INVESTIGATION OF LOW AND ERRATIC CONCRETE PAVEMENT CORE COMPRESSIVE STRENGTH
Project I 23061-021

MICHIGAN
HIGHWAY RESEARCH LABORATORY SECTION

MICHIGAN DEPARTMENT OF STATE HIGHWAYS

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Project I 23061-021

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Research Laboratory Section
Testing and Research Division
Research Project 72 TI-94
Research Report No. R-827

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This project originated following a discussion between D. L. Wickham of the Construction Division and L. T. Oehler and M. G. Brown of the Testing and Research Division after it was discovered that some 1972 test results of routine pavement cores were seen to be erratic, with some values below the minimum 28-day compressive strength design limit of 3,500 psi. Several additional cores were requested, to be taken from low strength areas on this particular project on I 69 and delivered to the Research Laboratory for examination. Also, a general analysis of pavement core strengths from the past three years was suggested.

The subject cores were cut from the south end of the southbound lanes on March 21, and delivered to the laboratory, where they were stored in the moist curing room. On March 30, D. L. Wickham and T. H. Green examined the cores. They were brought from the moist curing room in a saturated condition and were observed to have a differential rate at which the surface moisture evaporated. It was immediately obvious that water stored in voids within the core, particularly in the bottom half, was feeding moisture to various isolated places on the cylindrical surface. A view of these cores is shown in Figure 1.

Because the slip-form paving method was used, very low slump concrete was required and, due to its stiff consistency, effective consolidation was more difficult than with conventional paving methods. Since the concrete was placed in two lifts, with the reinforcing steel mesh sandwiched in between, it would be very difficult to secure any direct consolidation in the bottom lift by vibrating the top lift.

An apparent lack of homogeneity in the mortar fraction of some of the concrete cores was observed. One core was noted where the drilling process had abraded the mortar away from the coarse aggregate, and grooves could be scored in it with a pocket knife. It was suggested that the weak mortar might be the result of poor cement distribution within the mortar.

Routine core test results, as reported by the Testing Laboratory Section at Ann Arbor, were consulted. Test results on cores 72A-33 through 88 in the northbound roadway were reported on February 22, and 72A-1019 through 1046, and 1079 through 1104, from the southbound roadway were reported March 29. Results ranged from 2,310 psi at station 2834+20 to 4,710 psi at station 2822+14, both of which were poured on September 23, 1971, on the northbound outer lane. The highest value was 6,250 psi at station 2780+75 on the southbound outside lane which was poured on September 30, 1971. The low for this lane was 2,790 psi at 2832+26 poured September 7. The average compressive strengths for the southbound outside

