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CONSTRUCTING A STABILIZED SOIL BASE

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The reports of research published in this magazine are necessarily qualified by the conditions of the tests from which the data are obtained. Whenever it is deemed possible to do so, generalizations are drawn from the results of the tests; and, unless this is done, the conclusions formulated must be considered as specifically pertinent only to described conditions.

In This Issue

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STABILIZED BASE EXPERIMENT IN MINNESOTA

BY THE DIVISION OF PHYSICAL RESEARCH, PUBLIC ROADS ADMINISTRATION

Reported by Henry Aaron, Highway Engineer[1]

CONSTRUCTION of satisfactory low-cost, all-weather roads in the Red River Valley of Minnesota has always presented a difficult problem. Loose sand and gravel placed on the heavy clay soils typical of the area had to be continually replaced as the material gradually penetrated into the subgrade to great depths and produced no apparent increase in stability.

The blotter type of bituminous surface was a notable improvement over loose gravel. It consisted of an application of a bituminous prime or penetration coat to the prepared subgrade, followed by a second application as soon as the first had dried. This was immediately covered with gravel in the amount of about 350 cubic yards per mile. Although this road surface resulted in the elimination of dust and the conservation of gravel, it did not prove entirely satisfactory under an increasing traffic.

The excellent performance of stabilized bases with thin bituminous wearing courses in other localities suggested a better method of overcoming difficulties. This led to the problem of required thickness of base. The Minnesota Department of Highways and the Public Roads Administration in 1936 initiated an experiment to determine by means of a service test the thickness of stabilized base required on the heavy clay subgrades of the Red River Valley.

Federal-Aid Project 349–A was selected for the experiment. The project, located on U. S. Highway 75, begins at the crossing of the tracks of the Great Northern Railroad about 2 miles north of Hendrum and extends east approximately 13.4 miles to the west city limits of Ada. The lay-out of the project is shown on figure 1.

Construction of the original base course was started in July and completed in September 1936. Construction of the bituminous wearing course was delayed until 1938, when it was necessary to recondition the base owing to the reduction in thickness and crown resulting from the action of traffic. The base course was reconstructed during August 1938 and the bituminous wearing surface consisting of a bituminous prime coat and a double blotter type sealing coat were placed in September 1938.

A traffic count made in 1941 showed that the road carried 394 vehicles per day (the 24-hour average) of which 14 percent were commercial vehicles such as light, medium, and heavy trucks and busses.

CONDITIONS ON PROJECT DESCRIBED

Conditions on this highway with respect to soils, drainage, surfacing materials, and climate are typical of the entire region of level plains adjacent to the Red River which forms the boundary between Minnesota and North Dakota. The ground surface slopes toward the Red River at the rate of only a few inches per mile. The soils are heavy plastic clays or silty clays, commonly known as gumbo, and gravel for surfacing must be hauled for long distances.

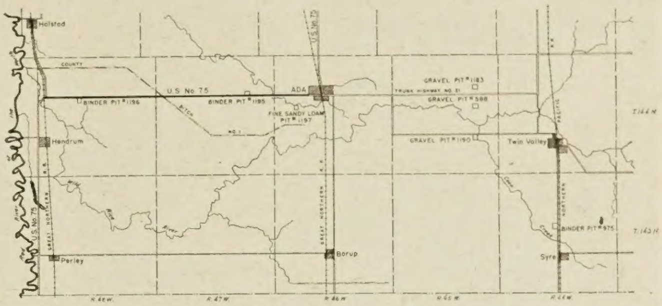

Figure 1.—LOCATION OF EXPERIMENTAL ROAD AND SOURCES OF MATERIALS.

Exceedingly low temperatures are recorded during the winter months and a heavy snowfall occurs. Owing to the flatness of the terrain, the road ditches become filled with water from melting snow and rain and remain that way for long periods in the spring.

In order to provide adequate surface drainage and also to facilitate snow removal, road grades are generally established a foot or more above the ground surface. Material for the fill is borrowed from alongside the road, resulting in wide bottom ditches 3 to 4 feet below the crown of the road.

A brief history of this section of road prior to the construction of the stabilized base will illustrate the performance of bituminous surfaces when placed directly on the clay subgrade.

In 1925 the roadway was graded to a width of 30 feet. In 1926 a blotter type bituminous surface was constructed, followed by re-treatments in 1927, 1928, 1929, 1931, and 1934. In 1936 only about 13 percent of the total length of the road was in good condition, while the remainder was rough as a result of cracking, breaking, pitting, scaling, and raveling. Typical failures are illustrated in figure 2.

DESCRIPTION OF EXPERIMENT

The experiment consisted of 16 test sections of stabilized base having thicknesses of 1, 2, 3, 4, 6, and 8 inches constructed on a roadbed which, as already described, was graded in 1925 and surfaced in 1926 with a bituminous-treated gravel. On four sections the base was placed directly on the existing bituminous surface. The bituminous mat was removed from the other sections before placing the base. The base on fourteen sections was a mixture of sand and gravel with binder soil and on two sections it consisted of sand and binder soil. Sand and gravel used in the mixtures were obtained from pits located in a ridge about 10 miles east of Ada. The gradations of the stabilized gravel mixtures were quite uniform as were those of the two stabilized sand mixtures. Variations in plasticity index were introduced by the use of binder soil obtained from

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[1] Lieutenant, U. S. Navy, and former highway engineer, Public Roads Administration.

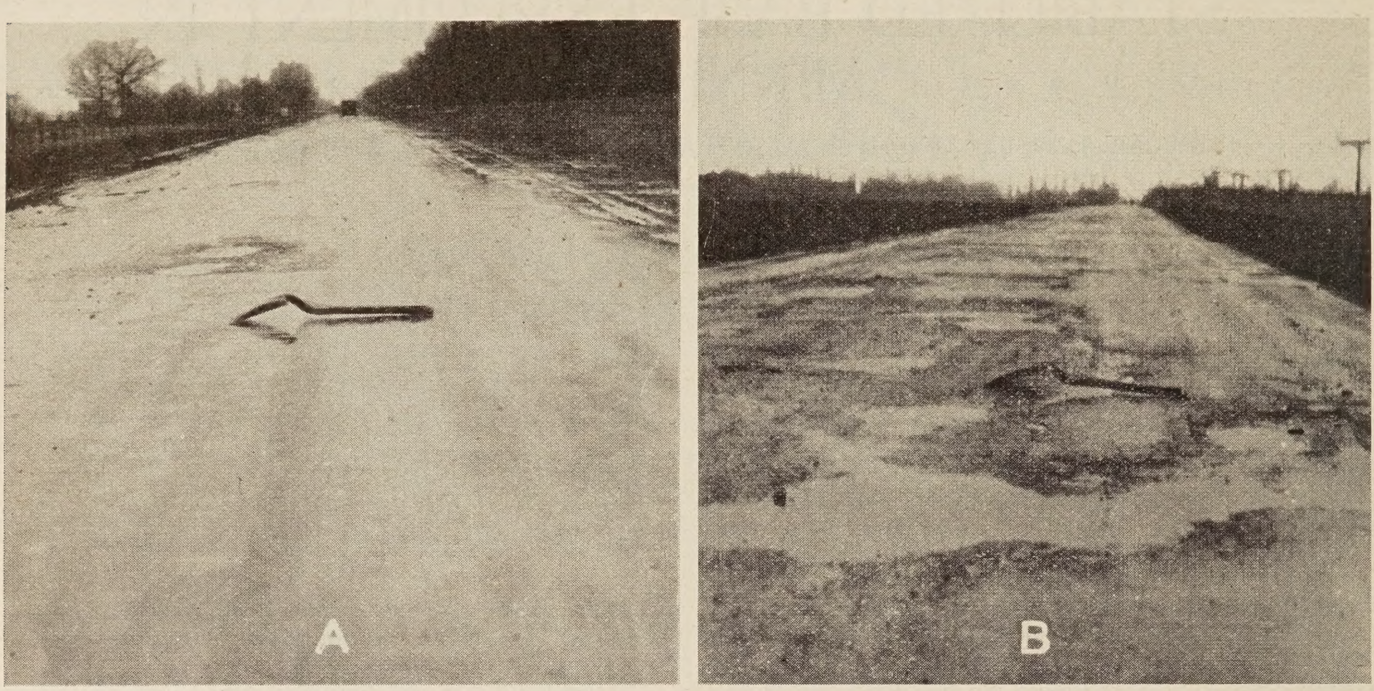
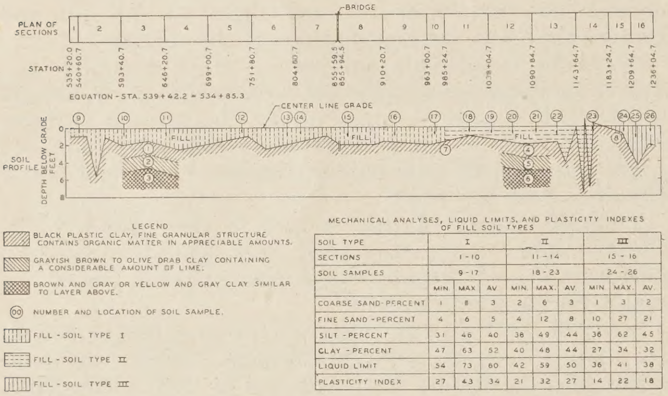


Figure 2.—Condition of Old Bituminous Mat, A, Typical of Better Portions of the Project and B, Typical of Sections Where Surfacing Was Completely Destroyed.

DESCRIPTION OF SUBGRADE SOILS

Subgrade soils on practically the full length of the project consist of fill material excavated from alongside the road. The height of fill and the soil profile are shown in figure 3. In general, the fill varies from 1 to 2.5 feet in height but reaches 5 to 8 feet at a few places where the road crosses drainage ditches and small streams.

The soil profile, typical of the area, consists of a layer of black plastic clay containing organic matter in various depths in three different pits. The distinguishing details of the various sections are given in table 1.



MECHANICAL ANALYSES, LIQUID LIMITS, AND PLASTICITY INDEXES OF FILL SOIL TYPES

SOIL TYPE	I			II			III		
SECTIONS	1 - 10			11 - 14			15 - 16		
SOIL SAMPLES	9 - 17			18 - 23			24 - 26		
	MIN.	MAX.	AV.	MIN.	MAX.	AV.	MIN.	MAX.	AV.
COARSE SAND - PERCENT	1	8	3	2	6	3	1	3	2
FINE SAND - PERCENT	4	6	5	4	12	8	10	27	21
SILT - PERCENT	31	46	40	38	49	44	36	62	45
CLAY - PERCENT	47	63	52	40	48	44	27	34	32
LIQUID LIMIT	54	73	60	42	59	50	36	41	38
PLASTICITY INDEX	27	43	34	21	32	27	14	22	18

Figure 3.—The Soil Profile.

Table 1.—*Details of experimental sections*

Section number	Length	Thickness	Binder soil		Subgrade
			Pit number	Limits from ground surface	
	Feet	*Inches*		*Inches*	
1	998	1	1196	6–36	Soil.
2	5, 280	4	1196	6–18	Do.
3	5, 280	4	1196	18–36	Do.
4	5, 280	4	1196	36–48	Do.
5	5, 280	4	975	24–60	Do.
6	5, 280	8	1196	18–48	Do.
7	5, 099	6	1196	18–48	Do.
8	5, 426	3	1196	18–48	Do.
9	5, 280	2	1196	18–48	Do.
10	2, 224	2	1195	18–54	Bit. mat.
11	5, 280	3	1195	18–54	Do.
12	5, 280	4	1195	18–54	Do.
13	5, 280	6	1195	18–54	Do.
14	3, 960	4	1195	18–36	Soil.
15 [1]	2, 640	6	1195	18–54	Do.
16 [1]	2, 640	3	1195	18–54	Do.

[1] Sections 15 and 16 are sand-clay while sections 1 to 14, inclusive, are sand-clay-gravel.

Table 2.—*Mechanical analyses and physical properties of subgrade soils*

Sample number	Mechanical analysis				Physical constants					
	Coarse sand (2 to 0.25 mm.)	Fine sand (0.25 to .05 mm.)	Silt (0.05 to .005 mm.)	Clay (smaller than 0.005 mm.)	Liquid limit	Plasticity index	Shrinkage limit	Shrinkage ratio	Centrifuge moisture equivalent	Field moisture equivalent
	Percent	*Percent*	*Percent*	*Percent*						
1	2	6	48	44	65	36	12	1. 9	45	32
2	1	3	43	53	62	36	17	1. 8	37	29
3	1	5	44	50	54	34	19	1. 7	32	35
4	7	24	(1)	(1)	66	29	18	1. 7	39	44
5	3	13	(1)	(1)	43	19	20	1. 8	25	26
6	2	7	(1)	(1)	49	25	20	1. 7	28	26
7	3	11	48	38	61	32	17	1. 7	37	39
8	1	29	53	17	43	12	18	1. 7	26	32
9	2	4	31	63	73	43	23	1. 6	42	29
10	2	5	40	53	61	36	13	1. 9	37	32
11	1	4	42	53	63	38	17	1. 8	28	26
12	3	6	44	47	56	34	15	1. 9	33	30
13	6	6	34	54	58	30	15	1. 9	41	32
14	5	6	39	50	54	30	13	1. 9	35	28
15	4	4	43	49	62	36	12	1. 9	35	29
16	3	4	46	47	54	27	13	1. 9	32	27
17	5	5	38	52	57	30	12	2. 0	34	29
18	2	7	48	43	42	21	14	1. 9	27	24
19	2	7	49	42	47	25	17	1. 9	30	27
20	4	4	44	48	52	30	14	1. 9	32	26
21	6	8	38	48	44	23	14	1. 8	29	24
22	4	11	45	40	59	32	16	1. 8	38	35
23	2	12	41	45	58	30	13	1. 9	34	35
24	2	26	38	34	41	22	14	1. 9	27	23
25	1	10	62	27	36	14	20	1. 8	26	24
26	3	27	36	34	37	19	13	1. 9	25	20

[1] Flocculated.

TABLE 3.—*Maximum dry densities and optimum moisture contents of samples of soil of each type*

Sample number	Type of soil	Dry density	Optimum moisture
		Lb. per cu. ft.	*Percent*
10	I	99	22
20	II	105	20
26	III	110	17

TABLE 4.—*Average densities and moisture contents of samples of each type of soil*

Sections	Type of soil	Dry density	Average moisture content
		Lb. per cu. ft.	*Percent*
1-10	I	92	27
11-14	II	105	22
15-16	III	102	22

appreciable amounts. This layer extends to a depth of 18 inches and is underlaid by a grayish-drab colored clay rich in lime. At a depth of about 36 inches, the soil changes to a mottled brown and gray or yellow and gray clay.

Material from the two upper layers of the soil profile was used in constructing the fill. As a result, the subgrade soil at any particular location consists of either the top layer, the second layer, or a mixture of the two layers. According to the results of tests, table 2, the soils in the fill as well as those representing the different layers of the soil profile have physical properties of the A-6 and A-7 groups with the lighter textured, less plastic varieties near the eastern end of the project in sections 15 and 16.

The subgrade soils in sections 1 to 10 were considerably more plastic and heavier textured than those in sections 15 and 16 while the fills in sections 11 to 14 were composed of materials intermediate between these two types. For this reason, the soils in the fills were divided into three types as shown in figure 3.

