Final Report on Durability Project, Michigan Test Road

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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. Several incidental studies were also carried out in connection with the construction of the project, and accelerated scaling tests were performed on the test areas during the first two winters after construction.

The most outstanding result 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 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 experimental sections of the pavement during the first 17 years 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.

• 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 Mich. 115 between US 10 and Mich. 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).

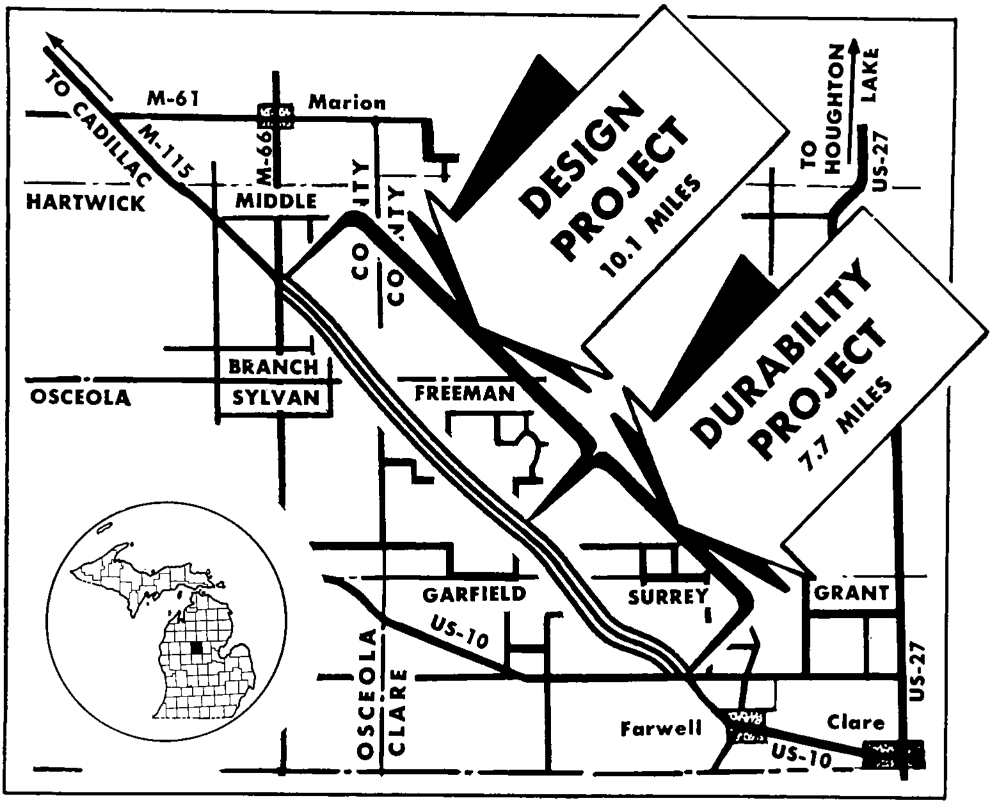


Figure 1. Location of Michigan Test Road.

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*) shortly after the test road was built. 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 (*5, 6, 7, 8, 9*) devoted exclusively to the Design Project have been issued, 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 1951-52, the remainder in 1957. Therefore, this is the final report on the Durability Project, and includes all observations for the 17-year period prior to resurfacing.

DESCRIPTION OF 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 (Table 1). Each series is subdivided into divisions and sections designated with letters and numerals, respectively. Figure 2 shows the locations of the test sections. A profile sketch is given in Figure 3.

In the construction of the 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.

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 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 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. It was added at the rate of 2 lb per sack of cement 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

TABLE 1

SUMMARY OF TEST AREAS IN DURABILITY PROJECT

Series	Division	Station Beg.	Station End	Length, ft.	Finish	Curing	Type of Standard Portland Cement	Admixture	b/b_0	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 natural cement	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[6]	692+10	693+00	90	Burlap	Wetted straw	Brand No. 1	None	0.76	
	D-11B[6]	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[6]	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[6]	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[6]	728+10	728+28	18	Burlap	Wetted straw	Brand No. 1	Modified sand	0.80	7E/7F 7E/12A
	F-12A[6]	728+28	729+00	72	Burlap	Wetted straw	Brand No. 1	None	0.76	
	F-12B[6]	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[6]	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[6]	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[6]	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	764+00	1054	Burlap	Wetted straw	Brand No. 1	None[5]	0.76	8A/8B 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] Devoted to additional design studies incorporated in durability project because of insufficient space in design project. R.S. = expansion relief section.

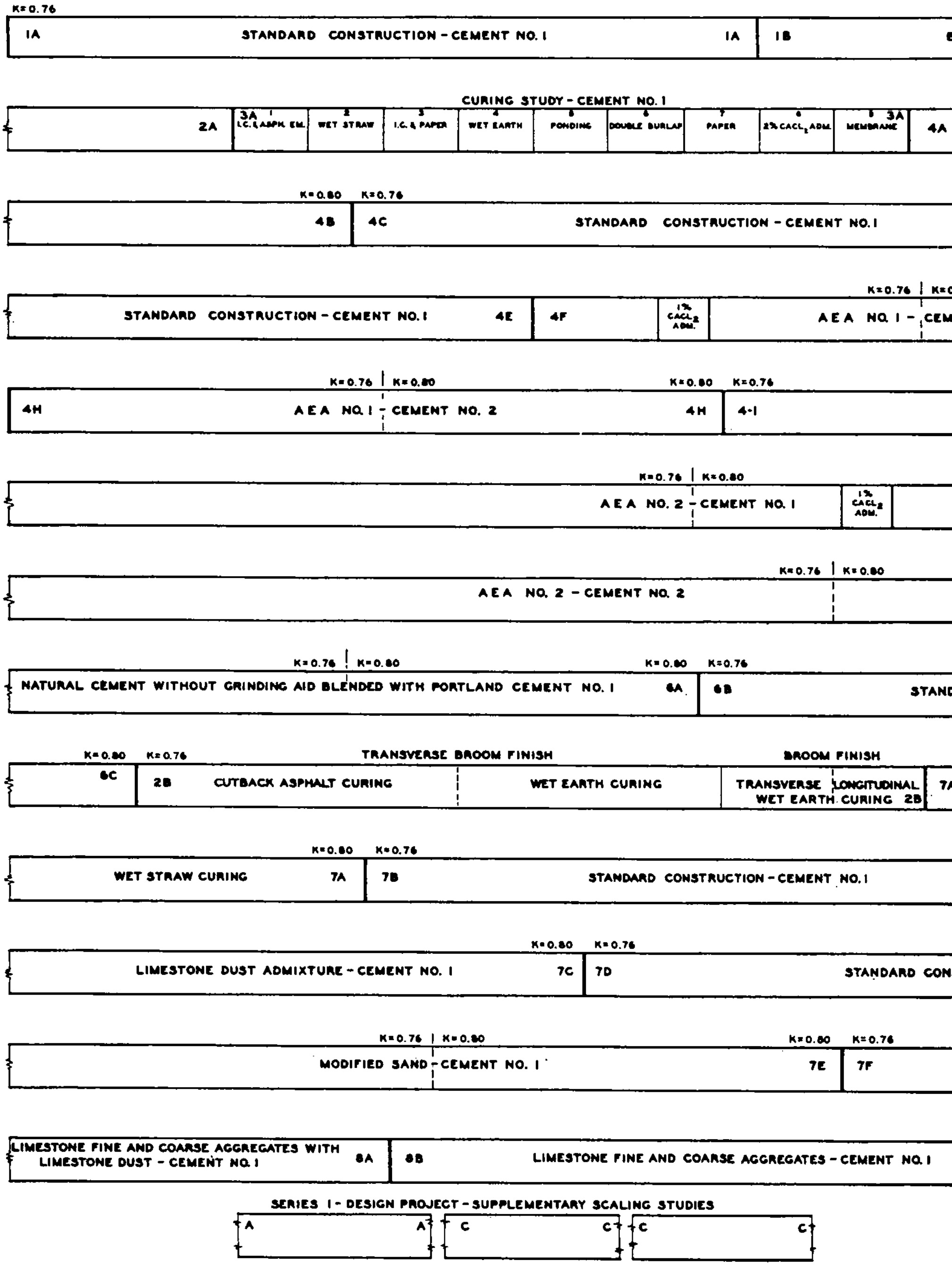
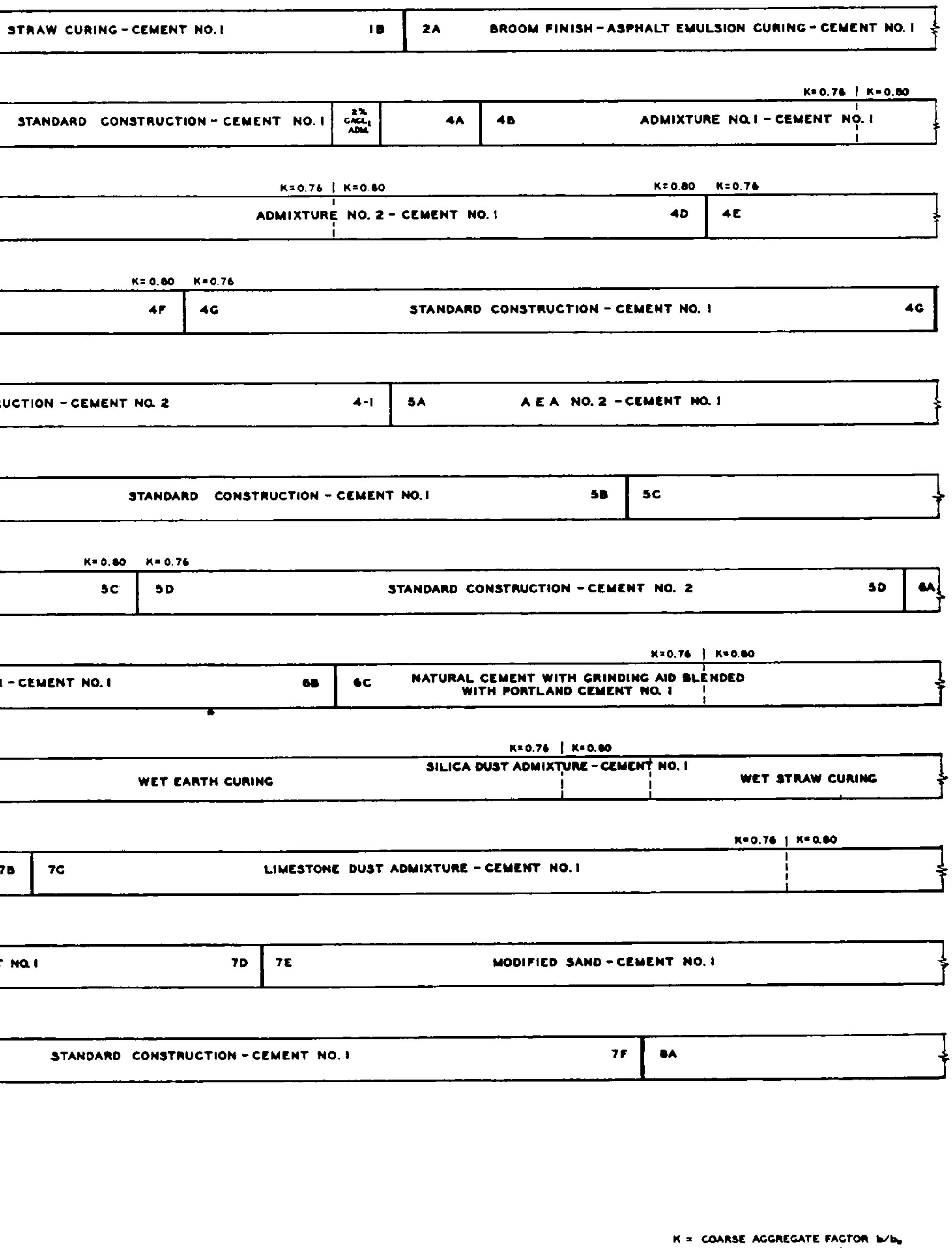


Figure 2. Schematic



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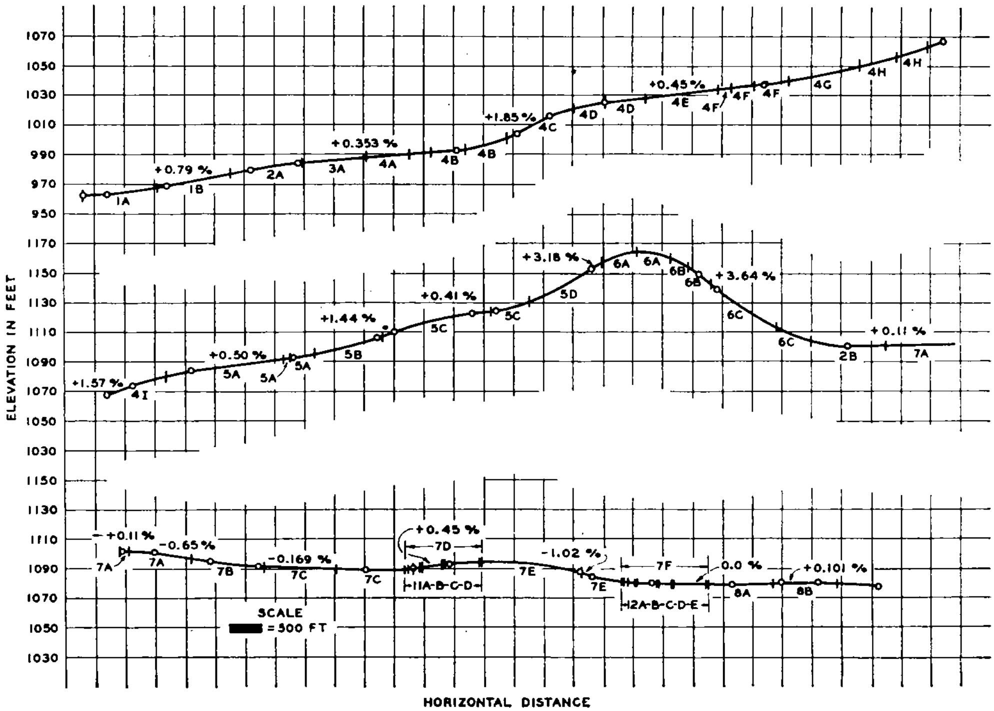


Figure 3. Profile of Durability Project.

ingredient. The organic oxy-acid was combined with an inert filler as a carrier to insure uniform distribution of the active ingredient throughout the concrete. Admixture No. 2, added to the dry batch at the mixer in the amount of 1 lb per sack of cement as recommended by the manufacturer, 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 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 pcf.

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 pcf of concrete of a specified consistency and cement content. It was found that 0.06 lb of agent in paste form per barrel of cement reduced weight approximately 5 pcf.

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 barrel 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 barrels) per cubic yard 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

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 in Michigan and 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. 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, Section 8B contained 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: (a) to indicate possible effects of cement brand on durability, and (b) 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 factors were involved in the studies: (a) burlap finish vs broom finish under standard curing conditions with wetted coverings, and (b) burlap finish vs 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, 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. Observations and measurements were made to evaluate the influence of the various curing methods on durability, especially with regard to scaling, and to determine the effect of these methods on thermal and moisture conditions within the slab. Also, it was 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 INFORMATION

During and after construction, various data were collected on factors which directly or indirectly influence pavement behavior.

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 ½- by 40-in. round tie bars spaced at 48 in.
Load transfer:
  At expansion joints, Translode angle unit with continuous base.
  At contraction joints, ¾- 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_0 of 0.76 and 0.80, respectively, were used for all sections containing admixtures. The coarse aggregate factor, b/b_0, 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_0 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 (Appendix A).

Materials. The two brands of cement are designated Cements Nos. 1 and 2; physical and chemical properties are listed in Table 13 (Appendix 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 1,750 nor more than 2,100 square centimeters per gram.

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

The natural fine and coarse aggregates were obtained from a Michigan commercial gravel producer, and the physical properties are summarized in Tables 15 and 16 (Appendix 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 (Appendix 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 Figure 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 (Table 19, Appendix A) 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 (Appendix A).

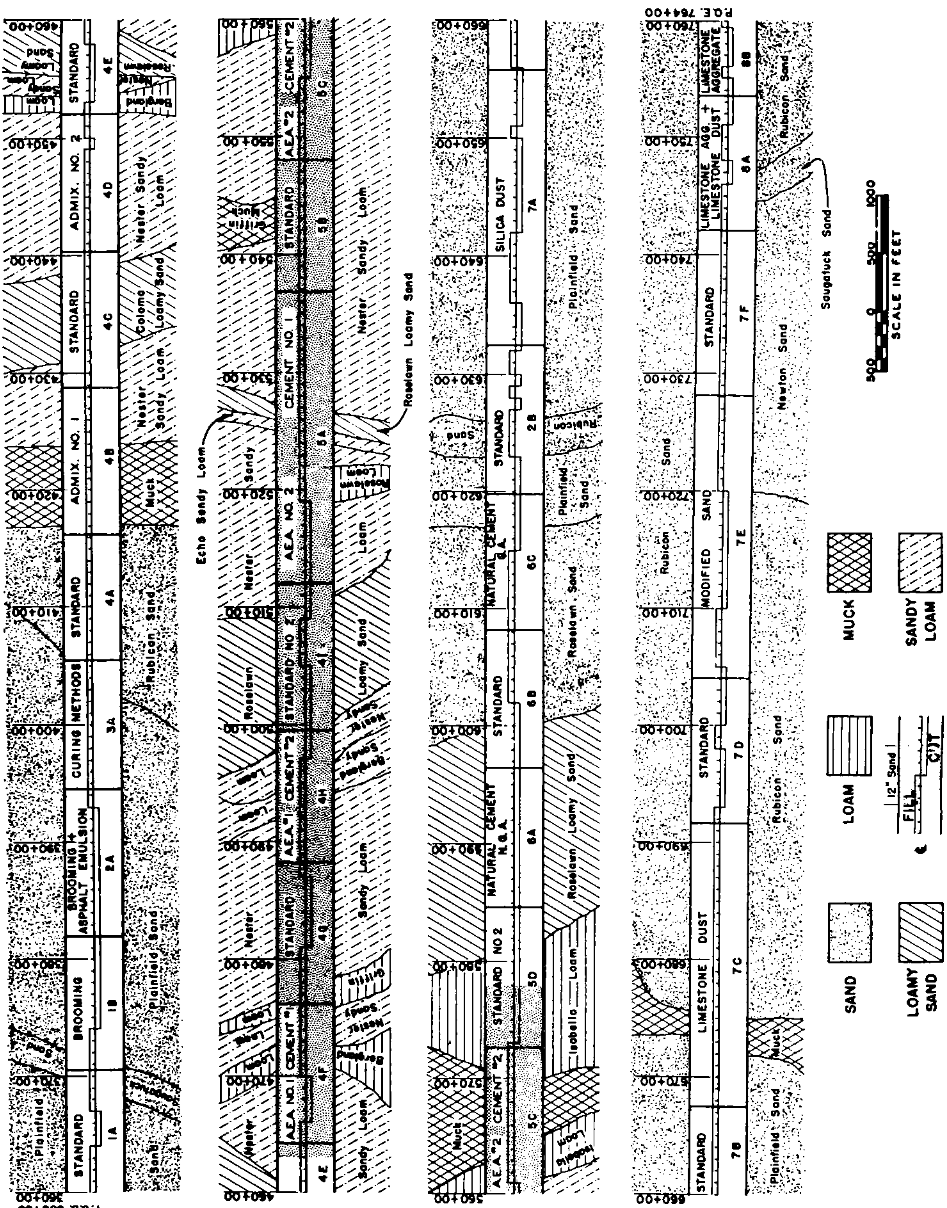


Figure 4. Soil types and earthwork operations.

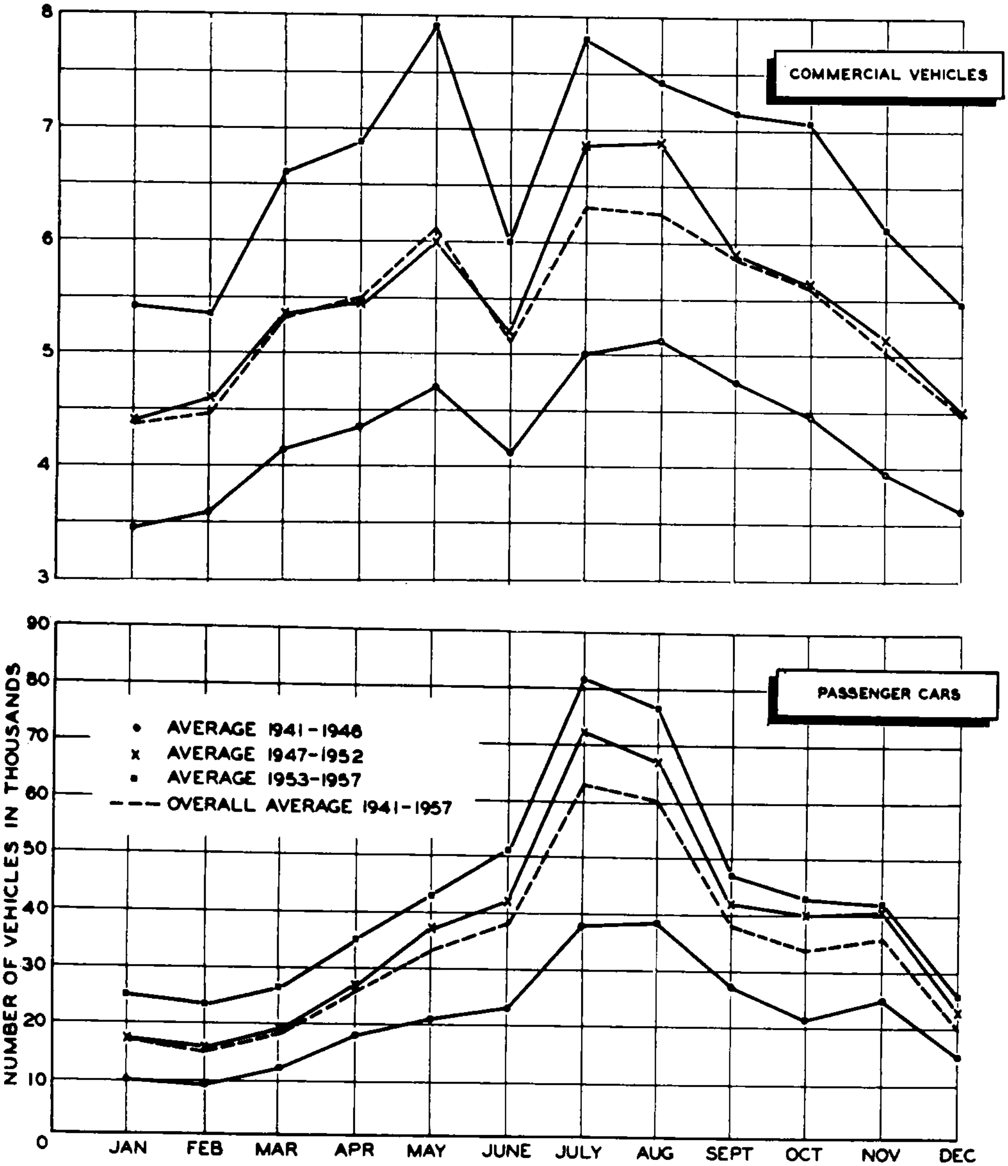


Figure 5. Average monthly traffic.