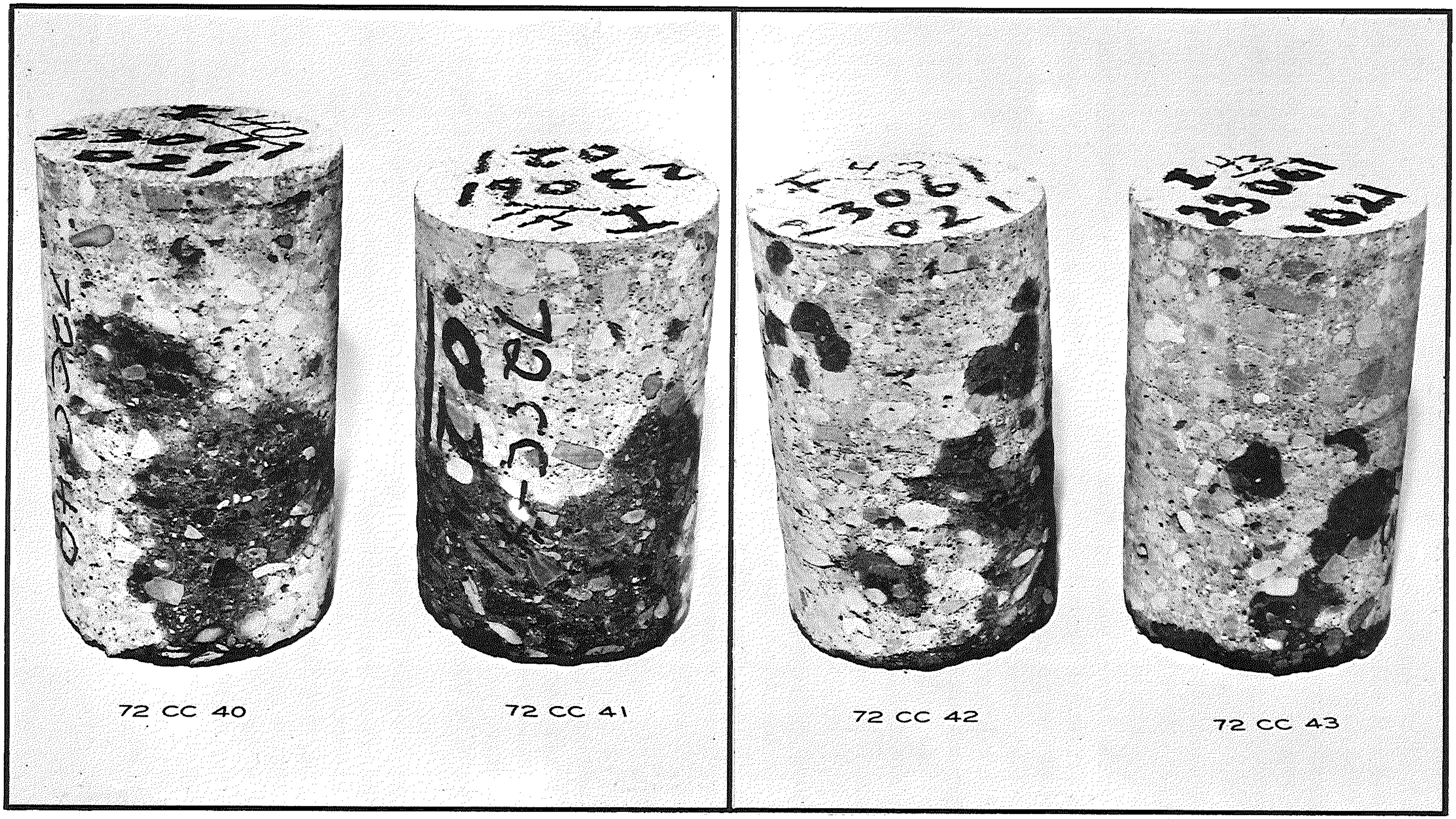


Figure 1. Appearance of saturated cores after several minutes of evaporation. Wetted surface areas are receiving their moisture from porous "reservoirs" within the core, particularly in the bottom half.

and inside lanes was 4,610 and 4,990 psi, respectively. The corresponding averages for the northbound outside and inside lanes was 3,840 and 4,690 psi. It is interesting to note that all but two of the cores under 3,500 psi were from the outside lanes which were paved first. There were four low and one borderline cores in the southbound outside lane and five low and five borderline cores in the northbound outside lane. These results would also suggest a lack of homogeneity or uniformity of mixing, or non-uniformity of consolidation, or both, throughout the project.

In discussing how the four extra cores should be tested, it was decided that a compression test would contribute very little since we already had many compression tests from the same areas, and it was obvious from the porosity of the cores and their variable mortar that they would not test very high. If it could be determined whether the density of the top half of the core was greater than that of the bottom half, it might tell us if the bottom half had been consolidated as effectively as the top. Thus, specific gravity of each half was determined independently.

The cores were cut in half at mid-depth such that the steel mesh was included in the top half. The specific gravity of each half was then determined and is shown in Table 1 along with other detailed information about the cores. It was found that in every case the specific gravity of the top half exceeded that of the bottom half by an average of 0.09. The obvious conclusion that the steel in the top half would raise its specific gravity was considered and was found to make a slight but not significant increase. Calculations showed that a 3/8-in. bar would raise the concrete specific gravity of a 6-in. diameter by 5-in. long cylinder by 0.02. This would account for only a small portion of the difference between the two halves.

The only conclusion that could be reached was that the top lift was much better consolidated than the bottom. The concrete on this project, at a 6.5 percent air level, would have a specific gravity of about 2.35 if well consolidated as calculated from actual batch weights used.

