the rate of 4 lb per sq yd.
3. Paper with initial burlap curing.
4. Wetted earth.
5. Ponding.
6. Double burlap.
7. Paper applied immediately after finishing.
8. Calcium chloride integrally mixed at the rate of 2 lb per sack of cement.
9. Transparent membrane applied at the rate of 1/20 gal per sq yd (180 sq ft per gal) after initial burlap curing.

With the exception of Section No. 9, the entire curing series was poured on Sept. 9, 1940. However, a slow rain started falling at noon after the first five sections were laid and the paver was stopped at 3 p. m. The series was completed the next day, but during the week immediately following the weather remained cool and damp with some rainfall on three different days.

Test Methods. Temperature and moisture were measured daily by thermocouples and companion moisture cells located at the top, middle, and bottom of the pavement slab. Moisture cells were of the electrical resistance type developed by Bouyoucos and Mick (26), and consisted of two bare wire terminals embedded 1 in. apart in plaster of paris blocks 1/2- by 1-1/2- by 2-1/2 in. in size. Calibration curves were obtained by casting similar cells in weighed blocks of concrete of known mix proportions and taking electrical bridge readings at intervals during a controlled drying period. After each decrement of moisture, the system was allowed to reach equilibrium in a sealed pan before taking resistance readings. Thus each value of moisture content represented the total in the concrete, including chemically bound, adsorbed, and free water. Since temperature affects the resistance of the cells, resistance readings were corrected to 70 F both in the laboratory and field tests.

Besides the measurements of internal temperature and moisture, pavement surface temperatures were taken with a track thermometer, and air temperature, relative humidity, precipitation, and evaporation were recorded for the duration of the test.

Results and Discussion. Complete data from the study are presented in Table 34 (App. B). On two occasions, the afternoon of Sept. 12 and morning of Sept. 13, internal slab temperatures could not be taken because of instrument trouble. In both cases temperatures were estimated for the purpose of moisture cell resistance correction on the basis of those taken at about the same time on another day having nearly the same air temperature. Moisture values derived from resistances corrected in this way are not included in the present discussion.

Moisture at the bottom of the slab varied from 6.0 to 6.5 percent, with most of the values falling in the still narrower range of 6.1 to 6.3 percent. Generally moisture content declined slightly at the bottom during the week although the effect of rains can be detected in some cases. Curing method apparently had little influence on water content of the concrete at this depth.

Moisture content of the concrete at the middle was a little more variable and sensitive to curing method. The wet methods, such as ponding, wetted earth, and wetted straw maintained water contents at the center nearly equal to those at the bottom with little loss during the 7-day curing period. Paper without the initial burlap cure had the same effect. Curing by burlap-and-paper, asphalt emulsion, transparent membrane, and calcium chloride permitted slightly higher water losses at this depth but the differences are not significant.

As might be expected, curing method influenced water retention most at the top of the slab. In spite of the transient effects of rainfall, moisture content at the top of most sections soon fell below that at the bottom and remained lower with slight variations for the remainder of the curing period. Exceptions were the areas cured with double burlap, wet straw, and asphalt emulsion, where moisture content at the top was fairly stable. In contrast to these three areas, there was a noticeable loss of moisture from the surface of the sections cured with calcium chloride, transparent membrane, and paper applied after initial curing with burlap. At 18 days the water contents at the top of these sections were 5.5, 5.5, and 5.6 percent respectively, compared to 5.9 to 6.1 percent for the others.

In interpreting these results it should be kept in mind that the total water content of the fresh concrete was 7.0 percent by design, and that cement hydration during the early hardening period is not significantly impaired until the loss of original mixing water exceeds about 20 percent (27). On this basis, water contents of 5.6 percent or more should be considered adequate for proper curing. All nine curing methods satisfied this requirement under the prevailing conditions.

Despite adverse weather for temperature comparisons, significant differences in thermal effects of the various curing methods were observed. These effects may be seen in Fig. 29 which shows the average temperature difference between air and the top and bottom of the slab. Uniformly low differences were maintained by the four wet curing methods. The lowest differences were attained in the calcium chloride section which had no covering of any kind. Asphalt emulsion produced the highest temperatures and the greatest temperature differences within the pavement, and transparent membrane the next highest. These higher temperatures under the membranes are due to the transmission and absorption of solar radiation, and the desire to minimize this objectionable feature led to the later development and use of white-pigmented membrane curing compounds (27).

Pavement Roughness

The Bureau of Public Roads made roughness surveys in 1941, 1949, and 1955 with a roughometer designed and assembled by its own personnel, with the results shown in Fig. 30. The 1941 measurements were made on the north lane only, so the 1949 and 1955 values are also shown only for this lane to provide a better comparison with the first survey.

When the pavement was new, the broom-finished sections of standard concrete were the smoothest and the sections containing limestone aggregates the roughest. By the time of the second survey, the riding qualities of all sections of the project had become pretty well equalized except for the two test areas containing limestone aggregates. Scaling was so severe in these sections that partial resurfacing was necessary 2 yr later, and this scaling was reflected in the roughness values. With these exceptions, the entire pavement was remarkably smooth riding for its age. The effect of progressive scaling was again evident in the 1955 survey. At that time the limestone sections had been resurfaced, but the three areas containing added fines had developed a pronounced increase in roughness corresponding with the increased scaling of these areas. The sections containing the proprietary admixtures, air-entraining agents, and natural cement blends increased moderately in roughness, but remained the smoothest riding in the project.

Concrete Volume Changes

Reference plugs were installed in all experimental pavement sections to study volume changes of the various concrete mixtures by measuring changes in joint width. At first, joint widths were measured four times

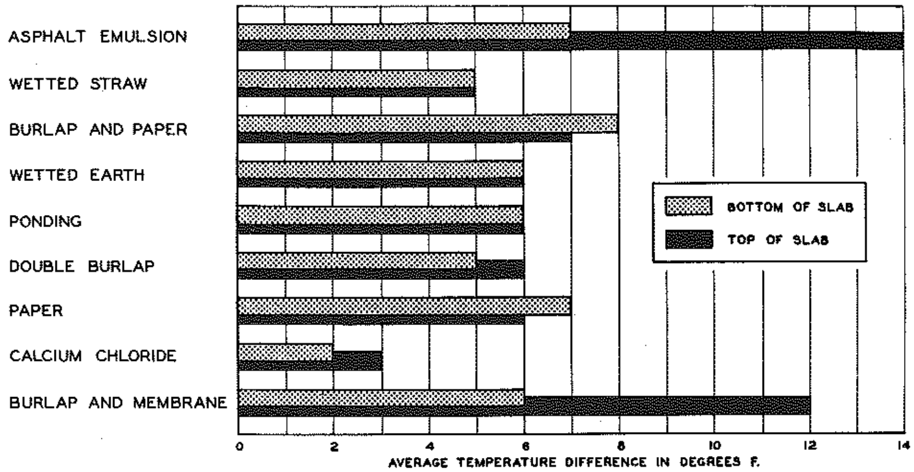


Figure 29. Average temperature difference between air and top and bottom of slab.

a year--winter, spring, summer, and fall. At the same time, temperature and moisture were measured with thermocouples and electrical-resistance cells as in the curing study. Spring and fall readings were discontinued after 1948 but winter and summer readings were taken until all the pavement sections were resurfaced.

In most sections reference plugs were installed at all joints in two consecutive 120-ft slabs. As stated earlier, expansion joints were 120 ft apart, with an intermediate contraction joint at 60 ft and two hinge, or dummy, joints at the quarter points. In those sections containing mixtures with two different coarse aggregate ratios, joint widths were measured in two consecutive slabs of each mixture and the results combined into a single series of values representing the basic mixture.

In Fig. 31, average changes in width of the three joint types are plotted against time in seasons of the year. Amplitudes of joint width change were approximately the same for all mixtures except those containing limestone aggregates, indicating that the various admixtures and air-entraining agents had little if any effect on volume change characteristics. The lower thermal expansion coefficient of limestone aggregates is reflected in the narrower range of joint widths in concrete containing these materials. Rupture of the steel reinforcement in several of the sections is revealed by the abrupt increase in dummy joint widths after about 12 yr.

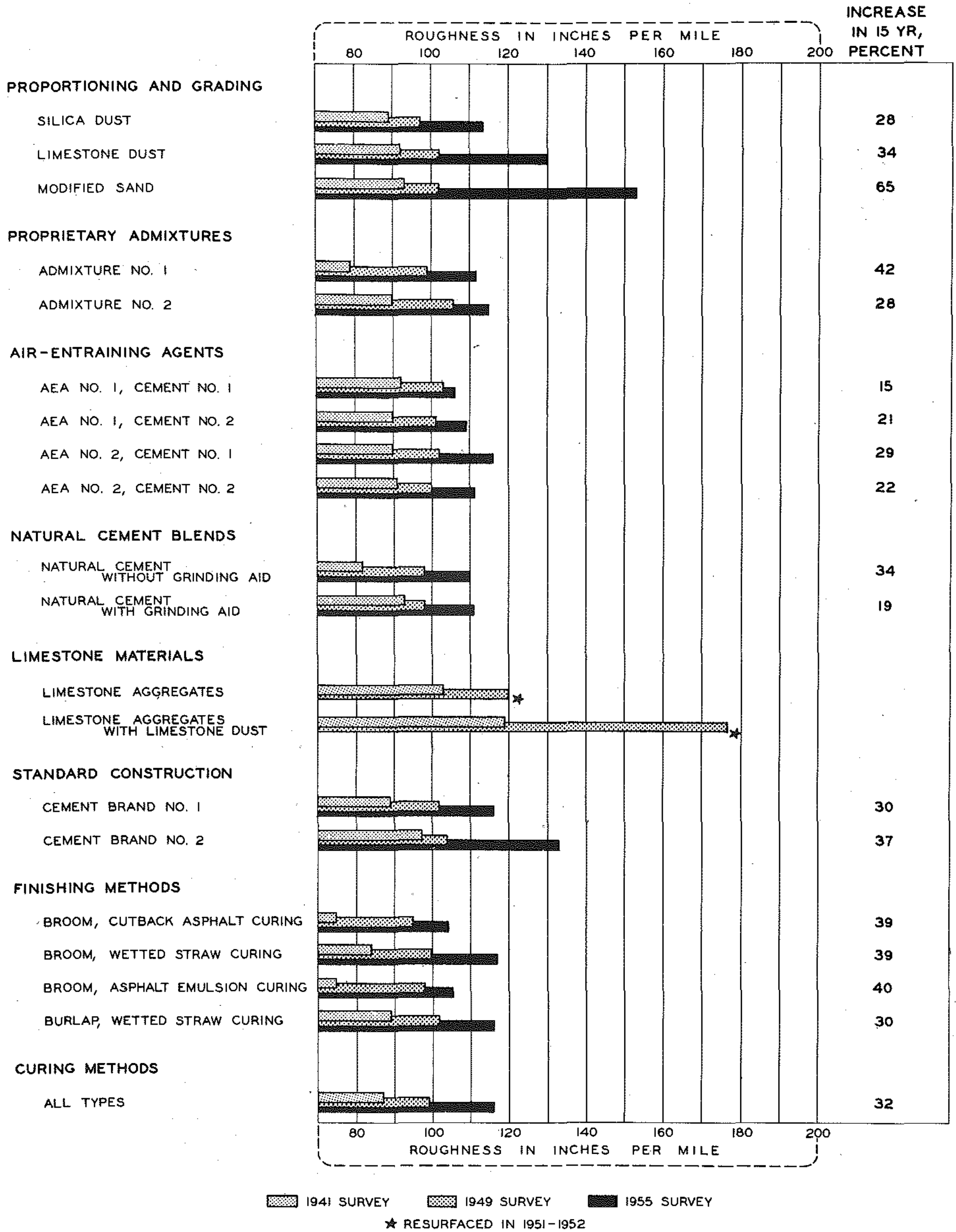


Figure 30. Pavement Roughness.

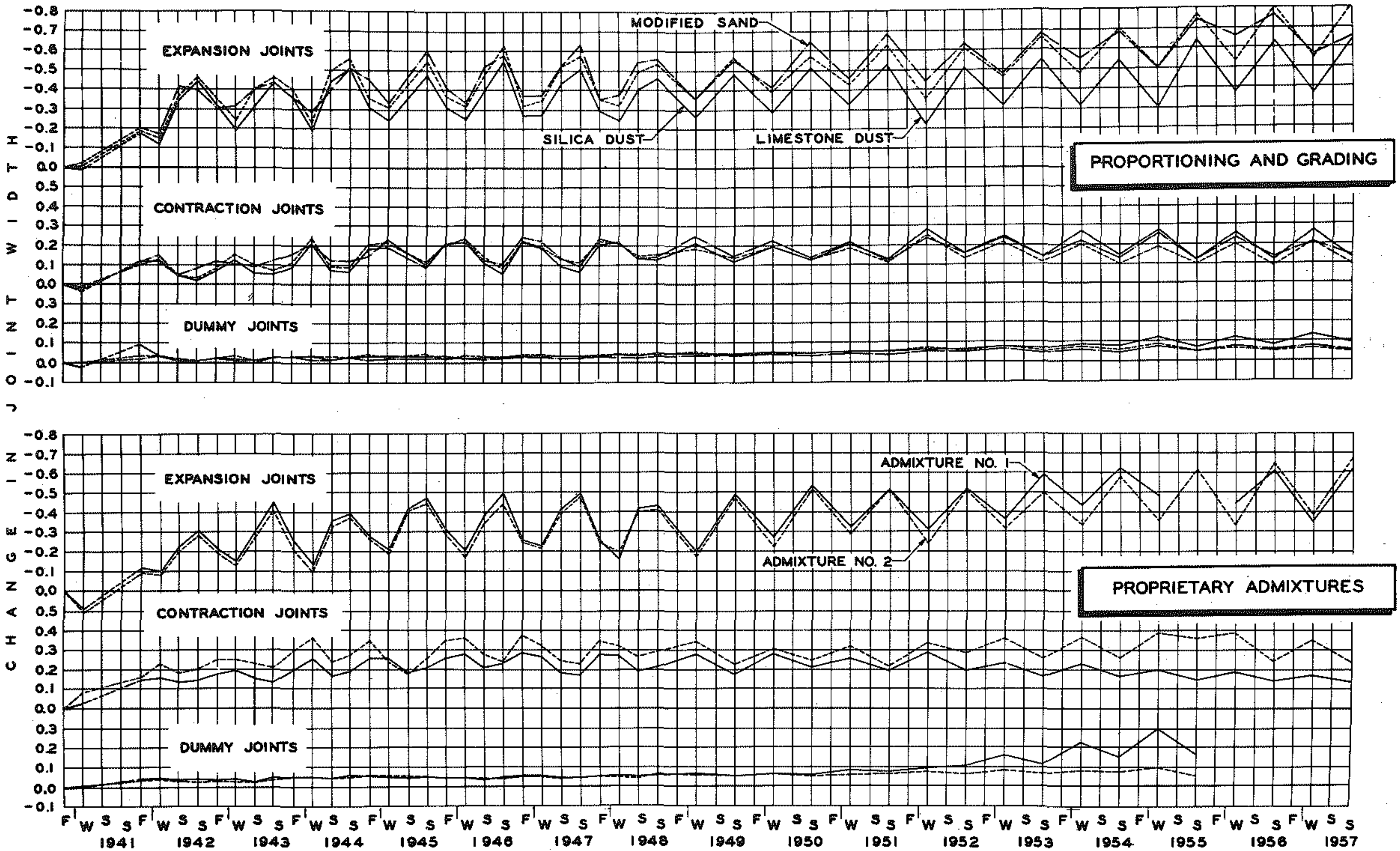


Figure 31. Joint width changes.

