ANALYSIS OF DATA FROM CONDITION SURVEYS OF A CONCRETE PAVING IN WHICH CHAT WAS USED AS COARSE AGGREGATE

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PREFACE

This thesis, which is being submitted, is an attempt to arrange and analyse the data accumulated by the Department of Highways of the State of Oklahoma during the first ten years of the life of a Concrete Paving in which Chat was used as coarse aggregate.

The period during which this data was accumulated was the ten years from 1936 to 1946. The data consisted of thirteen condition surveys, eleven of these surveys were made in the period from September, 1936 to May, 1941. The twelfth survey was made in December, 1942 and the last survey on this project was made during October in 1945.

This pavement was constructed as a joint research project of the Bureau of Public Roads and the Department of Highways of the State of Oklahoma. The primary object was to determine the desirability of making concrete with both fine and coarse aggregate produced in the Tri-State area of northeast Oklahoma, southeast Kansas, and southwest Missouri, when using either river sand or jig sand from this area as fine aggregate.

In addition to the usual construction records and supervision by the field forces of the Construction Department, personnel of the Materials Laboratory was assigned to this project and many additional tests were made and many special records were kept.

Before construction was started, the materials to be used were investigated in the laboratory and the various concrete mixes were designed.

The laboratory work and the securing of the data used in this analysis was done under the direction of Mr. Carl R. Reid, Materials Engineer for the Oklahoma Department of Highways.

The preliminary material investigation and mix design, as well as the laboratory field inspection and many of the condition surveys, was in direct charge of Mr. Bill Dale, Laboratory Assistant.

The writer made the last three condition surveys on this project and has also made two progress reports as a part of the research. The first report was made in February, 1942, and a second report in March, 1946.

This review and analysis is made as a final report on this project.

TABLE OF CONTENTS

ANALYSIS OF DATA FROM CONDITION SURVEYS OF A CONCRETE PAVING IN WHICH CHAT WAS USED AS COARSE AGGREGATE

THE VALUE OF PRESERVING STATISTICAL DATA FROM ENGINEERING PROJECTS:

The Chat Concrete Paving, which is the subject of this report, was Federal Aid Project 149C. This paving was an active research project during its first ten years of service.

The practicing engineer seldom has the opportunity to closely follow the work he builds through a ten year period after construction has ended.

It is unfortunate that long time observation of structures in service is the exception rather than a standard practice, for the plans and specifications are only dreams until the tests of time and service can prove the dream came true.

The final proof of theory lays all about us in the aging projects that once absorbed our interest.

Advancement in engineering is more often sought in theory than in statiscal data, possibly because there is a tendency among engineers to consider engineering an exact science. More consideration should be given to the fact that there are professions, which are respected and admired for their progress and advancement, in which equations are the exception rather than the rule.

The medical profession which deals with nature, as does engineering, owes much of its advancement to the data accumulated in its records. If records could be kept of engineering cases, as the hospitals keep them for medical cases, the answer to many unsolved engineering problems would be indicated to the engineers as facts are disclosed to the doctor by the evidence of the records he has kept.

In an effort to adopt a medical approach to one engineering case, to examine an unusual accumulation of data and salvage some small part of the truth that must be contained in them, and above all, to preserve the data that it will be available for others to examine, this analysis has been made.

DESCRIPTION OF THE PROJECT:

The project from which the data was obtained included 30,172 feet of concrete paving twenty feet in width. This paving is of Bates type section, having a seven inch thickness with a ten inch thickened edge. The work on this project was done by the Lewis Construction Company during the early summer of 1936. W. Carl Brown was Resident Engineer for the Department of Highways.

The paving which is included in this project was divided into two principal sections. The west 15,436 feet was designed as an experimental project to determine the suitability and practical use of mine chats and crushed flint as coarse aggregate, with river sand or jig sand as fine aggregate.

On the experimental part of this project, fifty-six different concrete mixes were placed during construction.

Double notched non-extruding metal shield expansion joints, one-half inch in width were used. The joints were spaced at thirty foot intervals and were sealed with a one-half inch depth of asphaltic joint seal.

Some of the sections were built with a one inch open textured sand cushion beneath the paving. On these sections, longitudinal French drains were placed along the edges of the concrete and French drain outlets were provided.

The non-experimental part of this project was 14,736 feet in length, and only one type of aggregate was used in the concrete. No sand cushion was placed on this part of the project and no French drains were necessary.

This non-experimental part of the project has not been considered in this analysis.

Concrete Mixes:

The materials used in the concrete mixes were Ada Cement, Arkansas River sand, Miami Jig sand, Miami Crushed Flint, and Miami Chat.

Three gradings of chat and one grading of crushed flint boulders were used as coarse aggregate. For fine aggregate, two gradings of river sand and one of jig sand were used.

The project was divided into six principal sections by the combination of aggregates used in the concrete. Four cement factors were used for each combination of aggregates.

For the purpose of this discussion, flint boulders are considered to be a sedimentary rock from this area, dark gray to black in color, composed essentially of minutely-crystalline silica. Chat is considered to be the material found intimately mixed with the lead-zinc ores of the tri-state area. Chat closely resembles chert and is blue gray or white in color. Jig sand is chat finely ground to sand sizes for the purpose of extracting the ore.

The grading specifications of the aggregates are shown in Table No. 1.