Upon request, the Project Engineer visited the laboratory on April 20, 1972, to supply some missing project data. He described the paving sequence shown in Figure 2, and said that it was poured in two lifts with a 12-ft slip-form paver. The concrete was vibrated as it was placed with paver-connected probe vibrators. In describing the mix time at the central batch plant, he said that the drum revolved continuously while the charge of aggregate, cement, and water were added from the open end. The time to begin measuring the mix time was not well defined; however, he discovered the concrete to be inadequately mixed at the time the paving operation had advanced to the north end of the outside lane of the southbound roadway.

TABLE 1

CONCRETE CORE DATA - SOUTHBOUND ROADWAY

Laboratory No.	Core No.	Length, in.	Steel Depth, in.	Station	Distance From E Edge, ft	Wet Bulk Specific Gravity		Visual Description
						Top Half	Bottom Half	
						WEST LANE		
72 CC-40	1	10.1	4.7	2753+65	6.2	2.35	2.30	Several 1/4 by 1/2-in. bridging air voids (BAV) and 1/16-in. trapped air voids (TAV) scattered over full depth. Bottom 2/3 appears to be porous with interconnected interior voids.
72 CC-41	2	9.2	4.2	2756+90	10.6	2.36	2.25	
72 CC-42	3	9.2	4.0	2765+09	2.2	2.36	2.25	
						EAST LANE		
72 CC-43	4	9.5	4.0	2861+49	5.0	2.43	2.35	Top half of core appears to have sound concrete. Bottom half is porous with several scattered 1/4 by 1/2-in. BAV and a few larger BAV