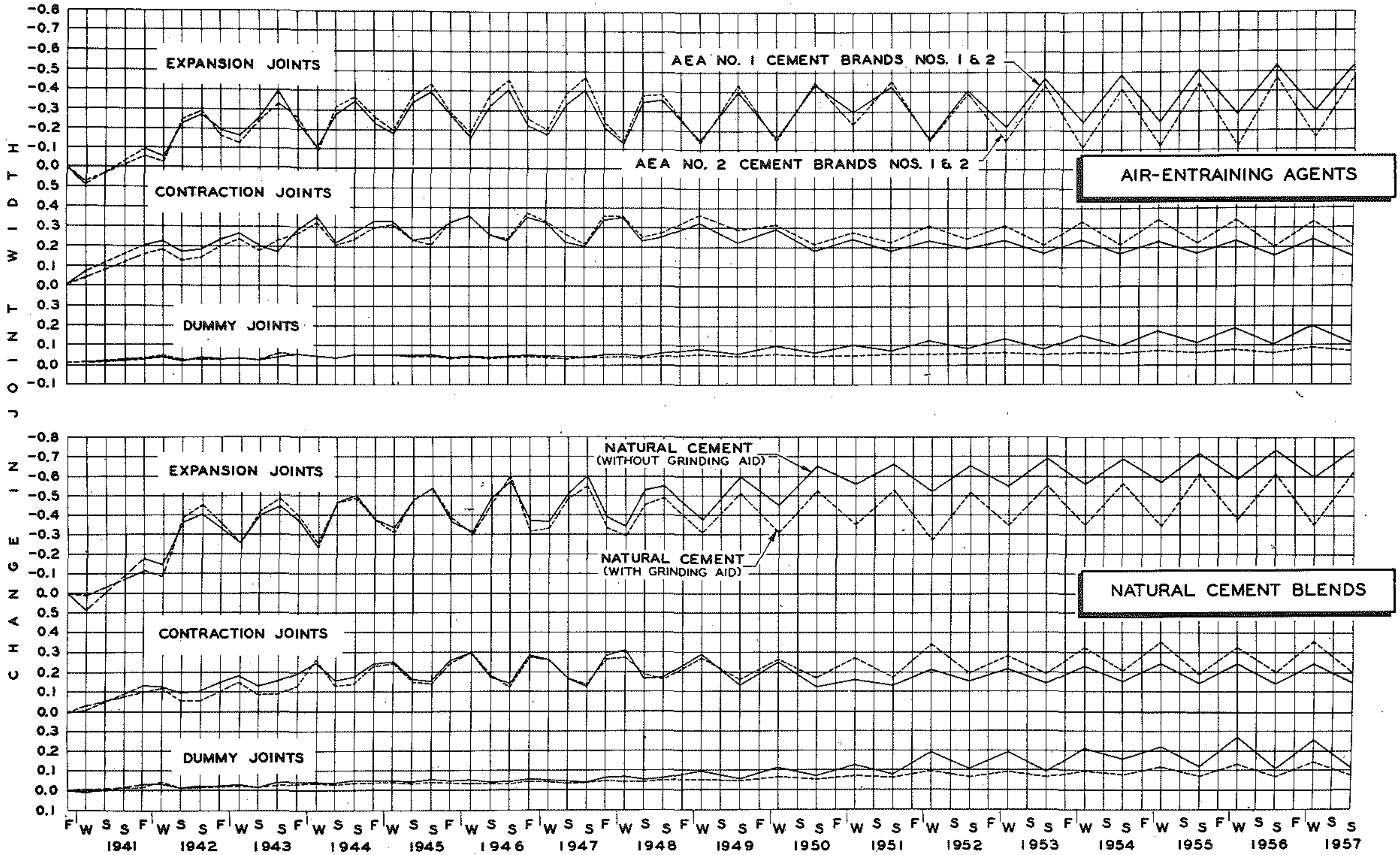


Figure 31. Joint width changes (continued).

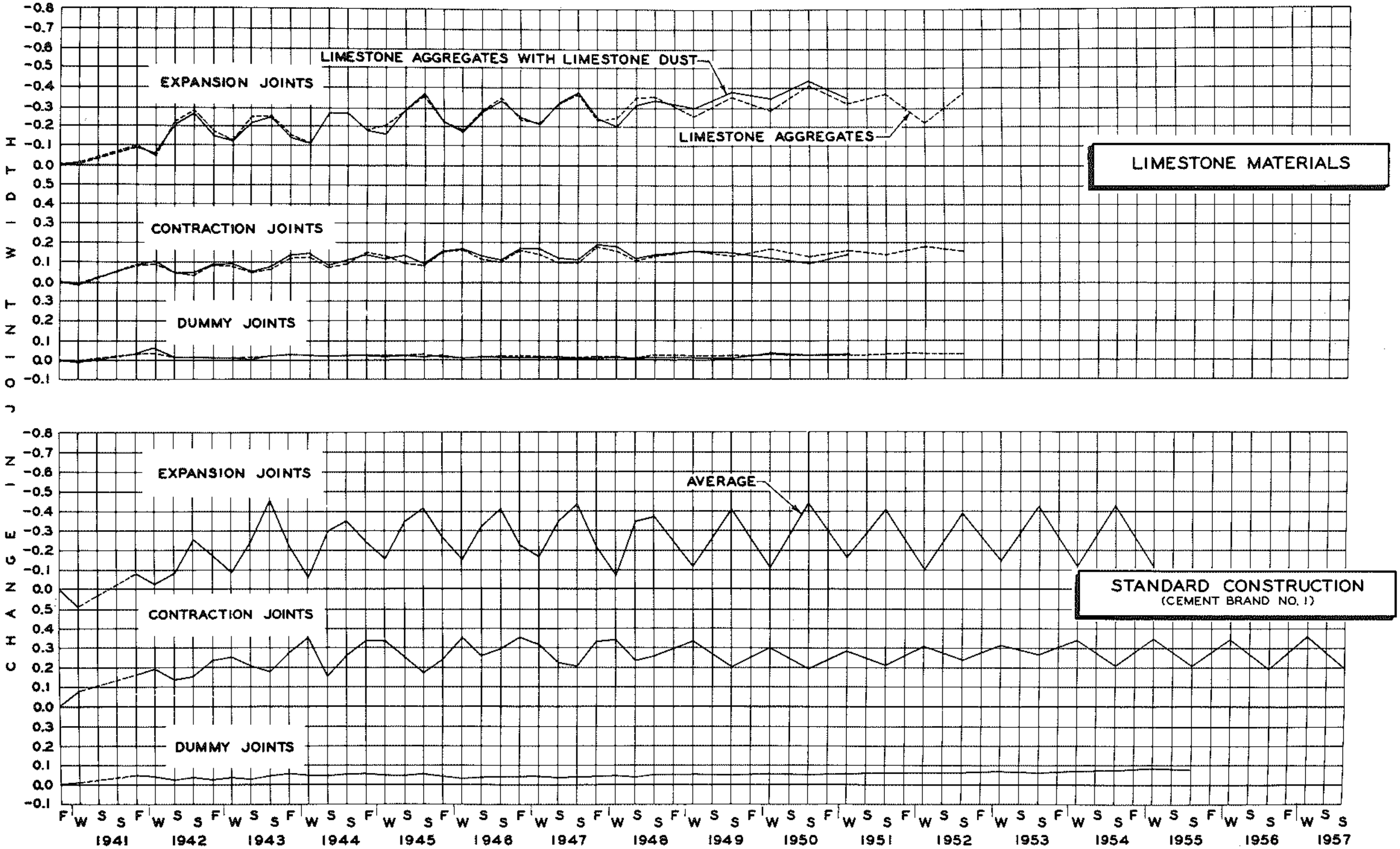


Figure 31. Joint width changes (continued).

To analyze the data more precisely, net changes in slab length were computed by algebraically summing the width changes of all joints in each 120-ft slab, taking half the end movement at each expansion joint for this purpose. These length changes were then plotted against temperature and the line of regression determined statistically as illustrated by the example in Fig. 32. Lines of regression for seven mixtures are shown in Fig. 33. Differences in thermal expansion coefficient appear as differences in slope of the lines. Permanent volume changes, growth or shrinkage, would appear as vertical shifts of the lines, up or down respectively, from the point representing initial length and temperature measurements. Initial points are not shown in Fig. 33. Considering the magnitude of statistical variation, shifts in the regression lines were not great enough to indicate permanent volume changes in any of the mixtures with certainty. However, there appeared to be some shift toward the growth side for several mixtures, particularly those containing limestone aggregates.

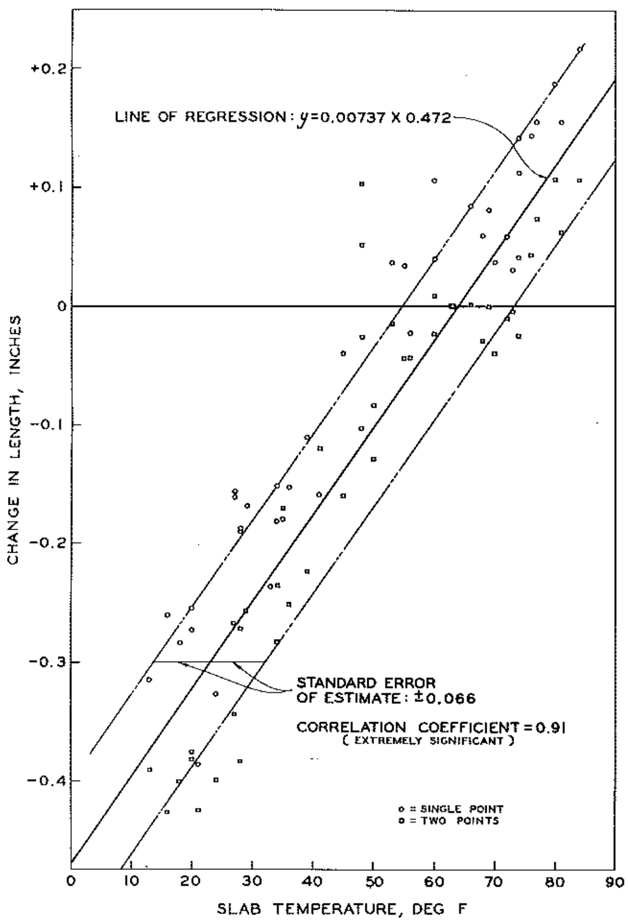
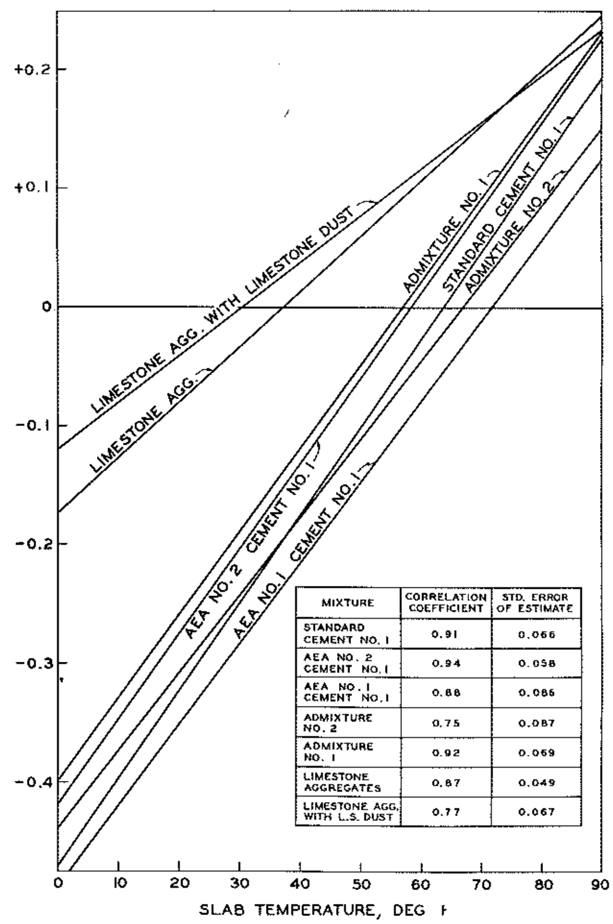


Figure 32. Change in 120-ft slab length with temperature for standard concrete with Cement No. 1.



MIXTURE	CORRELATION COEFFICIENT	STD. ERROR OF ESTIMATE
STANDARD CEMENT NO. 1	0.91	0.066
AEA NO. 2 CEMENT NO. 1	0.94	0.058
AEA NO. 1 CEMENT NO. 1	0.88	0.086
ADMIXTURE NO. 2	0.75	0.087
ADMIXTURE NO. 1	0.92	0.069
LIMESTONE AGGREGATES	0.87	0.049
LIMESTONE AGG. WITH L.S. DUST	0.77	0.067

Figure 33. Comparison of slab length changes for seven concretes.

Relation of slab length change to temperature was extremely significant, as shown by the table of correlation coefficients in Fig. 33. Because slab length change was so closely related to temperature, other factors including change in concrete moisture content must have been of secondary importance in causing slab length variations.

PHYSICAL CONDITION OF THE PAVEMENT

Twice each year the entire project was inspected to note the occurrence of scaling, cracking, spalling and other defects. The results of the last survey, made in June 1955, are shown in Table 11.

TABLE 11
PAVEMENT CONDITION
June 1955

Factor Studied	Percent Scale	Cracks					Spalls				
		Trans.	Long.	Diag.	Total	Number Per Slab	Exp. Joints	Contr. Joints	Dummy Joints	Total	Number Per Slab
Proportioning and Grading											
Silica Dust	6	-	-	-	-	0.0	20	40	20	80	4.0
Limestone Dust	6	-	-	-	-	0.0	4	28	16	48	2.5
Modified Sand	38	1	-	-	1	0.1	6	6	2	14	0.7
Proprietary Admixtures											
Admixture No. 1	0	29	-	1	30	2.7	-	5	4	9	0.8
Admixture No. 2	0	48	-	5	53	5.3	6	9	16	31	3.1
Air-Entraining Agents											
AEA No. 1, Cement No. 1	0	50	1	-	51	5.1	-	7	3	10	1.0
AEA No. 1, Cement No. 2	0	58	1	2	61	6.1	5	6	-	11	1.1
AEA No. 2, Cement No. 1	0	86	-	28	114	5.4	3	13	16	32	1.5
AEA No. 2, Cement No. 2	0	44	3	3	50	2.4	3	3	19	25	1.2
Natural Cement Blends											
Natural Cement Without Grinding Aid	1	10	-	3	13	1.3	7	12	19	38	3.8
Natural Cement With Grinding Aid	0	6	-	-	6	0.6	3	19	7	29	2.9
Limestone Materials											
Limestone Aggregates	70(1)	55	-	-	55	6.1(1)	-	-	-	0	0.0(1)
Limestone Agg. With Limestone Dust	90(2)	51	-	-	51	5.7(2)	-	-	-	0	0.0(2)
Standard Construction											
Cement Brand No. 1	8	131	4	4	139	2.1	47	87	61	195	2.9
Cement Brand No. 2	6	55	-	4	59	3.0	4	21	5	30	1.5
Finishing Methods											
Broom, Cutback Asphalt Curing	1	-	-	-	-	0.0	1	5	5	11	2.8
Broom, Wetted Straw Curing	4	4	-	-	4	0.4	9	11	5	25	2.5
Broom, Asphalt Emulsion Curing	2	18	-	-	18	1.8	6	16	10	32	3.2
Burlap, Wetted Straw Curing	8	131	4	4	139	2.1	47	87	61	195	2.9
Curing Methods											
Asphalt Emulsion	10	2	-	-	2	2.0	-	2	-	2	2.0
Wetted Straw	7	4	-	-	4	4.0	-	3	-	3	3.0
Paper With Initial Curing	8	2	-	-	2	2.0	-	2	-	2	2.0
Wetted Earth	10	2	-	-	2	2.0	3	-	1	4	4.0
Ponding	9	1	-	-	1	1.0	2	2	-	4	4.0
Double Burlap	10	2	-	-	2	2.0	1	3	-	4	4.0
Paper, No Initial Curing	3	6	-	-	6	6.0	2	3	5	10	10.0
$CaCl_2$, Integrally Mixed	9	5	-	-	5	5.0	2	-	2	4	4.0
Transparent Membrane	8	5	-	-	5	5.0	1	2	-	3	3.0

(1) Condition 1950, Resurfaced 1952
(2) Condition 1950, Resurfaced 1951

Spalling was unusually prevalent at transverse weakened-plane joints, and was caused mostly by tipping of the bituminous joint strip by the longitudinal float during construction. Evidently the longitudinal float was not properly coordinated with the finishing machine. Spalling from this cause was not related to consistency or workability of the concrete, since the widest difference in the number of spalled joints occurred in the three sections containing mixtures with added fines, all of which had excellent workability.

Cracking incidence was highest in the sections containing limestone aggregates, air-entraining agents, and Admixture No. 2, and lowest in those containing silica dust, limestone dust, and modified sand. However, this crack pattern cannot be attributed definitely to strength or durability of the concrete in these sections. Fig. 4 shows that the entire series of air-entrained concretes and three intermediate standard concrete sections were placed on a constructed sand subbase 12 in. thick. All three of these standard concrete sections developed more than twice as many cracks as the standard sections in other areas of the project, indicating a pronounced influence of the supporting base on slab cracking. Assuming a similar effect on the other sections in the same area, cracking of the air-entrained concretes was not excessive.

Extent of scaling at the time of the final survey is also shown in Table 11. This aspect of pavement performance was discussed earlier in connection with the various accelerated durability tests. Results of the accelerated scaling test are compared with pavement performance in Fig. 34. The accelerated scaling test gave a remarkably accurate forecast of subsequent pavement performance, with few exceptions. After 15 yr no appreciable scaling was evident on concrete containing the air-entraining materials and proprietary admixtures. Concrete containing the limestone aggregates and mixtures with the added mineral fillers scaled the most. In sections containing Admixture No. 2 and natural cement without the grinding aid, scaling which might have been expected from the results of the accelerated test failed to develop. Both of these areas were essentially scale-free when the pavement was resurfaced. Photographs of typical areas of the various experimental sections taken in the spring of 1957 just before the pavement was resurfaced are shown in Figs. 35-40.