TABLE NO. 1

GRADING SPECIFICATIONS FOR AGGREGATES

CRUSHED FLINT:

Pass 2-1/2" Round Screen	100%
Pass 1-1/2" Round Screen	60-95%
Pass 1" Round Screen	40-75%
Pass 1/4" Round Screen	Not over 5%

NUMBER 1 CHAT:

Pass 3/4" Round Screen	100%
Pass 1/4" Round Screen	30-35%
Pass No. 10 Sieve	Not more than 10%

NUMBER 2 CHAT:

Pass 3/4" Round Screen	100%
Pass 1/4" Round Screen	46-51%
Pass No. 10 Sieve	Not more than 20%

NUMBER 3 CHAT:

Pass 3/4" Round Screen	100%
Pass 1/4" Round Screen	Not more than 5%

JIG SAND: Fine ground mine chats, which conform to the following specifications:

Pass 1/4" Round Screen	100%
Pass No. 20 Sieve	75-85%
Pass No. 50 Sieve	12-22%
Pass No. 100 Sieve	Not more than 5%

Description of Concrete Mixes:

On this project there were six general types of mixes in regard to the type of aggregate used. These general types were designated by the letters A, B, C, D, E, and F. For each general type of mix, four different cement factors were used. These twenty-four mixes were varied by changes in the water cement ratio and sand void ratio, which resulted in a total of fifty-six different mixes being used on this project.

The six general types of mixes by the aggregates used were: "A" River Sand and No. 3 chats; "B" Jig Sand and No. 3 chats; "C" River Sand and No. 2 chats; "D" Jig Sand and No. 1 chats; "E" River Sand and No. 1 chats; and "F" River Sand and No. 1 chats and crushed flint rock. In each of these general types of mix, the four different cement ratios were used. Variations of the water cement ratio were in general such as to increase the effect of added cement. Sand void ratios were changed frequently in each type, but many of the changes are minor.

The principal mix types are shown in Table No. 2.

TABLE NO. 2

PRINCIPAL TYPES OF CONCRETE MIXES

SEC. NO.	Station to Station	Water Gals Per Sack	Cement Bbls. Per C. Y.
	(A) River Sand and Washed & Screened Chats. Grading No. 3		
1	21 + 26 to 15 + 19	6.34	1.65
2	15 + 19 to 9 + 08	6.25	1.60
3	9 + 08 to 3 + 20	6.39	1.55
4	3 + 20 to 467 + 67	6.60	1.50
	(B) Jig Sand and Washed & Screened Chats. Grading No. 3		
5	467 + 67 to 461 + 24	7.63	1.65
6	461 + 24 to 454 + 86	7.74	1.60
7	454 + 86 to 448 + 49	7.82	1.55
8	448 + 49 to 440 + 87	7.83	1.50
	(C) River Sand and Washed & Screened Chats. Grading No. 2		
9	42 + 84.4 to 36 + 71	6.6	1.65
10	36 + 71 to 30 + 61	6.66	1.60
11	30 - 61 to 26 + 18	6.77	1.55
12	26 + 18 to 21 + 26	7.00	1.50
	(D) Jig Sand and Washed & Screened Chats. Grading No. 1		
13	440 + 87 to 434 + 81	7.87	1.65
14	434 + 81 to 428 + 39	7.97	1.60
15	428 + 39 to 422 + 19	8.22	1.55
16	422 + 19 to 415 + 30	8.33	1.50
	(E) River Sand and Washed & Screened Chats. Grading No. 1		
17	415 + 30 to 409 + 37	6.4	1.65
18	409 + 37 to 403 + 29	6.27	1.60
19	403 + 29 to 397 + 23	6.77	1.55
20	397 + 23 to 391 + 05	6.84	1.50
	(F) River Sand and Washed & Screened Chats. Grading No. 1 Crushed Flint		
21	391 + 05 to 384 + 99	5.7	1.65
22	384 + 99 to 378 + 87	5.79	1.60
23	378 + 87 to 371 + 84	5.92	1.55
24	371 + 84 to 366 + 67	6.25	1.50

DISCUSSION OF CONDITION SURVEYS:

The condition surveys, from which the data used in this analysis was obtained, were made by walking over the project.

The paving was closely inspected and each crack was drawn in a note-book and its length and location recorded. Notations were made of other features, such as the condition of the joints and pumping slabs. Some measurements were made of the expansion and contraction of the joints. Surveys were made approximately twice a year for the first five years.

Longitudinal cracking, pumping joints and cracks, and other indications of pavement deterioration were only occasionally found on this project. The principal feature observed was transverse cracking. This type of cracking was found in varying intensity throughout the project and in practically all sections and mixes of concrete. It is for this reason that the intensity of transverse cracking has been used in making this analysis.

Description of Typical Cracks:

Most of the cracks on this project are of one general type. This typical crack is a transverse crack at the approximate mid-point between expansion joints at right angles to the centerline of the pavement. These cracks may extend either halfway or entirely across the roadway. The history of the development of these cracks, as shown by surveys made from time to time since the completion of the project, is that they may start either at the centerline or at the edge of the pavement. They may lengthen either rapidly or slowly. Sometimes between surveys, a new crack will develop entirely across the pavement. Other cracks may gradually grow in length over a period of several years.

Where the initial crack is only in one-half of the pavement, there is a tendency for the crack to extend across the centerline and across the other side of the paving. Sometimes both sides of the pavement will develop cracks at about the same time. They may join at the centerline or be several feet apart. When they fail to meet at the centerline, there is a tendency for each to cross to the other side and form two complete cracks across the pavement.