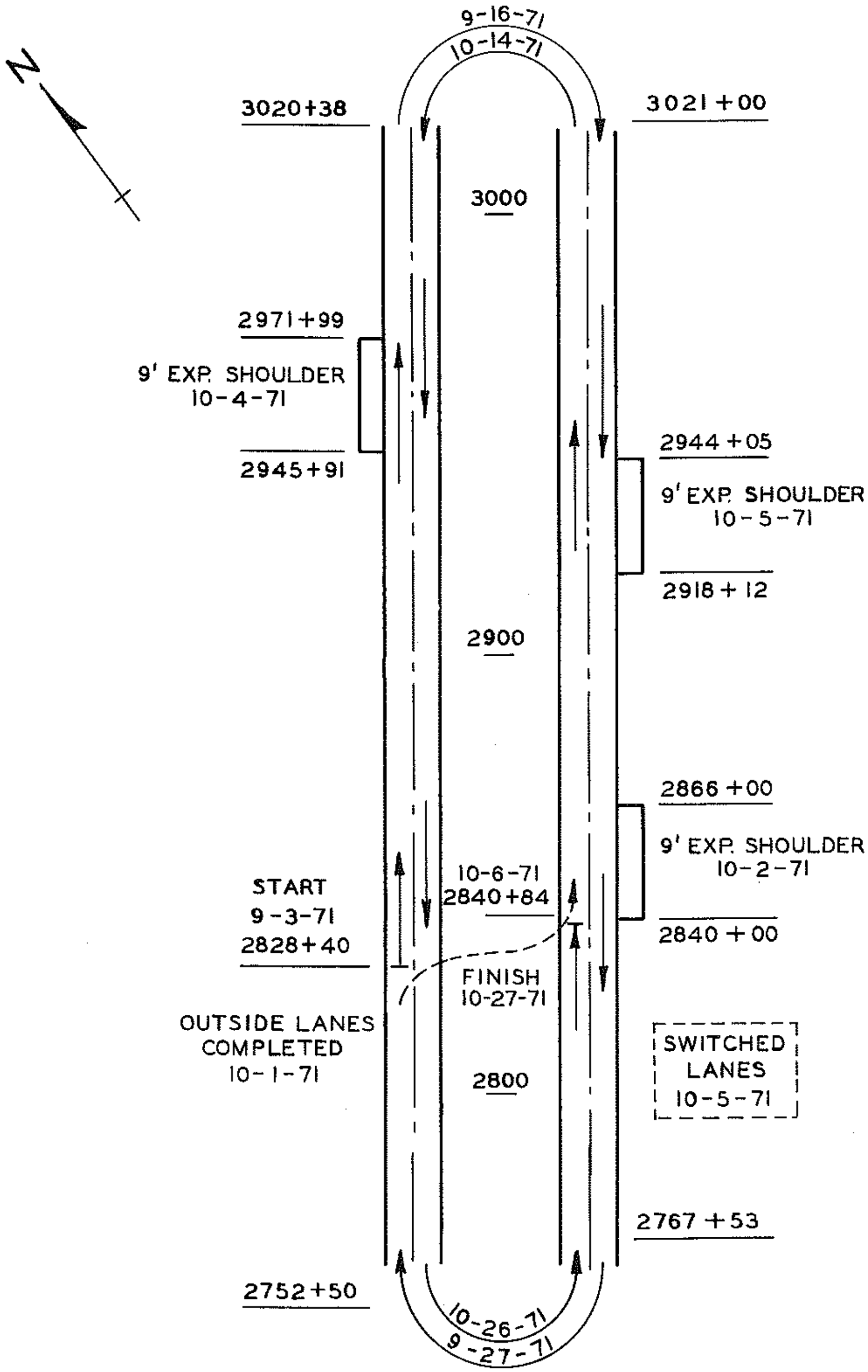


Figure 2. Paving sequence of I23061-021
I 69 South of Charlotte.

At that time he requested the contractor to begin measurement of the mix time only after all the mix components had been added. He said that he was sure the concrete in the remaining portion of the job had received the minimum specified mix time.

The Project Engineer also mentioned that the temperature of the cement as it was unloaded from the bulk trucks was quite high; sometimes being as hot as 130 F. This was due to the cement being used as fast as Peerless could produce it from all three of their plants (two in Detroit and one in Port Huron). He wondered if perhaps the high temperature of the cement would have some adverse effect on the quality of the concrete. He was advised that the only adverse effect would be a "flash set" of the concrete if the temperature were 90 F or over. A check of the recorded concrete mix temperatures showed only eight times when the temperature was over 80 F; these occurred in early September with a maximum temperature of 83 F on September 7, 1971.

It was noticed on the "Inspector's Report of Concrete Placed" records that air entrainment in the concrete in excess of 8 percent occasionally occurred; this fact was examined to see if high air content could be responsible for many of the low concrete core compressive strengths. In Table 2 the stationing of the day's pour limits is tabulated along with concrete beam and core strength data, and slump and entrained air measurements for that day. Although the stationing was not indicated at locations where the air and slump measurements were made, an attempt was made to approximately match the core strength station to the time of day at which the fresh concrete measurements were made. An examination of these data, however, is inconclusive since more high than low concrete strengths exist at time of high air measurements.

The high air entrainment measurements aroused speculation that excessively fine 2NS aggregate might be present in the concrete; examination of the "Aggregate Inspection Daily Report" forms showed a couple of days on September 7 and October 1 (Table 3) when aggregate piles were shipped to the batch plant and used in the concrete before the inspector's work revealed that they did not meet specification requirements. The amount of such aggregate used, however, amounted to less than 3 percent of the total 2NS sand approved.

Another avenue of comparison that was investigated was to see if the flexure beams, which were cast in areas recording low core strengths, would themselves agree with the cores in that the concrete was of lower