Samples 10, 20, and 26 (table 2) are typical of soil types I, II, and III, respectively. The results of standard compaction tests performed on these three samples are shown graphically in figure 4. Maximum dry densities and optimum moisture contents are shown in table 3.

The actual densities of the upper 12 inches of the subgrade at the locations of samples 10, 20, and 26 were respectively, 95, 104, and 106 pounds per cubic foot with corresponding moisture contents of 27, 22, and 20 percent. These values agree quite closely with the average densities and moisture contents determined prior to the construction of the base course as shown in table 4.

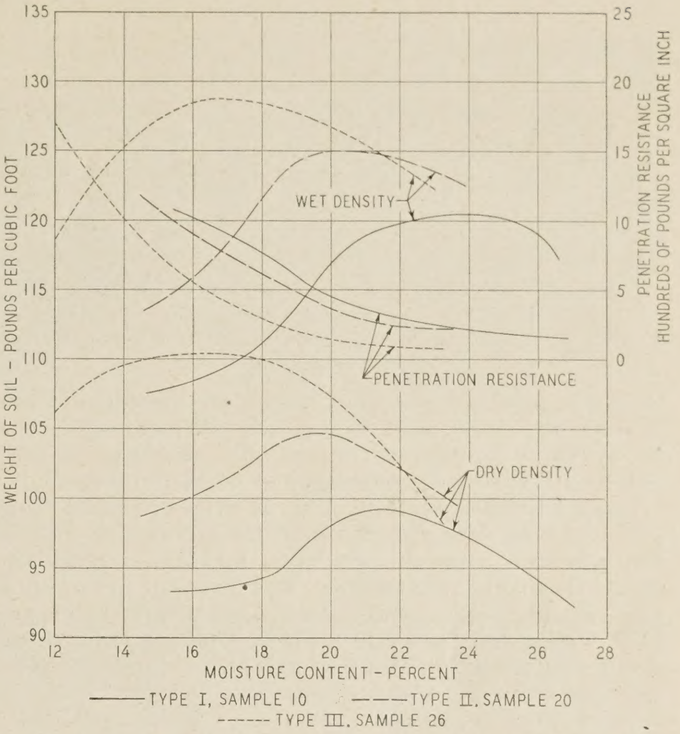


Figure 4.—TYPICAL DENSITY AND PENETRATION CURVES.

BASE-COURSE MATERIALS

The materials used in the stabilized mixtures were obtained from various pits located as shown on figure 1. Pits 975, 1195, and 1196 furnished the binder soils. The material from pit 975 was a clay till of glacial origin comparable to binder soils available in other sections of the State. The soils in pits 1195 and 1196 were lacustrine in origin and more or less typical of the soils found throughout the valley.

Results of mechanical analyses and physical and chemical tests performed on the different binder soils are given in table 5. Pit 1195 furnished a heavy clay with a considerable amount of both organic matter and lime. The material obtained from a depth of 6 to 18

TABLE 5.—*Results of tests on binder soils*

Pit number	Depth	Mechanical analysis				Physical characteristics of material						Chemical analysis						
		Coarse sand (2 to 0.25 mm.)	Fine sand (0.25 to 0.05 mm.)	Silt (0.05 to 0.005 mm.)	Clay (smaller than 0.005 mm.)	Liquid limit	Plasticity index	Shrinkage limit	Shrinkage ratio	Centrifuge moisture equivalent	Field moisture equivalent	Organic matter	CaO	MgO	CO_2	SiO_2	$Fe_2O_3+Al_2O_3$	pH
	Inches	*Percent*	*Percent*	*Percent*	*Percent*							*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	
975	24-60	3	12	35	50	42	25	14	1.9	26	23	1.23	12.3	5.2	12.8	49.2	13.9	8.4
1195	18-36	3	13	(1)	(1)	43	19	20	1.8	25	26	9.23	16.1	6.1	14.6	40.6	11.4	8.0
1195	18-54	2	7	(1)	(1)	49	25	20	1.7	28	26	4.05	11.3	6.6	13.9	46.6	12.4	8.2
1196	6-36	1	4	42	53	63	38	17	1.8	36	38	2.00	9.0	5.4	10.1	50.7	17.2	8.4
1196	6-18	2	6	48	44	65	36	12	1.9	45	32	4.59	1.1	3.4	.9	63.8	17.9	8.0
1196	18-36	1	3	43	53	62	36	17	1.8	37	29	1.45	9.8	6.2	11.6	48.7	16.3	8.6
1196	36-48	1	5	44	50	54	34	19	1.7	32	35	2.06	7.7	6.2	10.1	52.8	16.3	8.6
1196	18-48	1	3	32	64	60	33	17	1.8	37	35	0	9.7	6.3	11.4	49.3	16.7	8.6

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[1] Flocculated.

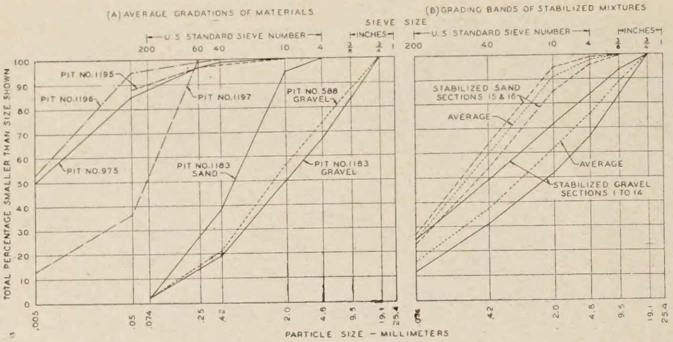

Figure 5.—Gradations of Materials and Mixtures Used in Original Construction.

inches in pit 1196 was high in organic matter and low in lime, while the other binder soils from this pit were heavy clays containing appreciable amounts of lime and relatively low percentages of organic matter.

Gravel for test sections 1 to 14 was produced from pits 1183 and 588, and the sand for sections 15 and 16 was screened from the gravel in pit 1183. Since the gravel from pits 1183 and 588 was deficient in fine sand and very fine sand, a fine sandy loam obtained from pit 1197 was added to the mixtures on all sections to improve the grading. This material also reduced the plasticity index of the highly plastic binder soils.

Average gradings of the sand, gravel, fine sandy loam, and binder soils are shown in table 6 and figure 5, *A*.

Table 6.—*Average gradations of materials used in stabilized mixtures*

Material	Pit number	Percentage smaller than—								
		¾-inch sieve	⅜-inch sieve	No. 4 sieve	No. 10 sieve	No. 40 sieve	No. 60 sieve	No. 200 sieve	0.05 mm.	0.005 mm.
Gravel	588	100	88	74	57	21	------	2	------	------
Do	1183	100	84	67	50	19	------	2	------	------
Sand	1183	------	------	100	95	38	------	2	------	------
Do.[1]	1197	------	------	------	------	100	99	------	36	13
Binder	975	------	------	------	100	99	97	------	85	50
Do	1195	------	------	------	100	98	97	------	88	------
Do	1196	------	------	------	------	100	99	------	95	53

[1] Fine sandy loam.

DESIGN OF EXPERIMENTAL SECTIONS

Typical base-course cross sections are shown in figure 6. Sections 1, 2, and 3 inches thick were constructed in a single layer; sections 4 inches in thickness in two 2-inch layers; sections 6 inches thick in two 3-inch layers; and the 8-inch section was composed of two layers 3 inches thick and one layer having a thickness of 2 inches.

On all sections consisting of more than one layer, the stabilized mixtures for all but the top layer were proportioned in accordance with the percentages by weight shown in table 7.

Flake calcium chloride was added to all sections consisting of a single layer and to the surface layer of those sections having more than one layer. The proportions by weight are shown in table 8.

Sections 15 and 16 consisted of mixtures of sand combined with the various other materials while gravel was used in sections 1 to 14. Section 5 differs from the other gravel sections in that the binder soil used in the mixture was a glacial till from pit 975. Sections 1 to 4 and 6 to 14 contained binder soil high in organic matter and lime from pits 1195 and 1196.

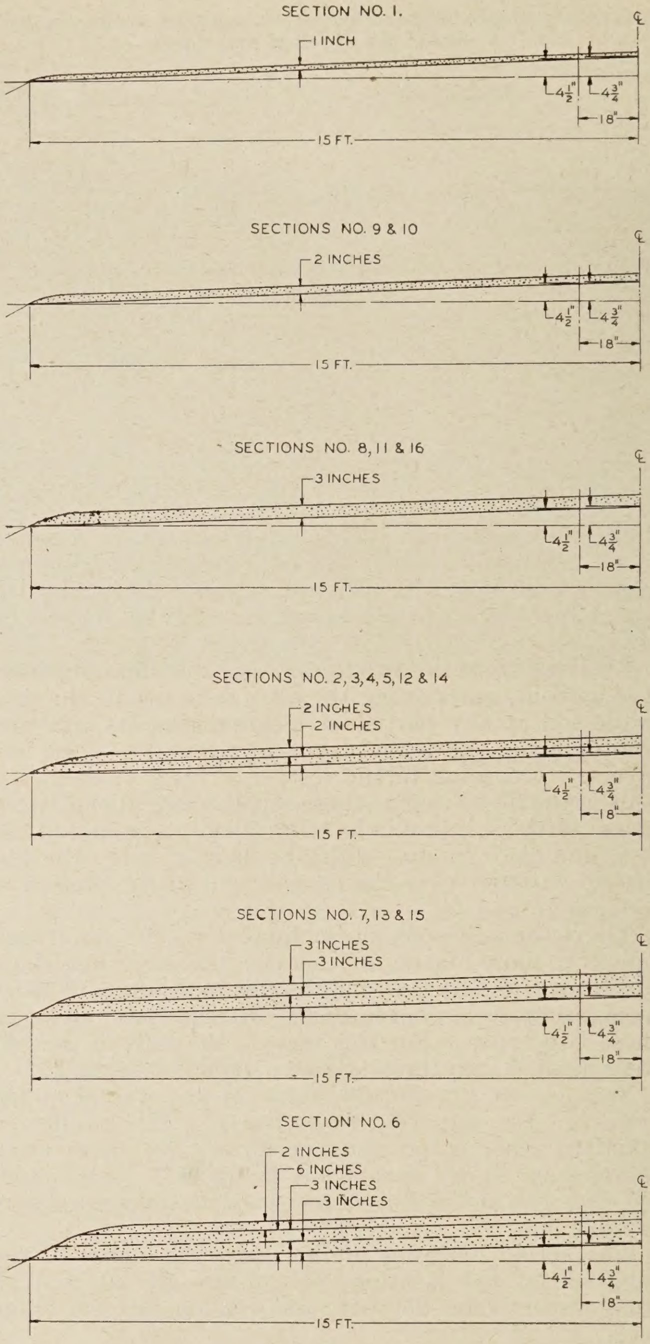

Figure 6.—Typical Cross Sections of the Stabilized Gravel Base. On All Sections the Center 3 Feet of the Roadway is to be Crowned One-Quarter of an Inch. The Slope From 18 Inches Right and Left of the Center Line is to be One-Third of an Inch per Foot.

Table 7.—*Percentages of materials by weight for all but the top layer on all multilayer sections*

Material	Sections 2, 3, 4, 6, 7, 12, 13, 14	Section 5	Section 15
	Percent	*Percent*	*Percent*
Gravel or sand	74.25	73.00	62.00
Binder soil	10.00	13.00	13.00
Fine sandy loam	7.25	5.50	16.50
Water	8.50	8.50	8.50

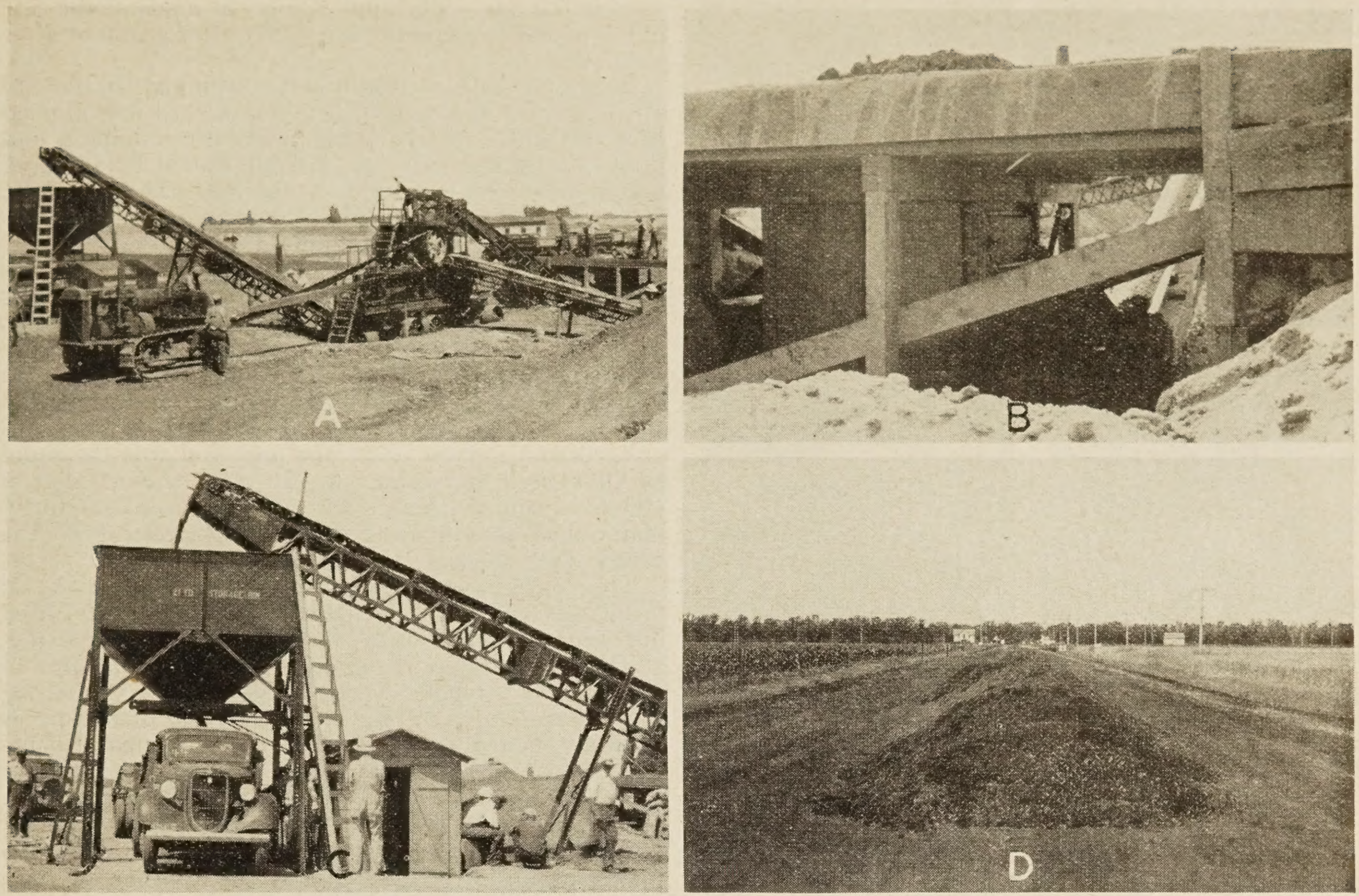

Figure 7.—Mixing Equipment: A, Central Mixing Plant, B, Loading Trap and Conveyor for Delivering Binder Soil to Shredder, C, Truck Resting on Platform Scale Being Loaded with Stabilized Mixture, and D, the Mixture Deposited in Windrow in Center of Road.