As a general thing, the cracks are open, sometimes as much as one-half inch. The percentage which the number of lineal feet of this type of crack, half or all the way across the roadway, is of the total lineal feet of cracking in the various principal sections, is shown in the following table.

TABLE NO. 3

FREQUENCY OF TYPICAL CRACKS

In Section A	75%
In Section B	89%
In Section C	92%
In Section D	61%
In Section E	90%

Because these cracks are located in the middle third of the slab between the joints, it seems very probable that the typical crack on this project is a contraction crack.

Data Used in Analysis:

The data used for this analysis consisted of the lineal feet of transverse cracking per one thousand feet of paving calculated for each survey and for each of the fifty-six sections which contain the same concrete mix.

A table containing this data follows:

TABLE NO. 4

Condition Survey Data — Lineal Feet of Cracking Per 1000 Ft. of Slab

Survey Number		1	2	3	4	5	6	7	8	9	10	11	12	13
Date of Survey		9-20-36	4-21-37	9-14-37	8-5-38	12-12-38	5-22-39	11-10-39	5-14-40	11-18-40	5-26-41	11-13-41	12-15-42	10-23-45
Months Since Previous Survey		0	7	4	11	4	6	5	7	6	6	5	13	45
Age of Paving in Months		4	11	15	26	30	36	41	48	54	60	65	78	45
Principal Section	Mix Section	Total Per 1000'	Total Per 1000'	Total Per 1000'	Total Per 1000'	Total Per 1000'	Total Per 1000'	Total Per 1000'	Total Per 1000'	Total Per 1000'	Total Per 1000'	Total Per 1000'	Total Per 1000'	Total Per 1000'
A	1-1	0	75	75	107	107	133	200	240	240	240	293	367	427
A	1-2	0	0	0	45	45	110	118	129	147	147	173	173	186
A	2-1	0	16	16	16	49	65	65	65	90	90	111	111	123
A	3-1	0	121	182	182	244	305	305	305	305	305	354	354	415
A	3-2	0	143	239	239	239	316	316	316	383	383	421	421	421
A	3-3	0	47	93	93	93	93	93	93	93	107	107	107	102
A	4-1	0	0	0	0	0	0	0	0	16	16	16	56	72
A	4-2	0	0	0	0	0	0	0	0	0	0	0	0	0
A	4-3	0	0	0	124	144	157	157	202	202	202	232	251	270
B	5-1	0	0	0	0	0	0	0	0	0	0	5	5	58
B	5-2	0	0	0	0	0	0	0	0	0	0	0	0	53
B	6-1	0	0	0	0	0	0	0	0	0	0	0	0	63
B	6-2	0	0	0	0	0	0	0	0	0	0	0	0	120
B	6-3	0	0	0	0	0	60	120	239	239	239	263	263	300
B	6-4	0	0	0	0	0	42	42	42	42	42	42	42	83
B	7-1	0	0	0	0	0	0	0	0	0	0	26	39	269
B	7-2	0	0	0	0	0	0	30	30	30	30	39	69	96
B	8-1	0	0	0	0	0	0	0	0	0	0	0	29	147
B	8-2	0	24	24	24	24	24	24	24	24	24	28	83	142
C	9-1	0	0	0	0	0	0	0	0	0	0	0	0	0
C	9-2	0	0	0	0	0	60	60	60	60	120	120	120	120
C	9-3	0	0	0	0	0	0	163	163	163	163	163	163	163
C	9-4	0	0	0	0	0	51	51	51	51	51	51	51	103
C	10-1	0	0	94	94	148	155	155	155	155	155	155	173	173
C	10-2	59	136	224	366	513	513	513	522	522	522	543	572	587
C	11-1a	0	0	145	145	145	145	145	145	168	168	197	292	365
C	11-1b	0	0	0	0	164	164	164	164	164	164	164	164	164
C	11-2	0	0	0	0	54	54	54	54	54	54	54	163	163
C	12-1	0	0	168	168	184	184	210	210	210	210	210	210	210
C	12-2	0	0	67	155	155	155	155	155	218	238	285	415	415
C	12-3	0	0	98	132	147	167	206	220	220	220	220	245	274
D	13-1	0	0	0	0	0	0	0	114	114	114	201	307	438
D	13-2	0	0	0	0	0	0	0	58	64	64	64	64	129
D	13-3	0	0	0	0	0	0	0	0	0	0	0	55	55
D	14-1	0	0	0	0	0	0	0	0	0	0	0	6	161
D	14-2	0	0	0	0	0	0	0	0	0	15	27	42	136
D	15-1	0	0	0	0	0	0	44	44	88	88	88	111	177
D	15-2	0	0	0	0	0	0	0	0	0	0	0	0	333
D	15-3	0	0	0	0	0	0	0	0	0	0	56	82	168
D	16-1	0	0	0	0	0	0	0	0	0	0	0	39	328
E	17-1	0	0	0	0	60	212	254	347	347	347	377	377	538
E	17-2	0	0	0	0	0	170	254	279	309	309	347	398	470
E	17-3	0	0	0	83	83	83	165	206	231	248	331	331	413
E	18-1	0	0	0	0	0	0	0	110	329	329	329	329	330
E	18-2	0	0	0	0	0	0	19	29	29	29	33	43	60
E	19-1	0	66	99	231	231	231	289	314	351	351	432	460	460
E	20-1	0	28	76	193	266	292	323	346	362	367	400	406	474
F	21-1	0	54	104	140	314	347	371	406	406	427	465	474	487
F	22-1	0	223	283	336	361	472	545	545	545	583	627	654	721
F	22-2	0	0	43	303	549	549	667	680	680	680	732	732	800
F	23-1	0	0	176	536	536	536	603	603	603	635	724	724	741
F	23-2	0	0	92	250	250	276	286	286	286	341	341	364	429
F	23-3	0	0	328	328	376	376	425	445	445	445	473	473	548
F	24-1	0	0	0	246	285	314	314	314	332	361	421	457	468
F	24-2	0	0	0	58	58	58	84	84	84	97	118	160	219

