PERFORMANCE TESTS ON A LARGE STATIONARY CONCRETE MIXER AT VARIOUS MIXING TIMES

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SYNOPSIS

During a normal Michigan paving operation using central-mixed air-entrained concrete, field and laboratory tests were conducted to evaluate the performance of an 8.5 cu yd mixer at various durations of mixing. Five mixing times were selected for study, ranging from a minimum of 60 sec to a maximum of 200 sec.

The test batches used were interposed into the paving operation at random intervals and differed from the normal batches only in mixing time. Time-dependent variations were minimized by random selection of three batches for detailed study for each mixing time. The front, middle, and rear portions of the mixer discharge were sampled and tested for slump, unit weight, air content, coarse aggregate content, and 28-day compressive strength. An additional air-content test was made on the middle portion of the batch after delivery to the paving site. Air-free unit weights of the concrete and mortar were calculated. The testing program was spread out over four days of paving.

Since suitable criteria for mixer performance are currently under study by various agencies, recommendations for a minimum time for satisfactory blending of concrete by this particular mixer are now considered premature. The data, however, point to a reduction from the usual requirement of 1 min for 1 cu yd, plus 15 sec per cu yd or fraction thereof of additional capacity.

Large, stationary concrete mixers are now being used for central mixing of portland cement concrete for pavements and bridge structures, with concrete hauled to the point of placing in agitating or non-agitating dump trucks. The requirement for the length of time that the concrete must be mixed is presently a fixed value as given by most specifications.

The Michigan State Highway Department "Standard Specifications for Road and Bridge Construction" (1960), Articles 4.14.03 (j) and 5.05.03 (c), and "Standard Specifications for Ready-Mixed Concrete" (ASTM Designation: C94-58), both state that the concrete shall be mixed 1 min for the first cubic yard plus 15 sec for each additional cubic yard or fraction thereof of capacity.

The primary purpose of this study was to obtain new information about the length of time necessary to mix concrete materials so that concrete discharged from the mixer will be uniform in gradation of aggregates, air content, consistency, and strength-producing properties, all of which are essential for high-quality concrete. Increased production and reduced costs would result from reducing mixing time. Widespread studies of this type have not been made before this on large stationary mixers, although a similar type of investigation has been made on 34-E paving mixers (2, 3).

This study has been made in response to Bureau of Public Roads Circular Memorandum 25-12 from E. H. Holmes, Assistant Commissioner, dated February 14, 1961, and is one of a series being conducted by several states to obtain operational information on large stationary mixers.

DESCRIPTION OF PROJECT

Location and Testing Organization

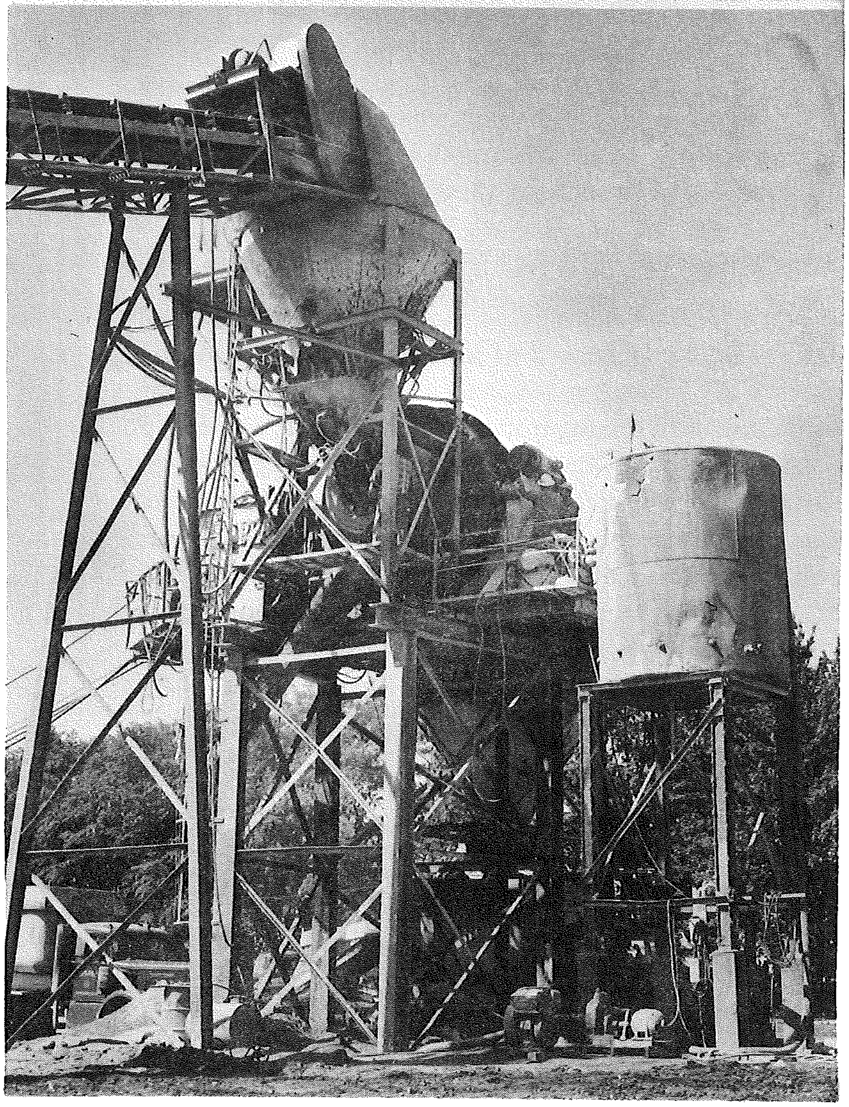
The Michigan stationary concrete mixer study was conducted on Project EBBF 76073, C2RN (Federal No. EBF 242 (22)) which includes 7 mi of dual 24-ft, 9-in. pavement on the M 78 relocation from Perry to Bancroft in Shiawassee County. The contractor was the C. F. Replogle Co., of Circleville, Ohio. Field testing started June 19 and was concluded June 22, 1961. Testing personnel included employees of the Michigan State Highway Department and the Detroit office of the Pittsburgh Testing Laboratory. Due to a shortage of Department testing personnel to conduct this work during the busy construction season, six Pittsburgh personnel were procured on a temporary basis to augment the testing staff. Supervision and all testing equipment used were furnished by the Department. In all, twelve persons were assigned to the field testing project, including the Pittsburgh personnel--a minimum number for the quantity of tests performed.

Contractor's Equipment

The central mixing plant (Fig. 1) consisted of a four-bin Noble-Mobile batching plant, an AGC 210 S (7.78 cu yd) Burmeister tilting concrete mixer, and suitable materials-handling equipment. The first two units were electrically interlocked to permit automatic batching and mixing. The batching plant was fed from three aggregate stockpiles and two cement silos. The fine aggregate was fed to the batching plant by a conveyor whose loading was controlled by the amount of fine aggregate passing through a bulkhead placed in the fine aggregate stockpile. The conveyor belt was kept to full charge by a crawler tractor pushing material to the bulkhead. The coarse aggregates (Michigan designations 4A and 10A) were moved from the stockpiles to the batching plant by cranes equipped with clamshell buckets. The cement (Type IA) was conveyed from the cement silos to the batching plant by a screw conveyor.

From the storage bins of the batching plant, materials were delivered by gravity to their respective weighing hoppers, in which the correct amount of each material was weighed to give an 8.5 cu yd batch (10 per-

▲ Figure 1. General view of batch plant and mixer.



◀ Figure 2. Mixer charging hopper (top). Water storage at right.

cent overload). The weighing hoppers, equipped with hydraulically actuated doors, discharged onto a conveyor belt which carried the aggregates and cement simultaneously to the dry storage bin on the mixing tower (Fig. 2), where they were held until the mixer was ready to receive a new charge of materials. The electrical interlocking system between the mixer and the batching plant allowed only one batch at a time to be discharged into the dry storage bin.

The return of the tilting mixer to a nearly horizontal position, after discharging a batch of mixed concrete, started the flow of water into the mixer and actuated the discharge gate at the bottom of the dry storage bin, allowing the materials to enter the mixer drum for mixing. The proper amount of air-entraining agent ("Airtex," a vinsol resin solution) was also introduced at this time. At the end of a predetermined mixing time, the batch of concrete was discharged (Fig. 3) into a surge hopper from which the Maxon non-agitating "Dumpcrete" trucks were loaded (Fig. 4). The surge hopper had a capacity equal to three 8.5-cu yd batches.

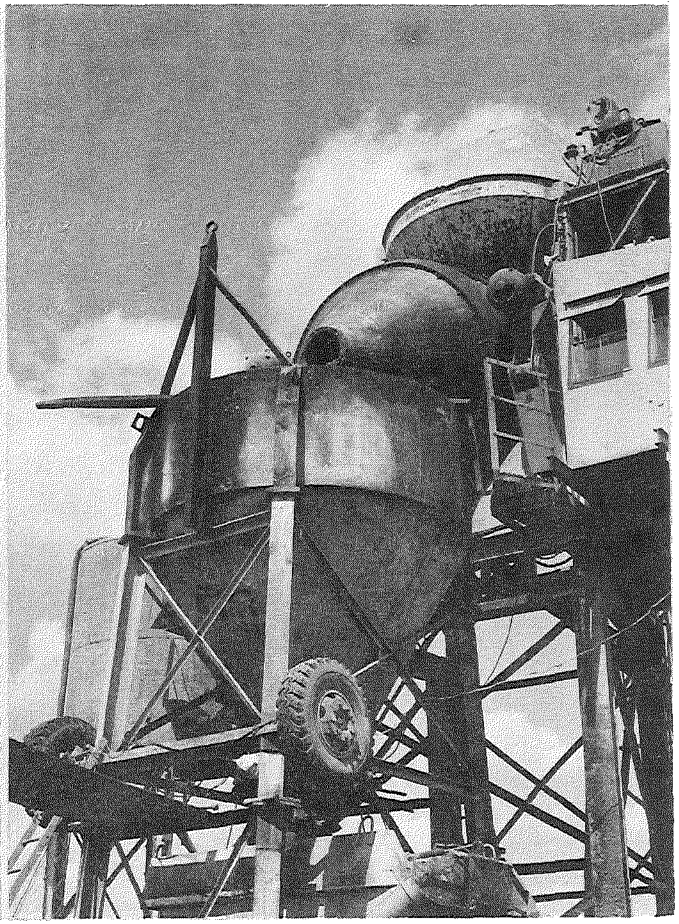
Hauling of the mixed concrete to the paving site was done by Maxon Dumpcrete trucks equipped with hydraulically controlled chutes and discharge doors. The Dumpcrete bodies were also equipped with vibrators to aid in discharging the concrete at the paving site. No agitating device was used while the concrete was in transit to the paving site or while awaiting discharge at the site.

The paving train was made up of two Maxon Dumpcrete concrete spreaders, one for the bottom layer of concrete and one for the top layer; a rig for placing steel between the two layers of concrete; concrete finishers and floats; and a concrete curing compound sprayer.

Materials

The coarse aggregate was gravel from Holly Manufacturing and Mining Co., Holly, Mich., and was furnished in two sizes, Michigan Specifications 4A (approximately 2 to 1 in.) and 10A (approximately 1 in. to No. 4). The batch proportions called for each size to be 50 percent by weight of the total coarse aggregate.

The fine aggregate was a natural sand, also from Holly Manufacturing and Mining Co., with an average fineness modulus of 2.61.



▲ Figure 3. Mixer discharging into surge tank.

◀ Figure 4. Surge tank discharging into "Dumpcrete" truck.

The portland cement was Peninsular brand, from the General Cement Corp. mill at Cement City, Mich. The cement was Type IA (air-entraining) as required by Michigan specifications. Laboratory tests (Table F) indicated the cement to be normal in all respects. An air-entraining admixture, known by the trade name Airtex, was used throughout the program in the amount of 0.32 oz per sack, or 15 oz per 8.5 cu yd batch. The water for the concrete was pumped from the Looking Glass River, a small stream located a short distance east of the central mixing plant.

The concrete mix was designed by the mortar-voids method, under the standard Michigan procedure, to contain 5.5 sacks of cement per cu yd with 4 to 7 percent entrained air. Specifications require such concrete to have a 28-day compressive strength of 3500 psi.

The pavement slab is 9 in. thick and 24 ft wide, poured full width, with steel reinforcement. Curing was provided by white pigmented concrete curing compound. The transverse joints are of the weakened-plane type with steel load-transfer dowels. The longitudinal center joint was made by sawing, several days after placing the concrete.

