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Construction of Concrete Pavement
Methods, Economics and Tests

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Construction of Concrete Pavement

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Contents

Use of Neutron Activation to Determine Cement Content of Portland Cement Concrete

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Many millions of dollars are spent each year by the construction industry for portland cement concrete. This concrete, produced by a variety of concrete mixer designs, varies in specified quality from low-strength concrete used in unstressed members to high-strength concrete used in prestressed and reinforced concrete construction. Uniformity of mixing is a good criterion by which to judge the quality of the concrete mix and mixing adequacy. In this research, cement content of mortar, fineness modulus of the aggregate, ultimate compressive strength, and usual inspection of mixing quality were used to indicate the uniformity of the mixed concrete. With the exception of cement content, all tests to determine the physical characteristics of the concrete were made by conventional ASTM methods.

Cement content of the concrete mortar was determined by neutron activation analysis of Ca^{49} produced in the calcium in the portland cement. The method of cement content determination proved to be feasible and could be used to predict the cement content within approximately ± 0.007 g 95 percent of the time. Analysis of variance generally indicated that no significant effect was observed for fineness modulus, ultimate compressive strength, and cement content for the main effects of mixing time, replication, and position in a concrete mixer for the experiment used in this research.

• DURING the past two years, approximately 800 million barrels of cement have been produced for use in every area of construction work. Of this 800 million barrels, 52 percent was shipped to ready-mix plants. It is estimated that 130 million cu yd of ready-mixed concrete was produced in each of the last two years at a cost of over $3.5 billion.

Testing Methods to Determine Mixing Uniformity

One of the most important characteristics that control the quality of portland cement concrete is the uniformity of mixing. Adequately mixed, portland cement concrete exhibits such desirable qualities as optimum strength, workability, and durability. Because of the demand for concrete in building and road construction, it has become increasingly important to develop some simple method for the evaluation of mixing efficiency.

Manufacturers of concrete mixers are interested in evaluating the mixing efficiency of mixers having different speeds of rotation, different shapes, different blade sizes, and different blade angles. Producers of ready-mixed concrete are interested in securing a uniform mix in the minimum mixing time, and State highway departments and other users of concrete are interested in obtaining concrete having optimum strength and durability from plants supplying concrete for buildings, bridges, and highways.

Concrete mixers of various designs range in size from 1.5 cu ft to 10 cu yd. Common designs in use at central batch plants are the turbine mixer, horizontal tilting drum, and the nontilting horizontal drum. The principal mixer used in concrete highway paving is the 34-E dual drum paver.

With a knowledge of the minimum time required for a specific mixer to produce concrete having a uniform dispersion of aggregate and cement throughout the mix, mixing time may well be reduced from the conventional time required by present specifications. This reduction should result in increased capacity and lower production costs with no sacrifice in quality.

Many tests may be run on samples of fresh concrete selected from a mixer to help evaluate mixing efficiency. To determine the uniformity of a concrete mix, samples from various positions were compared for their air content, moisture content, modulus of rupture, fineness modulus of aggregate, compressive strength, usual appearance for mixing adequacy, and cement content. It was not feasible to run each of these tests because of time and money considerations; therefore, the last four tests were selected to evaluate mixing efficiency.

Cement Content by Neutron Activation

The use of radioactive isotopes in industrial processes and research is expanding rapidly. Because gamma emission from radioisotopes is easy to measure, the identification of constituents of a sample is simplified. Irradiation in an accelerator or a reactor can make the sample radioactive, and a knowledge of the particle emissions from the sample then allows interpretation of the sample's composition.

Neutron activation analysis was used in this research to determine cement content. Cast samples of portland cement mortar were activated in a neutron source. The amount of radioactivity produced in the sample of mortar was proportional to its cement content. A curve was produced by determining the count rate for cement mortar samples containing various known weights of cement. The unknown weight of cement contained in any mortar sample can be determined by activating the sample in a neutron source, counting the activity, and determining the cement content from the cement content vs count rate curve.

Other Methods for Determination of Cement Content

Various methods have been devised in the past for determining the cement content in a sample of concrete. The most prevalent method consists of determining the amount of soluble silica and calcium oxide in a sample by chemical analysis, and then indirectly calculating the percentage of cement by assuming some definite values of calcium oxide and silica in the cement (1). The method was devised for determining the cement content of a large sample of concrete, but can be used equally well in processing small mortar samples. This method is time consuming, requires a well-equipped laboratory with trained personnel, and is not applicable to concrete containing aggregates (such as slag, diatomites, and sodium silicates) which liberate soluble silica under test conditions.

Dunagan (2) suggests a test intended for use in the field for determining the constituents of concrete before the initial hardening. According to this method, the sample is first weighed in air, then in water, and washed over a No. 100 sieve. The aggregate is again weighed in water and the immersed weight of cement is obtained by the difference in the two submerged weights. It is necessary to know the specific gravity of cement to calculate its weight in air. An appreciable error enters the calculations in the assumption that all material passing the No. 100 sieve is cement.

Another procedure for determining the cement content of a sample of freshly mixed concrete consists of using a heavy liquid and a centrifuge process for separating cement from the other ingredients of concrete (3). The heavy media used comprise a liquid mixture of which the specific gravity may be adjusted to a value intermediate between that of cement and fine aggregate, thereby permitting the cement to sink and the aggregate to float. By means of appropriate calibration curves, cement content may be estimated.

The basis of a method by Murdock (4) is the determination of the specific gravity of a cement suspension. After washing a sample of fresh concrete over a No. 100 sieve, hydrometer readings are recorded of the suspension collected. By reference to a control curve obtained from hydrometer readings of water in which known quantities of cement are suspended, the amount of cement can be determined. Here again, the assumption that all material passing through the No. 100 sieve is cement creates an appreciable error in the calculations.

Two additional methods for determining cement content were developed by Chadda (5). In the first method, cement content is estimated by a conductimetric method based on the determination of conductivity of pure water in which known quantities of unset cement-sand mixture have been shaken. From a standard curve showing the relationship between cement concentration and conductivity, the cement content of a sample can be interpolated from its conductivity measurement. Chadda's other method for determining cement content is based on the differential absorption characteristics of cement and sand particles. The percent absorption increases as the concentration of cement increases in the mixture.

The latter two methods can be satisfactorily employed only for the determination of cement content in a freshly prepared cement-sand mixture to which no water has been added.

Previous research in this field has been primarily concerned with methods for spot checking samples of fresh concrete to insure a contractor's adherence to design specifications as to the amount of cement present. To this date, no attempt has been made to determine the uniformity of cement dispersion throughout the concrete mix. One of the purposes of this research was to develop a method that will enable manufacturers of mixers, producers of ready-mixed concrete, and users of concrete to investigate the distribution of cement in a mixer operating under a given set of conditions, thereby allowing the optimum mixing time to be determined and operating characteristics of machinery design to be determined. In evaluating mixing efficiency, a sampling program and a rapid and accurate method for determining cement content of mortar samples will be developed.

EQUIPMENT

Van de Graaff Accelerator

Cast mortar samples were activated by Georgia Tech's 1,000,000-volt Van de Graaff positive ion accelerator made by the High Voltage Engineering Corporation.

The Van de Graaff is a special type of electrostatic accelerator which has a highly insulated terminal and a means of maintaining the terminal at a very high static potential with respect to ground. An ion injected into the high potential end of the machine is accelerated and directed by the electrostatic field downward through an evacuated acceleration tube to ground.

As an ion source, a mixture of ordinary and heavy hydrogen (deuterium) is used, which gives a beam containing about 25 μ amps each of protons and deuterons. The 25-μ amp mixed beam of deuterons and H_2^+ ions at 1,000,000 electron volts is directed through the evacuated tube on a target of beryllium metal to produce the reaction

$$_4Be^9 + {}_1d^2 \rightarrow {}_5B^{10} + {}_0n^1 + \text{energy}$$

A small general-purpose thermal neutron irradiator as shown in Figure 1 was constructed for use with the Van de Graaff in performing this project. The beryllium target is surrounded by a mass of paraffin having an aluminum sleeve for positioning the mortar samples several centimeters below the target. The thermal neutron flux at the sample position was of the order of 5 x 10^6 thermal neutrons per sq cm per sec.

The purpose of the paraffin is to thermalize the fast neutrons, thereby permitting their capture by the Ca^{48} atoms. The cadmium shield merely prevents the escape of thermal neutrons from the irradiator. Figure 2 shows the neutron irradiator situated in the Van de Graaff.

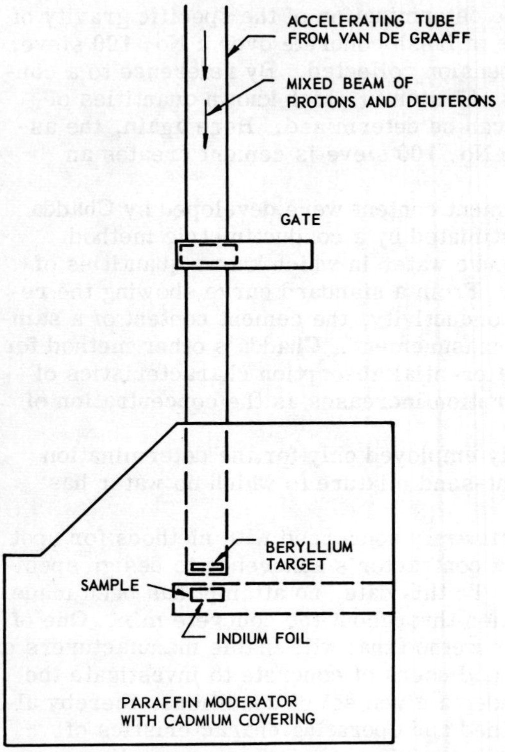

Figure 1. Thermal neutron moderator and the Van de Graaff accelerator.

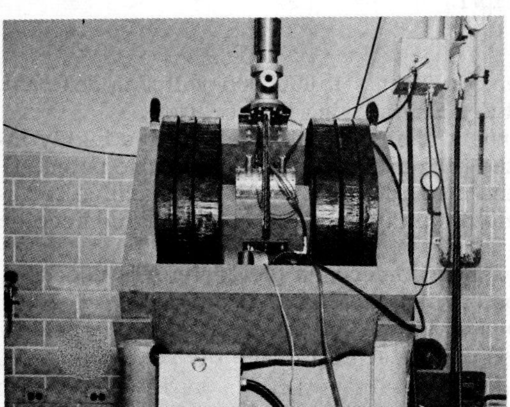

Figure 2. Neutron irradiator in the Van de Graaff accelerator.

Other Methods of Producing Neutrons

Most reactors can produce the neutron flux required for the activation of calcium. However, the Georgia Tech reactor now under construction will not be available for use until late 1962 or early 1963.

Radioactive sources are also available which can produce neutron fluxes of the strength required. The most desirable source to use for this purpose is americium-beryllium, which has the advantage of a long half-life and lack of gamma activity. Shielding is only required for neutron emission. Other sources which could be used either require extensive shielding for gamma radiation, have low specific activity, or have short half-lives. Unfortunately, americium sources of the size required to produce the neutron flux required are not readily available.

Radiation Detection

To date, the use of crystals of thallium-activated sodium iodide [NaI(Tl)] coupled to cesium-antimony phototubes is unchallenged as the most efficient method for detecting gamma rays. The following characteristics of this type of detector have resulted in a widespread application of the scintillation counter as a radiation detector and gamma ray spectrometer: high density of the inorganic crystals, which is mainly responsible for the higher stopping power and greater sensitivity to gamma rays; high light output; suitable index of refraction; response proportional to the incident radiation; and fast decay time.

The basis of a scintillation counting system is the ability of the phosphor to convert into light emissions some fraction of the energy lost by ionization during the passage of a gamma ray through the material. This emitted light is picked up by the sensitive photocathode of a photomultiplier tube. The photocathode produces an electrical pulse similar to the light output from the crystal in both magnitude and duration. Because the electrical pulse coming from the phototube is of insufficient size to activate a scaler, additional amplification is supplied by an external amplifer.

For a given crystal size and energy of gamma ray, the greatest total efficiency in counting is obtained from having the source situated in immediate contact with the crystal and on its central axis. In this experiment, not only is this proximity very

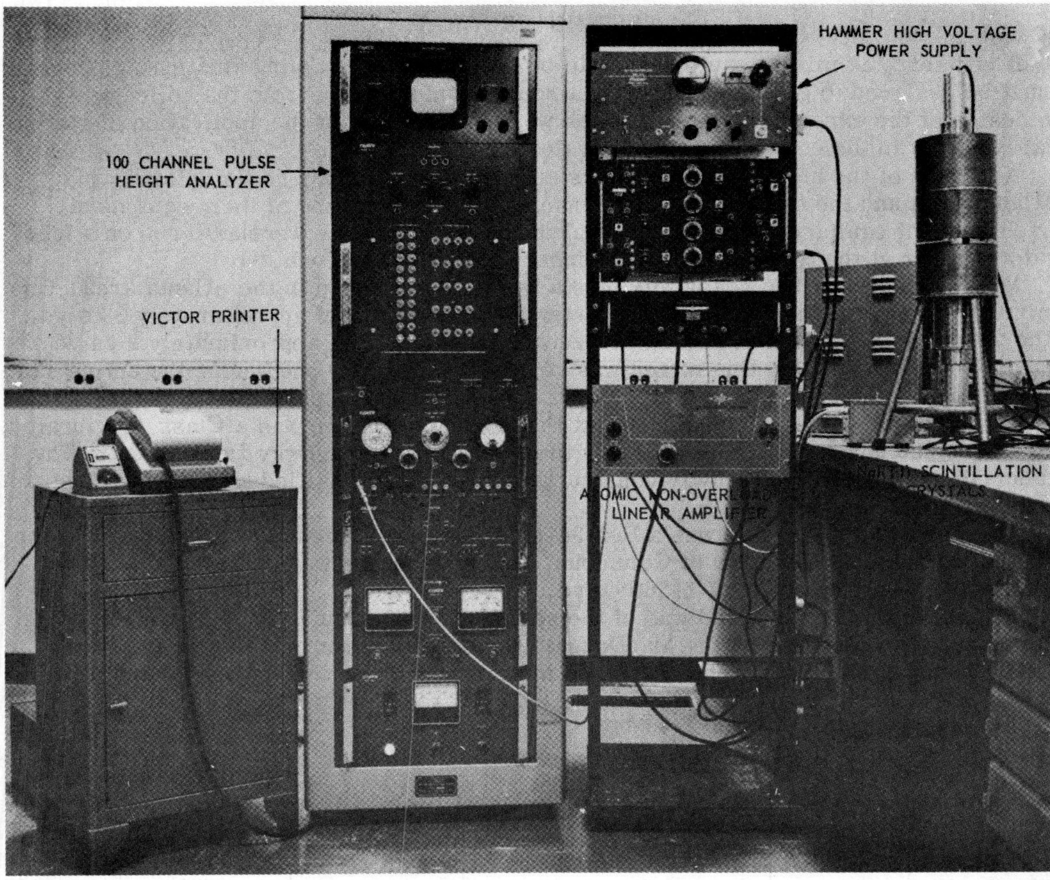

Figure 3. Radiation detection equipment.

nearly attained, but two scintillation crystals are also arranged with the sample situated between them, thereby approximating four-pi geometry. With the source situated in this manner, the emissions are isotropic, and thus a large number of interactions will occur laterally in the crystals.

Figure 3 shows the radiation-detection equipment located in the Radioisotopes Laboratory at Georgia Tech. On the right, the photo shows the two scintillation crystals with lead shields mounted vertically on a small tripod. The high voltage supply is at the top of the right center instrument bank and the external linear amplifier is at the bottom. The instrument in the left center of the photo is a 100-channel pulse height analyzer (Penco) manufactured by the Pacific Electro Nuclear Co. The Penco receives the electrical pulses from the external amplifier and stores them in channels according to their individual size. The memory of the Penco is recorded on tapes by a Victor printer shown at the right of the figure. Figure 4 is a block diagram of the pulse-counting equipment.

Equipment as expensive and elaborate as that shown in Figure 3 is not required for actual testing purposes. The equipment in the figure was used to determine the best energy range for analysis and also the minimum type of equipment that could be used for actual testing purposes.

The minimum equipment needed for measuring the activity of calcium-49 is (a) sodium iodide crystal, (b) linear amplifier, (c) discriminator, and (d) scaler. All of this equipment could be purchased for less than $3,000.

TESTING PROGRAM

If efficiency of mixing equipment is to be evaluated, a sampling and testing program must be designed to give the maximum amount of information from the collected data. In design of the experiment a statistician was consulted about the application of statistical concepts in the collection and the evaluation of these data.

A section of the highway on the Interstate system was under construction in the Atlanta area and the two contractors consented to the sampling of their equipment. Each piece of equipment was a 34-E dual drum paver. Tests were also run on a laboratory mixer at the School of Civil Engineering at Georgia Tech.

Mixers located at two ready mix plants were also sampled in the Atlanta area. One mixer was a tilting horizontal drum mixer with a capacity of approximately 3 cu yd. The second mixer was a nontilting horizontal drum mixer of approximately 2 cu yd capacity. Unfortunately this mixer was replaced with a new one before the entire sampling program was completed and the data for it are not complete.

The mixture selected for sampling at the ready-mix plants was a Class A, vibrated, air-entrained concrete, as specified by the Georgia State Highway Department. The concrete sampled at the highway construction sites was classified as a paving class concrete.

The first mixer sampled was a Rex 34-cu ft dual-drum highway paver owned by the Wright Contracting Company of Columbus, Ga. The mixer was operated at a 10 percent overload giving a mix of 1.385 cu yd.

The second mixer sampled was of the same type but manufactured by the Koehring Company. It was owned by the MacDougald Contruction Company of Atlanta, Ga. Specifications and photographs of the two mixers are shown in Figures 13 and 14 (Appendix B).

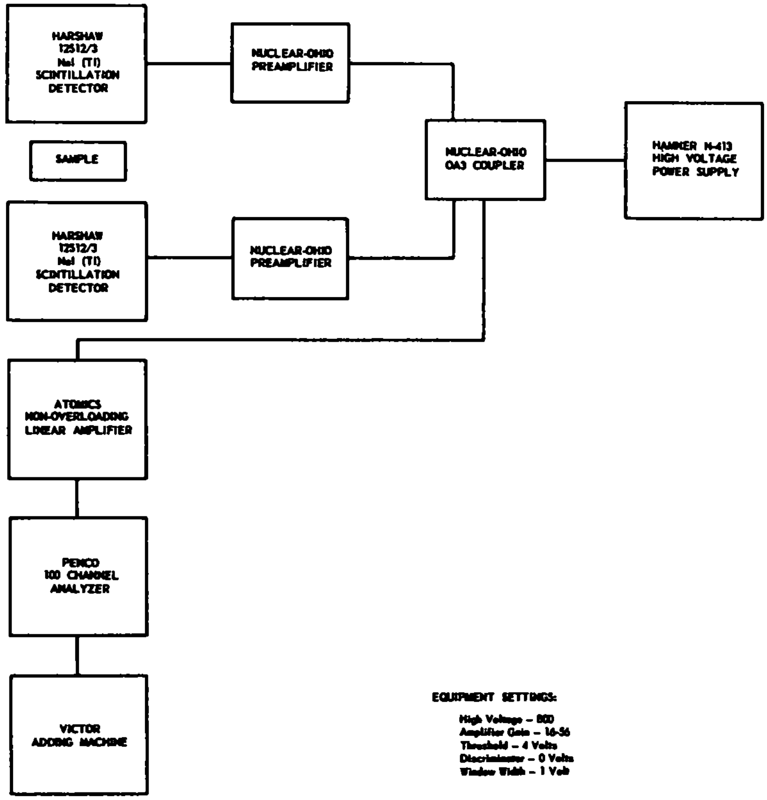

Figure 4. Schematic diagram of pulse counter.

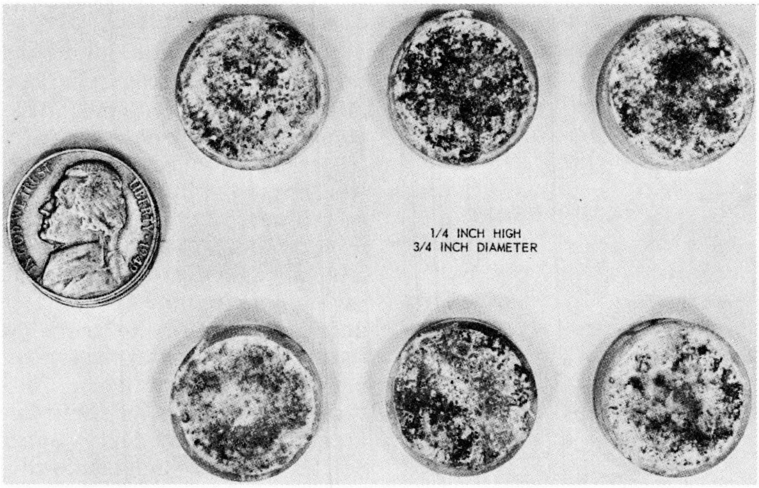

Figure 5. Cement mortar samples used for evaluating cement content.

Because of design, samples could not be withdrawn directly from the mixer but had to be collected as the concrete was discharged on to the roadbed.

The third mixer selected for sampling was a 3.5-cu yd horizontal tilting drum type manufactured by the T.L. Smith Corporation and owned by MacDougald Warren, Inc. The Hapeville Plant of MacDougald Warren, Inc., was selected because of its interest and cooperation, and because it possessed a standard type of stationary mixer used in the commercial production of ready-mixed concrete. Figure 15 (Appendix B) shows the plant and specifications of the mixer.

Again, because of design, it was impossible to withdraw samples directly from the different locations within the mixer. Therefore, after the predetermined mixing time, the mixer was tilted, and during the 20 to 25 sec necessary for discharge into a waiting truck, samples were drawn from the stream of concrete.

A laboratory mixer in the concrete laboratory at Georgia Tech was next sampled. A picture of this Worthington 6.0-cu ft nontilting horizontal drum mixer and its specifications are given in Appendix B.

A partial experiment was run on a 2-cu yd Koehring nontilting horizontal drum at the Campbell Materials Company before its breakdown and replacement. Figure 16 (Appendix B) shows the plant of the Campbell Materials Company in Atlanta and gives the specifications for the mixer.

Design of the Experiment

The experiment was chosen to consist of five different mix times: 30, 45, 60, 120, and 180 sec. Three samples were collected during the discharge of each batch and represented three different positions of the concrete in the mixer. The samples were evaluated for visual appearance of mixing adequacy, compressive strength, gradation of aggregate, and cement content. For the Hapeville and Georgia Tech mixers, the sampling and testing program was replicated three times to give a total of 45 samples for each mixer. The highway paving mixer experiments were replicated twice to give a total of 30 samples for each mixer, and the Campbell experiment was interrupted in the middle of the second replications.

The five mixing times used throughout the experiment were randomly selected and every effort was made to eliminate systematic errors. The materials used for any one mixer used during the tests were purchased from the same suppliers; the constituents of the batch were unchanged except for minor adjustment in water; the same person did the timing throughout the tests; the collection and processing of samples were as identical as possible; and the testing procedure was not altered.

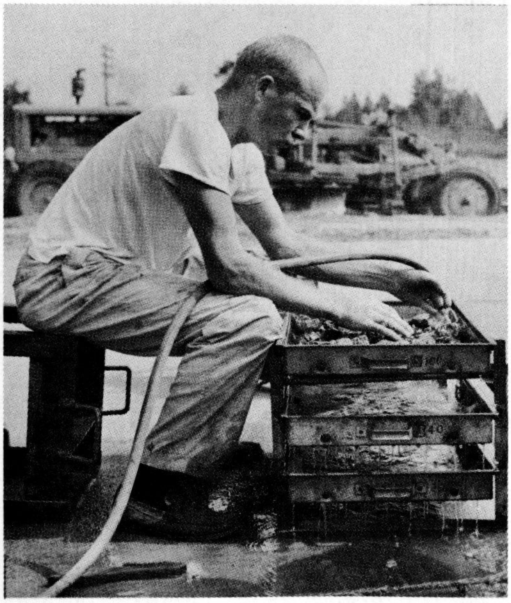

Figure 6. Washing technique for removing cement from aggregate.

Processing of Samples

Immediately after being drawn, the three samples were visually graded in one of three categories (well mixed, fair, and poor) and then processed for future testing. (Criteria for classification are as follows: well-mixed— uniform dispersion of batch constituents, proper workability; fair— uniform dispersion of cement and coarse and fine aggregate, dry or excessively wet giving ununiform workability; and poor— segregation of one or more constituents of the batch, dry or excessively wet giving ununiform workability.) Two mortar samples to be used in determining the dispersion of cement by neutron activation were collected from each of the three samples. These small samples were secured by first taking 50 to 100 g of the concrete mix, removing any large aggregate by passing the wet concrete through a No. 4 sieve, and then filling ¾-in. diameter by ¼- in. high polystyrene containers with the concrete mortar. Figure 5 shows six of the mortar samples ready for the determination of cement content. Conventional 6-in. diameter by 12-in. high compressive strength cylinders were cast, and the remainder of each sample was used for a gradation test of the aggregate contained in the concrete. Figure 6 shows the samples of fresh concrete used for the gradation test were washed over No. 4, 50, and 200 sieves to remove the cement in preparation of the sample for the gradation test.

Testing of Samples

To relate mixing time to uniformity of a concrete mix, strength and gradation of aggregate were evaluated in addition to the dispersion of cement. Tests were run first for determining the uniformity of the aggregate gradation in each sample. After being washed, the aggregate was dried at 235 F for 24 hr and its fineness modulus determined. (Fineness modulus is a numerical coefficient used to describe the sieve analysis of an aggregate. The percentage of material coarser than each sieve size is calculated, and the sum of these percentages divided by 100 is the fineness modulus. The larger the aggregate, the higher is its fineness modulus.) The 28-day ultimate compressive strength of the concrete was determined from the 6- by 12-in. cylinders under testing conditions prescribed by the American Society of Testing and Materials (C85-54).