FUNDEMENTAL ASSUMPTIONS AND EVIDENT FACTORS:

Because of the many factors entering into the life of a pavement, it seems that in order to indicate any opinion developed from this data, it is necessary to first make some assumptions in regard to the cracking of pavement. There is much in the data and in the grouping or arrangement of it that would not agree with the following things which have been assumed.

It has been assumed that the major causes of cracking on this project are:

Density of traffic and size of loads.

Soft spots in the subgrade.

Expansion of the pavement.

The type of subgrade soil.

Water in the subgrade.

The using or not using of a sand cushion.

The quality of the concrete.

It has been assumed that the total cracking would indicate the total of the above factors; also that the average cracking of groups of sections of paving, which were similar as to mix, soil, aggregate, and other features, would tend to eliminate the exception and would represent the condition of that group.

There are many things that enter into the progressive cracking of a pavement. The condition surveys definitely show that cracking was not the same intensity throughout the project. Therefore, conditions that prevail uniformly throughout the project can be of little help in determining the reasons for the difference in cracking. The density and type of traffic may be eliminated for this reason.

The expansion devices were also a constant factor throughout the project. The efficiency of the expansion device would be tested soon after construction of the pavement, and cracks caused by its failure to function would reach a maximun early in the life of the pavement, probably after a few cycles of summer heat and winter cold. Once a section had one crack across the pavement, there would be much less tendency to crack again between these two expansion joints. Though the expansion device has not proved to be efficient, the difference in cracking must be for other reasons.

As the joints on this project have been open to water most of the time since it was constructed, the open joints would also be a constant factor in all sections and would only serve to emphasize the susceptibility of the various soils to lose stability or develop volume changes and overstress the slab.

Soft spots in the subgrade, caused by other reasons than water content, would, in most cases, show themselves early in the life of the pavement. The frequent condition surveys did not disclose any localized areas of damage or settlements of the paving, and we may assume that loose subgrade was not a factor.

The records of this project do not indicate that ground water, such as springs, seeps, or wet spots in the subgrade, were found during construction, or later, and this type of defect need not be considered.

The stability of a soil depends on its moisture content. Rain water might be a factor by reason of its effect on the stability of the different types of soil in the subgrade. In dry weather, the difference in cracking in a good soil and a poor soil might not be evident. It is during the periods of the greatest rainfall that the greatest difference would be found. Besides rain and snow, open joints and sand cushion would also effect the quantity of moisture entering and retained in the subgrade.

ANALYSIS OF DATA FROM THE FIRST ELEVEN CONDITION SURVEYS:

When the project was sixty-five months old, an analysis was made of the data contained in the first eleven condition surveys.

An opinion gains value as it gets older, if the passing of time and the changes it brings continue to produce conditions that still point to the same opinion.

It is for this reason that the following grouping of sections and discussion of the tables is given as it was in the progress report made in 1942.

GROUPING OF SECTIONS BY SUBGRADE SOIL TYPES:

The grouping of the sections by the subgrade soil types divides them into groups with a greatly different intensity of cracking.

TABLE NO. 5

AVERAGE LINEAL FEET OF CRACKING PER 1000 FEET OF PAVING FOR THE SUBGRADE SOIL TYPES

Subgrade Soil Type	Number of Sections	Average Lineal Ft. of Cracking
A-2	25	91
A-4	12	201
A-7	19	325

This table shows that there is a difference in the cracking of the pavement on the various types of subgrade soil.

As was to be expected, the better soils have the least cracking. Since the type of subgrade soil seems to be such a large factor, future comparisons will, as far as possible, be made between those sections having the same type of subgrade and the same general type of concrete mix.

SECTIONS GROUPED IN REGARD TO THE USE OF SAND CUSHION:

TABLE NO. 6

AVERAGE LINEAL FEET OF CRACKING IN REGARD TO THE USE OF SAND CUSHION

Subgrade Soil Type	Type of Mix	Total No. of Sections	With Sand Cushion No. of Sections	With Sand Cushion Average Cracking	Without Sand Cushion No. of Sections	Without Sand Cushion Average Cracking	% Increase in cracking without Cushion
A-7	C	9	6	172	3	138	25
A-7	E	2	2	416	0	None	-
A-7	F	8	8	487	0	None	-
A-4	A	9	6	243	3	85	183
A-4	C	3	2	252	1	210	12
A-2	B	10	0	None	10	40	-
A-2	D	10	1	27	9	49	Decrease
A-2	E	5	3	315	2	181	74

This table gives rather consistant results. The only exception to the statement that all sections without sand cushion show better results than the similar sections with sand cushion, is the group having a "D" type mix on an A-2 soil.