Traffic Characteristics

Automatic recording equipment was installed on the test road to obtain a continuous daily record of traffic flow. Also, classification surveys were made periodically. 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 given in Table 21 (Appendix B). Except for the war years (1942-45), total traffic increased slightly

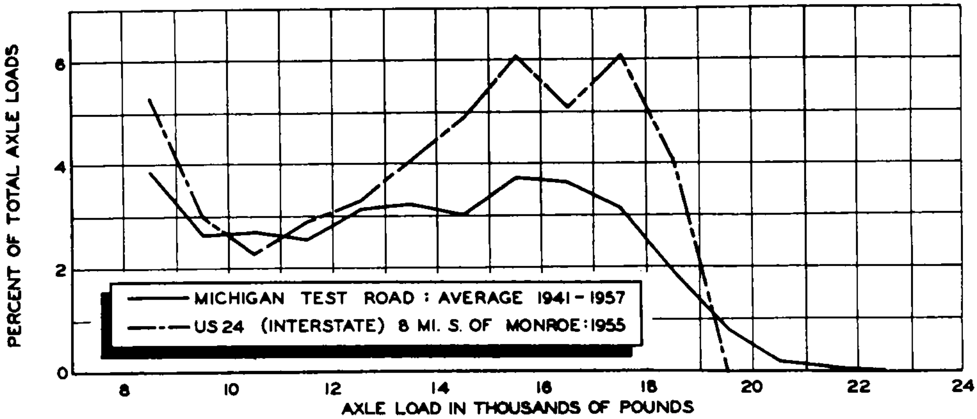


Figure 6. Axle load frequency.

each year. Commercial traffic generally increased at a rather uniform rate throughout the 17 years and by the end of this period had about doubled. The average monthly totals for passenger and commercial vehicles (Fig. 5) illustrate the seasonal pattern of total traffic flow over the project.

Average wheel load distribution is shown in Table 22 (Appendix B) and axle load frequency averaged for the 17 years, in Figure 6. For comparison, a similar curve is shown for 1955 commercial traffic on heavily-traveled US 24, 8 mi south of Monroe.

Climatological Data

Average daily air temperature variation and average daily air temperatures from 1941 to 1957 are shown in Figure 7. Daily variations in temperature were considerably less in winter than in summer. Daily range in winter varied from 4 to 39 F, with an average of about 17 F. During summer, daily range of air temperature varied from a low of 9 to a high of 45 F, with an average of about 27 F. Average daily temperature varied from 20 F in winter to 67 F in summer, a total average annual change of 47 degrees.

Total annual precipitation (1941-57) is shown in Figure 8. Average annual rainfall for the 17-year 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.

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 the tests were stopped.

Later, in the winter of 1944-45 when the pavement was a little over 4 years 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

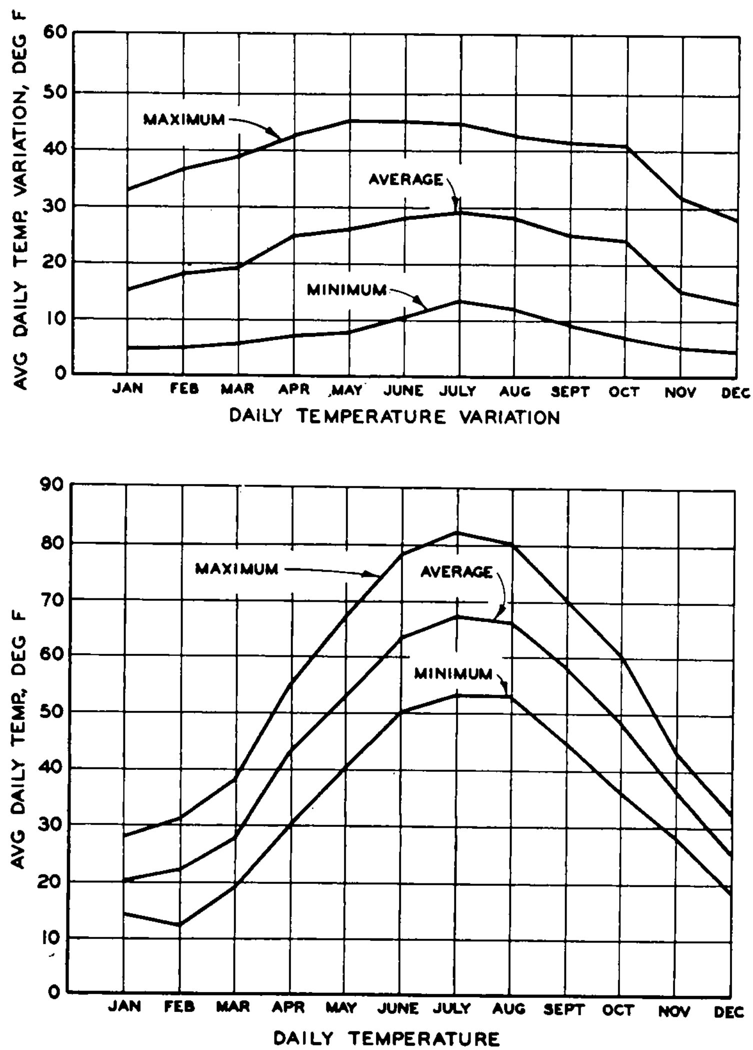


Figure 7. Air temperature record.

5 to 9 years. The results of this independent but related study indicated 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 years old remaining unscaled throughout the tests. Figure 9 shows the scope of the accelerated scaling studies.

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

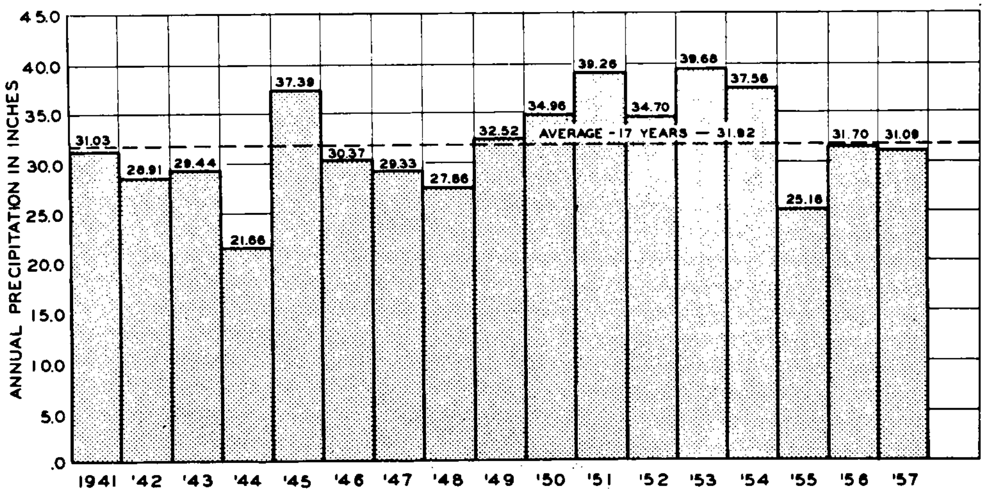


Figure 8. Annual precipitation.

and night to warn motorists of the presence of the test areas. A typical view of a test area in operation is shown in Figure 10.

Originally two test methods, A and B, were employed to determine resistance of the various pavement sections to calcium chloride attack. In Method A, a 10 percent solution of calcium chloride of ¼-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 ¼ 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 (Appendix B) and Figure 11. The condition of typical panels at the end of the accelerated tests is shown in Figure 10.

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. 11). 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.

Proprietary Admixtures. 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. 11). Moreover, in the section containing natural cement with a grinding aid no scaling was observed in the entire 2-year 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 is shown in Figure 10.

Standard Construction. The relative scale resisting properties of the two different cements are also shown in Figure 11. 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 of concrete containing Cement No. 2 is shown in Figure 10.

Finishing Methods. Finishing methods on standard concrete did not have a pronounced influence on durability in these tests (Fig. 11). 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 may have resulted from the application of the cutback 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 (Fig. 10) 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 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. 11).

Rain-Marked Surface. In conjunction with the regular scaling studies, extra panels were installed on the Design Proj-

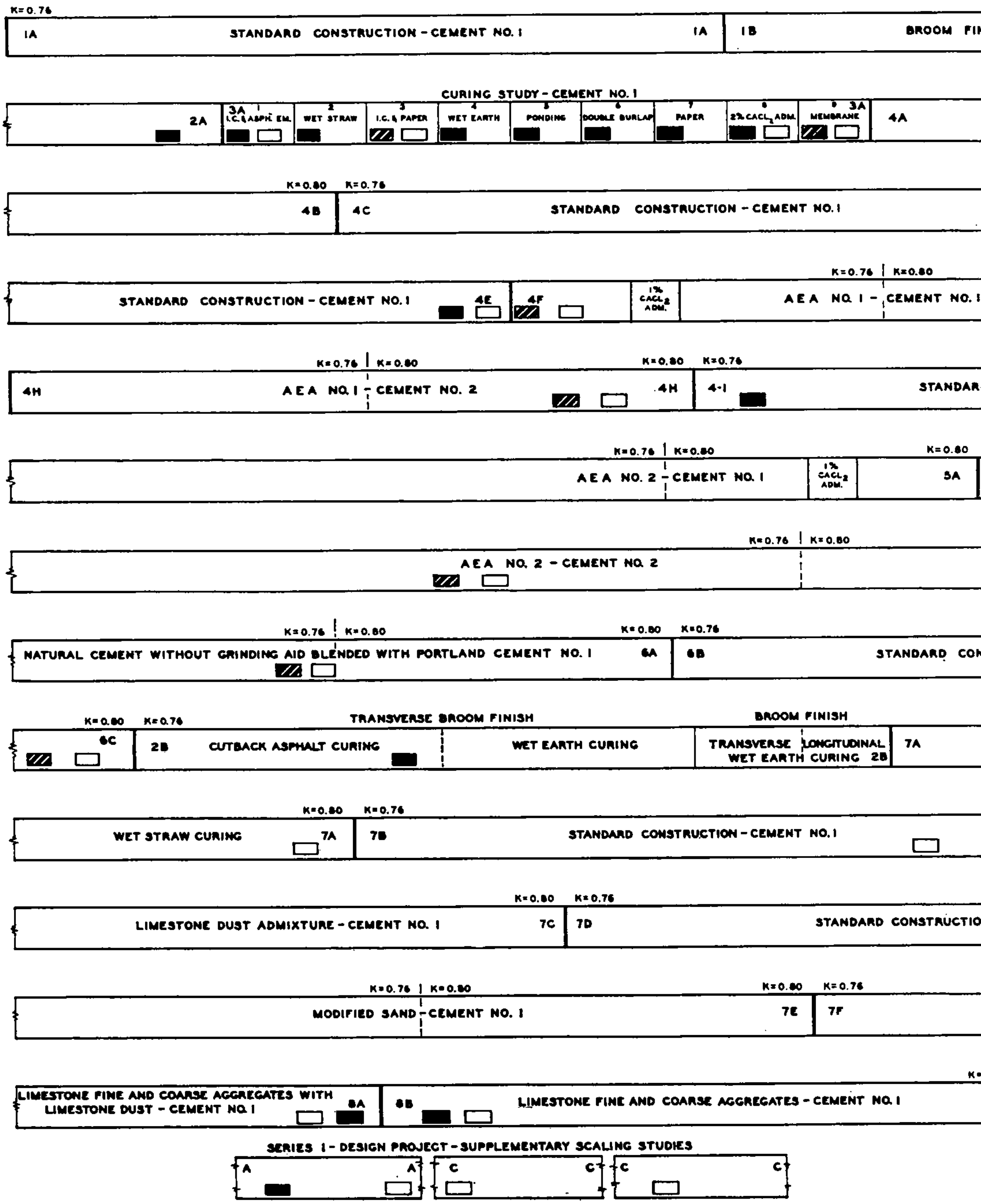
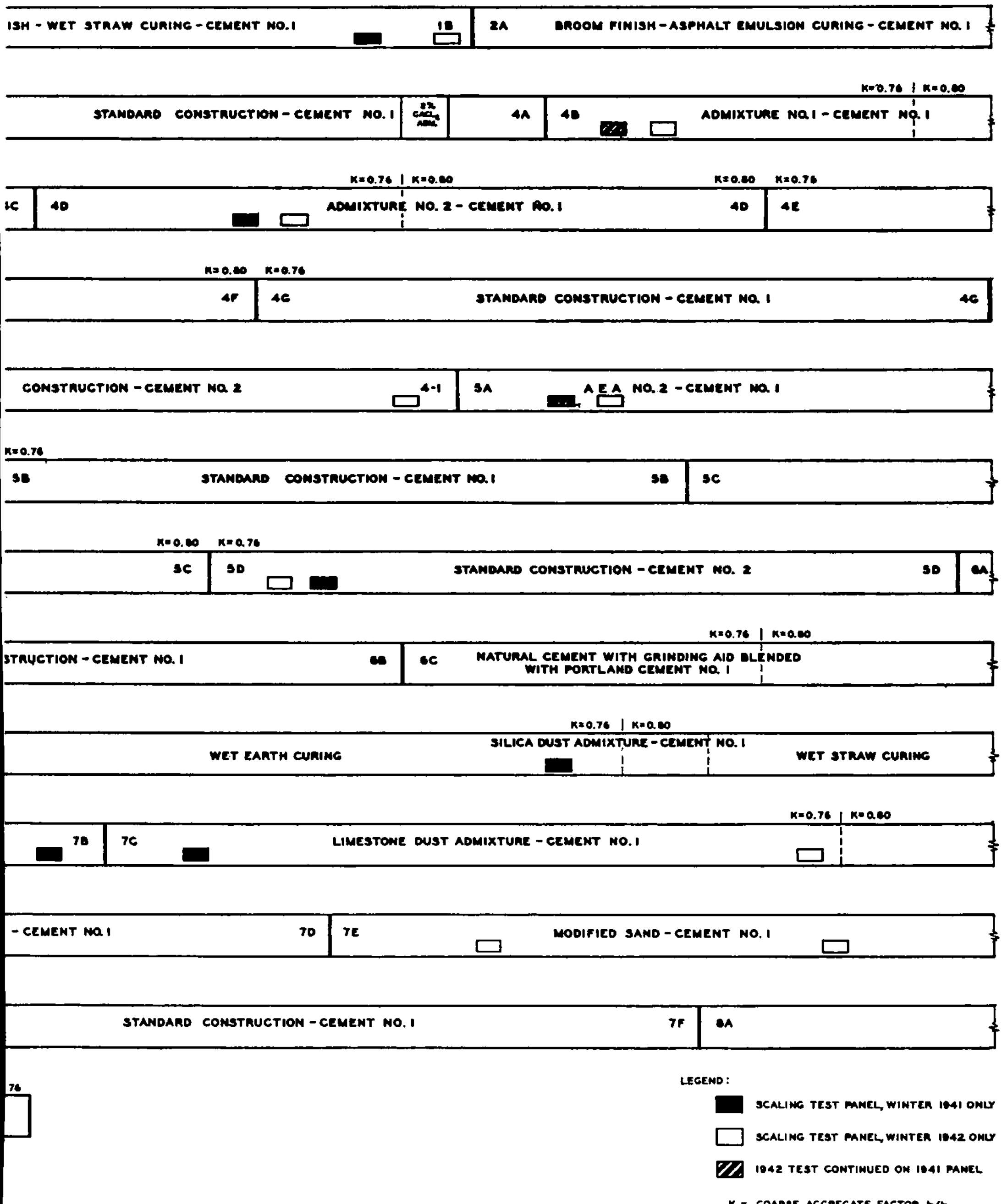


Figure 9. Location of panel



for accelerated scaling tests.


CAUTION
TEST
SECTION
(a)
(b)
712+32
(c)
381+72
(d)
752+94
(e)
679+58
(f)

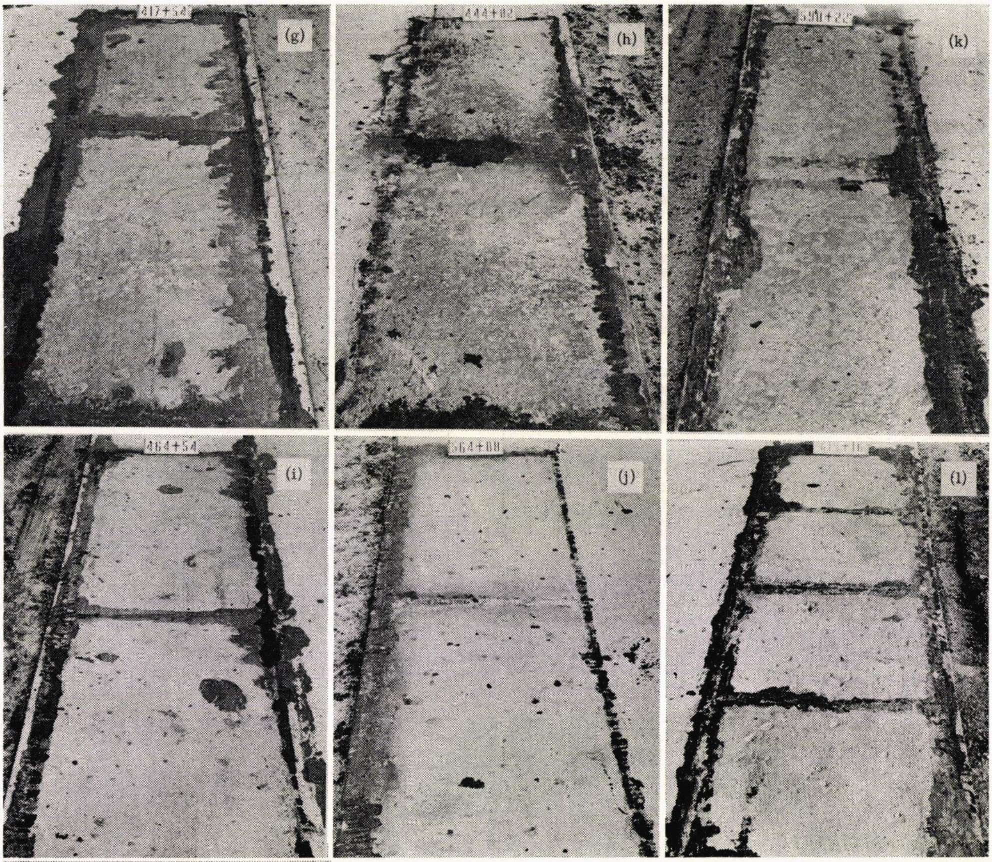


Figure 10. Condition of typical panels at end of accelerated scaling test, showing: (a) test area in operation; (b) silica dust, 33 cycles; (c) modified sand, 12 cycles; (d) broom finish, 23 cycles; (e) limestone aggregate with limestone dust, 22 cycles; (f) limestone dust, 8 cycles; (g) admixture No. 1, 93 cycles; (h) admixture No. 2, 61 cycles; (i) air-entraining admixture No. 1, 93 cycles; (j) air-entraining admixture No. 2, 94 cycles; (k) natural cement blend, no grinding aid, 90 cycles; (l) natural cement blend with grinding aid, 94 cycles; (m) standard concrete brand No. 2 cement, 32 cycles.

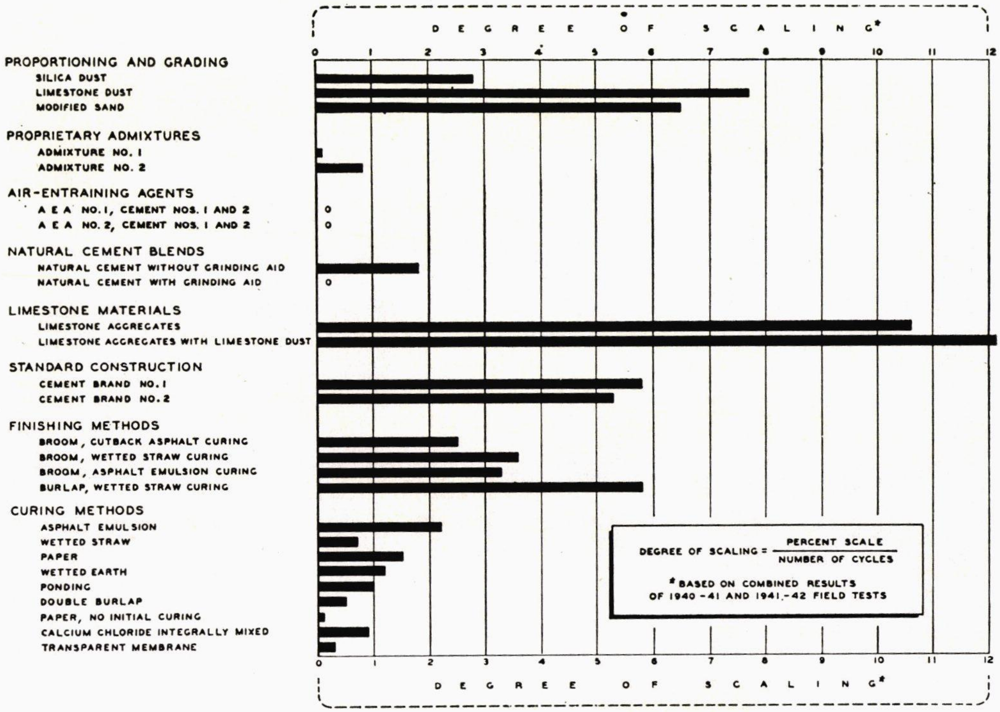


Figure 11. Scaling of experimental pavement sections in accelerated test.

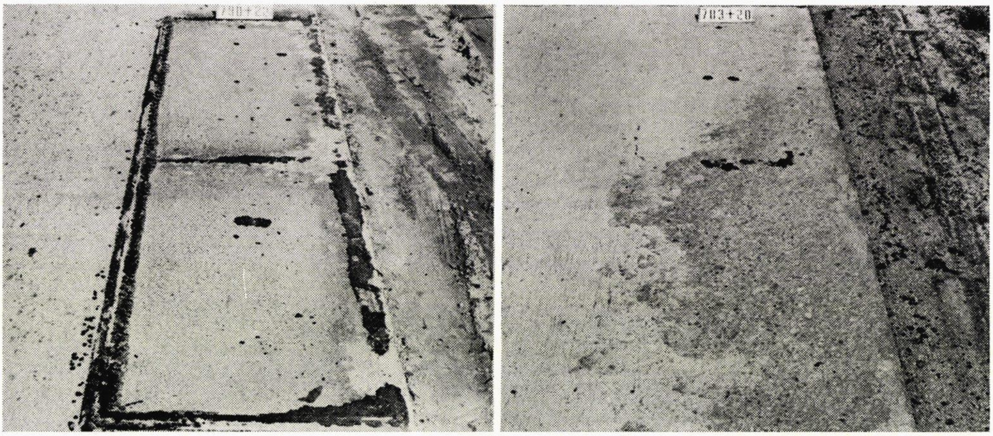


Figure 12. Effect of rain marking on resistance to scaling, showing: (left) rain-marked concrete, 61 cycles; and (right) unmarked concrete, 9 cycles.