Determination of Cement Dispersion

In determining the dispersion of portland cement throughout a concrete mix by the use of radioisotopes, two methods are immediately available in designing the experiment.

The first method utilizes the nuclear radiations emitted from a radioactive source that has been added to the mixer. The cement is tagged with an appropriate isotope, and after predetermined periods of mixing, samples from different parts of the batch are compared for radioactivity. Two objections or obstacles arise in using this method: (a) the inability to tag uniformly the large quantity of cement used in most commercial-size mixers, and (b) the danger of radiation exposure to plant personnel due to the dust generated during mixing of the concrete and the danger to workmen while placing radioactive concrete. These objections prevented the application of radioisotopes to the mixer.

The second method consists of activation analysis. This procedure allowed the samples to be collected without the danger of radiation exposure and to be processed in a laboratory with proper shielding and suitable monitoring devices to eliminate any health hazard. In activation, the samples to be analyzed are placed in a high flux of slow neutrons produced by the Van de Graaff for a length of time sufficient to produce a measurable amount of radioisotope of the element to be determined. The activity present is a quantitative measurement of the element. Concrete mortar samples are collected from different parts of the batch, activated, and compared for radioactivity.

The problem consisted of finding an element within the portland cement that was not present in the other constitutents of the concrete batch. Table 1 gives the chemical properties of the typical cement and aggregate used.

By weight, calcium oxide comprises about 65 percent of portland cement. For the material used in this experiment, calcium is only present in a very small percentage in the coarse aggregate, and is not found at all in the fine aggregate. Because only 1 percent of the coarse aggregate passes a No. 4 sieve, only a minute fraction of the calcium present in a mortar sample would be contributed by the coarse aggregate.

An investigation of calcium was made to determine whether an isotope existed which, when subjected to neutron activation, would become traceable. It was also

TABLE 1

CHEMICAL ANALYSIS OF PORTLAND CEMENT AND FINE AND COARSE AGGREGATE[a]

Material	Source	Chemical Compound	Percent by Weight
Portland cement	Universal Atlas, Birmingham, Ala.	CaO	65.66
		SiO_2	22.24
		Al_2O_3	5.96
		Fe_2O_3	2.16
		SO_3	1.88
		MgO	0.93
		Ins. res.	0.40
		K_2O	0.15
		Na_2O	0.03
Fine aggregate[b]	Taylor Sand Co., Junction City, Ga.	SiO_2	98.00
		Al_2O_3	1.20
		H_2O	0.56
		Org. matter	0.18
		Fe_2O_3	0.06
Coarse aggregate[c]	Tyrone Rock Products Co., Quarry 2, Mt. View, Ga.	SiO_2	74.70
		Al_2O_3	13.92
		Fe_2O_3	3.84
		CaO_3	3.76
		Na_2O	2.80
		K_2O	0.76
		MgO	0.20

[a]Values typical of proportions of chemical compounds found in other sources of aggregate and cement used in this research.
[b]Alluvial deposit known as Tuscaloosa formation.
[c]Biotite granite gneiss.

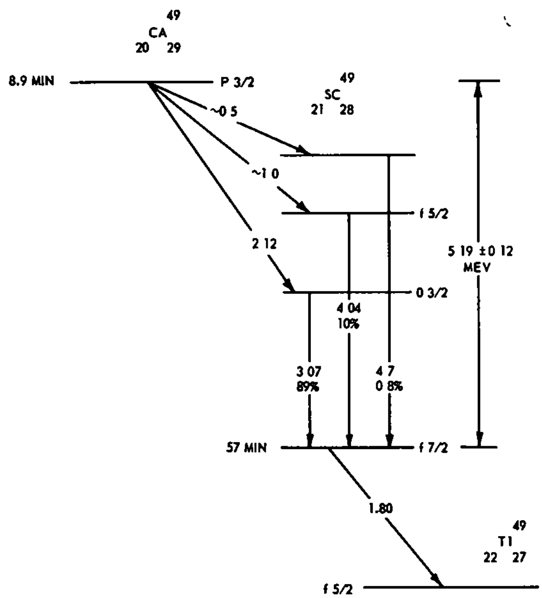

Figure 7. Decay scheme of Ca^{49} and Sc^{49}.

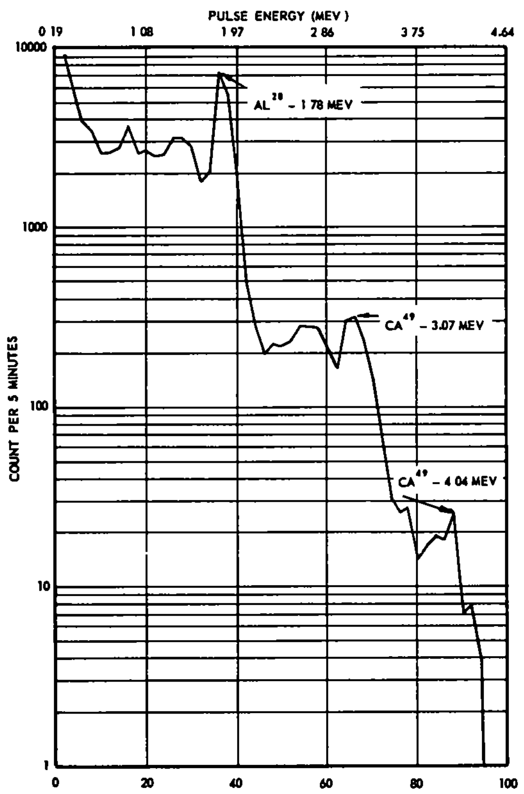

Figure 8. Gamma-ray spectrum of activated mortar sample.

necessary to examine isotopes of the other chemical elements constituting concrete to insure that their energy of radiation and disintegration did not interfere with calcium measurements. The results of this investigation are given in Table 2.

Although not in great abundance, $_{20}Ca^{48}$ was selected as the target nucleus which, after activation in the Van de Graaff, becomes the radioactive isotope $_{20}Ca^{49}$. This isotope was selected because of its relatively short half-life and traceable energy emissions during decay.

When bombarded by thermal neutrons, $_{20}Ca^{48}$ undergoes the following transformation:

$$_{20}Ca^{48} + {}_0n^1 \rightarrow {}_{20}Ca^{49}$$

$_{20}Ca^{49}$ has been found to decay with a half-life of 8.9 ± 0.2 min. The decay scheme, as determined by Martin, Cork, and Burson (6), is shown in Figure 7.

The gamma ray spectrum of an activated cement mortar sample was studied to insure that the 3.07-mev (million-electron-volts) gamma ray emitted by Ca^{49} could be detected using the two 3-in. diameter sodium iodide (thallium) crystals and the Penco 100-channel pulse height analyzer. The spectrum of an activated cement mortar sample as determined by the scintillation counting system is shown in Figure 8.

A calibration of the 100-channel analyzer was necessary to determine in which channel the 3.07-mev sum peak would fall. Sources with known energy emissions were counted and plotted against channel number to give a calibration curve. The channel numbers corresponding to the different energy peaks are given in Table 3. From the calibration curve shown in Figure 9, it was possible to select the channel in which a 3.07-mev energy pulse would fall.

A decay study was then made on the 3.07-mev energy peak of an activated mortar sample as a check of its half-life. After activation, the sample was transferred to the scintillation counter and three 5-min counts were recorded. The peak was found to cover channels 62-74. Table 4 gives the total counts recorded for the 3.07-mev peak at the end of each counting period.

Figure 10 is a partial plot of the spectrum at the end of each 5-min counting period; this plot shows the decay of the 3.07-mev energy peak. The figure shows the total counts recorded in channels 62-74

TABLE 2

ISOTOPES INHERENT IN ELEMENTS OF CONCRETE USED IN THE EXPERIMENT

Target Isotope	Abundance (%)	Radio-Nuclei	Type of Decay	Half-Life	Activation Cross-Section (barns)	Energy of Radiation and Disintegration mev	%
$_{1}H^{2}$	0.015	$_{1}H^{3}$	β^-	12.26 yr	0.6	0.18	
$_{8}O^{18}$	0.204	$_{8}O^{19}$	β^-	29.4 sec	0.21 mb	4.5	30
						2.9	70
						1.6	70
$_{11}Na^{23}$	100.	$_{11}Na^{24}$	γ- β^-	14.97 hr	0.6	4.122	100
						4.17	0.003
						1.380, 2.758	
$_{12}Mg^{26}$	11.29	$_{12}Mg^{27}$	γ- β^-	9.45 min	50	1.75	58
						1.59	42
						0.834, 1.015	
$_{13}Al^{27}$	100.	$_{13}Al^{28}$	γ- β^-	2.27 min	0.21	2.87	100
						1.78	
$_{14}Si^{30}$	3.05	$_{14}Si^{31}$	γ- β^-	2.62 hr	0.12	1.49	
						1.264	0.07
$_{16}S^{34}$	4.215	$_{16}S^{35}$	γ- β^-	87 days	0.26	0.167	100
$_{16}S^{36}$	0.017	$_{16}S^{37}$	β^-	5.04 min	0.14	1.6	90
						4.3	10
						3.09	
$_{19}K^{39}$	93.08	$_{19}K^{40}$	γ- β^-	1.25×10^{9} yr	3	1.33	89
						1.46	11
$_{19}K^{40}$	0.012	K^{41}	Electron capture				
$_{19}K^{41}$	6.91	$_{19}K^{42}$	β^-	12.52 hr	1.0	2.04	25
						3.58	75
						1.51	20
$_{20}Ca^{44}$	2.06	$_{20}Ca^{45}$	γ- β^-	164 days	0.63	0.254	
$_{20}Ca^{46}$	0.0033	$_{20}Ca^{47}$	β^-	4.7 days		0.70	76
						1.94	24
			γ			0.50	5
						0.81	5
						1.29	71
$_{20}Ca^{48}$	0.185	$_{20}Ca^{49}$	β^-	8.9 min	1.1	1.0,	
			γ			2.12	
						3.07	89
						4.04	10
						4.7	0.8
$_{26}Fe^{54}$	5.84	$_{26}Fe^{55}$	Electron capture	2.60 yr	0.7		
$_{26}Fe^{58}$	0.31	$_{26}Fe^{59}$	β^-	45.1 days	0.7	0.271	46
						0.462	54
			γ			1.560	0.3
						1.099	57
						1.289	43

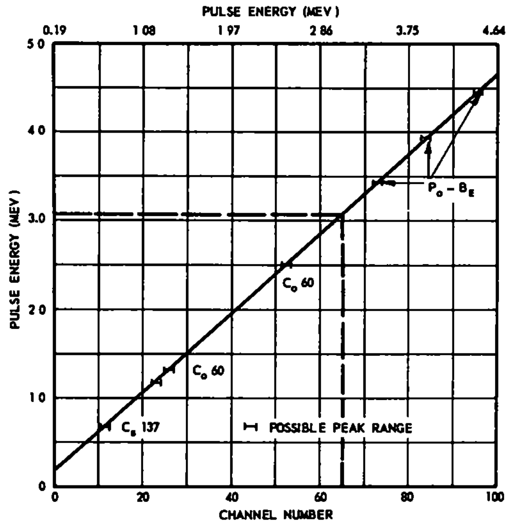

Figure 9. Calibration curve for scintillation spectrometer.

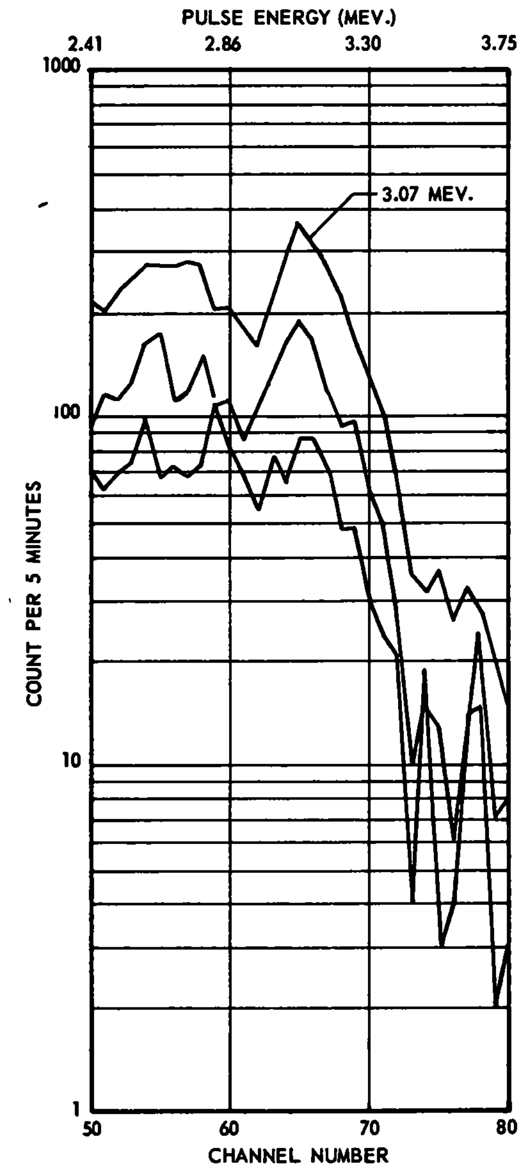

Figure 10. Decay of 3.07-mev peak.

for the three 5-min counts spaced 8 min apart. From Figure 11, the half-life of the peak was determined by reading the time on the abscissa corresponding to a 50 percent reduction in activity on the ordinate scale. A plot of the data determined the half-life of the peak to be 8.5 min. The difference of 0.4 min between theoretical and observed decay time for $^{20}Ca^{49}$ was probably due to the presence of sulfur-37 and oxygen-19.

When irradiated, $_{16}S^{36}$ nuclei enter the excited state of $_{16}S^{37}$ and decay, emitting 3.09-mev gamma rays with a half-life of 5.04 min. Sulfur ionization therefore contributes to some of the activity recorded in the 3.07-mev peak of the spectrum, but this should in no way reduce the accuracy in cement content determination, because sulfur is only present in the cement in very small quantities. Because $_8O^{19}$ has a half-life of 29.4 sec and counting did not start until 90 sec had elapsed from irradiation, the amount of activity caused by this isotope was considered to be negligible.

With the half-life of $_{20}Ca^{49}$ known to be approximately 8.9 min, it was decided that an irradiation period of 10 min for the collected mortar samples would give a sufficient number of counts to determine the cement content adequately. During this period the increase in activity is nearly linear with the time of irradiation.

The intensity of the beam on the Van de Graaff varies during this 10-min period among different samples and from day to day. Therefore, it was necessary to monitor the varying neutron flux with a small piece of indium foil that was irradiated along with each sample. The counts obtained from the indium foils were first normalized to correct for the varying foil weight, and then further normalized to correct for the variation in neutron flux. The count of each mortar sample could then be normalized to the value that would have been recorded had the neutron flux been constant during the testing period. An example of the calculations necessary to normalize the count for each sample is given in Appendix C.

After a 10-min exposure to the thermal neutron flux, the samples were removed from the irradiator and taken to the counting room. One min was allowed for the transfer of the sample and an additional 30 sec for transferring the monitoring indium foil, with each then being counted for 5 min.

The outputs from the two photomultiplier tubes were added electronically, giving a single composite spectrum which could be seen on the Penco pulse height analyzer scope. The spectrum was then printed on tape to give a permanent record of each sample's activity. The observed 5-min count of the indium foil was recorded by a Geiger-Mueller counter.

To determine the cement content of mortar samples collected, a standard chart or graph of cement content vs count was developed. Laboratory samples were made with known quantities of cement and were activated, counted, and plotted. Because of the random decay of radioactive isotopes, three observations were made of each standard sample and the best line through the points was determined by the method of least squares. The resulting cement content vs count rate curve is shown in Figure 12. It was from this graph that point estimates of the cement of cast mortar samples were determined for mortar samples containing unknown amounts of cement.

TABLE 3

GAMMA SOURCES FOR ENERGY CALIBRATION OF SCINTILLATION SPECTROMETER

Isotope	Energy Peaks (mev)	Channel No.
Cs^{137}	0.667	11½
Co^{60}	1.17	23
	1.33	26
	2.50	52½
Po-Be	3.43	73
	3.94	84
	4.45	96

TABLE 4

DECAY STUDY OF 3.07-MEV ENERGY PEAK

Time After End of Irradiation (min)	Count, Channels 62-74
1 - 6	2,409
9 - 14	1,242
17 - 22	648

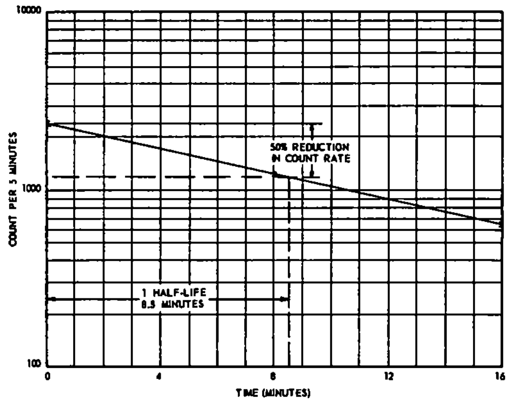

Figure 11. Half-life determination of 3.07-mev peak.

RESULTS

Analysis of Variance

Analysis of variance is probably the most powerful procedure in the field of experimental statistics. It allows the data collected to be rigorously analyzed and conclusions to be accompanied by probability statements as to the correctness of the inferences. To carry out the analysis, it is necessary to formulate a mathematical model in terms of the unknown parameters and the associated random variables. The quantitative physical characteristics (dependent variables) of interest in this study are the following:

1. Aggregate fineness modulus.
2. Compressive strength.
3. Cement content of mortar.
4. Visual evaluation of mixing.

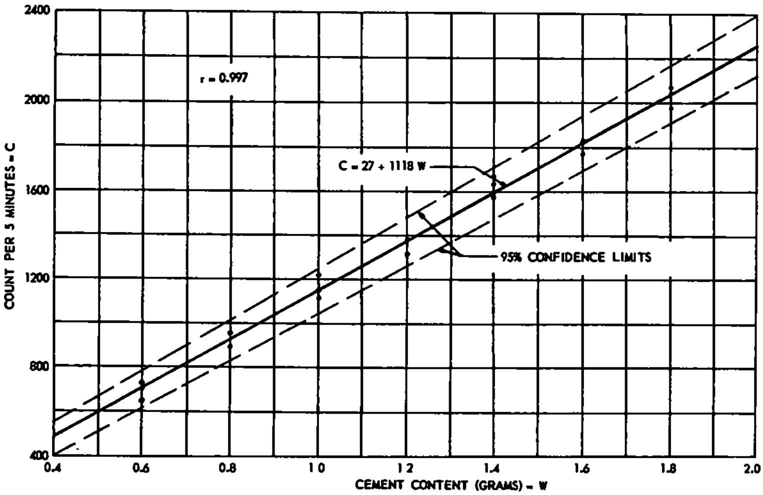

Figure 12. Cement content vs count.

Aggregate fineness modulus and cement content may appear to be independent variables because they are set by the particular mix samples. However, in this investigation, the constituents enter the mixer in segregated slugs. This research is concerned with the determination of the dispersion of the constituents; therefore, aggregate fineness modulus and cement content are dependent variables.

The independent variables of interest are as follows:

1. Mixing time (T) 30, 45, 60, 120, and 180 sec.
2. Position (P) of concrete in discharge stream or in mixer.
3. Replication (R) (experiment is run two or three times for each mixer).

Analysis was made on the strength and fineness modulus characteristics, and on the average of the two cement content determinations for each sample. The primary variables used in this analysis is shown in Table 5. The mathematical model can be written as

$$y_{ijk} = \mu + T_i + R_j + RT_{ij} + P_k + PR_{jk} + PT_{ik} + PRT_{ijk}$$

In effect, this formula states that for an individual concrete sample, the strength, fineness modulus, or cement content (determination) for the kth position in the jth replication, mixed for i seconds, will be an expected value μ, plus the sum of any main effects and interaction effects due to the three independent variables. This design is known as a split-plot experiment. RT is used as an estimate of the main plot error, and PRT is taken as an estimate of the split-plot error.

TABLE 5

PRIMARY VARIABLES FOR ANALYSIS OF VARIANCE

Factor	Abbreviation	Subscript	No. Levels	Model
Mix time	T	i	5	Fixed
Replication	R	j	3(2)[a]	Fixed
Discharge position	P	k	3	Fixed

[a]Wright and McDougald paving jobs.

Fineness Modulus

In Appendix A Tables 6, 8, 10, 12, and 14 give the values of aggregate fineness modulus of the samples collected during the experiment. Results of the analysis of variance are shown in Tables 7, 9, 11, and 13.

From Table 9, the interaction term, PR, is significant at the 1 or 5 percent level. The interaction terms are not significant in any of the other tables. The position is highly significant and replication is significant in Table 11. All other analysis of variance tables did not indicate any significant effect of mix time, replication or position of fineness modulus.

In Table 11 by rejecting the hypothesis that the position of the concrete in the discharge stream does not affect the fineness modulus, it is possible to determine which positions differ. By the application of Tukey's procedure of contrasts (7), one can conclude that the fineness modulus in position 1 differs significantly from the fineness modulus in positions 2 and 3, and that there is no significant difference between the fineness modulus in positions 2 and 3.

Compressive Strength

Compressive strength is universally used as the index of concrete quality, but, used alone, it may be misleading. Samples drawn from two different batches of concrete may exhibit similar strength even though their uniformity of mixing is quite different. A sample with inadequate moisture content may be unacceptable from the standpoint of workability, yet may give high strength after being cast in a cylinder mold.

Tables 15, 17, 19, 21, and 23 show the ultimate compressive strengths obtained in breaking tests on the 6- by 12-in. concrete cylinders. The analysis of variance computed for compressive strengths of concrete is given in Tables 16, 18, 20, and 22.

Numerous articles have been published correlating the strength of concrete with mixing time. It is the present consensus that 1 min is the minimum length of time for suitable mixing of concrete, and that 2 min is highly desirable. The value of F computer in the analysis of variance for testing the mixing time effect in Tables 16, 18, 20, and 22 indicated there was not a significant difference in strength for different mixing times. Position and replication also is not significant.

Immediately evident in Table 20 is the highly significant value of F = 12.23 for testing the position hypothesis. From the data of this experiment, the strength of concrete varied significantly among each of the three positions in the discharge stream. Observing the F values computed in the various other tables, one must accept the hypothesis that there is no significant difference in strength because of interaction effect among the independent variables.

Cement Content

Figure 11 shows the line of cement content vs count and gives its equation and correlation coefficient, r. The value of r (0.997) indicates a nearly perfect degree of association between the two related variables. The 95 percent confidence limits are also shown in Figure 11.

Because there is an underlying physical relationship between observed count and cement content, it is appropriate to make point estimates of the cement content associated with a particular count. However, because the observed count is subject to variation, a confidence interval estimate is also needed to enable probability statements to be made about the true cement content of the samples.

For this experiment, a 95 percent confidence interval was chosen around the regression line. For example, a sample having a normalized count of 600 between channels 62-74 would have a point estimate equal to 0.508 g of cement and a 95 percent confidence interval equal to ± 0.068 g. The point estimate for a sample recording a normalized cut of 1,800 per 5 min would equal 1.592 g of cement and would have 95 percent confidence interval of ± 0.066 g around this cement content.

Point estimates of cement content on mortar samples were made using Figure 11. A ratio of grams of cement per gram of mortar was then computed for the samples and this information is contained in Tables 24, 26, 28, 30, and 32. The analysis of variance for the data is given in Tables 25, 27, 29 and 31.

For testing the hypothesis that the position of the concrete in the discharge stream has no effect on the cement content of a sample, the value of F was 14.69 in Table 29 and 12.97 in Table 31. Because these values exceed both $F_{0.05}$ and $F_{0.01}$ values, one can conclude that there is a highly significant difference in cement content of mortar among samples located in different positions in the discharge stream or its corresponding position in the mixer. Replication effect is also significant in Table 31 at the 5 percent level.

Referring to the other values of F in the various Tables 25 and 27, the main effects and interaction effects among the variables did not cause the cement content to differ significantly.

Visual Inspection

An objective evaluation was attempted to determine whether the authors could visually ascertain the degree of mixing by judging the uniformity of mixing of concrete discharged from the mixer. The samples used in the previously described tests were classified in one of three categories: well-mixed, fair, and poor.

Compressive strength, fineness modulus, and cement content of samples were used to correlate visual classification to degree of mixing. Although an analysis of variance can not be performed on these data, it may be concluded that the authors were unable to determine visually the degree of mixing uniformity.

For example, some samples were classified as being well mixed and exhibited values of strength, fineness modulus, and cement content of the mortar which indicated the opposite may be true. On the other hand some samples were classified as being poorly mixed but indicated some of the characteristics of a well-mixed material.

SUMMARY

The results obtained for fineness modulus, compressive strength, cement content, and visual evaluation of adequacy of mixing are as follows for the various mixers studied:

1. Fineness Modulus.—For the dual drum 34-E Mixer used on the MacDougald paving job exhibited significant effect on fineness modulus for the position-replication interaction term was observed. For the MacDougald Warren mixer used at a ready-mixed plant, replication of the experiment had significant effect on fineness modulus and position of the mix in the mixer had very significant effect on fineness modulus. All other main and interaction effects for all of the mixers studied were not significant.
2. Compressive Strength.—For the MacDougald Warren, Inc., mixer replication of the experiment had significant effect, and position of the mix in the mixer had very significant effect on compressive strength. All other main and interaction effects for the mixers studied were not significant.
3. Cement Content of the Mortar.—For the MacDougald Warren mixer position of the mix in the mixer had very significant effect on cement content of the mortar. For the Georgia Tech mixer, replication of the experiment exhibited significant effect and position of the mix in the mixer had very significant effect on cement content in the mortar. All other main and interaction terms for the mixers studied were not significant.
4. Visual Inspection of Concrete Mixing Adequacy.—Using fineness modulus, compressive strength and cement content as criteria for adequacy of mixing, it was not possible to determine the adequacy of mixing by visual observation for the mixers studied in this experiment.