DESCRIPTION OF TEST PROGRAM

The sequence of sampling was planned to give a wide range of mixing times and to minimize time-dependent variations in aggregates, cement, air-entraining admixture, atmospheric conditions, and test techniques. The test batches were selected at random from the normal concrete production of the plant. This procedure was possible because the test batches differed from regular production batches only with respect to the length of mixing time. Mixing times of 60, 90, 120, 180, and 200 sec were used. The batches were sampled in this sequence of mixing times and the same sequence was then repeated two additional times. Thus, for each mixing time, measurements were procured on three test batches spread out at fairly regular intervals over a four-day period. Concrete samples were taken from the front, middle, and rear portions of each batch, upon which various tests and operations were performed. *

The testing program extended over a four-day period, June 19 to June 22, 1961, which was somewhat longer than anticipated due to adverse weather conditions and electrical difficulties at the central mixing plant.

Sampling Procedure

To obtain the samples for testing, the following procedure was carried out under the direction of the testing program supervisor:

1. The surge tank into which concrete batches discharged was emptied of all previous normal production batches.

2. The mixing plant was briefly switched from automatic to manual control, with the desired mixing time measured by a stopwatch. The mixing water and the dry materials were charged into the mixing drum,

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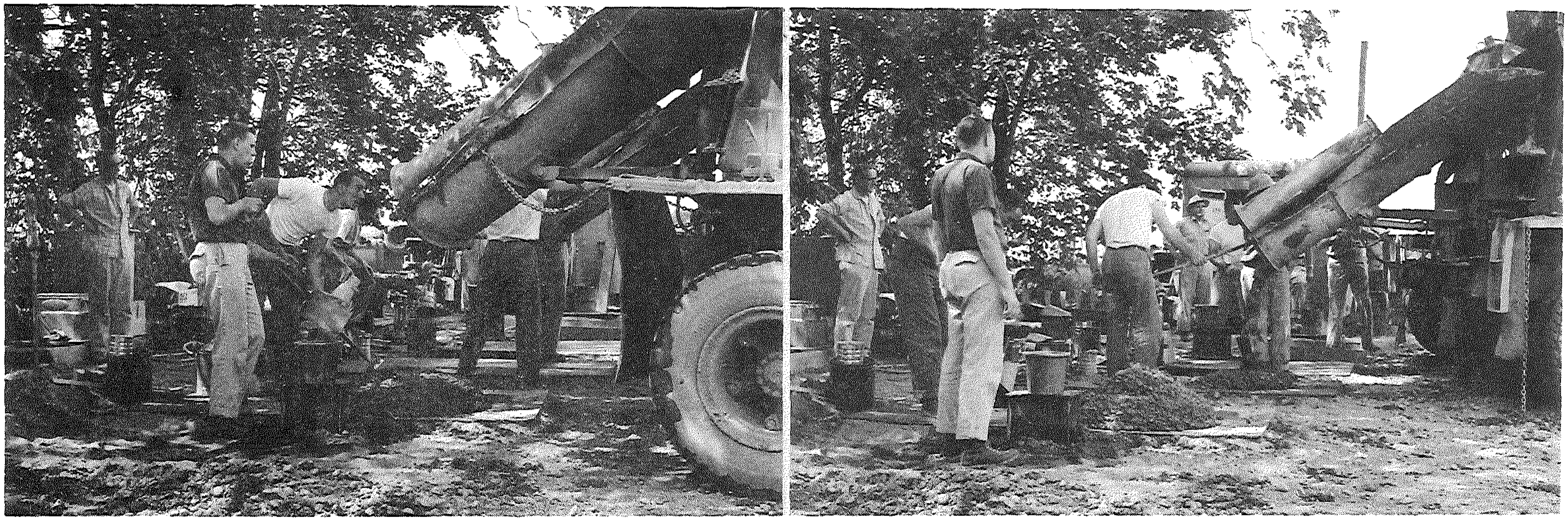
* Due to the manner of sampling, as described below, the assumption that the samples truly represent the "front," "middle," and "rear" of the batch may not be entirely valid. However, these designations are arbitrarily used throughout the remainder of this report. Knowledge is lacking concerning the precise flow line of the concrete as it discharges from the mixer drum.



Front portion of mix (Test Platform A)

Middle portion of mix (Test Platform B)

Rear portion of mix (Test Platform C)

Figure 5.
Sampling procedures.

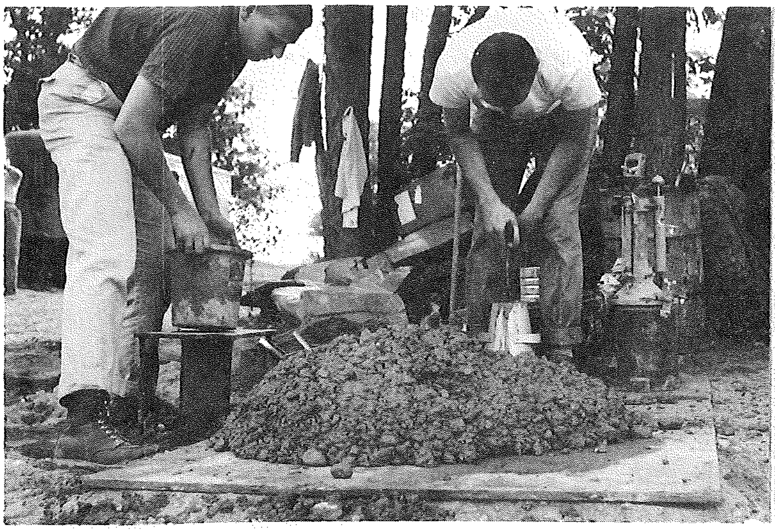
where they were mixed for the required test time. Mixing time, as defined by ASTM and Michigan State Highway Department specifications, was measured from the instant that all dry materials were in the mixer drum. Complete discharge of the dry storage bin into the mixer required 41 sec.

3. At the end of the mixing time, mixer rotation was stopped and the batch discharged into three haul trucks in the following manner: the mixer drum was slightly tilted, without further rotation of the mixer, until approximately 1 cu yd of concrete was discharged directly through the surge tank into a haul truck. This truck was directed to Test Platform A (Fig. 5), where 300 to 400 lb of concrete was deposited. The truck then returned to the line of waiting empty trucks to resume normal operations. A second truck moved under the surge tank and about 6.5 cu yd of the batch was discharged through the surge tank into this truck, by tilting the mixer drum further. This truck was directed to Test Platform B where 300 to 400 lb of concrete was deposited. This second truck then hauled the remaining load of concrete to the paving site. One of the test personnel accompanied the truck and determined the air content of this particular portion of the concrete batch after delivery at the paving site. The last of the test batch was discharged through the surge tank into a third truck, which was directed to Test Platform C, where 300 to 400 lb of concrete was deposited. To complete the discharge, a partial revolution of the mixer drum was required. This truck then returned to the mixer for a full load and resumed its normal operations.

On completion of this mixing and sampling procedure, the mixer returned to automatic control and production of concrete continued without further interruption by the testing personnel, until the next test batch was mixed. The procedure of test batch mixing and truck sampling consumed about 15 min during which the mixer production was interrupted only about half of the time. Tests of batches were conducted at a rate of approximately one per hour. The production of concrete for paving purposes was interrupted to a minimum.

Testing Procedures

Tests for slump, air content (pressure method), unit weight, and compressive strength of molded concrete cylinders were performed according to ASTM test procedures on each sample deposited on the test platforms (Fig. 6). Slump and air content tests were conducted simultaneously on all three portions of the batch. The unit-weight test and the molding of the cylinders were performed as soon as possible after the slump and air tests.



Slump and pressure air testing

Unit weight and pressure air testing

Making 6- by 12-in. compression test cylinders

Washout over No. 4 sieve (top) to recover coarse aggregate, and nest of 3/8-in. and No. 4 sieves being vibrated (bottom) to recover sample of mortar.

Figure 6.
Testing procedures.

In addition to the air content test at the plant, air content also was determined at the paving site on concrete samples taken from the haul trucks containing the middle portions of the test batches. This test was performed to detect any change in concrete air content occurring during the haul between the central mixing plant and the paving site.

Five test cylinders were molded in wax-coated cardboard 6- by 12-in. cylinder molds, from each of the three portions of the batch. They were marked for identification and stored immediately on a bed of wet sand, where they were covered with wet burlap and then buried under wet sand for 24 hr at the test site. At the end of 24 hr, the cylinders were removed from the wet sand storage, placed in a closed truck, and transported in their molds under wet burlap to the laboratory in Ann Arbor, approximately 70 mi away. Immediately upon arrival at the laboratory, the molds were removed and the cylinders marked for identification and placed in the moist storage room to await the 28-day compressive strength test.

The distribution of coarse aggregate throughout the batch was determined from concrete from the pressure air meter bowl, the contents of which were weighed before assembling for the air test. After completing the air tests, the concrete was immediately washed over a 16-in. -diam No. 4 sieve (Fig. 6). The aggregate retained on the sieve was bagged and shipped to the laboratory for drying, weighing, and determination of the percent of coarse aggregate.

Concrete mortar samples of each test batch were obtained by vibrating the concrete on standard 3/8-in. and No. 4 sieves and into a sieve pan. Each sieve was equipped with a split band to which was attached a clamping device for holding an electric spud-type vibrator. Vibrating the sieves with this apparatus simplifies an otherwise difficult operation. The arrangement of the sieves and electric vibrating equipment is shown in Fig. 6. The mortar samples were placed in test tubes, sealed, marked for identification, and sent to the laboratory for possible future analysis of the cement content.

The temperatures of the air and fresh concrete were determined for each test batch at the test site.

DISCUSSION OF TEST RESULTS

Data acquired in this study are listed fully in Table B and summarized in Table A.

Consistency

Concrete consistency was measured by the slump cone on the front, middle, and rear portions of each test batch. Of the fifteen batches tested, only four had ranges of slump within the batch greater than 1 in. The maximum range observed for a single batch was 1-5/8 in. The greatest individual slump determination was 3-3/4 in. and the lowest 1-3/8 in., indicating that concrete of uniform consistency was provided throughout the test program.

Slump was controlled by the mixer operator in the control cab adjacent to the mixer. The amount of current input to the electric motors causing rotation of the mixer drum was visible to him at all times on a large-faced ammeter. Experience with the central-mix paving operation enabled the mixer operator to adjust the water on the basis of these ammeter readings, so as to insure concrete of proper consistency for successful paving with the equipment used.

A comparison between the amount of water called for on the plant inspector's quantity sheet and the actual amount used in the mix as read from the water meter, showed that on the average 0.4 gal of water per sack of cement was added to the mix.

The data were reviewed to determine whether any pattern of slump values could be determined; for instance, whether the front portion had consistently high or low values. The front and middle portions of the batch appeared equally likely to have either the high, median, or low slump value, but the rear of the batch tended to be either the high or the low for the batch. Three out of the four batches having slump ranges greater than 1 in. had minimum slump values recorded for the rear portion of the batch.

The three values were averaged for slump from the front part of the three batches, for the same mixing time. The same was done for the three values from the middle and the rear portions of the three batches. The results of these computations are given in Table B and plotted in Fig. 7, which shows no definite pattern as to whether the front, middle, or rear of the batch will have consistently high, median, or low slumps, and average slumps are well confined in a band between 2 and 3 in.

The average within-batch variations in the second column of Table A tend to show minimum variation for 120-sec mixing time and increasing slump variations for either longer or shorter times. However, the rather wide scatter of values contributing to these averages indicates that many more repeat batches would have to be sampled before such a conclusion could be positively confirmed.