Table 8.—*Percentages of materials by weight in sections consisting of a single layer and in top layer of multilayer sections*

Material	Sections 1 to 4 and 6 to 14	Section 5	Sections 15 and 16
	Percent	*Percent*	*Percent*
Gravel or sand	74.00	72.75	61.75
Binder soil	9.90	12.90	12.90
Fine sandy loam	7.15	5.40	16.40
Water	8.50	8.50	8.50
Calcium chloride	.45	.45	.45

CONSTRUCTION METHODS

On all sections, exclusive of 10, 11, 12, and 13, the existing bituminous mat was scarified and removed from the road by blading it beyond the shoulders and was later used for dressing the shoulder slopes. The subgrade was then bladed to the typical cross section shown in figure 6 and rolled.

On sections 10, 11, 12, and 13, the old bituminous mat was left in place and the gravel placed directly on it. However, it was necessary to make many patches and blade the surface during hot weather in order to remove irregularities. Although the mat was in fairly good condition prior to placing the stabilized gravel, it was impossible to shape the surface to the desired section.

The different materials used in the stabilized mixtures were stock piled in a central mixing plant at Ada where they were combined (fig. 7, *A*). The plant consisted of a portable single pugmill continuous mixer equipped with a clay feeder; clay shredder; spray pipes for adding water; hoppers with adjustable gates for feeding the proper amounts of mineral salts, sand, and gravel; and belt conveyors for introducing the different materials into the mixer and discharging the mixture into a storage bin. Power was furnished by a 60-horsepower tractor. The output of the plant varied from 65 to 95 tons of mixed material per hour.

In the operation of the plant a controlled amount of clay was fed by screw conveyors to a belt conveyor which introduced the clay into the clay shredder at the top of the plant where it was pulverized before entering the pugmill. Figure 7, *B* shows the trap through which the binder soil was loaded into the clay feeder and the belt conveyor for delivering the soil to the shredder.

The same belt conveyor which elevated the binder soil was also used to deliver sacks of calcium chloride to the salt hopper at the top of the plant, from which it was fed at a controlled rate through an adjustable gate into the pugmill.

Simultaneously with the introduction of the binder soil, calcium chloride, and a regulated amount of water, the sand and gravel were introduced on another belt conveyor. The mixed material was discharged from the pugmill onto a third belt conveyor which carried the mixture to a storage bin located directly over a weighing platform.

Proportioning of the various materials was controlled by regulating the rate of feed to the mixer. First the speeds of the conveyor belts were determined while the plant was running at its normal operating speed. Then

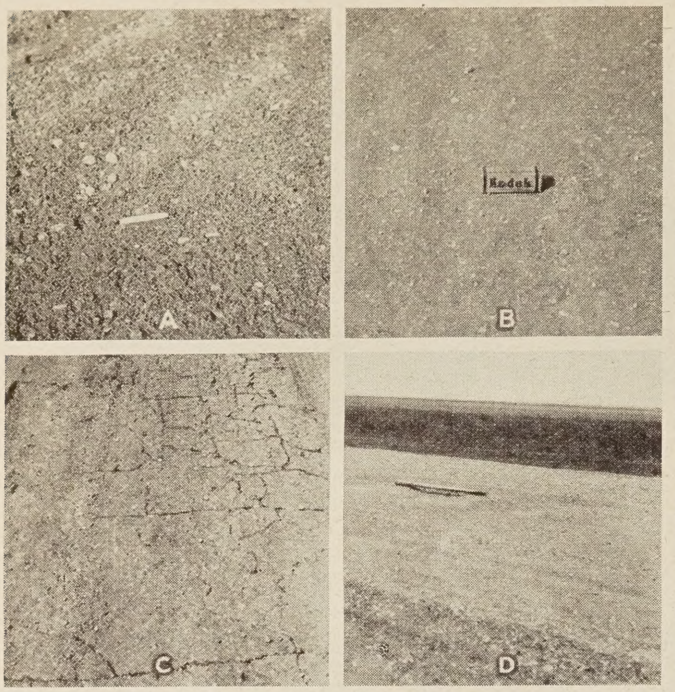

Figure 8.—Surface During Construction Showing: A, Appearance of Stabilized Mixture Prior to Rolling, B, Surface Texture After Compaction, C, Surfacing Displaced on Section 1, and D, Corrugations Produced by Traffic During Hot, Dry Weather, Characteristic of the Construction Period.

the plant was stopped and the weight of material on a 10-foot section of each belt was measured. From these two determinations the amount of each material delivered to the pugmill in a given time was calculated. Gate openings on the material hoppers were then adjusted until the desired proportions were obtained.

A final check on the proportioning was made by taking samples of the mixture discharged from the pugmill and determining their gradations, physical constants, and moisture contents.

The stabilized mixture was loaded from the storage bin into trucks resting on platform scales (fig. 7, *C*) and hauled out and deposited in the center of the road as shown in figure 7, *D*.

Distribution of the stabilized material on the road was controlled on the basis that the mixture would have a dry weight of 140 pounds per cubic foot after compaction. All trucks were loaded with 4.2 tons of the mixture and the loads were deposited a distance apart determined according to the compacted thickness of the layer to be constructed. The spacing of the loads of 4.2 tons varied from 22 feet for a 1-inch layer to 7.3 feet for a 3-inch layer.

The deposited material was spread and shaped to the desired cross section by a motor grader and compacted by a multiwheel, pneumatic tire roller (see cover illustration). The total weight of the roller and surcharged load was about 6 tons. Rolling was continued until a uniformly dense surface was obtained.

The appearance of the spread material before rolling is shown in figure 8, *A*. Figure 8, *B* shows the surface texture after final rolling.

Following the completion of sections 1 to 5, it was observed that a great deal of loose material developed under the action of traffic. It was therefore decided to apply calcium chloride to the surface in addition to that used in the mix. The application was made at the rate of 0.5 pound per square yard either after a rain or after sprinkling.

Beginning with section 6 and continuing to the end of the project, 0.25 pound per square yard was applied over the entire surface immediately after shaping and prior to the final rolling. An additional 0.25 pound per square yard was later spread over the central 24 feet following a rain or after sprinkling with 2,000 to 3,000 gallons of water per mile.

Section 1 was originally constructed with a thickness of 1 inch. Within 2 weeks after completion the surface became loose and raveled. Over large portions, the entire surface was worn away exposing the clay subgrade. This is illustrated in figure 8, *C*. Instead of attempting to maintain this section at its original thickness, it was reconstructed and the thickness increased to 4 inches. The new material was the same as that used in section 6. It was evident that a stabilized course 1 inch thick could not be satisfactorily maintained as a wearing surface when resting on the heavy clay subgrade typical of this project.

The construction period, July 11 to September 15, 1936, was unusually hot and dry. The surface dried out rapidly and became loose and corrugated (fig. 8, *D*). The first rains occurred on August 13 and 14 and soaked through the loosened material, softening the surface and resulting in a great deal of rutting as shown in figure 9, *A* and *B*. The rains proved beneficial, however, making it possible to remove all surface irregularities with motor graders. All the sections were maintained thereafter in good condition by light blading. Figure 9, *C* shows the general condition of the road at the time of completion of the project.

STABILIZED MIXTURES UNIFORMLY GRADED

Tests on samples taken from the different sections (table 9) show that the stabilized mixtures were well graded and that gradation of the mixtures was very uniform in all sections. Ranges in gradations are shown graphically in figure 5, *B*.

The uniformity of the mixtures indicates the efficiency of the methods of mixing and control adopted on this project. Study of the performance of the different sections is not complicated by lack of uniformity in the mix.

Table 9.—*Average gradations and physical properties of stabilized mixtures*

Section number	Gradation						Ratio B/A	Liquid limit	Plasticity index
	Percentage passing sieve indicated								
	¾-inch	⅜-inch	No. 4	No. 10	No. 40 (A)	No. 200 (B)			
1	100	84	71	57	37	15	0.41	23	7
2	100	89	76	64	39	17	.44	21	6
3	100	92	76	62	42	20	.48	23	8
4	100	91	80	64	35	16	.46	24	9
5	100	86	78	64	39	16	.41	18	4
6	100	91	81	68	41	18	.44	25	10
7	100	88	74	60	36	15	.42	22	8
8	100	89	72	60	39	18	.46	23	9
9	100	85	71	55	31	13	.42	23	8
10	100	89	77	64	39	18	.46	20	4
11	100	88	75	63	37	15	.41	18	4
12	100	86	74	58	32	13	.41	19	4
13	100	87	70	57	34	14	.41	18	4
14	100	91	76	62	36	14	.39	18	4
15		100	97	90	59	25	.42	18	4
16		100	99	95	62	27	.44	19	4

Figure 9.—Conditions of Surface Showing: A, Typical Section Completed 3 Weeks or More Before the Heavy Rain, B, Completed 2 Days Before the Heavy Rain, C, General View at the Time of Completion of the Project, and D, Surface Raveling.

Table 10.—*Comparison between liquid limits and plasticity indexes of binder soils and of stabilized mixtures*

Pit number	Liquid limit range		Plasticity index range	
	Raw soil	Mixture	Raw soil	Mixture
975	42	18	25	4
1195	43–49	18–20	19–25	4
1196	54–65	21–25	33–38	6–10

PHYSICAL PROPERTIES OF MIXTURES INFLUENCED BY BINDER SOIL

Since gradations of material in the stabilized mixtures are uniform, the variation in physical properties may be correlated with the characteristics of the binder soil. Table 10 shows that variations in the liquid limit and plasticity index of the binder soils are definitely reflected in the characteristics of the mixtures. The data of table 10 show further, when considered with the data of table 5, that the liquid limit and plasticity index of the mixture are not influenced by the origin of the binder soil used nor by its chemical composition, except insofar as these may affect the plasticity of the binder soil.

MEASUREMENTS OF DENSITY INDICATE UNIFORM COMPACTION

As the construction of the various sections was completed, density measurements were made on the layers

Table 11.—*Results of density determinations*

Section number	Design thickness	Number of days[1] after construction	Average densities: Upper 2 to 3 inches	Average densities: Bottom layer	Remarks
	Inches		*Lb. per cu. ft.*	*Lb. per cu. ft.*	
1	1	2	128		Tests at 50 days made on reconstructed section 4 inches thick.
		50	140		
2	4	1		130	Test on entire thickness gave 137 pounds per cu. ft.
		30	134		
		70	139		
3	4	24	136		
		64	140		
4	4	22	134		
		60	137		
5	4	16	141		
		80	139		
6	8	15	135	130	
		50	138	131	
7	6	5	130	130	
		46	136	133	
8	3	5	136		
		44	138		
9	2	42	140		
10	2	40	142		
11	3	38	141		
12	4	35	136		
13	6	31	137	134	
		63	137		
14	4	28	141	137	
15	6	26	130	132	Sand section.
		60	134	134	
16	3	26	137		Sand section.
		60	137		

[1] Approximate number of days from date of completion to date tests were made.

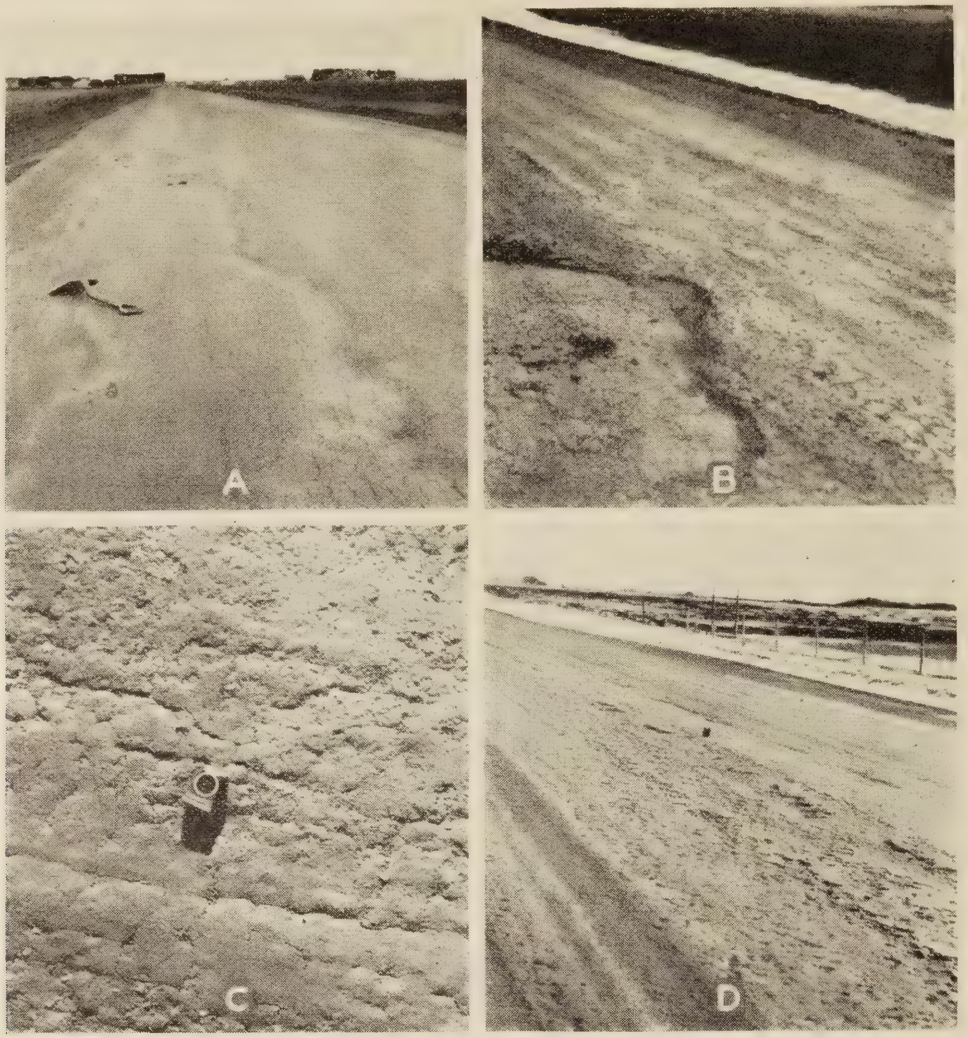

Figure 10.—Views of the Road Surface With: A, Entire Surface Displaced and Mat Exposed on Section 10, B, Scaling Condition, C, Shrinkage Cracks, and D, Pitting.

of the compacted stabilized mixtures. These measurements were later repeated to determine the effect of traffic on density. The average densities recorded on each section are given in table 11. The data for the gravel sections are summarized in table 12.

These results indicate uniform compaction throughout the length of the gravel portion of the project and a definite increase in compaction under the action of traffic during the first month following construction with practically no increase thereafter. The same is true for the stabilized sand mixtures. The sand sections, however, had lower average densities than the gravel sections.

BEHAVIOR OF STABILIZED GRAVEL UNDER TRAFFIC

The stabilized gravel was maintained under traffic for approximately 2 years prior to the construction of the bituminous surface. Condition surveys made during this period furnished information relative to the behavior of the various sections when used as road surfaces. The results of the condition surveys are summarized in table 13.