CONCLUSIONS

The ease with which the sampling and testing program described in this report can be used in evaluating mixing efficiency justifies its application. Activation analysis appears to be a feasible method for determining the cement content of cast mortar samples. Although not equaling the accuracy obtained by chemical analysis, the cement content could be predicted to within approximately 0.07 g of its true value 95 percent of the time for these experiments.

The principal advantages of activation analysis are the ease and speed of cement content determinations. The principal disadvantages are that a laboratory with trained personnel and equipped for irradiating samples and counting are required. This experiment may not be performed on concretes containing aggregates of limestone, marble, or other stone with an appreciable calcium content.

It may be concluded from the data collected that some of the mixers sampled did not produce a uniform concrete mixture. It is of interest to note that mixing time did not have significant effect on fineness modulus, compressive strength, or cement content of the mortar. Most mixing specifications for concrete require a minimum mixing time of 1 min. In these experiments, the analyses of data for the 30-sec mixes indicate no significant difference in quality of the mix for longer mixing times.

Although no conclusions can be definitely drawn about other mixers, the results of this research may be an indication that some changes are needed in the blade angles, speed of rotation, capacity, etc., to insure the production of a uniform concrete mixture.

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Appendix A

TABLES OF RESULTS AND ANALYSIS OF VARIANCE

TABLE 6

AGGREGATE FINENESS MODULUS, WRIGHT PAVING JOB

Replication	Position in Mixer or Discharge Stream	Fineness Modulus for Mixing Time				
		30 Sec	45 Sec	60 Sec	120 Sec	180 Sec
1	1	6.32	5.83	5.81	5.42	5.84
	2	5.86	5.67	5.62	5.27	5.77
	3	5.80	5.58	5.82	5.37	5.64
2	1	5.88	5.95	5.94	5.61	5.89
	2	5.77	5.61	5.97	5.89	5.93
	3	5.76	5.84	4.85	5.75	5.99

TABLE 7

ANALYSIS OF VARIANCE FOR FINENESS MODULUS, WRIGHT PAVING JOB

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests	
					$F_{0.05}$	$F_{0.01}$
Replication	0.0340	1	0.0340	0.37	7.71	21.2
Mix time	0.4583	4	0.1146	1.25	6.39	16.0
RT	0.3655	4	0.0914	—	—	—
Position	0.2189	2	0.1095	1.51	4.46	8.65
PR	0.0623	2	0.0312	0.43	4.46	8.65
PT	0.3177	8	0.0397	0.55	3.44	6.03
PRT	0.5805	8	0.0726	—	—	—
Total	2.0372	29				

TABLE 8

AGGREGATE FINENESS MODULUS, MACDOUGALD PAVING JOB

Replication	Position in Mixer or Discharge Stream	Fineness Modulus for Mixing Time				
		30 Sec	45 Sec	60 Sec	120 Sec	180 Sec
1	1	6 11	5 96	5 76	5 95	5 94
	2	5 99	5 96	5 76	5 80	5 92
	3	5 84	5 80	5 85	5 75	5 68
2	1	5 79	5 97	5.98	5 89	5 69
	2	5 90	5 77	5 92	5 74	5 68
	3	6 10	6 35	6 34	5 91	5 78

TABLE 9

ANALYSIS OF VARIANCE FOR FINENESS MODULUS, MACDOUGALD PAVING JOB

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests	
					$F_{0.05}$	$F_{0.01}$
Replication	0.0182	1	0.0182	0.45	7.71	21.2
Mix time	0.1586	4	0.0397	0.99	6.39	16.0
RT	0.1602	4	0.0401	—	—	—
Position	0.0470	2	0.0235	3.13	4.46	8.65
PR	0.2588	2	0.1294	17.25[a]	4.46	8.65
PT	0.1066	8	1.0133	1.77	3.44	6.03
PRT	0.0597	8	0.0075	—	—	—
Total	0.8091	29				

[a]Significant at 1 and 5 percent levels.

TABLE 10

AGGREGATE FINENESS MODULUS, MACDOUGALD WARREN, INC

Replication	Position in Mixer or Discharge Stream	Fineness Modulus for Mixing Time				
		30 Sec	45 Sec	60 Sec	120 Sec	180 Sec
1	1	4.61	4 78	4 72	5.03	5.09
	2	5 09	5.05	5.09	5.01	4 96
	3	5 22	4 98	5 09	5 17	5 09
2	1	4 76	4 49	4 76	4.99	4 31
	2	5.01	4 85	5 05	5.07	5.17
	3	5 07	4 96	4.78	4.96	5.30
3	1	4 73	4 69	4 68	4 32	4.96
	2	5 00	4 91	4 94	5.15	5.08
	3	5 16	4.81	5 00	5.27	4.97

TABLE 11

ANALYSIS OF VARIANCE FOR FINENESS MODULUS, MACDOUGALD WARREN, INC.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests	
					$F_{0.05}$	$F_{0.01}$
Replication	0.0853	2	0.0427	7.91[a]	4.46	8.65
Mix time	0.1689	4	0.0422	7.81	3.84	7.01
RT	0.0428	8	0.0054	—	—	—
Position	0.9913	2	0.4957	9.80[b]	3.63	6.23
PR	0.0455	4	0.0114	0.23	3.01	4.77
PT	0.0509	8	0.0064	0.13	2.59	3.89
PRT	0.8090	16	0.0506	—	—	—
Total	2.1939	44				

[a]Significant at the 5 percent level.
[b]Significant at the 1 and 5 percent levels (highly significant).

TABLE 12

AGGREGATE FINENESS MODULUS, GEORGIA TECH MIXER

Replication	Position in Mixer or Discharge Stream	Fineness Modulus for Mixing Time				
		30 Sec	45 Sec	60 Sec	120 Sec	180 Sec
1	1	5 26	5 32	5 33	5.12	5 40
	2	5 39	5.34	5 23	5 25	5.43
	3	5.55	5.16	5.08	5.77	5.11
2	1	5 66	5 55	5.33	5.25	5.35
	2	5.78	5.82	5.30	5.32	5.35
	3	5.57	6.14	5 19	5.26	5.60
3	1	5.74	5.41	5.46	5.56	5.38
	2	5.45	5.38	5.41	5.58	5 39
	3	5.44	5.37	5.50	5 47	5.33

TABLE 13

ANALYSIS OF VARIANCE FOR FINENESS MODULUS, GEORGIA TECH MIXER

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests	
					$F_{0.05}$	$F_{0.01}$
Replication	0.2745	2	0.1373	1 87	4 46	8.65
Mix time	0.3064	4	0.0766	1 04	3.84	7 01
RT	0.5886	8	0 0736	—	—	—
Position	0.0063	2	0.0032	0.09	3.63	6.23
PR	0.0621	4	0 0155	0 45	3 01	4.77
PT	0.1001	8	0.0125	0 37	2.59	3 89
PRT	0.5479	16	0.0342	—	—	—
Total	1.8859	44				

TABLE 14

AGGREGATE FINENESS MODULUS[a], CAMPBELL MATERIALS COMPANY

Replication	Position in Mixer or Discharge Stream	Fineness Modulus for Mixing Time			
		45 Sec	60 Sec	120 Sec	180 Sec
1	1	5.33	5 56	5.51	5.23
	2	5 33	5.64	5.52	5.18
	3	5 64	5.71	5.50	5.25
2	1	5 10	—	5.29	—
	2	5.21	—	5.28	—
	3	5.33	—	5.28	—

[a]Incomplete experiment.

TABLE 15

28-DAY COMPRESSIVE STRENGTHS IN POUNDS PER SQUARE INCH FOR WRIGHT PAVING JOB

Replication	Position in Mixer or Discharge Stream	Strength (psi) for Mixing Time				
		30 Sec	45 Sec	60 Sec	120 Sec	180 Sec
1	1	3,360	3,900	2,460	4,520	3,290
	2	3,310	3,530	2,460	5,010	3,290
	3	2,420	3,690	3,290	4,270	3,400
2	1	3,100	2,840	2,870	2,830	2,910
	2	3,240	2,790	3,160	2,740	3,000
	3	2,840	2,960	3,010	2,240	3,080

TABLE 16

ANALYSIS OF VARIANCE FOR COMPRESSIVE STRENGTHS FOR WRIGHT PAVING JOB

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests	
					$F_{0.05}$	$F_{0.01}$
Replication	24,596 033	1	24,596 033	2 0216	7 71	21 2
Mixing time	17,968 797	4	4,492 199	0.3692	6 39	16.0
RT	48,667.467	4	12,166.866	—	—	—
Position	915.267	2	457.6335	0.6328	4.46	8 65
PR	56.867	2	28.4335	0 0393	4.46	8.65
PT	11,449 403	8	1,431 175	1 9791	3 44	6.03
PRT	5,785 133	8	723 142	—	—	—
Total	109,438 967	29				

TABLE 17

28-DAY COMPRESSIVE STRENGTHS IN POUNDS PER SQUARE INCH FOR MACDOUGALD PAVING JOB

Replication	Position in Mixer or Discharge Stream	Strength (psi) for Mixing Time				
		30 Sec	45 Sec	60 Sec	120 Sec	180 Sec
1	1	4,030	5,390	4,120	2,780	3,340
	2	5,170	5,450	4,260	1,900	3,580
	3	3,330	5,550	4,140	3,140	3,530
2	1	3,000	4,040	4,650	4,420	4,760
	2	2,730	4,200	4,530	4,870	4,630
	3	3,050	3,940	3,980	4,640	4,430

TABLE 18

ANALYSIS OF VARIANCE FOR COMPRESSIVE STRENGTHS FOR MACDOUGALD PAVING JOB

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests	
					$F_{0.05}$	$F_{0.01}$
Replication	1,555 203	1	1,555.203	0.0467	7 71	21 2
Mixing time	59,299 2	4	14,824 8	0 4450	6 39	16.0
RT	133,253 47	4	33,313 37	—	—	—
Position	1,264 07	2	632 04	0.2467	4 46	8 65
PR	391 4	2	195 7	0 0764	4 46	8 65
PT	8,860 6	8	1,107 57	0 4324	3 44	6 03
PRT	20,493.93	8	2,561 7	—	—	—
Total	225,117 87	29				

TABLE 19

28-DAY COMPRESSIVE STRENGTHS IN POUNDS PER SQUARE INCH OF CLASS "A" CONCRETE FOR MACDOUGALD WARREN, INC.

Replication	Position in Mixer or Discharge Stream	Strength (psi) for Mixing Time				
		30 Sec	45 Sec	60 Sec	120 Sec	180 Sec
1	1	5,850	5,210	6,230	5,180	4,730
	2	4,210	4,980	5,210	4,720	3,980
	3	2,650	4,360	3,880	3,890	4,330
2	1	5,420	5,050	5,040	3,830	3,570
	2	5,110	5,370	4,880	3,300	2,810
	3	3,230	4,220	3,760	3,600	3,000
3	1	5,390	6,170	3,220	3,750	3,270
	2	4,380	4,650	3,040	3,290	3,390
	3	2,190	3,250	3,220	2,560	3,000

TABLE 20

ANALYSIS OF VARIANCE FOR COMPRESSIVE STRENGTHS FOR MACDOUGALD WARREN, INC

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests	
					$F_{0.05}$	$F_{0.01}$
Replication	71,448	2	35,724	5 28[a]	4 46	8 65
Mix time	83,942	4	20,986	3 10	3 84	7 01
RT	54,106	8	6,763	—	—	—
Position	145,230	2	72,615	12 23[b]	3 63	6 23
PR	6,061	4	1,515	0 25	3 01	4 77
PT	57,222	8	7,153	1 20	2 59	3 89
PRT	94,969	16	5,936	—	—	—
Total	512,978	44				

[a]Significant at the 5 percent level.
[b]Significant at the 1 and 5 percent levels (highly significant).

TABLE 21

28-DAY COMPRESSIVE STRENGTHS IN POUNDS PER SQUARE INCH OF CLASS "A" CONCRETE FOR GEORGIA TECH MIXER

Replication	Position in Mixer or Discharge Stream	Strength (psi) for Mixing Time				
		30 Sec	45 Sec	60 Sec	120 Sec	180 Sec
1	1	3,630	2,820	3,420	3,410	3,870
	2	3,240	2,730	2,910	2,770	3,560
	3	3,430	2,820	3,000	2,820	3,330
2	1	2,810	3,230	3,310	2,580	3,470
	2	2,870	3,400	2,860	2,730	3,270
	3	3,760	2,060	3,220	2,640	3,470
3	1	3,110	3,750	2,800	3,270	3,310
	2	2,740	3,530	2,060	3,360	3,090
	3.	3,450	3,520	3,280	2,090	3,170

TABLE 22

ANALYSIS OF VARIANCE FOR COMPRESSIVE STRENGTH FOR GEORGIA TECH MIXER

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests	
					$F_{0.05}$	$F_{0.01}$
Replication	1,458 179	2	729 0895	0 2951	4 46	8 65
Mix time	15,867 912	4	3,966 978	1 6055	3 84	7 01
RT	19,767 154	8	2,470 894	—	—	—
Position	4,845 645	2	2,422 823	1 8696	3 63	6 23
PR	1,951 288	4	487 822	0 3764	3 01	4 77
PT	17,295.688	8	2,161 961	1 6683	2 59	3 89
PRT	20,734 046	16	1,295 878	—	—	—
Total	81,919 912	44				

TABLE 23

28-DAY COMPRESSIVE STRENGTHS IN POUNDS PER SQUARE INCH OF CLASS "A" CONCRETE[a] FOR CAMPBELL MATERIALS COMPANY

Replication	Position in Mixer or Discharge Stream	Strength (psi) for Mixing Time			
		45 Sec	60 Sec	120 Sec	180 Sec
1	1	6,540	5,830	4,130	4,010
	2	4,840	4,210	3,820	4,280
	3	4,850	4,030	3,730	4,250
2	1	6,640	—	4,890	—
	2	5,920	—	5,160	—
	3	4,620	—	4,590	—

[a]Incomplete experience.

TABLE 24

CEMENT CONTENT OF MORTAR SAMPLES IN GRAMS CEMENT PER GRAMS MORTAR FROM WRIGHT PAVING JOB

Replication	Position in Mixer or Discharge Stream	Cement Content (g/g Mortar) for Mixing Time				
		30 Sec	45 Sec	60 Sec	120 Sec	180 Sec
1	1	0 33	0 38	0 37	0.39	0.38
		0 32	0 43	0 38	0 41	0.32
	2	0 38	0 35	0 32	0.34	0 36
		0 39	0.42	0 32	0.41	0 42
	3	0 30	0.37	0.33	0.37	0.41
		0.34	0.37	0.38	0 41	0 40
2	1	0.40	0.38	0 36	0.40	0.36
		0.41	0.38	0.41	0.35	0.37
	2	0.35	0.39	0.38	0 38	0 41
		0.39	0.41	0 34	0 41	0 38
	3	0.39	0.40	0 40	0.39	0.40
		0 38	0.38	0.35	0 37	0 40

TABLE 25

ANALYSIS OF VARIANCE FOR CEMENT CONTENT OF MORTAR SAMPLES FROM WRIGHT PAVING JOB

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests	
					$F_{0.05}$	$F_{0.01}$
Replication	0 0014	1	0 0014	2 33	7 71	21 2
Mix time	0 0042	4	0 00105	1.75	6 39	16 0
RT	0.0024	4	0 0006	—	—	—
Position	0 0000	2	0.0000	0.00	4 46	8 65
PR	0.0001	2	0 00005	0 11	4 46	8.65
PT	0.0043	8	0.0005375	1 23	3 44	6 03
PRT	0.0035	8	0.0004375	—	—	—
Total	0.0159	29				

TABLE 26

CEMENT CONTENT OF MORTAR SAMPLES IN GRAMS CEMENT PER GRAMS MORTAR FROM MACDOUGALD PAVING JOB

Replication	Position in Mixer or Discharge Stream	Cement Content (g/g Mortar) for Mixing Time				
		30 Sec	45 Sec	60 Sec	120 Sec	180 Sec
1	1	0.16	0 18	0 18	0 22	0.17
		0.16	0 16	0.24	0.19	0.20
	2	0.19	0 14	0.19	0.20	0.20
		0.21	0.19	0.20	0.23	0.19
	3	0 21	0.18	0.18	0.22	0.20
		0 19	0 14	0.23	0 23	0 19
2	1	0 21	0 14	0 18	0 18	0 19
		0 22	0.10	0.17	0.21	0.18
	2	0.20	0.17	0 15	0 20	0.17
		0.19	0.18	0.17	0.21	0.20
	3	0 22	0 18	0 17	0.21	0 21
		0 17	0 19	0.19	0.18	0.17

TABLE 27

ANALYSIS OF VARIANCE FOR CEMENT CONTENT OF MORTAR SAMPLES FROM MACDOUGALD PAVING JOB

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests	
					$F_{0.05}$	$F_{0.01}$
Replication	0.00066	1	0.00066	1.97	7 71	21.2
Mix time	0.00586	4	0.00142	4.24	6.39	16.0
RT	0.00134	4	0.000335	—	—	—
Position	0.00061	2	0.000305	0.84	4.46	8.65
PR	0.00000	2	0.00000	0.00	4.46	8.65
PT	0.00076	8	0.000095	0.26	3.44	6.03
PRT	0.00290	8	0.0003625	—	—	—
Total	0.01195	29				

TABLE 28

CEMENT CONTENT OF MORTAR SAMPLES IN GRAMS CEMENT PER GRAMS MORTAR FROM MACDOUGALD WARREN, INC

Replication	Position in Mixer or Discharge Stream	Cement Content (g/g Mortar) for Mixing Time				
		30 Sec	45 Sec	60 Sec	120 Sec	180 Sec
1	1	0.22	0.20	0.32	0.27	0 32
		0.22	0.22	0 36	0.33	0.30
	2	0.12	0.28	0.20	0.26	0.23
		0.22	0.21	0.23	0.29	0.29
	3	0.16	0.20	0.18	0.25	0.20
		0.18	0.21	0.26	0.18	0 28
2	1	0.35	0.33	0.25	0.21	0 21
		0.33	0.33	0.23	0.24	0.28
	2	0.27	0.21	0.25	0.21	0.21
		0.32	0 30	0.29	0.25	0.25
	3	0.24	0.19	0.19	0.18	0.14
		0.32	0.31	0.21	0.23	0.21
3	1	0.35	0.43	0.29	0.32	0.27
		0.34	0.36	0 32	0.32	0.13
	2	0.18	0.16	0.20	0.23	0.15
		0.25	0.19	0.24	0.20	0.20
	3	0.20	0.21	0.22	0.23	0.22
		0.20	0.24	0.28	0.18	0.23

TABLE 29

ANALYSIS OF VARIANCE FOR CEMENT CONTENT OF MORTAR SAMPLES FROM MACDOUGALD WARREN, INC.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests	
					$F_{0.05}$	$F_{0.01}$
Replication	0.0013	2	0.000650	0.14	4.46	8.65
Mix time	0.0033	4	0.000825	0.18	3.84	7.01
RT	0.0367	8	0.004587	—	—	—
Position	0.0435	2	0.02175	14.69[a]	3.63	6.23
PR	0.0128	4	0.0032	2.16	3.01	4.77
PT	0.0049	8	0.000612	0.41	2.59	3.89
PRT	0.0237	16	0.001481	—	—	—
Total	0.1262	44				

[a]Significant at the 1 and 5 percent levels (highly significant).

TABLE 30

CEMENT CONTENT OF MORTAR SAMPLES IN GRAMS CEMENT PER GRAMS MORTAR FROM GEORGIA TECH MIXER

Replication	Position in Mixer or Discharge Stream	Cement Content (g/g Mortar) for Mixing Time				
		30 Sec	45 Sec	60 Sec	120 Sec	180 Sec
1	1	0 21	0 22	0 19	0 23	0 23
		0 19	0 21	0 26	0 21	0.21
	2	0.18	0 25	0.22	0 19	0.19
		0.22	0 23	0 23	0.20	0 20
	3	0 21	0 18	0 16	0 24	0.22
		0 22	0 23	0.19	0 23	0 22
2	1	0 19	0.16	0 17	0 18	0 19
		0 18	0 20	0 19	0 21	0 21
	2	0 16	0 20	0 17	0 20	0.20
		0 18	0 17	0 17	0 19	0 17
	3	0 20	0 18	0 16	0 18	0.20
		0 17	0.18	0.18	0 18	0 20
3	1	0 20	0 19	0.20	0.21	0 22
		0.23	0 21	0 16	0 20	0 19
	2	0.23	0 20	0 17	0 19	0 22
		0 18	0 19	0 17	0 21	0 15
	3	0 20	0.19	0 18	0 19	0.17
		0 18	0 21	0 21	0 19	0 22

TABLE 31

ANALYSIS OF VARIANCE FOR CEMENT CONTENT OF MORTAR SAMPLES FROM GEORGIA TECH MIXER

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests	
					$F_{0.05}$	$F_{0.01}$
Replication	0.00569	2	0.002845	7.7701[a]	7 71	21.2
Mix time	0 00109	4	0 0002725	2 5057	6 39	16.0
RT	0 00087	8	0 00010875	—	—	—
Position	0 00245	2	0.001225	12.97[b]	4.46	8.65
PR	0 00007	4	0.0000775	0 18538	4 46	8 65
PT	0 00124	8	0 000155	1 6419	3.44	6 03
PRT	0 00151	16	0 0000944	—	—	—
Total	0.01292					

[a]Significant at the 5 percent level.
[b]Significant at the 1 and 5 percent levels (highly significant).

TABLE 32

CEMENT CONTENT OF MORTAR SAMPLES IN GRAMS CEMENT PER GRAMS MORTAR FROM CAMPBELL MATERIALS COMPANY[a]

Replication	Position in Mixer or Discharge Stream	Cement Content (g/g Mortar) for Mixing Time			
		45 Sec	60 Sec	120 Sec	180 Sec
1	1	0 27	0 32	0.25	0 30
		0 32	0 31	0.29	0 24
	2	0 21	0 27	0.28	0.28
		0 17	0 27	0.33	0.27
	3	—	0 29	0.23	0 24
		0 23	0 21	0 29	0 25
2	1	0 31	—	0 26	—
		0 31	—	0 27	—
	2	0 24	—	0 26	—
		0 34	—	0 26	—
	3	0 25	—	0 26	—
		0 32	—	0 28	—

[a]Incomplete experiment.

Appendix B

CONCRETE MIXER SPECIFICATIONS

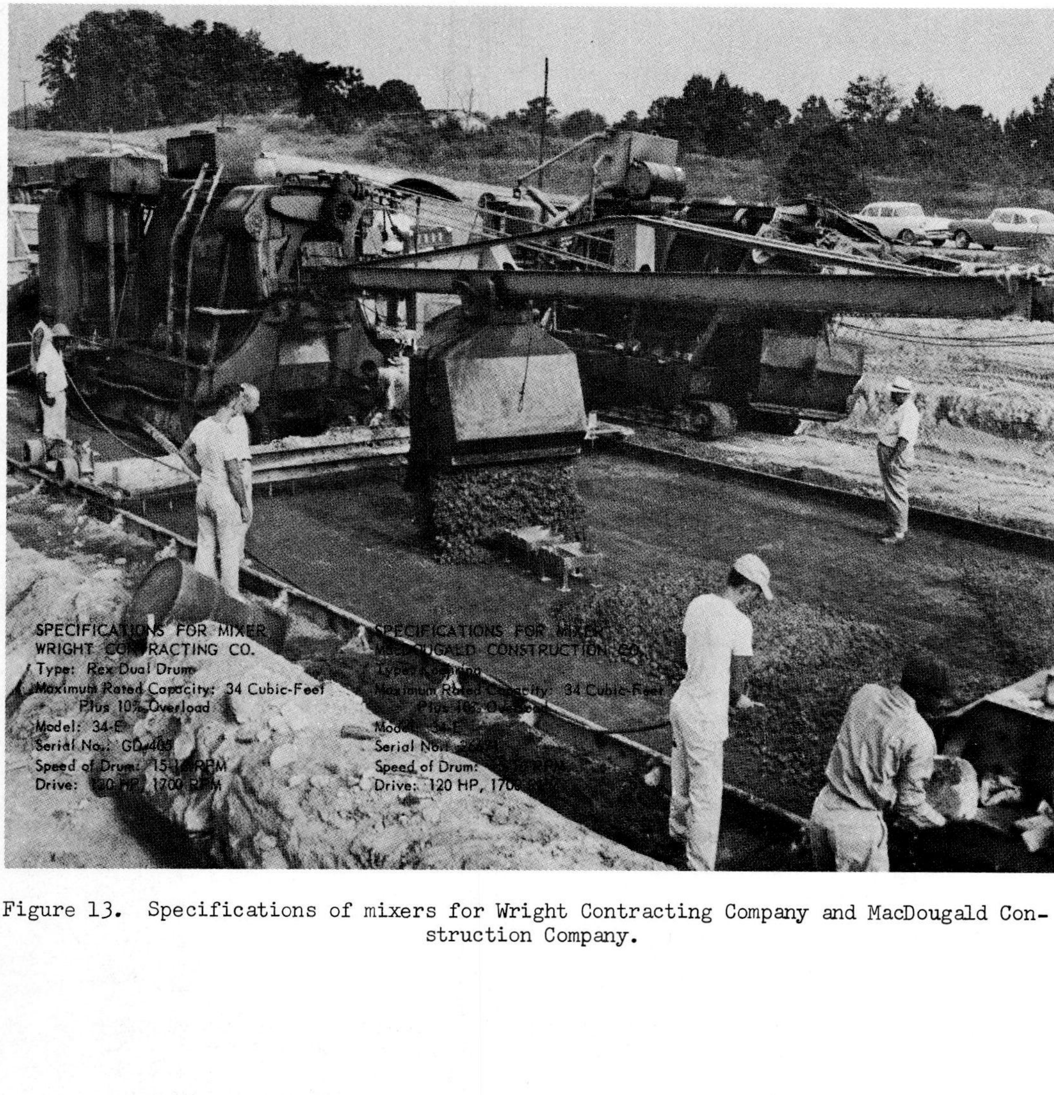

Figure 13. Specifications of mixers for Wright Contracting Company and MacDougald Construction Company.