The single section with sand cushion in this group is section D-16-2. Section D-13-1, which is one of the nine sections without sand cushion, had an average cracking of 201 lineal feet per one thousand feet of paving. This is twice as great as the next lowest in the group of "D" type mixes on A-2 soils without sand cushion, and is four times the 49 foot average of this group. The elimination of section D-13-1, would give an average for this group of 29 lineal feet.

In either case, it is indicated that on all types of subgrade soil and for all types of concrete mixes, the use of sand cushion increased the average cracking of the pavement with but the one exception.

THE EFFECT OF CENTER-LINE GRADES ON CRACKING:

The better drainage resulting from steeper centerline grades might be indicated by a decrease in cracking. The grades on this project are comparatively flat and this may be the reason that such a grouping gives little information.

Sections Grouped by Centerline Grade:

TABLE NO. 7

CENTERLINE GRADE AND CRACKING

Cracking Per 1000' of Paving	Centerline Grade 0 to .25	.25 to .50	.50 to 1.00	Over 1.00
0	3	1	5	1
0 to 49	0	1	4	4
50 to 99	1	0	4	0
100 to 199	3	2	4	0
200 to 299	1	1	4	1
300 to 399	0	0	2	4
400 to 499	1	0	5	0
500 +	1	0	3	0
TOTAL SECTIONS	10	5	31	10

It seems that about one-third of both the flat grades and steep grades have less than fifty feet of cracks per thousand lineal feet, and that there is a rather even distribution of all grades in both the good and bad sections. As stated above, this grouping gives little information.

Sections Grouped by Types of Aggregate Used:

TABLE NO. 8

GROUPING OF SECTIONS BY AGGREGATE TYPE

Aggregate Type	Average Cracking	Aggregate		Subgrade Soil Type	Use of Sand Cushion
		Sand	Chats		
B	40	Jig	No. 3	A-2	No
D	46	Jig	No. 1	A-2	9/10 No 1/10 Yes
C	180	River	No. 2	2/3 A-7 1/3 A-4	2/3 Yes 1/3 No
A	189	River	No. 3	A-4	2/3 Yes 1/3 No
E	321	River	No. 1	1/3 A-7 2/3 A-2	5/7 Yes 2/7 No
F	487	River	No. 1 and Crushed Flint	A-7	Yes

When considered by aggregate type, the sections are separated into groups with remarkably different intensities of cracking.

This would indicate that the aggregate was the principal factor having an influence on cracking. However, a further examination of the table will show that in this grouping we have, in a general way, also grouped the sections by subgrade soil type and as to whether they did or did not have sand cushion. It seems that there are four intensities of cracking indicated in the six types of mix. There is about 150 lineal feet difference in intensity of cracking separating the following combined groups of the B and D, the C and A, the E, and the F.

In general the B-D mixes are on A-2 subgrade and did not have sand cushion. The C-A mixes had sand cushion, the A mixes are in A-4 subgrade, and the C mixes are, in most cases, in A-7 soil. The E mix had sand cushion and the subgrade soil is mostly A-2. The mix with the greatest cracking, which is the type F, has an A-7 subgrade with sand cushion and is the only mix in which crushed flint was used as a part of the aggregate.

In this grouping the following things are indicated. There is little difference between the #1, #2, and #3 chats. Jig sand has given much better results than river sand, and the section using crushed flint had the greatest cracking.

Sand Void Ratio and Average Cracking:

The sand void ratio was changed in most cases for each of the four cement ratios used with each type of aggregate. There were also some cases where several sand void ratios were used with the same cement ratio. However, many of the changes were slight, and if the sand void ratio is averaged for each type of mix, the cracking and the sand void ratio do have this relationship. The two best types have the greatest average sand void ratio, and the two worst types have about the least average ratio, other than the type C, which would have to come between the E and F, the order of the average sand void ratio is the order of the average cracking. The sand void ratio used in the concrete mixes probably effected the cracking of the pavement.

The following table of mixes and average sand void ratio also seems to indicate that some of the mixes were under sanded.

TABLE NO. 9

CRACKING AND THE SAND VOID RATIO

Mix Type	Average Cracking	Average Sand Void Ratio
B	40	158
D	46	134
C	180	111
A	189	130
E	321	118
F	487	110

Cement Ratio and Water Cement Ratio:

In most cases when the cement factor was increased, the water cement ratio was decreased. The exceptions to this statement are not very numerous, nor very great. As a change in cement to increase the quality of the concrete is usually accompanied by a lowering of the water cement ratio, they may be considered as acting together. However, other factors seem to have about eliminated the effect of these changes.

A table follows showing the average cracking for each type of mix and each cement ratio.

TABLE NO. 10

AVERAGE CRACKING FOR THE DIFFERENT CEMENT RATIOS

Type Mix	Cement Ratio Bbls. per Cu. Yd.			
	1.65	1.60	1.55	1.50
A	238	111	294	81
B	3	76	32	14
C	82	349	138	238
D	88	14	48	14
E	351	181	432	400
F	465	679	507	269

For the A type mix the smallest cement ratio has the least cracking. In the B type mix the largest cement ratio has the least cracking, and the same is true of the C type. In the D type mix the cracking is the same in the 1.50 and 1.60 cement ratios. In the E type the 1.60 cement ratio has the best average, and in the F type mix the 1.50 cement ratio has the least cracking.

Cracking of Paving as Effected by Age:

To consider the cracking in regard to time, the total increase in average cracking which occurred in the period of time between succeeding condition surveys was used.