Table 12.—*Range in average density of gravel sections after different periods under traffic*

Number of days under traffic	Upper 2 to 3 inches	Bottom layer
	Lb. per cu. ft.	*Lb. per cu. ft.*
5 days or less	128 to 136	130
15 to 31 days	134 to 141	130 to 137
35 to 80 days	136 to 142	131 to 137

Formation of loose material on the surface as a result of the abrasive action of traffic was in evidence on all sections. Other surface defects formed such as corrugations, raveling, pitting, scaling, potholes, shrinkage cracks, and wearing out of the entire thickness of the stabilized surface. Figure 8, *D* shows examples of corrugations.

Raveling denotes a progressive breaking up of the surface resulting from the displacement of loosened material. It differs from the ordinary development of float on the surface in that loosening and displacement of measurable thicknesses occur in localized areas (fig. 9, *D*). In some places, raveling progressed to the extent that the entire surface was worn off (fig. 10, *A*). This has been recorded in table 13 as exposed subgrade, or exposed bituminous mat on the sections where the old bituminous mat was not removed prior to stabilization.

Scaling (fig. 10, *B*) refers to the condition where the surface peels off in layers.

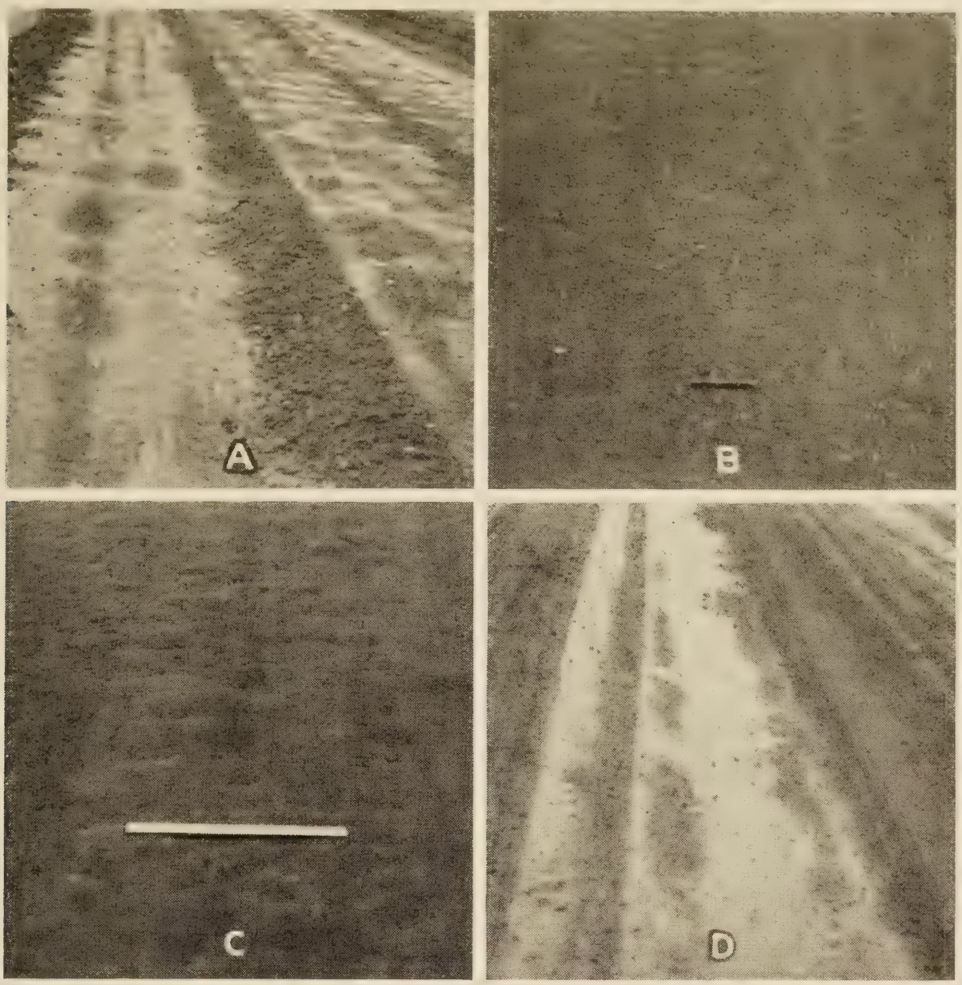

Figure 11.—Sections of Road Showing: A, Potholes Developed in Early Spring, B, Texture of Gravel Sections as Maintained Under Traffic, C, Sand Sections as Maintained Under Traffic Presenting a Highly Polished Surface Covered with Small Round Bumps, and D, the Slushy Condition of Surface During Heavy Rains After Blading Had Removed the Potholes. The Stabilized Material Beneath the Slush Is Firm and Compact.

Shrinkage cracks (fig. 10, *C*) occurred in the sections having a total thickness of 3 inches or less. No detrimental effects on the service behavior of the stabilized gravel were observed as a result of this condition.

Pitting (fig. 10, *D*) indicates the presence of abrupt surface cavities so small in size that, as a rule, they do not interfere with the riding qualities of the road. Potholes refer to cavities deep enough and large enough to cause excessive surface roughness (fig. 11, *A*).

Practically all of these defects occurred during dry summer weather. Areas, where the entire thickness of stabilized surfacing was displaced, were repaired by patching with a stabilized mixture of materials similar to those used in the original construction. The other defects were corrected with surface applications of calcium chloride and blading after rains. Following the blading of the moistened surface, no difference in condition was visible on the various sections.

A typical gravel section after traffic had compacted the bladed surface is shown in figure 11, *B*. The sand-clay sections (15 and 16) presented a surface highly polished and covered with small round bumps (fig. 11, *C*), which apparently resulted from the action of traffic on the fine-textured material containing some clay brought in from the shoulders during the blading operations. Further traffic abrasion caused this material to peel off and exposed the coarser textured sand-clay underneath.

Inspections during the winter disclosed that the surface was frozen solid and suffered very little wear. In the early spring, when most of the frost had left the ground and the surface was extremely wet as a result of melting snow and heavy rains, potholes developed over the entire project (fig. 11, *A*). Blading at this time filled the potholes and produced a smooth but slushy surface (fig. 11, *D*). The slushy material was splashed around a great deal by traffic but did not interfere in any way with the operation of vehicles. It is significant that this condition was confined to a thin layer on the surface. The stabilized material underneath was firm and compact and there was no rutting or breaking through to the subgrade.

The only condition which may be termed failure was where the entire thickness of stabilized mixture was displaced to the extent that the subgrade was exposed. This occurred on sections 9, 10, 11, 12, and 16. Failures were similar to those of section 1 prior to increasing the thickness from 1 inch to 4 inches.

Exposed subgrade was first observed on sections 10 and 9 (2 inches thick) within 2 weeks and 2 months, respectively, after completion of the road. The surfacing was worn off the center of the road for the entire

TABLE 13.—*Results of condition surveys covering 2-year period*

CONDITION

Date of survey	1	2	3	4	5	6	7	8
9-24-36	Good	Good	Good	Good	Local rough areas	Local rough areas	Local rough areas.	Good
10-27-36	Good	Good	Good	Good	Good	Good	Good	Good
11-18-36	Good	Good	Deeply scaled from 629+50 to 632+50.	Shallow pitting and scaling.	Good	Very rough due to corrugations.	Good	Good
12-16-36	Good	Shallow raveling	About 2 inches worn off from 628 to 633.	Shallow raveling	Shallow raveling	Shallow raveling	Good	Good
3-11-37								
4-14-37								
4-29-37								
6-30-37								Shrinkage cracks.
7-23-37								
8-6-37								
8-24-37								
9-8-37								
4-13-38								
7-28-38								

CHARACTERISTICS

	1	2	3	4	5	6	7	8
Thickness (inches)	4	4	4	4	4	8	6	3
Liquid limit	23	21	23	24	18	25	22	23
Plasticity index	7	6	8	9	4	10	8	9
Subgrade	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil

length of section 10 (2 inches thick) after 1 year of service and section 16 (3 inches thick) after 2 years. At the end of the 2 years, the exposed areas on sections 9 (2 inches thick) and 11 (3 inches thick) were quite extensive while on section 12 (4 inches thick) they were small and scattered.

Section 12 differed from the other 4-inch sections in that the old bituminous mat was left in place on the subgrade when the stabilized surface was constructed. Owing to the difficulty in shaping the subgrade where the old bituminous mat was not removed, there may have been many places where the thickness was less than designed. This may also explain the greater wear on section 10 than on section 9.

The difference in behavior between sections 11 and 16 (3 inches thick) indicates that the stabilized sand offered less resistance to traffic abrasion than stabilized gravel.

BASE COURSE RECONSTRUCTED

The wear and tear on the stabilized base during the 2 years it was used as a road surface necessitated reconstruction of the entire base prior to bituminous surfacing in September 1938. New base-course material was added on some of the sections and the surface was merely reshaped on others. The materials were mixed in place on the road in contrast with the plant mixing used in the original construction.

Sections 9 and 10, originally constructed 2 inches thick, were rebuilt with thicknesses of 4 inches. Sufficient material was added to sections 2, 3, 4, 5, 8, 11, 12, and 16 to bring them to their original thickness of 3 or 4 inches. The work on these sections was performed by placing the proper amounts of sand or gravel and binder soil in windrows along the shoulder of the road and mixing with motor graders and a retread mixer consisting of a multiple-blade device which mixes and spreads material. The mixture was spread in thin layers, sprinkled by pressure distributors, and compacted by a pneumatic tire roller.

Sections 1, 6, 7, 13, 14, and 15 were reconditioned by blading to the proper cross section.

The average gradations of the materials combined on the road to produce the stabilized mixtures are shown in figure 12, *A*. The sand and gravel came from pit No. 588 and the binder soil was obtained from a pit located about 7.5 miles east of Ada. The binder soil was a heavy sandy loam which pulverized readily and *prior to placing bituminous surface from September 1936 to 1938*

OF SECTIONS

9	10	11	12	13	14	15	16	Remarks
Good	Bituminous mat exposed locally.	Local rough areas.	Good	Local rough areas.	Good	Good	Good	Rough areas are corrugated.
Good	Patched	Good	Good	Good	Good	Good	Good	Bladed and reconditioned just prior to survey.
Subgrade exposed in local areas.	Patches destroyed	Slightly rough	Good	Good	Good	Good	Good	
Additional areas of exposed subgrade.	Additional areas of exposed mat.	Good	Good	Good	Good	Good	Good	
								No important changes in condition since December 16, 1936.
								Upper 2 inches of entire project softened as result of rains which occurred on Apr. 11, 12, and 13. Blading operations removed any differences in the condition of the various test sections. Subgrade was thawed to depth of 18 inches. No subgrade or base failures in evidence.
								Survey made during heavy rain. Portion of road had been bladed and was fairly smooth. Unbladed sections were rough and potholed. Surface of road was very slushy but there was no rutting or base failures. Stabilized material underneath the slush was firm and compact.
Exposed subgrade and shrinkage cracks.	Area of exposed mat increased.	Bituminous mat exposed locally. Shrinkage cracks.					Shrinkage cracks.	Potholes present in entire project in addition to condition noted on sections 8, 9, 10, 11, and 16.
								Following rains which occurred during week of July 12, the potholes were removed or partially filled by blading.
								Rains occurred on July 31 and August 1. Surface bladed August 2 and 3 filling potholes and producing smooth riding surface. By August 6 the material bladed into the potholes had been kicked out and the surface was again rough.
Area of exposed subgrade increased.	Bituminous mat exposed on entire section.	Area of exposed mat increased.	Bituminous mat exposed in local areas.	Shallow raveling and pitting.	Shallow raveling and pitting.	Shallow raveling and pitting.	Subgrade exposed in scattered areas.	Shallow raveling and pitting on sections 1 to 8. Weather quite dry since last survey.
								Heavy rains occurred Sept. 5. Blading on Sept. 6 removed irregularities and produced a smooth surface.
								Condition same as that on 8-24-37 except for additional areas of exposed subgrade and bituminous mat.
							Subgrade exposed on entire section.	Sections 1 to 15, inclusive, slightly more worn than shown by survey of 4-13-38. Final survey prior to placing bituminous surface.

OF SECTIONS

2	2	3	4	6	4	6	3
23	20	18	19	18	18	18	19
8	4	4	4	4	4	4	4
Soil	Bituminous mat	Bituminous mat.	Bituminous mat.	Bituminous mat.	Soil	Soil	Soil

was easily incorporated with the sand and gravel by road-mixing methods.

The thickness of the base course on each of the sections after reconstruction, together with the results of tests performed on the stabilized mixtures, are given in table 14. The range in gradations and average gradations are shown graphically in figure 12, *B*.

With respect to gradation, the materials in the different gravel sections were very similar. The mixtures in all sections had liquid limits less than 25 and, with the exception of sections 1, 6, and 7, had plasticity indexes not greater than 6. For the 14 gravel sections the average liquid limit was 18 and the average plasticity index was 4. The average density on the different sections just before placing the bituminous surface varied from 131 to 139 pounds per cubic foot.

Approximately 2 weeks after the base was reconstructed, a cut-back asphalt prime coat (MC–1) was applied at the rate of 0.20 to 0.25 gallon per square yard. This was followed by an application of 0.31 to 0.34 gallon per square yard of RC–2 cut-back asphalt and covered with 23 pounds per square yard of gravel having a maximum size of three-eighths inch. The surface was then broomed and rolled.

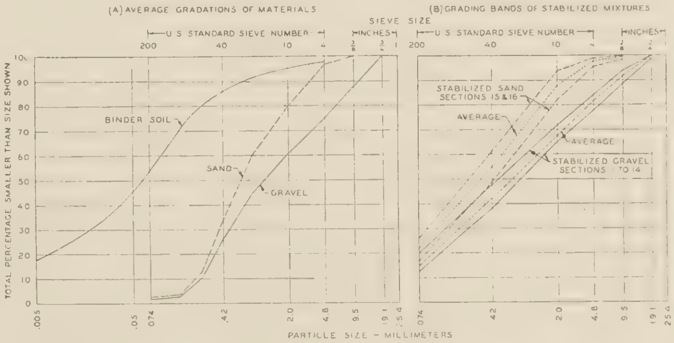

Figure 12.—Gradations of Materials and Mixtures, on the Reconstructed Base Course.

Seven days after the first gravel cover was applied the surface was given a second application of RC–2 material at the rate of 0.25 gallon per square yard and covered with sand at a rate of 12 pounds per square yard. This was followed by brooming and rolling. The resulting bituminous surface was approximately one-half inch thick.