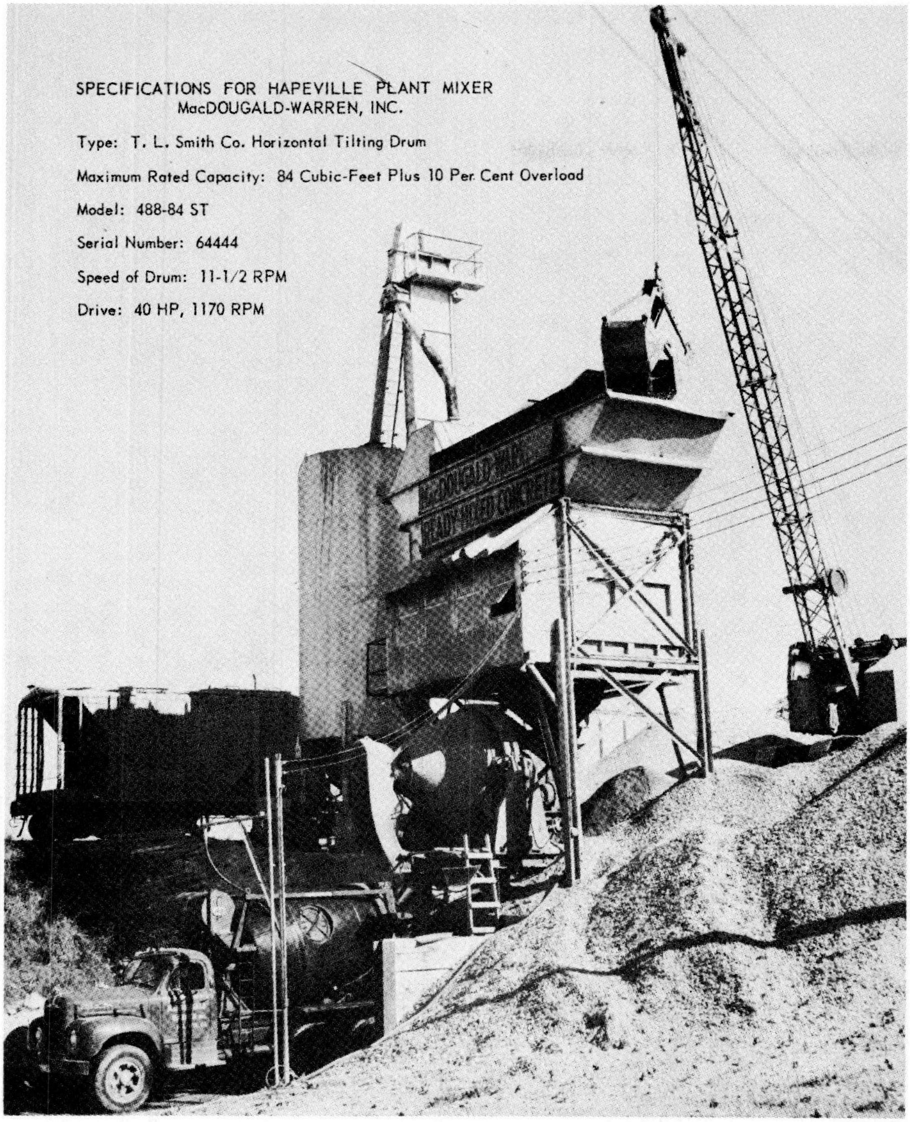

Figure 14. Specifications for Hapeville Plant mixer, MacDougald Warren, Inc.

SPECIFICATIONS FOR GEORGIA TECH LABORATORY MIXER

Type: Worthington

Maximum Rated Capacity: 6 Cubic-Feet Pulus 10% Overload

Model: 6S–2A

Serial No.: W59644

Speed of Drum: 18 RPM

Drive: 16 HP, 1750 RPM

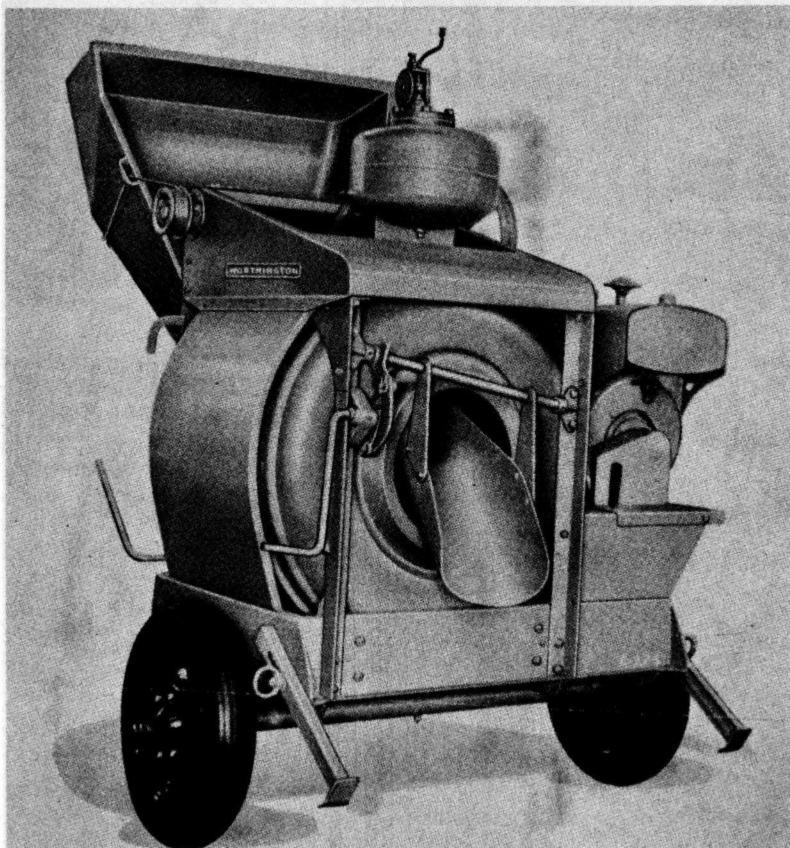

Figure 15. Georgia Tech's concrete laboratory mixer.

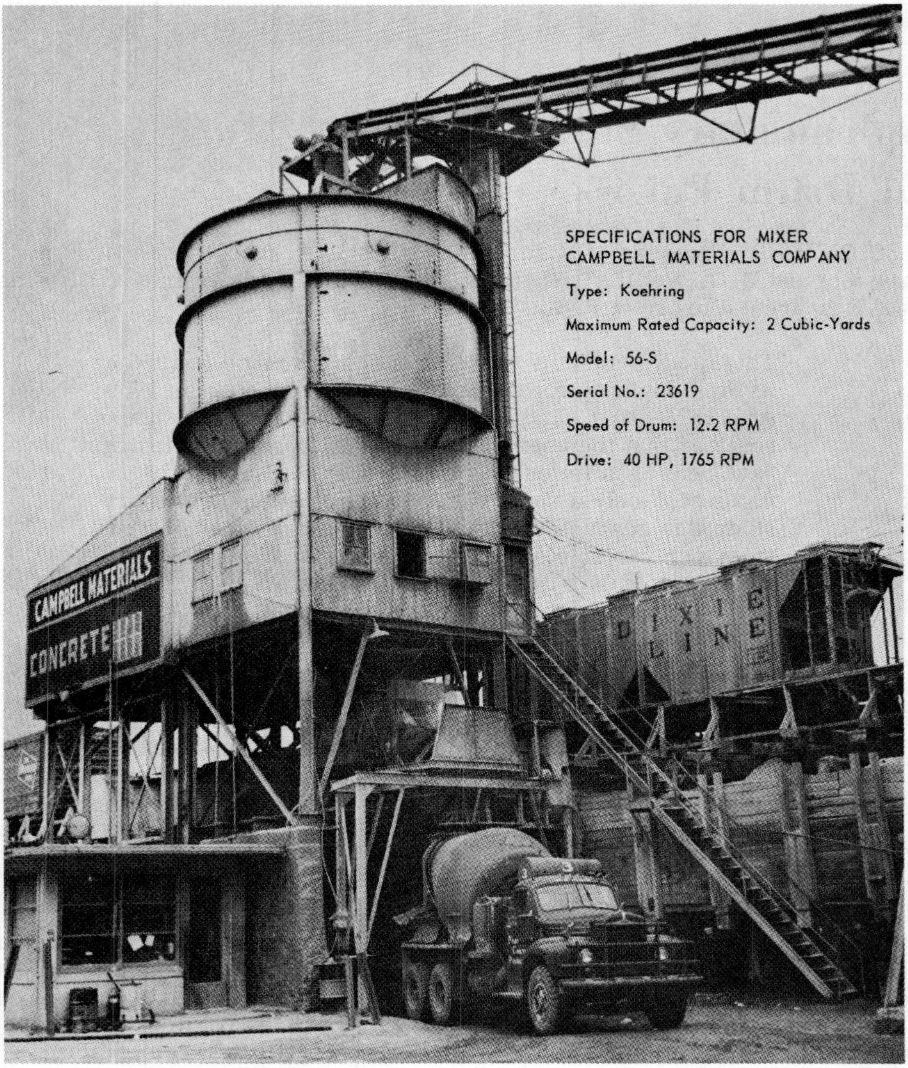

Figure 16. Specifications for mixer, Campbell Materials Company.

Appendix C

EXAMPLE CALCULATION FOR DETERMINING CEMENT CONTENT OF MORTAR SAMPLES

Sample Number	Indium Foil Data					Mortar Sample Data						
	Foil Count		True Count (N_t)	Foil Weight (mg)	N_t per 20 mg	Sample Count Channels 62-74	Sample Count for N_t = 300	Sample Weight (g)	Container Weight (g)	Net Sample Weight (g)	Weight Cement[a] (g)	Cement Content (g cement per g mortar)
	Per 5 Min	Per Sec										
334	77,039	257	299	201	298	1,301	1,310	5.18	0.94	4.24	1.14	0.27

[a]See Figure 12.

Supplementary Study of 34-E Dual Drum Pavers

H.W. SCHNEIDER, Engineer of Materials and Tests, Arkansas State Highway Commission; and D.O. WOOLF, Highway Physical Research Engineer, Division of Physical Research, Bureau of Public Roads

This study supplements an investigation made in 1958 by 13 State highway departments and presented at the 1960 Annual Meeting. In preparing the earlier report, it was realized that the number of tests made per variable might have been insufficient to explore fully the suitability of mixing for only a short time. When this supplementary study was conducted, a greater number of strength specimens per variable of mixing time was made to obtain suitably complete data for short mixing times.

The results obtained in this study agree with the findings of the earlier report that concrete of adequate strength can be secured with a mixing time of less than 60 sec. When a mixing time of as few as 20 sec. was used, the concrete was found to have a strength at 28 days comfortably in excess of 3,000 psi. Although the concrete was harsh, the strength results for the different mixing times had an average coefficient of variation of 15.5 percent, indicating excellent control of the concrete.

• DURING the construction season of 1958, a study of 34-E dual drum pavers was conducted by 13 State highway departments. A summary report of the results of this study was prepared by the Bureau of Public Roads (1). In the preparation of this report, it was realized that the number of test specimens prepared per variable in each study by different State highway departments might have been insufficient to average out the uncontrollable variables such as the weather and the physical condition of the operators. It is believed that insufficient data for short mixing times have been obtained. The Arkansas State Highway Commission had planned to cooperate in this study, but delays in the grading and drainage of the selected project prevented placing the pavement in 1958. When the pavement was programed in 1960, the Commission offered to conduct a supplementary study to check the data obtained in the previous studies.

PROGRAM OF STUDY

Of principal interest was the preparation of a large number of concrete test specimens for each variable of mixing time. It was believed that more information could be obtained per man-hour if strength test specimens were limited to cylinders, consequently the preparation of beams for flexural strength tests was eliminated from the study. The outline of tests called for the use of only one overload of 20 percent, mixing times of 20, 30, 45, and 60 sec exclusive of transfer time, the preparation of 108 cylinders for each mixing time, and a suitable number of tests for consistency, air content, and unit weight. Due to excessive rainfall during the study, the number of specimens was reduced, and only 72 specimens were made for some mixing times. The specimens made were divided equally for tests at 7 and 28 days.

The study was made during the construction of Arkansas Project F-021-3(8) on a relocation of US 67 between North Little Rock and Jacksonville. As previously stated, heavy rainfall interrupted the study which began on June 21 and was completed July 21.

The mixer used was a Koehring 34-E dual-drum, built in 1958 and found to be in excellent condition. The equipment in the paving train included a spreader and vibrator, a finisher, a longitudinal float, and a jointing machine. The concrete pavement was covered for 24 hr with wet burlap and then sprayed with a pigmented curing compound. An average of 1,500 ft per 10-hr day of pavement 24 ft wide and 9 in. thick was placed.

The concrete was designed in accordance with the Arkansas specifications. The mix contained $5\frac{1}{4}$ bags of cement per cu yd, and a maximum water content of 5.5 gal per bag. The slump was specified to be approximately 2 in. and the air content between 3 and 5 percent. The aggregates used were natural sand and crushed stone from a local commercial producer. The mix proportions were 94-186-428 by dry weight. This resulted in only 30 percent of sand in the total aggregate on a solid volume basis, and furnished a harsh mix. However, as the concrete was vibrated, a satisfactory finish of the pavement surface was obtained.

Samples for testing were taken from the last batch of concrete placed on the subgrade before the paver backed to place the top course. Batches were sampled every 20 to 30 min. Approximately 2 to 3 cu ft of concrete were shoveled into a pan from five locations in the pile. The pan was carried to a truck and then taken to a sample preparation site established for each day's work.

It was planned to make tests for penetration by the Kelly ball, slump, and air by the Chace meter on every sample; then six 6- by 12-in. cylinders were cast. The Kelly ball tests were made on the bucket load of concrete on the subgrade, but the other tests were made at the sample preparation site. Tests for unit weight and determinations of air content by a pressure meter were scheduled to be made on alternate batches. The concrete cylinders were cast in cardboard molds with metal bottoms, and the completed cylinders covered with 5 layers of wet burlap. On the following morning, the molds were stripped, the cylinders marked, and then stored in tanks of water. The cylinders were taken to the State testing laboratory one day before the date of testing and were capped with a sulfur compound.

Timing of the mixing for the test batches was handled by personnel of the Construction Economy Branch of the Bureau of Public Roads. The contractor usually used a mixing time of 50 sec. However, he could not operate continuously at a fixed mixing time due to poor subgrade outside the forms. Batch trucks could not back to the skip, discharge, and clear the skip in the required time. Consequently, when time for a test batch approached, four consecutive batches were mixed the specified time and a sample taken from the last batch. For the mixing time of 20 sec, the paver was operated manually and only one batch was mixed at a time.

No appreciable difference in appearance was observed between the concretes mixed for different lengths of time and even with the 20-sec mixing the aggregate seemed to be well coated.

The study was interrupted by heavy rains when about one-half completed. When clear weather resumed, the grade beside the forms was so bad that trucks could not operate on it. The contractor tried double batching; that is, using two pavers, one on the service road and one on the grade. After a batch had been mixed dry in the first paver, it was dumped into the skip of the paver on the grade, and with the addition of water, mixed to form concrete. This procedure was conducted for only a few hours when the inspector closed the project due to spillage of materials. No specimens for this study were taken from the concrete prepared under these conditions. When construction was resumed about 3 weeks later, the study was completed without incident.

EFFECT OF MIXING TIME

Six cylinders were prepared from each batch of concrete tested. One-half of these cylinders were tested for compressive strength at an age of 7 days and the remainder at 28 days. Average values for the compressive strength of each group of 3 cylinders are given in Table 1 with information and data covering when the specimens were made, mixing time, air temperature, and consistency, air content, and unit weight of concrete.

The relation between mixing time and strength of concrete is shown in Figure 1. Of the two curves presented, greater weight is given to that for tests at an age of 28 days.

TABLE 1

SUMMARY OF TEST DATA

Mıxıng Tıme (sec)	Date	Hour	Aır Temp. (° F)	Consıstency (ın.) Kelly Ball	Consıstency (ın.) Slump Cone	Aır Content (%) Chace Meter	Aır Content (%) Press. Meter	Unıt Weıght (pcf)	Average Compress. Strength (psı) 7 Days	Average Compress. Strength (psı) 28 Days
60	6-21	2 45	-	-	4 0	6 0	-	-	2,620	3,320
		3 15	-	4 0	3.7	6 9	-	141	2,610	3,180
		4 00	-	1 5	2.5	4 7	3.8	-	4,040	4,940
		4 40	-	1 2	1 6	4.3	-	148	4,110	4,990
	7-20	9 00	88	2.0	2.5	5.2	3.8	-	3,440	4,150
		9·25	94	1.5	2.4	5.0	-	148	3,220	4,210
		9 45	94	1 8	1.6	4.0	3.9	-	3,590	4,370
		10 15	91	2.0	1 9	5.0	-	146	3,400	4,260
		10 35	98	1.4	1 5	5.0	4.0	-	3,730	4,760
		11 00	98	1.3	1 4	5.0	-	-	3,610	4,600
		11 20	92	1.0	1.9	4.0	-	150	5,190	6,230
		11:40	89	1.2	2.2	4.0	3.8	-	4,210	4,730
		Avg.	-	1.7	2.3	5.0	3 9	147	3,650	4,480
45	6-22	10·10	98	2.0	-	4 3	4.3	-	3,680	4,500
		10 55	98	2.8	2.6	5.2	-	144	3,190	3,950
		11 30	98	1.8	0.8	3 9	-	-	3,150	3,980
		11·55	99	2 8	3 8	6.0	4.9	-	2,770	3,800
		1 50	-	2.8	1.3	4 3	-	-	4,000	4,660
		2 20	99	2 0	1.5	5.6	-	146	3,440	4,420
		2 45	98	1.1	1.5	3.5	3.8	-	4,370	5,510
		3 15	98	1.9	0.3	4.7	-	146	3,420	4,100
		3 50	-	1 8	1 1	4.3	-	-	3,170	4,180
	7-20	1 20	85	1 5	2 5	4.7	5.2	-	3,840	4,700
		1·45	85	0 6	1 0	-	-	149	3,810	5,780
		2 00	83	1.0	0 9	3 5	2.7	-	3,930	5,410
		2 20	83	1 5	1.9	-	-	147	3,930	4,820
		2·35	82	2.0	2.6	2 7	3.2	-	3,560	4,660
		2·50	83	2.2	2.4	-	-	148	2,940	4,140
		3·10	85	0 7	0.8	-	-	150	4,730	6,060
		3 30	83	2.0	3.0	-	4.2	-	2,720	3,470
		Avg.	-	1.8	1.8	4.4	4.0	147	3,570	4,600
30	6-23	10 35	-	1.6	2 5	4.7	5.1	-	3,150	4,170
		11·00	-	1.6	1.2	4.3	-	145	3,150	4,200
		11 35	-	0.9	0.9	4.3	-	-	4,270	5,680
		11 55	-	1 3	1 7	4.3	3 9	-	4,280	4,450
		1 35	-	1.4	2 4	4.3	-	146	3,380	4,160
		2:10	-	2.2	2.5	4 3	-	-	3,480	4,600
		2·45	95	0.9	1.8	4.3	3.6	146	3,120	4,240
		3·15	96	2.0	2.5	4.3	-	-	2,620	3,440
		3·35	95	2.4	2.0	4.3	-	-	2,670	3,830
	7-21	9 30	92	1.2	2 0	6.4	4.8	-	3,220	3,800
		9·55	95	1.8	1.6	6.4	-	148	3,180	3,960
		10 20	94	1.4	1.5	6.0	3.3	-	3,960	4,410
		10 55	96	0.5	0.9	4.3	-	-	4,260	5,120
		11 10	86	1.2	0.6	4.7	3.1	-	4,480	5,600
		11 40	91	2.3	1.9	5.2	-	145	3,540	4,170
		Avg.	-	1.5	1.7	4.7	4.0	146	3,520	4,390
20	6-24	9 45	90	1 7	2.5	4.7	4.6	-	2,840	3,700
		10 15	90	2.4	2.5	3.5	-	146	2,990	4,160
		10 40	91	1.6	2.2	4.3	-	-	2,690	3,590
		11 00	86	1.6	2.2	3.9	4.4	-	2,470	3,290
		11 25	89	0.5	0.6	3.9	-	147	5,070	6,220
		11 45	78	2.0	3.4	4.3	4.3	-	2,760	3,610
	7-21	1 25	89	1 5	2 6	4.3	3.7	-	2,490	3,440
		1.45	86	1.5	2.0	5.6	3.8	-	2,710	3,250
		2·10	84	1.3	2.1	5.3	-	147	3,600	4,900
		2·25	81	1.0	1.7	3.9	-	148	4,280	4,360
		2:40	80	1.4	2.5	3.9	3.8	-	2,300	3,540
		2·55	78	2.2	1.5	3.1	-	149	4,160	4,900
		Avg.	-	1.6	2.2	4.2	4.0	147	3,200	4,100

This shows that the maximum strength is obtained with a mixing time of 45 sec. (All times excluded transfer time.) With the results for the 60-sec mixing time considered as unity, the strength ratios for the various mixing times are given in Table 2.

The results obtained here for mixing times of less than 60 sec are somewhat superior to those given in the report published in the April 1960 issue of "Public Roads." However both sets of tests demonstrate conclusively that mixing times of as few as 30 sec could be used with little reduction in strength. The small differences found between the sets of tests probably reflect the mechanical efficiency of the mixers used.

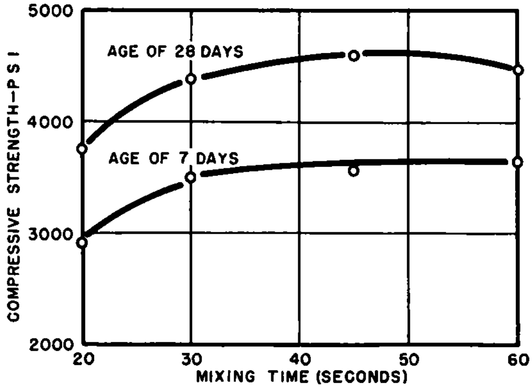

Figure 1. Effect of time of mixing on compressive strength.

VARIATIONS IN TEST RESULTS

The strengths obtained in tests of each individual group of cylinders at an age of 28 days are plotted in Figure 2. These data are presented to direct attention to some possibly unusual trends exhibited by specimens tested consecutively on the same day. One example is shown by the specimens representing 45-sec mixing time and starting with the 11th group. With one exception, the different groups of specimens show an almost uniform rate of loss of strength until this series of tests was completed. The exception concerns the next to last group of three specimens. This group has the highest compressive strength for any in this series of tests. The next and last group of the series has a low value agreeing with the general trend of the 11th to 15th groups.

Similar progressive increases or decreases of the test results can be seen in the plotted data for the other mixing times. For a mixing time of 20 sec, there are 2 sets of 3 groups of specimens which show uniform decreases in strength. The values for 30-sec mixing time show a set of 5 groups, the 10th to the 14th, with a fairly uniform rate of increase of strength. No marked changes similar to these were found for the specimens representing the 60-sec mixing time although the entire series of groups, the 5th to the 12th made on July 20, show with the exception of group 11, a slight but continual increase in strength. The group 11 shows wild results similar to certain single groups for each of the other mixing times.

TABLE 2

Mixing Time (sec)	Rel. Str. Ratio (%)
60	100
45	103
30	98
20	84[a]

[a]Six test specimens excluded (see discussion of Fig. 5).

The data collected during the course of this study fail to show any definite relation with all of the cases of progressive increase or decrease in the strength of all of the specimens previously mentioned. As mentioned later, available data correlate with one of these cases; however, with the others, some assumptions must be made.