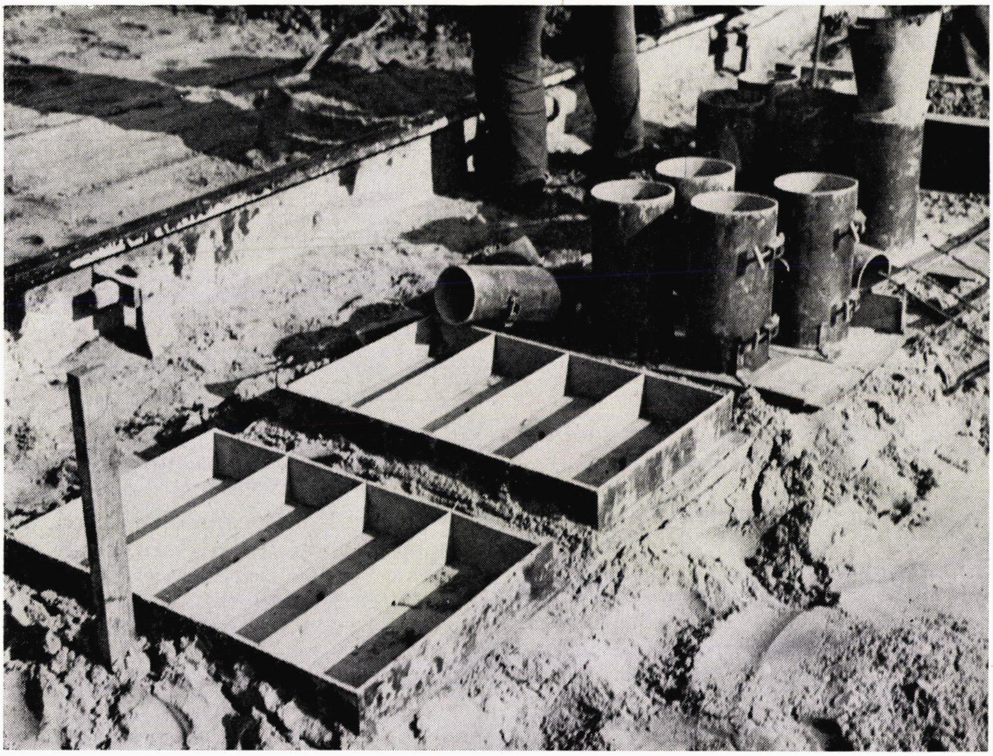


Figure 13. Steel molds ready for casting field specimens.

ect 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 (Appendix B). Figure 12 shows 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 result was not entirely unexpected, the same effect having been observed previously in other pavements built with non-air-entrained concrete.

LABORATORY FREEZING-AND-THAWING TESTS

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. 13). 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. Subsequently 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 months and 1 year, respectively. All cylindrical beams were included in the tests of the 5-month 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 $\frac{3}{16}$-in. wall thickness. Sufficient water was added to the containers to cover the specimens to a depth of $\frac{1}{4}$ 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.

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.

Freezing-and-Thawing Cycle. 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 (Fig. 14).

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.

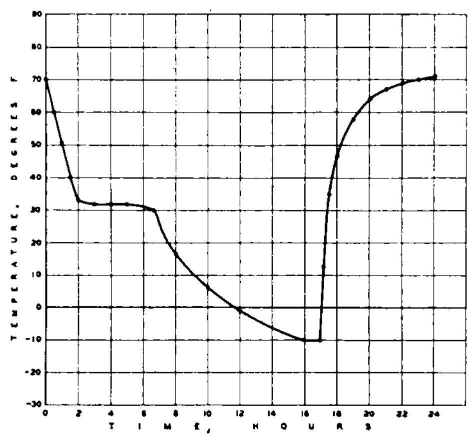


Figure 14. Freezing-and-thawing temperature cycle.

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.

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 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 (Appendix B) and

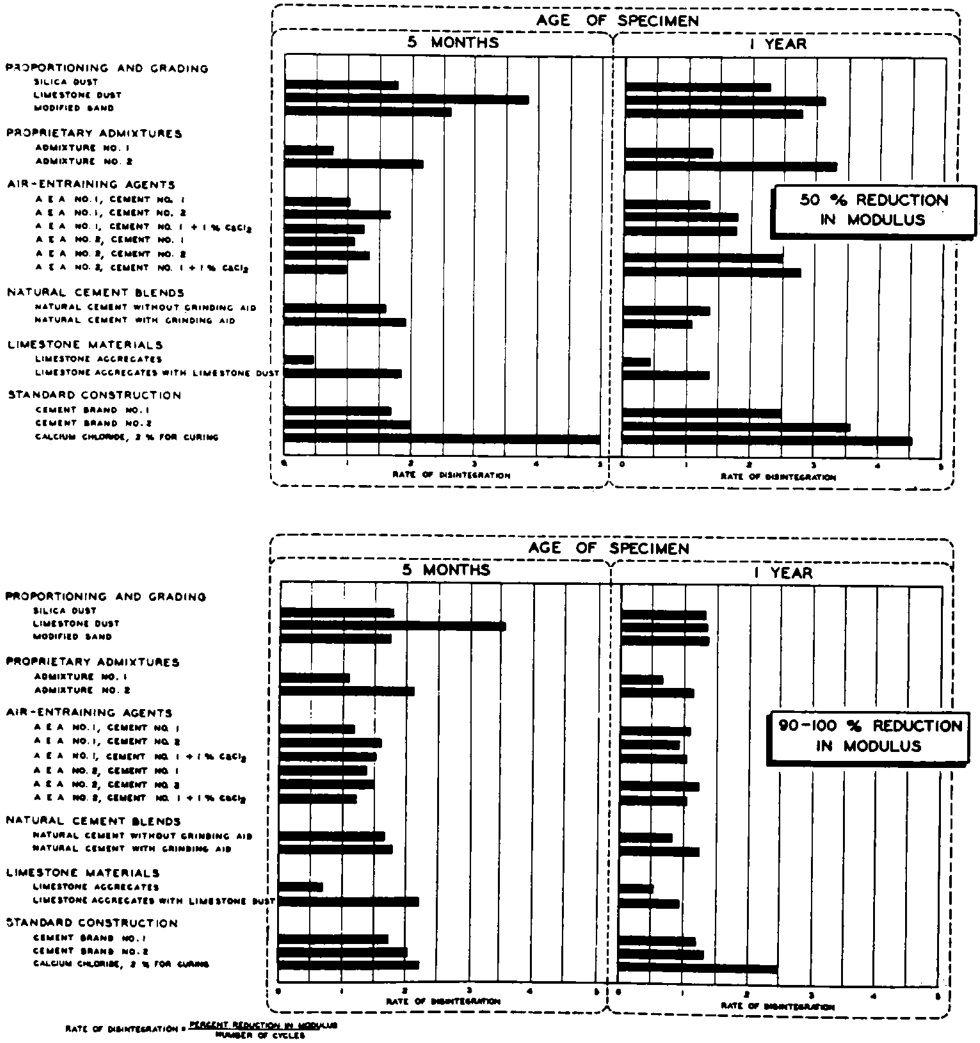


Figure 15. Rate of disintegration of field-molded specimens by freezing and thawing in water.

shown in Figure 15. Table 24 gives 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 table includes data for the rectangular beams only; the cylindrical specimens proved unsatisfactory for freezing-and-thawing studies. 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. Admixture No. 1 performed better in this test, and mixtures containing it were considerably superior to standard concrete. 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, Appendix 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. However, the fact that many specimens failed prematurely in the freeze-and-thaw test is 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 previously mentioned, 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, 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-year-old pavement almost invariably indicated a considerable gain in compressive strength over the 28-day and

TABLE 2

SUMMARY OF TEST DATA ON MOLDED SPECIMENS

Factor	Original Dynamic Modulus, psi × 10^6	Loss, %: Dynamic Modulus	Loss, %: Flexural Strength	Loss, %: Compressive Strength
Proportioning and grading:				
Silica dust	6.7	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

20-month 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 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

A laboratory study was also made to compare the durability of pavement cores from the various experimental sections. The core study had three objectives: (a) to gather additional data of significance in evaluating the factors under consideration; (b) to observe the relative durability of concrete at the top and bottom of the pavement slab; and (c) 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 months 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 com-

TABLE 3

SUMMARY OF CORE DURABILITY STUDY; FREEZING AND THAWING IN WATER

Factor	Core No.	Cement Brand	b/b_0	Cycles for Disintegration			Specific Gravity		
				Top	Bottom	% Var.	Top	Bottom	Var.
Proportioning and grading:									
Silica dust	241A	1	0.76	135	135	0	2.47	2.50	−0.03
Silica dust	242	1	0.80	90	135	−33	2.46	2.49	−0.03
Limestone dust	246	1	0.80	135	200	−33	2.46	2.48	−0.02
Modified sand	250	1	0.80	50	60	−17	2.48	2.51	−0.03
Proprietary admixtures:									
Admixture No. 1	215	1	0.80	200	155	+29	2.44	2.51	−0.07
Admixture No. 2	217A	1	0.76	135	190	−29	2.49	2.51	−0.02
Admixture No. 2	218	1	0.80	135	135	0	2.54	2.47	+0.07
Air-entraining agents:									
AEA No. 1	220	1	0.80	205	205	0	2.46	2.46	0.00
AEA No. 1	223	2	0.80	110	200	−45	2.48	2.46	+0.02
AEA No. 2	225A	1	0.76	175	170	+ 3	2.41	2.41	0.00
AEA No. 2	227	1	0.80	200	200	0	2.41	2.39	+0.02
AEA No. 2	229A	2	0.76	205	200	+ 3	2.48	2.49	−0.01
AEA No. 2	230	2	0.80	215	200	+ 8	2.46	2.50	−0.04
Natural cement blends:									
Without grind. aid	234	1	0.80	135	145	− 7	2.46	2.52	−0.06
With grind. aid	237	1	0.80	195	120	+63	2.44	2.44	0.00
Limestone materials:									
Limestone aggregates	255	1	0.76	135	205	−34	2.44	2.45	−0.01
Limestone agg. with limestone dust	253	1	0.76	50	155	−68	2.44	2.50	−0.06
Standard construction:									
Cement Brand No. 1	228	1	0.76	120	135	−11	2.48	2.50	−0.02
Cement Brand No. 1	243	1	0.76	120	195	−38	2.46	2.52	−0.06
Cement Brand No. 1	247	1	0.76	135	170	−21	2.47	2.51	−0.04
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	−0.05
Cement Brand No. 2	232	2	0.76	70	135	−48	2.50	2.51	−0.01
Finishing methods:									
Broom, asph. emulsion curing	204	1	0.76	110	135	−19	2.49	2.50	−0.01
Curing methods:									
Asphalt emulsion	205	1	0.76	80	200	−60	2.47	2.49	−0.02
Wetted straw	206	1	0.76	60	155	−61	2.47	2.51	−0.04
Paper with initial curing	207	1	0.76	155	155	0	2.50	2.52	−0.02
Wetted earth	208	1	0.76	60	135	−56	2.47	2.52	−0.05
Ponding	209	1	0.76	70	170	−59	2.47	2.48	−0.01
Double burlap	210	1	0.76	80	50	+60	2.48	2.43	+0.05
Paper, no initial curing	211	1	0.76	100	185	−46	2.49	2.50	−0.01
Membrane with initial curing	213	1	0.76	110	80	+38	2.48	2.48	0.00

pressive strength. At the time of the tests the concrete was 21 months 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 5 cycles and thoroughly agitated at the beginning of each freezing period.

At the end of each 5 or 10 cycles the specimens were removed from the rubber containers, wiped off, and visually exam-

TABLE 4

SUMMARY OF CORE DURABILITY STUDY; FREEZING AND THAWING IN 10 PERCENT $CaCl_2$ SOLUTION

Factor	Core No.	Cement Brand	b/b_0	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	−0.05
Silica dust	242	1	0.80	55	130	−58	2.45	2.47	−0.02
Limestone dust	246	1	0.80	50	70	−29	2.46	2.48	−0.02
Modified sand	250	1	0.80	20	25	−20	2.47	2.54	−0.07
Proprietary admixtures:									
Admixture No. 1	215	1	0.80	186	176	+ 6	2.42	2.52	−0.10
Admixture No. 2	217A	1	0.76	60	65	− 8	2.51	2.51	0.00
Admixture No. 2	218	1	0.80	95	55	+73	2.54	2.50	+0.04
Air-entraining agents:									
AEA No. 1	220	1	0.80	140	206	−32	2.43	2.46	−0.03
AEA No. 1	223	2	0.80	55	130	−58	2.51	2.45	+0.06
AEA No. 2	225A	1	0.76	145	186	−22	2.38	2.46	−0.08
AEA No. 2	227	1	0.80	186	165	+13	2.37	2.43	−0.06
AEA No. 2	229A	2	0.76	130	165	−21	2.48	2.48	0.00
AEA No. 2	230	2	0.80	130	145	−10	2.45	2.44	+0.01
Natural cement blends:									
Without grind. aid	234	1	0.80	75	165	−55	2.46	2.49	−0.03
With grind. aid	237	1	0.80	186	201	− 7	2.41	2.45	−0.04
Limestone materials:									
Limestone aggregates	255	1	0.76	60	186	−68	2.43	2.47	−0.04
Limestone agg. with limestone dust	253	1	0.76	35	105	−67	2.43	2.49	−0.06
Standard construction:									
Cement Brand No. 1	228	1	0.76	45	65	−31	2.49	2.50	−0.01
Cement Brand No. 1	243	1	0.76	35	78	−55	2.44	2.48	−0.04
Cement Brand No. 1	247	1	0.76	55	176	−69	2.47	2.49	−0.02
Cement Brand No. 1	251	1	0.76	45	155	−71	2.48	2.48	0.00
Cement Brand No. 2	224	2	0.76	50	35	+43	2.52	2.53	−0.01
Cement Brand No. 2	232	2	0.76	45	70	−36	2.48	2.51	−0.03
Finishing methods:									
Broom, asph. emulsion curing	204	1	0.76	60	100	−40	2.49	2.50	−0.01
Curing methods:									
Asphalt emulsion	205	1	0.76	50	155	−68	2.47	2.49	−0.02
Wetted straw	206	1	0.76	50	110	−55	2.47	2.52	−0.05
Paper with initial curing	207	1	0.76	60	155	−61	2.50	2.52	−0.02
Wetted earth	208	1	0.76	35	110	−68	2.47	2.52	−0.05
Ponding	209	1	0.76	50	85	−41	2.47	2.48	−0.01
Double burlap	210	1	0.76	50	25	+100	2.48	2.43	+0.05
Paper, no initial curing	211	1	0.76	75	110	−32	2.49	2.50	−0.01
Membrane with initial curing	213	1	0.76	45	130	−65	2.48	2.48	0.00

ined 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. 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 16.

Because specimen size and shape did not permit exact measurement of deterioration by the sonic method, only a qualitative 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

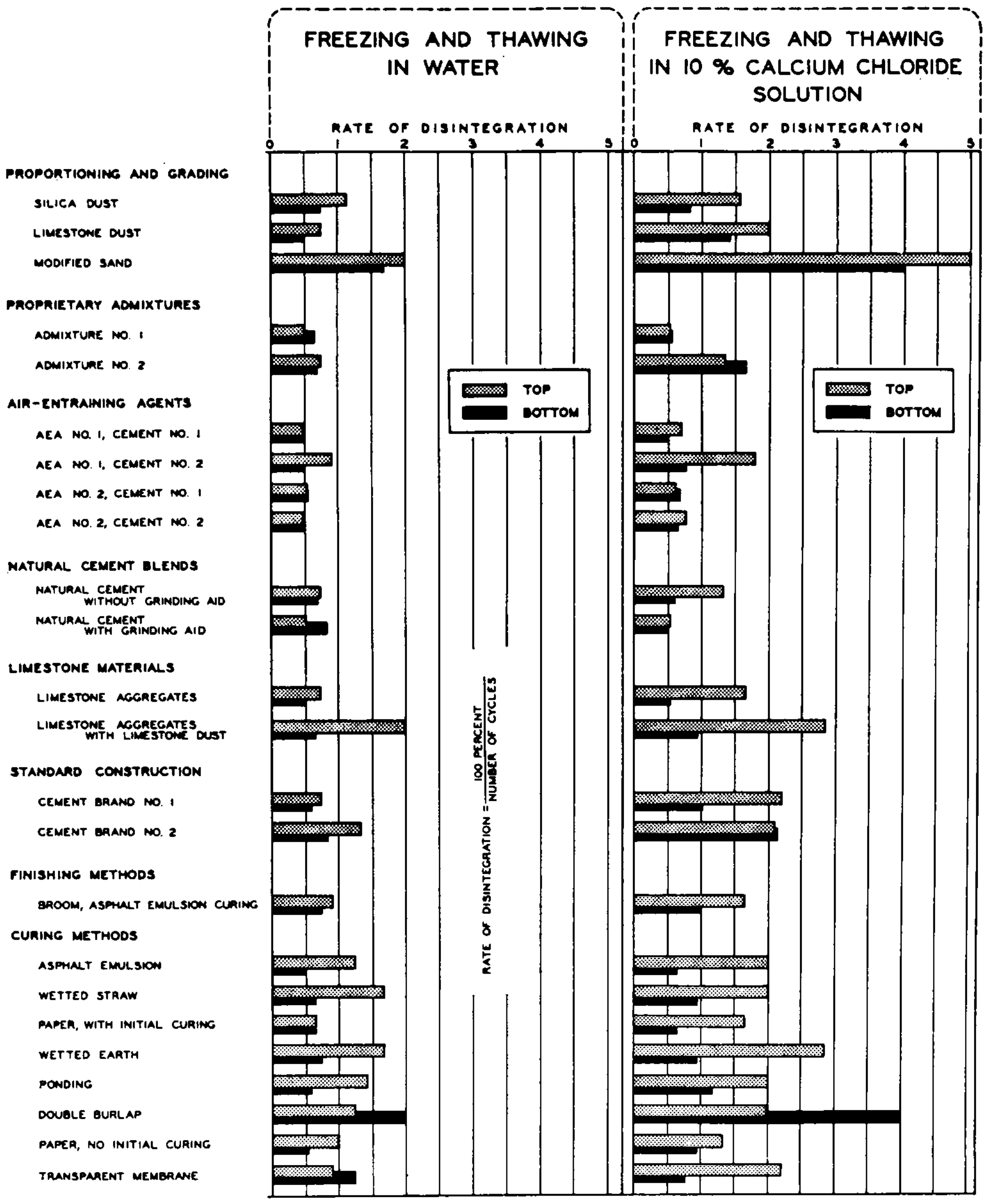


Figure 16. Rate of disintegration of core specimens by freezing and thawing.

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 finding was that, except for the air-entrained concretes, the core tops were less durable than the bottoms (Fig. 16). 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 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 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 (Fig. 16) 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, whereas those frozen in water failed by a general structural breakdown (Fig. 17). 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 illustrated difference in behavior 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 the Research Laboratory Division, thin plates of mortar and concrete have spontaneously disintegrated in a few weeks when stored continuously in a 30 percent $CaCl_2$ 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.

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

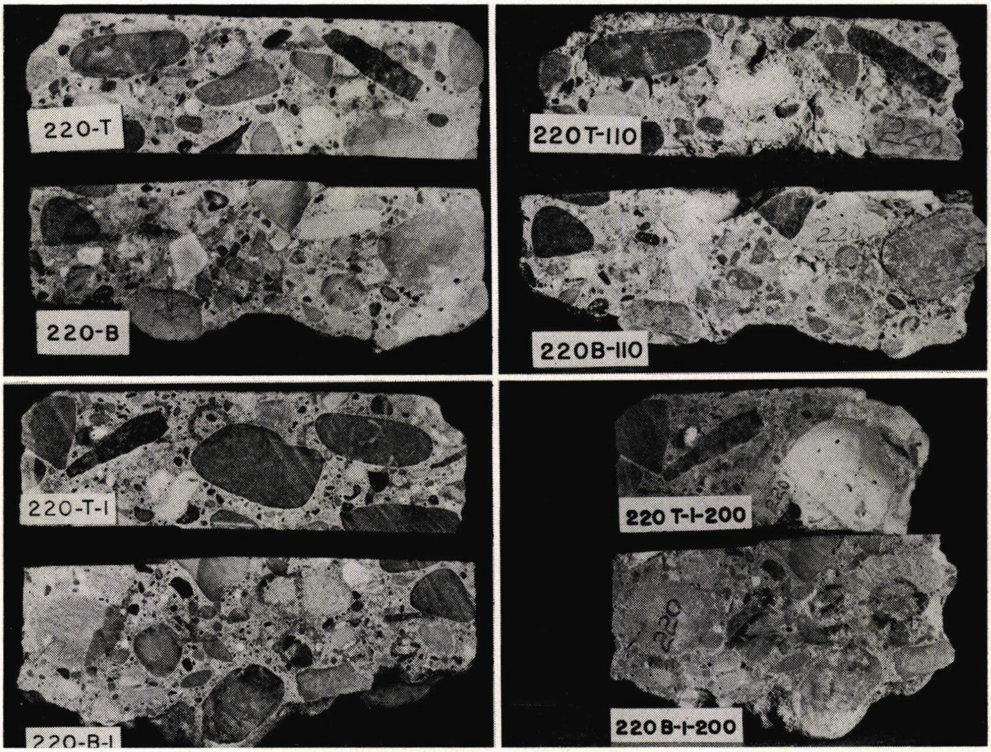


Figure 17. Effects of freezing and thawing, showing: (upper) core No. 220 before and after 110 cycles in 10 percent $CaCl_2$ solution, and (lower) before and after 200 cycles in water.

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 are given in Tables 3 and 4. A complete summary may be found in Table 25 (Appendix B).

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 (Tables 3 and 4). 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.

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 years in the laboratory atmosphere. After initial weighing they were dried at 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 to 75 F and surface-dry weights recorded at intervals of ½, 1, 3, 6, 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.

The data are summarized in Table 26 (Appendix B) and Figure 18. The rate of change of moisture content during the drying period is expressed as percent of the original moisture lost per hour for

TABLE 5

COMPARISON OF ACCELERATED TEST RESULTS WITH PAVEMENT PERFORMANCE

Factor	Rate of Disintegration[1]					Degree of Scaling,[2] Accelerated Scaling Tests	Percent Scale, Pavement 1955
	Pavement Cores				5 Mo. Beams		
	Freeze and Thaw in Water		Freeze and Thaw in 10% $CaCl_2$		Freeze and Thaw in Water 90–100% Reduction		
	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:							
Without grind. aid	0.74	0.69	1.33	0.61	1.67	1.8	1
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 $= \dfrac{\text{Percent Reduction}}{\text{Number of Cycles}}$.

[2] Degree of Scaling $= \dfrac{\text{Percent Scale}}{\text{Number of Cycles}}$.

[3] Condition in 1950, resurfaced in 1952.
[4] Condition in 1950, resurfaced in 1951.