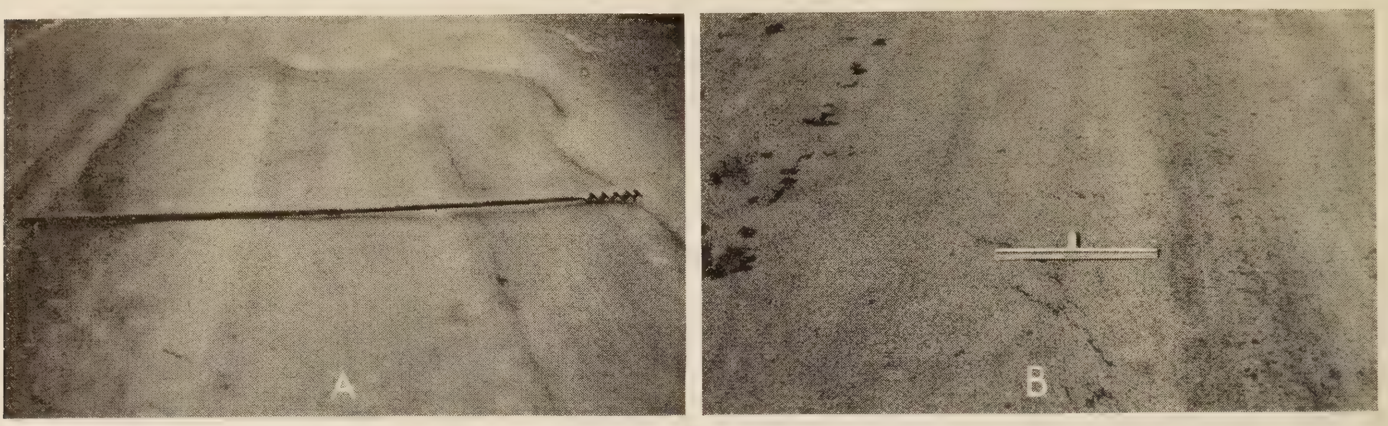

Figure 13.—A, Shoving in Bituminous Surface on Section 15, and B, Formation of Irregular Cracks During First Stages of Shoving.

Figure 14.—A Bituminous Surface That Failed After 1 Year of Service.

SHOVING OCCURRED IN BITUMINOUS SURFACE

Displacement or shoving of the bituminous surface developed quite extensively on section 15 during the summer of 1939. Figure 13, *A* shows the development of closely spaced irregular cracking or tearing resulting from destruction of bond within the mat on one side, and the accumulation, in the form of a ridge, of the shoved material on the other side. The formation of the irregular cracks during the first stages of shoving is illustrated in figure 13, *B*.

Table 14.—*Average thicknesses, gradation, and physical properties of stabilized mixtures of reconstructed base course*

Section number	Base thickness	Gradation						Ratio B/A	Liquid limit	Plasticity index
		Percentage passing sieve indicated								
		¾-inch	⅜-inch	No. 4	No. 10	No. 40	No. 200			
	Inches					(A)	(B)			
1	4.2	100	92	84	70	39	17	0.44	23	9
2	4.3	100	94	82	67	39	14	36	16	3
3	4.7	99	93	83	70	45	15	33	14	1
4	4.4	100	92	81	67	38	13	34	16	2
5	4.2	100	92	85	72	43	17	40	18	4
6	8.0	100	90	79	66	40	16	40	22	8
7	6.2	100	93	83	68	41	17	41	22	9
8	3.0	100	91	82	69	40	16	40	21	6
9	4.8	100	89	78	68	46	15	33	14	(1)
10	4.7	100	90	79	65	40	12	30	16	2
11	3.3	100	92	82	71	48	14	29	15	1
12	3.9	100	89	78	66	39	17	44	20	6
13	5.5	100	94	84	71	43	14	33	16	2
14	4.5	100	93	82	68	41	14	34	16	3
15	6.3	------	100	99	94	61	26	43	19	4
16	4.8	------	99	96	82	49	17	35	16	3

[1] Nonplastic value could not be obtained.

Investigation of the shoved areas in section 15 disclosed a plane of slippage at a depth of one-half inch or less below the bituminous mat. The lower portion, consisting of the original sand-clay base, was undisturbed and well consolidated. The upper portion of the base, displaced with the bituminous mat, consisted of a thin layer of sand-clay placed during the reconditioning of the base by blading back onto the road the material loosened by the abrasive action of traffic and accumulated on the shoulders. The plane of separation between the two layers was well defined and the surface of the lower portion of the base was smooth, indicating that the two layers were not bonded together and that the thin surface layer was sliding on the old base.

Displacement due to shoving, less in degree and extent than on section 15, was found on many of the other sections. Examination of these areas showed that there was a thin layer of loose material between the bituminous mat on top and the firm stabilized base below. On sections 9, 10, and 14 shoving occurred where an attempt had been made during reconstruction to bind and compact loose base-course material by the addition of some of the cut-back asphalt used in the surface.

All of the small areas where shoving developed were later ironed out but section 15 remained rough throughout the period of observations covered by this report.

CRACKING AND BREAKAGE INCREASED PROGRESSIVELY

After 1 year of service cracking and breakage of the bituminous surface began to develop on all sections except those having a base course 6 inches or more in thickness. Practically all failures were at the edges or within the outer 6 feet (fig. 14) where the base thickness was often found to be less than 3 inches.

In the spring of 1940, breakage had increased considerably over that of the previous year on those sections having bases less than 4 inches thick and failures were appearing in the 4-inch sections. Failures increased in area each year until the final survey was made in May 1942. The condition at that time is shown in figure 15.

All of the various types of failures mapped in figure 15 were accompanied by deformation. Slight deformation resulted in the typical alligator cracking shown in figure 16, *A*. As the deformation became greater, there was visible displacement of the base causing the surfacing to crack badly and peel off (fig. 16, *B*).

Breakage resulting from the cracking and deformation is illustrated in figures 16, *C* and *D*, and figure 17

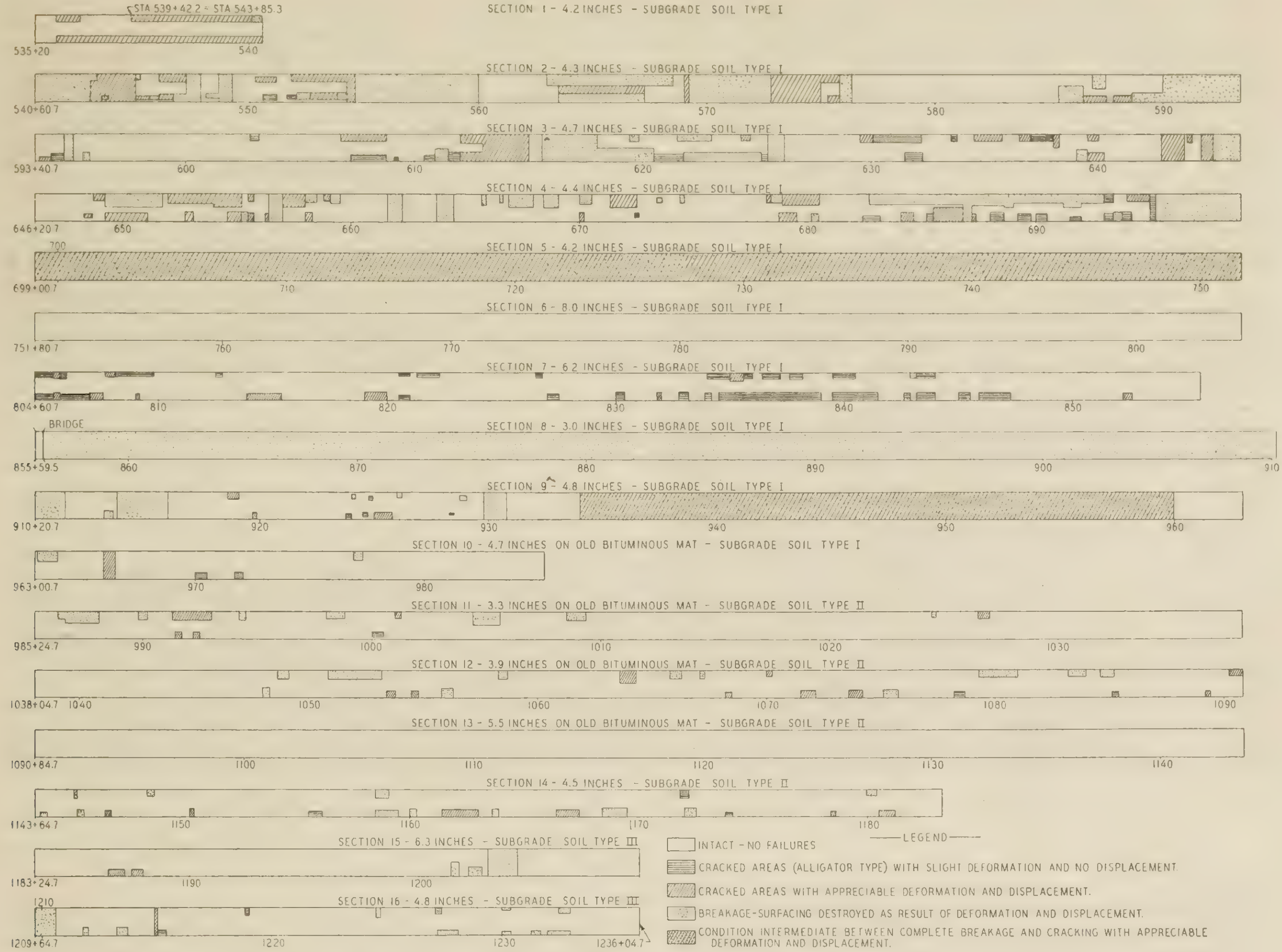

Figure 15.—The Results of the Final Survey Showing the Condition of the Stabilized Base.

shows the condition of the road surface where no failures occurred.

PERFORMANCE RELATED TO BASE THICKNESS

Deterioration was most pronounced on sections 1 to 5 and sections 8 and 9. Section 8 (3-inch base), the first to show signs of failure, was completely destroyed after approximately 4 years of service. Sections 1, 2, 3, 4, 5, and 9, having base courses with average thicknesses ranging from 4.2 to 4.8 inches, were approaching destruction at the time of the final inspection in May 1942.

Section 6 (8-inch base) was entirely free of failures while slight deformation, accompanied by alligator cracking, was starting to appear in the outer 6 feet on both sides of section 7, which had an average base thickness of 6.2 inches.

Much less deterioration occurred in sections 10 to 13, inclusive, which had base courses ranging in thickness from 3.3 to 5.5 inches. On these sections, however, the old bituminous mat was not removed when the new base course was constructed. On the contrary, repairs were made to true up the surface as much as practicable. The old mat was from 1½ to 2 inches thick and apparently was equivalent in traffic service to at least an equal thickness of stabilized base.

Section 13, having a base course 5.5 inches thick plus approximately 2 inches of the underlying bituminous mat, showed no signs of cracking or deformation and was just as sound in every respect as section 6, which had an 8-inch base placed directly on the clay subgrade. The benefit derived from the added thickness supplied by the old bituminous mat is further illustrated by the condition of section 9 compared with section 10 and of section 8 compared with section 11.

Although failures occurred in section 14, it was in much better condition than sections 1, 2, 3, 4, 5, and 9, which had approximately the same thicknesses of base. The densities as well as the physical properties of the subgrade soil in section 14 indicate a more stable subgrade, and consequently better support. This may account for the difference in behavior.

The condition of sections 15 and 16 as compared to that of other sections demonstrated conclusively that, for equal thicknesses, the performance of the stabilized sand base course was equal to that of the stabilized gravel base.

While the higher subgrade densities and lighter texture of the soil in sections 11 to 16 appear to have had some bearing on the behavior of the test sections, it is believed that these properties were of minor importance compared to the influence of base thickness.

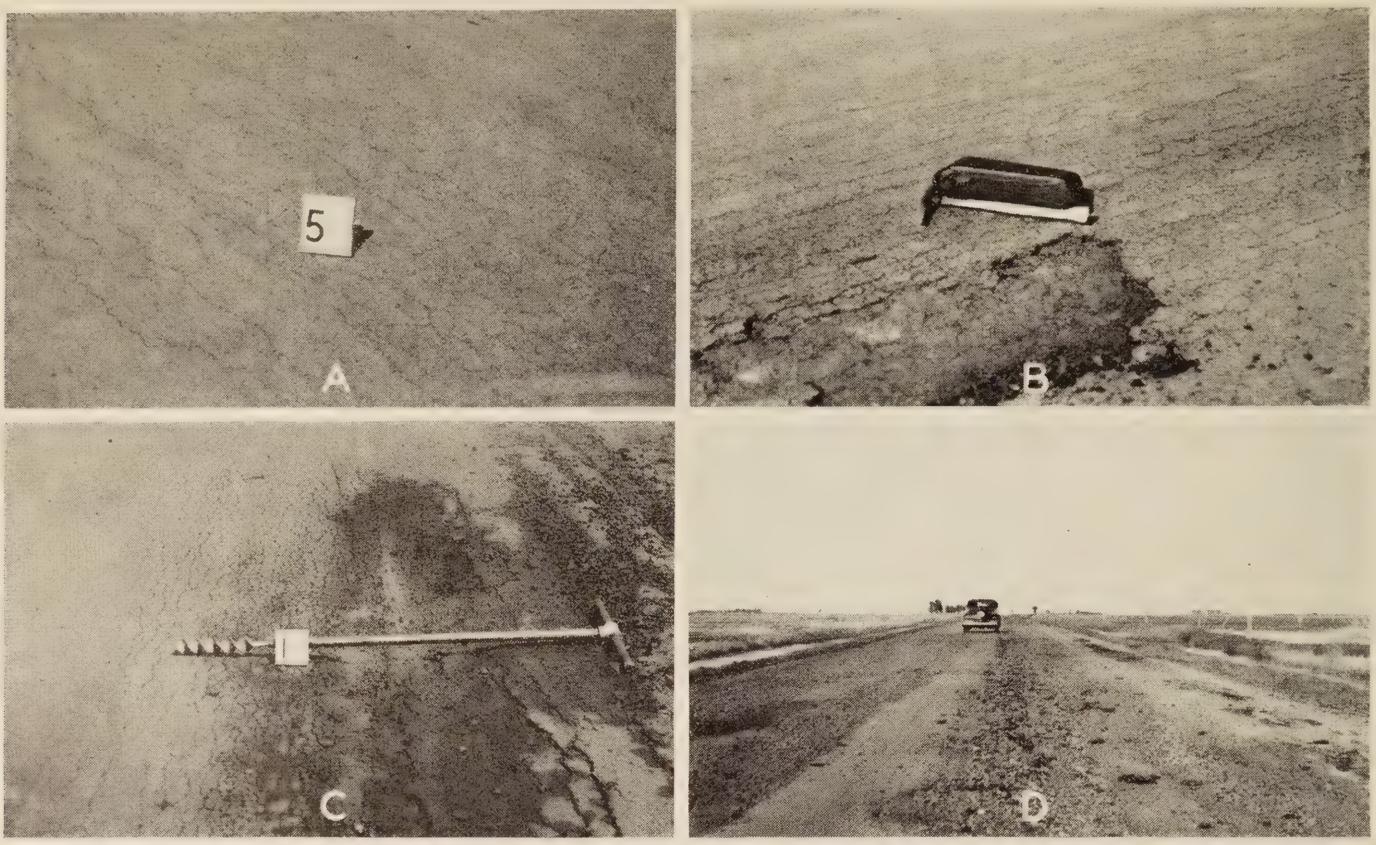

Figure 16.—Deformation of Surface by Cracking: A, Alligator Type Cracking With Slight Deformation, B, Appreciable Deformation and Displacement Causing the Surface To Crack Badly and To Peel Off, C, Breakage, and D, Surfacing on Section 8 Completely Destroyed.