With one exception, all of these progressive increases or decreases in strength occurred in July. The tests of the 60-sec mixing time were made during the morning

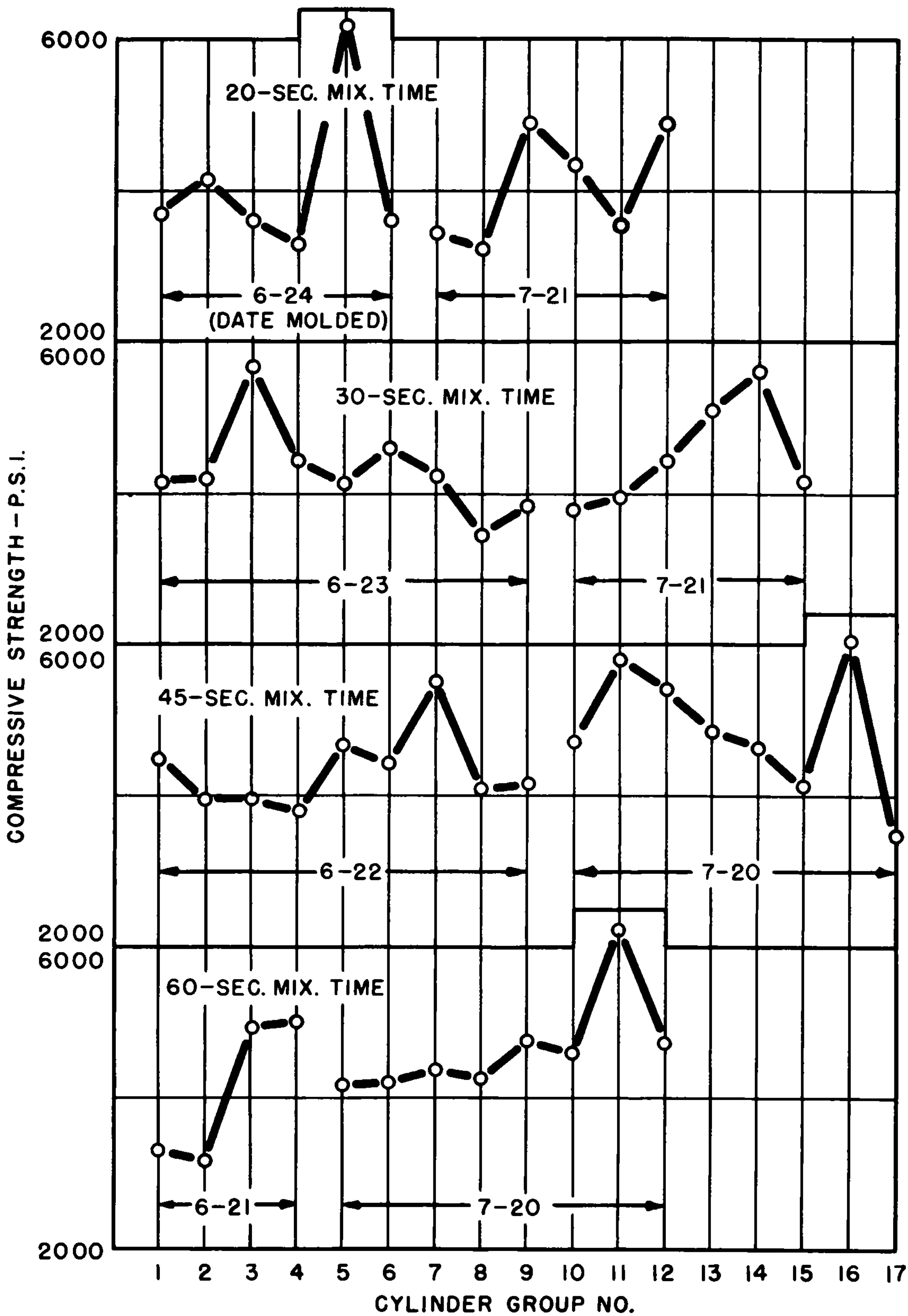

Figure 2. Strengths of groups of cylinders in order as molded; age of 28 days.

of July 20 and show, with one exception, rising strengths. During the afternoon of that day, tests were made with a mixing time of 45 sec. Six of the 8 groups of cylinders show progressively decreasing strength. On the following day, July 21, similar behavior was found. The tests of concrete prepared with a mixing time of 30 sec, which tests were made in the morning, show with one exception steadily increasing strength. Tests of the 20-sec mixing time made in the afternoon of July 21 gave confused results. Three consecutive groups of the six groups of cylinders did show steadily decreasing strengths, but the first two groups showed lower values, and the last a high value.

In attempting to explain unusual results of tests of concrete obtained in construction operations, writers frequently refer to items for which determined values are not available. The temptation to do that here is quite strong. Of all the various items that would have a marked effect on the strength of concrete and for which data are not available, first choice is given to the water content of the fine aggregate. Normal variations in this water content could be expected which might give the results mentioned. The receipt and use of a new lot of sand in a moist condition could cause the strength of concrete to decrease. Use of sand stockpiled and subjected to the high atmospheric temperatures shown for much of this study could cause the strength of concrete to be increased. However, in either case surplus or deficiency of water in the sand used should be reflected in changes in the consistency of the concrete.

Figures 3 and 4 show average values obtained in tests of concrete mixed for 20, 30, 45, and 60 sec, respectively. In each case, data are presented for compressive strength, Kelly ball penetration, slump, and air content by the Chase meter. In several cases data are not available, and the figure is so marked.

The average values for the 20-sec mixing time shown in Figure 3 do not disclose a reason for the two series of progressively decreasing strengths previously mentioned.

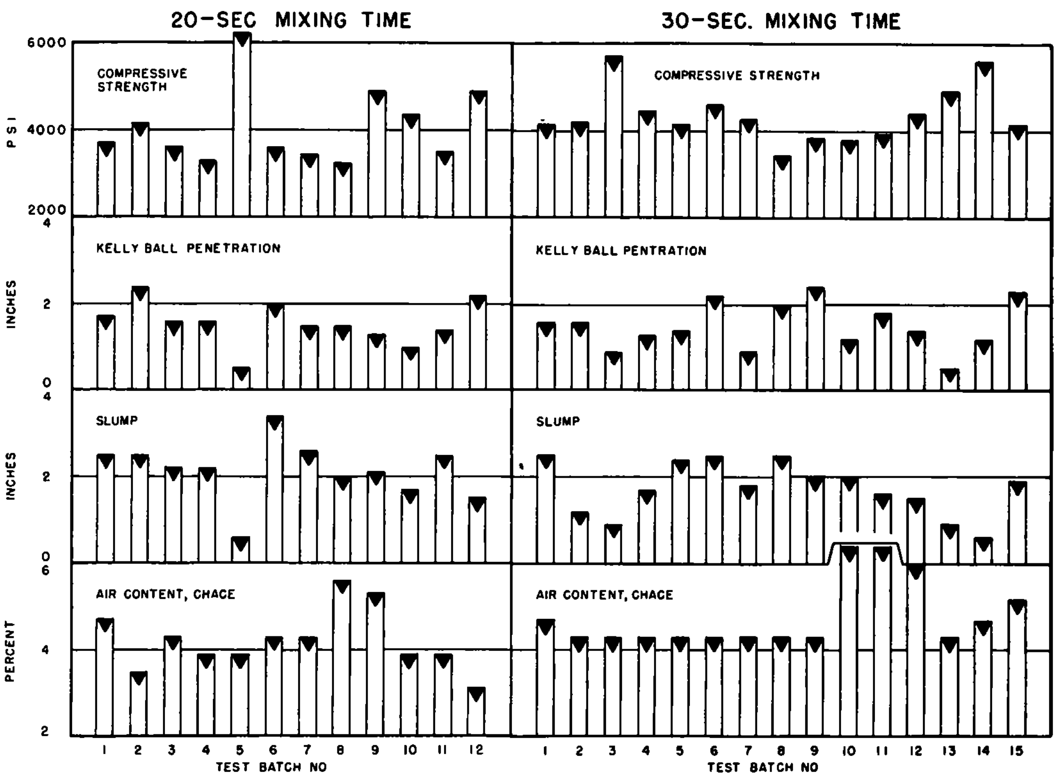

Figure 3. Average values determined from various tests on batches of concrete mixed for 20 and 30 seconds.

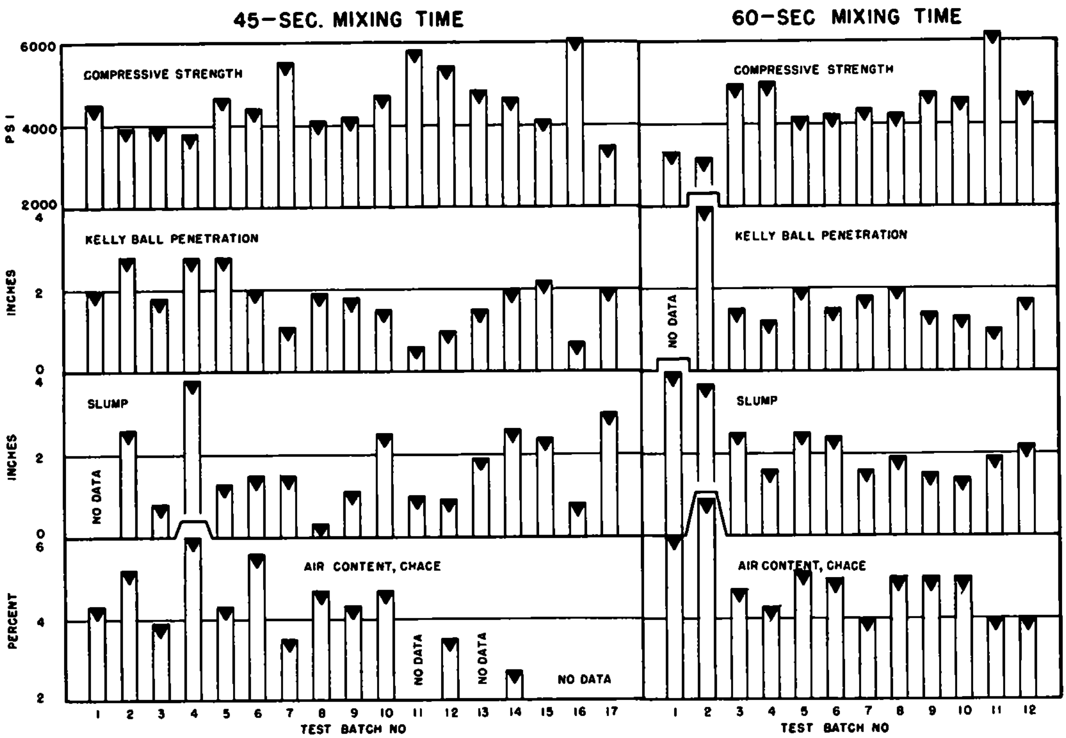

Figure 4. Average values determined from various tests on batches of concrete mixed for 45 and 60 seconds.

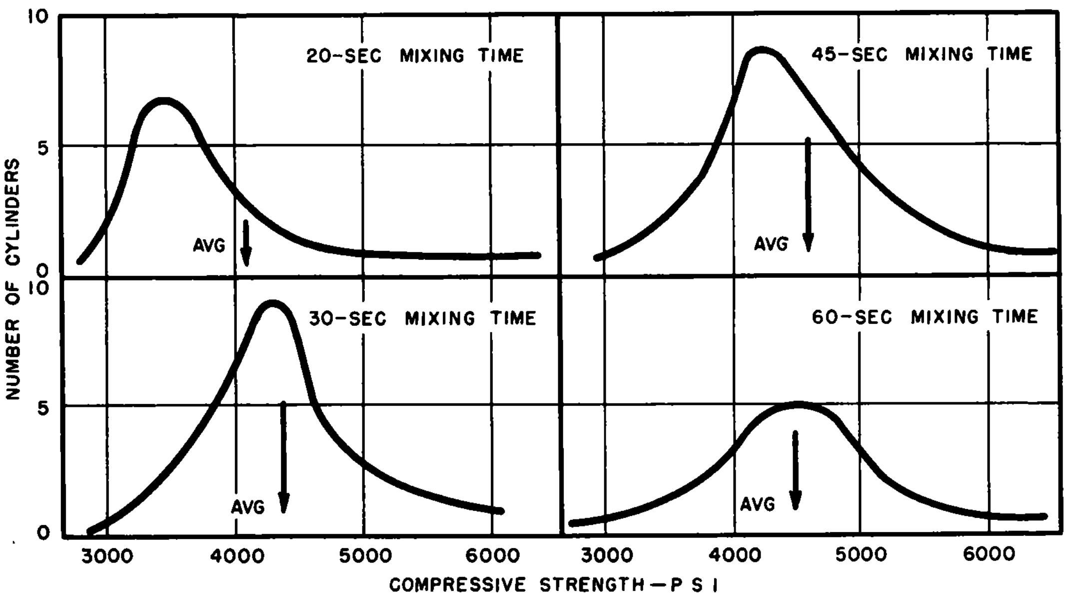

Figure 5. Frequency distribution of compressive strengths of concrete at 28 days.

On the contrary, the data obtained for consistency and air content of the concrete vary in a manner opposite to the trend of the results for strength. Little hope for an explanation of the performance of batches 2 through 4, and 9 through 11, is given here. The high strength of batch 5 is reflected however by the decrease in Kelly ball penetration and slump.

Information concerning the concrete produced with a 30-sec mixing time is also shown in Figure 3. This concrete shows high strengths for batches 3 and 14, and lowest strength for batch 8. Batches 10 through 14 show a set of continuously increasing strengths.

The records for slump of the concrete show for batches 10 through 14 a steady decrease which could well be associated with the increase in strength for these same concretes. The Kelly ball results for these batches are irregular, as are the determinations for air content. It seems to be somewhat questionable that a change in slump from 2.0 to 0.6 in. could cause a change in compressive strength from 3,800 psi to 5,600 psi. Possibly it would be proper to consider these slumps as indications that a change in consistency occurred which must have been accompanied by some other change to affect the compressive strength to such as extent.

The high strengths shown for batches 3 and 14, and the low strength for batch 8 are associated with low or high slumps, respectively. The results of the Kelly ball tests are of the same degree as those for slump, but not of similar magnitude.

Figure 4 for the concrete prepared with a 45-sec mixing time shows 3 batches with high or reasonably high strengths, and one low value. The highest value is an exception in a series of 7 batches which otherwise show a progressive decrease in strength. The first batch, No. 11 of this series, has a strength of 5,780 psi at 28 days, and the strengths decrease to 3,470 psi for batch 17. Kelly ball tests for batches 11 through 15 show a progressive increase in penetration, but the 16th batch has only a small value, and that for the 17th is only slightly above the average for all of the 45-sec tests. The slump of this 17th batch is of some magnitude, but the slumps for the other batches of this series are confused. No assistance in explaining the progressive increase in strength of this series of tests can be obtained from the Chace air determinations as so many of these tests were not made.

The tests of concrete prepared with a 60-sec mixing time (Fig. 4) fail to show other than a few correlations between strength and consistency or air content. Batches 1 and 2 have relatively low strength and high values for consistency. Batch 2 also has a high air content by the Chace meter. Batch 11 has the highest strength, but the determinations for consistency or air content fail to show any reason for this. Batches 5 through 10 show in general an irregular but small increase in strength from 4,150 to 4,600 psi. A somewhat similar decrease in slump is found for these same batches, but the Kelly ball and Chace air meter tests show no trends similar to those for strength.

In three of four cases, more definite correlation is found between the compressive strength of concrete and the slump than between the strength and either the Kelly ball or the Chace air meter determinations. This is somewhat of a disappointment. It had been hoped that the Kelly ball and Chace meter tests would correlate closely with strength tests of concrete. As these tests for consistency and air content can be made quickly, it was hoped that they could be used as acceptance tests with the definite knowledge of a close association with the strength of concrete. Such, however, is not found, and the slump test remains the more reliable indication of the quality of concrete.

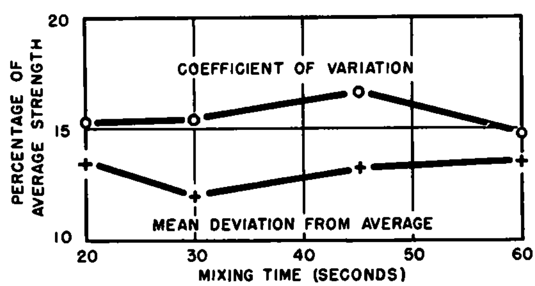

Figure 6. Comparison expressions for uniformity of compressive strengths of concrete.

CHACE AIR METER RESULTS

All of the tests for air content made with the Chace meter have an average value of 4.6 percent. This is sufficiently different from the average value of 4.0 percent obtained in tests with the pressure meter to warrant caution in accepting test results for the Chace meter. An air content of 4.0 percent is believed by many authorities to be about the least amount that will insure adequate resistance by concrete to the effects of freezing and thawing. Increase in the air content to 4.6 percent should be accompanied by a marked increase in the durability of the concrete. Consequently, the results obtained here with the Chase meter indicate for the concrete a durability that may be misleading. As mentioned by others in studies of the Chase meter, the test results obtained should be considered to indicate general ranges in air content—high, medium, or low. More precise indications should not be expected.

CONTROL OF CONCRETE

Abdun-Nur (2) in his paper on the probabilities of obtaining concrete of uniform strength, makes reference to the Bureau of Reclamation control of the strength of concrete. Under this control, a coefficient of variation of practically 15 percent is obtained. In the analysis of the data for the Arkansas project, it was decided to determine the coefficient of variation for each group of data and to compare the values obtained with those for the mean deviation from the average. This latter step was taken as the mean deviation is considered less difficult to compute and may be better understood by many engineers. In addition, frequency distribution curves were prepared from the test results for the specimens representing each of the four mixing times.

The frequency distribution curves are shown in Figure 5. It is seen that the curve for the 20-sec mixing time indicates that most values lie in a range from 3,100 to 4,300 psi. There are however some quite high test results which cause a marked misshape of the curve and a shift upward in the average value. In the interests of reliability of the findings of these tests, it might be appropriate to classify the six highest test results for single cylinders as sufficiently wild to warrant their rejection from the data considered. If this were done, the average value for the remaining test values would become 3,750 psi, a value more in keeping with the other findings of the study.

Although the curve for the 45-sec mixing time also shows a lopsidedness or skewness, the test data fail to show any particular point where higher values may be considered wild or unreliable. Consequently, no adjustment of the average value here is attempted.

Values for coefficient of variation and mean deviation from the average are plotted in Figure 6. The values for the 20-sec mixing time do not include the six wild results previously mentioned. Had these been included, the coefficient of variation would have been 21.8 percent, and the mean deviation from the average 17.2 percent. For the values presented, the coefficients of variation are close to the 15 percent mentioned by Abdun-Nur as denoting excellent control. Also, the mean deviation from the average follows closely the trend of the coefficient of variation.

From the frequency distribution curves in Figure 5, the most concordant test results were obtained with a mixing time of 30 sec.

In accordance with the requirements of their Standard Specifications, the Department drilled cores of the pavement for determinations of the thickness of the slab and the compressive strength of the concrete. The compression tests were made at an age of 3 months. For 59 cores tested an average strength of 4,430 psi was obtained, with

TABLE 3

CORE STRENGTHS

Mixing Time (sec)	No. of Specimens	Avg. Compress. Str. (psi)
20	2	3,760
30	3	4,180
45	4	4,060
60	3	4,530

maximum and minimum values of 6,060 and 2,410 psi respectively. Core strengths for the experimental sections of the pavement are given in Table 3. These values do not agree with those found in tests of the cylinders, but they do show that concrete of adequate strength was furnished even with a mixing time of only 20 sec.

Some concern has been expressed of the reason for the nonuniform results found throughout the study. As shown in Figure 5, values markedly different from the average occurred in the specimens prepared for each mixing time. The data associated with the strength results do not indicate why these variations were obtained. A review of data for the individual studies of mixing time conducted in 1958 generally showed more concordant strengths than those found in this study, but it was also observed that if the concrete was described as harsh, there was a tendency for a marked range in strength. The concrete used in this study was harsh, and it is believed that this harshness caused some exaggeration of the differences in strength normally found in tests of concrete. With a more plastic concrete, even lower values for coefficient of variation should be obtained than those reported here.

CONCLUSIONS

The results obtained in this study agree with the findings given in the earlier (1960) report to the effect that concrete of adequate strength can be secured with a mixing time of fewer than 60 sec, even including a mixing time of as few as 20 sec.

It is possible that the mechanical efficiency of the mixer used in this study permitted the attainment of better results for short mixing times than was found in the 1960 report.

For each mixing time used in this study, a considerable range in strength of concrete was found. Also for each mixing time, groups of specimens were found for which the strength of the concrete increased or decreased at a reasonably constant rate. It is possible that the harshness of the mix is responsible for some of the extreme test strengths obtained but no valid explanation for the progressive increase or decrease in strength of successive test batches is found from available data.

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1. Woolf, D.O., "A Study of 34-E Dual-Drum Pavers." Public Roads, 31:No. 1 (April 1960).
2. Abdun-Nur, E.A., "How Good Is Good Enough." Paper, Convention of Amer. Concrete Inst. (Feb. 1961).

An Analysis of Factors Influencing Concrete Pavement Cost

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The basic elements of concrete pavement construction costs are briefly discussed and evaluated. A cost analysis for an assumed project in a midwestern location is given to illustrate the effects of variations in design and construction practices on construction costs. Some of the cost factors discussed are (a) distributed steel and plain concrete pavement designs, (b) paving equipment and construction procedures, (c) differences in moduli of subgrade reactions, and (d) single-lane and dual-lane construction.

A principal objective is to show that detailed analysis of individual projects using local material and labor prices will reveal the most economical design for the anticipated traffic, subgrade, and climatic conditions of the pavement. Such an analysis will result in reduced pavement costs at no sacrifice in pavement quality.

• BESIDES laboratory and field tests there is another kind of research that can pay big dividends in design and construction savings at no sacrifice in pavement quality. This research is done by the engineer right at his desk—the analysis of various designs and construction methods suitable for a particular project.

To illustrate this type of research, traffic, subgrade k, concrete strength, and other factors needed to design a concrete pavement for a project in a midwestern State are assumed. A design analysis showed that two pavement designs are adequate for the assumed conditions:

1. A 9-in. concrete pavement on a 6-in. sand-gravel subbase.
2. An 8-in. concrete pavement on a 5-in. cement-treated subbase.

Detailed material and labor cost estimates were then made for these two basic designs with various joint designs and construction methods. Analysis of these estimates shows how different joint designs and construction procedures affect the total square yard pavement cost.

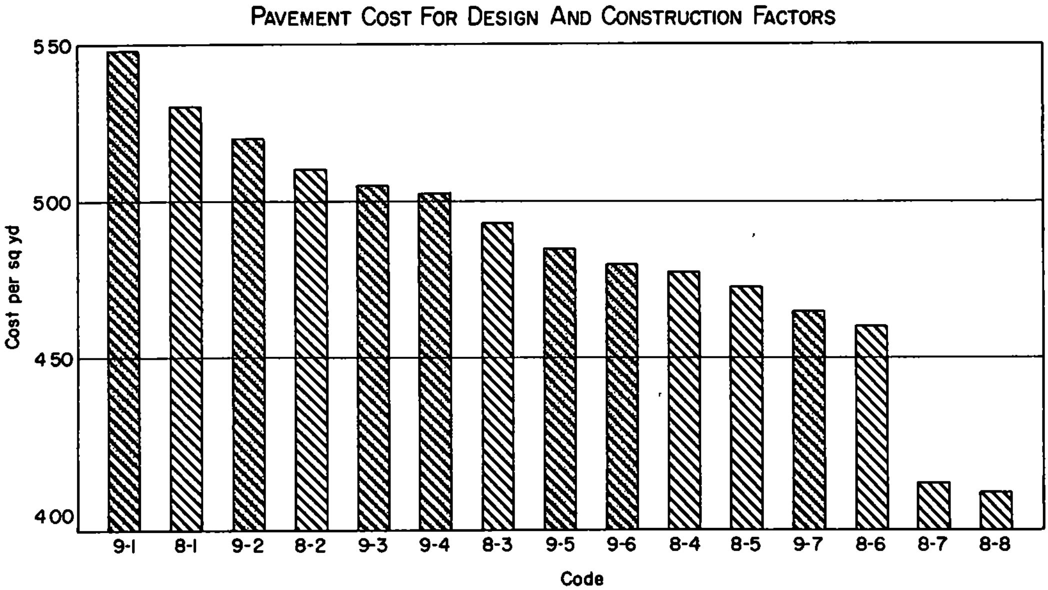
The economic analysis showed that the two basic pavement designs may vary in cost by as much as $1.36 per sq yd. This $1.36 reflects differences in jointing details and construction methods. One pavement cost $5.49 per sq yd. Its features are

1. 9-in. portland cement concrete pavement.
2. 6-in. sand-gravel subbase.
3. Doweled joints at 110 ft with 91-lb mesh.
4. 24-ft wide construction with conventional equipment and dual drum 34E pavers.

The other pavement cost $4.13 per sq yd. Its features are

1. 8-in. portland cement concrete pavement.
2. 5-in. cement-treated subbase.
3. Undoweled joints at 20 ft, no mesh.
4. 24-ft wide construction with slip-form and three-drum pavers.

The analysis reveals a variety of square yard costs between these extremes. For



DESIGN AND CONSTRUCTION FACTORS

CODE	CONSTRUCTION FACTORS	DESIGN FACTORS Dist. Steel	Jt. Spacing	Dowels
	9-in. Concrete Pavement on 6-in. Sand-Gravel Subbase			
9-1	Conv Equip -24 ft with Dual Drum Pavers	91 lb mesh	109 9 ft*	1-1/8 in
9-2	Conv Equip -24 ft with Dual Drum Pavers	40 lb mesh	42 7 ft*	1-1/8 in
9-3	Conv Equip -12 ft with Dual Drum Pavers	None	20 ft	1-1/8 in
9-4	Conv Equip -24 ft with Dual Drum Pavers	None	20 ft	1-1/8 in
9-5	Conv Equip. -24 ft with Three Drum Pavers	None	20 ft	1-1/8 in
9-6	Slip-Form-24 ft with Dual Drum Pavers	None	20 ft	1-1/8 in
9-7	Slip-Form-24 ft with Three Drum Pavers	None	20 ft	1-1/8 in
	8-in. Concrete Pavement on 5-in. Cement Treated Subbase			
8-1	Conv Equip -24 ft with Dual Drum Pavers	78 lb mesh	103 2 ft*	1 in
8-2	Conv Equip. -24 ft with Dual Drum Pavers	40 lb mesh	48 ft*	1 in
8-3	Conv Equip. -24 ft with Dual Drum Pavers	None	20 ft	1 in
8-4	Conv Equip -24 ft with Three Drum Pavers	None	20 ft	1 in
8-5	Slip-Form-24 ft with Dual Drum Pavers	None	20 ft	1 in.
8-6	Slip-Form-24 ft with Three Drum Pavers	None	20 ft	1 in
8-7	Slip-Form-24 ft with Three Drum Pavers	None	15 ft	None
8-8	Slip-Form-24 ft with Three Drum Pavers	None	20 ft	None

*The joint spacing shown is the maximum for the mesh weight used
See Figures 2 and 3

Figure 1.

convenience, the different combinations of joint design and construction methods are coded in the list preceding Figure 1.