TABLE 2
CONCRETE PHYSICAL DATA

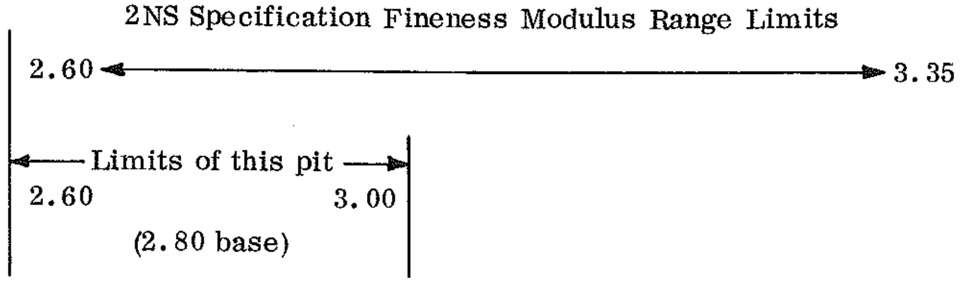
Pour Date	Stationing		Core Data			Flexure Beam Data				Related Mix Data		
	From	To	No.	Station	Comp. Strength	Time	Station	Avg. Strength, psi 7 Day	14 Day	Time	Entr. Air, percent	Slump, in.
SOUTHBOUND OUTSIDE LANE												
9-28-71	2752+50		173	2752+61	2,970					8:30 AM	9.5	2.0
			174	2760+10	3,780					10:30 AM	8.0	1.8
		2779+55	175	2770+09	3,850					2:00 PM	7.8	1.5
9-30-71	2779+55		176	2780+75	6,250					7:30 AM	6.8	1.5
			177	2789+35	5,740					10:00 AM	7.6	1.8
			178	2800+33	3,370					Noon	6.8	1.5
		2813+94	179	2811+05	4,610	3:00 PM	2813+50	606	639	2:10 PM	5.5	1.0
10-1-71	2815+32	2826+13	180	2820+78	4,580					Daily Avg	5.9	1.9
9-14-71	2827+09	2828+40								2:30 PM	5.2	1.5
9-3-71	2828+40	2831+74								Daily Avg	3.6	0.6
9-7-71	2831+74	2839+59	181	2832+26	2,790	1:00 PM	2832+50	616	727	Daily Avg	5.5	1.3
9-8-71	2839+59		182	2842+85	3,110					10:30 AM	5.8	1.5
		2854+54	183	2852+69	5,440					2:00 PM	4.6	1.0
9-9-71	2854+54		184	2862+91	5,150		2860+50	712	842	11:15 AM	5.6	1.3
			185	2874+18	5,100					1:30 PM	6.4	1.3
		2885+80	186	2882+75	4,700					4:00 PM	6.0	1.5
9-10-71	2885+80		187	2892+01	5,470					10:30 AM	3.2	1.5
			188	2901+95	5,370					11:05 AM	6.3	1.5
		2913+95	189	2913+04	3,640					1:00 PM	6.1	1.3
9-13-71	2913+95		190	2923+74	4,540	11:30 AM	2920+40	808	808	10:00 AM	8.3	1.8
			191	2933+65	4,700					Noon	5.9	1.5
		2946+62	192	2944+98	4,280					2:00 PM	5.8	1.8
9-14-71	2946+62		193	2954+92	5,520					11:00 AM	5.5	1.5
		2971+44	194	2964+88	4,550					1:30 PM	5.1	1.5
9-15-71	2971+44		195	2973+38	6,520					7:30 AM	6.0	1.5
			196	2981+97	5,120					9:45 AM	7.0	1.5
			197	2994+50	5,170	10:40 AM	2984+50	682	782	Noon	6.3	1.5
		3006+84	198	3003+09	5,020					2:15 PM	5.9	2.0
9-16-71	3006+84	3020+38	199	3013+06	4,100					10:15 AM	6.9	1.5
NORTHBOUND OUTSIDE LANE												
9-16-71	3021+00	3006+07	1674	3011+97	4,040					2:30 PM	5.3	1.3
9-17-71	3006+07		1673	3002+72	4,470	8:25 AM	3002+00	766	690	7:30 AM	7.5	2.0
			1672	2992+06	4,050					10:05 AM	7.1	1.5
			1671	2981+86	4,150					12:30 PM	8.4	1.5
			1670	2971+15	3,810					2:45 PM	7.7	1.3
		2958+10	1669	2963+31	4,300					4:00 PM	7.2	1.3
9-21-71	2958+10		1668	2952+60	3,810					8:00 AM	7.7	2.0
			1667	2943+36	3,610					10:00 AM	9.2	2.0
			1666	2933+43	3,990					Noon	6.6	1.3
			1665	2921+35	4,140					2:00 PM	6.9	1.5
			1664	2912+10	3,010							
		2904+07	1663B	2904+26	4,350					4:15 PM	5.8	1.5
9-22-71	2904+07		1663	2902+94	4,430					7:25 AM	6.0	1.8
			1663A	2901+41	3,600	8:00 AM	2900+50	703	755			
			1662	2893+60	4,020					9:45 AM	5.5	1.5
			1661	2882+21	2,750					Noon	7.2	1.5
			1660	2871+59	3,620					2:00 PM	6.5	1.5
			1659	2861+75	3,290							
			1658	2853+24	4,020							
			1657B	2845+04	4,580					4:15 PM	6.0	2.0
			1657	2843+60	3,520							
		2840+30	1657A	2842+16	4,130							
9-23-71	2839+84	2826+90										
	2825+95		1656	2824+20	2,310					2:35 PM	7.8	1.5
		2813+53	1655	2822+14	4,710					4:00 PM	7.1	1.8
9-24-71	2812+11		1654	2809+63	4,680					8:00 AM	8.2	2.0
			1653	2798+95	2,370					10:00 AM	9.0	2.5
			1652	2790+43	4,000					Noon	7.1	1.5
			1651	2781+19	3,560							
		2767+53	1650	2770+64	3,990					2:30 PM	6.0	1.5