TABLE NO. 11

TOTAL INCREASE IN AVERAGE CRACKING BETWEEN SURVEYS

Type of Mix	Age of Paving and the Increase in Average Cracks Per 1000 ft. of Paving 4 Mos.	11 Mos.	15 Mos.	26 Mos.	30 Mos.	36 Mos.	41 Mos.	48 Mos.	54 Mos.	60 Mos.	65 Mos.
B	0	24	0	0	0	102	90	Max. 119	0	0	68
D	0	0	0	0	0	0	44	Max. 172	77	15	155
A	0	Max. 402	103	301	115	258	87	93	113	14	217
C	59	77	Max. 640	264	471	138	230	21	82	80	100
E	0	94	81	332	133	Max. 348	316	327	327	22	269
F	0	277	749	Max. 1171	532	199	357	78	18	188	332
TOTAL PROJECT	59	874	1573	Max. 2068	1251	1045	1124	810	617	319	1141

Mixes B and D, which had the least cracking, show the cracking started after about 40 months, and the greatest increase was found at 48 months.

Mixes A and C started cracking at 4 and 11 months, and reached the greatest rate of cracking at 11 and 15 months, respectively. Mixes E and F started cracking at 11 months; E reached a peak at 36 months, and F at 26 months. The totals show that the rate of cracking in the E and F mixes increased rather rapidly up to 26 months, and then decreased till the pavement was 60 months old, and at the age of 65 months it again increased in cracking.

This gives us in regard to time, two general types of cracking. The B and D mixes, which started cracking at about 3 years, and reached a peak in 4 years, are the best sections. When taken together, they have an average of 43 lineal feet of cracks per 1000 feet of slab. The other four mixes all had started cracking not later than 11 months, and reached a peak at from 1 to 3 years.

Rainfall and Cracking:

We would expect to find some relationship between rainfall and cracking. If we take the average rainfall per month for the periods between surveys, as indicating protracted wet or dry periods, the total increase in the total cracking on the entire project at each survey should show a corresponding change. Out of the ten periods between surveys, in all but three periods, the cracking increased or decreased as did the average rainfall, as shown by the following table.

TABLE NO. 12

RAINFALL AND CRACKING

Survey No.	1	2	3	4	5	6	7	8	9	10	11
Av. Rain	3.7	2.8	3.9	4.0	2.0	2.7	2.9	2.7	4.7	3.5	7.8
Inc. in Cracks per M. Ft.	59	874	1573	2068	1251	1045	1124	810	617	319	1141
Rain ± from Prev. Survey		-	+	+	-	+	+	-	+	-	+
Cracks ± from Prev. Survey		+	+	+	-	-	+	-	-	-	+

Review of Factors Indicated:

Before going further it might be well to briefly re-state those things that have so far been indicated as being factors which influence cracking. Soil type seems to decidedly effect the cracking. Sand cushion seems to increase the cracking. Little difference is found by use of the various coarse aggregates with the possible exception of crushed flint. Jig sand is as good, or better, than river sand. The larger sand void ratios give better results. We find that the better drainage caused by steep centerline roadway grades does not seem to be accompanied by a decrease in cracking.

As far as we can determine, the rainfall, the soil, the sand cushion, the mix type in regard to aggregate, and the sand void ratio, seem to be the principal factors which influence the cracking. The entire project may be divided into thirteen groups in which these factors which affect cracking are identical, except the sand void ratio. As the sand void ratio shows a much smaller affect than the other factors, neglecting it when grouping the sections should not greatly alter the results.

Among the fifty-six sections into which the individual mixes divide this project, there are three sections in which the cracking is much greater, and two in which it is much less, than any of the other sections in the group of similar sections to which they belong.

The cracking is excessively large in sections B-6-3, D-13-1, and C-10-2, and it is very low in sections E-18-2 and F-24-2. If we eliminate these five sections and average the cracking for each of the thirteen groups of sections, the order of quality as indicated by the pavement cracking would be as shown in the following table.

TABLE NO. 13

GROUPS OF SECTIONS WITH SIMILAR FACTORS

Group No.	Average Cracking	Sections in Group	Type of Mix	Subgrade Soil Type	Use of Sand Cushion	Average Sand Void Ratio	Sections Eliminated From Groups
1	15	B-5-1-2, 6-1-2-3-4, 7-1-2, 8-1-2	B	A-2	No	158	B-6-3
2	27	D-16-2	D	A-2	Yes	127	
3	29	D-13-1-2-3, 14-1-2, 15-1-2-3, 16-1	D	A-2	No	135	D-13-1
4	85	A-4-1-3-2	A	A-4	No	132	
5	98	C-91-2-3-4, 10-1-2	C	A-7	Yes	126	C-10-2
6	138	C-11-1a-2-1b	C	A-7	No	138	
7	210	C-12-1	C	A-4	No	104	
8	223	A-1-1-2, 2-1, 3-1-2-3	A	A-4	Yes	129	
9	252	C-12-2-3	C	A-4	Yes	106	
10	315	E-17-1-2-3	E	A-2	Yes	120	
11	329	E-18-1-2	E	A-2	No	114	E-18-2
12	416	E-19-1, 20-1	E	A-7	Yes	119	
13	540	F-21-1, 22-1-2 23-1-2-3, 24-1-2	F	A-7	Yes	110	F-24-2

This table seems to indicate that the groups of sections give much the same arrangement of the factors as was found when each factor was considered separately.