Differences in square yard cost for these 15 combinations are shown in Figure 1.

The $1.36 difference between Code 9-1 and 8-8 represents a 25 percent reduction in pavement cost. Savings of this magnitude justify an engineer's investigation.

Comparison of Code 9-1, the maximum dowel joint-mesh cost, with Code 9-2 the most economical dowel joint-mesh combination, shows a reduction of $0.29 per sq yd. Comparison of Code 9-1 to Code 9-4, 20-ft doweled joints, without mesh, shows an additional $0.18 reduction.

The large difference between Code 8-6 and 8-7 represents the difference between a doweled and an undoweled 20-ft joint spacing of an 8-in. pavement on a cement-treated subbase.

Specifications that permit contractors to use the latest developments in construction equipment can produce excellent riding quality pavements at a reduced cost.

A comparison of Code 9-4 and 9-7 shows a $0.36 per sq yd reduction by using a slip-form with three-drum paver construction method in lieu of conventional equipment.

The idiosyncrasies of contractors, the habits of labor, material wastes, and human error in splitting time result in minor deviations between the theoretical and actual pavement costs. However, the engineer can arrive at a reasonable cost comparison in research of this type.

Engineers and contractors who fail to recognize continuing technological advances deprive taxpayers of more miles of pavement for the same construction dollars.

ESTIMATING PROCEDURE

There are no hard and fast rules for estimating procedures for the engineer to follow. They should be prepared in a form and with enough detail so that the estimator can distribute costs to permit direct comparison between the estimate and the actual cost of operations. It must be recognized that complete accuracy in cost distribution is unobtainable, but errors are not large enough to invalidate cost comparisons.

A detailed cost estimate can be made by following these basic procedures:

1. Inspecting local construction to determine:
   a. Number of men performing each operation.
   b. Hours worked by each man.
   c. Average production for each operation.
   d. Quantities of materials.
   e. Number, type, and size of equipment for each operation.
2. Obtaining from contractor:
   a. Pay rate for each trade including overtime rate.
   b. Union welfare rate for each trade.
   c. All additional assistance he is willing to offer.
3. Obtaining material prices from local suppliers.
4. Making reasonable assumptions from observations for material loss, overhead and fixed cost items.
5. Using the tables and references in this paper as a guide to incorporate the construction practices and pavement design desired.

ASSUMED CONDITIONS AND PAVEMENT DESIGN

This assumed paving project is a four-lane divided highway 10 mi in length. Only one of the 24-ft lanes, 140,000 sq yd, is considered for this estimate.

Typical midwestern loadometer data have been used to estimate the wheel loads for a 50-year design life based on capacity operation (Table 1). For the A-6 and A-7 subgrade soils which are prevalent in the midwest and for the traffic conditions used, a subbase is needed to prevent mud-pumping. A 6-in. sand-gravel subbase has been selected so that a cost comparison could be made between this subbase and the same material with the top 5 in. treated with cement.

Pavement thickness was determined by the methods set forth in "Concrete Pavement

TABLE 1

TYPICAL LOADOMETER DATA (7)

Wheel Load Group (kips)	Expected Repetitions in 50 Years
13 to 14	12,972
12 to 13	21,720
11 to 12	199,255
10 to 11	1,268,985
9 to 10	5,565,707
8 to 9	11,342,886
7 to 8	13,309,942

Design" (8) using a concrete mix that will have an expected 28-day flexural strength of 600 psi (ASTM C-78, 3rd point loading). Data for the two subbases are given in Table 2. Calculations are given in Table 3.

The designs are a 9-in. concrete pavement with a 6-in. granular subbase, and an 8-in. pavement with a 5-in. cement-treated subbase.

Table 4 gives the labor and union welfare rates used. Although sometimes considered as overhead, all union welfare and insurance as shown under labor is included in each operation to show how they reflect in the unit cost of individual pavement operations. Union welfare rates apply to working hours only.

The 10 percent for insurance on labor cost is for workmen's compensation, social security, and contractor's liability. Overhead is considered as a flat 5 percent on all labor, equipment, and material. Overhead has been applied to each operation in an effort to show how the "cost of doing business" affects each operation.

The weekly rates were obtained from "Contractor's Equipment Ownership Expense" (2) based on purchase prices furnished by leading equipment manufactures. All material prices used, with the exception of those noted, have been quoted by leading midwestern material suppliers. Concrete materials are approximately the current national averages (12).

BASIC ESTIMATE

The basic estimate, for the sake of comparison, assumes the use of conventional paving equipment and two 34E dual-drum mixers operating from the shoulder. As shown in Table 5, production is assumed as 60 batches per hr per mixer (1). A 10-hr working day, 6 days per week, has been used. This basic estimate is figured for 39,600 sq yd of 9-in. pavement per week.

Labor and Equipment for Placing

Table 5 is a detailed cost breakdown for labor and equipment for one week's work. This basic estimate considers the use of conventional equipment; i.e., a spreader, either screw or plow type, a two-screed transverse finishing machine, and one longitudinal float finisher. All foreman time directly related to an individual operation is included with that operation and not as supervision. Curing is assumed to be a white pigmented curing compound applied by an automatically propelled curing machine.

Construction practices will vary depending on location and conditions. One such variable is the use of "Flagmen," shown in Table 5 and carried throughout the estimate to illustrate its effect on the over-all pavement cost.

The last operation in Table 5, "Longitudinal Joints, Sawing and Sealing," was kept separate from the other longitudinal joint operation so that a direct comparison could be made later to lane-at-a-time construction.

Batching and Hauling

Table 6 gives a complete labor and equipment cost breakdown for all batching and

TABLE 2

SUBGRADE AND SUBBASES

Subgrade Type	CBR	k^3 pci	Subbase depth in.	Subbase Type	Design k pci
A-6, A-7 clay	3	100	6	Sand Gravel[1]	130[4]
A-6, A-7 clay	3	100	5	Cement treated[2]	450[5]

1. 6 in. sand-gravel graded to meet AASHO Designation 147, gradings C, D, E or F.
2. Top 5 in of sand-gravel (1) treated with 6 per cent cement by volume to obtain a minimum of 300 psi compressive strength in 7 days.
3. See Fig. 1, page 11, Ref. 8
4. See Fig. 2, page 9, Ref. 9
5. See Ref. 10

Concrete Design (4)

Cement - 6 bags per cu. yd.

Coarse Aggregate - 1 in. maximum.

Fine Aggregate - well graded natural sand.

Strength - M R = 600 psi.

TABLE 3

CALCULATION OF CONCRETE PAVEMENT DEPTH

(For use with "Concrete Pavement Design")

Project Midwest

Class Divided Roadway - Typical Traffic No. of Lanes 4

Subgrade k 100 pci Subbase (type and depth) (1) 6" Sand-Gravel (2) 5" Cement treated

Combined k (1) 130, (2) 450 pci. Design M. R. 600 psi. Load Impact Factor 20%

PROCEDURE

1 Fill in Columns 1, 2, and 6 List wheel loads in decreasing order with heaviest wheel load at the top. (H B 26 gives procedures for determining numbers and weights of wheel loads)

2 Compute controlling wheel load = 15.0 kips (Controlling wheel load is the average of the 100,000 heaviest expected wheel loads on one lane during design life)

3 Find required pavement depth for the controlling wheel load from Fig 4, page 19, using a working stress of 1/2 the design M R (Safety Factor of 2). Depth = 9.2 in. (to 0 1 in) For first trial depth use nearest even 1/2 in. = 9.0 .

4 Compute fatigue consumption for first trial depth by completing Columns 3, 4, 5 and 7 below.

5 Analyze other trial depths, varying by 1/2 in , and using

A Different depths with the same M. R.

B. Different depths with different M. R. s.

C Different depths with cement-treated subbases.*

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
Static Wheel Load Groups**	Maximum for Group Plus Impact 20%	Stresses (From Fig 4 page 19 of R-18)	Safety Factors M.R ÷ Stresses in Col. 3	Allowable Load Repetitions (From Fig 13 page 32 of R-18)	Expected Load Repetitions for Design Life	Fatigue Resistance Used.*** (Col. 6 ÷ Col. 5 X 100)
Kips	Kips	psi		No.	No.	Per Cent
(1) 6" Sand-gravel Subbase	FIRST TRIAL DEPTH. 9 in					
13-14	16.8	335	1.79	40,500	12,972	32%
12-13	15.6	312	1.92	70,000	21,720	31%
11-12	14.4	293	2.05	unlimited	199,255	-
10-11	13.2	272	2.21	"	1,268,985	-
9-10	12.0	250	2.40	"	5,565,707	-
8-9	10.8	<250	>2.40	"	11,342,886	-
7-8	9.6	<250	>2.40	"	13,309,942	-
					Total -	63%
(2) 5" Cement-Treated Subbase	SECOND TRIAL DEPTH. 8 in.					
13-14	16.8	333	1.80	42,000	12,972	31%
12-13	15.6	315	1.90	64,500	21,720	34%
11-12	14.4	298	2.01	unlimited	199,255	-
10-11	13.2	278	2.16	"	1,268,985	-
9-10	12.0	255	2.35	"	5,565,707	-
8-9	10.8	<255	>2.35	"	11,342,886	-
7-8	9.6	<255	>2.35	"	13,309,942	-
					Total -	65%

*6 in. cement-treated subbases have k values of 400 to 600 pci.

**List wheel load groups down to the first group with more than 100,000 expected repetitions

***Total Fatigue Resistance used should not exceed about 115 per cent. Gain in strength with pavement age will reduce actual fatigue consumption below computed values

TABLE 4

LABOR SCALE & WELFARE RATES

TRADE	RATE PER HOUR	WELFARE PER WORKING HOUR
Finisher		
Foreman	$ 3.55	$ 0.10
Finisher	3.30	0.10
Labor		
Air Tools	$ 2.75	$ 0.075
Common Labor	2.60	0.075
Dump Batch Trucks	2.80	0.075
Operating Engineers		
Cement Plant	$ 3.25	$ 0.05
Compressor	3.00	0.05
Concrete Saw	3.00	0.05
Crane-Material	3.60	0.05
Curing Machine	3.00	0.05
Dozer	3.35	0.05
End Loader (Up to 1 cu. yd.)	3.10	0.05
End Loader (Over 1 cu. yd.)	3.35	0.05
Fine Grader	3.35	0.05
Finishing Machines	3.25	0.05
Form Grader	3.25	0.05
Mixer Concrete 34E	3.60	0.05
Mixing Machine (Soil)	3.60	0.05
Motor Grader	3.35	0.05
Oiler	2.60	0.05
Power Shovel 1/4 cu. yd.	3.60	0.05
Pump	2.60	0.05
Roller-All types	3.25	0.05
Spreader-Concrete	3.35	0.05
Chauffeur		
Batch Truck - 6 wheel	$ 2.75	$ 0.075
Dump - 6 wheel	2.60	0.075
Dump - 25 ton	3.00	0.075
Semi-Tractor-Trailer	3.00	0.075
Service-Stake Body	2.60	0.075
Mechanic	3.00	0.075

TABLE 5
LABOR AND EQUIPMENT ESTIMATE FOR CONCRETE PAVEMENT
(Conventional Equipment)

Production per week
Two 34E Dual Drum Mixers
60 batches per hour per mixer[1]
10 hrs per day, 6 days per week
2x60x10 = 1,200 batches per day
1,200 batches at 1-1/4 cu yd + 10% overload = 1,650 cy/day
1,650 cu yd x 6 days = 9,900 cu yd/wk

9,900 cy/wk = 44,550 sq yd/wk for 8" pavement or 2,784 lin ft per day
39,600 sq yd/wk for 9" pavement or 2,475 lin ft per day

Pay hours include time and one-half for over 40 hours
(70 pay hrs = 40 at straight time + 20 at time and one-half)

Union welfare based on number of working hours

No Men	Operation	Per Man: Man Hrs	Per Man: Pay Hrs	Total Pay Hrs	Labor: Rate	Labor: Amount	Labor: Union Welfare	Labor: Ins 10%	Labor: Total	Labor: $/sq yd	Equipment[2]: $/wk	Equipment[2]: $/sq yd	Overhead: 5% Lab & Equip	Overhead: $/sq yd	Total Cost Per sq yd	Remarks
1	Superintendent		wk			$ 200 00			$		$ 50 00					Automobile
1	Timekeeper		wk			125 00					50 00					"
1	Engineer		wk			175 00					50 00					"
	Subtotal					$ 500 00		50 00	$ 550 00	0 0139	$ 150 00	0 0038	35 00	0 0009	0 0186	
	Forms															
1	Foreman		wk			$ 175 00			$		$ 40 00					Pick up
4	Linemen	60	70	280	2 60	728 00	18 00				20 00					Small Tools
1	Form Grader	60	70	70	3 25	227 50	3 00				150 00					
6	Laborers	60	70	420	2 60	1,092 00	27 00				800 00					10,000 ft of forms
2	Pin Drivers	60	70	140	2 75	385 00	9 00									
1	Compressor Oper	60	70	70	3 00	210 00	3 00				115 00					105 c f Compressor incl Pin Hammers
	Subtotal					$ 2,817 50	60 00	281 75	$ 3,159 25	0 0798	$1,125 00	0 0284	214 21	0 0054	0 1136	
	Fine Grade															
1	Foreman		wk			$ 175 00			$		$ 40 00					
1	Operator	63	74-1/2	74-1/2	3 35	249 58	3 15				400 00					Self propelled machine
3	Laborers	60	70	210	2 60	546 00	13 50									
1	Roller Steel	60	70	70	3 25	227 50	3 00				140 00					
1	End Loader	60	70	70	3 10	217 00	3 00				190 00					1 cu yd front end
1	Dump Truck	60	70	70	2 60	182 00	4 50				150 00					5 Ton Dump
1	Water Tank	60	70	70	2 60	182 00	4 50				120 00					2,000 Gal tank
	Scratch Temp	54	61	61	2 60	158 60	4 05				20 00					
	Subtotal					$ 1,937 68	35 70	193 77	$ 2,167 15	0 0547	$1,060 00	0 0268	161 38	0 0041	0 0856	
	Longitudinal Jt															
1	Labor (tie bar)	60	70	70	2 60	$ 182 00	4 50	18 20	$ 204 70	0 0052			10 24	0 0002	0 0054	See last item for sawing and sealing
	Haul Road															
1	Grader	60	70	70	3 35	$ 234 50	3 00	23 45	$ 260 95	0 0066	$ 290 00	0 0073	27 55	0 0007	0 0146	Maintain Haul Road
	Mix & Place															
1	Foreman		wk			200 00					40 00					
2	Mixer Oper	66	79	158	3 60	568 80	6 60				2,560 00					
1	Laborer (Hose)	60	70	70	2 60	182 00	4 50									
2	Dump Men	63	74-1/2	149	2 80	417 20	9 45									
2	Water Tanks	63	74-1/2	149	3.00	447 00	9 45				480 00					2 Tanks towed
1	Pump Oper	60	70	70	2 60	182 00	3 00				20 00					3 in pump
1	Spreader	66	79	79	3 35	264 65	3 30				360 00					
1	Finisher Trans	66	79	79	3 25	256 75	3 30				300 00					
1	Float Long	66	79	79	3 25	256 75	3 30				170 00					
4	Puddlers (Laborers)	66	79	316	2 60	821 60	19 80				5 00					Small tools
1	Grade Sprinkler	60	70	70	2 60	182 00	4 50									
	Subtotal					$ 3,778 75	67 20	377 87	$ 4,223 82	0 1066	$3,935 00	0 0994	407 94	0 0103	0 2163	
	Finish															
1	Finisher Foreman	66	79	79	3 55	$ 280 45	6 60		$		$ 40 00					Working foreman
3	Finishers	66	79	237	3 30	782 10	19 80				20 00					Finishing Tools
3	Helpers	60	70	210	2 60	546 00	13 50				20 00					Burlap Bridge
	Subtotal					$ 1,608 55	39 90	160 86	$ 1,809 31	0 0457	$ 80 00	0 0020	94.47	0 0024	0 0501	
	Cure															
1	Operator	66	79	79	3 00	$ 237 00	3 30		$		$ 115 00					Self propelled machine
1	Laborer	60	70	70	2 60	182 00	4 50									
	Subtotal					$ 419 00	7 80	41 90	$ 468 70	0 0118	$ 115 00	0 0029	29 18	0 0008	0 0155	
	Pull & Move Forms															
2	Truck Driver	66	79	158	2.60	$ 410 80	9 90		$		$ 250 00					Form hoist truck
4	Helper	66	79	316	2 60	821 60	19 80									
	Subtotal					$ 1,232 40	29 70	123 24	$ 1,385 34	0 0350	$ 250 00	0 0063	81 77	0 0021	0 0434	
	Service															
1	Truck Driver	66	79	79	2 60	$ 205 40	4 95		$		$ 100 00					Miscellaneous items not charged above
1	Helper	66	79	79	2 60	205 40	4 95									
	Subtotal					$ 410 80	9 90	41 08	$ 461 78	0 0117	$ 100 00	0 0025	28 08	0 0007	0 0149	
	Flagman															
2	Laborers	60	70	140	2 60	$ 364 00	9 00	36 40	$ 409 40	0 0103	$		20 47	0 0004	0 0107	
	Subtotal for above operations								$15,100 40	0 3813	$7,105 00	0 1794	1110 29	0 0280	0 5887	
	Longitudinal Joint															
	Sawing & Sealing															
1	Saw Operator	60	70	70	3 00	$ 210 00	3 00		$		$ 670 00					Incl. diamond blade $630.00
1	Truck Water	60	70	70	2 60	182 00	4 50				120 00					
1	Air Compressor	60	70	70	3 00	210 00	3 00				115 00					
2	Laborers	60	70	140	2 60	364 00	9 00									
	Subtotal					$ 966 00	19 50	96 60	$ 1,082 10	0 0273	$ 905 00	0 0228	99 35	0 0025	0 0526	
	Total								$16,182 50	0 4086	$8,010 00	0 2022	1209 64	0 0305	0 6413	

[1] Average batches per hour - See Ref 1

[2] See Ref 2 for Equipment Rates

TABLE 6
LABOR AND EQUIPMENT ESTIMATE FOR BATCHING AND HAULING

Three Stop Plant to supply two 34E Dual Drum Mixers
60 hrs per week = 39 600 sq yd of 9 in. pavement
Project 140,000 sq yd. Approx 10 mi of 24 ft pavement

Plant set up on Railroad siding located 2-1/2 mi from center of project - Average 10 mi round trip for entire job

Batch Truck Requirements[1]

a. Batch time = 60 sec (daily average)
b. Round trip = 10 miles
c Average speed = 20 mph
d. Delays, - load, etc = 10 min
e 4 Batches per truck
f Extra trucks required due to conjestion at plant and paver

No of trucks $= \frac{60}{ae} \; \frac{60b}{c} + d$ No of Mixers + f

No of trucks $= \frac{60}{60x4} \; \frac{60x10}{20} + 10$ 2 + 2 = 22 trucks

No Men	Operation	Per Man: Man Hrs	Per Man: Pay Hrs	Total Pay Hrs	Labor: Rate	Labor: Amount	Labor: Union Welfare	Labor: Ins 10%	Labor: Total	Labor: $/sq yd	Equipment: $/wk	Equipment: $/sq yd	Overhead: 5% Lab & Equip	Overhead: $/sq yd	Total Cost Per Sq Yd
	Material Handling														
1	Foreman		wk			$ 175 00					$ 40 00				
1	Cement Bin Oper	66	79	79	3 25	256 75	3 30								
3	Hopper Operators	60	70	210	2 60	546 00	13 50								
2	Crane Operators	66	79	158	3 60	568 80	6 60				1 400 00				
1	Oiler	66	79	79	2 60	205 40	3 30								
2	End Loaders	60	70	140	3 35	469 00	6 00				500 00				
3	Car Cleaners	66	79	237	2 60	616 20	14 85								
1	Laborer	66	79	79	2.60	205 40	4 95								
1	Grader road	60	70	70	3 35	234 50	3 00				290 00				
						$3,277 05	55 50	327 71	$3 660 26	0 0924	$2,230 00	0 0563	$ 294 51	0 0074	0 1561
	Material Hauling														
1	Foreman		wk			150 00					40.00				
2	Mechanic	72	88	176	3 00	528 00	10 80				100 00				
1	Mechanic Helper	72	88	88	2.60	228 80	5 40								
22	Truck Drivers	60	70	1540	2 75	4,235 00	99 00				5,500.00				
						$5,141.80	115.20	514.16	$5,771.16	0.1457	$5,640.00	0 1424	$ 570 85	0 0144	0 3025
	Fixed Cost to Set Up & Move on & Off Job														
	Cost spread over 140,000 sq yds														
	Land Rental for Batch Plant & Storage 3 mo												$ 3,000 00		
	Batch Plant for 3 mo @ $2,500 per mo												7,500 00		
	Batch Plant move in, erect and dismantle												5,500 00		
	Railroad Siding												1,500 00		
	Paving Eqpt - move in, adjust and move out												6,000 00		
													$23,500 00	1679	1679
	Total for 9 in pavement									0 2381		0 1987		0 1897	0 6265

[1] Ref 3 for batch Truck Requirements

TABLE 7
MATERIAL ESTIMATE

Cement.	$4 05 bbl rail fob job site
Course Aggregate 1-1/2 in. max	$2.70 ton delivered
Sand	$2 30 ton delivered

Material	Weight(1) Per cu yd	Cost	$/cu yd	Yield Loss 4%	Subtotal $ per cu yd	Cost per sq yd 9" Pvmt	Overhead 5%	Total Cost per sq yd: 9 in Pvmt	Total Cost per sq yd: 8 in Pvmt(3)
Cement	564 lbs	$4.05 bbl	6 0750	0 2430	6.3180	1 5795	0 0790	1 6585	1 4742
Course Aggregate	2,007 lbs	2 70 ton	2 7095	0 1084	2 8179	0 7045	0 0352	0 7397	0 6575
Sand	1,193 lbs	2 30 ton	1 3720	0 0549	1 4269	0 3567	0 0178	0 3745	0 3329
Water	29 gal	No charge							
Air Entraining Agent(2)	5% Air		0 0400	0 0020	0 0420	0 0105	0 0005	0 0110	0 0098
Subtotal concrete			$10 1965	0 4083	10 6048	2 6512	0 1325	2.7837	2 4744
Curing Compound	150 s f /gal	$0 70/gal		0 03/gal	0 73/gal	0 0438	0 0022	0 0460	0 0460
Center Joint tie bars	#5 by 30-in at 30 in ctrs				$7 63/cwt	0 0286	0 0014	0 0300	0 0300
Joint Sealing Compound (For longitudinal Joint)	25#/100 lin ft	0 13/lb	0.0325/ft	0 0013/ft	0 0338/ft	0 0127	0 0006	0 0133	0 0133
Total								2 8730	2 5637

(1) See Ref 4 - Table 2 - Mix III for weights
(2) Cost based on Suppliers quotation to maintain 5% Air
(3) Concrete material 8/9 of 9 in pavement

hauling necessary to supply two 34E dual-drum pavers furnishing 60 batches per hr, 60 hr per week.

It was assumed that a three-stop batch plant was set up at a railroad siding located 2½ mi off the center of the project. This made an average round trip haul of 10 mi for batch trucks. All batch hauling is done by four-compartment trucks.

Fixed Costs

Certain fixed cost operations have been applied to overhead for this job. These are shown at the bottom of Table 6 and must be spread over the 140,000 sq yd to be paved. They are for moving field office and equipment on to the job site, setting up, dismantling,

TABLE 8
COST ESTIMATE SUMMARY
of Table 4, 5 and 6

OPERATION	Cost Components Per Sq Yd				Unit Cost per Sq Yd	
	Labor	Equipment	Materials	Overhead	9 in Pvmt	8 in Pvmt[1]
Supervision General	$0 0139	$0.0038		$0 0009	$0.0186	$0 0165
Forms	0.0798	0.0284		0.0054	0 1136	0.1010
Fine Grade	0.0547	0.0268		0.0041	0.0856	0.0225[2]
Longitudinal Jt	0.0052	-		0.0002	0.0054	0.0048
Haul Road	0.0066	0.0073		0.0007	0.0146	0.0130
Mix & Place	0.1066	0.0994		0.0103	0.2163	0.1922
Finish	0.0457	0.0020		0.0024	0.0501	0.0445
Cure	0.0118	0.0029		0.0008	0.0155	0.0138
Pull & Move Forms	0.0350	0.0063		0.0021	0.0434	0.0385
Service	0.0117	0.0025		0.0007	0.0149	0.0132
Flagman	0.0103	-		0.0004	0.0107	0.0095
Longitudinal Saw & Seal	0.0273	0.0228		0.0025	0.0526	0.0468
Subtotal	0.4086	0.2022		0.0305	0.6413	0.5163
Material Handling	0.0924	0.0563		0.0074	0.1561	0.1387
Material Hauling	0.1457	0.1424		0.0144	0.3025	0.2689
Set Up and Moves				0.1679	0.1679	0.1679
Subtotal	0.2381	0.1987		0.1897	0.6265	0.5755
Concrete Material						
Cement			1.5795	0.0790	1.6585	1.4742
Coarse Aggregate			0.7045	0.0352	0.7397	0.6575
Sand			0.3567	0.0178	0.3745	0.3329
Air-Entraining Agent			0.0105	0.0005	0.0110	0.0098
Subtotal			2.6512	0.1325	2.7837	2.4744
Misc. Material						
Curing Compound			0.0438	0.0022	0.0460	0.0460
Center Tie Bars			0.0286	0.0014	0.0300	0.0300
Joint Sealer			0.0127	0.0006	0.0133	0.0133
Subtotal			0.0851	0.0042	0.0893	0.0893
Total (Transverse Joints and Subbase not included)	0.6467	0.4009	2.7363	0.3569	4.1408	3.6555

[1] Cost for 8 in pavement based on production of 44,550 sq yd per week

[2] Fine grading for 8 in pavement is reduced to compensate for that portion of the work included in cement treated Subbase (Table 13)

and moving off the job. Also included is land rental for batch plant set up and storage yard as well as cost to cover charges to the railroad siding.