TABLE 2 (Cont.)
CONCRETE PHYSICAL DATA

Lane	Pour Date	Stationing: From	Stationing: To	Core Data: No.	Core Data: Station	Core Data: Comp. Strength	Flexure Beam Data: Time	Flexure Beam Data: Station	Flexure Beam Data: Avg. Strength, psi, 7 Day	Flexure Beam Data: Avg. Strength, psi, 14 Day	Related Mix Data: Time	Related Mix Data: Entr. Air, percent	Related Mix Data: Slump, in.
SOUTHBOUND INSIDE LANE	10-15-71	3020+38		226	3012+35	4,480					9:30 AM	8.5	2.0
				225	3003+10	4,520					11:30 AM	8.5	1.5
				224	2991+69	4,780					Noon	6.5	1.5
				223	2982+60	5,230	1:20 PM	2985+00	622	724	1:00 PM	8.5	2.0
			2969+33	222	2972+66	4,520					3:00 PM	6.6	1.5
	10-18-71	2969+33		221	2962+76	5,520					8:00 AM	6.3	1.5
				220	2953+52	5,350					9:15 AM	6.3	1.8
				219	2943+26	4,440					11:00 AM	7.5	1.5
				218	2932+70	5,090					1:00 PM	6.8	1.5
			2916+10	217	2922+02	5,190					3:30 PM	6.4	1.8
	10-19-72	2916+10		216	2910+93	4,870					7:30 AM	6.0	1.5
				215	2903+07	4,570	10:00 AM	2900+00	652	744	9:30 AM	7.1	1.8
				214	2893+10	4,550					11:30 AM	7.3	1.8
				213	2884+45	5,970					1:30 PM	8.2	1.5
				212	2872+10	5,160					3:00 PM	7.7	1.8
			2862+36	211	2826+80	4,920							
	10-20-71	2862+36		210	2852+35	4,600					9:30 AM	5.4	1.5
			2840+40	209	2843+65	5,080					11:30 AM	6.3	1.8
		2839+69	2827+00	208	2832+62	5,130					2:30 PM	7.8	1.8
		2826+18	2825+03										
	10-21-71	2825+03	2815+23	207	2822+17	5,490					11:00 AM	7.3	1.5
		2813+55		206	2811+04	5,920	11:00 AM	2813+00	688	733	1:00 PM	6.7	2.0
			2797+00	205	2800+35	4,790					2:45 PM	7.0	1.8
	10-25-71	2797+00		204	2788+27	5,460					8:00 AM	6.0	1.8
				203	2779+35	4,680							
				202	2770+10	5,320					10:00 AM	6.0	1.5
			2760+33	201	2760+83	4,350					1:00 PM	5.6	1.5
		2759+62	2753+25	200	2753+25	4,780					3:15 PM	5.5	1.5
NORTHBOUND INSIDE LANE	10-26-71	2768+25		1675	2771+27	4,910					8:00 AM	6.5	1.5
				1676	2779+08	5,210					10:00 AM	7.0	1.8
				1677	2791+85	4,170					11:00 AM	7.1	1.8
				1678	2800+41	4,880	1:35 PM	2804+00	580	722	1:00 PM	6.4	1.5
			2812+21	1679	2808+91	4,950					3:15 PM	6.6	1.8
	10-27-71	2813+90	2825+85	1680	2821+27	4,600					10:15 AM	8.5	1.5
		2827+20	2839+85	1681	2832+48	6,920					Noon	4.6	1.5
		2840+30	2840+95										
	10-6-71	2840+84	2850+90	1682	2844+00	4,040					8:00 AM	5.9	1.5
	10-7-71	2850+90		1683	2851+12	4,850					7:45 AM	8.4	2.0
				1684	2862+46	5,160					9:15 AM	7.0	1.8
				1685	2872+27	5,160					11:15 AM	5.4	1.5
				1686	2882+93	5,700					1:30 PM	4.7	1.5
			2895+55	1687	2893+75	2,760	3:00 PM	2889+50	619	655	3:00 PM	7.7	1.8
	10-8-71	2895+55		1688	2902+14	2,920					7:45 AM	9.4	2.0
			2920+42	1689	2911+38	4,430					11:30 AM	6.3	1.5
	10-11-71	2920+42		1690	2922+77	5,040					7:45 AM	5.7	2.0
				1691	2931+99	4,470					1:15 PM	7.4	2.0
			2950+98	1692	2942+62	3,970	3:30 PM	2944+00	629	698	3:00 PM	6.3	1.9
	10-12-71	2950+98		1693	2954+03	4,590					7:30 AM	9.1	1.8
				1694	2961+15	3,890					9:15 AM	9.6	1.8
				1695	2972+57	5,320					12:30 PM	6.7	2.0
				1696	2982+58	4,680					3:00 PM	6.1	2.0
				1697	2991+34	5,170							
			3005+36	1698	3002+01	4,690							
	10-13-71	3005+36		1699A	3011+97	5,280							
				1699	3014+09	4,750	10:44 AM		615	807	10:00 AM	8.0	2.5
			3018+15	1699B	3015+50	4,080							
	10-14-71	3018+15	3021+00								8:00 AM	7.6	2.0