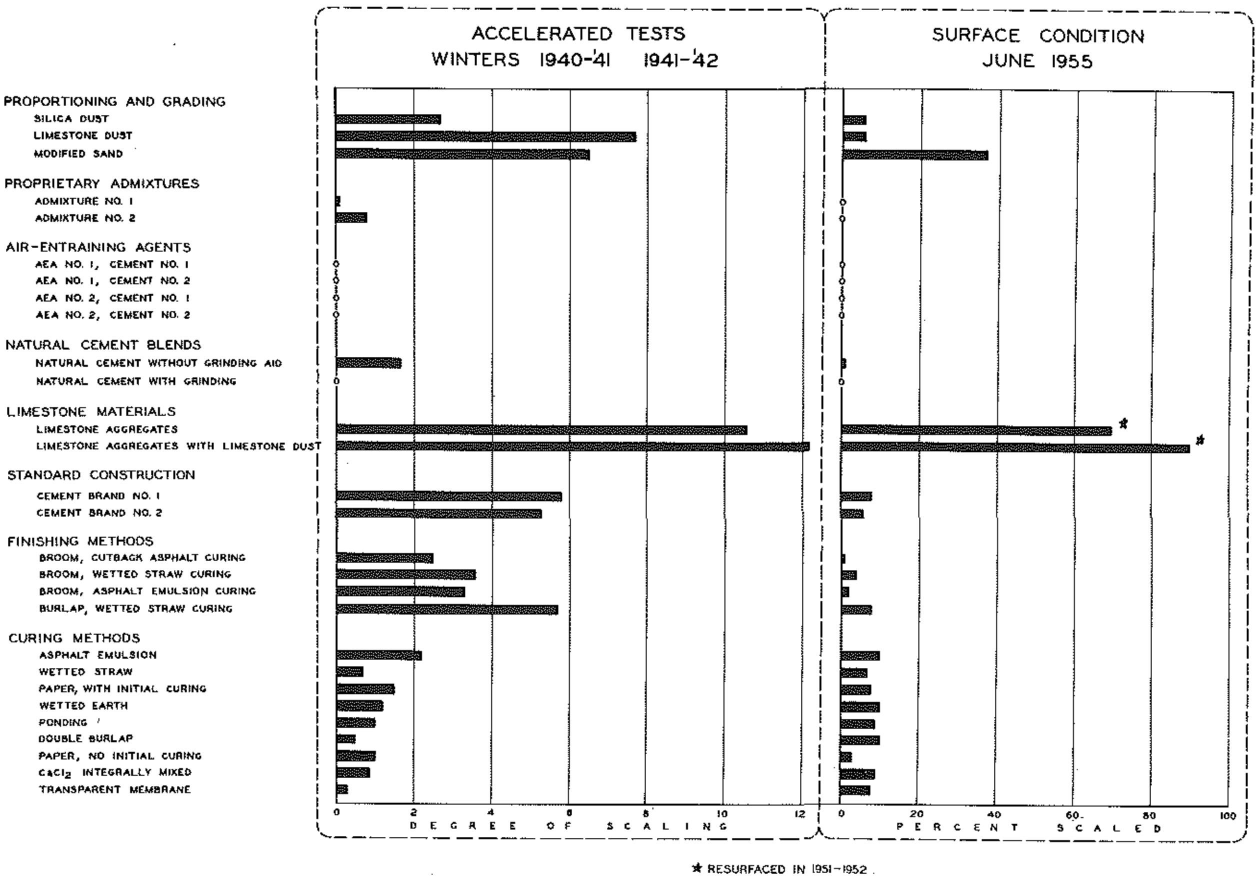
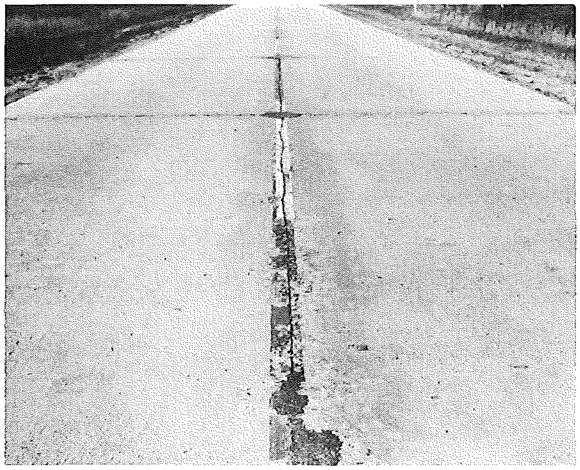
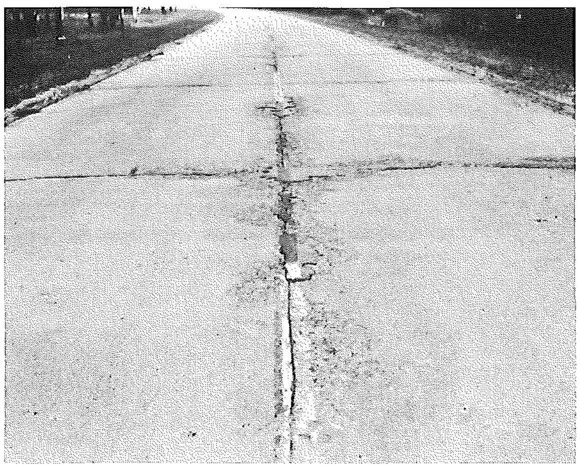


Figure 34. Comparison of accelerated scaling tests with pavement performance.

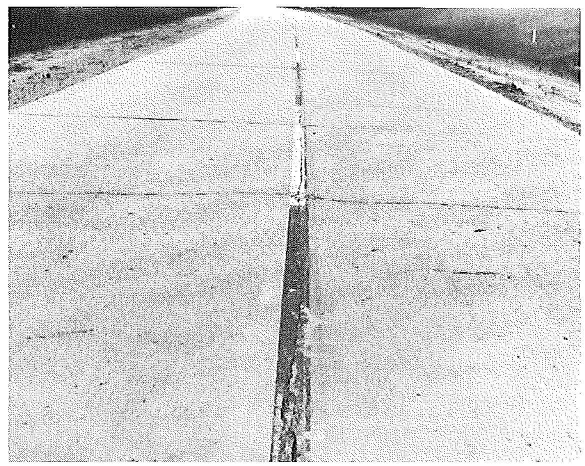


Silica dust
Section 7A, Sta. 634+00

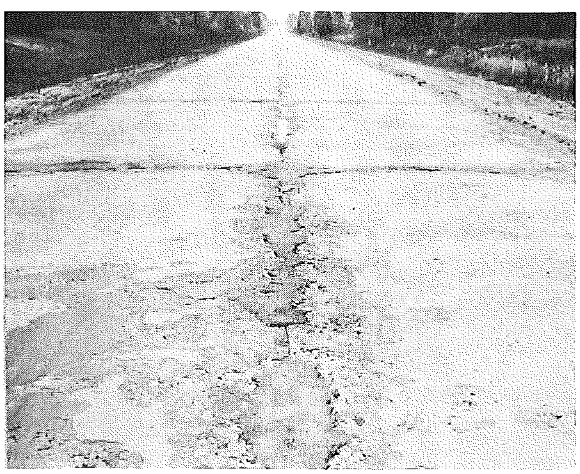
Admixture No. 1
Section 4B, Sta. 418+00



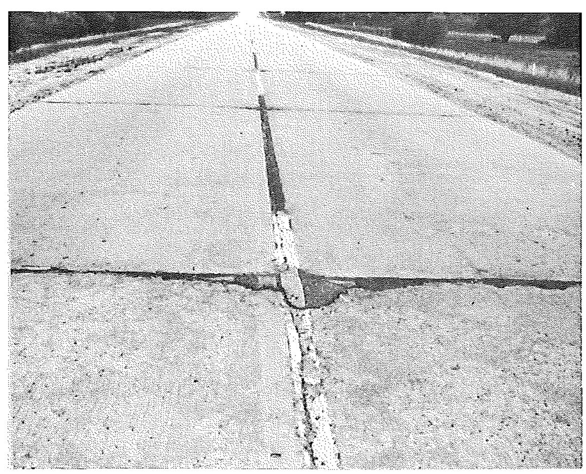
Limestone Dust
Section 7C, Sta. 669+70



Admixture No. 2
Section 4D, Sta. 440+65

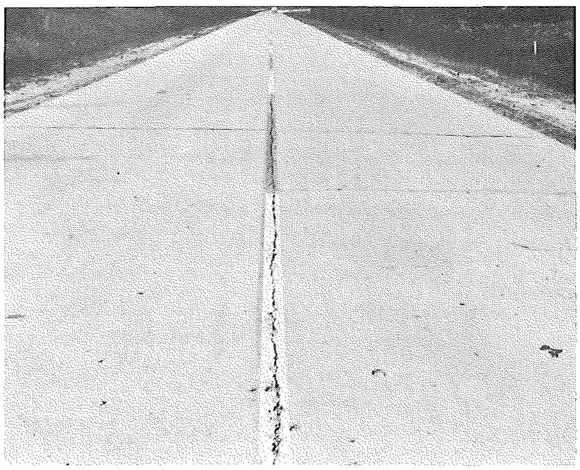


Modified Sand
Section 7E, Sta. 713+00

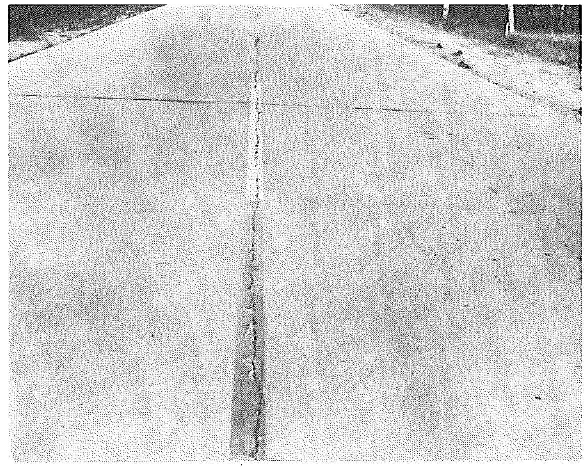


Standard construction, Cement No. 1
Construction joint in foreground
Section 6B, Sta. 599+15

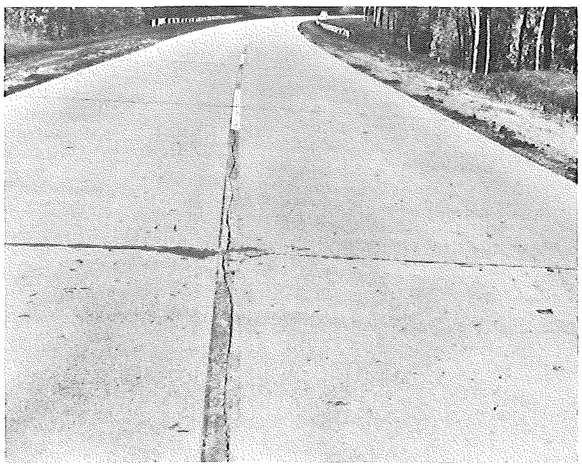
Figure 35. Pavement condition, May 1957.
Proportioning and grading of aggregates, proprietary admixtures.



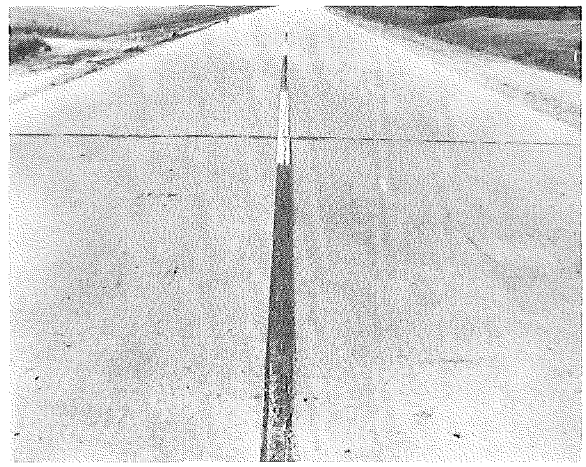
AEA No. 1, Cement No. 1
Section 4F, Sta. 464+50



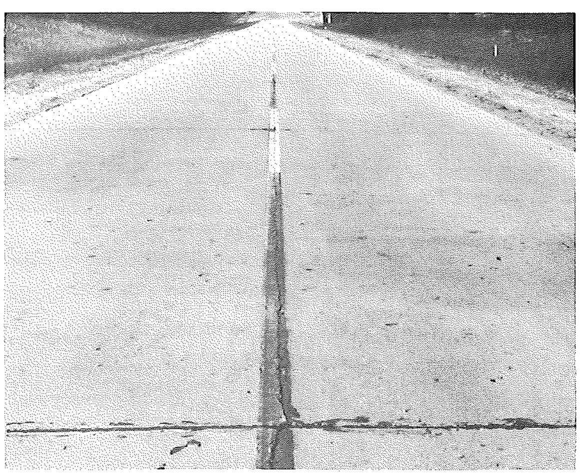
AEA No. 2, Cement No. 1
Section 5A, Sta. 519+00



AEA No. 1, Cement No. 2
Section 4H, Sta. 488+40



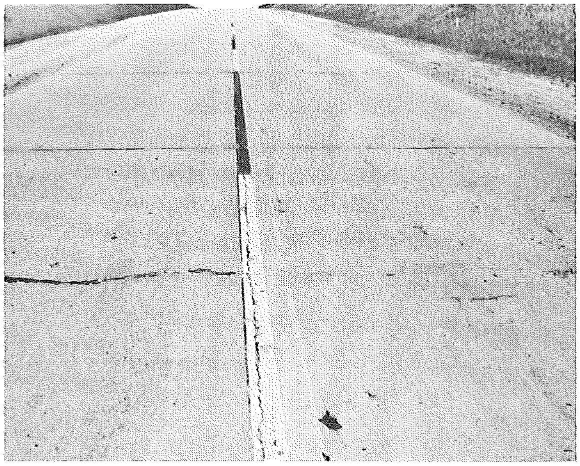
AEA No. 2, Cement No. 2
Section 5C, Sta. 549+00



AEA No. 1 with 1% $CaCl_2$, Cement No. 1
Section 4F-1, Sta. 466+50

AEA No. 2 with 1% $CaCl_2$, Cement No. 1
Section 5A-1, Sta. 532+50

Figure 36. Pavement condition, May 1957. Air-entraining agents.

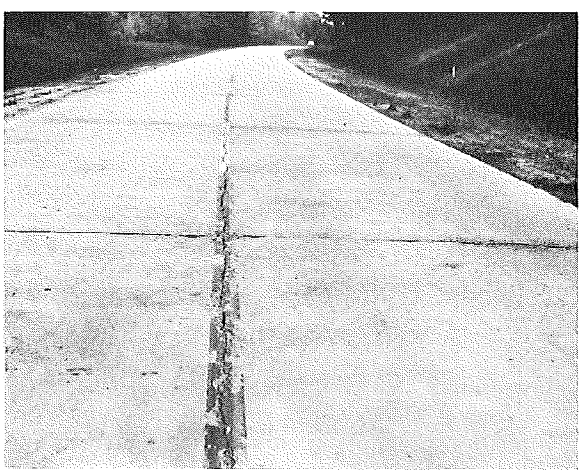


Natural cement without grinding aid
Section 6A, Sta. 584+80

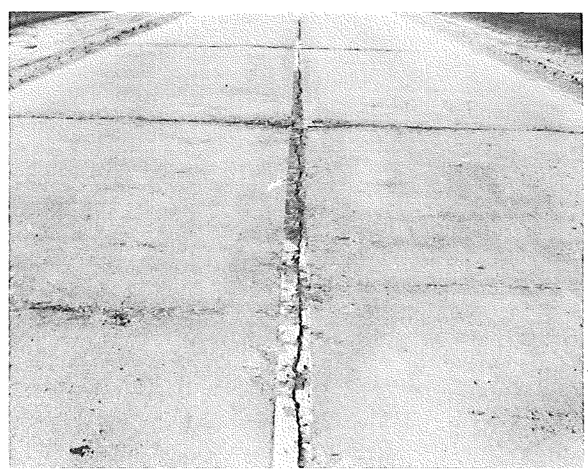
Natural cement with grinding aid
Section 6C, Sta. 609+00

Limestone aggregates (May 1951)
Section 8B, approx. Sta. 758

Limestone aggregate with limestone dust
(May 1951)
Section 8A, Sta. 753+46

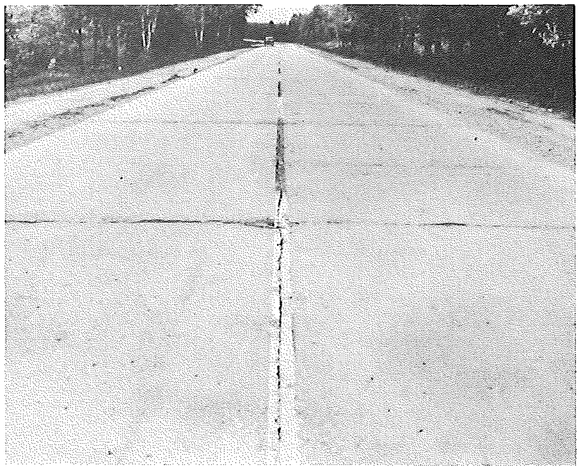


Standard construction, Cement No. 2
Section 4I, Station 560+50

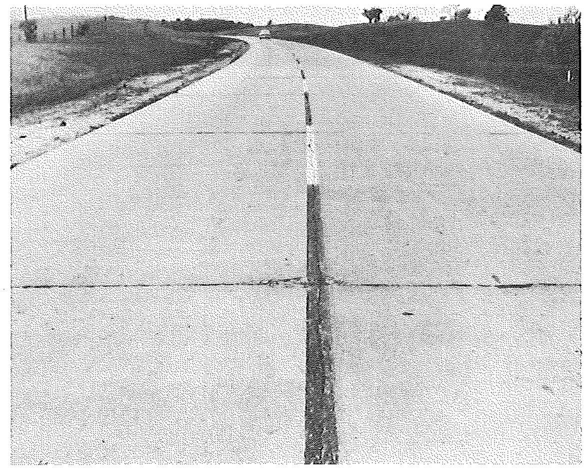


Standard construction, Cement No. 2
Section 5D, Sta. 582+00

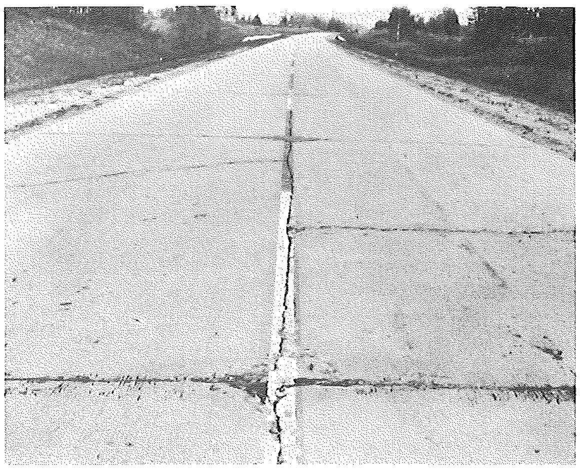
Figure 37. Pavement condition, May 1957. Natural cement blends, limestone materials, and standard construction with Cement No. 2.