Materials

Table 7 gives a breakdown for concrete and miscellaneous paving materials. The detailed breakdown is for a 9-in. pavement. However, square yard costs of materials for an 8-in. pavement are also shown. These were computed by taking $8/9$ of the square yard cost for the 9-in. pavement.

The table makes allowance for a 4 percent loss in yield due to differences between actual and theoretical quantities. These differences stem from low grade, waste over the forms, spillage from the mixer skip, and bucket and plant loss.

Summary

Tables 5, 6, and 7 are summarized in Table 8 which gives a complete breakdown per unit cost for labor, equipment, materials, and overhead required to construct the 9- and 8-in. pavements. The breakdown covers all costs for concrete materials and for handling, hauling, and placing concrete. Transverse joints and subbases are not considered in the estimate at this time because they are variables that are considered in a later discussion.

The cost breakdown given in Table 8 for the 8-in. pavement is based on a production of 44,550 sq yd per week. The costs for certain items are the same for both the 8- and 9-in. pavements. These items include (a) fixed costs for setting up and moving out, and (b) unit costs for curing compound, tie bars, and joint-sealing materials.

Fine grading costs less for the 8-in. pavement than for the 9-in. pavement. This is because a cement-treated subbase is used under the 8-in. pavement. Practically all fine grading of cement-treated subbase is done during the subbase construction period before the subbase gets too hard. For this reason most of the cost for fine grading below the 8-in. pavement is included in the subbase estimate given later in Table 13.

DISTRIBUTED STEEL AND DOWELED JOINTS

Unloading

Table 9 gives a labor and equipment cost breakdown for distributed steel. The distributed steel considered in this estimate is the mesh type and was delivered to the job by rail. Cost for unloading the material as shown for a 9-in. pavement is $0.0119 per sq yd. This would also apply as the cost for an 8-in. pavement.

TABLE 9
DISTRIBUTED STEEL ESTIMATE
140,000 Sq yd Rail delivery to job site

No Men	Operation	Per Man Man Hrs	Per Man Pay Hrs	Total Pay Hrs	Labor Rate	Labor Amount	Labor Union Welfare	Labor Ins 10%	Labor Total	Labor $/sq yd	Equipment Total	Equipment $/sq yd	Overhead 5% Lab & Equip	Overhead $/sq yd	Total Cost per sq yd 9 in Pvmt	Total Cost per sq yd 8 in Pvmt
	Unload RR															
1	Foreman	40		4 days	35/day	$ 140 00					$ 40 00					
1	Crane Operator	40	44	44	3.60	158 40	2 00				700 00					
4	Laborers	40	44	176	2.60	457 60	12 00									
	Subtotal on 140,000 sq yd					$ 756.00	14.00	75 60	$ 845 60	0 0060	$740 00	0 0053	79 28	0 0006	0 0119	0 0119
	Distribute															
1	Foreman	60	70	70		$ 175 00					$ 40 00					
1	Crane Operator	60	70	70	3.60	252 00	3.00				700 00					
1	Truck Driver	60	70	70	3 00	210 00	4.50				200 00					
4	Laborers	60	70	280	2.60	728 00	18 00									
	Subtotal on 70,000 sq yd per wk					$1,365 00	25 50	136 50	$1,527 00	0 0216	$940 00	0 0134	123.35	0 0017	0 0369	0.0369
	Place															
1	Spreader	66	79	79	3.35	$ 264.65	3 30				$360 00					
2	Laborers	66	79	158	2 60	410 80	9 90									
	Subtotal on 39,600 sq yd per wk for 9 in pavement					$ 675 45	13 20	67 55	$ 756 20	0 0191	$360 00	0 0091	55 81	0 0014	0 0296	0.0263[1]
	Total									0 0469		0 0278		0 0037	0 0784	0 0751

[1] Placing cost is 8/9 of the cost of a 9 in. pavement

Handling and Placing

The cost per handling and distributing the steel to the job is $0.0369 per sq yd for both the 9- and 8-in. pavements.

Placing the steel requires one additional concrete spreader and operator and two laborers who work in conjunction with two of the puddlers as shown in the "Mix and Place" operation of Table 5. These four laborers pick up the mesh, place it in the concrete after the initial strike-off, and tie the adjacent pieces together. The cost for placing mesh in the 9-in. pavement is $0.0296 whereas the cost for an 8-in. pavement is $0.0263 reflecting the difference in weekly production. The labor and equipment cost per square yard for distributed steel for a 9-in. pavement is $0.0784. Many contractors show this cost with the pavement and not the mesh.

Transverse Joints

The next factor is the cost of transverse joints, given in Table 10. The total is given as cost per lineal foot. This cost is based on a weekly production of 14,850 lineal ft of pavement and a transverse joint spacing of 20 ft. The cost of a 1- by 14-in. dowel being $0.07 less than a 1⅛- by 16-in. long dowel (5).

Table 11 gives the cost of distributed steel with doweled contraction joints for a 9-in. pavement, and the cost of the doweled joint at 20-ft spacing without distributed steel. Any thorough pavement design requires a careful economic analysis of two alternates.

The first alternate design is that of a plain pavement with doweled joints spaced to control transverse cracking. The designer should select the maximum joint spacing that will control transverse cracking. This selection is usually based on the type of aggregate being used and prior experience with conditions similar to the project under design.

The other alternative design employs doweled contraction joints with distributed steel. With this design, contraction joints are not spaced to control cracking. Instead, the distributed steel is designed to prevent slab faces from separating after cracking occurs and joint spacing is based on analysis of relative cost of distributed steel and doweled joints for various spaces. As shown in Table 11, the amount and cost of distributed steel increases as slab length is increased and the cost of joints increases as slab length decreases. The weights of mesh used to compute this table are the most

TABLE 10

TRANSVERSE JOINT ESTIMATE

No Men	Operation	Per Man Man Hrs	Per Man Pay Hrs	Total Pay Hrs	Labor Rate	Labor Amount	Labor Union Welfare	Labor Ins 10%	Labor Total	Labor Cost Per sq yd	Equipment Cost Per wk.	Equipment Cost Per sq yd	Material Cost Per lin ft	Overhead 5%	Overhead Unit Cost	Total Unit Cost Per sq yd	Remarks
	Dowels																
	Handle & Distribute																
1	Truck Driver	60	70	70	2 60	$182 00	4 50		$		100 00						
2	Laborers	60	70	140	2 60	364 00	9 00										
	Subtotal					$546.00	13 50	54 60	$ 614 10	0 0155	100 00	0 0025		35 70	0 0009	0 0189	
	Place																
2	Laborers	60	70	140	2 60	$364.00	9 00		$		10 00						
1	Laborer (Grease, etc)	60	70	70	2 60	182 00	4.50										Misc. tools
	Subtotal					$546.00	13 50	54 60	614 10	0 0155	10 00	0 0003		31.20	0 0008	0 0166	
	Saw & Seal																
1	Saw Operator	60	70	70	3 00	$210 00	3 00				160 00						4 blade gang saw
1	Water Truck	60	70	70	2 60	182 00	4 50				120 00						
1	Air Compressor	60	70	70	3 00	210 00	3 00				115 00						
2	Laborers	60	70	140	2 60	364 00	9 00										
	Subtotal					$966.00	19 50	96 60	$1 082 10	0 0273	395 00	0 0100		73.86	0 0018	0 0391	
	Labor and Equipment Total																
	For 9 in. pavement								$2 310 30	0 0583	505 00	0 0128		140 76	0 0035	0 0746	
	For 8 in. pavement															0 0663	
	Material															Per Lin Ft	
	Saw Blades[1]												0 0424		0 0021	0 0445	
	Joint Sealing Compound[2]												0 0338		0 0017	0 0355	
	Dowel Assembly 1-1/8 by 16-in. at 12 in. ctrs[3]												1 0150		0 0507	1 0657	
	Dowel Assembly 1 by 14-in. at 12 in. ctrs[3]												0 9450		0 0472	0 9922	
	Material Total for 9 in. pavement												1 0912		0 0545	1 1457	
	Material Total for 8 in. pavement												1 0212		0 0510	1 0722	

[1] Diamond Blade - Cost based on average of 3,500 ft per blade
[2] See Table 7 - Joint Sealing Compound
[3] Dowel Size - See Ref. 5 - Cost furnished by local supplier
Note: Estimate figured on cost per lin ft of joint based on weekly pavement production of 14,850 lin ft for 9 in. pavement and 16,704 lin ft for 8 in pavement and a transverse joint spacing of 20 ft.

economical for any given cross-sectional area of mesh that is commonly manufactured. The table shows that the most economical dowel and mesh combination costs $0.7672 per sq yd at a joint spacing of 42.7 ft.

Assuming that the aggregate used in this particular estimate is capable of providing 20-ft joint spacings that will not have intermediate cracking and consequently would not require intermediate mesh, the joint cost would be $0.5895 per sq yd. The 20-ft doweled joint is $0.1777 per sq yd less than the most economical dowel mesh combination. The calculations in Table 11 have been transferred to a graph in Figure 2 for a clearer picture of the variations in cost of combination mesh and dowel design with respect to joint spacing.

Figure 2 shows that the most economical combination of distributed steel and doweled joints is at 42.7 ft. Using the combined mesh doweled design, a savings of $0.2912 per sq yd can be realized by using the 42.7-ft spacing with 40-lb mesh against the use of 110-ft spacing with 91-lb mesh. Steel mesh fabricators do not charge any more for cutting mesh to lengths that would be convenient for slabs comparable to those shown in Column D, Table 11. In many studies made of this type for various States throughout the country, the most economical combination of distributed steel and doweled joints has always occurred somewhere between the 40- to 60-ft joint spacing. An analysis of this type has been put into practice in many States as is evident in current mesh designs, with joint spacings of approximately 40 and 60 ft. This same analysis has been computed in Table 12 and shown in Figure 3 for a mesh doweled contraction joint combination for an 8-in. pavement. Because a 15-ft joint spacing without dowels is currently used in some States, this cost is given in Table 12.

SUBBASES

Another factor of pavement design is the subbase. For this analysis a sand-gravel subbase was used to illustrate how the same material treated with cement would affect the total cost of the pavement. The sand-gravel material is obtained from a pit located near the batch plant and crushed to a 1-in. maximum size. Table 13 shows the labor

TABLE 11

COST OF DISTRIBUTED STEEL & DOWELED CONTRACTION JOINTS FOR 9 in. PAVEMENT

Distributed Steel (Mesh)								Contraction Joint			Combined Cost(3)	
A	B	C	D	E	F	G	H	J	K	L	M	N
Mesh lbs per 100 sq ft HB-21(1)	Area-A_s sq in/ft Long steel HB-21	2s/fw(2) HB-21	$L=A_s(2s/fw)$ Col BxC Max Joint Spacing	Pavement Area between Joints 2 67 Col D sq yds	Cost at Job site $/sq yd	Lab & Equip (Table 9) $/sq yd	Total Mesh Cost Col F+G $/sq yd	Material Cost per lin ft (Table 10) $/lin ft	Cost/sq yd Col Jx24ft ÷ Area (Col E) $/sq yd	Labor and Equip (Table 10) $/sq yd	Total Cost Mesh & Joints Col H+K+L $/sq yd	Max Cost for Mesh Wt. as Joint Spacing Decreases Max $/sq yd
27	049	533 3	26 1	70	0 2603	0 0784	0 3387	1 1457	0 3928	0 0746	0 8061	0 9282 Col H-27 lb Mesh + Col K&L-no Mesh-20 ft Joints
32	058	533 3	30 9	82 5	0 3070	0 0784	0 3854	1. 1457	0 3333	0 0746	0 7933	0 8528 Col H-32 lb Mesh + Col K&L-27 lb Mesh
37	067	533 3	35 7	95 3	0 3483	0 0784	0 4267	1 1457	0 2885	0 0746	0 7898	0 8346 Col H-37 lb Mesh + Col K&L-32 lb Mesh
40	080	533 3	42 7	114	0 3730	0 0784	0 4514	1 1457	0 2412	0 0746	0 7672	0 8145 Col H-40 lb Mesh + Col K&L-37 lb Mesh
45	093	533 3	49 6	132	0 4114	0 0784	0 4898	1 1457	0 2083	0 0746	0 7727	0 8056 Col H-45 lb Mesh + Col K&L-40 lb Mesh
52	108	533 3	57 6	154	0 4685	0 0784	0 5469	1 1457	0 1786	0 0746	0 8001	0 8298 Col H-52 lb Mesh + Col K&L-45 lb Mesh
56	126	533 3	67 2	179	0 5045	0 0784	0 5829	1 1457	0 1536	0 0746	0 8111	0 8361 Col. H-56 lb Mesh + Col. K&L-52 lb Mesh
65	148	533 3	78 9	211	0 5797	0 0784	0 6581	1 1457	0 1303	0 0746	0 8630	0 8863 Col H-65 lb Mesh + Col K&L-56 lb Mesh
78	172	533 3	91 7	245	0 6957	0 0784	0 7741	1 1457	0 1122	0 0746	0 9609	0 9790 Col H-78 lb Mesh + Col K&L-65 lb Mesh
91	206	533 3	109 9	293	0 8116	0 0784	0 8900	1 1457	0 0938	0 0746	1 0584	1 0768 Col H-91 lb Mesh + Col K&L-78 lb Mesh
Dowels - No Mesh			20	53 4				1 1457	0 5149	0 0746	0 5895	

(1) Distributed Steel Design - See Ref 6 (HB-21)

(2) s = 45,000 psi, f = 1 5, w = 12 5 lbs x pavement thickness (wt in lbs per sq ft of pavement)

(3) See Fig 2 for curve of cost

and equipment breakdown for the subbase material. This subbase costs $0.2899 per sq yd in place.

Cement-Treated Subbases

The next factor considered was that of treating the sand-gravel subbase material with 6 percent cement by volume. By treating the top 5 in. of subbase with 6 percent cement, the subgrade reaction is increased to 450 pci (10). Table 3 shows that the pavement thickness, for the same traffic frequency and loads and for the same concrete strength, can be reduced from 9 to 8 in. The cost of treating the sand-gravel subbase as shown in the lower half of Table 13 is $0.4369 per sq yd. This cost is for treating the top 5 in. of the material that has already been placed in the previous subbase estimate. The total cost per sq yd for this cement-treated subbase is now $0.7268 per sq yd.

Construction

Due to procedures employed in constructing a cement-treated subbase, certain

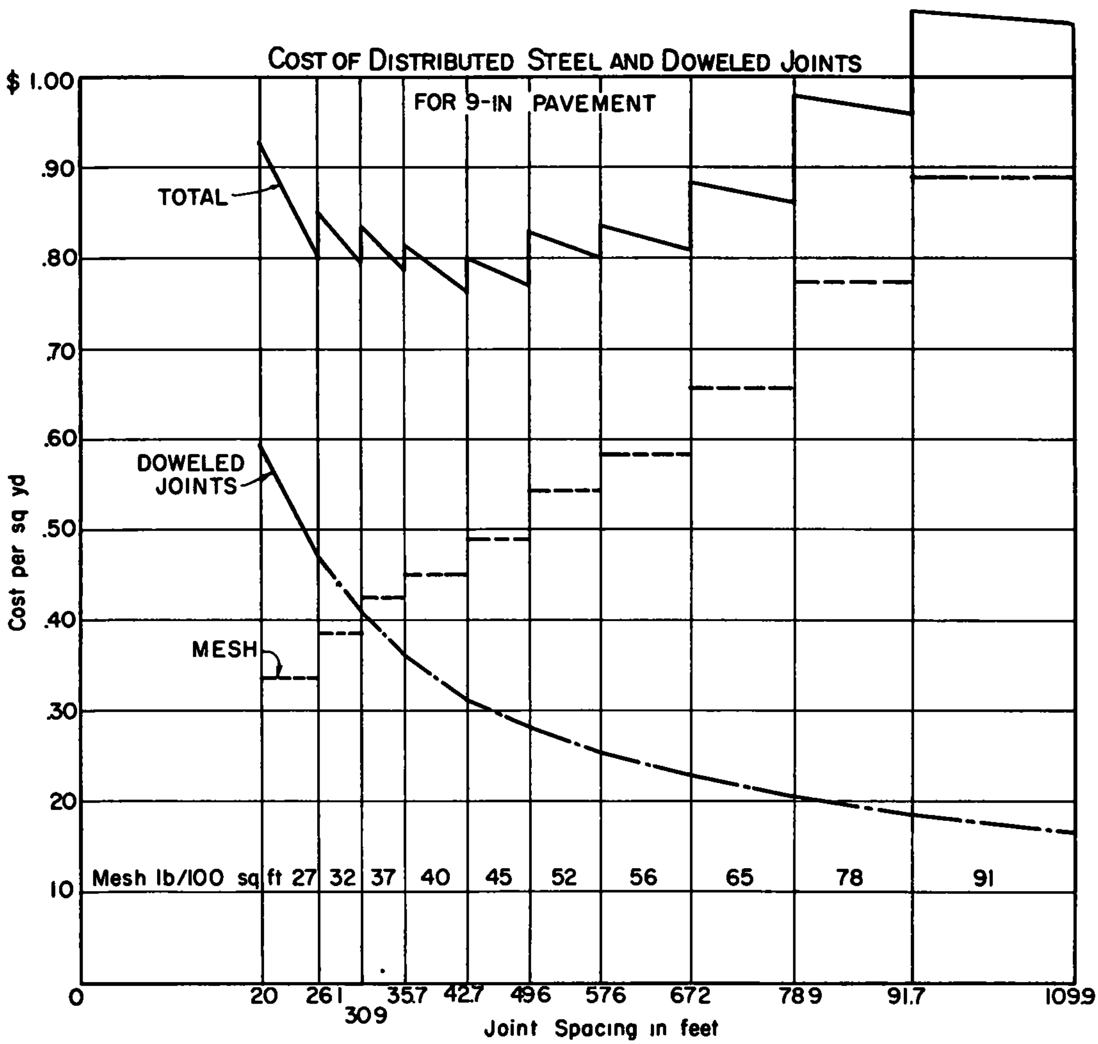


Figure 2.

operations in the pavement estimate must be altered to obtain a realistic cost of a concrete pavement with a cement-treated subbase. The form grader and operator were removed from the "Form" operation in Table 5. One additional laborer will be required to drill holes through the cement-treated subbase to facilitate driving of form pins. This amounts to a reduction of $0. 0046 per sq yd for an 8-in. pavement. The "Fine Grade" operation in Table 8 for the 8-in. pavement shows the cost of a subgrade planer pulled with a tractor, an operator, and two laborers which amounts to $0. 0225 per sq yd. This is a reduction of $0. 0536 per sq yd for an 8-in. pavement, which is accounted for in all 8-in. pavement calculations.

Table 13 shows how a 6-in. sand-gravel subbase compares to a similar subbase treating the top 5 in. with 6 percent cement. Table 17 shows a cost advantage of $0. 09 per sq yd for the 8-in. slab on the cement-treated subbase. This comparison is between the 9- and 8-in. 24 ft wide pavement using conventional equipment, dual drum pavers and doweled joints at 20 ft. $0. 04 of this saving is due to the reduction in dowel size.

Other Factors

There are other factors that cannot be shown in an estimate of this type because it is hard to put a price tag on such items. For instance, cement-treated subbases also provide uniform and stable support for concrete pavement. They retain strength and stability during the spring thaw period and protect the subgrade during rainy weather. As a result, paving work that is interrupted by bad weather can be resumed with a minimum of lost time. This factor is especially important in areas where the construction season is already shortened by winter weather. If conditions are such that construction must be discontinued during the winter season, it is not necessary to reconstruct a cement-treated subbase as is often the case with a granular subbase. In many areas of the country it is necessary to use a more expensive subbase material than that considered in this estimate. If this is the case, an analysis should be made to compare such material against the cost for using a borderline material treated with cement.

INCREASED PRODUCTION

The next factor is that of increasing production by means of employing large-capacity mixers.

TABLE 12

COST OF DISTRIBUTED STEEL AND DOWELED CONTRACTION JOINTS FOR 8 IN. PAVEMENT

Distributed Steel (Mesh)								Contraction Joint			Combined Cost (3)	
A	B	C	D	E	F	G	H	J	K	L	M	N
Mesh lbs per 100 sq ft HB-21(1)	Area A_s sq in/ft Long Steel HB-21	2s/fw(2) HB-21	$L = A_s (2s/fw)$ Col. BxC Max. Joint Spacing - Ft	Pavement Area Between Joints 2 67 Col D sq yd	Cost at Job site $/sq yd	Lab. & Equip (Table 9) $/sq yd	Total Mesh Cost Col F+G $/sq yd	Material Cost per lin ft (Table 10) $/lin ft	Cost/sq yd Col. J x 24 ft ÷ Area(Col. E) $/sq yd	Labor and Equip (Table 10) $/sq yd	Total Cost Mesh + Joints Col H+K+L $/sq yd	Max. Cost for Mesh wt as Joint Spacing Decreases (See Col N Table 11) Max. $/sq yd
27	049	600	29 4	78 5	0 2603	0 0751	0 3354	1 0722	0 3278	0 0663	0 7295	0 8836
32	058	600	34 8	92 9	0 3070	0 0751	0 3821	1 0722	0 2770	0 0663	0 7254	0 7762
37	067	600	40 2	107 3	0 3483	0 0751	0 4234	1 0722	0 2398	0 0663	0 7295	0 7667
40	080	600	48 0	128 2	0 3730	0 0751	0 4481	1 0722	0 2007	0 0663	0 7151	0 7542
45	093	600	55 8	149 0	0 4114	0 0751	0 4865	1 0722	0 1727	0 0663	0 7255	0 7535
52	108	600	64.8	173 0	0 4685	0 0751	0 5436	1 0722	0 1487	0 0663	0 7586	0 7826
56	126	600	75 6	201 8	0 5045	0 0751	0 5796	1 0722	0 1275	0 0663	0 7734	0 7946
65	148	600	88.8	237 1	0 5797	0 0751	0 6548	1 0722	0 1085	0 0663	0 8296	0 8486
76	172	600	103 2	275 5	0 6957	0 0751	0 7708	1 0722	0 0934	0 0663	0 9305	0 9456
91	206	600	123.6	330 0	0 8116	0 0751	0 8867	1 0722	0 0780	0 0663	1 0310	1 0464
Dowels - No Mesh			20 0	53 4				1 0722	0 4819	0 0663	0 5482	
No Dowels - No Mesh			20 0	53 4				0 0800	0 0360	0 0348	0 0708	
No Dowels - No Mesh			15.0	40 0				0 0800	0 0480	0 0348	0 0828	

(1) Distributed Steel Design - See Ref 6 (HB-21)

(2) s = 45 000 psi, f = 1.5, w = 12 5 lbs x pavement thickness (wt in lbs per sq ft of pavement)

(3) See Fig 3 for curve of cost.

Central-Mixed Concrete

Quality concrete produced by the central-mixed method at a substantial savings has led to increased acceptance of this method by contractors and engineers. The savings resulting from the use of central mix operations has been reported in previous papers. A paper by Yamarick (11) compared plant cost and production of central-mixed and 34E Dual Drum Paver Plants. There are three major areas of savings inherent to the central mix method: (a) lower investment per yard of production, (b) reduced labor costs, and (c) lower hauling costs. Contractors using the central-mix method have said that savings of upwards of $1.50 per cu yd can be realized.

There are many factors involved in comparing a central-mix method with the basic estimate of this paper. This would require an analysis that could more justifiably be done in a separate paper.