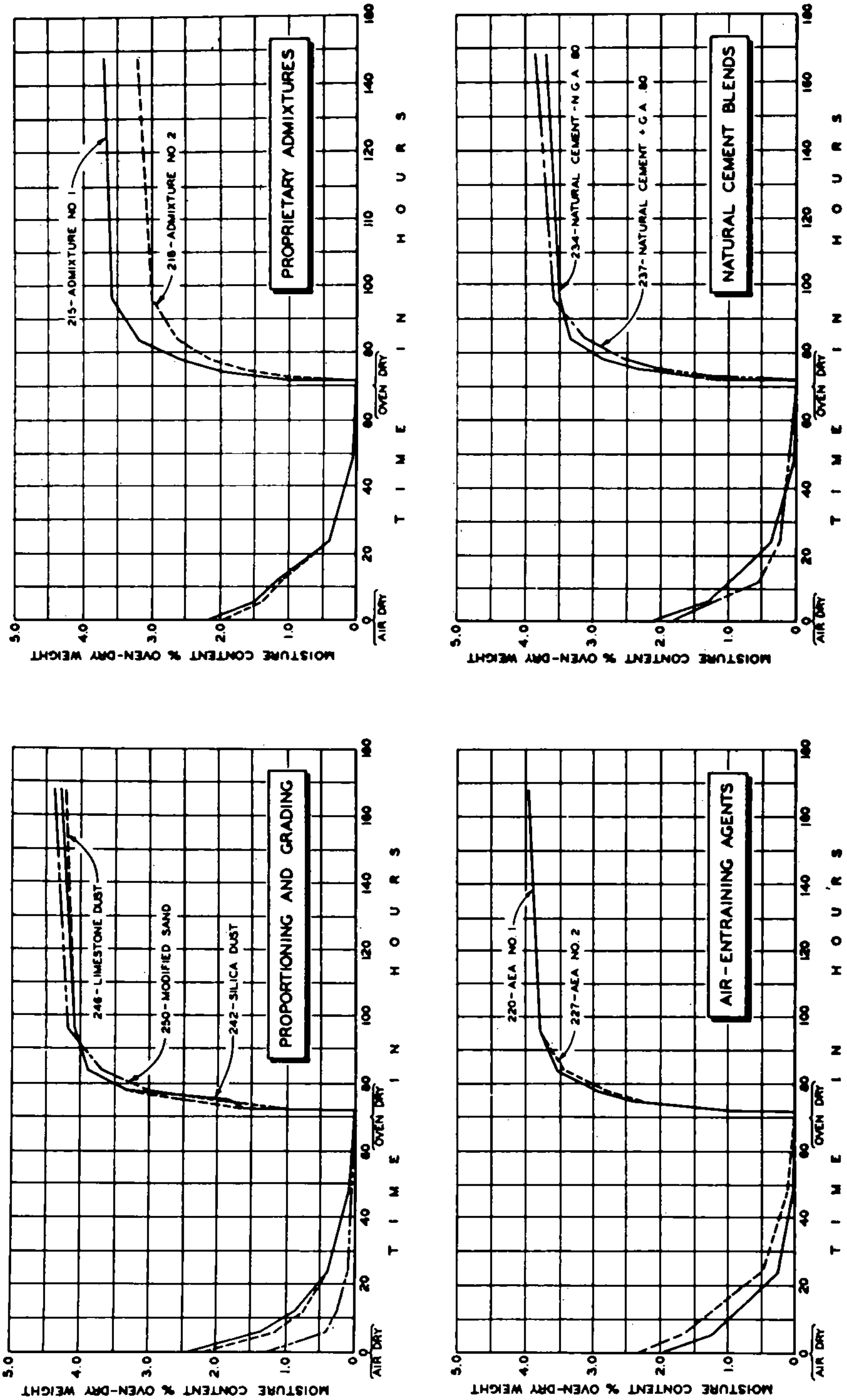
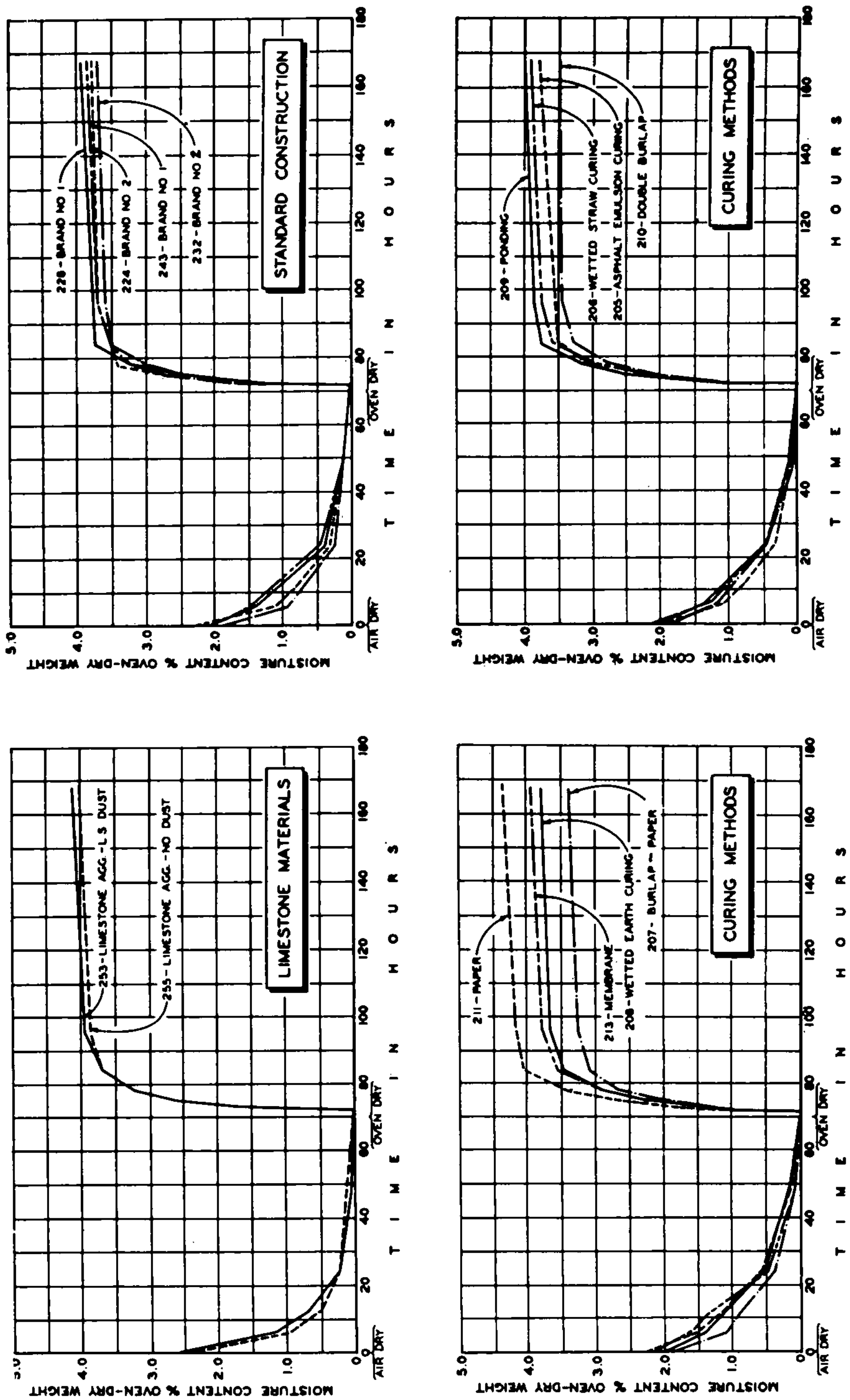


Figure 18. Rate of abs


STANDARD CONSTRUCTION
228 - BRAND NO 1
224 - BRAND NO 2
243 - BRAND NO 1
232 - BRAND NO 2
CURING METHODS
209 - PONDING
206 - WETTED STRAW CURING
205 - ASPHALT EMULSION CURING
210 - DOUBLE BURLAP
LIMESTONE MATERIALS
253 - LIMESTONE AGG. - L.S. DUST
255 - LIMESTONE AGG. - NO DUST
CURING METHODS
211 - PAPER
213 - MEMBRANE
208 - WETTED EARTH CURING
207 - BURLAP - PAPER
MOISTURE CONTENT % OVEN-DRY WEIGHT
TIME IN HOURS
AIR DRY
OVEN DRY

ment cores.

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 (Appendix 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 although 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 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 2½ to 3 in. thick and about 5¾ 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 watertight 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.

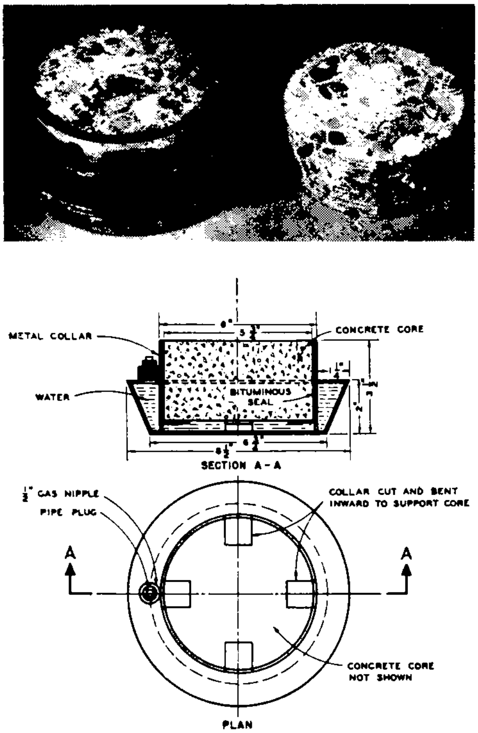


Figure 19. Permeability assembly.

19). 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 (Table 27, Appendix B, and Fig. 20) show only a rough correlation with those of the durability tests. Again, the method used 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. Verbeck (*24*) has discussed the significance of concrete properties related to pore structure.

INCIDENTAL STUDIES

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 (Appendix B), arranged as an ungrouped frequency distribution of values in increments of ¼ in. Figure 21 shows a grouped frequency distribution in ½-in. cells. These data indicate that slump varied from 0 to 5¼ 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. Because these qualities affect scale resistance of the hardened concrete, the characteristics of the

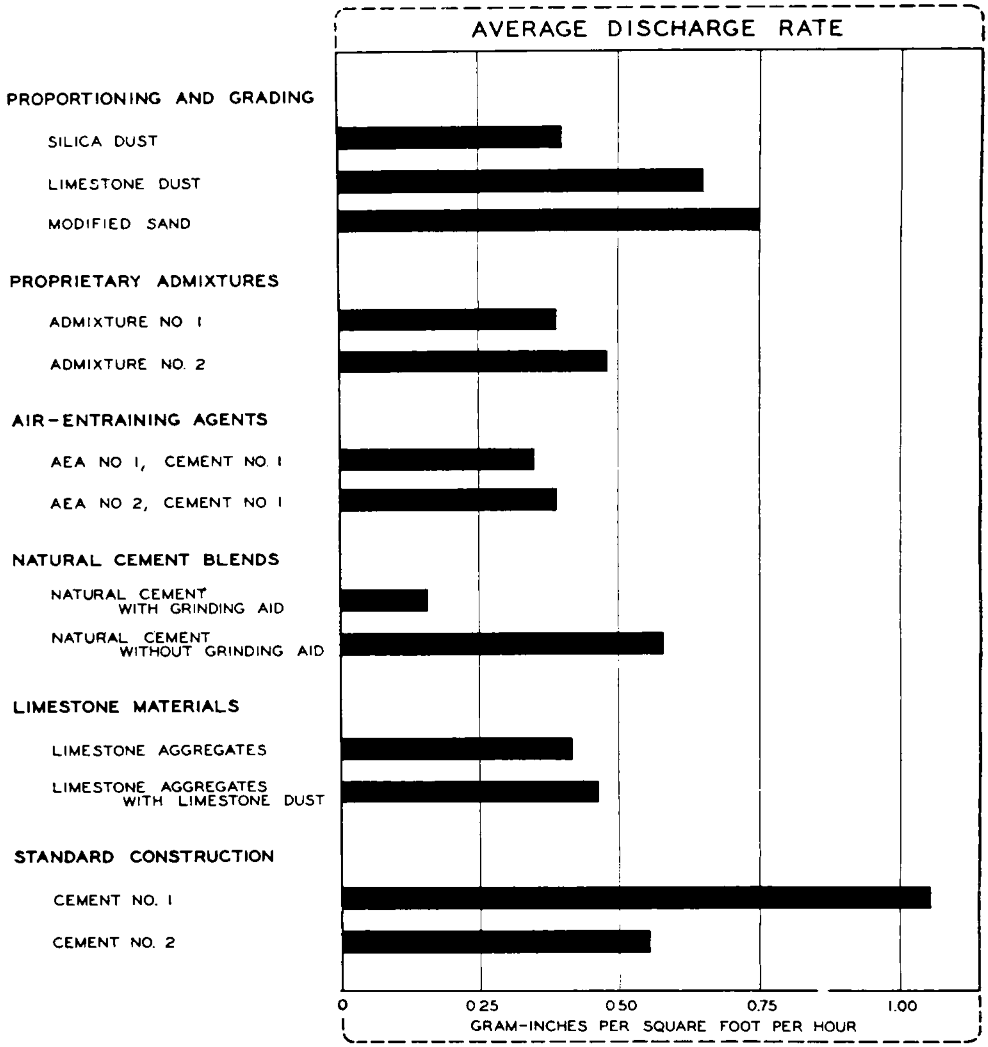


Figure 20. Rate of water passage through core sections.

various mixtures are 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. Figure 22 is a typical example of the unusual plasticity of a concrete mix with added fines. 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 was 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.

Although 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

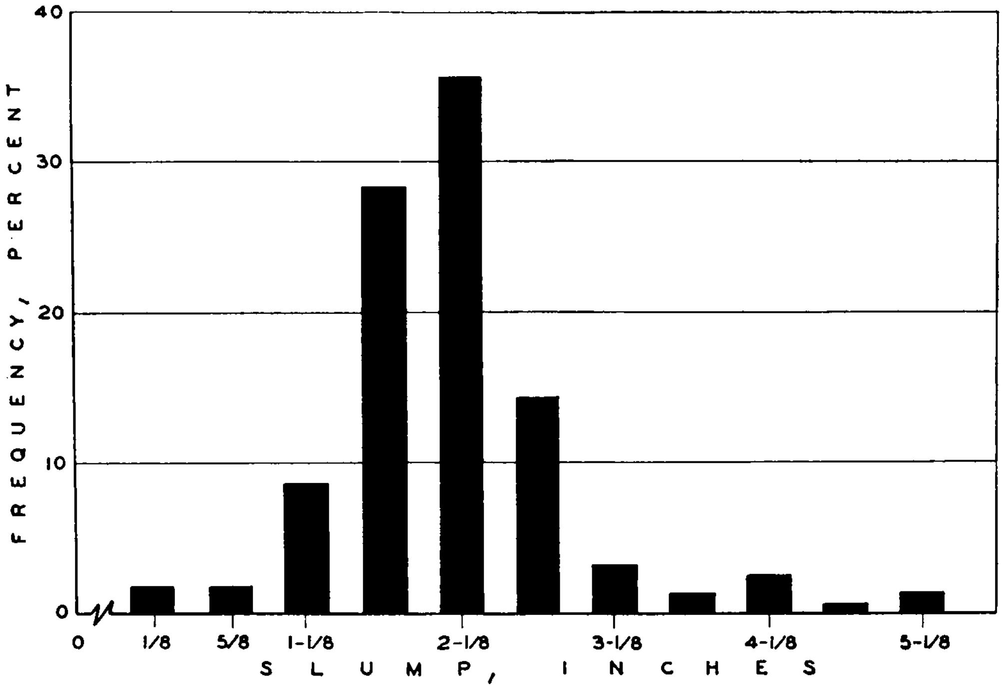


Figure 21. Grouped frequency distribution of slump values.

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_0, 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. 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 displacement 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 1½ in. The most noticeable characteristic of this admixture was 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 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

Figure 22. Typical appearance of concrete containing added fines.

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. Figure 23 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 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

TABLE 6

AIR CONTENT OF AIR-ENTRAINED MIXTURES

Mixture	Cement No. 1			Cement No. 2		
	Unit Wt.,[1] pcf	Drop in Wt., pcf	% Air	Unit Wt.,[1] 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

[1] Determined at an average slump of 2 in.

Figure 23. Typical appearance of air-entrained concrete.

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 ¾ pcf, and natural cement with no grinding aid a drop of 0.4 pcf. 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. 24). 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

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: (a) compare actual proportions with design quantities; (b) determine uniformity of proportions from top to bottom of the slab as a measure of the degree of bleeding and segregation; and (c) compare the uniformity of the fresh

Figure 24. Bleeding of concrete containing limestone fine and coarse aggregates.

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 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, indicating little or no selective effect of construction operations on proportions of the various mixtures.

Table 8 gives the results of the tests for segregation. About the only conclusion that can be drawn 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 the operation may have had on vertical distribution of the constituents were not great enough to be distinguishable by this test.

In all three 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

TABLE 7

COMPARISON OF ACTUAL MIX PROPORTIONS WITH DESIGN VALUES

Factor	Cement Brand	Cement b/b_0	Ratio by Weight			Parts by Weight					
			Water: Cement			Fine Aggregate			Coarse Aggregate		
			Design	Actual	% Diff.	Design	Actual	% Diff.	Design	Actual	% Diff.
Proportioning and grading:											
Silica dust	1	0.76	0.569	0.573	+0.8	2.29	2.40	+4.8	4.08	4.13	+1.2
Silica dust	1	0.80	0.557	0.574	+3.1	2.22	2.42	+9.0	4.18	4.34	+3.9
Limestone dust	1	0.76	0.570	0.563	−1.2	2.32	2.62	+12.9	4.07	3.84	−5.5
Limestone dust	1	0.80	0.560	0.625	+11.7	2.26	2.68	+18.6	4.19	4.09	−2.3
Modified sand	1	0.76	0.566	0.613	+8.4	2.31	2.36	+2.1	4.07	4.39	+7.9
Modified sand	1	0.80	0.547	0.588	+7.5	2.16	2.13	−1.4	4.30	4.50	+4.7
Proprietary admixtures:											
Admixture No. 1	1	0.76	0.505	0.452	−10.5	2.32	2.10	−9.5	4.07	3.70	−9.1
Admixture No. 1	1	0.80	0.470	0.458	−2.6	2.19	2.15	−1.8	4.30	4.04	−6.1
Admixture No. 2	1	0.76	0.525	0.459	−12.6	2.36	2.22	−5.9	4.08	3.93	−3.7
Admixture No. 2	1	0.80	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	0.76	0.530	0.485	−8.5	2.29	2.13	−7.0	4.08	4.20	+2.9
AEA No. 1	1	0.80	0.510	0.478	−6.3	2.13	2.03	−4.7	4.30	4.01	−6.7
AEA No. 1	2	0.76	0.529	0.556	+5.1	2.30	2.35	+2.2	4.08	4.18	+2.5
AEA No. 1	2	0.80	0.510	0.515	+1.0	2.16	2.17	+0.5	4.31	4.19	−2.8
AEA No. 2	1	0.76	0.528	0.557	+5.5	2.32	2.49	+7.3	4.07	3.68	−9.6
AEA No. 2	1	0.80	0.518	0.566	+9.3	2.24	2.27	+1.3	4.19	3.75	−10.5
AEA No. 2	2	0.76	0.528	0.558	+5.7	2.33	2.38	+2.1	4.07	4.20	+3.2
Natural cement blends:											
Without grinding aid	1	0.76	0.570	0.532	−6.7	2.27	2.29	+0.9	4.08	4.04	−0.9
With grinding aid	1	0.76	0.569	0.615	+8.1	2.21	2.50	+12.9	4.08	4.55	+11.5
Limestone materials:											
Limestone aggregates	1	0.76	0.538	0.526	−2.2	2.59	2.34	−9.5	3.58	3.11	−13.1
Limestone agg. with limestone dust	1	0.76	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	0.76	0.523	0.496	−5.0	2.37	2.25	−4.9	4.07	3.89	−4.3
Cement brand No. 2	2	0.76	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	Cement Brand	b/b_0	Water, lb/sack cement			Parts by Weight							
						Fine Aggregate				Coarse Aggregate			
			Top	Bottom	% Var.	Design	Top	Bottom	% Var.	Design	Top	Bottom	% Var.
Proportioning and grading:													
Silica dust	1	0.76	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	0.80	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	0.76	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	0.80	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	0.76	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	0.80	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	0.76	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	0.80	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	0.76	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	0.80	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	0.76	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	0.80	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	0.76	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	0.80	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	0.76	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	0.80	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	0.76	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:													
Without grinding aid	1	0.76	52.8	47.7	+10.7	2.27	2.33	2.29	+1.7	4.08	4.15	4.10	+1.2
With grinding aid	1	0.76	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	0.76	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	0.76	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	0.76	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	0.76	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	Cement Brand	b/b_0	Water, lb/sack cement			Parts by Weight					
						Fine Aggregate			Coarse Aggregate		
			Before	After	% Var.	Before	After	% Var.	Before	After	% Var.
Proportioning and grading:											
Silica dust	1	0.76	53.0	57.7	+8.8	2.38	2.41	+1.26	3.55	3.32	−6.48
Silica dust	1	0.80	54.9	57.0	+3.8	2.35	2.48	+1.27	4.78	4.10	−14.22
Limestone dust	1	0.76	53.6	55.0	+2.6	2.64	2.55	−3.41	3.85	3.54	−8.04
Modified sand	1	0.76	60.2	61.6	+2.3	2.47	2.41	−2.43	3.91	4.24	+18.70
Modified sand	1	0.80	49.5	59.1	+19.4	1.99	2.08	+4.53	4.19	4.87	+16.22
Proprietary admixtures:											
Admixture No. 1	1	0.76	42.5	45.6	+7.3	2.12	2.14	+0.94	3.32	3.82	+15.05
Admixture No. 1	1	0.80	47.1	43.6	−9.5	2.18	2.12	−2.75	4.26	4.44	+4.22
Admixture No. 2	1	0.76	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	0.76	47.2	45.5	−3.6	2.16	2.08	−3.70	4.00	3.35	−16.22
AEA No. 1	2	0.76	—	52.5	—	2.39	2.32	−2.92	4.21	3.92	−6.88
AEA No. 1	2	0.80	49.3	46.9	−4.9	2.16	2.14	−0.93	4.08	4.02	−1.47
AEA No. 2	1	0.76	56.1	53.1	−5.3	2.60	2.38	−8.46	3.78	3.31	−12.42
AEA No. 2	2	0.76	53.6	50.0	−6.7	2.43	2.30	−5.36	3.82	3.58	−6.28
Natural cement blends:											
Without grinding aid	1	0.76	50.5	55.2	+9.3	2.21	2.44	+10.4	4.30	4.15	−3.49
With grinding aid	1	0.76	57.2	59.5	+4.0	2.48	2.55	+3.10	4.64	4.71	+1.51
Limestone aggregates:											
Limestone aggregates	1	0.76	50.4	46.0	−8.7	2.32	2.31	−0.43	2.82	3.10	+10.00
Limestone agg. with limestone dust	1	0.76	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	0.76	46.6	48.6	+4.3	2.26	2.23	−1.33	3.86	3.92	+1.55
Cement brand No. 2	2	0.76	51.1	48.1	−5.9	2.42	2.32	−4.13	3.96	3.75	−5.31

be taken for each determination. Several other sources of error discussed by Dunagan (*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 atmospheric conditions. 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 ¼ in. was measured by a spring scale supporting the specimen (Fig. 25). Specimens were prepared by filling the pan with mortar obtained by passing the fresh concrete through a ¼-in. sieve. A load of 20 oz for ¼-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 (Appendix B) and Figure 26. In spite of variability induced by differences in air temperature and humidity, there are two well-defined indications. 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 Table 13 (Appendix A), which shows 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.