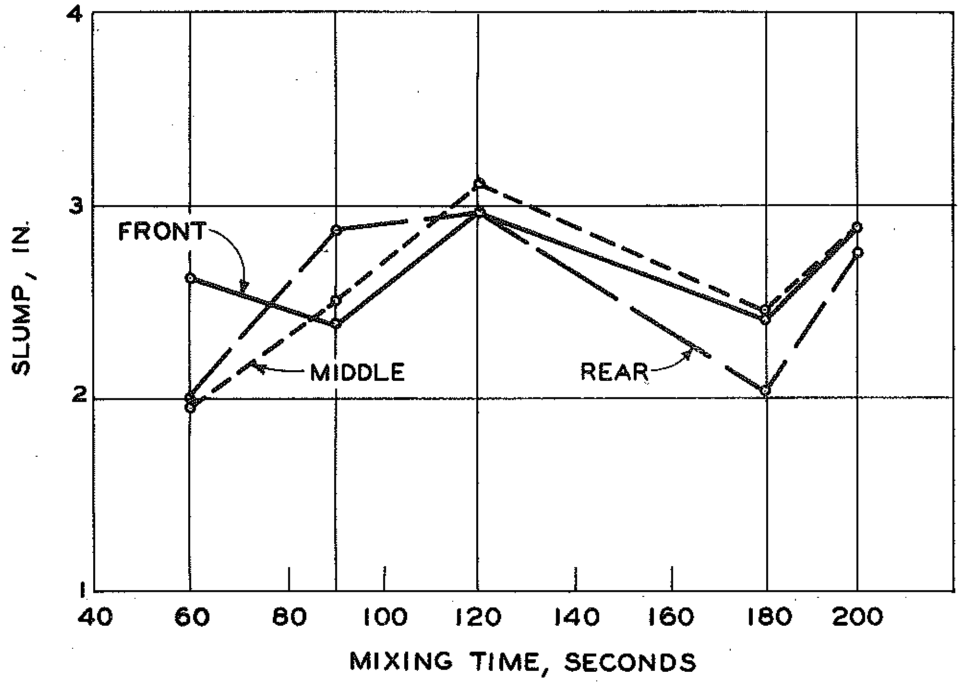


Figure 7. Slump of concrete.

Air Content of Mixes

Air content was measured, using the pressure method, on each portion (front, middle, and rear) of all test batches, as well as on the middle portion of all test batches after delivery to the paving site. All air measurements were performed simultaneously on each portion of a batch at the plant site. The air-entraining agent, Airtex (vinsol resin solution), was used in all mixes in the amount of 15 oz per 8.5 cu yd batch. No additional Airtex was added to the test batches, even though it was realized that for some mixing times air content would be low, but not so low as to provide inadequate frost resistance. This policy was followed in order to eliminate a complicating variable.

Air contents for single batches ranged from 2.9 percent for the first batch of the 60-sec mix period to 4.9 percent for the third batch of the 200-sec period (Table B). All values tended to be on the low side of Michigan's specified 4 to 7 percent air content for paving concrete. The range in air content within single batches varied from 0.0 to 0.8 percent (Table B).

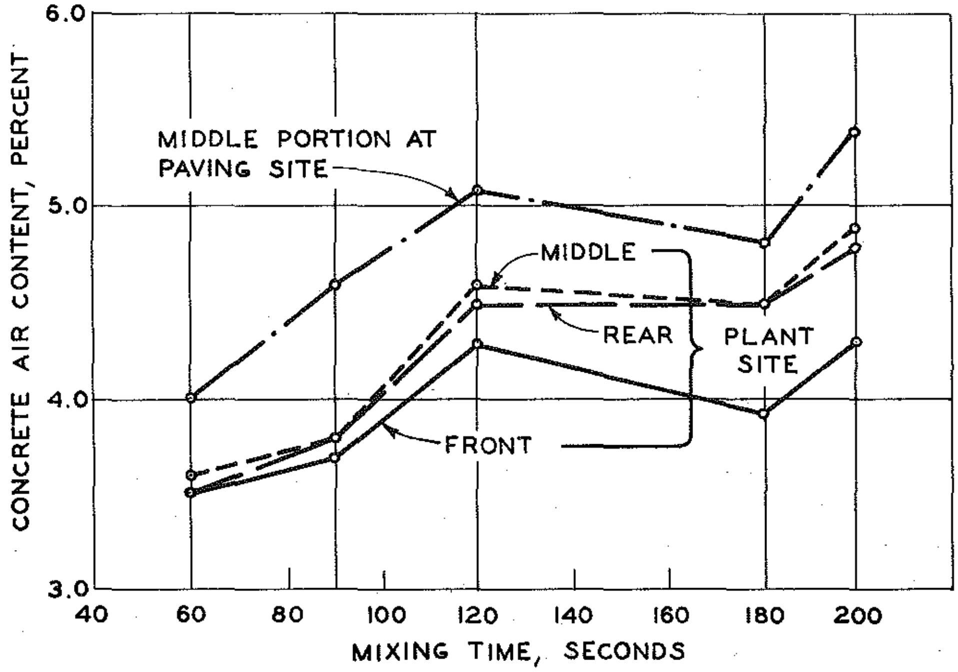


Figure 8. Air contents at plant site and at paving site.

For further investigation of the possibility that one portion of the batch might always contain a high or low amount of air for the various mixing times, the air contents were averaged for the front, middle, and rear portions of the three batches for the same mixing time. The results are given in Table B and Fig. 8, which shows that average air content for the front portion of a mix is always lowest and the middle portion always highest, regardless of mixing time. It will also be noted that the spread in average values increases as mixing time increases, but is not large. Different portions of an average batch at 180-sec mixing time provided average air contents varying within the batch by only 0.7 percent, which is the maximum spread for all test mixing times.

The general trend of the data indicates increased air at increased mixing times. Although air contents for all mixing times could presumably be brought to a common level by appropriate changes in dosage of air-entraining admixture, the question can be raised as to whether all would then possess equally effective air void systems. Independent study would be required to settle this matter.

The upper line in Fig. 8 represents the air content in the middle portion of the test batches, after concrete had been hauled from the central mixing plant to the paving site. The distance of this haul diminished from 3.4 to 2.5 mi during the course of the testing program. A composite sample was taken for the air content test, as the haul truck discharged into the paving spreader. The air content tests resulted in higher values at the paving site than for the same portion of the batch at the plant test site. The difference may be due in part to a somewhat segregated sample having been obtained, as indicated by one coarse aggregate determination made on the contents of the air meter bowl after the air content had been determined at the paving site. The percent of coarse aggregate in this sample was found to be 48.8 as compared to an average of 53.6 for all samples taken from the middle portion of the test batches at the plant.

To verify the accuracy of the air meters used at the plant site and the paving site, a quantity of concrete was transported in a sample pan from the paving site back to the plant, where simultaneous air content determinations were made on the concrete, using the air meters for the middle portion of the test batches employed at the plant and the paving site. These determinations showed that the percent of air varied only by 0.1 between the two air meters. A second air determination was made about an hour later with the same two air meters on a sample from the middle portion of a test batch. This test was conducted 37 min after the sample was deposited on the test platform. The difference in the air percentages was only 0.2. Both these determinations indicate that the air meter used to determine the air content on the middle portion of the test batches at the paving site was in satisfactory working condition. Therefore, it is logical to assume that the high air contents determined at the paving site may have been due to some segregation in the samples there, even though precautions were taken to eliminate this condition.

Another possible cause of higher air content at the paving site might be that as the concrete is transported to the paving site, some of the small air bubbles may coalesce into larger bubbles. Such action would reduce air pressure within the bubbles, thus increasing the apparent air content.

Unit Weight of Fresh Concrete, Hardened Concrete, and Yield

The weight per cubic foot of fresh concrete was determined for each of the three portions of the test batches by use of a 0.5 cu ft measure. The results of the field determinations are given in Table B.

The data show that the front portion of the batch is most likely to have the highest unit weight of the three portions. The other two portions, middle and rear, are about equally likely to contain the low value for unit weight. Averaging the various portions of the batches, with respect to the same mixing time, produces the same trend, as shown in the three lower lines of Fig. 9.

The range of values for unit weight within the individual test batches is from 0.0 to 2.1 lb. Averaging the ranges for individual batches for the same mixing time, shows that the average range decreases from 1.70 at 60 sec to 0.73 at 120 sec, and then increases to 1.20 at 200 sec. These values, shown in Fig. 10, indicate that the mixes having the most uniform unit weight were produced in mixing periods of 120 and 180 sec. The conclusions, based upon unit weight of hardened concrete, and presented later, do not entirely confirm this trend.

The unit weight of the concrete after hardening 28 days was determined by weighing the cylinders molded for compressive strength, both in air and when suspended in water immediately upon removal from the moist room and just prior to capping. Five cylinders were made from each of the three portions, front, middle, and rear, of each test batch; thus, a total of 15 cylinders were made per test batch, for which unit weights were determined. Unit weight values determined and their averages are shown in Table B.

The following analysis is based on average unit weight of the 15 cylinders molded from the front, middle, and rear portions of each of the three test batches having the same mixing time. These data are shown in Table A, Table B, and by the upper three lines of Fig. 9. These tabulations, and particularly Fig. 9, show that unit weight of the hardened concrete averages 1.3 lb heavier than the unit weight determined for fresh concrete. Fig. 9 shows further that as mixing time increases, the spread in values for unit weight between portions of the batches increased from 0.1 lb at 60 sec to 1.6 lb at 200 sec mixing time. Because the spread in these values is small--approximately 1.1 percent of the average unit weight--it can be said that rather uniform concrete was produced. Finally, Fig. 9 also shows that at mixing times of 120 sec or more, average values for the front, rear, and middle portions of the batch always have the highest, median, and lowest unit weight values, respectively.

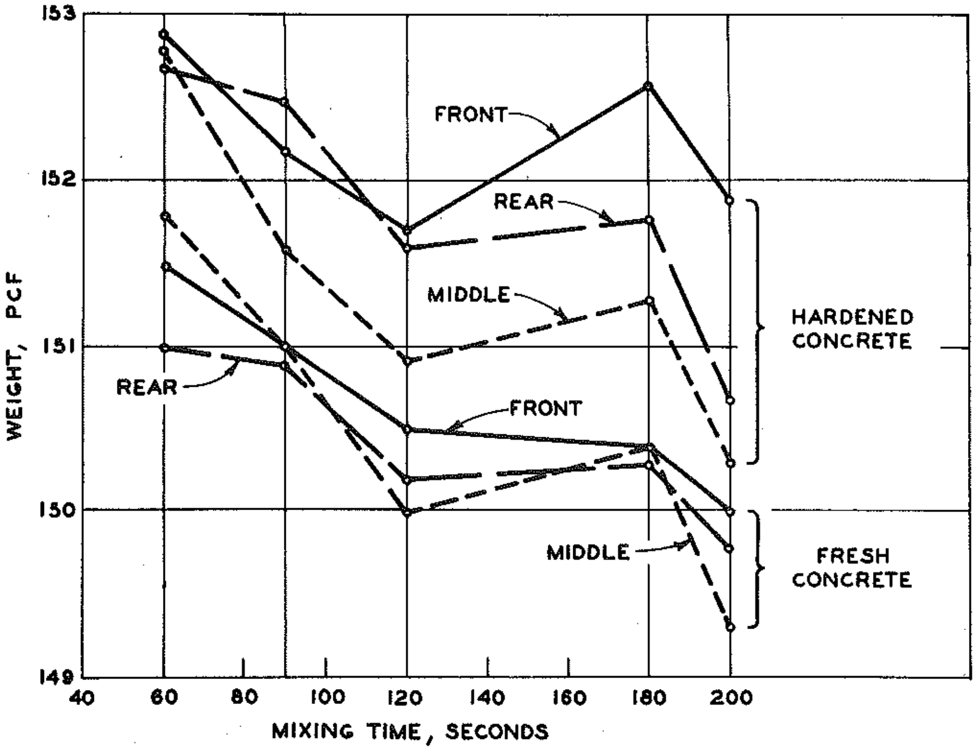


Figure 9. Unit weight of hardened concrete determined from cylinders (average of 15), and fresh concrete determined from 0.5 cu ft measure (average of 3).

Comparison of Figs. 8 and 9 shows that unit weight curves are approximately inverse images of the air content curves. This reflects the normal relationship between these two properties of concrete, for as air content increases, unit weight decreases.