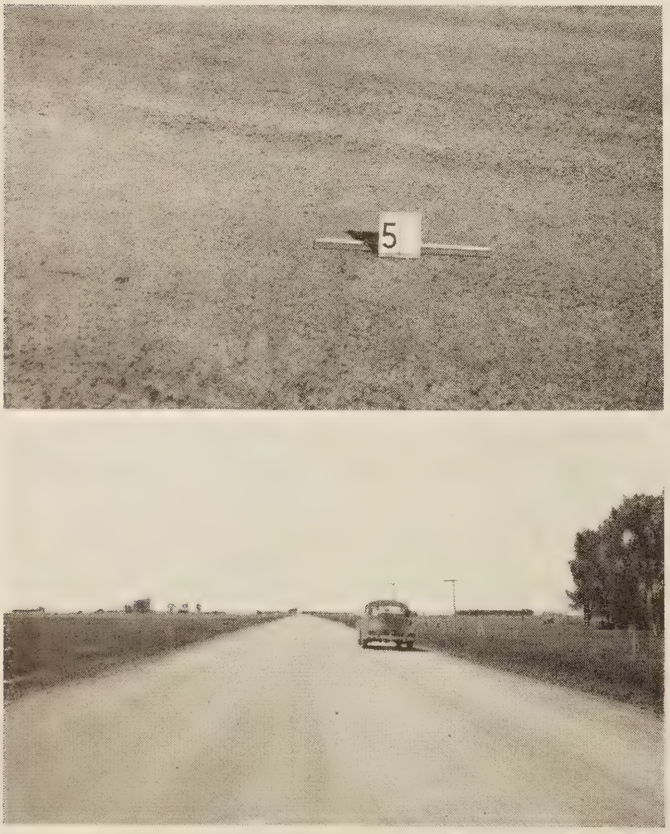

Figure 17.—Surfaces Free of Failures During 4 Years of Service.

SUMMARY AND CONCLUSIONS

With respect to materials and methods of construction, the foregoing discussion may be summarized as follows:

Heavy clay soils may be combined with granular material to produce stabilized mixtures of uniform quality by means of the mixing plant described in this report without any previous preparation such as drying and pulverizing generally required in ordinary road-mix methods of construction.

Neither the origin nor the chemical composition of the binder soils used in this experiment had any influence on the performance of the stabilized mixtures. For equal proportions of binder soil and granular material, the liquid limits and plasticity indexes of the resulting mixtures varied in accordance with liquid limits and plasticity indexes of the binder soils regardless of their source, organic content, or lime content.

A definite increase in compaction (approximately 4 percent) under the action of traffic was observed during the first month following construction with practically no increase thereafter.

Calcium chloride in the amount used integrally on this work (0.45 percent by weight or approximately 1 pound per square yard for a 2-inch layer) was not sufficient to maintain the surface in a moist condition during the hot, dry weather characteristic of the construction period. Additional applications of calcium chloride (about 0.5 pound per square yard) after light rains or sprinkling helped considerably towards maintaining a smooth surface.

(*Continued on p. 54.*)

A STUDY OF THE PAT TEST FOR DETERMINING ALKALI-REACTIVE AGGREGATES

BY THE DIVISION OF PHYSICAL RESEARCH, PUBLIC ROADS ADMINISTRATION

Reported by D. G. RUNNER, Materials Engineer

DURING THE PAST FEW YEARS, the marked expansion that has been observed in certain concrete structures, particularly in the West, has raised a question as to the possibility of a reaction between the alkalies in the cement and certain constituents in the aggregates. The interest in this problem is indicated by the amount of literature [1] on the subject that has been developed within a relatively short time and is evidence that considerable time and effort have been spent in attempting to understand something of the nature of this reaction.

Recent experiences in California (*13*) and Washington (*15*) have focused attention upon a chemical reaction between certain aggregates, or ingredients in aggregates, and the alkali content of the cements as one of the major factors in the deterioration of concrete. In many instances this reaction has caused a volume change of sufficient magnitude to induce serious failure of the concrete.

One fact brought out by investigators is that opal and volcanic glass react with cements high in total alkali content.

The usual and more or less standard practice in identifying alkali-reactive aggregates has been to measure length changes of small mortar bars of about a 1:2 mix which are placed in moist storage for an indefinite period. This practice precludes the use of the procedure as a rapid laboratory test and, with this thought in mind, the California Division of Highways proposed a so-called pat test which was found to shorten considerably the time necessary to determine whether or not a given aggregate is reactive with alkalies in the cement (*14*).

In view of the obvious need for a test of this nature it seemed desirable to conduct additional tests to study further the nature of the reaction as well as to determine the extent of application of the procedure. For this reason several short series of tests involving a rather wide variety of aggregates and some modifications of the original procedure have been made by the Public Roads Administration. The observations from these tests have been assembled in this report with the thought that the trends revealed may be of some value to engineers interested in this subject.

It should be emphasized that these tests were not conducted as parts of a coordinated program planned in advance. They represent for the most part tests made from time to time with materials on hand in the laboratory. This accounts for the obvious gaps in the data, especially the lack of a more complete coverage of possible variations in alkali contents of cements.

METHOD OF MAKING THE PAT TEST

In making this test on coarse aggregates, pats of neat cement about three-fourths inch thick and 4½ inches in diameter are prepared and the broken stone or gravel fragments are embedded in the top of the fresh paste. In the investigation of sand aggregate a 1:2 mortar is used. After molding, the pats are placed in the moist closet for at least 24 hours, after which the surface of the pat is ground smooth to expose the aggregate. The grinding is done on a metal lap using water and No. 220 carborundum grit as a grinding agent. The pat is then washed clean and stored for 4 days at normal temperature in an airtight container in a solution of one part one-half normal solution NaOH, one part one-half normal solution KOH, and two parts saturated limewater.

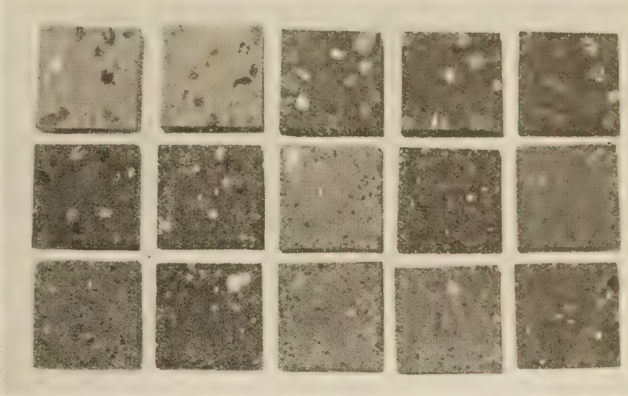

Figure 1.—VIEW OF LABORATORY SET-UP FOR MAKING PAT TESTS.

In the tests reported herein, the only major deviations from the California method consisted in reducing the size of the pats from 4½ inches in diameter to 3-inch squares, and in placing the broken stone and gravel fragments in the bottom of the mold and covering them with the cement paste. This procedure made certain that each fragment would be at or near the surface of the pat upon removal from the mold, and in addition made the molding operations a little easier. The Public Roads Administration method of storing the pats is illustrated in figure 1. A reactive aggregate produces a whitish reaction product, which appears on and near the exposed aggregate particle. This product is assumed to result from the activity of the alkalies in the cement and certain ingredients in the aggregate. A test period of 5 days has been suggested, but in many instances periods greater than this were necessary for the reaction product to appear. The physical appearance of an unusually reactive substance is shown in figure 2.

TESTS WITH OPAL

According to Stanton (*14*) the concrete failures in California reported earlier were caused by the reaction between opaline silica, or impure limestone, and the alkalies in the cement. Although other materials have been found to be reactive, Stanton states that opal has been proven definitely to be a highly reactive mineral

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[1] Italic numbers in parentheses refer to bibliography at end of article.

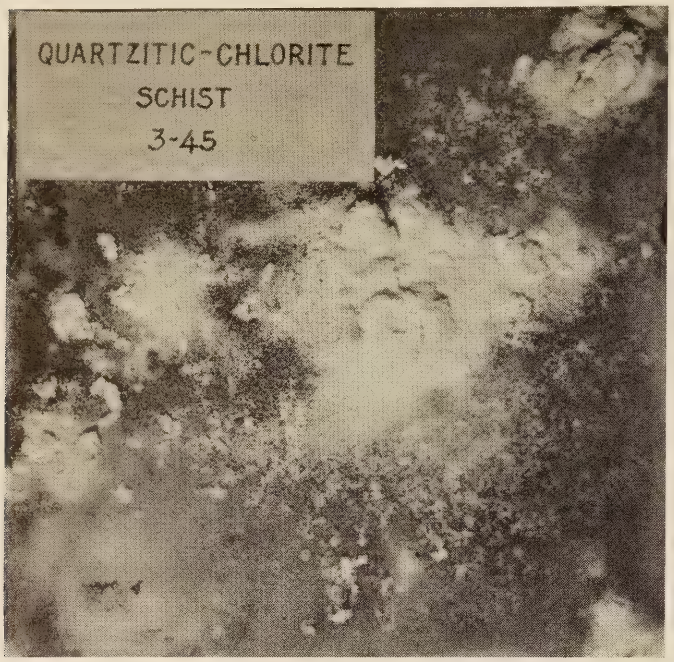

Figure 2.—Reaction Product Formed With Quartzitic-Chlorite Schist After 63 Days in Caustic Solution. Cement Contained an Average of 0.92 Percent Total Alkalies.

and with one exception is an essential part of all California rocks identified as reactive.

For the tests reported herein, supplies of semiprecious and wood opal were purchased. As a matter of general interest the properties of this mineral as listed by Dana and Ford (7) are:

Mineral class:	Oxide
Composition:	$SiO_2\ nH_2O$, with percentage of water varying from 2 to 13 percent
Hardness:	5.5 to 6.5
Specific gravity:	1.9 to 2.3; when pure 2.1 to 2.2
Luster:	Vitreous
Color:	White, yellow, red, brown, green, gray, blue
Fracture:	Conchoidal
Crystal form:	Amorphous (colloidal)
Varieties:	Precious, fire-opal, wood-opal, hyalite, cacholong, milk-opal, hydrophane, * * *
Chemical properties:	* * * Soluble in hydrofluoric acid somewhat more readily than quartz; also soluble in caustic alkalies, but more readily in some varieties than in others.
Observations:	Opal is a non-crystalline, colloidal substance belonging to the group of the mineral-gels. It has been deposited at low temperatures from silica-bearing waters. It occurs in connection with many rock types, igneous, sedimentary, and metamorphic. It is found filling seams and fissures of igneous rocks * * * It occurs in some mineral veins and is deposited from many hot or warm springs. It is further formed during the weathering and alteration of many rocks.

The data developed in the investigation of the reaction between opal and cement are shown in table 1. Two variations of opal were tested for reactiveness under several different conditions. Samples of semiprecious opal placed in pats of high alkali cement produced reaction within 2 days, although in one instance a reaction product did not become evident until the 18th day. It was thought that the water content of the opal might explain its reactive characteristics. Three samples were heated in a test tube until the water was given off, as evidenced by change in color of the mineral, and the amount of moisture collected on the side of the test tube. Pats containing this dehydrated opal were stored in the caustic solution and moderate to heavy reaction was noted in 5 to 18 days. As far as could be determined, the reactive product from the dehydrated opal was in no way different from the hydrated or regular opal. Wood opal, tested under hydrated and dehydrated conditions, in general, produced similar results.

In further tests with wood opal three pats were made, each differing from the others in alkali content of the cement. Instead of regular tap water, the cement was mixed with one-half normal caustic solution such as was used in the soaking bath. After 220 days none of the opal showed any visible signs of reacting with any of the cements. The reason for this behavior is not completely understood at this time. However, it is probable that the caustic solution used as mixing liquid had a neutralizing effect. Possibly reaction is delayed and will commence at some future time.

The thought has occurred from time to time that the aggregates used in the pat test may react with the alkalies in the caustic solution instead of the alkalies in the cement. To investigate this possibility wood opal was used in three pats; one containing high alkali cement, the second a medium alkali cement, and the third a low alkali cement. All three pats were then immersed in distilled water. In 12 days the opal in the high alkali cement pat showed signs of reaction, and in 10 days the medium alkali cement and opal began to react. There were no signs of reaction in the low alkali cement pat at the end of 185 days.

In an effort to retard the reaction between opal and high alkali cement, a pat containing these ingredients was placed in a caustic solution and kept at a tempera-

Table 1.—*Results of tests with various samples of opal*

Varieties and sample	Alkalies in cement		Number of days in caustic solution to produce reaction indicated			
	Na_2O	K_2O	None	Slight	Moderate	Heavy
Semiprecious:	*Percent*	*Percent*				
A	1.13	0.02	--------	--------	2	4
B	1.13	.02	--------	--------	18	30
C	1.13	.02	--------	--------	5	--------
D	1.13	.02	--------	--------	--------	5
Semiprecious, dehydrated:						
A	1.13	.02	--------	--------	18	30
B	1.13	.02	--------	--------	5	--------
C	1.13	.02	--------	--------	--------	5
Wood:						
A	1.13	.02	--------	1	--------	2
B	1.13	.02	--------	1	--------	2
C	1.13	.02	--------	--------	3	--------
D	1.13	.02	--------	--------	--------	4
Wood, dehydrated:						
A	1.13	.02	--------	--------	--------	4
Wood [1]:						
A	1.13	.02	220	--------	--------	--------
B	.13	.22	220	--------	--------	--------
C	.10	.12	220	--------	--------	--------
Wood [2]:						
A	1.13	.02	--------	12	240	--------
B	(3)	(3)	--------	10	185	--------
C	.10	.12	185	--------	--------	--------
Wood [4]:						
A	1.13	.02	(5)	--------	--------	--------
Hyalite:						
A	1.13	.02	150	--------	--------	--------
B	.13	.22	150	--------	--------	--------

[1] One-half normal caustic solution (NaOH+KOH) used as "mixing water" in place of tap water.

[2] Pats stored in distilled water instead of caustic solution.

[3] The sum of the alkalies is 0.68.

[4] Pat stored in caustic solution at 45° C. for 30 days.

[5] Opal completely dissolved at end of 30 days (see fig. 3).

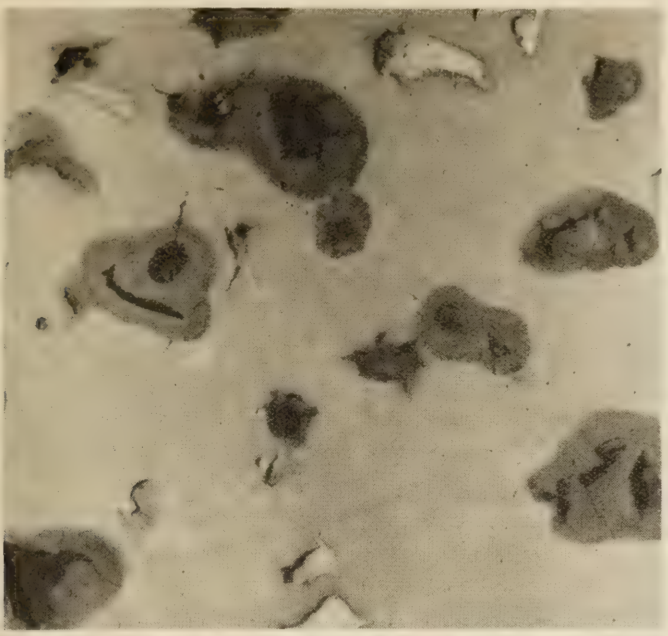

Figure 3.—Dissolving Effect of Caustic Solution Upon Wood Opal After 30 Days at 45° C. Cement Contained 1.13 Percent Na_2O and 0.02 Percent K_2O. Dark Areas Around Holes Are Moisture Remaining After Pat was Washed in Tap Water.

ture of 45° C. (113° F.) for 30 days. At the end of this period there was no typical reaction product such as usually was found, but the wood opal had been dissolved, so that upon washing the pat nothing remained except a mold or cast where the opal had been embedded. This condition is shown in figure 3. The dark spots around the cavities are moisture remaining from the washing operation.