TABLE 3
DAILY FINE AGGREGATE PRODUCTION
(Michigan Aggregate Corporation - Pit No. 13-84
Sampled and Approved for Use on Project I 23061-021)

2NS Specification Fineness Modulus Range Limits



Sample Date	Daily Production, cu yd	
	Fineness Modulus Range	
	Less than 2.60	2.60 - 3.00
9-1-71		200
9-2-71		200
9-7-71	100	250
9-9-71		100
9-13-71		50
9-14-71		50
9-15-71		250
9-16-71		200
9-17-71		600
9-20-71		400
9-21-71		150
9-22-71		150
9-23-71		150
9-24-71		100
9-27-71		400
9-28-71		300
9-29-71		50
9-30-71		250

Sample Date	Daily Production, cu yd	
	Fineness Modulus Range	
	Less than 2.60	2.60 - 3.00
10-1-71	50	300
10-4-71		150
10-5-71		100
10-6-71		100
10-7-71		200
10-8-71		200
10-11-71		200
10-12-71		150
10-14-71		150
10-15-71		200
10-18-71		400
10-19-71		300
10-20-71		200
10-21-71		200
10-26-71		350
10-27-71		100
10-28-71		200

TABLE 4
WITHIN-PROJECT VARIATION AND AVERAGE STRENGTH
BY YEAR OF CONSTRUCTION

		Construction Year			
		1965	1969	1970	1971
	Number of Projects	16	18	16	8
Within-Project Variation	Standard Deviation, avg for year, psi	645	678	666	738
	Upper Confidence Limit (3 σ), psi	905	933	923	910
	Average Contract Size (cores per project)	42	33	36	40
Within-Year Average	Total Number of Cores	669	590	590	319
	Average Compressive Strength, psi	5,391	5,670	5,518	4,947*
	Lower Confidence Limit (3 σ), psi	5,342	5,336	5,336	5,299

* "out of control," or below lower confidence limit.

strength. However, all beam breaks throughout the contract indicated acceptable concrete in general and superior concrete in many areas (Table 2). The one primary difference between the concrete in the beams and the cores would be the degree of consolidation; the beams which were hand tamped would possibly be better consolidated than were the cores from the slip-formed pavement.

To complete the inspection of the available data, the "Aggregate Inspection Daily Report," the "Concrete Proportioning Data," and the "Concrete Proportioning Plant Report" records were reviewed. It was noted that the volume proportioning of fine aggregate to total aggregate in the concrete varied between 36 and 37 percent depending upon the dry unit weight of the coarse aggregate. Although this is a typical design for pavement concrete with gravel aggregate, it might possibly be slightly harsh, especially in this low slump concrete, and would itself contribute to the consolidation problems. However, with adequate vibration this standard pavement mix design should consolidate to a good, uniform pavement.