Cement No. 1
Section 4A, Sta. 407+15



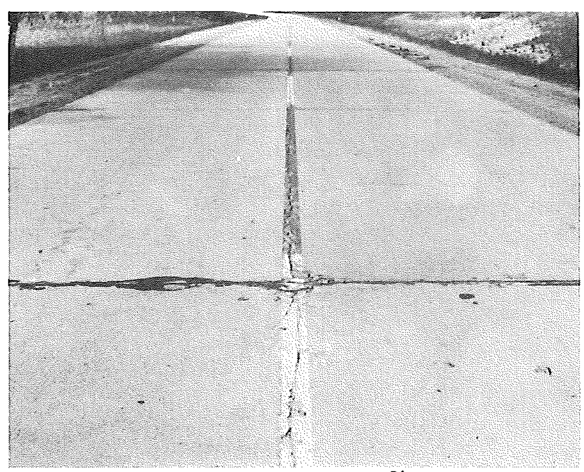
Cement No. 1
Section 4C, Sta. 428+90



Cement No. 1
Section 5B, Sta. 539+00

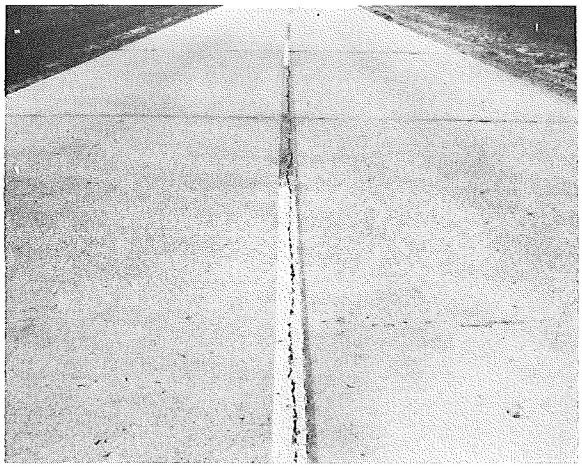
Cement No. 1
Section 6B, Sta. 598+00

Cement No. 1
Section 7B, Sta. 661+30

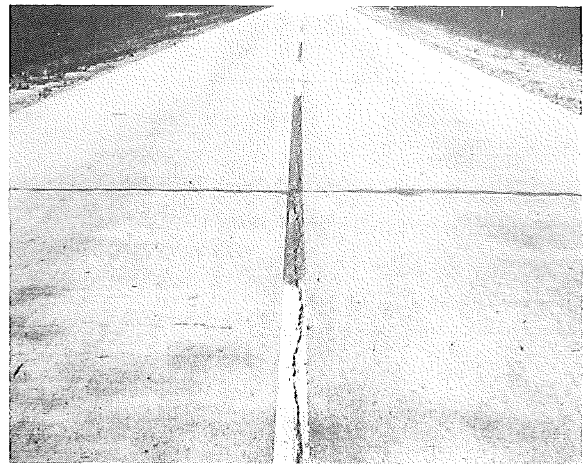


Cement No. 1 with 2% $CaCl_2$
Section 4A-1, Sta. 412+40

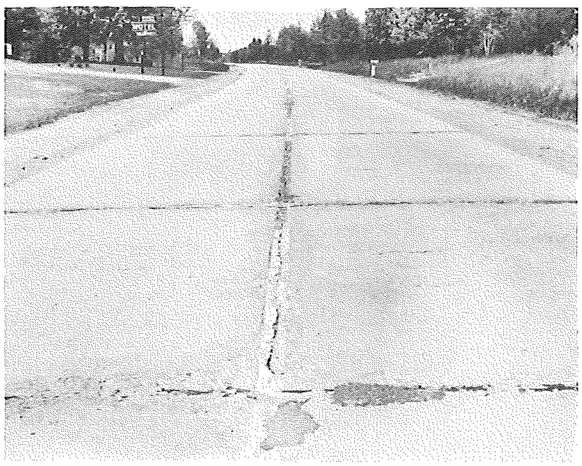
Figure 38. Pavement condition, May 1957. Standard construction with Cement No. 1.



Broom finish, wet earth curing
Section 1B-1, Sta. 625+00

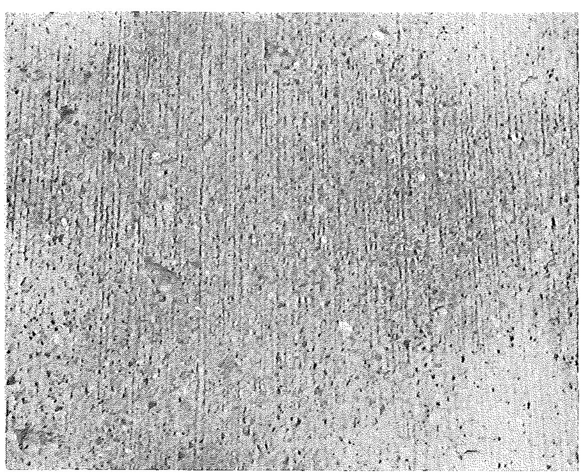


Broom finish, cutback asphalt curing
Section 2B, Sta. 620+00

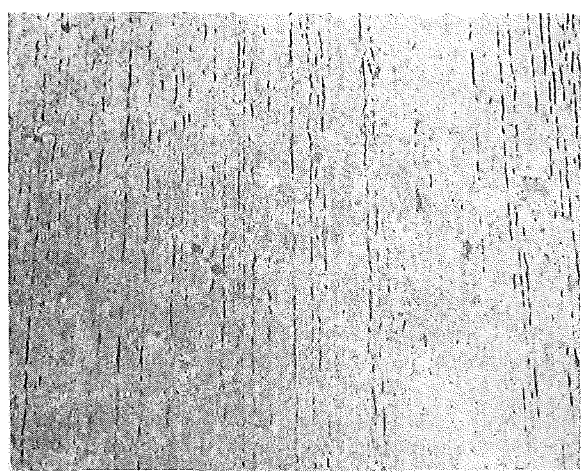


Broom finish, wet straw curing
Section 1B, Sta. 377+10

Broom finish, asphalt emulsion curing
Section 2A, Sta. 384+00

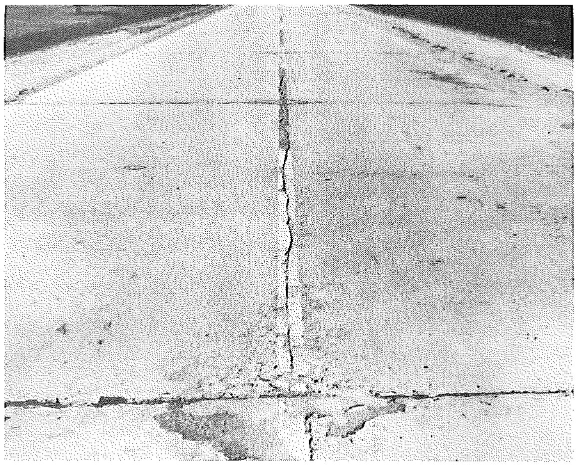


Texture of broomed surface
Section 1B, Sta. 377+85

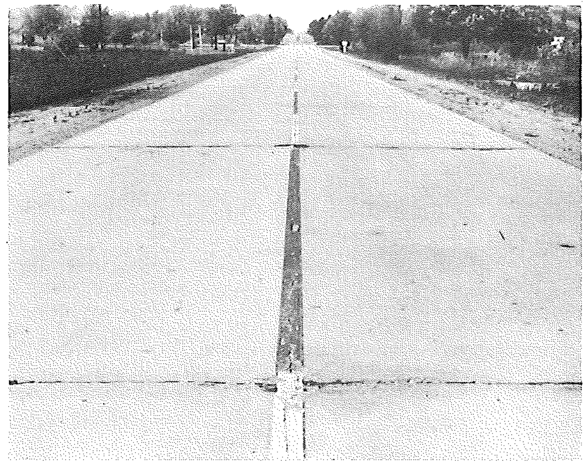


Texture of broomed surface
Section 2A, Sta. 384+20

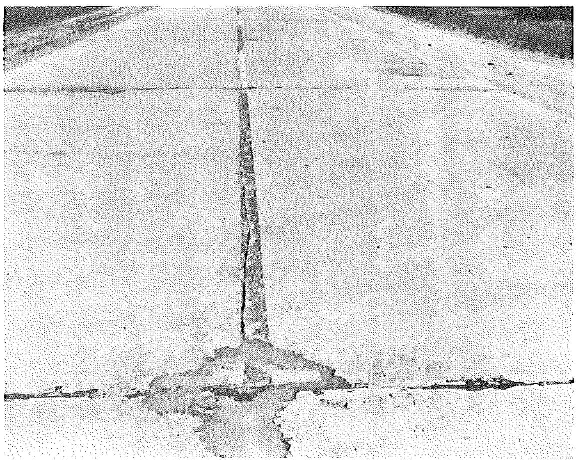
Figure 39. Pavement condition, May 1957. Finishing methods.



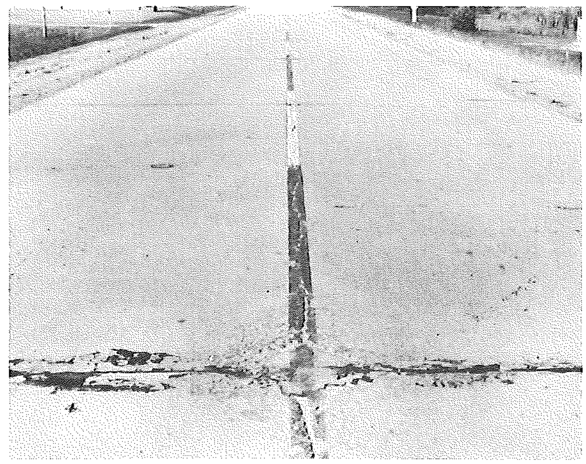
Wetted earth curing
Section 3A-4, Sta. 398+10



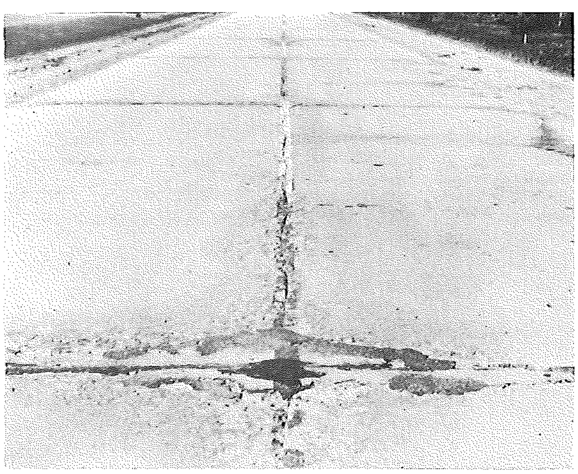
Asphalt emulsion curing
Section 3A-1, Sta. 394+50



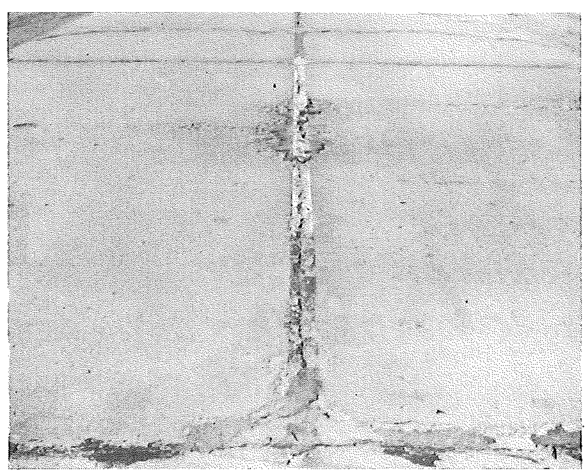
Ponding
Section 3A-5, Sta. 399+30



Paper with initial burlap
Section 3A-3, Sta. 396+90



Double burlap
Section 3A-6, Sta. 400+50



Transparent membrane
Section 3A-9, Sta. 404+10

Figure 40. Pavement condition, May 1957. Curing methods.

GENERAL SUMMARY

This investigation of concrete durability was undertaken to find ways of increasing the scale resistance of concrete pavements by changing the characteristics of the concrete and improving construction methods. In the Durability Project particular attention was given to the effects of various concrete-making materials, admixtures, and construction operations on strength and durability for comparison with the performance of standard concrete construction. The principal results are recapitulated as follows:

1. Air entrainment was the most effective method of eliminating or minimizing scaling of concrete surfaces. The same result was achieved regardless of the means used to entrain the air. Flexural and compressive strengths were appreciably reduced by the presence of air but not enough to endanger the pavement structurally.

2. Adding fines to supplement fine aggregate grading had no value as a scale prevention measure. None of these mixtures was more durable than standard concrete and one was considerably less.

3. Both proprietary admixtures produced scale-resistant concrete, Admixture No. 1 proving especially effective because of its air-entraining ability.

4. Blending natural cement with portland cement was also successful in checking scaling; natural cement with the air-entraining grinding aid had the same beneficial effect as air-entraining cement.

5. Limestone aggregates in mixtures without entrained air were conducive to excessive scaling. Adding limestone dust aggravated rather than relieved this effect.

6. Brooming was moderately beneficial but not greatly superior to burlap finishing in its effect on surface durability.

7. Curing methods had little influence on ultimate durability. All methods provided sufficient water retention, but the bituminous and transparent membranes caused undesirable temperature effects in the concrete.

8. None of the admixtures or air-entraining materials affected setting time of the concrete enough to interfere with the normal sequence of construction operations.

9. None of the admixtures or air-entraining materials significantly affected volume change characteristics of the concrete. Mixtures containing limestone aggregates expanded and contracted less than the others because of the lower thermal expansion coefficient of these aggregates. No longtime volume growth could be detected with certainty by the method of measurement used in this study.

10. Changing the coarse aggregate ratio, b/b_0, from 0.76 to 0.80 did not consistently affect strength or durability and in most cases had no adverse effect on workability.

11. Accelerated scaling tests on the pavement gave the most accurate forecast of subsequent performance of the various experimental sections. Freezing and thawing core specimens in a 10-percent calcium chloride solution was a more significant laboratory test than freezing and thawing either cores or molded beams in water.