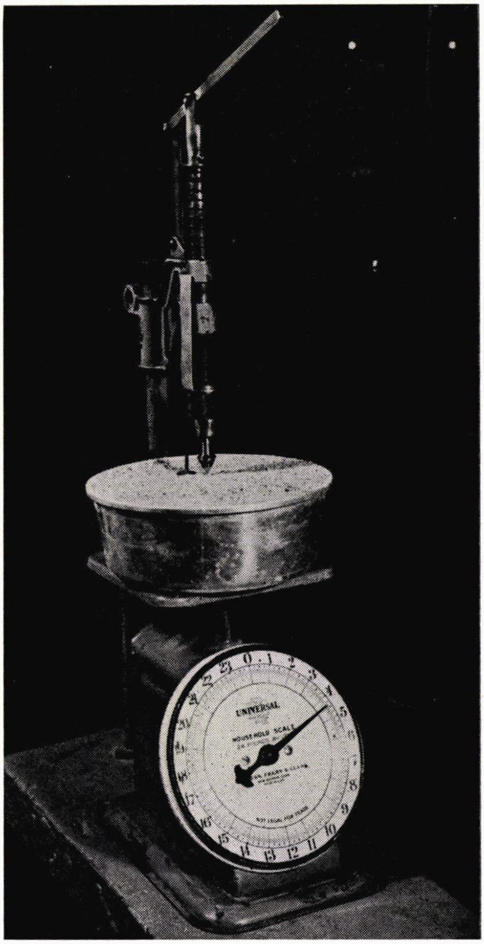


Figure 25. Burggraf penetrometer.

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

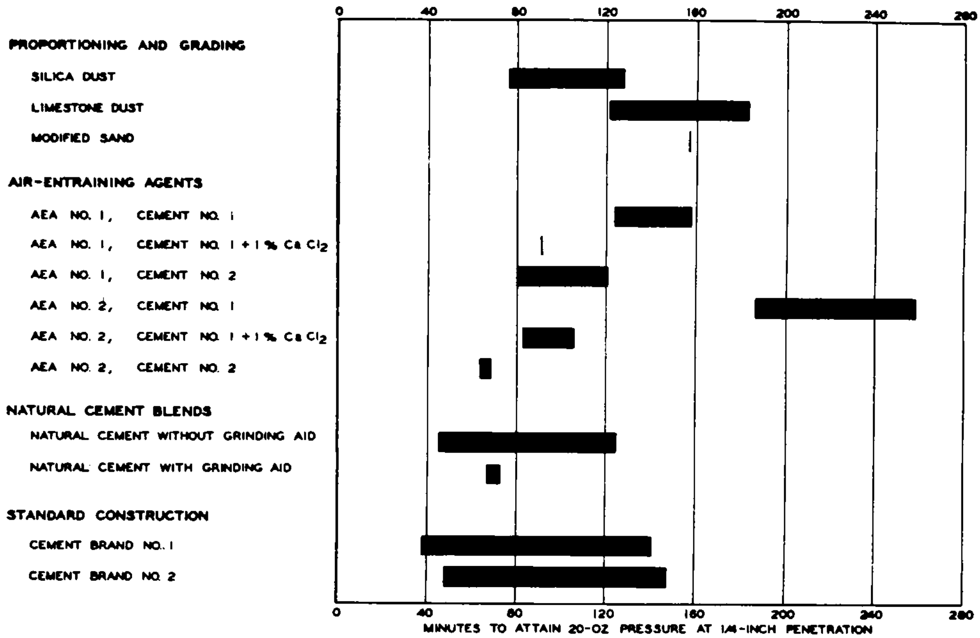


Figure 26. Setting time of concrete.

beams were kept in the moist room for 10 years and then tested for dynamic modulus of elasticity and flexural strength.

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 farther 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 summary of average 7- and 28-day compressive strengths is given in Table 30 (Appendix 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 Figure 27. Compressive strengths of all mixtures were well above the specification requirement of 2,500 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

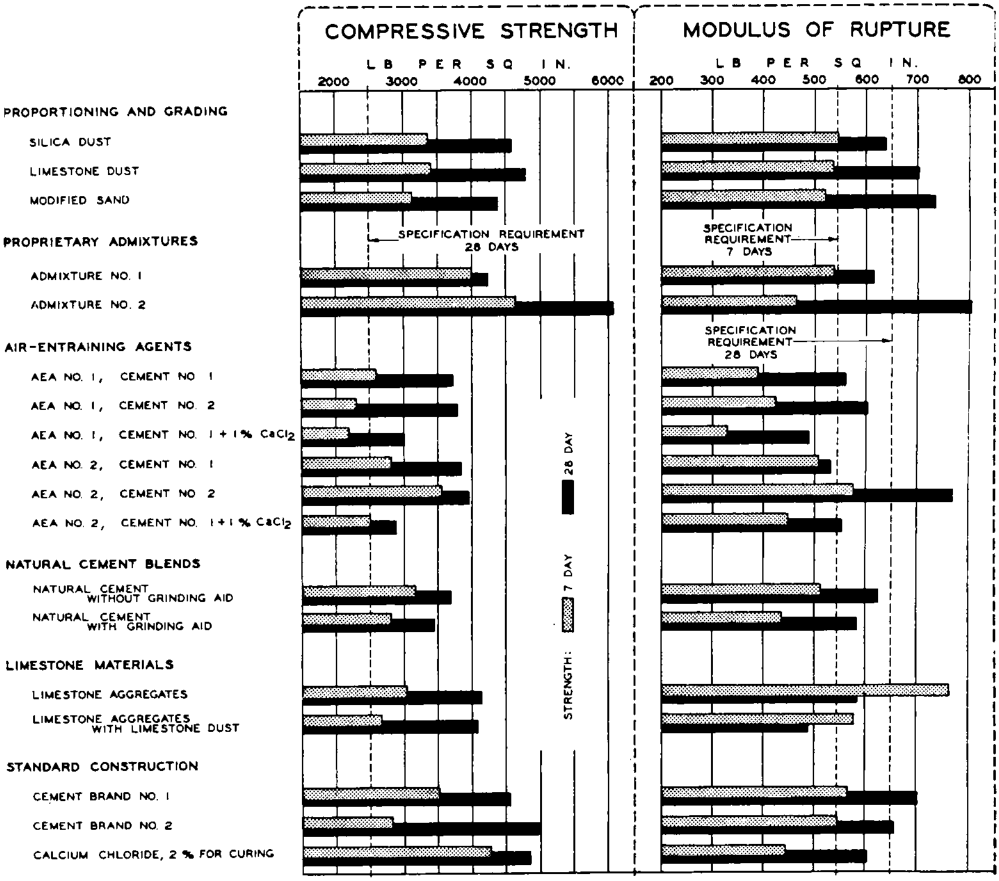


Figure 27. Compressive and flexural strengths of field-molded specimens.

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 consistently produced noticeably higher strengths at all ages. Table 10 gives values of air content, 10-year strengths, and extent of pavement scaling in 1955 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 24- and 36-in. lengths. These beams were cured in the same way as the pavement they represented, and broken 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.

Flexural test results are shown in Table 31 (Appendix B) and Figure 27. Values 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

TABLE 10

AIR CONTENT IN RELATION TO STRENGTH AND DURABILITY

Factor	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	7,450	128	842	6
Limestone dust	1.4	6,580	114	935	6
Modified sand	1.0	6,800	117	—	38
Proprietary admixtures:					
Admixture No. 1	4.0	4,900	85	828	0
Admixture No. 2	1.3	7,350	127	828	0
Air-entraining agents:					
AEA No. 1, Cement No. 1	3.7	5,600	97	797	0
AEA No. 1, Cement No. 2	4.0	5,800	100	707	0
AEA No. 2, Cement No. 1	5.7	3,850	66	—	0
AEA No. 2, Cement No. 2	2.3	5,100	88	—	0
Natural cement blends:					
Without grinding aid	1.6	6,650	115	—	1
With grinding aid	2.8	5,200	90	723	0
Limestone materials:					
Limestone aggregates	1.4	7,200	124	—	70[2]
Limestone agg. with limestone dust	1.0	5,600	97	929	90[2]
Standard construction:					
Cement Brand No. 1	1.5	5,800	100	904	8
Cement Brand No. 2	1.9	7,300	126	—	8

[1] Camera lucida method.
[2] Condition in 1950, resurfaced in 1951–1952.

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 years are listed in Table 32 (Appendix 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 2,000 psi. The dynamic values are, of course, higher than the secant moduli, because the former are determined at no load. Table 32 shows that the dynamic modulus of all mixtures increased appreciably over the 10-year 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_o, were used in the design of mixtures containing the various additions. Compressive and flexural strengths of these mixtures are given in Table 33 (Appendix B). Increasing b/b_o 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 previously in this report. Briefly, the principal objectives were: (a) to evaluate the influence of the various curing methods on durability, especially with regard to scaling; and (b) 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.

This 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 $\frac{1}{20}$ 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 $\frac{1}{20}$ 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 ½ by 1½ by 2½ 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. Because 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; 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 (Appendix 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

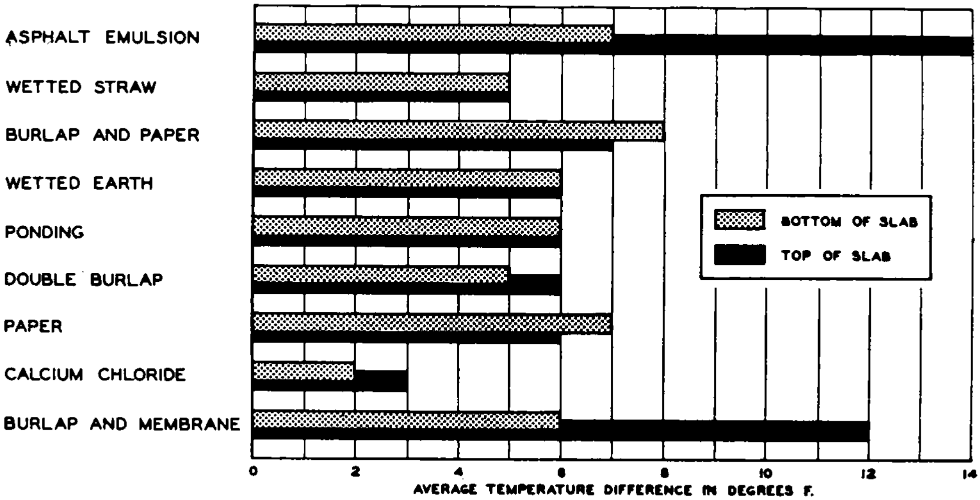


Figure 28. Average temperature difference between air and top and bottom of slab.

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. Figure 28 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 (Fig. 29). 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

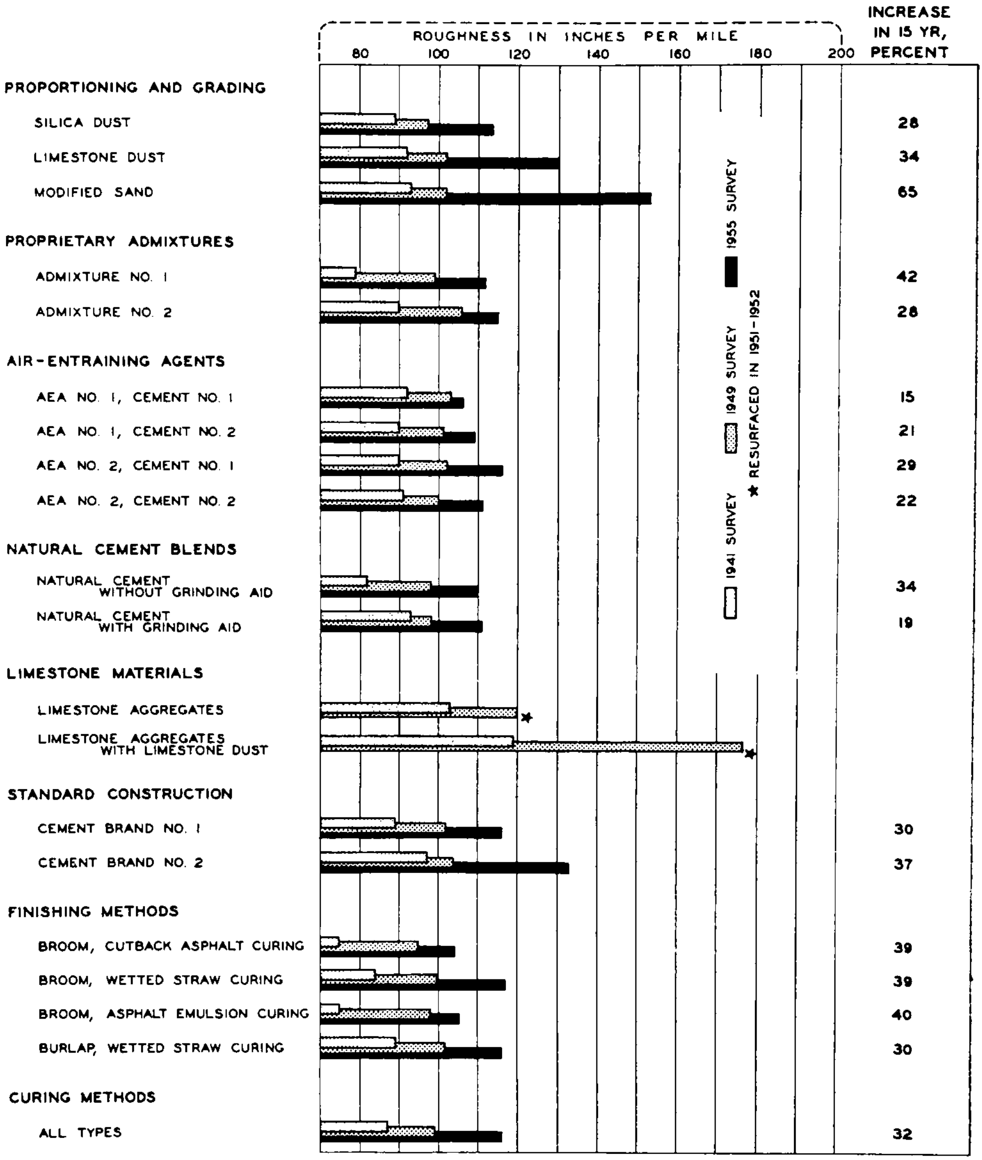


Figure 29. Pavement roughness.

broom-finished sections of standard concrete were the smoothest and the sections containing limestone aggregates the roughest. By 1949 the riding qualities of all sections of the project had become fairly 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 re-

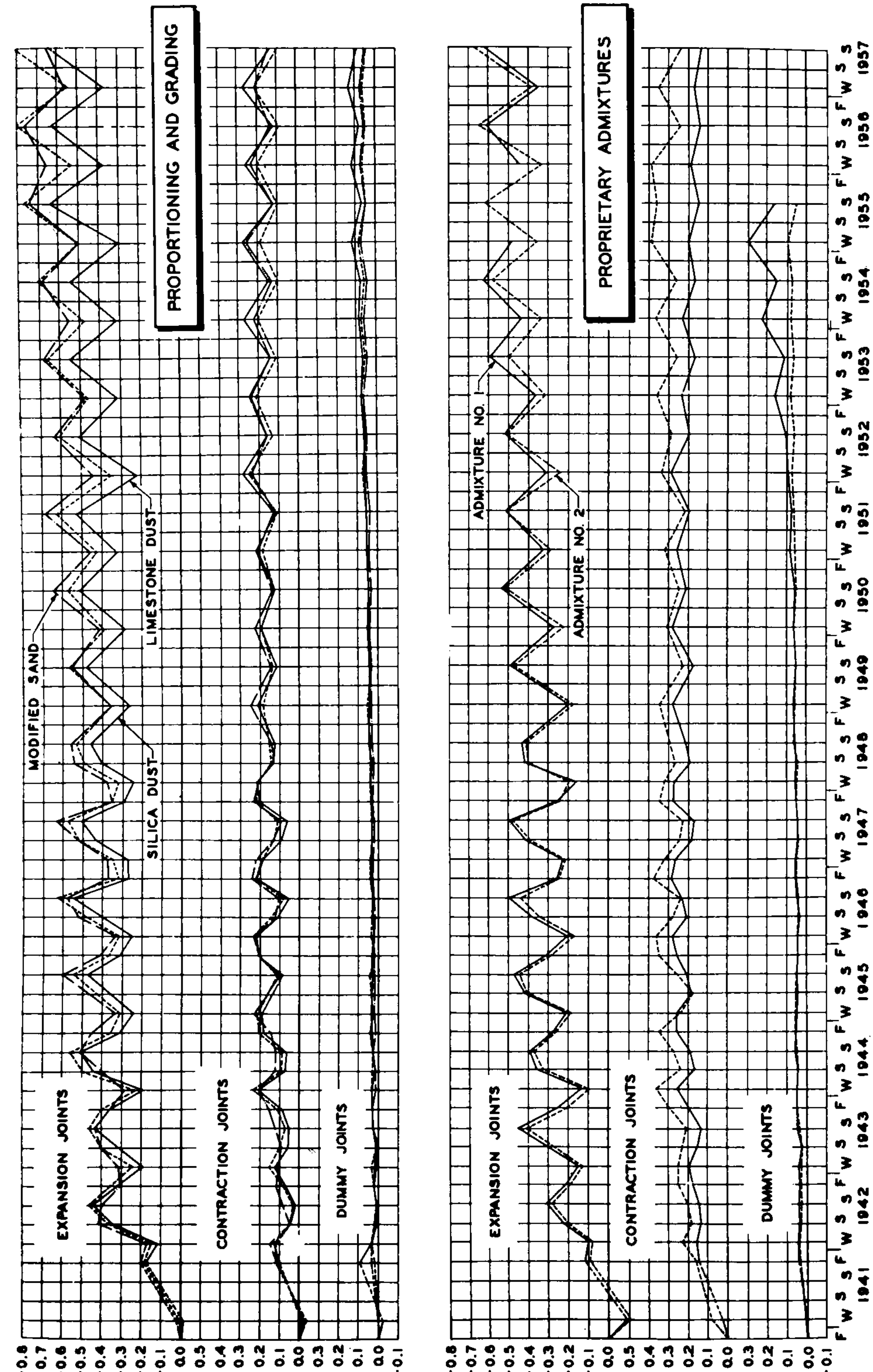


Figure 30. Joint width changes.

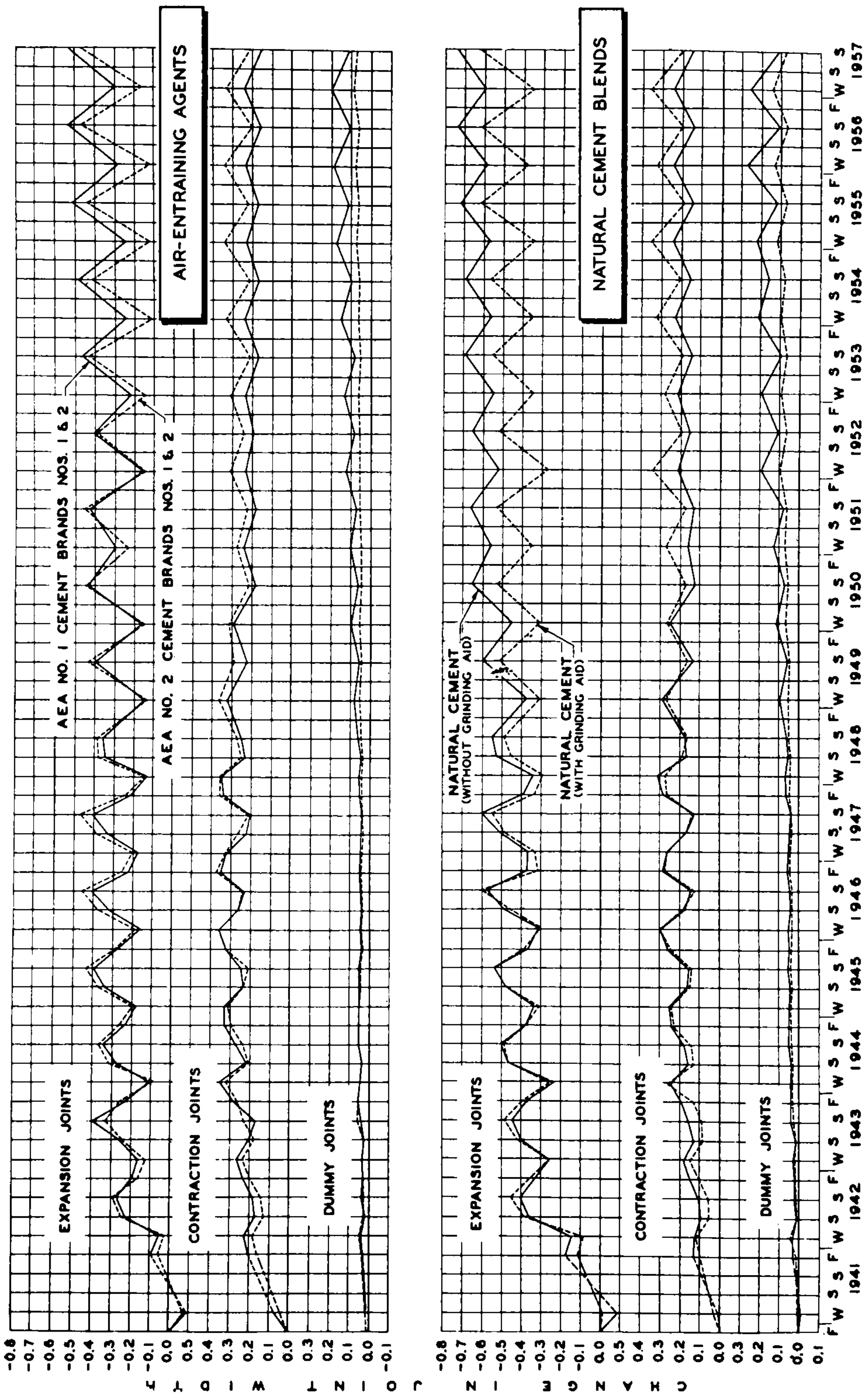


Figure 30 (Continued).