Hyalite, a whitish translucent variety of opal, developed no signs of reaction after 150 days' storage in caustic solution.

To further investigate the reaction between opal and alkalies, a pat was made using a cement with a total alkali content of 1.15 percent and containing several pieces of wood opal. After curing for 24 hours, and after being removed from the mold, the pat was placed on a shelf in the moist closet. The temperature and humidity were 70° F. and 95 percent, respectively. In about 1 month the reaction product began to form. At times there was a jellylike globule at the junction point of the opal and the cement. Eventually this globule would dry, leaving a white precipitate in its place. The condition of this pat after 8 months storage in the moist closet is shown in figure 4. From all indications, it must be concluded that the opal reacts with certain ingredients in the cement, probably the alkalies. The results of these tests are not tabulated.

USE OF CEMENTS WITH DIFFERENT TOTAL ALKALI CONTENT

Considerable research has been carried out in connection with cements containing relatively high alkali content, and aggregates known to be reactive. The question arose regarding the reaction of cements of low alkali content. To investigate this problem several aggregates, all of which were suspected of being reactive, were made into pats and then immersed in caustic solution. The total alkali content of the cements used ranged from 0.19 to 1.15 percent. The results obtained with these cements are shown in table 2.

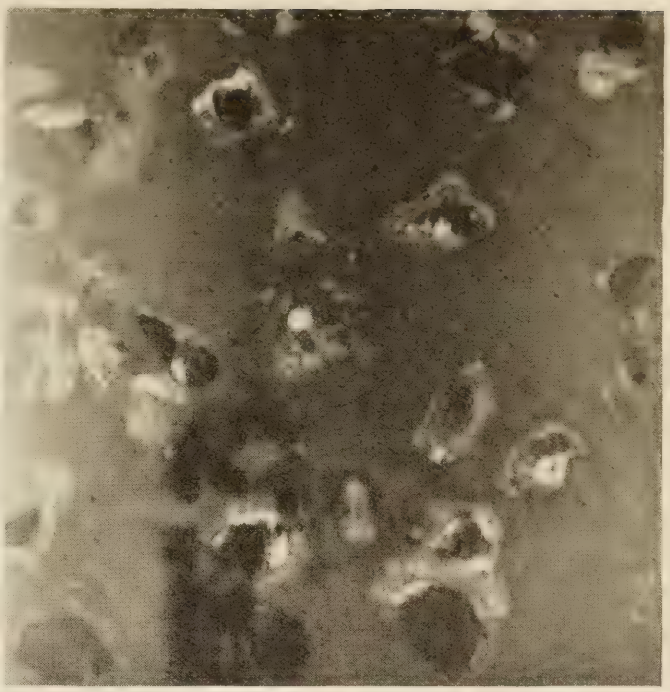

Figure 4.—Reaction Formed on Pat Prepared With Wood Opal and Cement Containing 1.13 Percent Na_2O and 0.02 Percent K_2O, After 8 Months' Storage in Moist Closet at a Temperature of 70° F. and a Humidity of 95 Percent.

Table 2.—*Results of tests using cements of high, medium, and low alkali content*

Aggregate	Alkalies in cement		Number of days in caustic solution to produce reaction indicated		
	Na_2O	K_2O	None	Slight	Heavy
	Percent	*Percent*			
Feldspar basalt	(1)	(1)		35	
	(2)	(2)		35	
Olivine basalt	(1)	(1)	63		
	(2)	(2)	63		
Tuffaceous rhyolite	(1)	(1)		35	63
	(2)	(2)		35	63
Sand, Burnt River [3]	1.13	.02		3	
	(4)	(4)		3	
	.10	.12		3	
Gravel, Burnt River [3]	1.13	.02		3	13
	(4)	(4)		3	13
	.10	.12		3	13
Sand, Toutle River [5]	1.13	.02		39	
	(4)	(4)		39	
	.10	.12		39	
Gravel, Toutle River [5]	1.13	.02		16	
	(4)	(4)		38	
	.10	.12		16	

[1] The sum of the percentages of alkalies is 0.92.

[2] The sum of the percentages of alkalies is 0.19.

[3] Contains rhyolite, granite, quartzite, basalt, quartz plus minor quantities of other rock types.

[4] The sum of the alkalies is 0.68.

[5] Contains basalt, andesite, rhyolite, felsite plus minor quantities of other rock types.

It was necessary in most cases to keep the specimens in solution longer than 5 days in order to develop reaction products. It is interesting to note that reaction was obtained with low alkali cement as well as with high alkali cement. Photographs of the reaction obtained by both low and high alkali cements with tuffaceous rhyolite are shown in figure 5.

In the case of sand and gravel from the Burnt River in Oregon and the Toutle River in Washington pats

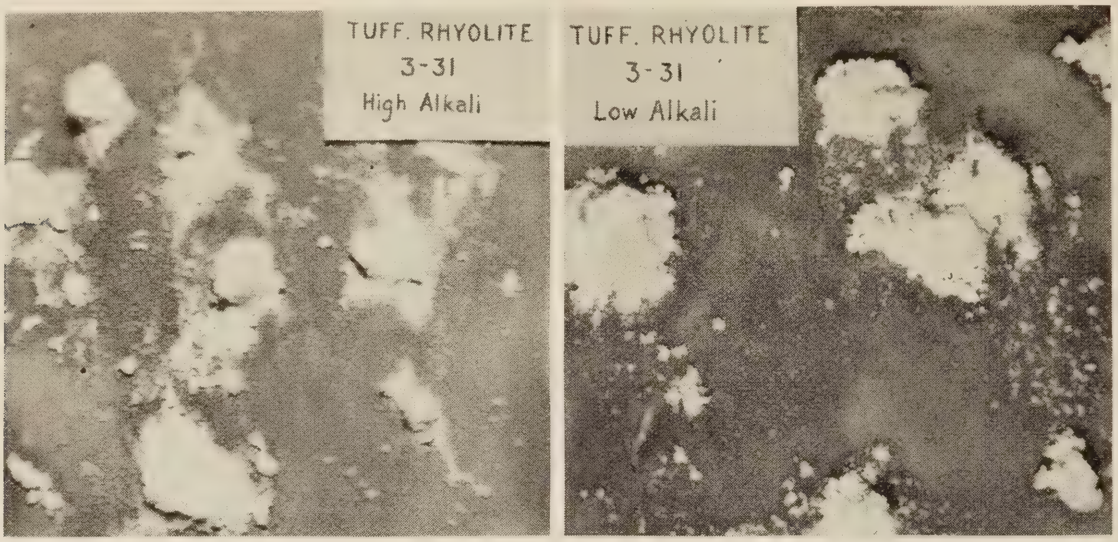

Figure 5.—Reaction Product Formed Using a High Alkali and a Low Alkali Cement with Tuffaceous Rhyolite, After 63 Days' Storage in Caustic Solution. The High Alkali Cement Contained an Average of 0.92 Percent Total Alkalies and the Low, 0.19 Percent.

were made using high, medium, and low alkali cements. In every instance reaction took place with each cement and aggregate. The aggregate from the Burnt River developed slight reaction at 3 days, while it took considerably longer for the aggregate from the Toutle River to react. In the latter case, the reaction was slight but, nevertheless, it was indicative that some reactivity could be expected when this aggregate and a cement containing at least 0.22 percent total alkali were used. Petrographic analyses of Burnt River and Toutle River aggregates show a preponderance of the igneous rock types, among which are basalt, rhyolite, felsite, and granite. According to available information these materials have a doubtful service record. The test results reported herein indicate that they will react unfavorably with cements low in total alkalies as well as with those containing relatively large amounts of total alkalies.

TESTS ON VARIOUS MINERALS

In an effort to identify the minerals reacting with high alkali cements, a number of minerals ranging widely in chemical composition were selected for tests. These minerals consisted chiefly of the feldspars, zeolites, and silicates with one fluorite, a carbonate, and a silicate containing beryllium. The complete list of minerals and the results obtained are shown in table 3. The feldspars and silicic minerals were included because of their suspected reaction, and connection with distress exhibited by concrete in which aggregate from the Platte River areas was used. The zeolites and remaining minerals were added in the hope that they might furnish some information regarding the reaction between minerals of certain chemical composition and the alkali content of cement. All of the minerals shown in table 3 were tested in pats containing high alkali cement which were in storage in the solution from 53 to 74 days. The reaction in every case was negative.

TESTS ON ROCK OF VARIOUS TYPES

In a further study of the pat test, it was decided to test various types of igneous, sedimentary, and metamorphic rock. With few exceptions, all the pats were made up with cement containing 0.92 percent total alkalies. The results obtained with these various rocks are shown in table 4.

Referring to table 4, it will be noted that only eight rocks developed any reaction products, and the length of time required to develop the reaction ranged from 3 to 65 days. Of the rocks in the igneous group that were reactive, two could be classed as acid type (obsidian and dacite), one of intermediate type (trachyandesite), and one of basic type (feldspar basalt), all based upon the probable silica content of the rock. It took 9 days for any reaction to develop in the case of the igneous rocks against 3 days for the metamorphic and 4 days for the sedimentary rocks. This difference in time may be due to the rock texture as well as to the mineral content of the rocks. Two of the igneous rocks classed as reactive have been identified as "altered," that is, some of the minerals in the rocks have been changed from their original composition, either by weathering or other means. Although there is nothing definitely conclusive about this feature, indications are present and it might be well to investigate completely before use, any aggregate that has been subject to weathering, especially if a high alkali cement is to be used with it. Figure 6 illustrates the reaction obtained with altered trachyandesite.

Referring to table 4, the materials identified as opaline chert and siliceous-magnesian limestone proved

Table 3.—*Results of tests on various minerals*

Mineral	Chemical composition [1]	Alkalies in cement		Number of days in caustic solution	Reaction produced
		Na_2O	K_2O		
		Percent	*Percent*		
Microcline	$K_2O.Al_2O_3.6SiO_2$	1.13	0.02	54	None.
Anorthite	$CaO.Al_2O_3.2SiO_2$	1.13	.02	54	Do.
Scolecite	$CaO.Al_2O_3.3SiO_2.3H_2O$	1.13	.02	54	Do.
Prehnite	$H_2Ca_2Al_2(SiO_4)_3$	1.13	.02	54	Do.
Calcite	$CaCO_3$	1.13	.02	54	Do.
Quartz	SiO_2	1.13	.02	53	Do.
Diatomite	Essentially SiO_2	1.13	.02	53	Do.
Chert (white)	SiO_2	1.13	.02	54	Do.
Chert (brown)	SiO_2	1.13	.02	54	Do.
Fluorite	CaF_2	1.13	.02	53	Do.
Beryl	$3BeO.Al_2O_3.6SiO_2$	1.13	.02	74	Do.

[1] The chemical compositions of the minerals are those given by Dana and Ford (7).

Table 4.—*Results of tests on igneous, sedimentary, and metamorphic rocks*

Rock type	Classification	Source	Total alkalies in cement	Number of days in caustic solution to produce reaction indicated			
				None	Slight	Moderate	Heavy
			Percent				
Obsidian	Igneous	Oregon	[1] 0.92			15	
Do	do	do	.92	65			
Vitreous basalt	do	do	.92	65			
Feldspar basalt	do	do	.92	65			
Trachyte	do	do	.92	65			
Altered trachyandesite	do	do	.92		9		65
Pumice	do	do	.92	65			
Do	do	do	.92	65			
Altered dacite	do	do	.92		35		41
Altered diabase	do	Washington	.92	65			
Granite	do	Arizona	.92	65			
Augite syenite	do	do	.92	65			
Olivine basalt	do	California	.92	65			
Tuffaceous rhyolite	do	Colorado	.92	65			
Feldspar basalt	do	New Mexico	.92		64		
Basalt	do	Wyoming	.92	65			
Do	do	do	.92	65			
Obsidian	do	do	[2] 1.15	65			
Do	do	do	[3] .22	65			
Gabbro	do	Virginia	1.15	64			
Opaline chert	Sedimentary	California	[1] .92		4		6
Siliceous-magnesian limestone.	do	do	.92		5		8
Porous sandstone	do	Oregon	.92		4		6
Argillaceous sandstone	do	Colorado	.92	65			
Conglomeratic sandstone	do	New Mexico	.92	65			
Pyroxene quartzite	Metamorphic	Colorado	[1] .92	65			
Quartzitic-chlorite schist	do	South Dakota	.92		3		5
Micaceous quartzite	do	do	.92	65			

[1] Three cements were blended for these tests. Average total alkali content, 0.92 percent. Range from 0.85 to 1.06 percent.

[2] Na_2O=1.13 percent, K_2O=0.02 percent.

[3] Na_2O=0.10 percent, K_2O=0.12 percent.

Figure 6.—Reaction Obtained in 65 Days With Cement Containing 0.92 Percent Total Alkalies and Altered Trachyandesite, an Igneous Rock Type.

to be very reactive, and the data of these tests correlate with the results obtained by the California Division of Highways. Photographs of the reaction developed by these two aggregates are shown in figure 7.

Porous sandstone developed a slight reaction in 4 days and a much heavier reaction in 6 days. The extent of the reaction after about 9 weeks in the caustic solution is shown in figure 8.

The only metamorphic rock, of the three tested, to develop any reaction was a quartzitic-chlorite schist. Here, the reaction was noticeable within a period of 3 days. Figure 2 shows the reaction at the end of 63 days.

Figure 7.—Reaction Obtained Using Opaline Chert and Siliceous-Magnesian Limestone With Cement Containing 0.92 Percent Total Alkalies.

RESULTS OF TESTS ON SAND AND GRAVEL

The results obtained by the pat test method with a number of commercial aggregates, mostly sands and gravels from different areas of the United States, are shown in table 5. Because of the interest evidenced in the disintegration of certain concrete roads in Nebraska, a number of aggregates from this region are included in the group shown in table 5. The table shows that only slight action was developed in four of the samples from Nebraska and the number of days necessary to produce this reaction ranged from 35 to 103. The evidence of the reaction for one aggregate, which is typical, is shown in figure 9. The only other material to develop reaction products, was the cherty sand from Tennessee. Here again the reaction was classified as slight and 63 days was necessary to produce it. There

Table 5.—*Results of tests of various types of sands and gravels*

Kind and mineralogical type of aggregate	Source	Alkalies in cement		Days in caustic solution to produce—	
		Na_2O	K_2O	No reaction	Slight reaction
		Percent	*Percent*		
Gravel:					
Siliceous	Scottsbluff, Nebr	(1)	(1)		103
Do	North Platte, Nebr	(1)	(1)		36
Do	Lexington, Nebr	(1)	(1)	90	
Do	Kearney, Nebr	(1)	(1)	90	
Do	Grand Island, Nebr	(1)	(1)		35
Do	Central City, Nebr	(1)	(1)	90	
Do	Columbus, Nebr	(1)	(1)	90	
Do	South Bend, Nebr	(1)	(1)	90	
Do	Oreapolis, Nebr	(1)	(1)		38
Do	Louisville, Nebr	(1)	(1)	90	
Sand:					
Siliceous	Platte River, Nebr	0.36	0.56	63	
Do	do	.26	.67	63	
Do	do	.26	.47	63	
Do	do	.19	.43	63	
Cherty	Estill Springs, Tenn	.36	.56		63
Do	do	.26	.67		63
Do	do	.26	.47		63
Do	do	.19	.43		63
Quartzitic	Long Island, N. Y	.36	.56	63	
Do	do	.26	.67	63	
Do	do	.26	.47	63	
Do	do	.19	.43	63	
Stone sand:					
Calcareous	Chicago, Ill	.36	.56	63	
Do	do	.26	.67	63	
Do	do	.26	.47	63	
Do	do	.19	.43	63	
Sand:					
Siliceous	Alexander, N. Y	1.13	.02	63	
Do	Albany, N. Y	1.13	.02	63	
Do	Alfred, N. Y	1.13	.02	63	
Do	Springville, N. Y	1.13	.02	63	

[1] The sum of the alkalies is 0.92 percent.