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APPENDIX A
MATERIALS CHARACTERISTICS

TABLE 12
SUMMARY OF BASIC CONCRETE MIX DESIGNS

Factor Studied	b/b_o	Cement Brand	Materials, lb per sack of cement			
			Water	Fine Aggregate	Coarse Aggregate	Admixture
Proportioning and Grading						
Silica Dust	0.76	1	53.1	215	384	15.45
Silica Dust	0.80	1	52.2	209	394	15.45
Limestone Dust	0.76	1	53.4	218	383	15.45
Limestone Dust	0.80	1	52.4	212	394	15.45
Modified Sand	0.76	1	53.0	185	383	31.82
Modified Sand	0.80	1	51.2	173	404	31.82
Proprietary Admixtures						
Admixture No. 1	0.76	1	45.4	218	384	2.0
Admixture No. 1	0.80	1	43.8	205	404	2.0
Admixture No. 2	0.76	1	49.2	222	384	1.0
Admixture No. 2	0.80	1	47.3	207	404	1.0
Air-Entraining Agents						
AEA No. 1	0.76	1	49.7	215	384	0.015
AEA No. 1	0.80	1	47.8	200	404	0.015
AEA No. 1	0.76	2	49.5	216	384	0.015
AEA No. 1	0.80	2	47.7	203	405	0.015
AEA No. 2	0.76	1	49.5	218	383	0.050
AEA No. 2	0.80	1	48.5	211	394	0.050
AEA No. 2	0.76	2	49.5	219	383	0.038
AEA No. 2	0.80	2	48.7	211	394	0.038
Natural Cement Blends						
Without Grinding Aid	0.76	1	53.4	214	384	15.0
Without Grinding Aid	0.80	1	52.4	207	394	15.0
With Grinding Aid	0.76	1	53.3	208	383	15.0
With Grinding Aid	0.80	1	52.2	201	394	15.0
Limestone Materials						
Limestone Aggregates	0.76	1	57.6	240	336	15.45
Limestone Agg. with Limestone Dust	0.76	1	53.7	243	336	-----
Standard Construction						
Cement No. 1	0.76	1	49.2	223	383	-----
Cement No. 2	0.76	2	49.2	226	383	-----

TABLE 13
CHARACTERISTICS OF PORTLAND CEMENTS

Item	Portland Cement			
	Standard		With Interground Resin	
	No. 1	No. 2	No. 1	No. 2
Specific Surface, sq cm per g	1,650	1,800	1,745	2,001
Specific Gravity	3.12	3.07	3.13	3.11
Normal Consistency	24.8	27.4	26.4	27.0
Initial Setting Time, hr-min	3-40	3-35	4-10	3-35
Final Setting Time, hr-min	5-40	5-20	6-40	5-35
Passing No. 100 Sieve, percent	100	100	100	100
Passing No. 200 Sieve, percent	95	98	96	98.5
Interground Resin, percent	--	--	0.050	0.038
Loss on Ignition, percent	1.25	1.06	1.30	1.17
Insoluble Matter, percent	0.19	0.20	0.22	0.21
Sulphuric Anhydride (SO_3), percent	1.74	1.65	1.80	1.58
Silica (SiO_2), percent	20.88	22.67	21.11	22.73
Ferric Oxide (Fe_2O_3), percent	2.70	2.09	2.68	2.10
Aluminum Oxide (Al_2O_3), percent	6.62	4.68	6.71	4.59
Lime (CaO), percent	62.83	64.52	63.01	64.12
Magnesia (MgO), percent	3.17	3.16	3.00	2.98

TABLE 14
SPECIFICATIONS FOR INTERGROUND RESIN, AEA No. 2

Item	Minimum	Maximum
Melting point, Hercules Drop Method, deg C	110	125
Acid number	85	105
Gasoline-insoluble, percent	85	--
Toluene-insoluble, percent	15	30
Acetone-insoluble, percent	--	2
Ash, percent	--	0. 3
Passing No. 30 Sieve, percent	100	--
Passing No. 80 Sieve, percent	90	100
Passing No. 200 Sieve, percent	60	80

TABLE 15
TYPICAL GRADING OF NATURAL SAND AND BLEND SAND

Sieve Size	Total Percent Passing	
	Natural Sand 2NS	Blend Sand
3/8 in.	100	--
No. 4	98	99
No. 10	75	--
No. 20	45	--
No. 40	--	99
No. 50	16	--
No. 100	3	69
No. 200	--	51
Silt and Clay, 0. 005 mm	--	40
Clay, 0. 001 mm	--	5

TABLE 16
CHARACTERISTICS OF NATURAL COARSE AGGREGATES

Item	Amount, Percent	
	4A	10A
Passing 2-1/2-in. sieve	100	--
Passing 2-in. sieve	100	--
Passing 1-1/2-in. sieve	84	--
Passing 1-in. sieve	23	100
Passing 1/2-in. sieve	--	55
Passing 3/8-in. sieve	1.7	25
Passing No. 4 sieve	--	1.1
Loss by washing	0.2	0.1
1. Soft and non-durable particles	1.2	0.6
2. Chert particles	0.7	9.0
3. Hard absorbent sandstone	1.8	0.7
Sum of 1, 2, and 3	3.7	10.3
Thin elongated particles	0.7	0.5
Incrusted particles, greater than 1/3 surface area	1.4	0.3
Incrusted particles, 1/3 surface area or less	1.7	1.8
Crushed material in abrasion	29.1	--
Percent of wear, modified "A" abrasion	3.7	--
Specific Gravity, bulk, dry basis	2.65	2.62
Absorption, percent	1.09	1.73

TABLE 17
CHARACTERISTICS OF LIMESTONE FINE AND COARSE AGGREGATES

Item	Coarse Aggregate		Fine Aggregate
	4A	10A	2SS
Passing 2-1/2-in. sieve, percent	100	--	--
Passing 2-in. sieve, percent	100	--	--
Passing 1-1/2-in. sieve, percent	67	--	--
Passing 1-in. sieve, percent	13	100	--
Passing 1/2-in. sieve, percent	--	53	--
Passing 3/8-in. sieve, percent	1.1	37	100
Passing No 4 sieve, percent	--	7.3	99
Passing No. 8 sieve, percent	--	--	88
Passing No. 16 sieve, percent	--	--	52
Passing No. 30 sieve, percent	--	--	28
Passing No. 50 sieve, percent	--	--	13
Passing No. 100 sieve, percent	--	--	4.3
Loss by washing, percent	0.3	0.7	2.0
Soft and non-durable particles, percent	0.0	0.0	--
Thin elongated particles, percent	--	7.7	--
Percent wear, modified "A" abrasion	11.9	--	--
Absorption, percent	0.58	0.66	1.47
Specific Gravity, bulk	2.66	2.66	2.62

TABLE 18
MECHANICAL ANALYSIS OF MINERAL FILLERS

Sieve Size	Total Percent Passing		
	MSHD Spec.	Silica Dust	Limestone Dust
No. 40	100	100	100
No. 80	--	98.8	99.4
No. 100	--	98.4	99.2
No. 200	75 min	78.4	89.8

TABLE 19
SUMMARY OF SUBBASE CONDITIONS AT TIME OF POURING CONCRETE SLAB

Station	9 in. Below Surface		18 in. Below Surface	
	Moisture, percent	Natural Density, pcf	Moisture, percent	Natural Density, pcf
474+40	8.8	103	9.3	124
598+00	3.0	107	3.7	105
600+50	9.8	110	5.4	108
605+80	8.1	111	5.0	110
609+75	8.5	121	7.4	115
629+50	5.3	108	5.5	108
632+75	6.4	111	4.9	110
677+00	5.1	108	2.6	107
730+00	4.0	110	5.0	113
740+00	4.5	111	4.4	113

TABLE 20
TYPICAL MECHANICAL ANALYSIS OF GRANULAR SUBBASE MATERIAL

General Characteristics: Loose, incoherent, fine, granular material	
Gravel, percent retained by No. 10 sieve	6.2
Sand, percent retained by No. 270 sieve	85.5
Silt, percent larger than 0.005 mm	5.7
Clay, percent larger than 0.001 mm	2.6

APPENDIX B
SUPPLEMENTARY TABLES

TABLE 21
CLASSIFICATION OF ANNUAL AVERAGE DAILY TRAFFIC

Year	Total Daily Traffic	Passenger		Commercial	
		No.	%	No.	%
1941	1058	946	89.4	112	10.6
1942	870	701	80.6	169	19.4
1943	580	430	74.1	150	25.9
1944	598	475	79.4	123	20.6
1945	805	667	82.9	138	17.1
1946	1206	1056	87.6	150	12.4
1947	1185	1035	87.3	150	12.7
1948	1368	1208	88.3	160	11.7
1949	1467	1272	86.7	195	13.3
1950	1411	1221	86.5	190	13.5
1951	1411	1231	87.2	180	12.8
1952	1587	1397	88.0	190	12.0
1953	1649	1429	86.7	220	13.3
1954	1606	1406	87.5	200	12.5
1955	1622	1402	86.4	220	13.6
1956	1664	1444	86.8	220	13.2
1957	1694	1469	86.7	225	13.3

TABLE 22
AVERAGE WHEEL LOAD DISTRIBUTION

Wheel Load	1941-46		1947-52		1953-57		1941-57	
	No.	%	No.	%	No.	%	No.	%
Under 4000	3653	61.54	6835	62.38	1011	71.75	11,499	62.83
4000 - 4499	191	3.22	414	3.78	60	4.26	665	3.63
4500 - 4999	144	2.43	327	2.98	36	2.55	507	2.77
5000 - 5499	180	3.03	358	3.27	24	1.70	562	3.07
5500 - 5999	157	2.64	352	3.21	27	1.92	536	2.93
6000 - 6499	222	3.74	411	3.75	29	2.06	662	3.62
6500 - 6999	231	3.89	376	3.43	32	2.27	639	3.49
7000 - 7499	225	3.79	404	3.69	22	1.56	651	3.56
7500 - 7999	329	5.54	416	3.80	27	1.92	772	4.22
8000 - 8499	283	4.77	376	3.43	39	2.77	698	3.81
8500 - 8999	156	2.63	315	2.86	56	3.98	527	2.88
9000 - 9499	109	1.84	207	1.89	28	1.99	344	1.88
9500 - 9999	54	0.91	95	0.87	12	0.85	161	0.88
10,000 - 10,499	2	0.03	39	0.36	2	0.14	43	0.24
10,500 - 10,999			18	0.16	2	0.14	20	0.11
11,000 - 11,499			5	0.05	1	0.07	6	0.03
11,500 - 11,999			3	0.03	1	0.07	4	0.02
12,000 - 12,499								
12,500 - 12,999			1	0.01			1	0.01
13,000 - 13,499			3	0.03			3	0.02
13,500 - 13,999			1	0.01			1	0.01
46,500 - 46,599			1	0.01			1	0.01
Totals	5936	100.00	10,957	100.00	1409	100.00	18,302	100.00

TABLE 23
CLASSIFIED SUMMARY OF DATA FROM ACCELERATED SCALING TESTS

Factor Studied	Cement Brand	Scaling Studies 1940-1941				Scaling Studies 1941-1942			
		Panel No.	Test B		Degree Scale[1]	Panel No.	Test B		Degree Scale[1]
			Cycles	% Scale			Cycles	% Scale	
Proportioning and Grading									
Silica Dust	1	24	33	70	2.1	26	33	100	3.0
Limestone Dust	1	26	33	94	2.8	28	8	100	12.5
Modified Sand	1	27	21	100	4.8	29	12	100	8.3
Proprietary Admixtures									
Admixture No. 1	1	12	33	1	0.0	8	93[2]	6	0.1
Admixture No. 1	1	--	--	--		9	61	8	0.1
Admixture No. 2	1	13	33	22	0.7	10	61	56	0.9
Air-Entraining Agents									
AEA No. 1	1	15	33	0	0.0	12	93[2]	0	0.0
AEA No. 1	1	--	--	--	---	13	60	0	0.0
AEA No. 1	2	16	33	0	0.0	14	94[2]	0	0.0
AEA No. 1	2	--	--	--	---	15	61	0	0.0
AEA No. 2	1	18	33	0	0.0	17	93[2]	0	0.0
AEA No. 2	1	--	--	--	---	18	60	0	0.0
AEA No. 2	2	19	33	0	0.0	19	94[2]	0	0.0
AEA No. 2	2	--	--	--	---	20	61	0	0.0
Natural Cement Blends									
Nat. Cem. Without Grinding Aid	1	21	29	0	0.0	22	90[2]	44	0.5
Nat. Cem. Without Grinding Aid	1	--	--	--	---	23	31	100	3.2
Nat. Cem. With Grinding Aid	1	22	33	0	0.0	24	94[2]	0	0.0
Nat. Cem. With Grinding Aid	1	--	--	--	---	25	61	0	0.0
Limestone Materials									
Limestone Aggregates	1	29	22	100	4.5	31	6	100	16.7
Limestone Agg. with Limestone Dust	1	28	13	100	7.7	30	6	100	16.7
Standard Construction									
Cement Brand No. 1	1	14	33	61	1.8	11	41	100	2.4
Cement Brand No. 1	1	25	13	100	7.7	27	9	100	11.1
Cement Brand No. 2	2	17	27	56	2.1	16	9	100	11.1
Cement Brand No. 2	2	20	21	100	4.8	21	32	100	3.1
Finishing Methods									
Broom, Cutback Asphalt Curing [3]	1	23	33	83	2.5	--	--	---	---
Broom, Wetted Straw Curing	1	1	33	95	2.9	1	23	100	4.3
Broom, Asphalt Emulsion Curing	1	2	28	92	3.3	--	--	---	---
Curing Methods									
Asphalt Emulsion [5]	1	3	28	61	2.2	2	47	100	2.1
Wetted Straw	1	4	28	19	0.7	--	--	---	---
Paper [5]	1	5	28	0	0.0	3	89[2]	68	0.8
Paper [5]	1	--	--	--	---	4	47	100	2.1
Wetted Earth	1	6	28	33	1.2	--	--	---	---
Ponding	1	7	28	28	1.0	--	--	---	---
Double Burlap [3]	1	8	28	14	0.5	--	--	---	---
Paper, No Initial Curing [3]	1	9	28	3	0.1	--	--	---	---
Calcium Chloride Integrally Mixed [4]	1	10	28	17	0.6	5	61	73	1.2
Transparent Membrane [5]	1	11	28	0	0.0	6	89[2]	36	0.4
Transparent Membrane [5]	1	--	--	--	---	7	61	12	0.2
Special Study in Design Project									
Rain-Marked Surface	2	--	--	--	---	32	61	4	0.1
Standard Construction	2	30	29	92	3.2	33	9	100	11.1
Standard Construction	2	--	--	--	---	34	7	100	14.3

(1) $\text{Degree Scale} = \dfrac{\text{Percent Scale}}{\text{Number of Cycles}}$

(2) 1942 Scaling tests continued on 1941 panels; number indicates total cycles at end of 1942 tests.

(3) Curing applied immediately after finishing operations.

(4) No subsequent curing employed.

(5) Initial 24-hr burlap cure.

TABLE 24
SUMMARY OF FREEZING AND THAWING DATA
3- by 6- by 15-in. Sonic Beams

Factor Studied	Cement Brand	Age of Specimens, 5 Months					Age of Specimens, 1 Year				
		Number of Specimens	To 50% Reduction in Modulus		To Failure 90-100% Reduction		Number of Specimens	To 50% Reduction in Modulus		To Failure 90-100% Reduction	
			No. Cycles	Rate(1)	No. Cycles	Rate(1)		No. Cycles	Rate(1)	No. Cycles	Rate(1)
Proportioning and Grading											
Silica Dust	1	4	28	1.79	56	1.79	2	22	2.27	75	1.33
Limestone Dust	1	4	13	3.85	28	3.57	2	16	3.13	74	1.35
Modified Sand	1	4	19	2.63	57	1.75	2	18	2.78	73	1.37
Proprietary Admixtures											
Admixture No. 1	1	4	66	0.76	91	1.10	2	36	1.39	150	0.67
Admixture No. 2	1	3	23	2.17	47	2.13	2	15	3.33	88	1.14
Air-Entraining Agents											
AEA No. 1	1	3	48	1.04	84	1.19	2	37	1.35	90	1.11
AEA No. 1	2	4	30	1.67	62	1.61	2	28	1.79	105	0.95
AEA No. 1 plus 1% $CaCl_2$	1	2	40	1.25	66	1.52	2	28	1.79	95	1.05
AEA No. 2	1	2	45	1.11	73	1.37	-	--	----	--	----
AEA No. 2	2	4	37	1.35	67	1.49	2	20	2.50	81	1.23
AEA No. 2 plus 1% $CaCl_2$	1	2	51	0.98	83	1.20	1	18	2.78	95	1.05
Natural Cement Blends											
Nat. Cem. without Grinding Aid	1	4	31	1.61	60	1.67	1	37	1.35	120	0.83
Nat. Cem. with Grinding Aid	1	4	26	1.92	56	1.79	2	46	1.09	80	1.25
Limestone Materials											
Limestone Aggregates	1	2	107	0.47	143	0.70	2	117	0.43	182	0.55
Limestone Agg. with Limestone Dust	1	2	27	1.85	45	2.22	2	37	1.35	105	0.95
Standard Construction											
Cement Brand No. 1	1	2	30	1.67	58	1.72	2	20	2.50	83	1.20
Cement Brand No. 2	2	4	25	2.00	49	2.04	2	14	3.57	75	1.33
Calcium Chloride, 2% for Curing	1	2	10	5.00	45	2.22	2	11	4.55	40	2.50

(1) Rate of Disintegration = $\frac{\text{Percent Reduction}}{\text{Number of Cycles}}$