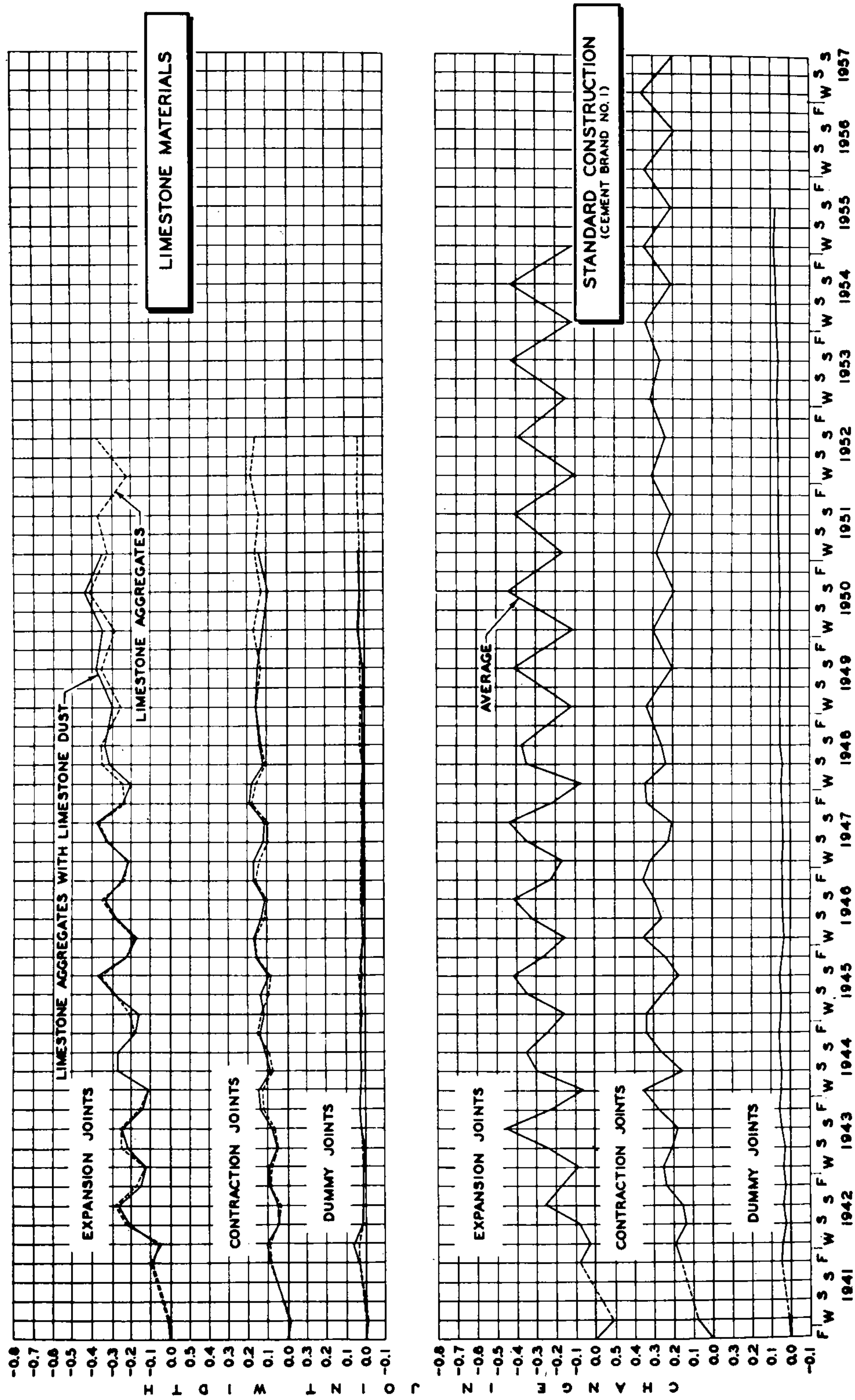


Figure 30 (Continued).

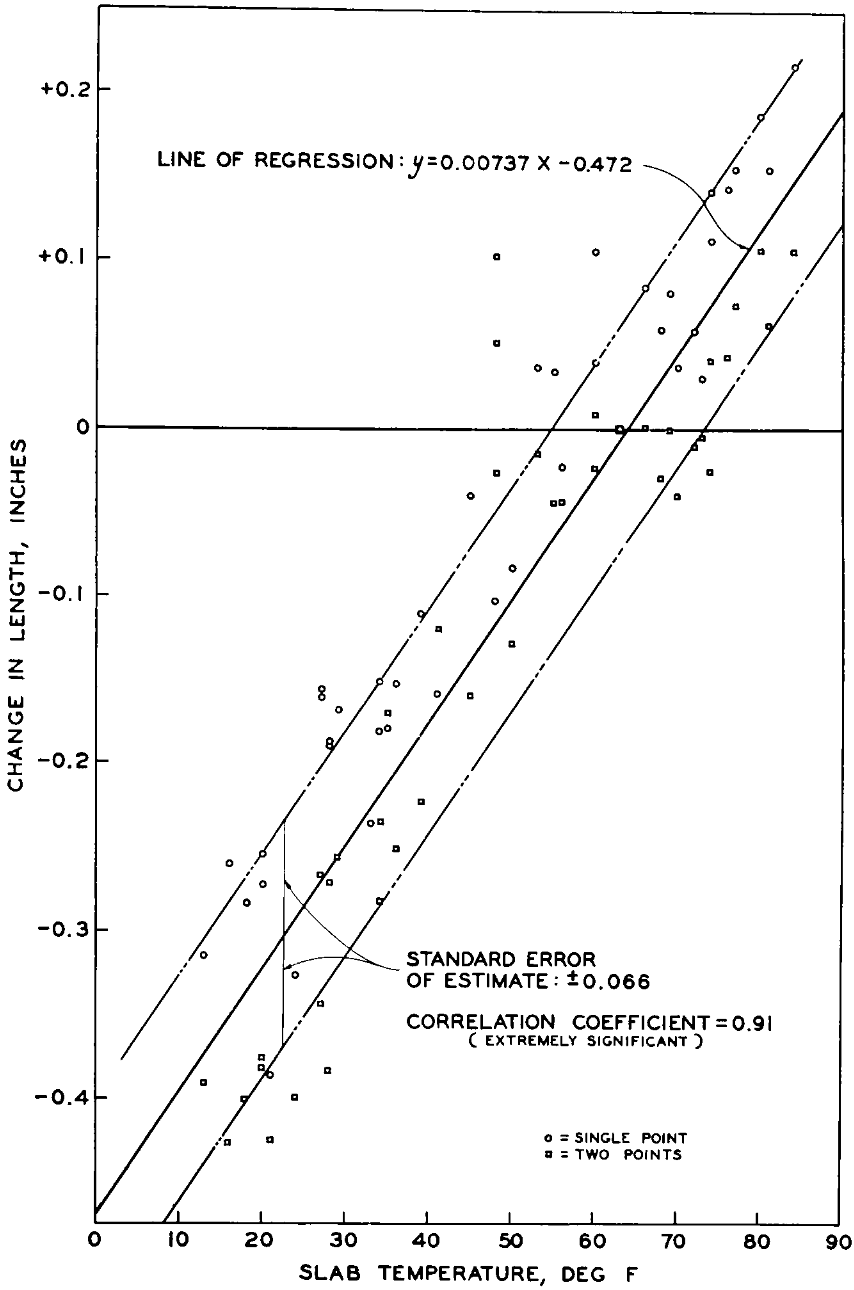
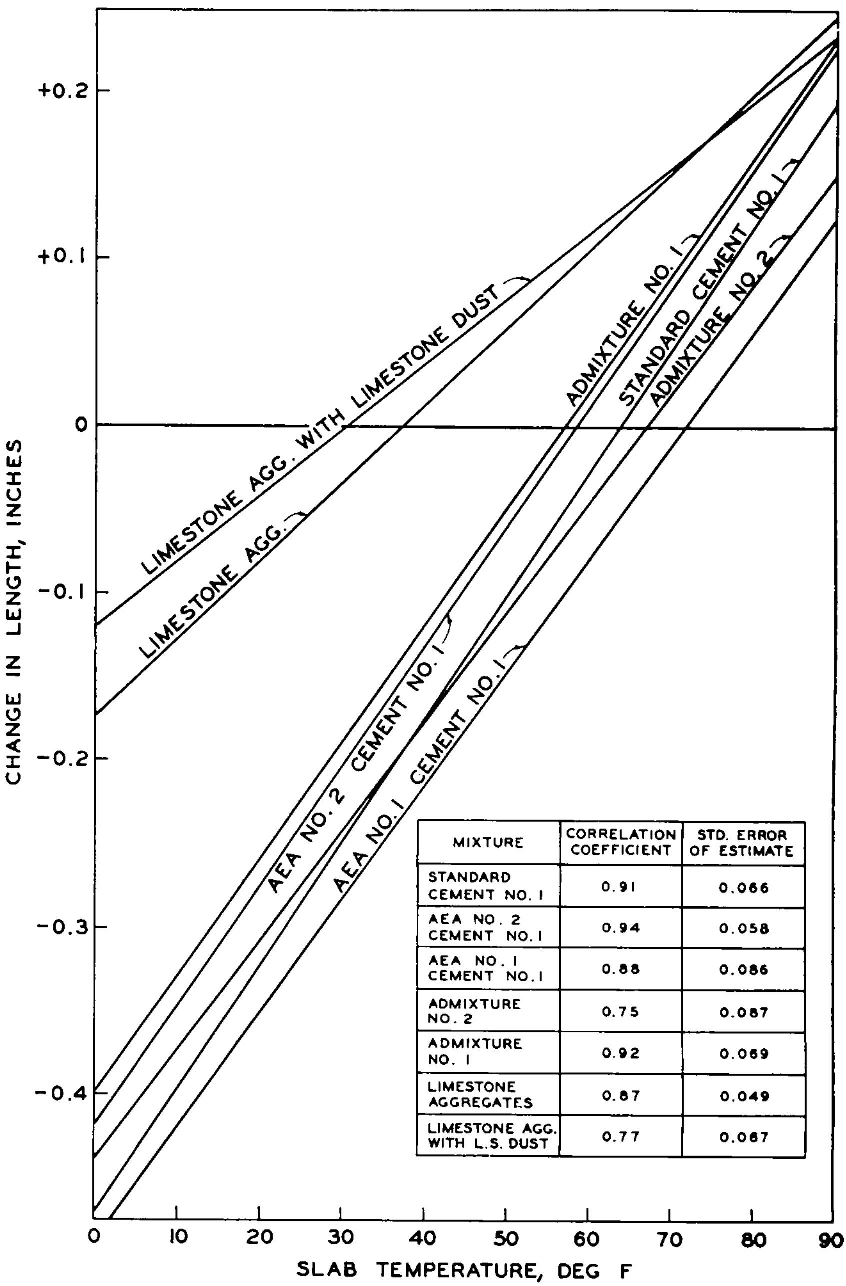


Figure 31. Change in 120-ft slab length with temperature for standard concrete with cement No. 1.



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 32. Comparison of slab length changes for seven concretes.

surfaced, 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 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.

Figure 30 plots average changes in width of the three joint types 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 years.

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 shown by the example in Figure 31. Figure 32 shows lines of regression for seven mixtures. 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 Figure 32. 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.

Relation of slab length change to temperature was extremely significant (Fig. 32). 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 (June 1955) are given in Table 11.

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

TABLE 11

PAVEMENT CONDITION, JUNE 1955

Factor	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:											
Without grinding aid	1	10	—	3	13	1.3	7	12	19	38	3.8
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.

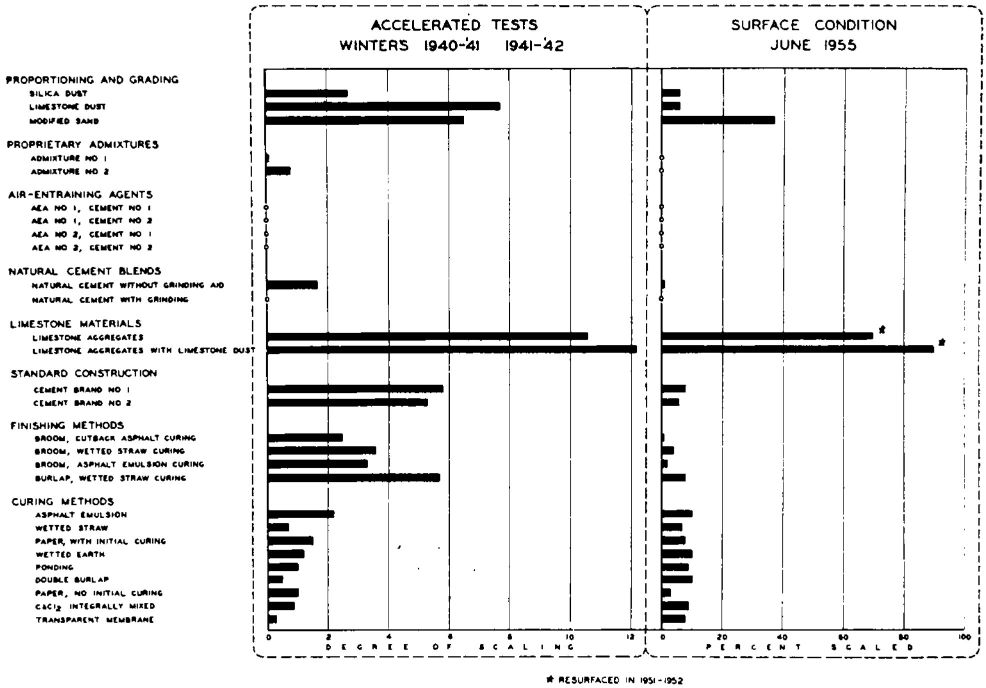


Figure 33. Comparison of accelerated scaling tests with pavement performance.

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. Figure 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. Results of the accelerated scaling test are compared with pavement performance in Figure 33. 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. Figures 34-39 show typical areas of the various experimental sec-

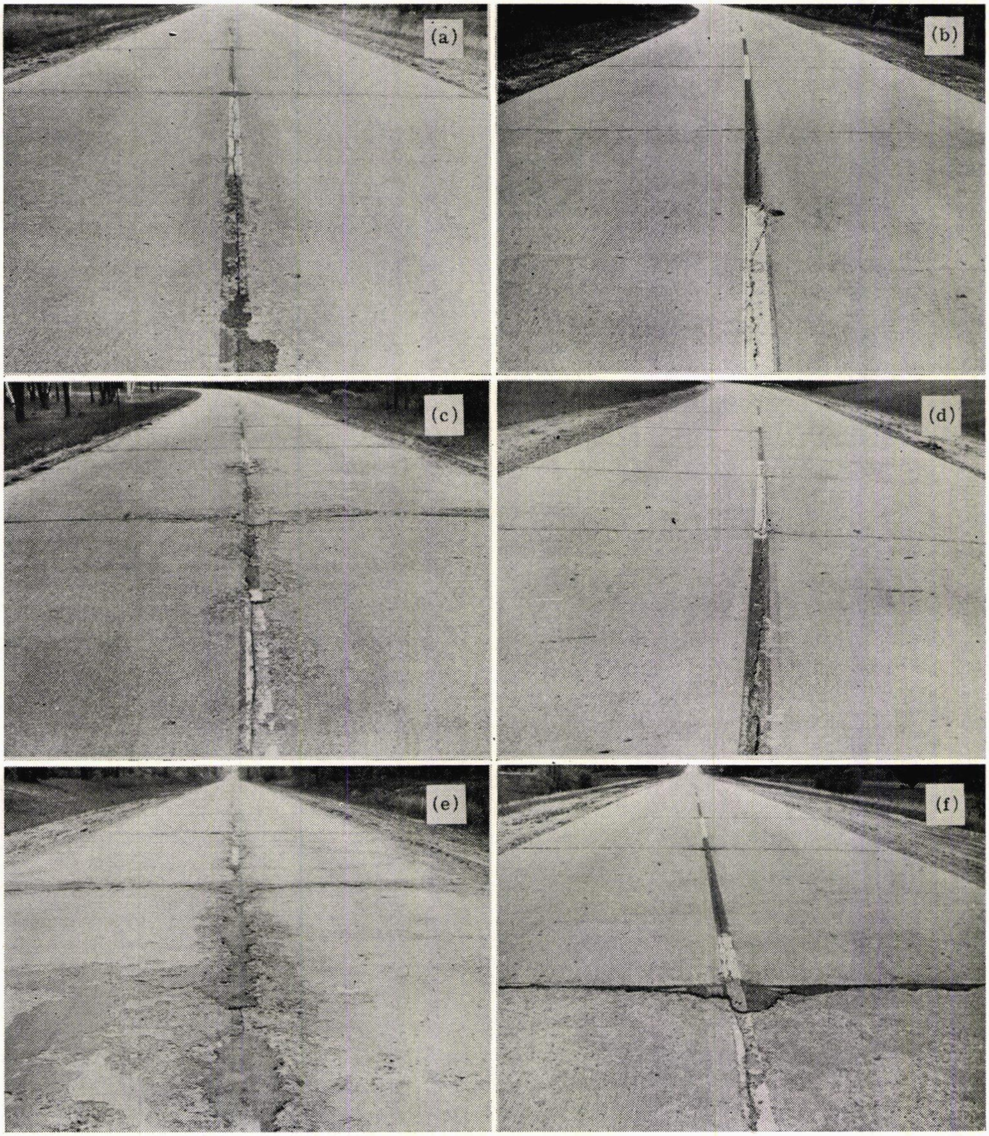


Figure 34. Pavement condition, May 1957; proportioning and grading of aggregates, proprietary admixtures, showing: (a) silica dust, Section 7A, Sta. 634+00; (b) admixture No. 1, Section 4B, Sta. 418+00; (c) limestone dust, Section 7C, Sta. 669+70; (d) admixture No. 2, Section 4D, Sta. 440+65; (e) modified sand, Section 7E, Sta. 713+00; (f) standard construction, cement No. 1, construction joint in foreground, Section 6B, Sta. 599+15.

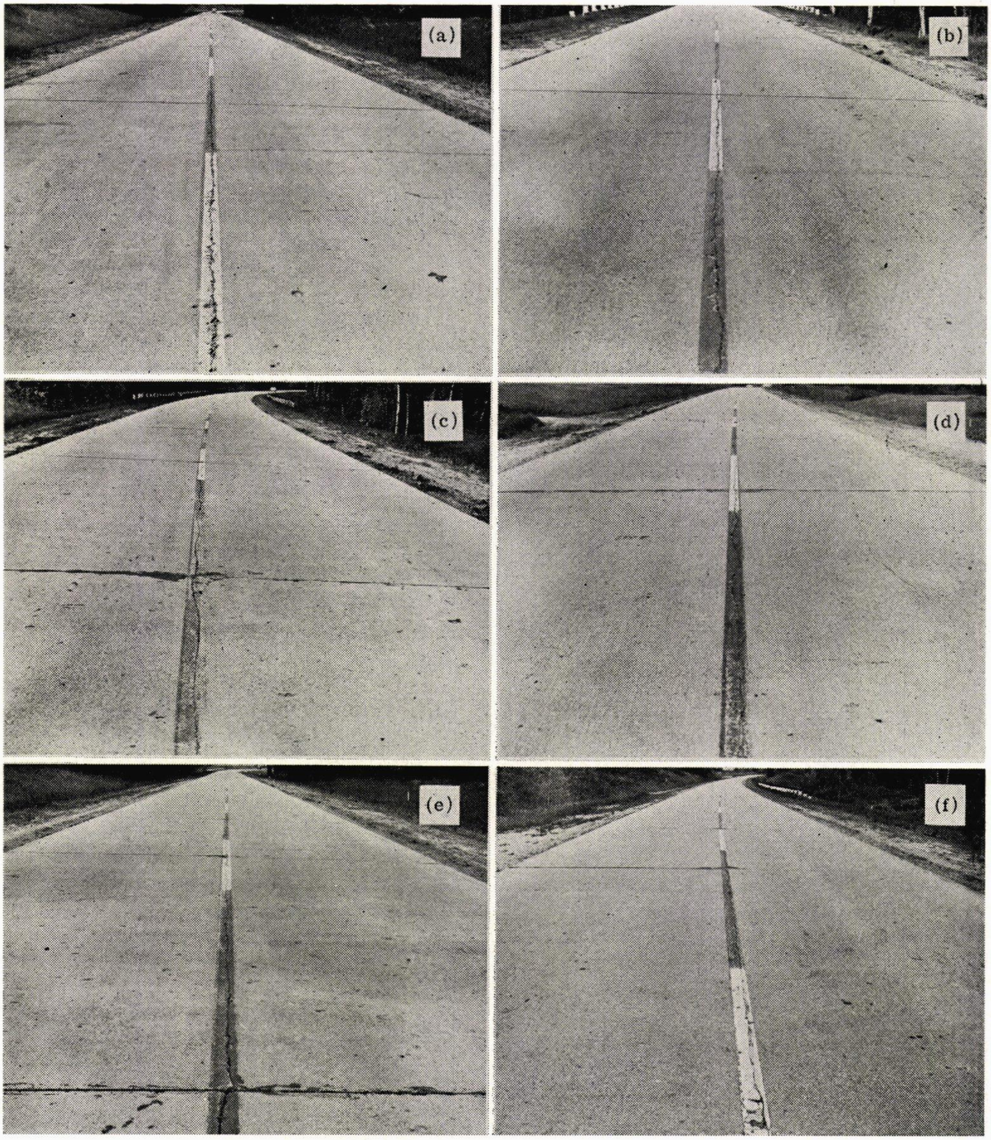


Figure 35. Pavement condition, May 1957; air-entraining agents, showing: (a) AEA No. 1, cement No. 1, Section 4F, Sta. 464+50; (b) AEA No. 2, cement No. 1, Section 5A, Sta. 519+00; (c) AEA No. 1, cement No. 2, Section 4H, Sta. 488+40; (d) AEA No. 2, cement No. 2, Section 5C, Sta. 549+00; (e) AEA No. 1 with 1 percent $CaCl_2$, cement No. 1, Section 4F-1, Sta. 466+50; (f) AEA No. 2 with 1 percent $CaCl_2$, cement No. 1, Section 5A-1, Sta. 532+50.

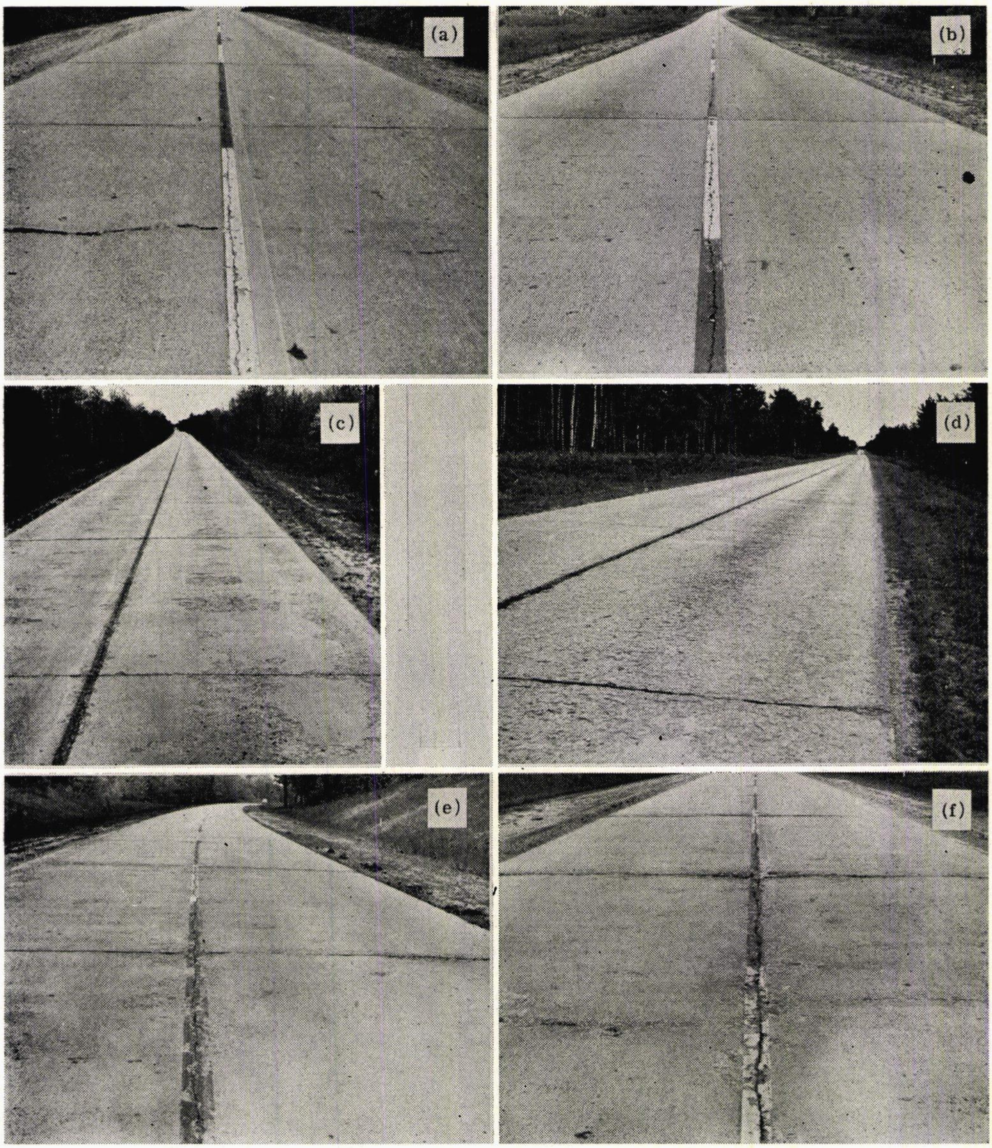


Figure 36. Pavement condition, May 1957; natural cement blends, limestone materials, and standard construction with cement No. 2, showing: (a) natural cement without grinding aid, Section 6A, Sta. 584+80; (b) natural cement with grinding aid, Section 6C, Sta. 609+00; (c) limestone aggregates (May 1951), Section 8B, Sta. 758+00; (d) limestone aggregate with limestone dust (May 1951), Section 8A, Sta. 753+46; (e) standard construction, cement No. 2, Section 4I, Sta. 560+50; (f) standard construction, cement No. 2, Section 5D, Sta. 582+00.