Figure 8.—Extent of Reaction Product Developed Between a Porous Sandstone and Cement Containing an Average of 0.92 Percent Total Alkalies, After 9 Weeks' Storage in Caustic Solution.

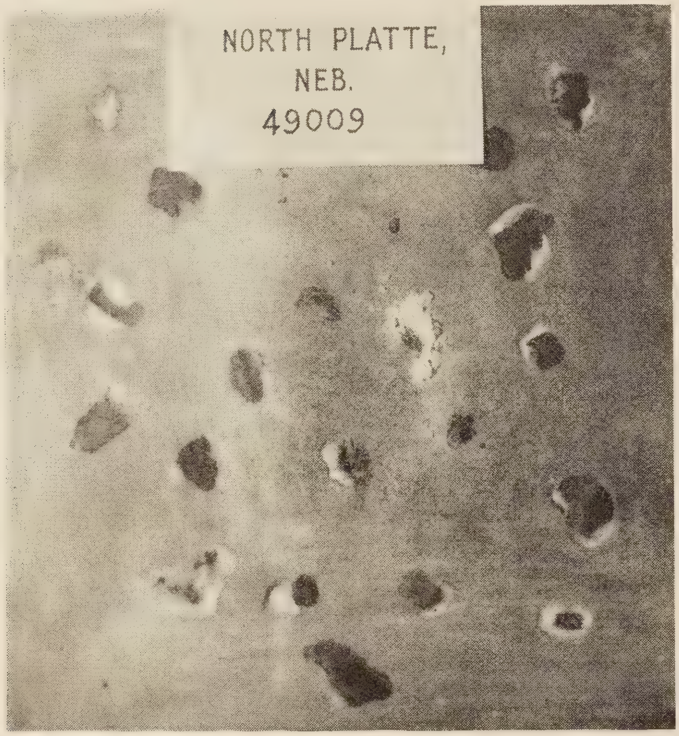

Figure 9.—Reaction After 36 Days in Aggregate From North Platte, Nebr. Cement Contained an Average of 0.92 Percent Total Alkalies.

is a possibility that the chert represented by this sample contains opaline silica, or some other form of silica may have been the active ingredient. The total alkali contents of the cements used in testing this aggregate ranged from 0.69 to 0.93 percent, so that they could be called medium to high alkali cements.

The stone sand from Chicago and the aggregates from New York State did not develop any reaction. The durability of these aggregates when used in concrete has been questioned. The fact that they developed no reaction products in the pat test, does not necessarily mean that they are free from suspicion.

INVESTIGATION OF AGGREGATES FROM PACIFIC NORTHWEST

Because of the disintegration of concrete in Washington and Oregon, and the widespread interest in the reaction between certain aggregates and cements it was decided to include aggregates and various cements from this immediate locality. The aggregates tested were produced mainly in Washington and Oregon and have been used for a number of years in pavement and bridge construction. With one exception, the cements used with the aggregates in this part of the investigation were produced in the northwest. The chemical analyses of these 12 cements are given in table 6. The specific surface fineness ranged from 1,590 to 1,930 sq. cm. per gm. The results obtained in this part of the investigation on reactive aggregates are shown in table 7. Five of the aggregates gave negative results with all 12 cements. Sand and gravel from the Cowlitz River in Washington, sand from Grandview, Wash., and both sand and gravel from the Toutle River in Washington, produced little or no reaction. However, table 2 shows that aggregate from the Toutle River with cement containing 1.15 percent total alkalies produced reaction in from 16 to 39 days. This aggregate was also used to develop the information given in table 7, but was used at a different time.

Table 6.—*Chemical analyses of cements used with aggregates from the Pacific northwest arranged in decreasing total alkali content*

Sample	SiO_2	$Al_2O_3+Fe_2O_3$	CaO	MgO	SO_3	Ignition loss	Insoluble residue	Na_2O [1]	K_2O [1]	Total alkalies	Specific surface
											Cm.^{2} *per gm.*
A	21.98	8.06	62.58	1.82	1.76	2.89	0.19	0.61	0.42	1.03	1,750
B	19.58	10.02	63.52	2.60	1.26	2.24	14	58	39	97	1,680
C	20.68	8.00	63.34	2.38	1.76	3.00	23	21	75	96	1,870
D	21.62	7.90	65.32	1.39	1.64	1.28	13	18	64	82	1,860
E	22.22	8.32	62.24	2.97	1.26	2.22	16	50	28	78	1,920
F	21.42	8.70	64.22	1.96	1.25	1.51	14	52	22	74	1,600
G	22.18	7.62	64.02	1.88	1.46	2.56	15	49	23	72	1,590
H	22.76	6.84	66.08	0.78	1.93	1.33	15	22	45	67	1,790
I	20.98	9.50	64.56	2.14	1.53	1.17	06	46	14	60	1,800
J	24.50	4.94	66.26	1.18	1.56	1.26	09	25	27	52	1,930
K	23.46	7.00	64.78	1.64	1.56	1.01	20	13	22	35	1,680
L	21.98	7.44	65.12	2.14	1.78	1.50	23	11	16	27	1,780

[1] A. S. T. M. Method C 114-40 used in determining these oxides.

A possible reason for some of the negative results indicated in table 7 for certain of the cements may have been the small amount of the reactive material in the entire sample as submitted to the laboratory.

The greatest amount of reaction seems to have taken place in the aggregate from Pocatello, Idaho; the White River in Washington; Dixie School, Oreg.; and the Burnt River in Oregon. Four of these aggregates developed a reaction with all 12 cements while in the combinations of the other 3 aggregates with the 12 cements there were only 9 which failed to develop a reaction. It will be recalled that the total alkalies of the cements ranged from 0.27 to 1.03 percent (see table 6). This indicates that certain aggregate types will react with low alkali cements as well as with high alkali cements. This is shown clearly in figure 10, where the extent of the reaction is very marked for all 12 cements. Petrographic analyses indicate that in general the aggregates showing reaction contained one of the following minerals: Quartz, rhyolite, basalt, felsite, granite, limestone, and sandstone. In view of the wide variation in the mineral content, it is a very difficult matter to discredit any one type of aggregate. Much research remains to be done with minerals and rock of definite types before final conclusions can be reached.

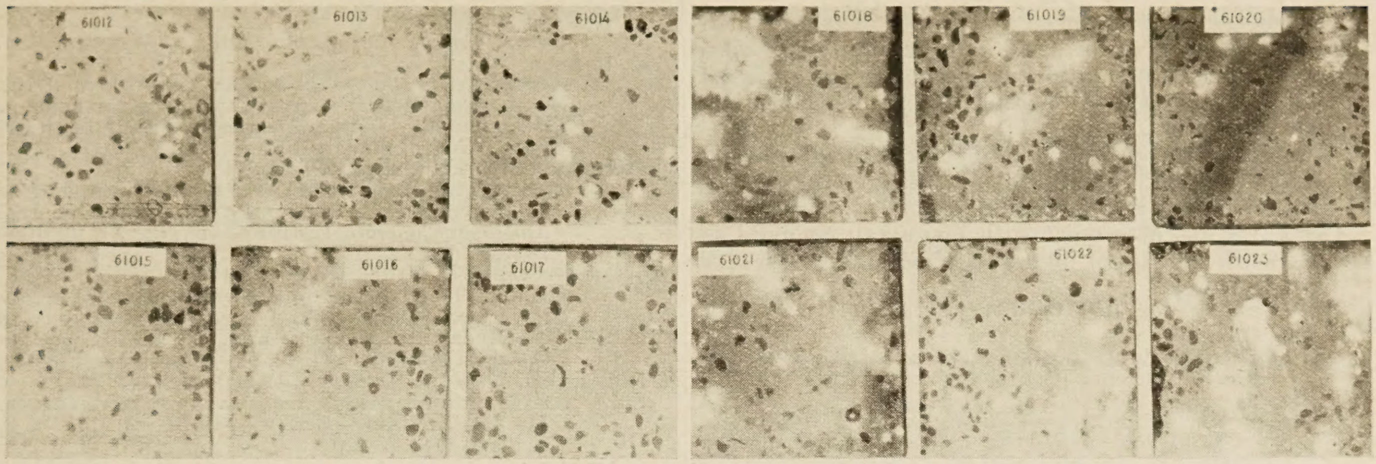

Figure 10.—RESULTS OF PAT TESTS USING 12 DIFFERENT CEMENTS WITH SAND FROM POCATELLO, IDAHO, AFTER 40 DAYS IN CAUSTIC SOLUTION. ALKALI CONTENTS OF CEMENTS RANGED FROM 0.27 TO 1.03 PERCENT.

TABLE 7.—*The extent of reaction on aggregates using cements of different alkali content after 40 days in caustic solution* [1]

Material	Source	Total alkalies in cements											
		1.03	0.97	0.96	0.82	0.78	0.74	0.72	0.67	0.60	0.52	0.35	0.27
Rock	Spray, Oreg	N	N	N	N	N	N	N	N	N	N	N	N
Sand	Pocatello, Idaho	M	M	M	S	M	M	M	S	S	S	M	M
Gravel	do	S	S	M	M	S	M	M	M	S	S	N	S
Sand	Cowlitz River in Washington	S	S	S	S	S	S	S	S	S	S	S	S
Gravel	do	S	VS	VS	N	S	S	N	S	N	N	N	N
Sand	White River in Washington	H	M	M	H	M	M	M	M	M	M	H	M
Gravel	do	M	H	H	H	M	M	M	H	S	M	H	H
Sand	Grandview, Wash	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS
Gravel	do	N	N	N	N	N	N	N	N	N	N	N	N
Rock	Dixie School, Oreg	H	M	H	S	H	H	H	H	H	M	M	H
Sand	Burnt River in Oregon	S	M	S	M	N	S	M	M	S	M	VS	VS
Gravel	do	N	M	N	VS	VS	N	M	N	VS	N	N	N
Sand	Toutle River in Washington	VS	VS	N	VS	VS	N	VS	N	VS	VS	N	N
Gravel	do	N	N	VS	VS	VS	S	N	VS	N	N	N	N
Gravel	Spokane, Wash	N	N	N	N	N	N	N	N	N	N	N	N
Sand A	do	N	N	N	N	N	N	N	N	N	N	N	N
Sand B	do	N	N	N	N	N	N	N	N	N	N	N	N

[1] Reaction classified as: N=none; VS=very slight; S=slight; M=moderate; H=heavy.

MISCELLANEOUS TESTS

In the search for a clue as to the nature of the reaction product presumed to be formed by aggregate and alkalies, a pat of high alkali cement (1.15) was made in which were embedded pieces of wood opal. After proper curing, the pat was one-half immersed, in a horizontal position with aggregate particles on top of pat, in caustic solution and stored for about 8 months. At the end of this period, a heavy, sirupy, gelatinous material covered approximately two-thirds of the top of a 3- by 3-inch pat. Some of this gel was carefully removed and a chemical analysis made. The results are given below:

	Percent
SiO_2	66.5
Na_2O	19.8
K_2O	12.1
$Fe_2O+Al_2O_3$	0.9
CaO	0.4
MgO	0.3
Total	100.0

The analysis indicates that the gelatinous material is a silicate of sodium and potassium. It seems from all indications that the reaction gel may have been formed by one of three combinations, as follows: (1) Opal plus alkalies in cement; (2) opal, alkalies in cement, and caustic solution; and (3) opal plus caustic solution.

From the high silica content of the gel, there can be no doubt as to the source of this ingredient. Since the pat was only half immersed in the caustic solution, the sodium and potassium must have been derived largely from the alkalies in the cement, aided possibly by a small portion of the alkalies in the solution itself.

CONCLUSIONS

From the data obtained in this investigation and considering the test conditions, the following conclusions appear to be warranted:

The pat test is of little value as a short time laboratory test method for identifying reactive aggregates except in the case of opal-bearing materials. The test has value in detecting the presence of opal thereby indicating that further tests should be made to determine the degree of reactivity with any given cement. To be of diagnostic value for other than opal-bearing aggregates, the test period must be considerably more than 5 days.

Certain varieties of opal, such as wood opal and semiprecious opal are reactive with high alkali cements. Dehydrating the opal fails to delay its reaction with cement appreciably.

The pure silicon dioxide minerals, such as quartz, do not produce reaction when tested with high alkali cements.

Reaction has been found to take place in certain aggregates of types of the igneous, sedimentary, and metamorphic rock.

No reaction was produced in 220 days between wood opal and cements of low, medium, or high alkali contents when caustic solution in the concentration used in this test was used as "mixing water" instead of the regular tap water.

Analysis of the reaction product developed between wood opal and high alkali cement indicates that it is a silicate of sodium and potassium.

Certain aggregates react with low alkali cements as well as with cements of high alkali content.

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(*Continued from p. 46.*)

The following conclusions appear justified on the basis of the performance of the various test sections prior to construction of the bituminous wearing surface.

Surface defects such as corrugations, raveling, pitting, scaling, and potholing occurred on all sections regardless of thickness or physical properties of the mixtures. Resistance to abrasion on sections having plasticity indexes from 7 to 10 was no greater than on the sections having plasticity indexes of 4 to 6.

Surface wear resulting from the action of traffic amounted to about three-fourths inch per year.

A stabilized layer 1 inch thick cannot be satisfactorily maintained as a surface course when resting on the heavy clay typical of this road.

A 2-inch wearing surface on the heavy clay is likely to be worn out completely after 1 year of service owing to the fact that following the loss of 1 inch by traffic abrasion, the remaining 1 inch may soon be displaced in the manner described for section 1.

Stabilized sand suffers greater losses from abrasion than stabilized gravel.

The behavior of the reconstructed test sections when used as a base course seem to warrant the following conclusions:

A thin bituminous wearing surface such as the double blotter type seal requires a base course having a thickness of at least 8 inches to provide adequate support under the conditions of traffic, climate, and soils typical of this road.

With respect to the use of thicker bituminous surfaces, it was indicated that a re-treatment might have prevented the slight deformation and cracking starting to occur on section 7, which had a base thickness of 6 inches. The performance of the test sections constructed on the old bituminous mat, which was approximately 2 inches thick, suggests that a combined thickness of wearing course and base course amounting to 8 inches is required to give satisfactory service on the highly plastic clay soils of the Red River Valley. There was no definite indication that a lesser thickness would prove adequate on the relatively less plastic, lighter textured soils found on the eastern portion of the experiment.

It was clearly demonstrated that the service behavior of a stabilized sand base course was equal in every respect to that of a stabilized gravel base of the same thickness.

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