TABLE 25
SPECIFIC GRAVITY OF PAVEMENT CORES

Test Area	Factor Studied	Core Identification		Brand of Cement	b/b_o	Whole Core	Top			Middle, Whole	Bottom		
		Station	Core No.				Whole	A	B		Whole	A	B
2 A	Broom Finish, Asphalt Emulsion Curing	393+45	204	1	0.76	2.485	2.492	2.505	2.486	2.499	2.497	2.505	2.502
3 A-1	Asphalt Emulsion Curing, Initial Curing	394+65	205	1	0.76	2.495	2.469	2.463	2.483	2.548	2.492	2.519	2.497
3 A-2	Wetted Straw	395+85	206	1	0.76	2.493	2.466	2.486	2.466	2.502	2.516	2.518	2.515
3 A-3	Paper, Initial Curing	397+05	207	1	0.76	2.497	2.501	2.482	2.504	2.512	2.517	2.547	2.495
3 A-4	Wetted Earth	398+25	208	1	0.76	2.486	2.473	2.480	2.477	2.495	2.520	2.503	2.564
3 A-5	Ponding	399+45	209	1	0.76	2.491	2.472	2.504	2.459	2.516	2.482	2.504	2.492
3 A-6	Double Burlap	400+65	210	1	0.76	2.467	2.482	2.468	2.494	2.514	2.429	2.464	2.422
3 A-7	Paper	401+85	211	1	0.76	2.481	2.486	2.484	2.502	2.481	2.495	2.515	2.500
3 A-8	2% Calcium Chloride	403+95	212	1	0.76	2.473	-----	-----	-----	-----	-----	-----	-----
3 A-9	Membrane	404+25	213	1	0.76	2.482	2.475	2.470	2.535	2.499	2.484	2.473	2.498
4 B	Admixture No. 1	427+95	215	1	0.80	2.453	2.414	2.439	2.425	2.454	2.508	2.514	2.524
4 D	Admixture No. 2	443+85	217A	1	0.76	2.509	2.499	2.491	2.513	2.538	2.510	2.505	2.508
4 D	Admixture No. 2	451+95	218	1	0.80	2.490	2.535	2.538	2.536	2.526	2.475	2.467	2.500
4 F	AEA No. 1	475+05	220	1	0.80	2.432	2.427	2.463	2.426	2.465	2.441	2.458	2.458
4 F	AEA No. 1	497+85	222A	2	0.80	2.429	2.405	2.397	2.430	2.424	2.465	2.446	2.505
4 F	AEA No. 1	499+05	223	2	0.80	2.457	2.194	2.478	2.509	2.454	2.449	2.458	2.452
4 I	Standard Construction	501+25	223A	2	0.76	2.521	2.498	2.490	2.535	2.549	2.502	2.509	2.532
4 I	Standard Construction	506+25	224	2	0.76	2.490	2.496	2.478	2.517	2.511	2.522	2.534	2.528
5 A	AEA No. 2	512+25	225	1	0.76	-----	2.372	-----	-----	2.524	2.463	-----	-----
5 A	AEA No. 2	514+65	225A	1	0.76	2.387	2.377	2.408	2.376	2.387	2.417	2.407	2.458
5 A	AEA No. 2	532+35	227	1	0.80	2.390	2.380	2.405	2.373	2.412	2.404	2.394	2.426
5 B	Standard Construction	545+85	228	1	0.76	2.481	2.479	2.476	2.492	2.515	2.481	2.497	2.501
5 C	AEA No. 2	563+85	229A	2	0.76	2.456	2.462	2.483	2.483	2.458	2.477	2.489	2.478
5 C	AEA No. 2	566+25	230	2	0.80	2.452	2.428	2.457	2.450	2.482	2.462	2.502	2.444
5 D	Standard Construction	573+45	231	2	0.76	2.463	2.479	2.483	2.495	2.487	2.474	2.486	2.486
5 D	Standard Construction	583+05	232	2	0.76	2.497	2.488	2.504	2.478	2.516	2.507	2.509	2.514
6 A	Natural Cement without Grinding Aid	594+95	234	1	0.80	2.479	2.450	2.464	2.462	2.502	2.494	2.518	2.488
6 C	Natural Cement with Grinding Aid	614+25	236	1	0.80	2.417	2.394	2.379	2.392	2.458	2.446	2.455	2.437
6 C	Natural Cement with Grinding Aid	619+05	237	1	0.80	2.444	2.412	2.435	2.409	2.462	2.441	2.437	2.450
2 B	Broom, Cutback Asphalt	624+25	239	1	0.76	2.478	2.471	2.475	2.499	2.507	2.462	2.479	2.461
7 A	Silica Dust	643+35	241A	1	0.76	2.465	2.441	2.465	2.441	2.487	2.480	2.503	2.486
7 A	Silica Dust	645+45	242	1	0.80	2.461	2.435	2.455	2.448	2.472	2.471	2.494	2.473
7 B	Standard Construction	656+25	243	1	0.76	2.452	2.443	2.462	2.443	2.488	2.488	2.515	2.476
7 C	Limestone Dust	680+25	246	1	0.80	2.471	2.454	2.457	2.462	2.501	2.465	2.483	2.482
7 D	Standard Construction	692+25	247	1	0.76	2.459	2.464	2.472	2.474	2.479	2.484	2.510	2.485
7 E	Modified Sand	722+25	250	1	0.80	2.486	2.450	2.484	2.470	2.482	2.509	2.514	2.537
7 F	Standard Construction	734+15	251	1	0.76	2.450	2.484	-----	-----	2.462	2.476	-----	-----
8 A	Limestone Agg. with Limestone Dust	752+25	253	1	0.76	2.458	2.428	2.442	2.426	2.472	2.481	2.504	2.492
8 B	Limestone Aggregate	761+85	255	1	0.76	2.450	2.424	2.440	2.427	2.518	2.455	2.448	2.471

TABLE 26
RATE OF MOISTURE CHANGE IN CORES DURING DRYING AND SATURATION

Factor Studied	Durability F & T Cycles		Moisture Content Percent Oven Dry Weight		Rate of Moisture Loss, Drying Period Percent of Original Moisture Per Hour					Rate of Moisture Gain, Saturation Period Percent of Final Moisture Per Hour						
	Water	$CaCl_2$	Air Dry	Saturated	Per. 1 6 hr	Per. 2 6 hr	Per. 3 12 hr	Per. 4 24 hr	Per. 5 24 hr	Per. 1 1/2 hr	Per. 2 1/2 hr	Per. 3 2 hr	Per. 4 3 hr	Per. 5 6 hr	Per. 6 12 hr	Per. 7 72 hr
Proportioning and Grading																
Silica Dust	113	93	2.45	4.30	7.61	3.06	1.63	.54	.14	54.0	22.8	11.2	5.57	2.21	.39	.07
Limestone Dust	168	60	2.29	4.26	8.30	2.91	1.07	.40	.13	57.2	21.6	11.4	5.32	2.23	.35	.06
Modified Sand	55	23	1.44	4.42	12.32	1.62	.81	.20	.12	50.6	17.7	9.5	5.05	2.64	.87	.08
Proprietary Admixtures																
Admixture No. 1	178	181	2.22	3.73	5.63	2.40	2.67	.68	.15	55.3	17.2	9.0	5.01	2.64	.89	.06
Admixture No. 2	124	60	1.99	3.23	4.85	2.34	2.89	.78	.15	47.0	17.9	9.6	4.85	2.48	1.03	.09
Air-Entraining Agents																
AEA No. 1, Cement No. 1	205	173	2.34	3.99	5.27	2.64	2.89	.57	.18	52.2	19.6	10.2	5.18	2.55	.75	.06
AEA No. 1, Cement No. 2	155	93	2.17	4.35	5.30	2.84	2.84	.56	.15	71.9	24.4	12.3	5.06	1.07	.17	.05
AEA No. 2, Cement No. 1	200	176	2.01	3.99	6.47	2.74	2.69	.44	.08	57.6	18.6	10.9	4.76	2.42	.61	.06
AEA No. 2, Cement No. 2	208	138	2.03	2.91	6.00	3.21	2.30	.58	.14	84.6	28.9	----	----	2.81	.29	.09
Natural Cement Blends																
Natural Cement without Grinding Aid	140	120	2.12	3.69	6.37	2.75	2.28	.63	.11	62.4	22.8	10.5	4.97	1.99	.45	.06
Natural Cement with Grinding Aid	158	194	1.91	3.84	8.90	2.62	1.56	.35	.15	51.6	16.7	9.0	4.86	2.56	.93	.09
Limestone Materials																
Limestone Aggregates	170	123	2.47	4.03	10.25	2.83	1.01	.25	.13	62.6	20.4	11.4	5.30	1.90	.31	.07
Limestone Agg. with Limestone Dust	103	70	2.58	4.10	9.16	2.90	1.58	.29	.07	61.0	21.5	10.9	5.12	1.99	.45	.06
Standard Construction																
Cement Brand No. 1	151	82	2.30	4.04	7.77	2.59	1.96	.41	.14	59.5	22.5	11.3	5.54	2.01	.32	.06
Cement Brand No. 2	99	50	2.03	3.82	6.71	2.50	2.33	.54	.17	65.8	22.0	12.5	5.06	1.44	.26	.06
Finishing Methods																
Broom Finish, Asphalt Emulsion Curing	123	80	2.02	4.05	7.10	2.48	1.90	.62	.21	59.8	20.2	12.5	5.85	1.85	.23	.05
Curing Methods																
Asphalt Emulsion	140	103	2.01	3.80	7.38	2.57	1.87	.56	.19	59.0	21.1	11.8	5.44	1.97	.31	.06
Wetted Straw	108	80	2.20	3.93	6.67	2.20	2.24	.63	.21	53.9	18.8	11.2	5.93	2.33	.47	.05
Paper	155	108	1.94	3.41	6.62	2.15	2.23	.62	.24	54.0	21.1	11.3	6.06	2.15	.37	.06
Wetted Earth	98	73	2.08	3.82	5.37	2.24	2.40	.78	.28	55.5	20.4	10.6	5.58	2.44	.48	.05
Ponding	120	68	2.12	4.04	5.50	2.36	2.60	.67	.24	55.4	20.8	11.4	6.03	2.39	.25	.05
Double Burlap	65	38	1.65	3.62	6.40	2.44	1.80	.83	.23	55.8	20.5	11.1	5.62	2.30	.39	.06
Paper, No Initial Curing	146	93	2.30	4.35	5.66	2.54	2.17	.79	.24	57.9	20.2	11.9	5.66	2.14	.25	.06
Membrane, With Initial Curing	95	88	2.20	3.96	4.77	2.28	2.96	.80	.13	51.0	18.7	11.4	5.65	2.52	.55	.05

TABLE 27
PERMEABILITY OF PAVEMENT CORES

Factor Studied	Durability F & T Cycles		Water Passage in Gram-Inches Per Hour Per Square Foot for Successive Periods*										
	Water	$CaCl_2$	Period 1 4 Days	Period 2 4 Days	Period 3 4 Days	Period 4 4 Days	Period 5 4 Days	Period 6 5 Days	Period 7 3 Days	Period 8 5 Days	Period 9 3 Days	Period 10 4 Days	Average
Proportioning and Grading													
Silica Dust	124	90	0.43	0.29	0.43	0.57	0.29	0.57	0.19	0.34	0.19	0.72	0.40
Limestone Dust	168	60	X	X	X	0.63	0.78	0.75	0.63	0.50	0.63	0.63	0.65
Modified Sand	55	23	0.31	0.63	X	X	X	X	0.84	0.88	1.05	0.79	0.75
Proprietary Admixtures													
Admixture No. 1	178	181	0.15	0.44	0.44	0.44	0.44	X	0.39	0.35	0.58	0.29	0.39
Admixture No. 2	124	69	0.15	0.46	0.61	0.31	0.61	0.61	0.61	0.61	0.41	0.46	0.48
Air-Entraining Agents													
AEA No. 1, Cement No. 1	205	173	0.18	0.18	0.18	0.53	0.53	0.43	0.24	0.43	0.24	0.53	0.35
AEA No. 2, Cement No. 1	186	171	X	0.44	X	X	X	X	0.39	0.35	0.39	X	0.39
Natural Cement Blends													
Natural Cement Without Grinding Aid	140	120	0.68	0.68	0.51	0.51	0.68	0.55	0.23	0.68	0.46	0.85	0.58
Natural Cement With Grinding Aid	158	194	0.17	X	X	X	0.00	0.41	0.23	0.14	0.00	0.17	0.16
Limestone Materials													
Limestone Aggregates	170	123	X	0.61	0.61	0.30	0.45	0.36	0.40	0.24	0.40	X	0.42
Limestone Agg. with Limestone Dust	103	70	0.27	0.27	0.27	X	0.82	0.76	0.54	0.33	0.54	0.41	0.47
Standard Construction													
Cement Brand No. 1	151	82	X	1.23	0.92	0.77	0.77	1.10	1.23	1.23	1.23	X	1.06
Cement Brand No. 2	99	50	0.37	0.58	0.51	0.37	0.43	0.75	0.41	0.52	0.58	1.14	0.56

* Gram-inches = Water loss in grams x core thickness in inches
X Indicates faulty test. Water lost through seal.

TABLE 28
UNGROUPED FREQUENCY DISTRIBUTION OF SLUMP VALUES

Slump, In.	0	1/4	1/2	3/4	1	1-1/4	1-1/2	1-3/4	2	2-1/4	2-1/2	2-3/4	3	3-1/4	3-1/2	3-3/4	4	4-1/4	4-1/2	4-3/4	5	5-1/4
Frequency	1	2	3	0	7	7	27	18	26	31	17	6	4	1	1	1	3	0	1	0	1	1

TABLE 29
SETTING TIME OF CONCRETE

Concrete Mixture	Number of Tests	Temperature Range, deg F	Setting Time Range min	Average Setting Time min
Proportioning and Grading				
Silica Dust	4	50-57	76-127	96
Limestone Dust	4	59-70	121-183	148
Modified Sand	1	46	157	157
Air-Entraining Agents				
AEA No. 1, Cement No. 1	2	71-76	123-158	141
AEA No. 1, Cem. No. 1 + 1% $CaCl_2$	1	77	91	91
AEA No. 1, Cement No. 2	2	79-86	80-121	101
AEA No. 2, Cement No. 1	2	60-66	187-259	229
AEA No. 2, Cement No. 1 + 1% $CaCl_2$	2	60	83-106	95
AEA No. 2, Cement No. 2	4	55-63	64-69	66
Natural Cement Blends				
Natural Cement without Grinding Aid	4	68-75	45-125	85
Natural Cement with Grinding Aid	4	72-73	67-73	70
Standard Construction				
Cement No. 1	7	52-66	38-141	71
Cement No. 2	4	59-69	48-148	85

TABLE 30
CONDENSED SUMMARY OF COMPRESSIVE STRENGTHS

Factor Studied	Cement Brand	Field-Molded Cylinders					Pavement Cores				Swiss Hammer[1]	
		7 Day		28 Day			20 Mo		10 Yr		15 Yr	
		Compressive Strength, psi	Percent of Standard No. 1	Compressive Strength, psi	Percent of Standard No. 1	Percent of Spec. Requirement, 2500 psi	Compressive Strength, psi	Percent of Standard No. 1	Compressive Strength, psi	Percent of Standard No. 1	Compressive Strength, psi	Percent of Standard No. 1
Proportioning and Grading												
Silica Dust	1	3371	95	4606	100	184	4367	81	7450	128	7850	98
Limestone Dust	1	3417	96	4817	105	193	5520	103	6580	114	8150	101
Modified Sand	1	3125	88	4407	96	176	5740	107	6800	117	8300	103
Proprietary Admixtures												
Admixture No. 1	1	4000	113	4249	93	170	4730	88	4900	85	8000	99
Admixture No. 2	1	4655	131	6080	133	243	6320	118	7350	127	9400	117
Air-Entraining Agents												
AEA No. 1	1	2608	74	3728	81	149	3962	74	5600	97	6100	76
AEA No. 1	2	2324	66	3857	84	154	3820	71	5800	100	6200	77
AEA No. 1 + 1% $CaCl_2$	1	2213	62	3035	66	121	----	---	----	---	----	---
AEA No. 2	1	2845	80	3867	84	155	4010	75	3850	66	5950	74
AEA No. 2	2	3580	101	3991	87	160	5420	101	5100	88	7800	94
AEA No. 2 + 1% $CaCl_2$	1	2518	71	2895	63	116	----	---	----	---	----	---
Natural Cement Blends												
Nat. Cement without Grinding Aid	1	3190	90	3711	81	148	4345	81	6650	115	7000	87
Nat. Cement with Grinding Aid	1	2813	79	3479	76	139	3225	60	5200	90	6600	82
Limestone Materials												
Limestone Aggregates	1	3069	87	4176	91	167	5765	107	7200	124	----(2)	---
Limestone Agg. with Limestone Dust	1	2694	76	4099	89	164	5050	94	5600	97	----(2)	---
Standard Construction												
Cement Brand No. 1	1	3543	100	4587	100	183	5375	100	5800	100	8050	100
Cement Brand No. 2	2	2837	80	4597	100	184	6600	123	7300	126	8200	102
Calcium Chloride, 2% for Curing	1	4281	121	4867	106	195	----	---	----	---	----	---

(1) On pavement immediately adjacent to core locations
(2) Resurfaced 1951 - 1952

TABLE 31
CONDENSED SUMMARY OF FLEXURAL STRENGTHS
Third-Point Loading, ASTM Method C 78-39