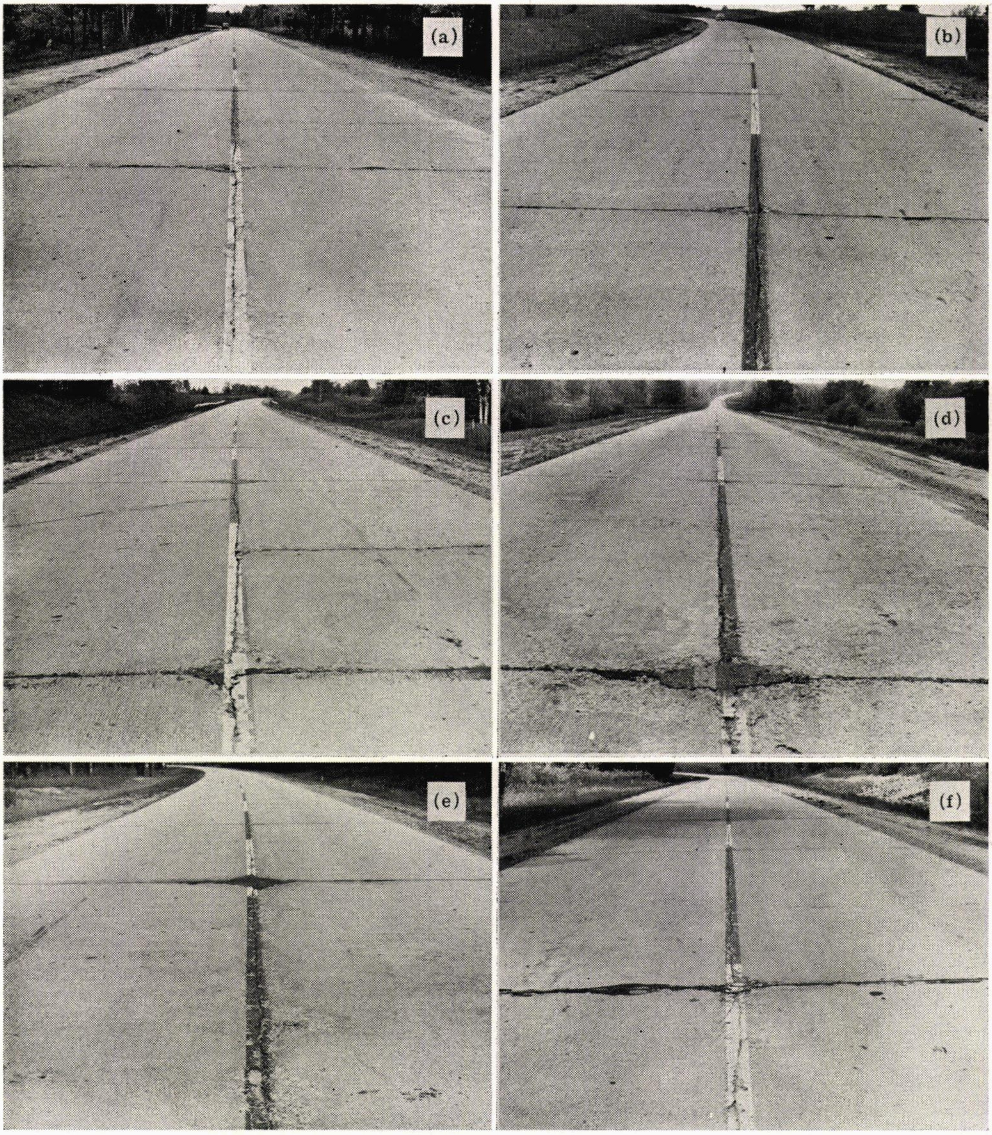


Figure 37. Pavement condition, May 1957; standard construction with cement No. 1, showing: (a) Section 4A, Sta. 407+15; (b) Section 4C, Sta. 428+90; (c) Section 5B, Sta. 539+00; (d) Section 6B, Sta. 598+00; (e) Section 7B, Sta. 661+30; (f) 2 percent $CaCl_2$ added, Section 4A-1, Sta. 412+40.

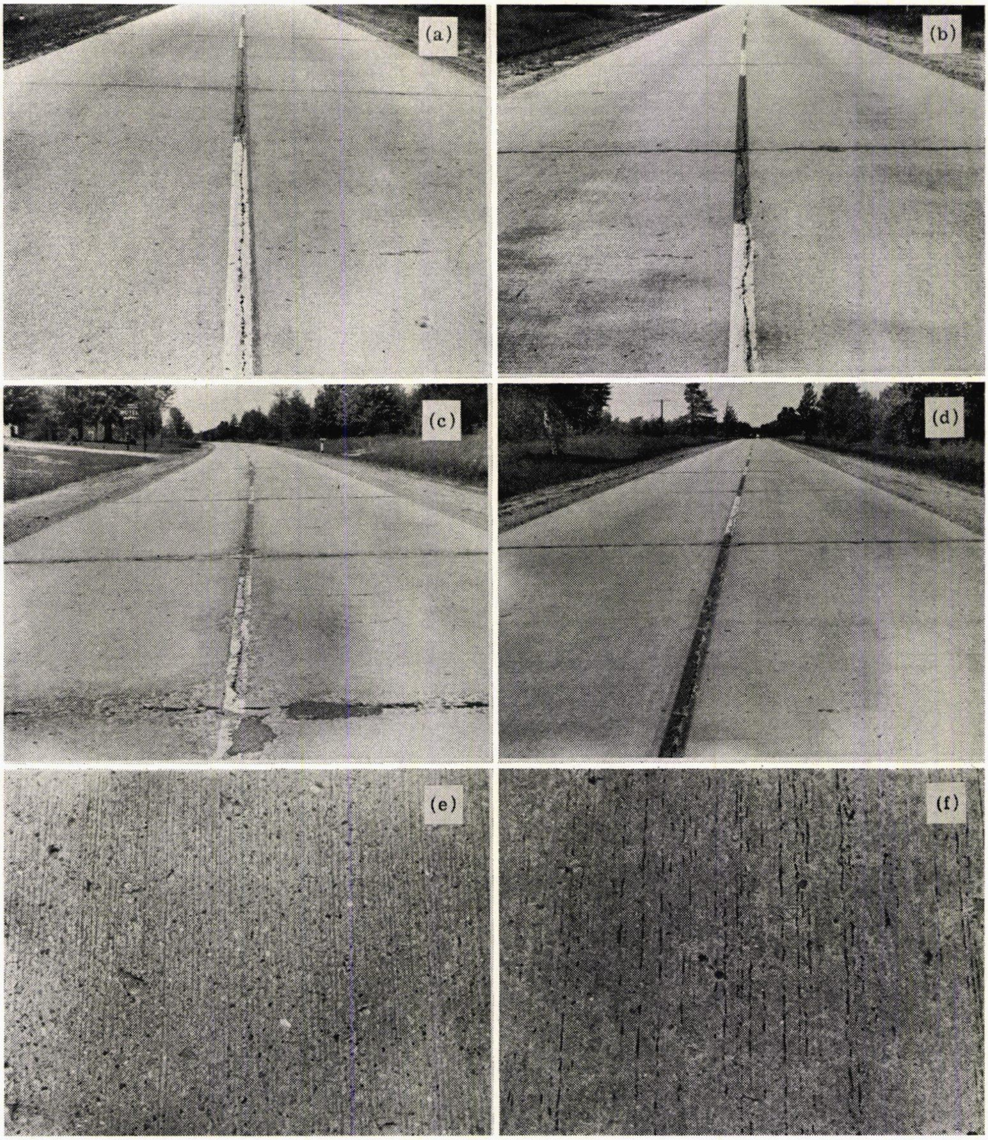


Figure 38. Pavement condition, May 1957; finishing methods, showing: (a) broom finish, wet earth curing, Section 1B-1, Sta. 625+00; (b) broom finish, cutback asphalt curing, Section 2B, Sta. 620+00; (c) broom finish, wet straw curing, Section 1B, Sta. 377+10; (d) broom finish, asphalt emulsion curing, Section 2A, Sta. 384+00; (e) texture of broomed surface, Section 1B, Sta. 377+85; (f) texture of broomed surface, Section 2A, Sta. 384+20.

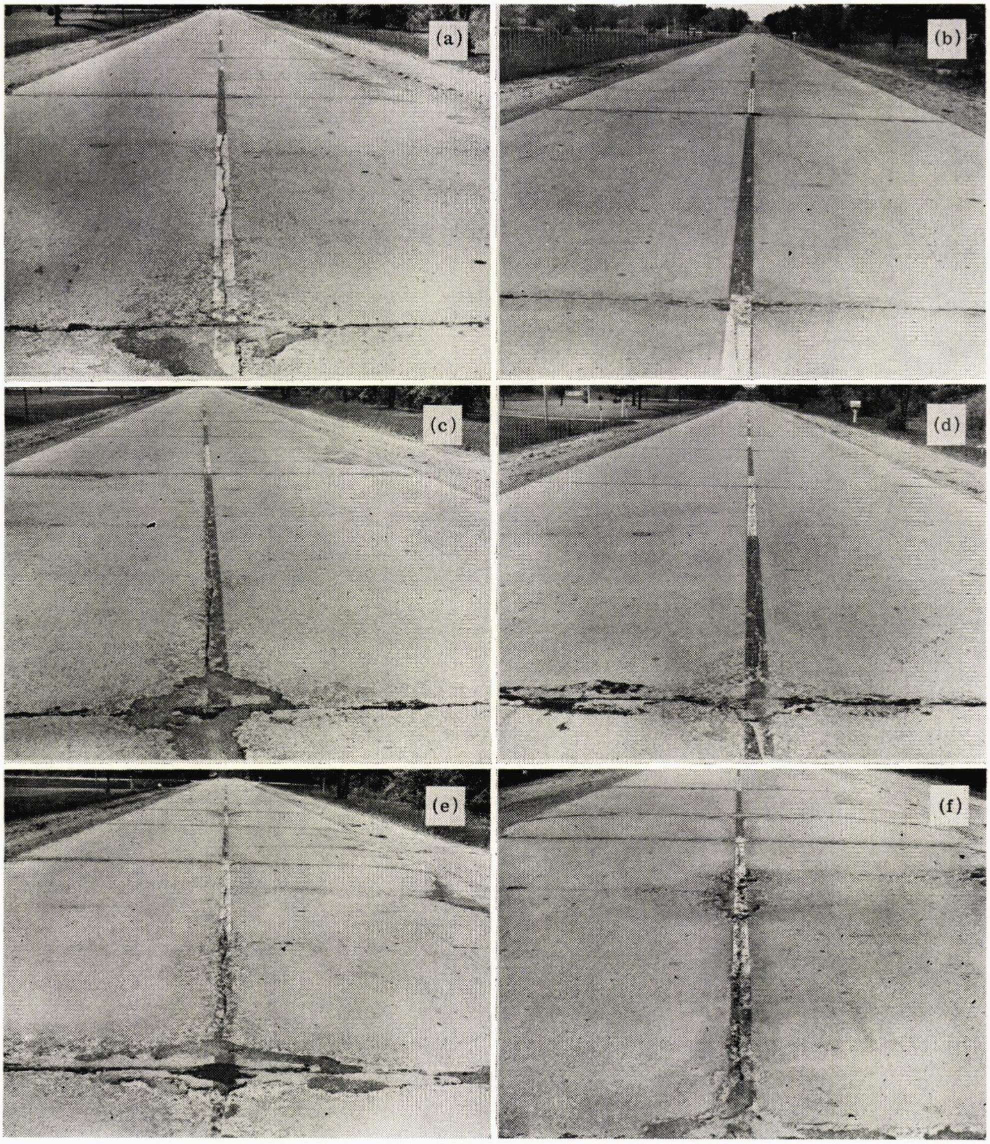


Figure 39. Pavement condition, May 1957; curing methods, showing: (a) wetted earth curing, Section 3A-4, Sta. 398+10; (b) asphalt emulsion curing, Section 3A-1, Sta. 394+50; (c) ponding, Section 3A-5, Sta. 399+30; (d) paper with initial burlap, Section 3A-3, Sta. 396+90; (e) double burlap, Section 3A-6, Sta. 400+50; (f) transparent membrane, Section 3A-9, Sta. 404+10.

tions taken in the spring of 1957 just before the pavement was resurfaced.

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 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.

ACKNOWLEDGMENTS

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The authors gratefully acknowledge the assistance of many members of the laboratory staff, both in the early work associated with the inception and construction of the experimental pavement and the subsequent collection and compilation of data. A. A. Smith was responsible for making the field measurements and condition surveys, O. L. Lindy and his staff processed the data, and L. T. Oehler statistically analyzed the concrete volume change data. R. W. Ormsby and his staff prepared the figures and A. D. Emerich and Mrs. Janice Schallhorn assisted in preparing and typing the manuscript.

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APPENDIX A
MATERIALS CHARACTERISTICS

TABLE 12

SUMMARY OF BASIC CONCRETE MIX DESIGNS

Factor	b/b_0	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, %	100	100	100	100
Passing No. 200 sieve, %	95	98	96	98.5
Interground resin, %	—	—	0.050	0.038
Loss on ignition, %	1.25	1.06	1.30	1.17
Insoluble matter, %	0.19	0.20	0.22	0.21
Sulphuric anhydride (SO_3), %	1.74	1.65	1.80	1.58
Silica (SiO_2), %	20.88	22.67	21.11	22.73
Ferric oxide (Fe_2O_3), %	2.70	2.09	2.68	2.10
Aluminum oxide (Al_2O_3), %	6.62	4.68	6.71	4.59
Lime (CaO), %	62.83	64.52	63.01	64.12
Magnesia (MgO), %	3.17	3.16	3.00	2.98

TABLE 14

SPECIFICATIONS FOR INTERGROUND RESIN, AEA NO. 2

Item	Minimum	Maximum
Melting point,[1] °C	110	125
Acid number	85	105
Gasoline-insoluble, %	85	—
Toluene-insoluble, %	15	30
Acetone-insoluble, %	—	2
Ash, %	—	0.3
Passing No. 30 sieve, %	100	—
Passing No. 80 sieve, %	90	100
Passing No. 200 sieve, %	60	80

[1] Hercules drop method.

TABLE 15

TYPICAL GRADING OF NATURAL SAND AND BLEND SAND

Sieve Size	Total Percent Passing	
	Natural Sand 2NS	Blend Sand
⅜ 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, %	
	4A	10A
Passing 2½-in sieve	100	—
Passing 2-in. sieve	100	—
Passing 1½-in. sieve	84	—
Passing 1-in. sieve	23	100
Passing ½-in. sieve	—	55
Passing ⅜-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 ⅓ surface area	1.4	0.3
Incrusted particles, ⅓ 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, %	1.09	1.73

TABLE 17

CHARACTERISTICS OF LIMESTONE FINE AND COARSE AGGREGATES

Item	Coarse Aggregate		Fine Aggregate
	4A	10A	2SS
Passing 2½-in. sieve, %	100	—	—
Passing 2-in. sieve, %	100	—	—
Passing 1½-in. sieve, %	67	—	—
Passing 1-in. sieve, %	13	100	—
Passing ½-in. sieve, %	—	53	—
Passing ⅜-in. sieve, %	1.1	37	100
Passing No. 4 sieve, %	—	7.3	99
Passing No. 8 sieve, %	—	—	88
Passing No. 16 sieve, %	—	—	52
Passing No. 30 sieve, %	—	—	28
Passing No. 50 sieve, %	—	—	13
Passing No. 100 sieve, %	—	—	4.3
Loss by washing, %	0.3	0.7	2.0
Soft and non-durable particles, %	0.0	0.0	—
Thin elongated particles, %	—	7.7	—
Percent wear, modified "A" abrasion	11.9	—	—
Absorption, %	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, %	Natural Density, pcf	Moisture, %	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[1]

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

[1] General Characteristics: Loose, incoherent, fine, granular material.

APPENDIX B

SUPPLEMENTARY TABLES

TABLE 21

CLASSIFICATION OF ANNUAL AVERAGE DAILY TRAFFIC

Year	Total Daily Traffic	Passenger		Commercial	
		No.	%	No.	%
1941	1,058	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	1,206	1,056	87.6	150	12.4
1947	1,185	1,035	87.3	150	12.7
1948	1,368	1,208	88.3	160	11.7
1949	1,467	1,272	86.7	195	13.3
1950	1,411	1,221	86.5	190	13.5
1951	1,411	1,231	87.2	180	12.8
1952	1,587	1,397	88.0	190	12.0
1953	1,649	1,429	86.7	220	13.3
1954	1,606	1,406	87.5	200	12.5
1955	1,622	1,402	86.4	220	13.6
1956	1,664	1,444	86.8	220	13.2
1957	1,694	1,469	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 4,000	3,653	61.54	6,835	62.38	1,011	71.75	11,499	62.83
4,000–4,499	191	3.22	414	3.78	60	4.26	665	3.63
4,500–4,999	144	2.43	327	2.98	36	2.55	507	2.77
5,000–5,499	180	3.03	358	3.27	24	1.70	562	3.07
5,500–5,999	157	2.64	352	3.21	27	1.92	536	2.93
6,000–6,499	222	3.74	411	3.75	29	2.06	662	3.62
6,500–6,999	231	3.89	376	3.43	32	2.27	639	3.49
7,000–7,499	225	3.79	404	3.69	22	1.56	651	3.56
7,500–7,999	329	5.54	416	3.80	27	1.92	772	4.22
8,000–8,499	283	4.77	376	3.43	39	2.77	698	3.81
8,500–8,999	156	2.63	315	2.86	56	3.98	527	2.88
9,000–9,499	109	1.84	207	1.89	28	1.99	344	1.88
9,500–9,999	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	5,936	100.00	10,957	100.00	1,409	100.00	18,302	100.00

TABLE 23

SUMMARY OF DATA FROM ACCELERATED SCALING TESTS

Factor	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:									
Without grinding aid	1	21	29	0	0.0	22	90[2]	44	0.5
Without grinding aid	1	—	—	—	—	23	31	100	3.2
With grinding aid	1	22	33	0	0.0	24	94[2]	0	0.0
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 ON 3- BY 6- BY 15-IN. SONIC BEAMS

Factor	Cement Brand	Age of Specimens, 5 Months: Number of Specimens	5 Months: To 50% Reduction in Modulus, No. Cycles	5 Months: To 50% Reduction in Modulus, Rate[1]	5 Months: To Failure 90–100% Reduction, No. Cycles	5 Months: To Failure 90–100% Reduction, Rate[1]	Age of Specimens, 1 Year: Number of Specimens	1 Year: To 50% Reduction in Modulus, No. Cycles	1 Year: To 50% Reduction in Modulus, Rate[1]	1 Year: To Failure 90–100% Reduction, No. Cycles	1 Year: To Failure 90–100% Reduction, 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:											
Without grinding aid	1	4	31	1.61	60	1.67	1	37	1.35	120	0.83
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 $= \dfrac{\text{Percent Reduction}}{\text{Number of Cycles}}$.