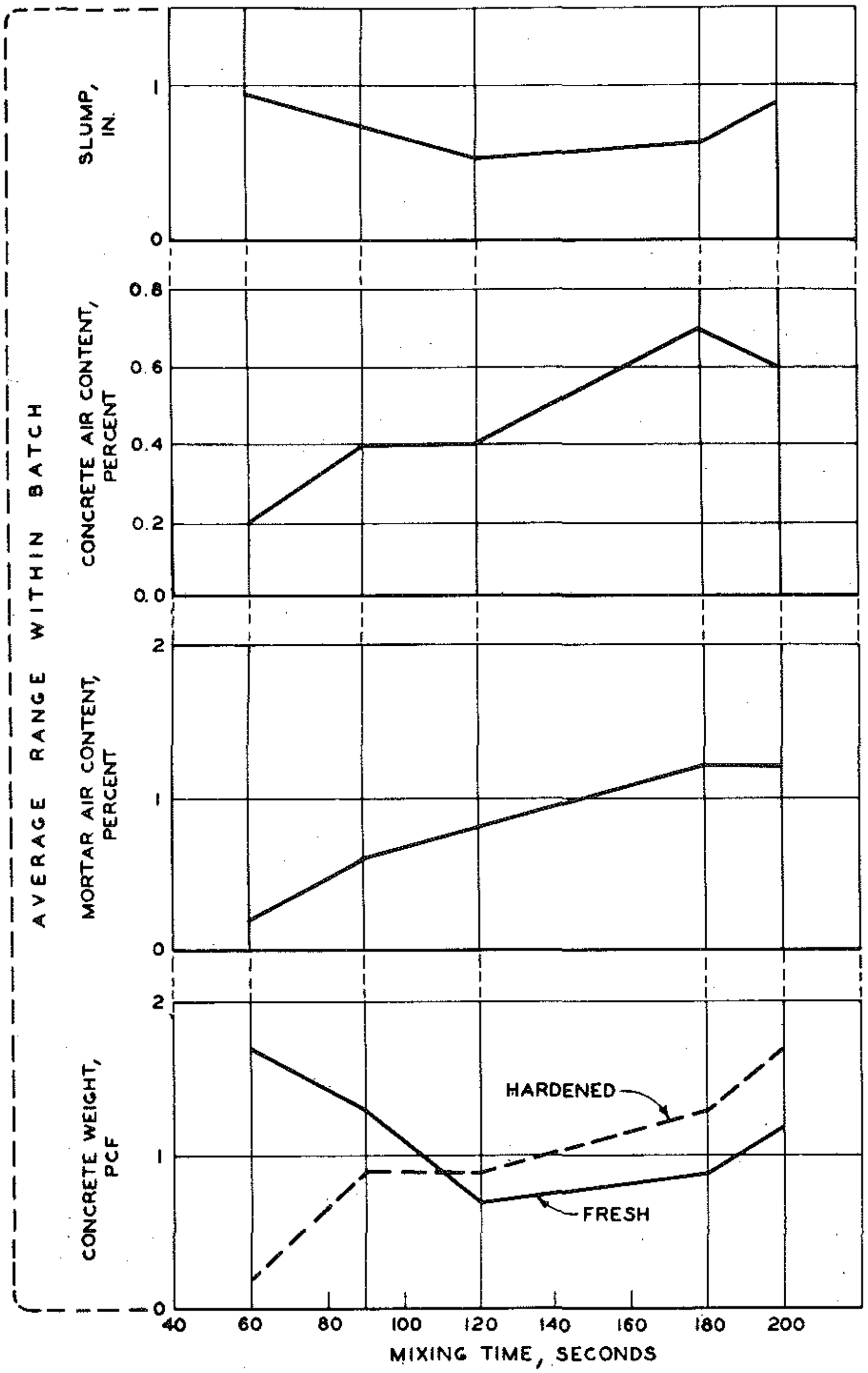


Figure 10. Average ranges of variation within batches.

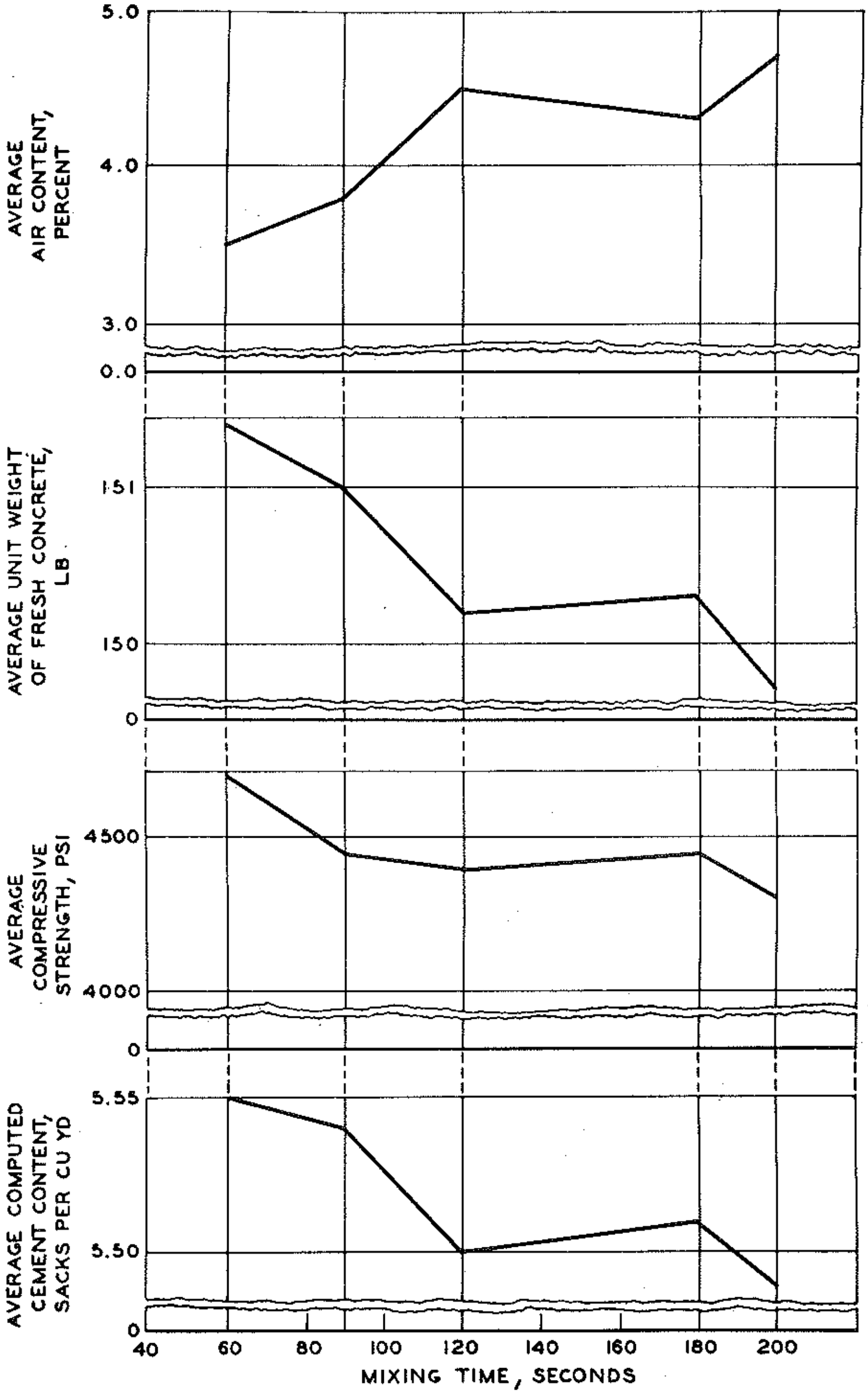


Figure 11. Average computed cement content, compressive strength, unit weight, and air content.

The average range of unit weight values, as determined from hardened concrete for the same mixing time, is shown in Table A and Fig. 10. The curve representing average ranges for hardened concrete is similar to that for fresh concrete, except at the 60-sec mixing time. Review of the data does not disclose any specific reason for the discrepancy between the fresh and hardened concrete values at the 60-sec mixing time.

The yield of all test batches, as computed from weight per cubic foot of concrete and batch weights, varied from 98.8 to 100.6 percent, with an average yield equal to 99.7 percent.

Actual cement content per cubic yard, again calculated from unit weight and known batch quantities, varied from 5.47 to 5.57 sacks per cu yd. Average actual cement content was 5.52, within 0.5 percent of the design cement content of 5.5 sacks per cu yd. A correlation between the unit weight of fresh concrete, actual cement in sacks per cu yd, and average compressive strength may be observed in Table B and Fig. 11. All three of these properties follow the same pattern, with the highest value occurring at 60-sec and the lowest in the 200-sec mixing time. Fig. 11 also shows the usual inverse relationship between these properties and air content, thus indicating that these properties are in their proper relationship with one another as occurs in well mixed concrete of uniform consistency.

Percent of Coarse Aggregate in Concrete

The amount of coarse aggregate in each portion of a test batch was determined by washing the previously weighed concrete sample, contained in the air meter bowl, over a No. 4 sieve; then drying the aggregate to an oven-dry condition; and weighing in air. The percentage of coarse aggregate was determined by dividing the weight of oven-dry aggregate retained on the No. 4 sieve by the original weight of the concrete sample and multiplying by 100. The results of the individual determinations and their averages are tabulated in Table B. The average values for each portion (front, middle, and rear) of the test batches for the same mixing time are shown in Fig. 12. No one portion of the test batches for any one mixing time consistently contained the high or low value for coarse aggregate percentage. Therefore, no pattern of relative position was established for any portion of the batch.

A more significant pattern, however, is found by reviewing average range values as tabulated in Table A and plotted in Fig. 13. The value for average range in coarse aggregate percentage decreases rapidly as mixing time increases, indicating that coarse aggregate was distributed throughout the batch more uniformly at longer mixing times.

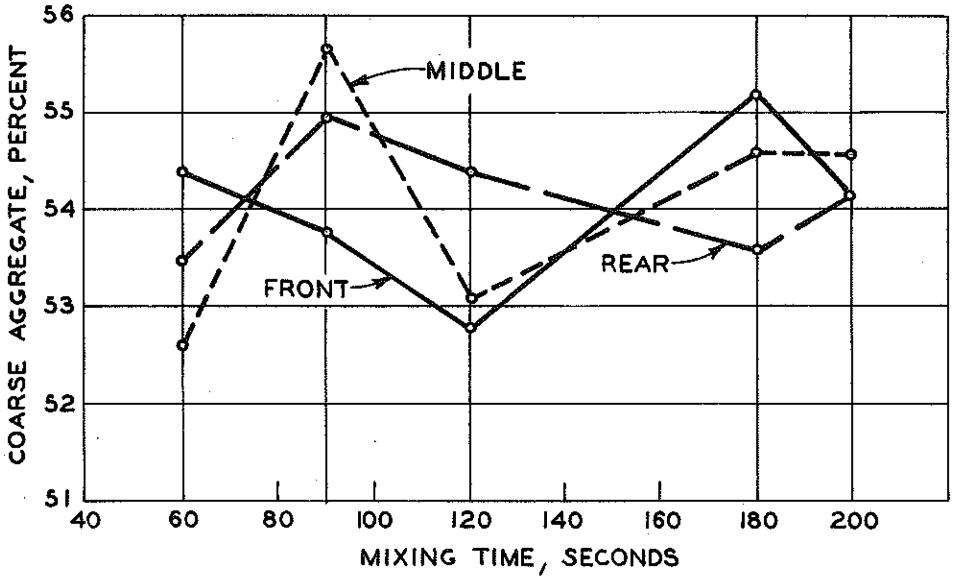


Figure 12. Coarse aggregate content.

Compressive Strength of Molded Concrete Cylinders

The 28-day compressive strength of the concrete test batches was determined by loading the test cylinders to failure in a hydraulic compression testing machine, as in ASTM Test Method C39-59. Immediately after being weighed in air and in water, the cylinders were capped with "Hydro-Stone," a commercial capping compound. The capped cylinders were covered with wet burlap until testing. The weighing operation was part of the unit weight determination for hardened concrete, and was performed immediately after the cylinders were removed from the moist room.

The results of the compressive strength tests are given in Table B and summarized in Table A. The test data reveal that only 3 of the 225 cylinders failed to meet Michigan's 28-day compressive strength specification of 3500 psi or more. The data also indicate that the average compressive strength for each test batch, as determined from 15 cylinders, ranged from 5430 to 3910 psi, and that the grand average of all cylinders was 4450 psi. Only 3 of the 15 test batches averaged less than 4000 psi.