Factor Studied	Cement Brand	Field-Molded Beams								Swiss Hammer[1]	
		6- by 8- by 36 Inches						3- by 6- by 15 Inches			
		7 Day			28 Day			10 Yr		15 Yr	
		Modulus of Rupture, psi	Percent of Standard No. 1	Percent of Spec. Requirement, 550 psi	Modulus of Rupture, psi	Percent of Standard No. 1	Percent of Spec. Requirement, 650 psi	Modulus of Rupture, psi	Percent of Standard No. 1	Modulus of Rupture, psi	Percent of Standard No. 1
Proportioning and Grading											
Silica Dust	1	549	97	100	638	91	98	842	93	890	97
Limestone Dust	1	537	95	98	704	100	108	935	104	910	99
Modified Sand	1	521	92	95	737	105	113	---		920	100
Proprietary Admixtures											
Admixture No. 1	1	538	95	98	617	88	95	828	92	900	98
Admixture No. 2	1	465	82	85	807	115	124	828	92	1050	114
Air-Entraining Agents											
AEA No. 1	1	389	69	71	562	80	87	797	88	760	83
AEA No. 1	2	425	75	77	602	86	93	707	78	765	83
AEA No. 1 + 1% $CaCl_2$	1	328	58	60	489	70	75	---	--	---	--
AEA No. 2	1	508	90	92	529	75	81	---	--	745	81
AEA No. 2	2	576	102	105	771	110	119	---	--	870	95
AEA No. 2 + 1% $CaCl_2$	1	449	79	82	552	79	85	---	--	---	--
Natural Cement Blends											
Nat. Cement without Grinding Aid	1	515	91	94	626	89	96	---	--	820	89
Nat. Cement with Grinding Aid	1	437	77	80	585	83	90	723	80	800	87
Limestone Materials											
Limestone Aggregates	1	768	135	140	585	83	90	---	--	---(2)	--
Limestone Agg. with Limestone Dust	1	578	102	105	489	70	75	929	103	---(2)	--
Standard Construction											
Cement Brand No. 1	1	567	100	103	702	100	108	904	100	920	100
Cement Brand No. 2	2	546	96	99	659	94	101	---	--	905	98
Calcium Chloride, 2% for Curing	1	445	79	81	605	86	93	---	--	---	--

(1) On pavement immediately adjacent to core locations
(2) Resurfaced 1951 - 1952

TABLE 32
MODULUS OF ELASTICITY OF BEAMS AND CORES

Factor Studied	Dynamic Modulus, 3- by 6- by 15-in Beams			Secant Modulus at 2000 psi, 10-Yr Cores, psi
	28 Days, psi	10 Yr, psi	Percent Increase	
Proportioning and Grading				
Silica Dust	6.7×10^6	7.6×10^6	13	5.0×10^6
Limestone Dust	6.5	8.0	23	5.9
Modified Sand	6.8	7.3	7	5.6
Proprietary Admixtures				
Admixture No. 1	6.5	7.7	19	6.1
Admixture No. 2	7.1	7.8	10	6.0
Air-Entraining Agents				
AEA No. 1, Cement No. 1	5.8	6.7	16	5.1
AEA No. 1, Cement No. 2	5.9	6.8	15	4.3
AEA No. 2, Cement No. 1	5.7	---	--	5.2
AEA No. 2, Cement No. 2	6.9	---	--	5.9
Natural Cement Blends				
Nat. Cement without Grinding Aid	6.7	---	--	5.0
Nat. Cement with Grinding Aid	6.1	6.8	12	5.4
Limestone Materials				
Limestone Aggregate	6.1	6.5	7	6.2
Limestone Agg. with Limestone Dust	5.9	7.3	24	6.0
Standard Construction				
Cement Brand No. 1	6.0	7.9	32	5.3
Cement Brand No. 2	6.4	---	--	5.9

TABLE 33
EFFECT OF COARSE AGGREGATE RATIO ON COMPRESSIVE AND FLEXURAL STRENGTHS

Factor Studied	b/b_o	Compressive Strength, psi		Flexural Strength, psi	
		7 day	28 day	7 day	28 day
Proportioning and Grading					
Silica Dust	0.76	3364	4946	561	649
	0.80	3078	4346	538	628
Limestone Dust	0.76	3461	4842	513	562
	0.80	3372	4790	704	---
Modified Sand	0.76	3372	4180	341(1)	755
	0.80	2816	4630	701	720
Proprietary Admixtures					
Admixture No. 1	0.76	3580	3955	615	764
	0.80	4420	4349	655	784
Admixture No. 2	0.76	4850	6080	465	807
	0.80	4460	3890(1)	445	605
Air-Entraining Agents					
AEA No. 1	0.76	2520	3477	431(2)	615(2)
	0.80	3005	4105	420(2)	590(2)
AEA No. 2	0.76	3536(2)	3700(2)	584(2)	863(2)
	0.80	3622(2)	4281(2)	568(2)	680(2)
Natural Cement Blends					
Nat. Cement without Grinding Aid	0.76	3145	3500	586	---
	0.80	3235	3922	515	626
Nat. Cement with Grinding Aid	0.76	2864	3485	347	578
	0.80	2773	3471	527	592

(1) Poor specimen
(2) Cement Brand No. 2

TABLE 34
SUMMARY OF TEMPERATURE AND MOISTURE DATA, CURING STUDY

	A-1 ASPHALT EMULSION - INITIAL CURING - STA. 395+60								A-2 WET STRAW - STATION 396+75							
Date, 1940	9-9	9-10	9-11	9-12		9-13	9-17	9-28	9-9	9-10	9-11	9-12		9-13	9-17	9-28
Precipitation, In.	--	0.55	0.40	--		0.19	0.01	--	--	0.55	0.40	--		0.19	0.01	--
Humidity, percent	62	44	45	48		51	57	56	62	44	45	48		51	57	56
Evaporation, mm.	1.69	1.07	2.10	1.43		1.67	2.23	4.79	1.69	1.07	2.10	1.43		1.67	2.23	4.79
Time	12:25	2:15	11:05	7:35	4:35	8:55	9:50	11:30	1:30	3:15	11:15	7:45	4:45	8:50	10:00	11:40
Air Temp., °F	78	57	57	48	67	61	62	69	75	55	57	49	67	61	64	69
Slab Surf. Temp., °F	77	69	63	50	--	--	64	70	74	60	59	57	--	--	66	70
Slab Int. Temp., °F-1[(a)]	80	83	76	60	--	--	71	87	75	64	66	66	--	--	67	65
" " " 2	72	80	70	61	--	--	68	74	77	64	64	66	--	--	69	68
" " " 3	72	78	68	63	--	--	66	69	75	66	66	67	--	--	68	61
Slab Moisture, percent - 1	6.1	6.1	6.0	6.0	6.0	6.0	6.0	6.0	6.3	6.1	6.1	6.1	6.1	6.1	6.1	6.0
" " " 2	6.1	6.1	6.0	6.0	6.0	6.0	5.9	5.9	6.3	6.2	6.2	6.1	6.1	6.1	6.1	6.1
" " " 3	6.1	6.2	6.1	6.1	6.1	6.0	6.0	6.0	6.6	6.2	6.4	6.2	6.1	6.1	6.1	6.2

	A-3 BURLAP AND PAPER - STATION 397+95								A-4 WET EARTH - STATION 399+10							
Date, 1940	9-9	9-11		9-12		9-13	9-17	9-28	9-9	9-11		9-12		9-13	9-17	9-28
Precipitation, In.	--	0.40		--		0.19	0.01	--	--	0.40		--		0.19	0.01	--
Humidity, percent	62	45		48		51	57	56	62	45		48		51	57	56
Evaporation, mm.	1.69	2.10		1.43		1.67	2.23	4.79	1.69	2.10		1.43		1.67	2.23	4.79
Time	1:40	6:45	12:00	7:50	4:50	8:45	10:00	11:45	1:50	7:00	12:15	8:00	5:00	8:40	10:30	12:00
Air Temp., °F	75	47	57	49	67	59	64	69	69	45	57	50	67	59	65	70
Slab Surf. Temp., °F	73	51	64	55	--	--	68	70	74	52	60	54	--	--	68	72
Slab Int. Temp., °F-1	80	61	66	61	--	--	66	70	78	55	59	55	--	--	71	71
" " " 2	78	64	66	63	--	--	65	67	75	58	58	59	--	--	67	68
" " " 3	77	67	66	66	--	--	65	64	76	60	60	59	--	--	68	68
Slab Moisture, percent - 1	6.2	5.8	5.8	5.8	5.8	5.7	5.7	5.6	6.2	6.1	6.1	6.0	6.0	6.0	6.0	5.9
" " " 2	6.2	5.9	5.9	5.8	5.8	5.8	5.7	5.7	6.1	6.2	6.1	6.1	6.1	6.0	6.0	6.1
" " " 3	6.3	6.2	6.2	6.1	6.1	6.1	6.0	6.1	6.4	6.2	6.3	6.2	6.2	6.2	6.3	6.0

	A-5 PONDING - STATION 400+35								A-6 DOUBLE BURLAP - STATION 401+55							
Date, 1940	9-9	9-11		9-12		9-13	9-17	9-28	9-10	9-11		9-12		9-13	9-17	9-28
Precipitation, In.	--	0.40		--		0.19	0.01	--	0.55	0.40		--		0.19	0.01	--
Humidity, percent	62	45		48		51	57	56	44	45		48		51	57	56
Evaporation, mm.	1.69	2.10		1.43		1.67	2.23	4.79	1.07	2.10		1.43		1.67	2.23	4.79
Time	2:05	7:20	12:25	8:15	5:05	8:30	10:40	12:10	12:00	7:45	12:30	8:25	5:10	8:25	10:50	12:15
Air Temp., °F	66	45	57	50	66	59	65	70	54	46	62	50	65	59	65	70
Slab Surf. Temp., °F	72	51	63	54	--	--	70	74	59	51	68	53	--	--	70	74
Slab Int. Temp., °F-1	76	54	62	57	--	--	69	70	66	53	63	53	--	--	73	77
" " " 2	76	56	62	58	--	--	70	68	67	56	63	54	--	--	71	71
" " " 3	74	58	61	60	--	--	68	66	67	58	62	55	--	--	69	67
Slab Moisture, percent - 1	6.1	6.3	6.2	6.2	6.1	6.1	6.1	6.1	6.4	6.8	6.5	6.5	6.1	6.3	6.1	5.9
" " " 2	6.1	6.5	6.3	6.5	6.8	6.5	6.3	6.3	6.3	6.8	6.5	6.4	6.2	6.2	6.1	6.1
" " " 3	6.1	6.4	6.2	6.2	7.1	6.6	6.4	6.4	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1

	A-7 PAPER - STATION 402+80								A-8 $CaCl_2$ INTEGRAL MIX - STATION 403+95							
Date, 1940	9-10	9-11		9-12		9-13	9-17	9-28	9-10	9-11		9-12		9-13	9-17	9-28
Precipitation, In.	0.55	0.40		--		0.19	0.01	--	0.55	0.40		--		0.19	0.01	--
Humidity, percent	44	45		48		51	57	56	44	45		48		51	57	56
Evaporation, mm.	1.07	2.10		1.43		1.67	2.23	4.79	1.07	2.10		1.43		1.67	2.23	4.79
Time	11:45	8:00	2:00	8:35	5:15	8:20	11:00	12:25	11:30	6:25	2:15	8:45	5:20	7:30	11:10	12:35
Air Temp., °F	54	47	60	52	65	59	69	70	54	48	58	56	65	54	69	70
Slab Surf. Temp., °F	60	51	69	58	--	--	70	78	58	50	59	58	--	52	70	74
Slab Int. Temp., °F-1	71	63	66	63	--	--	62	64	66	54	61	59	--	54	59	75
" " " 2	71	62	66	63	--	--	62	66	66	54	58	60	--	54	57	76
" " " 3	72	62	69	63	--	--	65	69	66	55	58	59	--	56	56	72
Slab Moisture, percent - 1	6.1	6.0	6.0	6.0	6.0	6.0	6.0	5.9	6.1	6.0	6.0	5.9	5.9	5.9	5.8	5.5
" " " 2	6.2	6.2	6.2	6.1	6.1	6.1	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	5.9
" " " 3	6.2	6.5	6.3	6.5	6.5	6.2	6.2	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1

	A-9 MEMBRANE - STATION 405+18								4-A WET STRAIN - STATION 405+95							
Date, 1940	9-10	9-11		9-12		9-13	9-17	9-28	9-10	9-11		9-12		9-13	9-17	9-28
Precipitation, In.	0.55	0.40		--		0.19	0.01	--	0.55	0.40		--		0.19	0.01	--
Humidity, percent	44	45		48		51	57	56	44	45		48		51	57	56
Evaporation, mm.	1.07	2.10		1.43		1.67	2.23	4.79	1.07	2.10		1.43		1.67	2.23	4.79
Time	1:00	9:00	2:30	8:50	5:30	8:00	11:15	12:45	1:15	9:15	2:40	9:00	5:35	8:05	11:25	12:55
Air Temp., °F	54	52	57	56	66	58	70	70	54	52	55	56	60	58	71	70
Slab Surf. Temp., °F	57	53	57	56	--	--	71	74	63	56	59	60	--	--	72	74
Slab Int. Temp., °F-1	71	64	75	65	--	--	74	83	63	64	63	62	--	--	74	70
" " " 2	68	64	72	63	--	--	70	78	64	64	63	62	--	--	77	74
" " " 3	65	64	68	63	--	--	67	73	63	63	62	61	--	--	80	77
Slab Moisture, percent - 1	6.1	6.4	6.3	6.0	5.9	5.8	5.6	5.5	6.1	5.9	6.0	6.1	6.1	6.1	6.1	5.9
" " " 2	6.1	6.4	6.3	6.1	6.1	6.1	6.0	6.0	6.1	6.0	6.0	6.0	6.0	6.0	5.9	5.9
" " " 3	6.4	6.4	6.3	6.2	6.2	6.1	6.2	6.3	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1

[(a)] 1 - Top
2 - Middle
3 - Bottom

TABLE 35
SUMMARY OF CONCRETE SCALING STUDY
1940-41 and 1941-42

Series	Division	Panel Number		Location of Panels			Estimated Scale						Description of Concrete				
				1940-41		1941-42	1940-41				1941-42						
							Method A		Method B		Method B						
		1940-41	1941-42	Method A	Method B	Method B	Cycles	% Scale	Cycles	% Scale	Cycles	% Scale	Finish	Curing	Cement Brand	Admixture	b/b_o
Durability Project																	
1	B	1	1	381+30	381+42	381+60	5	100	33	95	23	100	Broom	Wetted Straw	1	None	0.76
2	A	2	-	393+64	393+76	------	6	22	28	92	--	---	Broom	Asphalt Emulsion	1	None	0.76
3	A-1	3	2	394+84	394+96	395+40	6	42	28	61	47	100	Burlap	Asphalt Emulsion (3)	1	None	0.76
	A-2	4	-	396+00	396+12	------	6	6	28	19	--	---	Burlap	Wetted Straw	1	None	0.76
	A-3	5	3	397+22	397+34	397+34(1)	6	Trace	28	Trace	89(2)	68	Burlap	Paper (3)	1	None	0.76
	A-3	-	4	------	------	397+54	-	---	--	--	47	100	Burlap	Paper (3)	1	None	0.76
	A-4	6	-	398+43	398+55	------	6	14	28	33	--	---	Burlap	Wetted Earth	1	None	0.76
	A-5	7	-	399+64	399+76	------	6	Trace	28	28	--	---	Burlap	Ponding	1	None	0.76
	A-6	8	-	400+84	400+96	------	6	Trace	28	14	--	---	Burlap	Double Burlap	1	None	0.76
	A-7	9	-	402+04	402+16	------	6	0	28	3	--	---	Burlap	Paper	1	None	0.76
	A-8	10	5	403+24	403+36	403+50	6	Trace	28	17	61	73	Burlap	2% $CaCl_2$	1	None	0.76
	A-9	11	6	404+44	404+56	404+56(1)	6	0	28	0	89(2)	36	Burlap	Membrane (3)	1	None	0.76
	A-9	-	7	------	------	404+73	-	---	--	--	61	12	Burlap	Membrane (3)	1	None	0.76
4	B	12	8	417+30	417+42	417+42(1)	7	0	33	1	93(2)	6	Burlap	Wetted Straw	1	Admixture No. 1	0.76
	B	-	9	------	------	417+60	-	---	--	--	61	8	Burlap	Wetted Straw	1	Admixture No. 1	0.76
	D	13	10	443+60	443+72	443+90	7	0	33	22	61	56	Burlap	Wetted Straw	1	Admixture No. 2	0.76
	E	14	11	463+80	463+92	463+38	7	11.2	33	61	41	100	Burlap	Wetted Straw	1	None	0.76
	F	15	12	464+42	464+54	464+54(1)	7	0	33	0	93(2)	0	Burlap	Wetted Straw	1	AEA No. 1	0.76
	F	-	13	------	------	464+70	-	---	--	--	60	Trace	Burlap	Wetted Straw	1	AEA No. 1	0.76
	H	16	14	497+70	497+82	497+82(1)	7	Trace	33	0	94(2)	0	Burlap	Wetted Straw	2	AEA No. 1	0.80
	H	-	15	------	------	498+00	-	---	--	--	61	0	Burlap	Wetted Straw	2	AEA No. 1	0.80
	I	17	16	500+10	500+22	510+76	6	33	27	56	9	100	Burlap	Wetted Straw	2	None	0.76
5	A	18	17	514+50	514+62	514+62(1)	7	0	33	Trace	93(2)	Trace	Burlap	Wetted Straw	1	AEA No. 2	0.76
	A	-	18	------	------	514+80	-	---	--	--	60	Trace	Burlap	Wetted Straw	1	AEA No. 2	0.76
	C	19	19	563+70	563+82	563+82(1)	7	0	33	0	94(2)	Trace	Burlap	Wetted Straw	2	AEA No. 2	0.76
	C	-	20	------	------	564+08	-	---	--	--	61	Trace	Burlap	Wetted Straw	2	AEA No. 2	0.76
	D	20	21	574+24	574+36	573+04	5	100	21	100	32	100	Burlap	Wetted Straw	2	None	0.76
6	A	21	22	590+10	590+22	590+22(1)	7	6	29	Trace	90(2)	44	Burlap	Wetted Straw	1	Natural Cement, no grinding aid	0.76
	A	-	23	------	------	590+42	-	---	---	--	31	100	Burlap	Wetted Straw	1	Natural Cement, no grinding aid	0.76
	C	22	24	618+92	619+04	619+04(1)	7	0	33	0	94(2)	0	Burlap	Wetted Earth	1	Natural Cement, with grinding aid	0.80
	C	-	25	------	------	619+20	-	---	--	--	61	0	Burlap	Wetted Earth	1	Natural Cement, with grinding aid	0.80
2	B	23	-	623+70	623+82	------	7	42	33	83	--	---	Broom	Cutback Asphalt	1	None	0.76
7	A	24	-	642+90	643+02	------	7	17	33	70	--	---	Burlap	Wetted Earth	1	Silica Dust	0.76
	A	-	26	------	------	654+90	-	---	--	--	33	100	Burlap	Wetted Straw	1	Silica Dust	0.80
	B	25	27	666+90	667+02	665+12	3	100	13	100	9	100	Burlap	Wetted Straw	1	None	0.76
	C	26	28	669+30	669+42	679+38	7	59	33	94	8	100	Burlap	Wetted Straw	1	Limestone Dust	0.76
	E	27	29	706+50	706+62	712+20	3	100	21	100	12	100	Burlap	Wetted Straw	1	Modified Sand	0.76
8	A	28	30	753+16	753+28	752+82	3	100	13	100	6	100	Burlap	Wetted Straw	1	Lime. Dust with Lime. Agg.	0.76
	B	29	31	753+76	753+88	754+30	5	100	22	100	6	100	Burlap	Wetted Straw	1	Limestone Aggregate	0.76
Design Project																	
1	A	30	33	771+20	771+32	773+20	6	47	29	92	9	100	Burlap	Wetted Straw	2	Not Rain Marked	0.76
1	C	-	34	------	------	783+08	-	---	--	--	7	100	Burlap	Wetted Straw	2	Not Rain Marked	0.76
1	C	-	32	------	------	790+10	-	---	--	--	61	4	Burlap	Wetted Straw	2	Rain Marked	0.76