The mix types make a rather uniform arrangement in this grouping, which includes other factors, as they did in Table No. 8, when the sections were grouped by the mix type alone.

From this table, using the average lineal feet of transverse cracking per 1000 feet of paving, as an indication of the quality of the paving, the following statements could be made.

The probable order of the quality of the mixes by aggregate is B, D, C, A, E, F. This order is rather clearly indicated for all mixes, except type A. The table does not clearly indicate whether the A mix should come before or after the type C mix.

For this grouping it is also shown that as a general thing, the better soils when used in the subgrade resulted in less cracking of the pavement.

It can also be said that when the open graded sand cushion was used under the paving there was more cracking in the concrete.

The group with the greatest sand void ratio had the least cracking, and in general, as the sand void ratio was reduced, the cracking increased.

Discussion of the Results Obtained:

There are many other factors besides those which have been discussed that enter into the life and deterioration of a paving. But even with this limited number of causes, the fifty-six type of mix, when combined with the factors which have been considered, can produce a very large number of possible combinations. The combinations of the variables found on this project have been combined, by the use of the intensity of transverse cracking, into thirteen groups which contain fifty-one of the fifty-six sections. These groups, when listed in the order of their quality, as indicated by the transverse cracking, were brought into approximate order as to the type of soil in the subgrade, the use of sand cushion, and the sand void ratio. It is unlikely that this approximate order could result from chance alone.

One isolated project, such as this, can furnish no definite conclusions as to the value of either the method or the results indicated. It can only be said that this analysis has made it something more than an even chance that if a sufficient number of projects were observed and the data analyzed, some definite facts would be obtained.

ANALYSIS OF THE DATA WHEN ALL SURVEYS ARE INCLUDED:

To determine whether the foregoing analysis would apply to this project after it became older, two more condition surveys were made. A survey was made in 1942, when the paving was seventy-eight months old, and the last condition survey was made in October, 1945, when the paving was ten years and three months old.

When a table for the thirteen groups that were used in the first analysis is again prepared, using all the data accumulated through the ten years, the following table results.

TABLE NO. 14

GROUP OF SECTIONS WITH SIMILAR FACTORS
AFTER TEN YEARS SERVICE

Group No.	Average Cracking	Sections in Group	Type of Mix	Subgrade Soil Type	Use of Sand Cushion	Average Sand Void Ratio	Sections Eliminated From Groups
1	121	(B5) 1-2, (B6)1-2-3-4 (B7) 1-2, (B8)1-2	B	A-2	No	158	(B6)-3
5	121	(C9) 1-2-3-4, (C10)1-2	C	A-7	Yes	126	(C10)-2
3	130	(D13) 1-2-3, (14) 1-2, (15) 1-2-3, (D16) 1	D	A-2	No	135	(D13)-1
4	134	(A4) 1-2-3	A	A-4	No	132	
2	145	(D16) 2	D	A-2	Yes	127	
7	210	(C12) 1	C	A-4	No	104	
8	223	(A1) 1-2(A2) 1 (A3) 1-2-3	A	A-4	Yes	129	
6	226	(C11) 1a-2-1b	C	A-7	No	138	
11	330	(E18) 1-2	E	A-2	No	114	(E18)-2
9	342	(C12) 2-3	C	A-4	Yes	106	
12	467	(E19) 1, (E20) 1	E	A-7	Yes	119	
10	485	(E17) 1-2-3	E	A-2	Yes	120	
13	596	(F21) 1, (F22) 1-2, (F23) 1-2-3, (F24) 1-2	F	A-7	Yes	110	(F24)-2

Discussion of Table No. 14

In this table the five sections were eliminated as in the table of 1942.

A comparison of the two group tables discloses the following changes in the order of cracking.

Of the thirteen groups, nine have changed in place. None of these changes are great. Two groups, No. 5 and No. 2, have the greatest change, which is three places. No. 5 is now in second place, and No. 2 is now in the fifth place. The remaining seven changes are of either one or two places.

This table can be said to agree with the table of 1941 in a general way. The table of 1941 seems to be more systematic in the grouping of mix types.

Revision of Table No. 14:

There is an abundance of evidence to prove that the subgrade soil groups of the Bureau of Public Roads have a very definite effect on paving life.

If we accept this fact it may be used as a guide in determining the merit of evaluating a concrete paving by the intensity of its cracking.

Because the later surveys tend to reduce differences which suggested the eliminating of five sections in the table of 1941, also since the grouping of the subgrade soils is not as uniform in the later table, the thirteen groups have been listed, using all of the fifty-six mixes in obtaining the average cracking. This resulted in the following table.

TABLE NO. 15

GROUPS OF SECTIONS WITH SIMILAR FACTORS WHEN ALL SECTIONS ARE INCLUDED

Group No.	Average Cracking	Sections in Group	Type of Mix	Subgrade Soil Type	Use of Sand Cushion	Average Sand Void Ratio
11	100	(E18) 1-2	E	A-2	No	114
1	132	(B5) 1-2, (B6) 1-2-3-4, (B7) 1-2, (B8) 1-2	B	A-2	No	158
4	134	(A4) 1-2-3	A	A-4	No	132
2	145	(D16) 2	D	A-2	Yes	127
3	192	(D13) 1-2-3, (D14)1-2, (15) 1-2-3, (D16) 1	D	A-2	No	135
7	210	(C12) 1	C	A-4	No	104
8	223	(A1) 1-2, (A2) 1, (A3) 1-2-3	A	A-4	Yes	129
6	226	(C11) 1a-2-1b	C	A-7	No	138
5	250	(C9) 1-2-3-4, (C10)1-2	C	A-7	Yes	126
9	342	(C12) 2-3	C	A-4	Yes	106
12	467	(E19) 1, (E20) 1	E	A-7	Yes	119
10	485	(E17) 1-2-3	E	A-2	Yes	120
13	560	(F21) 1, (F22) 1-2, (F23) 1-2-3, (F24) 1-2	F	A-7	Yes	110

The thirteen groups cannot be evenly divided, but we can compare the first six groups with the last six groups.