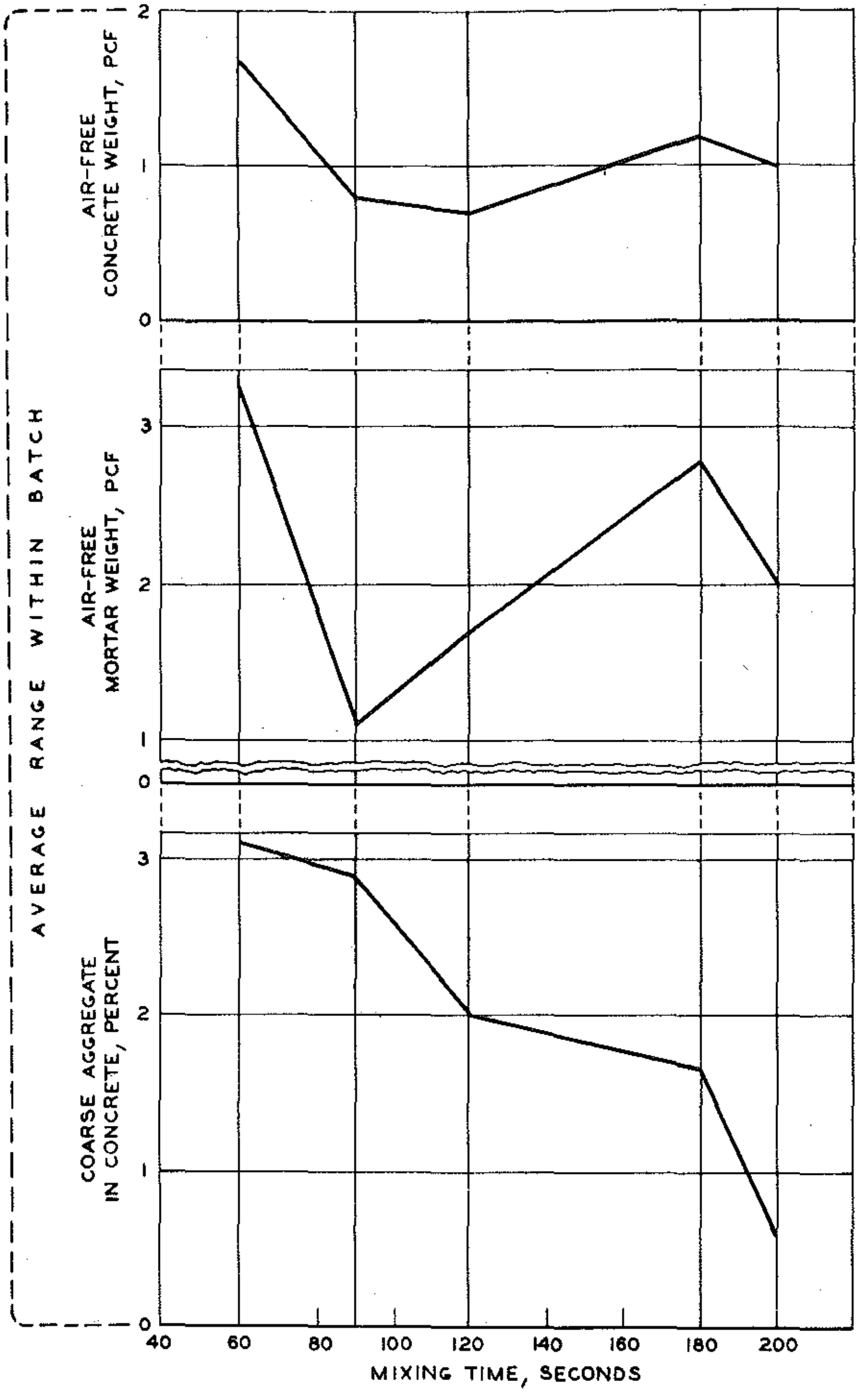


Figure 13. Average ranges of variation within batches.

Average compressive strengths for the front, middle, and rear of the test batches, for common mixing times, are given in Table B. These averages are plotted in Fig. 14, which shows that the middle of the batch always has the least average compressive strength, except for the 60-sec mix period. Of the other two portions, the rear of the batch tends to have slightly higher average compressive strengths. Comparison of Figs. 14 and 9 indicates that lines representing the front, middle, and rear of the test batches are in the same relative positions. This relationship between unit weights and compressive strength is as would be expected in well mixed concrete. It also should be noted that the compressive strength lines of Fig. 14 closely resemble the inverse of the air content lines of Fig. 7, as also would be expected.

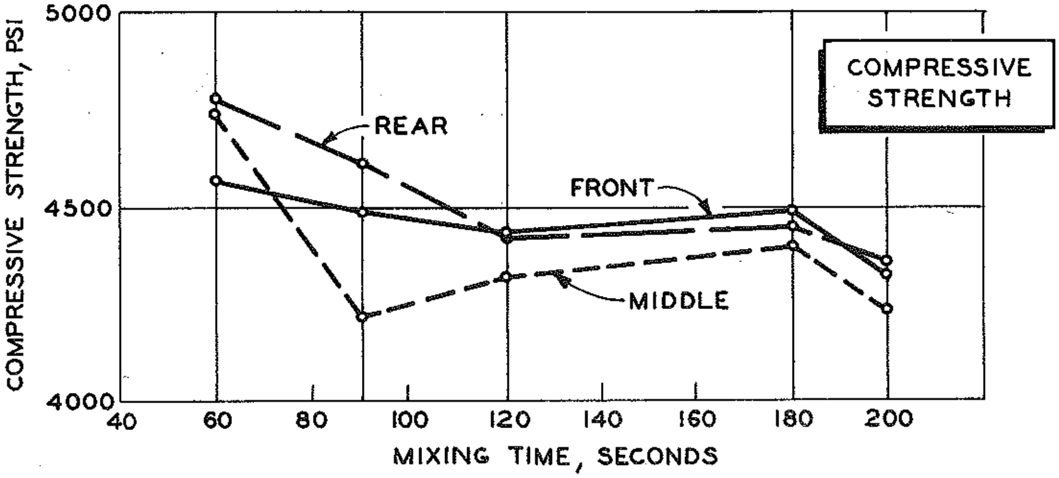


Figure 14. Compressive strengths of the three batch portions.

Test data in Table B were reviewed for any significant variability of compressive strengths among test batches. The data reveal that the cylinders molded during the first series of mixing times had higher average compressive strengths than the cylinders molded during the other two series of mixing times, as may be observed in the values of Table 1, which is a summary of data from Table B.

Plausible causes were sought to explain the fact that average compressive strengths of cylinders molded during the three rounds varied in average strength level. Such variations might arise from changes in concrete materials, techniques of molding or testing cylinders, temperatures of air and fresh concrete, or in moisture available to the cylinders during the first 24 hr of curing. Nothing can be detected from the plant inspector's data sheet to indicate that concrete materials changed to any degree during the test period. The temperatures of the air and fresh concrete given in Table C reveal nothing of an adverse nature. During the first 24 hr of curing, every effort was made to provide the cylinders with proper strength-producing protection. No evidence is known to the contrary. The technique used to mold the cylinders appeared to be in accord with standard test procedures. Uniformity in the technique of molding and testing the cylinders, however, may be checked by computing

TABLE 1
AVERAGE COMPRESSIVE STRENGTH

Test Series	Mixing Time, seconds	Batch No.	Avg Compressive Strength, psi*
1 (June 19-20, 1961)	60	1	5430
	90	2	4890
	120	3	4930
	180	4	4940
	200	5	4840
			Average 5010
2 (June 21, 1961)	60	6	4290
	90	7	3910
	120	8	3990
	180	9	4050
	200	10	3940
			Average 4040
3 (June 21-22, 1961)	60	11	4370
	90	12	4520
	120	13	4250
	180	14	4320
	200	15	4130
			Average 4320

* Average of 15 cylinders per test batch.

the coefficients of variation of the compressive strengths of the five cylinder groups for each portion of all test batches. Coefficients of variation were computed, and average values for each portion of a test batch are given in Table 2. The average coefficients of variation for the second round of mixing times are higher than average coefficients of variation for the other two rounds, thus indicating the probability of some minor change in techniques of molding or handling these test cylinders.

TABLE 2
COEFFICIENTS OF VARIATION
OF COMPRESSIVE STRENGTH

Test Series	Mixing Time, seconds	Batch No.	Avg Coefficient of Variation, percent
1 (June 19-20, 1961)	60	1	2.64
	90	2	3.86
	120	3	2.76
	180	4	3.45
	200	5	3.70
		Average	3.28
2 (June 21, 1961)	60	6	5.41
	90	7	8.74
	120	8	6.12
	180	9	5.69
	200	10	4.79
		Average	6.15
3 (June 21-22, 1961)	60	11	3.88
	90	12	5.25
	120	13	2.22
	180	14	3.75
	200	15	3.01
		Average	3.62

Comparing average coefficients of variation in Table 2 with corresponding average compressive strengths in Table 1 indicates that the highest coefficients of variation and lowest average compressive strengths both occur within the second series. Referring to Table B, it will be noted that Test Batches 7, 9, and 10 each contain one test cylinder with a 28-day compressive strength less than the specified 3500 psi. All these batches were mixed during the second series of mixing times, thus giving additional evidence that the low compressive strength for these three second-round cylinders was primarily due to a change in cylinder molding or testing techniques.

It should be reiterated, however, that all batches tested provided compressive strengths well above Michigan's 3500 psi requirement.

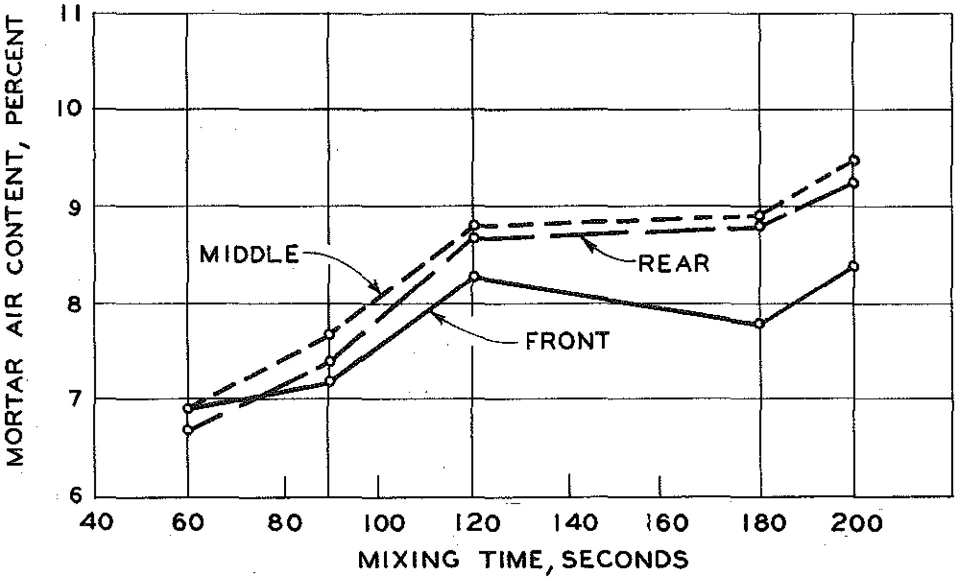


Figure 15. Mortar air content.

Percent of Air in Mortar

The percent of air in the mortar of the concrete test batches was determined by computation from the field test data, with the results given in Table B and plotted in Fig. 15. Comparing Figs. 15 and 8 shows that the lines representing mortar air percentage are similar in shape to those for concrete air percentage. The major difference lies in the magnitude of the air percentage values. The percent of air for mortar is approximately twice as great as the percent of air in the concrete, a relationship that should be expected.

Unit Weight of Air-Free Mortar

The unit weight of air-free mortar is the density of concrete mortar exclusive of air. Excessive variations in the unit weight reflect changes in water or in proportions of cement and sand. For example, according to Bloem, Gaynor, and Wilson, "if water alone is varied, and proportions of sand and cement remain the same, a difference in air-free unit weight of mortar of 1 lb per cu ft corresponds to a change in water of about 2 gal per cu yd in the opposite direction" (5).