Analysis of Pavement Core Strengths

While the construction records and test data of the subject project were being examined, a statistical analysis of certain concrete core compressive strength data was made. The data consisted of test results from a minimum of 8 and a maximum of 18 construction projects for each of the years, 1965, 1969, 1970, and 1971. The objective was to determine if any significant changes in between-year strengths or within-project variations were occurring. Control chart techniques were used to make these determinations and to provide graphic evidence.

Table 4 shows that there are no significant differences in within-project variation over the indicated years. The slight variations that can be observed must be considered to be due to chance; that is, no assignable causes are at work. A significant deviation would have been evident if a point had fallen outside the control limits, or exceeded the three standard deviation upper confidence limit.

On the other hand, Table 4 indicates that there has been a significant change in mean compressive strength when averaged over all test results for all projects for a given year. The mean value for 1971 is "out of control" in the sense that the extreme low value would not be expected to occur due to random fluctuations based on the limited data at hand.

Each year was independently analyzed in a similar manner, i.e., using control charts. In general the variation between contracts within years is in control. The contract mean strengths for a given year do differ significantly with respect to the year average, however. It is of interest to note that of the two projects in 1971 "out of control," the worst one was the subject I 69 job with an average compressive strength of 4,520 psi. In fact, this project, 23061-021, had the lowest average core strength of all 58 projects analyzed. There does not appear to be any sort of trend from year-to-year. Each year has several project averages out of control[1] as indicated as follows:

Year	No. of Contracts	Out-Of-Control	
		No.	Percent
1971	8	2	25
1970	16	3	19
1969	18	5	28
1965	16	7	44

Of the out-of-control projects there were 1, 2, and 0 slip-formed projects for 1971, 1970, and 1969, respectively. In the statistical analysis of core strength from 58 projects constructed during four years no attempt was made to correct for variations in age of cores at time of test.

Summary and Recommendations

After examining all available data on the subject project, and the analysis of core data of projects from four construction years, the following factors would appear to have produced the variable nature of the concrete strength on the I 69 project, in particular. These are listed in probable order of importance as follows:

1) Lack of proper consolidation in the bottom half of the pavement. Many of the cores examined were found to contain more and larger voids at and below the steel mesh. The same paving equipment used on the subject I 69 project in 1971 was observed on an experimental project by the same contractor to the south this year (I 23061-020). The two Maxon spreaders ahead of the CMI paver had only one and three surface vibrators mounted on the transverse screed on the first and second spreader, respectively. The bottom lift of 5 to 6 in. generally appeared to be loosely consolidated at time of mesh placement. The degree of consolidation of the

[1] with respect to at least the 2 control limit.

first lift appeared to depend on the amount of excess concrete contained in the first spreader box. It would seem that a bank of probe vibrators of proper size and spacing, possibly 1 to 1-1/2 ft apart, would be more effective in obtaining a uniform degree of consolidation in the bottom lift. Some visual indicators that all vibrators are operating on the paving equipment might be worth requiring also.

2) Lack of uniformity of mixing possibly related to mixing time. A number of the cores from the southbound roadway, including the four special ones for specific gravity tests, appeared to have portions with a non-uniform appearance in the mortar fraction. The old central mix plant used on the subject project in 1971 was checked, and met uniformity tests in 1972 but using a higher slump concrete for conventional paving. The adjoining project on I 69 done this year used concrete from a new central mix plant. Possibly a number of central mixers furnishing low slump concrete for slip-form paving should be checked for uniformity to establish whether the minimum mix times of Table 7. 01-3 of the 1970 Standard Specifications are adequate, particularly for older mixers.

3) Our basic mix design factors, in particular the sand to coarse aggregate ratio, may need to be considered. However, Michigan's pavement concrete design is quite comparable to that of other states using a nominal 1 in. maximum size coarse aggregate. Quite often problems may be increased, such as edge slumping, if the sand content is increased. It is believed that on the subject project and other slip-form paving jobs, the most critical factor is the placement and consolidation of the lower portion of the roadway slab. A greater effort is needed by the equipment manufacturers and our own specification and inspection requirements to solve this problem.