The including of the five sections has improved the grouping in regard to subgrade soils. The first six groups are all A-2 or A-4 soils; all the A-7 soils are in the last groups. Only one A-2 subgrade and one A-4 subgrade are among the last six groups, and they have sand cushion and a rather low sand void ratio.

DISCUSSION OF TABLES 13, 14 & 15

Three different tables have been made showing the thirteen groups of sections. All three of these tables indicate that the intensity of transverse cracking on this particular project is influenced by the type of concrete mix, the soil type of the subgrade, the sand void ratio, and whether or not a sand cushion has been used. This is also in agreement with the tables which show each of these factors considered separately.

If we assume for the purpose of comparing the three tables of thirteen groups, that the table which most uniformly arranges the subgrade soil groups nearest represents the facts, we can make a table for their comparison.

The following table shows for the soils, and also the other factors, the percent of the total number of groups using each factor that we find in the best seven groups in each of the three tables.

TABLE NO. 16

TABLE OF PERCENTAGES OF THE SEVEN BEST GROUPS WHICH HAVE THE VARIOUS FACTORS

		Subgrade Soil			Sand Cushion		Mix Type by Aggregate						Average Sand Void Ratio
		A-2	A-4	A-7	No	Yes	A	B	C	D	E	F	
Table of 1941	5 sections Eliminated	60	50	50	80	28	50	100	75	100	0	0	136
Tables of 1945	5 Sections Eliminated	60	75	25	67	43	100	100	50	100	0	0	130
	All Sections	80	75	0	83	17	100	100	25	100	33	0	128

The table of 1945, which includes all the fifty-six sections, has a greater percent of the sections having A-2 and A-4 soils and the least number having A-7 soils among the seven best groups, and for this reason will be used in the following discussion.

DISCUSSION OF THE ANALYSIS OF CONDITION SURVEY DATA:

The methods used in this analysis, which consisted of the grouping of like factors and of using averages, becomes more dependable as the number of units averaged is increased. In many cases, averages have been made of a small number of units, and for this reason should probably be given less weight than groups with a larger number of sections.

With fifty-six sections and thirteen groups, four would be about the number of sections in an average group. There are five groups which contain more than four sections.

A table of these five groups has been made.

TABLE NO. 17

TABLE OF GROUPS CONTAINING MORE THAN FOUR SECTIONS

Group Number	Number of Sections in Group	Average Cracking	Aggregate Chats	Aggregate Sand	Mix Type	Sub-Grade Soil	Use of Sand Cushion	Sand Void Ratio
1	10	132	No. 3	Jig	B	A-2	No	158
3	9	192	No. 1	Jig	D	A-2	No	135
8	6	223	No. 3	River	A	A-4	Yes	129
5	6	250	No. 2	River	C	A-7	Yes	138
13	8	560	No. 1	River	F	A-7	Yes	110

All types of concrete mix in regard to aggregate are represented in this table, except type E. From the preceding tables, the E mix can safely be placed as the next to the last between the C and F mixes. With this addition of the E mix, Table 17 represents the results of this analysis in regard to the factors listed in the table.

CONCLUSION:

A total of eight factors have been considered, two of these factors, the rainfall and the cracking in regard to time, apply to the entire project. They were included more as a test of the method of analysis than as an attempt to prove the rather widely accepted conclusions that were obtained in the analysis. First, that rainfall softens the subgrade and frequently damages paving, and also that weaknesses in a paving will become evident in the first few years of service.

Two other factors, the centerline grade and the cement ratios, gave no definite information. Since the grades on this project were rather flat and the cement factors were rather large, it seems likely that the effect of these two factors, within the ranges of variation found on this project, are so small that other more dominant factors determined the results.

The remaining factors are contained in Table 17, and the results of this analysis may be briefly summed as follows: For the aggregates, it is likely that the type of sand had more effect on the mix than the type of chats. The soil type of the subgrade is a major factor. It is also indicated that the use of sand cushion is a very definite factor, and cracking is increased by its use. This is indicated more definitely in some of the other tables than it is in Table 17. The total cracking increases as the sand void ratio is decreased . The exceptions to this rule are probably because other factors were sufficient to more than over-balance the effect of the sand void ratio.

Today this project is almost fourteen years old. In the summer of 1949, the Portland Cement Association inspected the paving and gave it a rating of very good.

To dwell so much on its defects might give the impression that this paving was poor. In spite of its defects, it has always been a good road. It is one of the heaviest traveled highways in Oklahoma, and has always had a good riding surface.

Because of a lack of soil knowledge at the time of its construction, the heavy truck traffic of the war years caused considerable damage from pumping slabs. This damage has been repaired.

The type of expansion joint used was the principal defect in the project, but in spite of this defect, this chat concrete paving must be given credit for fourteen years of excellent service, and it can be expected to continue giving the service it was intended to give for many years to come.

Typed By

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