The unit weight of air-free mortar was computed from the field test data using the equation developed by the Bureau of Reclamation (6), with the results given in Tables A and B. Average values for the unit weight of air-free mortar for each portion of the test batches for a common mixing time, as given in Table B, are plotted in Fig. 16. From this graph it is seen that average values for the batch portions vary considerably for mixing times of 60 and 180 sec. This spread in values is shown in Fig. 13, which gives the relation between average ranges in unit weights and mixing times. An explanation for this wide spread in values was sought in the available data. No adequate explanation could be found or proposed other than to assume, at least for the 60-sec mixing time, that the concrete was not uniformly mixed. Criteria for mix uniformity have been developed by the Bureau of Reclamation and the U. S. Army Corps of Engineers Waterways Experiment Station (8), both of which restrict the amount of variation, and are based on an average of samples taken from the test batch. The formulas for computing the percent of variation are as follows:

Bureau of Reclamation

$$\text{Percent Variation} = \frac{\text{average of front and rear values} - \text{front value}}{\text{average of front and rear values}} \times 100$$

Waterways Experiment Station

$$\text{Percent Variation} = \frac{\text{average of three values} - \text{value to produce maximum difference}}{\text{average of three values}} \times 100$$

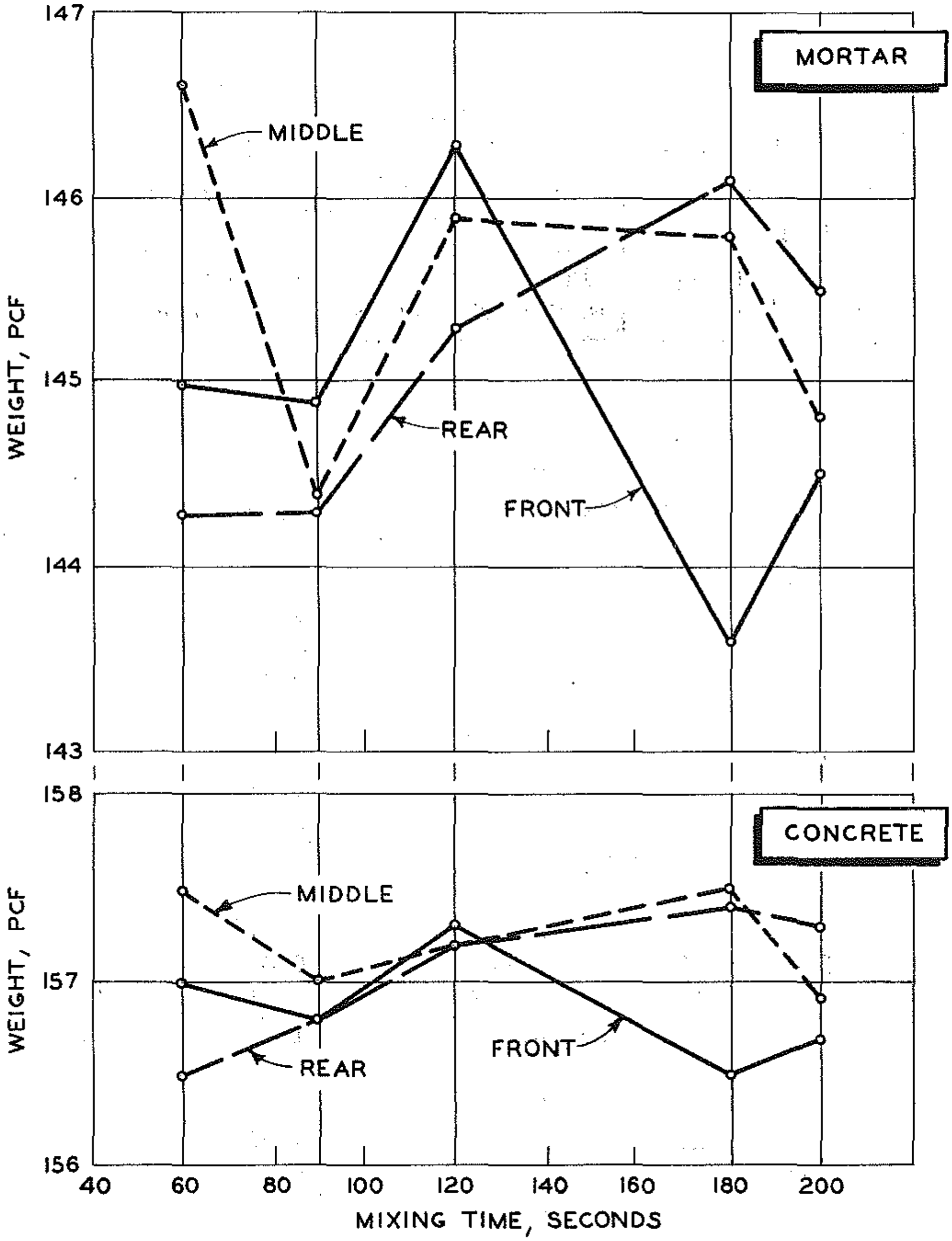


Figure 16. Weights of air-free mortar and air-free concrete.

By either method, the suggested maximum variation is 0.8 percent. The variation was computed by both methods and the results are tabulated in Table 3.

TABLE 3
PERCENT VARIATION IN UNIT WEIGHT OF AIR-FREE MORTAR

Mixing Time, seconds	Batch No.	Percent Variation	
		Bureau of Reclamation	Waterways Experiment Station
60	1	0.63	1.54*
60	6	0.68	0.75
60	11	0.62	1.30*
	Average	0.64	1.20
90	2	0.49	0.84*
90	7	0.21	0.35
90	12	0.00	0.07
	Average	0.23	0.42
120	3	0.62	0.90*
120	8	0.68	0.68
120	13	0.27	0.48
	Average	0.52	0.69
180	4	1.10*	1.37*
180	9	0.21	0.48
180	14	1.24*	1.45*
	Average	0.85	1.10
200	5	0.00	0.28
200	10	0.82*	1.45*
200	15	0.14	0.55
	Average	0.32	0.76

* Failed proposed criteria.

Applying the criterion of 0.8-percent maximum variation in the unit weight of air-free mortar to the values in Table 3, it will be noted that only 3 of the 15 test batches failed to show uniformity of mixing by the

Bureau of Reclamation method of computing maximum variation, while 7 of the 15 test batches failed by the Waterways Experiment Station method of computation. The latter method of computing the maximum percent variation in the unit weight of air-free mortar in rare cases provides values equal to the Bureau of Reclamation method, but generally they are higher.

As was stated previously, the average unit weights for portions of the test batches varied considerably for mixing times of 60 and 180 sec. Table 3 shows that the batches mixed 60 sec met the Bureau of Reclamation criterion, but that two of the batches mixed 180 sec failed to meet it. This situation is due to the method of computing the average unit weights, and to the fact that values of the front and rear portions used to compute average unit weight for 60-sec batches happened to be nearly equal, while the values used for the 180-sec batches were quite widely spread. Referring to Table B, it is seen that the middle portion of only 4 of the 15 batches tested had unit weights which were median to the unit weights of the front and rear portions of the batches, thus leading one to suspect that an average based on the front and rear portions frequently does not reflect the unit weight of the middle portion of the batch.

The Waterways Experiment Station method of computing the maximum variation eliminates this difficulty, for it includes all three portions of each batch, which seems to be a more logical approach in determining the maximum percent variation. Using this method of computing the maximum percent of variation and its criterion value of 0.8 percent, Table 3 demonstrates that serious departures from the criterion occurred at all mixing times except 90 and 120 sec.

Unit Weight of Air-Free Concrete

The unit weight of air-free concrete is the density of concrete exclusive of air. The basic difference between the unit weight of air-free concrete and the unit weight of air-free mortar is that the concrete value not only includes the proportions of water, sand, and cement in the mix, but also the proportion of coarse aggregate. Any variation in the unit weight of the air-free concrete will reflect variations in the proportions of all these materials.

The unit weight of air-free concrete was determined by computation from field test data. Results of the computations are given in Tables A and B. The average unit weights for each portion of the test batches for common mixing times are also plotted in Fig. 16. Comparison of these curves with those for air-free mortar shows a similarity between the two sets of curves. The coarse aggregate was quite uniformly distributed throughout the batches, especially in the batches with the longer mixing times, and thus had little effect on the shape of these unit-weight curves.

The only known criterion by which the unit weight of air-free concrete can be judged is one proposed by ASTM Committee C-9 on Concrete and Concrete Aggregates (4). This proposed criterion states that the unit weight of air-free concrete should not differ by more than 1 lb between samples taken at the front and rear of a test batch. Applying this limitation to the values for unit weight of air-free concrete given in Table B, 7 of the 15 test batches failed to meet the criterion. It is of interest to note that all five of the test batches that failed to meet the U. S. Army Corps of Engineers Ohio River Division criterion for unit weight of air-free mortar (1), are included in these seven batches. From data available it appears that the unit weight of air-free concrete may not be as sensitive an indicator of mix uniformity as the unit weight of air-free mortar, and therefore is of relatively minor importance.

Temperature of Air and Concrete

The temperatures of the air and of the fresh concrete were determined both at the plant and paving sites. The values observed are presented in Table C. The maximum difference between air and concrete temperatures at the plant site was 12 deg. On the average, concrete temperatures at the two sites were the same.

SUMMARY

This investigation was conducted primarily to obtain information relative to the length of time necessary to mix concrete materials in one large stationary mixer, when charged in the manner stated, so that concrete discharged from this mixer will be uniform in gradation of aggregates, air content, consistency, and strength-producing properties. Several tests, as previously described and discussed, were performed on the samples of concrete. The following observations are drawn from the results of these tests.

Slump. Within-batch variations of slump were reasonably uniform at all mixing times, but smallest variations occurred at 120 sec, with increasing variations both at shorter and longer mixing times.

Air Content of Fresh Concrete. At a constant level of air-entraining admixture dosage to supplement the air provided by the Type IA cement employed in this project, overall air content of the fresh concrete increased with mixing time except for a slight, inexplicable decrease at a mixing time of 180 sec. Within-batch uniformity of the air tended to diminish at longer mixing times but was equal for 90 and 120 sec. On the average, the front portions of batches showed lowest air contents.

Unit Weight of Concrete. Unit weight of both fresh and hardened concrete reflected the effects of concrete air content at all mixing times. Except for the 60-sec mixes, duration of mixing had only slight effect on the uniformity of unit weight for the fresh concrete.

Percent of Coarse Aggregate. Increased mixing time increased the uniformity of coarse aggregate distribution throughout the test batches. No particular portion of the test batches was consistently high or low in its quantity of coarse aggregate.

Compressive Strengths. Compressive strengths of test batches reflected the effect of concrete air content. Air content increased with longer mixing time, and strength decreased. This air-strength relationship also held true between portions of the test batches. The middle portions of the test batches, which on the average contained the highest air contents, produced the lowest strengths for all mixing times except 60-sec. Strengths were more uniform among portions of the test batches at mixing times of 120 seconds or more.

Unit Weight of Air-Free Mortar. Unit weight of air-free mortar, reflecting proportions of water, sand, and cement in a batch or portions of a batch, was on the average quite uniform in value for three of the five mixing times (90, 120, and 200 sec), thus indicating that uniformly mixed concrete was produced. No portion of the test batches, regardless of mixing time, consistently had the high or low values.

Unit Weight of Air-Free Concrete. Unit weight of air-free concrete reflects not only the proportions of water, sand, and cement in a concrete batch, but also the proportion of coarse aggregate. Because of the uniform distribution of coarse aggregates in the test batches, conclusions for unit weight of air-free concrete are primarily duplications of those given for the unit weight of air-free mortar. Again, mixing times of 90, 120, and 200 sec were more favorable.

Percent of Air in Mortar. The percent of air in the mortar increased as mixing time increased, and was about twice that in concrete. No new information was gained in calculating this item.

Concrete Mixer Performance Limits

Various manuals and reports (1, 4, 5, 6, 8) on concrete mixer performance propose specific limits on within-batch uniformity of slump; air content; unit weight of fresh concrete, air-free concrete, and air-free mortar; percent of coarse aggregate; and 7- and 28-day compressive strengths. These publications do not all advocate the same tests as a measure of mixer performance. However, all do advocate the use of unit weight of air-free mortar and percent of coarse aggregate as suitable determinations for concrete mixer performance. Compliance of a mixer with specified limits is variously based on tests on three samples of concrete from the front, middle, and rear of the mixer drum, or on two samples taken at equal distances from the front and rear of the drum. The degree of compliance of the present mixer with the specified limits, on the particular four days of operation observed, is given in Table D.

Lacking more extensive data, it must be assumed that the observations pertain only to this mixer when charged in the manner described and when using the particular paving mix used on this job. If the criteria of the four organizations listed are composited, the 90- and 120-sec mixing times are equally successful in compliance. Either shorter or longer times are less favorable.

Another approach to estimating the overall performance of this mixer is to list the mixing times at which each property of the concrete is provided with best uniformity within the batch. Below are listed these times for the properties observed:

Property	Mixing Time for Optimum Uniformity, sec				
	60	90	120	180	200
Slump			x		
Air Content	x				
Unit Weight			x		
Coarse Aggregate Content					x
Compressive Strength (Alternative Times)			x	x	x
Unit Weight of Air-Free Mortar		x			

Due to scatter of the data and limited number of batches sampled, the selection of a single optimum mixing time for a given property is surrounded by some uncertainty. In one case, the data definitely did not warrant selection of a single optimum time and alternative times are listed. It is observed from the tabulation that 120-sec mixing provided the best chance of simultaneously providing optimum uniformity of all properties. Uniformity of coarse aggregate distribution was best at 200-sec mixing. However, the significance of this latter departure from the trend may not be serious, since the proposed criteria of all four organizations would consider coarse aggregate distribution satisfactory for all batches at mixing times greater than 60 sec. Similarly, uniform distribution of air in the concrete appeared to be best at 60 sec, but excessive variations did not occur at any mixing time.