TABLE 25

SPECIFIC GRAVITY OF PAVEMENT CORES

Test Area	Factor	Core Identification		Brand of Cement	b/b_0	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
		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
		497+85	222A	2	0.80	2.429	2.405	2.397	2.430	2.424	2.465	2.446	2.505
		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
		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	—	—
		514+65	225A	1	0.76	2.387	2.377	2.408	2.376	2.387	2.417	2.407	2.458
		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
		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
		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
		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
		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	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	Satu-rated	Per 1 6 hr	Per 2 6 hr	Per 3 12 hr	Per 4 24 hr	Per 5 24 hr	Per 1 ½ hr	Per 2 ½ 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	0.54	0.14	54.0	22.8	11.2	5.57	2.21	0.39	0.07
Limestone dust.....	168	60	2.29	4.26	8.30	2.91	1.67	0.40	0.13	57.2	21.6	11.4	5.32	2.23	0.35	0.06
Modified sand......	55	23	1.44	4.42	12.32	1.62	0.81	0.20	0.12	50.6	17.7	9.5	5.05	2.64	0.87	0.08
Proprietary admixtures:																
Admixture No. 1...	178	181	2.22	3.73	5.63	2.40	2.67	0.68	0.15	55.3	17.2	9.0	5.01	2.64	0.89	0.06
Admixture No. 2...	124	69	1.99	3.23	4.85	2.34	2.89	0.78	0.15	47.0	17.9	9.6	4.85	2.48	1.03	0.09
Air-entraining agents:																
AEA No. 1, Cement No. 1...........	205	173	2.34	3.99	5.27	2.64	2.89	0.57	0.18	52.2	19.6	10.2	5.18	2.55	0.75	0.06
AEA No. 1, Cement No. 2...........	155	93	2.17	4.35	5.30	2.84	2.84	0.56	0.15	71.9	24.4	12.3	5.06	1.07	0.17	0.05
AEA No. 2, Cement No. 1...........	200	176	2.01	3.99	6.47	2.74	2.69	0.44	0.08	57.6	18.6	10.9	4.76	2.42	0.61	0.06
AEA No. 2, Cement No. 2...........	208	138	2.03	2.91	6.00	3.21	2.30	0.58	0.14	84.6	28.9	—	—	2.81	0.29	0.09
Natural cement blends:																
Without grinding aid	140	120	2.12	3.69	6.37	2.75	2.28	0.63	0.11	62.4	22.8	10.5	4.97	1.99	0.45	0.06
With grinding aid...	158	194	1.91	3.84	8.90	2.62	1.56	0.35	0.15	51.6	16.7	9.0	4.86	2.56	0.93	0.09
Limestone materials:																
Limestone aggre-gates............	170	123	2.47	4.03	10.25	2.83	1.01	0.25	0.13	62.6	20.4	11.4	5.30	1.90	0.31	0.07
Limestone agg. with limestone dust....	103	70	2.58	4.10	9.16	2.90	1.58	0.29	0.07	61.0	21.5	10.9	5.12	1.99	0.45	0.06
Standard construction:																
Cement brand No. 1	151	82	2.30	4.04	7.77	2.59	1.96	0.41	0.14	59.5	22.5	11.3	5.54	2.01	0.32	0.06
Cement brand No. 2	99	50	2.03	3.82	6.71	2.50	2.33	0.54	0.17	65.8	22.0	12.5	5.06	1.44	0.26	0.06
Finishing methods:																
Broom finish, asphalt emulsion curing...	123	80	2.02	4.05	7.10	2.48	1.90	0.62	0.21	59.8	20.2	12.5	5.85	1.85	0.23	0.05
Curing methods:																
Asphalt emulsion...	140	103	2.01	3.80	7.38	2.57	1.87	0.56	0.19	59.0	21.1	11.8	5.44	1.97	0.31	0.06
Wetted straw......	108	80	2.20	3.93	6.67	2.20	2.24	0.63	0.21	53.9	18.8	11.2	5.93	2.33	0.47	0.05
Paper............	155	108	1.94	3.41	6.62	2.15	2.23	0.62	0.24	54.0	21.1	11.3	6.06	2.15	0.37	0.06
Wetted earth.......	98	73	2.08	3.82	5.37	2.24	2.40	0.78	0.28	55.5	20.4	10.6	5.58	2.44	0.48	0.05
Ponding...........	120	68	2.12	4.04	5.50	2.36	2.60	0.67	0.24	55.4	20.8	11.4	6.03	2.39	0.25	0.05
Double burlap......	65	38	1.85	3.62	6.40	2.44	1.80	0.83	0.23	55.8	20.5	11.1	5.62	2.30	0.39	0.06
Paper, no initial cur-ing..............	146	93	2.30	4.35	5.66	2.54	2.17	0.79	0.24	57.9	20.2	11.9	5.66	2.14	0.25	0.06
Membrane, with initial curing.....	95	88	2.20	3.96	4.77	2.28	2.96	0.80	0.13	51.0	18.7	11.4	5.65	2.52	0.55	0.05

TABLE 27

PERMEABILITY OF PAVEMENT CORES

Factor	Durability F & T Cycles		Water Passage in Gram-Inches per Hour per Square Foot for Successive Periods [1]										
	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	113	93	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	× [2]	×	×	0.63	0.78	0.75	0.63	0.50	0.63	0.63	0.65
Modified sand	55	23	0.31	0.63	×	×	×	×	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	×	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	200	176	×	0.44	×	×	×	×	0.39	0.35	0.39	×	0.39
Natural cement blends:													
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
With grinding aid	158	194	0.17	×	×	×	0.00	0.41	0.23	0.14	0.00	0.17	0.16
Limestone materials:													
Limestone aggregates	170	123	×	0.61	0.61	0.30	0.45	0.36	0.40	0.24	0.40	×	0.42
Limestone agg. with limestone dust	103	70	0.27	0.27	0.27	×	0.82	0.76	0.54	0.33	0.54	0.41	0.47
Standard construction:													
Cement brand No. 1	151	82	×	1.23	0.92	0.77	0.77	1.10	1.23	1.23	1.23	×	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

[1] Gram-inches = water loss in grams times core thickness in inches.
[2] × indicates faulty test. Water lost through seal.

TABLE 28

UNGROUPED FREQUENCY DISTRIBUTION OF SLUMP VALUES

Slump, in.	0	¼	½	¾	1	1¼	1½	1¾	2	2¼	2½
Frequency	1	2	3	0	7	7	27	18	26	31	17
Slump, in.	2¾	3	3¼	3½	3¾	4	4¼	4½	4¾	5	5¼
Frequency	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:				
Without grinding aid	4	68–75	45–125	85
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	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	3,371	95	4,606	100	184	4,367	81	7,450	128	7,850	98
Limestone dust	1	3,417	96	4,817	105	193	5,520	103	6,580	114	8,150	101
Modified sand	1	3,125	88	4,407	96	176	5,740	107	6,800	117	8,300	103
Proprietary admixtures:												
Admixture No. 1	1	4,000	113	4,249	93	170	4,730	88	4,900	85	8,000	99
Admixture No. 2	1	4,655	131	6,080	133	243	6,320	118	7,350	127	9,400	117
Air-entraining Agents:												
AEA No. 1	1	2,608	74	3,728	81	149	3,962	74	5,600	97	6,100	76
AEA No. 1	2	2,324	66	3,857	84	154	3,820	71	5,800	100	6,200	77
AEA No. 1 + 1% $CaCl_2$	1	2,213	62	3,035	66	121	—	—	—	—	—	—
AEA No. 2	1	2,845	80	3,867	84	155	4,010	75	3,850	66	5,950	74
AEA No. 2	2	3,580	101	3,991	87	160	5,420	101	5,100	88	7,600	94
AEA No. 2 + 1% $CaCl_2$	1	2,518	71	2,895	63	116	—	—	—	—	—	—
Natural Cement Blends:												
Without grinding aid	1	3,190	90	3,711	81	148	4,345	81	6,650	115	7,000	87
With grinding aid	1	2,813	79	3,479	76	139	3,225	60	5,200	90	6,600	82
Limestone Materials:												
Limestone aggregates	1	3,069	87	4,176	91	167	5,765	107	7,200	124	—[2]	—
Limestone agg. with limestone dust	1	2,694	76	4,099	89	164	5,050	94	5,600	97	—[2]	—
Standard construction:												
Cement brand No. 1	1	3,543	100	4,587	100	183	5,375	100	5,800	100	8,050	100
Cement brand No. 2	2	2,837	80	4,597	100	184	6,600	123	7,300	126	8,200	102
Calcium chloride, 2% for curing	1	4,281	121	4,867	106	195	—	—	—	—	—	—

[1] On pavement immediately adjacent to core locations.
[2] Resurfaced 1951–52.

TABLE 31

CONDENSED SUMMARY OF FLEXURAL STRENGTHS

Third-Point Loading, ASTM Method C 78–39

Factor	Cement Brand	Field-Molded Beams								Swiss Hammer[1]	
		6- by 8- by 36 inches						3- by 6- by 15 inches		15 Yr	
		7 Day			28 Day			10 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	1,050	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:											
Without grinding aid	1	515	91	94	626	89	96	—	—	820	89
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 1951–52.

TABLE 32

MODULUS OF ELASTICITY OF BEAMS AND CORES

Factor	Dynamic Modulus, 3- by 6- by 15-in. Beams			Secant Modulus at 2,000 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:				
Without grinding aid	6.7	—	—	5.0
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	b/b_0	Compressive Strength, psi		Flexural Strength, psi	
		7 day	28 day	7 day	28 day
Proportioning and grading:					
Silica dust	0.76	3,364	4,946	561	649
	0.80	3,078	4,346	538	628
Limestone dust	0.76	3,461	4,842	513	562
	0.80	3,372	4,790	704	—
Modified sand	0.76	3,372	4,180	341[1]	755
	0.80	2,816	4,630	701	720
Proprietary admixtures:					
Admixture No. 1	0.76	3,580	3,955	615	764
	0.80	4,420	4,349	655	784
Admixture No. 2	0.76	4,850	6,080	465	807
	0.80	4,460	3,890[1]	445	605
Air-entraining agents:					
AEA No. 1	0.76	2,520	3,477	431[2]	615[2]
	0.80	3,005	4,105	420[2]	590[2]
AEA No. 2	0.76	3,536[2]	3,700[2]	584[2]	863[2]
	0.80	3,622[2]	4,281[2]	568[2]	680[2]
Natural cement blends:					
Without grinding aid	0.76	3,145	3,500	586	—
	0.80	3,235	3,922	515	626
With grinding aid	0.76	2,864	3,485	347	578
	0.80	2,773	3,471	527	592

[1] Poor specimen.
[2] Cement brand No. 2.

TABLE 34

SUMMARY OF TEMPERATURE AND MOISTURE DATA, CURING STUDY

Test			Precip., in.	Humidity, %	Evap., mm.	Time	Temperature, °F					Slab Moisture, %		
									Slab Interior					
No.	Type	Sta.					Air	Slab Surf.	Top	Middle	Bottom	Top	Middle	Bottom
A-1	Asph. emuls., init. curing	395+60												
	Sept. 9		—	62	1.69	12:25	78	77	80	72	72	6.1	6.1	6.1
	Sept. 10		0.55	44	1.07	2:15	57	69	83	80	78	6.1	6.1	6.2
	Sept. 11		0.40	45	2.10	11:05	57	63	76	70	68	6.0	6.0	6.1
	Sept. 12		—	48	1.43	7:35	48	50	60	61	63	6.0	6.0	6.1
						4:35	67	—	—	—	—	6.0	6.0	6.1
	Sept. 13		0.19	51	1.67	8:55	61	—	—	—	—	6.0	6.0	6.0
	Sept. 17		0.01	57	2.23	9:50	62	64	71	68	66	6.0	5.9	6.0
	Sept. 28		—	56	4.79	11:30	69	70	87	74	69	6.0	5.9	6.0
A-2	Wet straw	396+75												
	Sept. 9		—	62	1.69	1:30	75	74	75	77	75	6.3	6.3	6.6
	Sept. 10		0.55	44	1.07	3:15	55	60	64	64	66	6.1	6.2	6.2
	Sept. 11		0.40	45	2.10	11:15	57	59	66	64	66	6.1	6.2	6.4
	Sept. 12		—	48	1.43	7:45	49	57	66	66	67	6.1	6.1	6.2
						4:45	67	—	—	—	—	6.1	6.1	6.1
	Sept. 13		0.19	51	1.67	8:50	61	—	—	—	—	6.1	6.1	6.1
	Sept. 17		0.01	57	2.23	10:00	64	66	67	69	68	6.1	6.1	6.1
	Sept. 28		—	56	4.79	11:40	69	70	65	68	61	6.0	6.1	6.2
A-3	Burlap and paper	397+95												
	Sept. 9		—	62	1.69	1:40	75	73	80	78	77	6.2	6.2	6.3
	Sept. 11		0.40	45	2.10	6:45	47	51	61	64	67	5.8	5.9	6.2
						12:00	57	64	66	66	66	5.8	5.9	6.2
	Sept. 12		—	48	1.43	7:50	49	55	61	63	66	5.8	5.8	6.1
						4:50	67	—	—	—	—	5.8	5.8	6.1
	Sept. 13		0.19	51	1.67	8:45	59	—	—	—	—	5.7	5.8	6.1
	Sept. 17		0.01	57	2.23	10:00	64	68	66	65	65	5.7	5.7	6.0
	Sept. 28		—	56	4.79	11:45	69	70	70	67	64	5.6	5.7	6.1
A-4	Wet earth	399+10												
	Sept. 9		—	62	1.69	1:50	69	74	78	75	76	6.2	6.1	6.4
	Sept. 11		0.40	45	2.10	7:00	45	52	55	58	60	6.1	6.2	6.2
						12:15	57	60	59	58	60	6.1	6.1	6.3
	Sept. 12		—	48	1.43	8:00	50	54	55	59	59	6.0	6.1	6.2
						5:00	67	—	—	—	—	6.0	6.1	6.2
	Sept. 13		0.19	51	1.67	8:40	59	—	—	—	—	6.0	6.0	6.2
	Sept. 17		0.01	57	2.23	10:30	65	68	71	67	68	6.0	6.0	6.3
	Sept. 28		—	56	4.79	12:00	70	72	71	68	68	5.9	6.1	6.0
A-5	Ponding	400+35												
	Sept. 9		—	62	1.69	2:05	66	72	76	76	74	6.1	6.1	6.1
	Sept. 11		0.40	45	2.10	7:20	45	51	54	56	58	6.3	6.5	6.4
						12:25	57	63	62	62	61	6.2	6.3	6.2
	Sept. 12		—	48	1.43	8:15	50	54	57	58	60	6.2	6.5	6.2
						5:05	66	—	—	—	—	6.1	6.8	7.1
	Sept. 13		0.19	51	1.67	8:30	59	—	—	—	—	6.1	6.5	6.6
	Sept. 17		0.01	57	2.23	10:40	65	70	69	70	68	6.1	6.3	6.4
	Sept. 28		—	56	4.79	12:10	70	74	70	68	66	6.1	6.3	6.4

A-6	Double burlap	401 +55													
	Sept. 10		0.55	44	1.07	12:00	54	59	66	67	67	6.4	6.3	6.1
	Sept. 11		0.40	45	2.10	7:45	46	51	53	56	58	6.8	6.8	6.1
						12:30	62	68	63	63	62	6.5	6.5	6.1
	Sept. 12		—	48	1.43	8:25	50	53	53	54	55	6.5	6.4	6.1
						5:10	65	—	—	—	—	6.1	6.2	6.1
	Sept. 13		0.19	51	1.67	8:25	59	—	—	—	—	6.3	6.2	6.1
	Sept. 17		0.01	57	2.23	10:50	65	70	73	71	69	6.1	6.1	6.1
	Sept. 28		—	56	4.79	12:15	70	74	77	71	67	5.9	6.1	6.1
A-7	Paper	402 +80													
	Sept. 10		0.55	44	1.07	11:45	54	60	71	71	72	6.1	6.2	6.2
	Sept. 11		0.40	45	2.10	8:00	47	51	63	62	62	6.0	6.2	6.5
						2:00	60	69	66	66	69	6.0	6.2	6.3
	Sept. 12		—	48	1.43	8:35	52	58	63	63	63	6.0	6.1	6.5
						5:15	65	—	—	—	—	6.0	6.1	6.5
	Sept. 13		0.19	51	1.67	8:20	59	—	—	—	—	6.0	6.1	6.2
	Sept. 17		0.01	57	2.23	11:00	69	70	62	62	65	6.0	6.0	6.2
	Sept. 28		—	56	4.79	12:25	70	78	64	66	69	5.9	6.0	6.1
A-8	$CaCl_2$ integral mix	403 +95													
	Sept. 10		0.55	44	1.07	11:30	54	58	66	66	66	6.1	6.0	6.1
	Sept. 11		0.40	45	2.10	8:25	48	50	54	54	55	6.0	6.0	6.1
						2:15	58	59	61	58	58	6.0	6.0	6.1
	Sept. 12		—	48	1.43	8:45	56	58	59	60	59	5.9	6.0	6.1
						5:20	65	—	—	—	—	5.9	6.0	6.1
	Sept. 13		0.19	51	1.67	7:30	54	52	54	54	56	5.9	6.0	6.1
	Sept. 17		0.01	57	2.23	11:10	69	70	59	57	56	5.8	6.0	6.1
	Sept. 28		—	56	4.79	12:35	70	74	75	76	72	5.5	5.9	6.1
A-9	Membrane	405 +18													
	Sept. 10		0.55	44	1.07	1:00	54	57	71	68	65	6.1	6.1	6.4
	Sept. 11		0.40	45	2.10	9:00	52	53	64	64	64	6.4	6.4	6.4
						2:30	57	57	75	72	68	6.3	6.3	6.3
	Sept. 12		—	48	1.43	8:50	56	56	65	63	63	6.0	6.1	6.2
						5:30	66	—	—	—	—	5.9	6.1	6.2
	Sept. 13		0.19	51	1.67	8:00	58	—	—	—	—	5.8	6.1	6.1
	Sept. 17		0.01	57	2.23	11:15	70	71	74	70	67	5.6	6.0	6.2
	Sept. 28		—	56	4.79	12:45	70	74	83	78	73	5.5	6.0	6.3
4-A	Wet strain	405 +95													
	Sept. 10		0.55	44	1.07	1:15	54	63	63	64	63	6.1	6.1	6.1
	Sept. 11		0.40	45	2.10	9:15	52	56	64	64	63	5.9	6.0	6.1
						2:40	55	59	63	63	62	6.0	6.0	6.1
	Sept. 12		—	48	1.43	9:00	56	60	62	62	61	6.1	6.0	6.1
						5:35	60	—	—	—	—	6.1	6.0	6.1
	Sept. 13		0.19	51	1.67	8:05	58	—	—	—	—	6.1	6.0	6.1
	Sept. 17		0.01	57	2.23	11:25	71	72	74	77	80	6.1	5.9	6.1
	Sept. 28		—	56	4.79	12:55	70	74	70	74	77	5.9	5.9	6.1

TABLE 35

SUMMARY OF CONCRETE SCALING STUDY, 1940–41 AND 1941–42

Series	Division	Panel Number 1940–41	Panel Number 1941–42	Location of Panels 1940–41 Method A	Location of Panels 1940–41 Method B	Location of Panels 1941–42 Method B	Estimated Scale 1940–41 Method A Cycles	Estimated Scale 1940–41 Method A % Scale	Estimated Scale 1940–41 Method B Cycles	Estimated Scale 1940–41 Method B % Scale	Estimated Scale 1941–42 Method B Cycles	Estimated Scale 1941–42 Method B % Scale	Finish	Curing	Cement Brand	Admixture	b/b_0
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 $CaCl_2$.

TABLE 36

SUMMARY OF CORE ABSORPTION STUDY

Factor	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	½	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:														
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
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 lime. 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 init. 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 init. 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	Core No.	Thickness in.	Cumulative Water Passage in Grams (g) and in Gram-Inches (C)[1]																			
			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:																						
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
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

[1] C = g × core thickness in inches.

TABLE

SUMMARY OF

Cement Brand	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: 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
1	3 d	—	—	—	—	—	—	—	—	—	2630	—
		—	—	—	—	—	—	—	—	—	2210	—
	avg										2420	
	7 d	3360	2895	3465	3115	3360	3110	2190	3360	1870	2650	—
		3530	2720	3890	3180	3282	3180	2470	2650	1698	3110	
		3320	2895	3320	3360	3885	3640	2370		1770	3250	
		3430	2755	3980	2658	3460	3570	2260		2015	2370	
		3220				3320	3360	2470		2760		
								2190		2470		
								3110		2470		
								2860		2650		
								2760				
	avg	3372	2816	3664	3078	3461	3372	2520	3005	2213	2845	
		3125		3371		3417		2608				
	28 d	3785	4840	4530	3990	4490	4980	3720	4320	3360	3820	—
		4730	4670	4560	3710	4840	4490	2650	3890	3890	3960	
		3995	4530	4880	4420	4810	5020	4060		3710	3820	
		4210	4490	4880	4590	5230	4670			2479		
				5480	5020					2120		
										2650		
	avg	4180	4633	4866	4346	4843	4790	3477	4105	3035	3867	
		4407		4606		4817		3728				
2	7 d	—	—	—	—	—	—	2650	2120	—	3430	3890
								2580	1945		3110	3360
											3465	3810
											4140	3430
								2615	2033		3537	3623
	avg							2324			3580	
	28 d	—	—	—	—	—	—	4350	3180	—	3990	3780
								4598	3360		4060	5120
											3530	4240
											3460	3465
											3460	4800
								4474	3270		3700	4281
	avg							3857			3991	

[1] Poor specimen, not used in averages.

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COMPRESSION TESTS

and Air-Entraining Agents						Natural Cement Blends				Limestone Materials			
AEA No. 2 $CaCl_2$	Adm. No. 1		Adm. No. 2		$CaCl_2$	Nat. Cement with Grinding Aid		Nat. Cement without Grinding Aid		Limestone Aggregrate	Limestone Agg. with Limestone Dust	Standard Construction	
0.80	0.76	0.80	0.76	0.80	0.76	0.76	0.80	0.76	0.80	0.76	0.76		
2155	—	—	—	—	3170	—	—	—	—	—	—	2300	2190
1855	—	—	—	—	2980	—	—	—	—	—	—	2370	
2005					3075							2287	
2580	3580	4420	4850	4460	4480	3215	2475	3465	3360	2475	2475	3465	4420
2895					3882	2545	2830	2825	3110	3430	3500	3360	2685
2650					4480	2830	2830			3005	2405	2935	4240
1945						2865	2900			2935	2900	4060	3110
							2830			3500	2190	3885	3250
												3640	3460
2518	3580	4420	4850	4460	4281	2864	2773	3145	3235	3069	2694		
	4000		4655			2813		3190				3543	
1170[1]	3955	4310	6080	3890[1]	5190	3465	4130	3535	3890	3533	4340	4240	5130
2540		4490			4880	3325	3215	3465	3955	3890	4670	4490	5050
3250		4240			4530	2755	3640			4340	3675	5130	6010
						3890	2900			4940	3710	3780	3890
						3990						4950	4840
												3960	3820
												5860	4000
												4525	4170
												4670	4280
												4980	3960
2895	3955	4347	6080	3890	4867	3485	3471	3500	3922	4176	4099		
	4249		4985			3479		3711				4587	
—	—	—	—	—	—	—	—	—	—	—	—	3010	3080
												2475	3465
												2190	3250
												2475	3075
												2510	
												2837	
—	—	—	—	—	—	—	—	—	—	—	—	4710	4950
												4770	4060
												4420	4600
												5090	4170
													4600
												4597	

TABLE

SUMMARY OF MODULUS

			Proportioning and Grading						Admixtures					
	Cement Brand	Age Spec.	Modified Sand		Silica Dust		Limestone Dust		AEA No. 1		AEA No. 1 $CaCl_2$		AEA No. 2	
			0.76	0.80	0.76	0.80	0.76	0.80	0.76	0.80	0.76	0.80	0.76	0.80
Third-Point Loading ASTM Method C78-39	1	3 d	418	310	427	250	438	242	457	418	—		300	—
		7 d	341	701	561	538	513	562	—	389	328		508	—
		28 d	755	720	649	628	704	—	562 587	533 550	489		529	—
	2	3 d	—	—	—	—	—	—	—	367	—		395	540
		7 d	—	—	—	—	—	—	431	420	—		584	568
		28 d	—	—	—	—	—	—	615	590	—		863	680
Cantilever Loading MSHD Method	1	7 d	532	—	663 544	540	620 570	540 586	459 744	476	—		526	—
		28 d	—	—	—	—		—	—	—	—		644	—
	2	7 d	—	—	—	—	—	—	549	494	—		652 631	646
		28 d	—	—	—	—	—	—	654	603	—		764 800	642

[1] Poor specimens.

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OF RUPTURE TESTS

and Air-Entraining Agents						Natural Cement Blends				Limestone Materials			
AEA No. 2 CaCl2	Adm. No. 1		Adm. No. 2		CaCl2	Nat. Cement with Grinding Aid		Nat. Cement without Grinding Aid		Limestone Aggregrate	Limestone Agg. with Limestone Dust	Standard Construction	
0.76 0.80	0.76	0.80	0.76	0.76	0.76 0.80	0.76	0.80	0.76	0.80	0.76 0.80	0.76		
391	—	478	367	—	267	369	317	—	399	606	436	410	444
449	—	538	465	—	445	347	527	—	515	768	578	567	
—	—	—	807	—	605	578	592	—	626	585[1]	489[1]	819	586
—	—	—	—	—	—	—	—	—	—	—	—	387	447
—	—	—	—	—	—	—	—	—	—	—	—	511	582
—	—	—	—	—	—	—	—	—	—	—	—	686	686
												605	
457	571	626	634	629	640	526	—	586	—	—	703	705	775
	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	
690	781	784	—	920	—	—	—	—	—	—	—	810	768
	747			906								792	827
												795	846
—	—	—	—	—	—	—	—	—	—	—	—	629	
—	—	—	—	—	—	—	—	—	—	—	—	—	