(1) 1942 tests continued on 1941 panels
(2) Accumulated cycles at end of 1942 tests
(3) Initial burlap cure

Test Methods:
Method A - Weekly cycle of 10% $CaCl_2$ solution.
Method B - Daily cycle of freezing water on surface and thawing with $CaCl_2$.

* Not cited in text.

TABLE 36
SUMMARY OF CORE ABSORPTION STUDY

Factor Studied	Core No.	Moisture Content - Percent of Oven-Dry Weight												
		Drying Period (110 C), hr						Saturation Period (25 C), hr						
		Air Dry 0	6	12	24	48	Oven Dry 72	1/2	1	3	6	12	24	Saturated 96
Proportioning and Grading														
Silica Dust	242	2.45	1.33	0.88	0.40	0.08	0.00	1.16	1.65	2.61	3.33	3.90	4.10	4.30
Limestone Dust	246	2.29	1.15	0.75	0.29	0.07	0.00	1.22	1.68	2.65	3.33	3.90	4.08	4.26
Modified Sand	250	1.44	0.39	0.25	0.11	0.04	0.00	1.12	1.51	2.35	3.02	3.72	4.18	4.42
Proprietary Admixtures														
Admixture No. 1	215	2.22	1.47	1.15	0.44	0.08	0.00	1.03	1.35	2.02	2.58	3.17	3.57	3.73
Admixture No. 2	218	1.99	1.41	1.13	0.44	0.07	0.00	0.76	1.05	1.67	2.14	2.62	3.02	3.23
Air-Entraining Agents														
AEA No. 1, Cement No. 1	220	2.34	1.60	1.23	0.42	0.10	0.00	1.04	1.43	2.24	2.86	3.47	3.83	3.99
AEA No. 1, Cement No. 2	223	2.17	1.48	1.11	0.37	0.08	0.00	1.56	2.09	3.16	3.82	4.10	4.19	4.35
AEA No. 2, Cement No. 1	227	2.01	1.23	0.90	0.25	0.04	0.00	1.15	1.52	2.39	2.96	3.54	3.83	3.99
AEA No. 2, Cement No. 2	230	2.03	1.30	0.91	0.35	0.07	0.00	1.23	1.65	----	2.14	2.63	2.73	2.91
Natural Cement Blends														
Natural Cement without Grinding Aid	234	2.12	1.31	0.96	0.38	0.06	0.00	1.15	1.57	2.34	2.89	3.33	3.53	3.69
Natural Cement with Grinding Aid	237	1.91	0.89	0.59	0.23	0.07	0.00	0.99	1.31	2.00	2.56	3.15	3.58	3.84
Limestone Materials														
Limestone Aggregates	255	2.47	0.95	0.53	0.23	0.08	0.00	1.26	1.67	2.59	3.23	3.69	3.84	4.03
Limestone Aggregates with Limestone Dust	253	2.58	1.16	0.71	0.22	0.04	0.00	1.25	1.69	2.58	3.21	3.70	3.92	4.10
Standard Construction														
Cement Brand No. 1	228	2.15	1.40	1.05	0.35	0.08	0.00	1.21	1.68	2.61	3.31	3.71	3.78	3.94
Cement Brand No. 1	243	2.38	1.13	0.77	0.29	0.07	0.00	1.31	1.75	2.74	3.44	3.91	4.06	4.24
Cement Brand No. 1	247	2.38	1.06	0.70	0.27	0.08	0.00	1.09	1.52	2.35	2.97	3.56	3.79	3.95
Cement Brand No. 2	224	2.11	1.47	1.12	0.43	0.09	0.00	1.21	1.60	2.50	3.11	3.54	3.71	3.88
Cement Brand No. 2	232	1.94	0.97	0.71	0.26	0.07	0.00	1.30	1.75	2.76	3.31	3.54	3.61	3.76
Finishing Methods														
Broom Finish, Asphalt Emulsion Curing	204	2.02	1.16	0.86	0.40	0.10	0.00	1.21	1.62	2.63	3.34	3.79	3.90	4.05
Curing Methods														
Asphalt Emulsion	205	2.01	1.12	0.81	0.36	0.09	0.00	1.12	1.52	2.42	3.04	3.49	3.63	3.80
Wetted Straw	206	2.20	1.32	1.03	0.44	0.11	0.00	1.06	1.43	2.31	3.01	3.56	3.78	3.93
Paper	207	1.94	1.17	0.92	0.40	0.11	0.00	0.92	1.28	2.05	2.67	3.11	3.26	3.41
Wetted Earth	208	2.08	1.41	1.13	0.53	0.14	0.00	1.06	1.45	2.26	2.90	3.46	3.78	3.82
Ponding	209	2.12	1.42	1.12	0.46	0.12	0.00	1.12	1.54	2.46	3.19	3.77	3.89	4.04
Double Burlap	210	1.85	1.14	0.87	0.47	0.10	0.00	1.01	1.38	2.18	2.79	3.29	3.46	3.62
Paper, No Initial Curing	211	2.30	1.52	1.17	0.57	0.13	0.00	1.26	1.70	2.74	3.48	4.04	4.17	4.35
Membrane - With Initial Curing	213	2.20	1.57	1.27	0.49	0.07	0.00	1.01	1.38	2.28	2.95	3.55	3.81	3.96

TABLE 37
CAPILLARITY AND EVAPORATION TEST ON MIDDLE SECTIONS OF CORES

Factor Studied	Core No.	Thickness, in.	Cumulative Water Passage in Grams (g) and in Gram-Inches (C)*																			
			4 Days - 1		8 Days - 2		12 Days - 3		16 Days - 4		20 Days - 5		25 Days - 6		28 Days - 7		33 Days - 8		36 Days - 9		40 Days - 10	
			g	C	g	C	g	C	g	C	g	C	g	C	g	C	g	C	g	C	g	C
Proportioning and Grading																						
Silica Dust	242	2.48	3	7	5	12	8	20	12	30	14	35	19	47	20	50	23	57	24	60	29	72
Limestone Dust	246	2.71	6	16	13	35	19	52	23	62	28	76	34	92	37	100	41	111	44	119	48	130
Modified Sand	250	2.72	2	5	6	16	13	35	19	52	28	76	43	117	47	128	54	147	59	161	64	174
Proprietary Admixtures																						
Admixture No. 1	215	2.52	1	3	4	10	7	18	10	25	13	33	18	45	20	50	23	58	26	66	28	71
Admixture No. 2	218	2.64	1	3	4	11	8	21	10	26	14	37	19	50	22	58	27	71	29	77	32	85
Air-Entraining Agents																						
AEA No. 1, Cement No. 1	220	3.08	1	3	2	6	3	9	6	18	9	28	12	37	13	40	16	49	17	52	20	62
AEA No. 2, Cement No. 1	227	2.54	4	10	7	18	13	33	18	46	28	71	33	84	35	89	38	97	40	102	44	112
Natural Cement Blends																						
Natural Cement without Grinding Aid	234	2.96	4	12	8	24	11	33	14	41	18	53	22	65	23	68	28	83	30	89	35	104
Natural Cement with Grinding Aid	237	2.96	1	3	7	21	16	47	20	59	20	59	23	68	24	71	25	74	25	74	26	77
Limestone Materials																						
Limestone Aggregates	255	2.62	8	21	12	31	16	42	18	47	21	55	24	63	26	68	28	73	30	79	36	94
Limestone Agg. with Limestone Dust	253	2.35	2	5	4	9	6	14	13	31	19	45	26	61	29	68	32	75	35	82	38	89
Standard Construction																						
Cement Brand No. 1	228	2.52	5	13	10	25	16	40	29	73	50	126	71	179	82	207	99	250	109	275	118	297
Cement Brand No. 1	243	2.65	12	32	20	53	26	69	31	82	36	96	45	119	51	135	61	162	67	178	82	217
Cement Brand No. 2	224	2.38	2	5	6	14	9	22	11	26	14	33	19	45	21	50	26	62	29	69	39	93
Cement Brand No. 2	232	2.58	3	8	7	18	11	28	14	36	17	44	25	65	27	70	31	80	34	88	40	103

* C = g x core thickness in inches

TABLE 38
SUMMARY OF COMPRESSION TESTS

Brand Cement	Age Spec.	Proportioning and Grading: Modified Sand 0.76	Modified Sand 0.80	Silica Dust 0.76	Silica Dust 0.80	Limestone Dust 0.76	Limestone Dust 0.80	Admixtures and Air-Entraining Agents: AEA No. 1 0.76	AEA No. 1 0.80	AEA No. 1 $CaCl_2$ 0.76	AEA No. 2 0.76	AEA No. 2 0.80	AEA No. 2 $CaCl_2$ 0.80	Adm. No. 1 0.76	Adm. No. 1 0.80	Adm. No. 2 0.76	Adm. No. 2 0.80	$CaCl_2$ 0.76	Natural Cement Blends: Nat. Cement with Grinding Aid 0.76	Nat. Cement with Grinding Aid 0.80	Nat. Cement without Grinding Aid 0.76	Nat. Cement without Grinding Aid 0.80	Limestone Materials: Limestone Aggregate 0.76	Limestone Agg. with Limestone Dust 0.76	Standard Construction
1	3 d	---- ----	---- ----	---- ----	---- ----	---- ----	---- ----	---- ----	---- ----	---- ----	2630 2210 2420	---- ----	2155 1855 2005	---- ----	---- ----	---- ----	---- ----	3170 2980 3075	---- ----	---- ----	---- ----	---- ----	---- ----	---- ----	2300 2190 2370 2287
	7 d	3360 3530 3320 3430 3220	2895 2720 2895 2755	3465 3890 3320 3980	3115 3180 3360 2658	3360 3282 3885 3460 3320	3110 3180 3640 3570 3360	2190 2470 2370 2260 2470 2190 3110 2860 2760	3360 2650	1870 1698 1770 2015 2760 2470 2470 2650	2650 3110 3250 2370	----	2580 2895 2650 1945	3580	4420	4850	4460	4480 3882 4480	3215 2545 2830 2865	2475 2830 2830 2900 2830	3465 2825	3360 3110	2475 3430 3005 2935 3500	2475 3500 2405 2900 2190	3465 4420 3360 2685 2935 4240 4060 3110 3885 3250 3640 3460
	avg	3372	2816	3664	3078	3461	3372	2520	3005	2213	2845		2518	3580	4420	4850	4460	4281	2864	2773	3145	3235	3069	2694	
		3125		3371		3417		2608						4000		4655			2813		3190				3543
	28 d	3785 4730 3995 4210	4840 4670 4530 4490	4530 4560 4880 4880 5480	3990 3710 4420 4590 5020	4490 4840 4810 5230	4980 4490 5020 4670	3720 2650 4060	4320 3890	3360 3890 3710 2479 2120 2650	3820 3960 3820	----	1170[1] 2540 3250	3955	4310 4490 4240	6080	3890[1]	5190 4880 4530	3465 3325 2755 3890 3990	4130 3215 3640 2900	3535 3465	3890 3955	3533 3890 4340 4940	4340 4670 3675 3710	4240 5130 4490 5050 5130 6010 3780 3890 4950 4840 3960 3820 5860 4000 4525 4170 4670 4280 4980 3960
	avg	4180	4633	4866	4346	4843	4790	3477	4105	3035	3867		2895	3955	4347	6080	3890	4867	3485	3471	3500	3922	4176	4099	
		4407		4606		4817		3726						4249		4985			3479		3711				4587
2	7 d	----	----	----	----	----	----	2650 2580	2120 1945	----	3430 3110 3465 4140	3890 3360 3810 3430	----	----	----	----	----	----	----	----	----	----	----	----	3010 3080 2475 3465 2190 3250 2475 3075 2510
								2615	2033		3537	3623													2837
	avg							2324			3580														
	28 d	----	----	----	----	----	----	4350 4598	3180 3360	----	3990 4060 3530 3460 3460	3780 5120 4240 3465 4800	----	----	----	----	----	----	----	----	----	----	----	----	4710 4950 4770 4060 4420 4600 5090 4170 4600
								4474	3270		3700	4281													
	avg							3857			3991														4597

(1) Poor specimen, not used in averages.

TABLE 39
SUMMARY OF MODULUS OF RUPTURE TESTS

Method	Brand Cement	Age Spec.	Proportioning and Grading: Modified Sand		Proportioning and Grading: Silica Dust		Proportioning and Grading: Limestone Dust		Admixtures and Air-Entraining Agents: AEA No. 1		AEA No. 1 $CaCl_2$		AEA No. 2		AEA No. 2 $CaCl_2$		Adm. No. 1		Adm. No. 2		$CaCl_2$		Natural Cement Blends: Nat. Cement with Grinding Aid		Nat. Cement without Grinding Aid		Limestone Materials: Limestone Aggregates		Limestone Agg. with Limestone Dust	Standard Construction	
			0.76	0.80	0.76	0.80	0.76	0.80	0.76	0.80	0.76	0.80	0.76	0.80	0.76	0.80	0.76	0.80	0.76	0.80	0.76	0.80	0.76	0.80	0.76	0.80	0.76	0.80	0.76		
THIRD-POINT LOADING ASTM METHOD C78-39	1	3 d	418	310	427	250	438	242	457	418	---		300	---	391		---	478	367	---	267		369	317	---	399	606		436	410	444
		7 d	341	701	561	538	513	562	---	389	328		508	---	449		---	538	465	---	445		347	527	---	515	768		578	567	
		28 d	755	720	649	628	704	---	562	533	489		529	---	---		---	---	807	---	605		578	592	---	626	585 (1)		489 (1)	819	586
									587	550																					
	2	3 d	---	---	---	---	---	---	---	367	---		395	540	---		---	---	---	---	---		---	---	---	---	---		---	387	447
		7 d	---	---	---	---	---	---	431	420	---		584	568	---		---	---	---	---	---		---	---	---	---	---		---	511	582
		28 d	---	---	---	---	---	---	615	590	---		863	680	---		---	---	---	---	---		---	---	---	---	---		---	686	686
																														605	
CANTILEVER LOADING MSHD METHOD	1	7 d	532	---	663	540	620	540	459	476	---		526	---	457		571	626	634	629	640		526	---	586	---	---		703	705	775
					544		570	586	744								659	685	891	587	769									745	640
																														704	609
																														710	658
																														705	652
																														692	643
																														574	696
																														842	591
																														640	661
																														769	674
																														653	575
																														842	
		28 d	---	---	---	---		---	---	---	---		644	---	690		781	784	---	920	---		---	---	---	---	---		---	810	768
																	747			906										792	827
																														795	846
	2	7 d	---	---	---	---	---	---	549	494	---		652	646	---		---	---	---	---	---		---	---	---	---	---		---	629	
													631																		
		28 d	---	---	---	---	---	---	654	603	---		764	642	---		---	---	---	---	---		---	---	---	---	---		---	---	
													800																		

(1) Poor specimens