The data point to the conclusion that this mixer, at the time of observation, satisfactorily blended the concrete ingredients in a shorter time than the 180 sec presently prescribed by ASTM and Michigan State Highway Department specifications.

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APPENDIX

TABLE A
SUMMARY OF TEST RESULTS FOR FRESH AND HARDENED CONCRETE

	Mixing Time, seconds	Slump, in.	Air Content of Concrete, percent		Concrete Weight, pcf		Coarse Aggregate Content, percent	28-Day Compressive Strength, psi	Batch Yield, cu yd	Yield, percent of design	Actual Cement Content, sacks/cu yd	Air-free Weight, pcf		Mortar Air Content, percent
			Plant Site	Paving Site	Fresh	Hardened						Concrete	Mortar	
Grand Averages	60	2.19	3.5	4.0	151.4	152.8	53.5	4700	8.42	99.1	5.55	157.0	145.3	6.8
	90	2.58	3.8	4.6	151.0	152.1	54.8	4440	8.45	99.4	5.54	156.9	144.5	7.4
	120	3.01	4.5	5.1	150.2	151.4	53.4	4390	8.50	99.9	5.50	157.2	145.8	8.6
	180	2.31	4.3	4.8	150.3	151.9	54.5	4440	8.48	99.8	5.51	157.1	145.2	8.4
	200	2.83	4.7	5.4	149.7	151.0	54.4	4300	8.52	100.3	5.49	157.0	144.9	9.0
Batch to Batch Variation (Range of Avg)	60	0.67	1.2	1.1	1.1	1.5	4.1	1140				0.9	3.5	1.9
	90	1.25	1.3	2.2	1.2	2.0	4.0	980				1.0	3.0	2.4
	120	0.62	0.5	0.8	0.9	0.7	1.5	940				1.0	1.9	0.9
	180	0.79	0.1	0.9	0.7	0.3	1.6	890				0.7	0.7	0.5
	200	0.84	0.7	0.3	0.9	1.0	2.1	900				0.5	2.0	1.2
Within Batch Variation (Avg of Ranges)	60	0.96	0.2		1.7	0.2	3.1	325				1.7	3.3	0.2
	90	0.75	0.4		1.3	0.9	2.9	505				0.8	1.1	0.6
	120	0.54	0.4		0.7	0.9	2.0	175				0.7	1.7	0.8
	180	0.63	0.7		0.9	1.3	1.7	205				1.2	2.8	1.2
	200	0.87	0.6		1.2	1.7	0.6	150				1.0	2.0	1.2

TABLE B
TEST RESULTS FOR FRESH AND HARDENED CONCRETE

Mixing Time, seconds	Batch No.	Batch Portion	Slump, in.	Concrete Air Content, percent		Concrete Weight, pcf							Coarse Aggregate Content, percent	28-Day Compressive Strength, psi						Batch Yield, cu yd	Yield, Percent of Design	Actual Cement Content, sacks/cu yd	Air-Free Weight, pcf		Mortar Air Content, percent	Time and Distance Between Plant and Paver	
				Plant Site	Paving Site	Fresh	Hardened																Concrete	Mortar		Minutes	Miles
							1	2	3	4	5	Average		1	2	3	4	5	Average								
60	1	Front	2.25	2.9	4.0	150.7	152.9	152.9	153.5	154.1	153.5	153.4	55.6	5090	5140	5180	5000	5270	5140				155.2	141.1	5.8		
		Middle	1.62	2.9		152.8	153.2	153.8	153.7	154.2	153.3	153.6	55.3	5830	5530	5230	5800	5510	5580				157.4	145.3	5.9		
		Rear	1.50	2.8		152.1	153.1	153.2	153.5	153.4	153.8	153.4	56.9	5480	5670	5370	5710	5550	5560				156.5	142.8	5.8		
		Average	1.79	2.9		151.9						153.5	55.9						5430	8.40	98.8	5.57	156.4	143.1	5.8	15	3.4
		Range	0.75	0.1		2.1						0.2	1.6						440				2.2	4.2	0.1		
	6	Front	3.50	4.1	4.5	151.5	151.1	152.7	151.6	153.0	152.2	152.1	52.5	4580	4080	4290	3960	4170	4220				158.0	147.7	7.8		
		Middle	2.00	4.1		150.9	151.7	151.7	152.7	152.7	151.2	152.0	52.6	3980	4420	4510	3760	4130	4160				157.4	146.4	7.8		
		Rear	1.88	4.2		149.9	152.3	152.0	151.7	152.3	151.9	152.0	50.2	4490	4450	4890	4310	4360	4500				156.5	145.7	7.6		
		Average	2.46	4.1		150.8						152.0	51.8						4290	8.47	99.6	5.52	157.3	146.6	7.7	12	3.0
		Range	1.62	0.1		1.6						0.1	2.4						340				1.5	2.0	0.2		
	11	Front	2.12	3.5	3.4	152.3	152.6	153.3	154.0	152.8	152.9	153.1	55.2	4350	4170	4730	4430	4060	4350				157.8	146.1	7.0		
		Middle	2.25	3.8		151.6	153.1	153.1	152.8	152.5	152.6	152.8	49.8	4200	4520	4470	4630	4560	4480				157.6	148.0	6.9		
		Rear	2.62	3.5		150.9	152.6	152.4	154.3	152.2	152.7	152.8	53.3	4100	4280	4470	4190	4360	4280				156.4	144.3	6.8		
		Average	2.33	3.6		151.6						152.9	52.8						4370	8.40	98.8	5.57	157.3	146.1	6.9	9	2.7
		Range	0.50	0.3		1.4						0.3	5.4						200				1.4	3.7	0.2		
Average of Portions		Front	2.62	3.5		151.6						152.9	54.4						4570				157.0	145.0	6.9		
		Middle	1.96	3.6		151.8						152.8	52.6						4740				157.5	146.6	6.9		
		Rear	2.00	3.5		151.0						152.7	53.5						4780				156.5	144.3	6.7		
Grand Average			2.19	3.5	4.0	151.4						152.8	53.5						4700	8.42	99.1	5.55	157.0	145.3	6.8		
Average Range Within Batch			0.96	0.2		1.7						0.2	3.1						325				1.7	3.3	0.2		
90	2	Front	3.25	3.2	4.9	151.6	153.1	153.4	152.4	154.3	154.0	153.4	55.2	5230	4930	4750	4890	5120	4980				156.6	143.9	6.4		
		Middle	3.38	3.6		150.4	152.0	151.9	152.4	152.4	152.1	152.2	57.2	4580	4770	4590	4240	4540	4540				156.0	141.7	7.4		
		Rear	3.25	3.0		152.1	154.0	153.6	153.7	153.5	152.7	153.5	58.6	5070	5490	5270	5140	4810	5160				156.8	142.6	6.4		
		Average	3.29	3.3		151.4						153.0	57.0						4890	8.40	98.8	5.57	156.5	142.7	6.7	12	3.1
		Range	0.13	0.6		1.7						1.3	3.4						620				0.8	2.2	1.0		
	7	Front	2.50	4.7	5.5	149.7	151.4	150.0	150.0	151.3	152.2	151.0	52.8	3940	2580	4190	4120	3820	3730				157.1	145.8	8.9		
		Middle	1.88	4.4		151.2	151.0	151.1	149.8	150.1	150.7	150.5	56.7	4030	3870	4030	3690	3820	3890				158.2	146.2	9.0		
		Rear	2.88	4.7		149.7	151.7	150.9	151.1	151.8	152.7	151.6	54.1	3920	3890	3820	4400	4520	4110				157.1	145.2	9.1		
		Average	2.42	4.6		150.2						151.0	54.5						3910	8.50	100.0	5.50	157.5	145.7	9.0	11	2.9
		Range	1.00	0.3		1.5						1.1	3.9						380				1.1	1.0	0.2		
	12	Front	1.38	3.2	3.3	151.7	152.0	152.0	152.6	152.0	152.0	152.1	53.5	5160	4750	4470	5000	4380	4750				156.7	145.0	6.2		
		Middle	2.25	3.5		151.4	151.6	152.0	152.4	151.9	152.5	152.1	53.2	4260	4030	4220	4150	4620	4240				156.9	145.2	6.8		
		Rear	2.50	3.6		150.9	151.9	152.3	153.5	151.9	152.1	152.3	52.2	4520	5000	4450	4560	4260	4560				156.5	145.0	6.8		
		Average	2.04	3.4		151.3						152.2	53.0						4520	8.44	99.3	5.54	156.7	145.1	6.6	14	2.6
		Range	1.12	0.4		0.8						0.2	1.3						510				0.4	0.2	0.6		
Average of Portions		Front	2.38	3.7		151.0						152.2	53.8						4490				156.8	144.9	7.2		
		Middle	2.50	3.8		151.0						151.6	55.7						4220				157.0	144.4	7.7		
		Rear	2.88	3.8		150.9						152.5	55.0						4610				156.8	144.3	7.4		
Grand Average			2.56	3.8	4.6	151.0						152.1	54.8						4440	8.45	99.4	5.54	156.9	144.5	7.4		
Average Range Within Batch			0.75	0.4		1.3						0.9	2.9						505				0.8	1.1	0.6		

TABLE B (Cont.)
TEST RESULTS FOR FRESH AND HARDENED CONCRETE

Mixing Time, seconds	Batch No.	Batch Portion	Slump, in.	Concrete Air Content, percent		Concrete Weight, pcf							Coarse Aggregate Content, percent	28-Day Compressive Strength, psi						Batch Yield, cu yd	Yield, Percent of Design	Actual Cement Content, sacks/cu yd	Air-Free Weight, pcf		Mortar Air Content, percent	Time and Distance Between Plant and Paver	
				Plant Site	Paving Site	Fresh	Hardened																Concrete	Mortar		Minutes	Miles
							1	2	3	4	5	Average		1	2	3	4	5	Average								
120	3	Front	2.88	4.1		150.3	151.6	151.8	153.0	152.3	152.5	152.2	52.3	4820	5230	5040	5160	5000	5050				156.7	145.2	7.8		
		Middle	3.75	4.8	5.5	149.1	150.1	151.0	150.8	150.5	150.4	150.6	51.6	5090	4910	4790	4630	4840	4850				156.6	145.4	8.9		
		Rear	3.38	4.0		150.3	152.3	151.8	153.0	151.8	151.0	152.0	55.7	4810	4950	5040	4880	4700	4880				156.6	143.4	8.0		
		Average	3.33	4.3		149.9						151.6	53.2						4930	8.51	100.1	5.49	156.6	144.7	8.2	10	3.1
		Range	0.87	0.8		1.2						1.6	4.1						200				0.1	2.0	1.1		
	8	Front	3.00	4.8		150.4	150.5	151.6	150.8	151.9	149.8	150.9	52.6	4080	3670	3900	4260	3710	3920				158.0	147.6	9.1		
		Middle	3.12	4.8	5.2	150.1	151.0	150.8	150.2	150.7	151.0	150.7	53.1	3800	3890	4130	4240	3640	3940				157.7	146.7	9.2		
		Rear	2.88	4.8		149.4	151.4	151.4	149.7	151.5	151.9	151.2	52.6	4100	3570	4400	4330	4080	4100				156.9	145.6	9.1		
		Average	3.00	4.8		150.0						150.9	52.8						3990	8.52	100.2	5.49	157.5	146.6	9.1	10	2.9
		Range	0.24	0.0		1.0						0.5	0.5						180				1.1	2.0	0.1		
	13	Front	3.00	4.1		150.8	151.3	151.8	152.4	151.7	152.3	151.9	53.4	4190	4290	4610	4150	4310	4310				157.2	146.0	7.9		
		Middle	2.50	4.2	4.7	150.8	151.7	150.7	151.8	150.8	152.0	151.4	54.7	3990	4170	4360	4200	4060	4160				157.4	145.7	8.3		
		Rear	2.62	4.6		150.8	151.5	150.8	152.1	152.3	151.3	151.6	54.8	4490	4220	4330	4260	4120	4280				158.1	146.9	9.1		
		Average	2.71	4.3		150.8						151.6	54.3						4250	8.46	99.5	5.53	157.6	146.2	8.4	9	2.5
		Range	0.50	0.5		0.0						0.5	1.4						150				0.9	1.2	1.2		
Average of Portions		Front	2.96	4.3		150.5						151.7	52.8						4430				157.3	146.3	8.3		
		Middle	3.12	4.6		150.0						150.9	53.1						4320				157.2	145.9	8.8		
		Rear	2.96	4.5		150.2						151.6	54.4						4420				157.2	145.3	8.7		
Grand Average			3.01	4.5	5.1	150.2						151.4	53.4						4390	8.50	99.9	5.50	157.2	145.8	8.6		
Average Range Within Batch			0.54	0.4		0.7						0.9	2.0						175				0.7	1.7	0.8		
180	4	Front	3.12	3.9		150.6	153.0	152.6	152.7	152.8	152.6	152.7	56.2	4770	4660	5110	5000	4750	4860				156.7	143.6	7.9		
		Middle	2.88	4.5	5.3	150.7	150.9	150.2	151.1	151.0	150.5	150.7	54.7	4820	4860	5050	5120	5040	4980				157.8	146.3	8.9		
		Rear	2.00	4.4		150.9	151.3	152.4	151.9	152.9	152.6	152.2	53.6	4750	5300	4770	4910	5180	4980				157.8	146.9	8.5		
		Average	2.67	4.3		150.7						151.9	54.8						4940	8.46	99.5	5.53	157.4	145.6	8.4	10	3.1
		Range	1.12	0.6		0.3						2.0	2.6						120				1.1	3.3	1.0		
	9	Front	1.62	3.9		151.0	151.8	153.0	153.2	152.5	152.3	152.6	56.1	3780	4310	4130	4350	4560	4230				157.1	144.4	7.9		
		Middle	2.00	4.6	4.7	150.3	151.1	151.0	151.0	151.9	151.8	151.4	55.3	4100	3830	3940	3980	3370	3840				157.5	145.8	9.2		
		Rear	2.00	4.7		149.5	150.5	152.1	151.2	152.2	151.4	151.5	53.9	3960	4280	3830	4100	4280	4090				156.9	145.0	9.1		
		Average	1.88	4.4		150.3						151.8	55.1						4050	8.49	99.9	5.51	157.2	145.1	8.7	13	2.8
		Range	0.38	0.8		1.5						1.2	2.2						390				0.6	1.4	1.3		
	14	Front	2.50	3.9		149.5	152.8	152.8	152.4	152.2	153.0	152.6	53.4	4280	4470	4240	4560	4310	4370				155.6	142.8	7.5		
		Middle	2.50	4.4	4.4	150.2	150.6	153.1	152.2	151.7	151.2	151.8	53.7	4660	4310	4170	4450	4120	4340				157.1	145.4	8.5		
		Rear	2.12	4.5		150.4	151.8	151.5	151.5	152.3	152.1	151.8	53.3	4100	4200	4560	4310	4120	4260				157.6	146.4	8.7		
		Average	2.38	4.3		150.0						152.1	53.5						4320	8.50	100.0	5.50	156.7	144.9	8.2	9	2.5
		Range	0.38	0.6		0.9						0.8	0.4						110				1.9	3.6	1.2		
Average of Portions		Front	2.41	3.9		150.4						152.6	55.2						4490				156.5	143.6	7.8		
		Middle	2.46	4.5		150.4						151.3	54.6						4390				157.5	145.8	8.9		
		Rear	2.04	4.5		150.3						151.8	53.6						4440				157.4	146.1	8.8		
Grand Average			2.31	4.3	4.8	150.3						151.9	54.5						4440	8.48	99.8	5.51	157.1	145.2	8.4		
Average Range Within Batch			0.63	0.7		0.9						1.3	1.7						205				1.2	2.8	1.2		

TABLE B (Cont.)
TEST RESULTS FOR FRESH AND HARDENED CONCRETE

Mixing Time, seconds	Batch No.	Batch Portion	Slump, in.	Concrete Air Content, percent		Concrete Weight, pcf							Coarse Aggregate Content, percent	28-Day Compressive Strength, psi						Batch Yield, cu yd	Yield, Percent of Design	Actual Cement Content, sacks/cu yd	Air-Free Weight, pcf		Mortar Air Content, percent	Time and Distance Between Plant and Paver	
				Plant Site	Paving Site	Fresh	Hardened																				
							1	2	3	4	5	Average		1	2	3	4	5	Average				Concrete	Mortar		Minutes	Miles
200	5	Front	2.75	3.9		150.6	153.3	152.5	152.2	152.1	152.0	152.4	55.5	4880	4880	5020	4860	4930	4910				156.7	143.8	7.8		
		Middle	2.62	4.4	5.4	150.1	150.8	151.1	151.2	151.4	151.0	151.1	55.9	4820	4980	4660	4840	4610	4780				157.0	144.3	8.8		
		Rear	3.62	4.2		150.0	150.8	151.3	152.1	151.7	161.2	151.4	55.4	5040	4890	4930	4810	4510	4840				156.6	143.7	8.4		
		Average	3.00	4.2		150.2						151.6	55.6						4840	8.48	99.8	5.51	156.8	143.9	8.3	10	3.0
		Range	1.00	0.5		0.6						1.3	0.5						130				0.4	0.6	1.0		
	10	Front	3.38	4.6		149.3	151.3	151.6	151.8	151.2	150.7	151.3	53.4	3960	3780	4120	3600	4200	3930				156.5	144.6	8.8		
		Middle	3.75	5.0	5.2	148.3	149.5	149.1	149.4	149.6	150.4	149.6	54.5	3410	4030	4080	3870	3780	3830				156.1	143.3	9.7		
		Rear	2.38	4.9		150.3	150.8	150.8	151.3	150.9	160.2	150.8	54.0	3990	4170	3900	4050	4170	4060				158.0	147.1	9.5		
		Average	3.17	4.8		149.3						150.6	54.0						3940	8.55	100.6	5.47	156.9	145.0	9.3	10	2.8
		Range	1.37	0.4		2.0						1.7	1.1						230				1.9	3.8	0.9		
	15	Front	2.50	4.4		150.0	152.4	152.6	152.8	150.8	151.9	152.1	53.6	4310	3920	4190	4260	3980	4130				156.9	145.2	8.5		
		Middle	2.25	5.2	5.5	149.5	150.5	149.7	150.4	150.7	149.5	150.2	53.3	4190	4050	3890	4200	4120	4090				157.7	146.7	10.0		
		Rear	2.25	5.2		149.0	150.2	149.4	149.6	150.0	150.1	149.9	53.6	4170	4100	4360	4060	4220	4180				157.2	145.7	10.0		
		Average	2.33	4.9		149.5						150.7	53.5						4130	8.53	100.4	5.48	157.3	145.9	9.5	9	2.5
		Range	0.25	0.8		1.0						2.2	0.3						90				0.8	1.5	1.5		
Average of Portions		Front	2.88	4.3		150.0						151.9	54.2						4320				156.7	144.5	8.4		
		Middle	2.87	4.9		149.3						150.3	54.6						4230				156.9	144.8	9.5		
		Rear	2.75	4.8		149.8						150.7	54.3						4360				157.3	145.5	9.3		
Grand Average			2.83	4.7	5.4	149.7						151.0	54.4						4300	8.52	100.3	5.49	157.0	144.9	9.0		
Average Range Within Batch			0.87	0.6		1.2						1.7	0.6						150				1.0	2.0	1.2		

TABLE C
TEMPERATURES AND TIME OF SAMPLING

Mixing Time, seconds	Batch No.	Temperature, F			Date	Time
		Air	Concrete			
		Plant Site	Plant Site	Paving Site		
60	1	72	80		6-19-61	4:15 pm
90	2	60	72		6-20-61	1:00 pm
120	3	60	72		6-20-61	1:50 pm
180	4	61	73		6-20-61	2:51 pm
200	5	61	73		6-20-61	3:38 pm
60	6	63	74	73	6-21-61	10:30 am
90	7	63	74	74	6-21-61	11:19 am
120	8	68	74	76	6-21-61	1:20 pm
180	9	68	74	76	6-21-61	2:18 pm
200	10	68	74	77	6-21-61	3:10 pm
60	11	70	76	77	6-21-61	4:07 pm
90	12	64	72	70	6-22-61	8:21 am
120	13	68	74	73	6-22-61	9:15 am
180	14	70	74	72	6-22-61	10:08 am
200	15	69	74	74	6-22-61	10:54 am
Average		65.7	74.0	74.2		

TABLE D
CONCRETE MIXER PERFORMANCE LIMITS

	Agency Proposing Limits of Variation*	Agency Limits of Variation						
		Slump	Air Content		Air-Free Unit Weight		Coarse Aggregate Content	Compressive Strength
			Concrete	Mortar	Concrete	Mortar		
PERFORMANCE STANDARDS	American Society for Testing Materials (4)	3/4-in. (a)	1% (a)		1 lb (a)	0.8% (b)	6% (a)	7.5% (7-day) (c)
	National Sand and Gravel Association-National Ready-Mix Concrete Assn. (5)	2-in. (a)	1% (a)			2 lb (a)	5% (a)	10% (28-day) (c)
	U.S. Army Corps of Engineers Ohio River Division (1)			20% (d)		1.5% (d)	8% (d)	
	U.S. Army Corps of Engineers Waterways Experiment Station (8)					0.8% (e)	5% (e)	

	Agency	Mixing Time, seconds	Total Batches Tested	Total Batches Within Agency Limits of Variation						
				Slump	Air Content		Air-Free Unit Weight		Coarse Aggregate Content	Compressive Strength
					Concrete	Mortar	Concrete	Mortar		
PERFORMANCE TEST RESULTS	ASTM	60	3	2	3		0	3	3	2
		90	3	2	3		3	3	3	2
		120	3	3	3		2	3	3	3
		180	3	2	3		1	1	3	3
		200	3	1	3		2	2	3	3
	NSGA-NRMCA	60	3	3	3			3	3	3
		90	3	3	3			3	3	3
		120	3	3	3			3	3	3
		180	3	3	3			1	3	3
		200	3	3	3			2	3	3
	U.S. Army-Ohio	60	3			3		1	2	
		90	3			3		3	3	
		120	3			3		3	3	
		180	3			3		1	3	
		200	3			3		2	3	
	U.S. Army-Waterways	60	3					1	2	
		90	3					2	3	
		120	3					2	3	
		180	3					1	3	
		200	3					2	3	

* Parenthesized numbers indicate references cited on p. 39.

Methods of Computing Variations Within Batches:

(a) Difference between front and rear values

(b) $$\frac{\text{Average of front and rear values} - \text{front value}}{\text{Average of front and rear values}} \times 100$$

(c) $$\frac{\text{Front value} - \text{rear value}}{\text{Average of front and rear values}} \times 100$$

(d) $$\frac{\text{Maximum value} - \text{minimum value}}{\text{Average of three values}} \times 100$$

(e) $$\frac{\text{Average of three values} - \text{value to produce maximum difference}}{\text{Average of three values}} \times 100$$

TABLE E
DESIGN AND BATCH QUANTITIES

Design Quantities

Batch design volume, cu yd	8.5
Coarse aggregate weight, dry, loose, pcf	108.0
Design batch weights, lb	
Cement	4394.5
Fine aggregate	8532.0
Coarse aggregate, 4A	9666.0
Coarse aggregate, 10A	9666.0
Water, total	2024.3

Batch Quantities	Batch Number				
	1	2	3, 4, & 5	6, 7, & 8	9, 10, 11, 12 13, 14, & 15
Batch weights, adjusted for moisture, lb					
Fine aggregate	9078.0	9044.0	9069.0	9086.0	8967.0
Coarse aggregate, 4A	9772.0	9782.0	9743.0	9762.0	9840.0
Coarse aggregate, 10A	9849.0	9820.0	9888.0	9927.0	9927.0

Weight of Water Added at Mixer

Batch No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Water added at mixer, lb	1349	1299	1333	1333	1299	1299	1299	1333	1333	1333	1266	1333	1333	1316	1316

Physical Constants of Materials

	Specific Gravity (Dry)	Absorption
Cement	3.12	
Fine aggregate	2.63	1.19
Coarse aggregate, 4A	2.72	0.67
Coarse aggregate, 10A	2.68	1.23

TABLE F
TEST RESULTS FOR PORTLAND CEMENT

Physical Properties	Silo 4 (61C-2014-17)	Silo 20 (61C-2589-99)	Silo 27 (61C-1608-33)
Setting Time (Gillmore), hr:min			
Initial	3:05	3:10	3:25
Final	5:20	5:10	5:25
Mortar Air Content, percent	19.6	20.7	19.0
Specific Surface (air permeability test), sq cm per g	3365	3229	3392
Autoclave Expansion, percent	0.23	0.21	0.14
Compressive Strength (mortar cubes), psi			
7 days	3650	3240	3400
28 days	4840	4330	4510