Three-Drum Pavers

For this analysis production is increased by employing two three-drum 34E pavers in lieu of the two-drum 34E pavers used. Using a 40 percent increased capacity (13) for a three-drum paver at the estimate average of 60 batches per hr would produce an increase of 15,840 sq yd of 9-in. pavement per week. Two three-drum pavers would produce 55,440 sq yd per week. The additional weekly equipment charge for the pavers using the same applied ratio would be $546.00 including overhead. A unit cost breakdown based on a production of 55,440 sq yd per week is given in Table 14. Certain

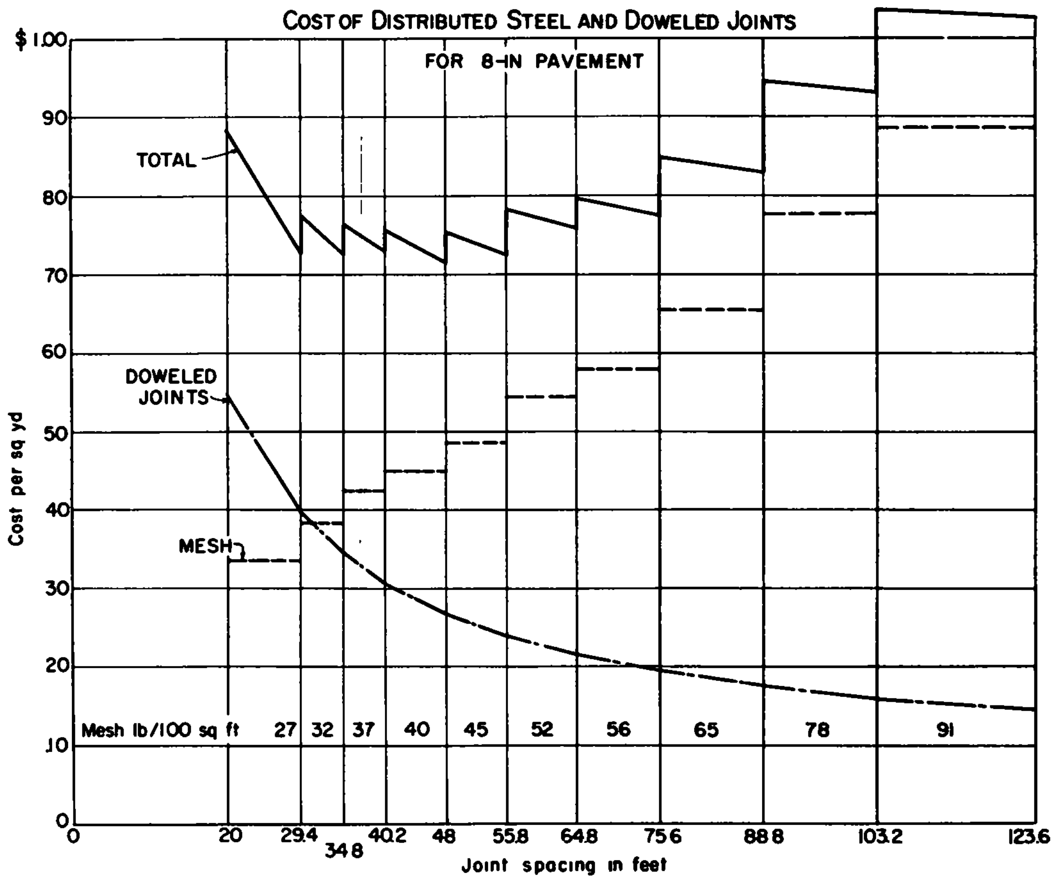


Figure 3.

TABLE 13
SUBBASE ESTIMATE

Material Sand-Gravel 1 in max
Thickness 6 in compacted
Weight, 130 lbs per cu ft
Cost to contractor $0 20 ton

Production 4, 000 ton per day = 13, 680 sq yds, 6 in compacted
24, 000 ton per wk = 82, 080 sq yds per wk

Trucks required 15 ton per truck travel 30 min
load 2 min
dump 1 min
wait 7 min
40 min = 15 trips per truck per 10 hr day

15 trips @ 15 ton = 225 ton
4, 000 ÷ 225 = 18 trucks

Cement treated Subbase
Treat top 5 in of Sand-Gravel with 6% cement by Vol
Production 10, 000 sq yds/day 60, 000 sq yds/wk
Cure Asphalt 0. 20 gal per sq yd at $0 14 per gal

Cement Quantity per sq yd 3 75 cu ft/sq yd
3 75 x 6% = 2250 cu ft

$\frac{2250 \text{ cu ft}}{4 \text{ cu ft/bbl}}$ = 05625 bbl/sq yd

05625 bbl x $4 05/bbl = $0 2278/sq yd

No Men	Operation	Per Man Man Hrs	Per Man Pay Hrs	Total Pay Hrs	Labor Rate	Labor Amount	Labor Union Welfare	Labor Ins 10%	Labor Total	Labor $/sq yd	Equipment $/wk	Equipment $/sq yd	Material Cost	Material $/sq yd	Overhead 5% Lab & Equip	Overhead $/sq yd	Total Cost Per sq yd
	Supervision																
1	Superintendent			wk		$ 200 00			$		$ 50 00		$				
1	Timekeeper			wk		125 00					50 00						
						$ 325 00		32 50	$ 357 50	0 0044	$ 100 00	0 0012			22 88	0 0003	0 0059
	Pit Operation																
1	Power Shovel 1-1/4 cu yd	60	70	70	3 60	$ 252 00	3 00		$		$ 700 00		$				
2	25 Ton dump trucks	60	70	140	3 00	420 00	9 00				1, 200 00						
1	Dozer	60	70	70	3 35	234 50	3 00				300 00						
1	Crusher Plant	60	70	70	3 25	227 50	3 00				750 00						
1	Dump Man (Pit trucks)	60	70	70	2 60	182 00	4 50										
1	Load Man (Haul trucks)	60	70	70	2 60	182 00	4 50										
						$1, 498 00	27 00	149 80	$1, 674 80	0 0204	$2, 950 00	0 0359			231 24	0 0028	0 0591
	Haul																
1	Truck Mechanic	72	88	88	3 00	$ 264 00	5 40		$		$ 50 00		$				
1	Truck Helper	72	88	88	2 60	228 80	5 40										
18	Truck Drivers	60	70	1260	2 75	3, 465 00	81 00				4, 500 00						
						$3, 957 80	91 80	395 78	$4, 445 38	0 0542	$4, 550 00	0 0554			449 77	0 0055	0 1151
	Place																
1	Foreman			wk		$ 175 00			$		$ 40 00		$				
1	Tractor Crawler	60	70	70	3 35	234 50	3 00				300 00						
	Spreader										70 00						
1	Dump Man	60	70	70	2 60	182 00	4 50										
1	Motor Grader	60	70	70	3 35	234 50	3 00				290 00						
3	Laborers	60	70	210	2 60	546 00	13 50										
2	Rollers	60	70	140	3 25	455 00	6 00				400 00						
2	Water trucks 1, 500 gal	60	70	140	2 60	364 00	9 00				240 00						
						$2, 191 00	39 00	219 10	$2, 449 10	0 0298	$1, 340 00	0 0163			189 45	0 0023	0 0484
	Material												$0 20 ton	0 0585		0 0029	0 0614
	Total per sq yd for Sand Gravel Subbase									0 1088		0 1088		0 0585		0 0138	0 2899
	Cement treated S/B																
	Handling																
1	Cement bin Oper	60	70	70	3 25	$ 227 50	3 00				$ 200 00						
1	Cement bin laborer	60	70	70	2 60	182 00	4 50										
4	Cement trucks	60	70	280	2 75	770 00	18 00				600 00						
1	Portable truck scale	60	70	70	2 60	182 00	4 50				37 50						
3	Cement spreader	60	70	210	2 60	546 00	13 50				50 00						
						$1, 907 50	43 50	190 75	$2, 141 75	0 0357	$ 887 50	0 0148			151 46	0 0025	0 0530
	Processing																
	Foreman			wk		$ 175 00			$		$ 40 00						
1	Mixing Machine	60	70	70	3 60	252 00	3 00				1, 325 00						
1	Mixer Helper	60	70	70	2 60	182 00	4 50										
1	Pneumatic tire roller	60	70	70	3 25	227 50	3 00				135 00						
1	Motor Grader	60	70	70	3 35	234 50	3 00				290 00						
1	3 Wheel Steel roller	60	70	70	3 25	227 50	3 00				200 00						
1	Form Grader	60	70	70	3 25	227 50	3 00				150 00						
	Grade planer on tracks										110 00						
1	Tractor track type	60	70	70	3 35	234 50	3 00				300 00						
4	Laborers	60	70	280	2 60	728 00	18 00										
						$2, 488 50	40 50	248 85	$2, 777 85	0 0463	$2, 550 00	0 0425			266 39	0 0044	0 0932
	Water																
2	1, 500 gal Water trucks	60	70	140	2 60	$ 364 00	9 00		$		$ 240 00						
1	Pump, 3 in	60	70	70	2 60	182 00	3 00				20 00						
						$ 546 00	12 00	54 60	$ 612 60	0 0102	$ 260 00	0 0043			43 63	0 0007	0 0152
	Cure																
1	Bituminous distributor	60	70	70	2 75	$ 192 50	4 50		$		$ 180 00						
						$ 192 50	4 50	19 25	$ 216 25	0 0036	$ 180 00	0 0030			19 82	0 0003	0 0069
	Subtotal for adding Cement									0 0958		0 0646				0 0079	0 1683
	Material																
	Cure												14/gal	0 0280			
	Cement													0 2278			
	Total Material													0 2558		0 0128	0 2686
	Total per sq yd for adding Cement plus Sand-Gravel Subbase									0 0958		0 0646		0 2558		0 0207	0 4369
	Total per sq yd for Cement treated Subbase									0 2046		0 1734		0 3143		0 0345	0 7268

operations would maintain the same unit cost because of additional labor and equipment or longer working hours required to compensate for the additional production. However, other operations would show a definite savings because they require no additional labor or equipment.

TABLE 14
Three Drum Paver Estimate
Unit Cost per sq yd of pavement
based on Two 3-drum pavers
(Conventional Equipment)

	Thickness	
Operation	9 in [4] $/sq yd	8 in [5] $/sq yd
Supervision General	0.0133	0.0118
Forms[1]	0.1136	0.1010
Fine Grade[1]	0.0856	0.0225
Longitudinal Joint	0.0039	0.0035
Haul Road	0.0104	0.0092
Mix & Place[2]	0.1644	0.1461
Finish	0.0358	0.0318
Cure	0.0111	0.0099
Pull & Move Forms	0.0310	0.0276
Service	0.0106	0.0094
Flagman	0.0076	0.0068
Longitudinal Saw & Seal[1]	0.0526	0.0468
Subtotal	0.5399	0.4264
Material Handling	0.1115	0.0991
Material Hauling[3]	0.2868	0.2549
Set Up & Moves[1]	0.1679	0.1679
Subtotal	0.5662	0.5219
Material Concrete[1]	2.7837	2.4744
Material Misc.[1]	0.0893	0.0893
Total	3.9791	3.5120

(Trans. Jts. and Subbase not included)

1 The unit cost for this item remains the same as that shown for the corresponding item in Table 8
2 This item includes the additional cost of the pavers.
3 This item includes 8 additional trucks to compensate for increased production.
4 Cost based on weekly production of 55,440 sq yd (.7143 of Unit Cost in Table 8)
5 Cost based on weekly production of 62,370 sq yd (.7143 of Unit Cost in Table 8)

Comparing the unit cost with each operation in Table 14 with the corresponding operation in Table 8, column heading "Unit Cost Per Sq Yd 9-In. Pavement," shows the savings and operations affected by the increased production. The savings amount to $0.1617 per sq yd or approximately 4 percent of the pavement cost.

FINISHING EQUIPMENT

Long Wheel Base Finishers

In recent years there have been many new developments in concrete paving equipment. The combination of units for spreading and finishing concrete has resulted in lower unit costs, a reduction in labor, and most important, an increase in performance. The attaching of the pan float to the transverse finisher has become a highly accepted practice in most areas of the United States today.

Long wheel base machines have greatly improved the riding quality of pavements because the elevation of the various finishing components is less affected by minor form irregularities. They have also reduced the amount of hand finishing work required behind the machine. The savings resulting from reduced hand work is not always realized due to resistance by some trade unions.

The long wheel base finisher replaced two machines. By removing from Table 5 under the operation "Mix and Place" the amount charged to the "Finisher Transverse" and the equipment charged to "Float Longitudinal," and adding the weekly rate as applied to this estimate for a long wheel base finisher, a savings of $0.0061 per sq yd can be realized. This 140,000-sq yd project will materialize a savings of $854.00. The reduction of just one finisher would amount to $0.0078 per sq yd or a savings of $1,092.00 over the entire job.

It is difficult to evaluate the savings that might be warranted due to better yield of material, tighter operations of the hand finishing crew, etc.

TABLE 15
SLIP-FORM PAVING ESTIMATE

No. Men	Operation	Per Man: Man hrs	Per Man: Pay hrs	Total Pay hrs	Labor: Rate	Labor: Amount	Labor: Union Welfare	Labor: Ins 10%	Labor: Total	Labor: $/sq yd	Equipment: $/wk	Equipment: $/sq yd	Overhead: 5% Lab & Equip	Overhead: $/sq yd	Total Cost per sq yd: Two drum pavers 9 in	Two drum pavers 8 in[2]	Three drum pavers 9 in[3]	Three drum pavers 8 in[4]
	Supervision[1]									0 0139		0 0038		0 0009	0 0186	0 0165	0 0133	0 0118
	Fine Grade[1]									0 0547		0 0268		0 0041	0 0856	0 0225	0 0856	0 0225
	Longitudinal Jt[1]									0 0052				0 0002	0 0054	0 0048	0 0039	0 0035
	Haul Road[1]									0 0066		0 0073		0 0007	0 0146	0 0130	0 0104	0 0092
	Mix and Place																	
	Foreman		wk			200 00					40							
2	Mixer Oper	66	79	158	3 60	568 80	6 60				2,560							
1	Laborer (Hose)	60	70	70	2 60	182 00	4 50											
2	Dump Men	63	74-1/2	149	2 80	417 20	9 45											
2	Water Tanks	63	74-1/2	149	3 00	447 00	9 45				480							
1	Pump Oper	60	70	70	2 60	182 00	3 00				20							
1	Slip form Oper	66	79	79	3 35	264 65	3 30				850							
2	Puddlers (Laborers)	66	79	158	2 60	410 80	9 90				5							
1	Grade Sprinkler	60	70	70	2 60	182 00	4 50											
						2 854 45	50 70	285 45	3,190 60	0 0806	3,955	0 0999	357 28	0 0090	0 1895	0 1685	0 1453	0 1291
	Finish																	
1	Finisher Foreman	63	74-1/2	74-1/2	3 55	264 48	6 30				40							
1	Finisher	63	74-1/2	74-1/2	3 30	245 85	6 30				10							
2	" Helpers	63	74-1/2	149	2 60	387 40	9 45				10							
						897 73	22 05	89 77	1,009 55	0 0255	60	0 0015	53 48	0 0014	0 0284	0 0252	0 0203	0 0180
	Cure[1]									0 0118		0 0029		0 0008	0 0155	0 0138	0 0111	0 0099
	Service[1]									0 0117		0 0025		0 0007	0 0149	0 0132	0 0106	0 0094
	Flagman[1]									0 0103				0 0004	0 0107	0 0095	0 0076	0 0068
	Long Joint(Saw and Seal)[1]									0 0273		0 0228		0 0025	0 0526	0 0468	0 0526	0 0468
	Subtotal									0 2476		0 1675		0 0207	0 4358	0 3338	0 3607	0 2670
	Material Handling[1]														0 1561	0 1387	0 1115	0 0991
	Material Hauling[1]														0 3025	0 2689	0 2868	0 2549
	Set Up and Moves[1] (Paving Eqpt Move in, adjust and move out (Table 6) - Reduced by $3,000 00														0 1465	0 1465	0 1465	0 1465
	Subtotal														0 6051	0 5541	0 5448	0 5005
	Material - Concrete[1]														2 7837	2 4744	2 7837	2 4744
	Material - Misc[1]														0 0893	0 0893	0 0893	0 0893
	Total														4.9139	3 4516	3 7785	3 3312

(1) See Table 8 for operations not itemized. Cost based on production of 39,600 sq yds per week
(2) Production of 44,550 sq yds per week.
(3) " " 55,440 " " " "
(4) " " 62,370 " " " "

Combination Machines

There are several units operating in selected areas of the country which combine the operations of the spreader, the transverse finisher, and the final float. This spreader-finisher-float machine,is used as a single-pass unit with one power supply and controlled by one operator.

The same analogy can be applied to show a savings of $0.0110 per sq yd or $1,540.00 over the entire job for the use of a single combination machine replacing the three conventional paving machines used in this estimate. The rate for a combination machine would be $890.00 per week. Reducing the finishing operation by four men—two finishers and two helpers—would result in an additional $0.0217 per sq yd savings or $3,038.00 for this job.

TABLE 16

ESTIMATE FOR PAVING 12 FT LANES 9 IN PAVEMENT

Operation	Per man hrs	Man pay hrs	Total pay hrs	Labor: Rate	Labor: Amount	Labor: Union Welfare	Labor: Ins 10%	Labor: Total	Labor: $/sq yd	Equipment: $/wk	Equipment: $/sq yd	Overhead: 5% Lab & Equip	Overhead: $/sq yd	Total	Remarks
ipervision														0 0186	
orms															
First Lane															
oreman		wk			175 00					40 00					
inemen	60	70	420	2 60	1,092 00	27 00				40 00					
orm Graders	60	70	140	3 25	455 00	6 00				300 00					
aborers	60	70	840	2 60	2,184.00	54 00				1,600 00					
in Drivers	60	70	280	2 75	770 00	18 00									
ompressor Oper	60	70	140	3 00	420 00	6 00				230 00					
ibtotal					5,096 00	111 00	509 60	5,716 60	0 1444	2,210 00	0 0558	396 33	0 0100	(0 2102)	First lane only
econd Lane															
oreman		wk			175 00					40 00					
inemen	60	70	210	2 60	546 00	13 50				20 00					
orm Grader	60	70	70	3 25	227 50	3 00				150 00					
abors	60	70	420	2 60	1,092 00	27 00				800 00					
in driver	60	70	140	2 75	385 00	9 00									
ompressor	60	70	70	3 00	210 00	3 00				115 00					
ibtotal					2,635 50	55 50	263 55	2,954 55	0 0746	1,125 00	0 0284	203 98	0 0052	(0 1082)	Second lane only
ombined form cost					7,731 50	166 50	773 15	8,671 15	0 1095	3,335 00	0 0421	600 31	0 0076	0 1592	Average of First & Second Lane
ine Grade					2,119 68	40 20	211 97	2,371 85	0 0599	1,012 00	0 0255	169 19	0 0043	0 0897	1 Laborer added Equip reduced by $48 00
ongitudinal Jt															
aborers-tie bars	60	70	210	2 60	546 00	13 50	54 60	614 10	0 0155	10 00	0 0003	31 20	0 0008	0 0166	2 Laborers Added
aul Road														0 0146	
ix & Place					3,778 75	67 20	377 87	4,223 82	0 1066	3,835 00	0 0968	402 94	0 0102	0 2136	Equip reduced by $100 00
inish															
inisher Foreman	66	79	79	3 55	280 45	6 60				40 00					
inisher	66	79	79	3 30	260 70	6 60				7 00					
elpers	60	70	210	2 60	546 00	13 50				20 00					
ibtotal					1,087 15	26 70	108 72	1,222 57	0 0309	67 00	0 0017	65 13	0 0016	0 0342	2 Finishers removed
ire					419 00	7 80	41 90	468 70	0 0118	101 00	0 0026	28 49	0 0007	0 0151	Equip reduced by $14 00
ill & Move Forms															
ruck Drivers	66	79	158	2 60	410 80	9 90				250 00					
elpers	66	79	474	2 60	1,232 40	29 70									
ibtotal					1,643 20	39.60	164 32	1,847 12	0 0466	250 00	0 0063	104 86	0 0026	0 0555	2 Helpers Added
rvice														0 0149	
agman														0 0107	
ng Joint Seal															
r Compressor	60	70	70	3 00	210 00	3 00				115 00					
aborers	60	70	140	2 60	364 00	9 00									
ibtotal					574 00	12 00	57 40	643 40	0 0162	115 00	0 0029	37 92	0 0010	0 0201	Clean & Seal only
uip Move, Wheel Changes etc												500 00	0 0036	0 0036	
dditional Material															
Bent tie bars														0 0040	
Keyway														0 0112	
tal for 12 ft Lane construction														0 6816	
' ' 24 ft construction (See Table 8)														0 6413	
dditional cost for 12 ft lane construction														0 0403	
Pavement Cost 12 ft lane construction $4,1408 (See Table 8) + $0 0403 = $4 1811															

It is easy to visualize additional savings due to maintaining and moving one piece of equipment rather than the conventional three pieces. Because of the many intangibles resulting in this type of comparison, these particular operations have not been shown in the tables.

SLIP-FORM

General

One of the most significant advances in paving equipment has been the development of the slip-form paver. The far-reaching acceptance of this machine warrants a discussion of its cost-saving advantages at this time.

The slip-form machine, in addition to insuring a cost-savings method, is a single-unit device that performs at least the functions of the conventional spreader, transverse finisher, longitudinal float, and burlap drag machine, commonly used with form-type paving. Also, with this machine only one operator is required where three or possibly

TABLE 17
SUMMARY

Construction Variables		Design Variables		
Equipment[3]	Cost inc S B $/sq yd	Distributed Steel and Joints	Cost $/sq yd	Total Cost $/sq yd
9-in concrete pavement on 6-in. sand-gravel subbase[1]				
Conv - two DD-24.	4.4307	91#mesh, doweled joints at 109 9 ft	1.0584	5.4891
Conv - two DD-24	4 4307	40#mesh, doweled joints at 42 7 ft	0.7672	5.1979
Conv - two DD-24	4.4307	No mesh, doweled joints at 20 ft	0.5895	5.0202
Conv - two DD-12	4.4710	No mesh, doweled joints at 20 ft	0.5895	5.0605
Conv - two 3D-24	4.2690	No mesh, doweled joints at 20 ft	0.5895	4.8585
SF - two DD-24	4.2038	No mesh, doweled joints at 20 ft	0.5895	4.7933
SF - two 3D-24	4.0684	No mesh, doweled joints at 20 ft	0.5895	4.6579
8-in concrete pavement on 5-in cement treated subbase[2]				
Conv - two DD-24	4.3823	78#mesh, doweled joints at 103.2 ft	$0.9305	5.3128
Conv - two DD-24	4.3823	40#mesh, doweled joints at 48 ft	0.7151	5.0974
Conv - two DD-24	4 3823	No mesh, doweled joints at 20 ft	0.5482	4.9305
Conv - two 3D-24	4.2388	No mesh, doweled joints at 20 ft	0.5482	4.7870
SF - two DD-24	4.1784	No mesh, doweled joints at 20 ft	0.5482	4.7266
SF - two 3D-24	4.0580	No mesh, doweled joints at 20 ft	0.5482	4.6062
SF - two 3D-24	4 0580	No mesh, no dowels, joints at 20 ft	0.0708	4.1288
SF - two 3D-24	4 0580	No mesh, no dowels, joints at 15 ft	0.0828	4.1409

1 6-in sand-gravel subbase cost $0.2899 per sq yd
2 Cement treating 5 in of 6 in sand-gravel cost $0.7268 per sq yd
3 Conv - Conventional equipment
DD - Dual-drum paver
3D - Three-drum paver
24 - 24-ft paving width
12 - 12-ft paving width
SF - Slip-form paver

four are required in the conventional method of paving. Another factor regarding labor costs in the operation of the slip-form paving is that all personnel have to be within the confines of the over-all length of the machine and its trailing forms. Therefore, at the end of the day when in a good many cases final finishing machines and hand finishers may have to work anywhere from ½ to 2 hr after the day's run has been completed, these added overtime costs are eliminated. Within a few minutes after the last bucket of concrete has been deposited, all work is completed for the day.

Savings

Some savings accumulated by this method of paving cannot actually be shown in an estimate of this type. The savings shown are those pertaining only to labor and equipment that can be itemized as in Table 15. Comparing Table 15 for slip-form paving with Table 5 for conventional paving, it can be seen that the items "Forms" and "Pull and Move Forms" have been deleted from the estimate. The operations of "Mixing and Placing" and "Finishing" have been changed to conform to the slip-form method. Because this type of machine is self-propelled and can be loaded and transported as well as moved on the job easier than conventional equipment, and due to the fact that three machines have been replaced with one, a reduction in the "Fixed Cost" can be shown, as in Table 6, which results in a saving of slightly over $0.02 per sq yd over the entire job. The total cost for a 9-in. pavement using the slip-form method can amount to $3.9139 per sq yd vs a cost of $4.1408 per sq yd with conventional equipment for the same pavement. This is a saving of $0.2269 per sq yd based on this conservative estimate.

There is much evidence from highway departments and contractors that a saving is gained in concrete yield. There is less waste over the side forms and a greater accuracy attained in yield due to a better control of subgrade finishing. Several contractors have reported that their yield loss was less than 1 percent. If a 1 percent loss was taken into account instead of the 4 percent as used in this estimate, this slip-form operation would show a saving of approximately $0.08 per sq yd in addition to that already calculated. The total reduction would be about $0.31 per sq yd.

By comparing a 9-in. pavement, using conventional equipment and dual drum pavers, with a slip-form and three-drum paver operation, considering a 1 percent yield loss, a saving of about $0.44 per sq yd can be realized.

Articles have been published concerning the slip-form work in Colorado which show actual bid price savings of about $0.50 per sq yd (14, 15).

SINGLE-LANE CONSTRUCTION

The next factor considered is that of paving a single-lane (12-ft wide) pavement in comparison to the conventional 24-ft wide pavement. The same production (square yards) has been used. There is exactly twice as much footage to be paved per day in paving single-lane in comparison to full-width construction.

Ohio Experience

Twenty-six paving projects were studied on the Ohio Turnpike. Nine of these projects paved 12-ft width and 12 projects paved 24-ft width. Production in square yards of pavement for both types construction was approximately equal. The amount of production is usually limited by the number of pavers used, the size of the batch, and the mixing time.

Factors Considered

There are several factors that affect the unit cost of both types of pavement. One factor is that an additional formline is required for 12-ft construction. The second factor that must be considered is that of a longitudinal construction joint in a 12-ft pavement compared to a sawed or formed joint with 24-ft construction. There is a difference in equipment charges for 12-ft machinery in comparison with a 24-ft machine. Generally, two more finishers are required for 24-ft construction than would be required for 12-ft construction.

Another consideration is that the contractor must purchase more paving forms. Finally, consideration should be given to whether the pavement is in rural areas, where there are few intersections, or in metropolitan areas where there would be many structures involved. Due to the delay involved in curing the pavement before the adjacent lane can be placed, it can easily be seen that in a metropolitan area, where there are numerous structures, the cost for paving two 12-ft lanes in place of one 24-ft lane would be higher than in a rural area where there were fewer structures.

Estimate

The estimate for single-lane construction is given in Table 16. The operations that vary are shown in detail so that they can be compared to full width construction in Table 5.

The "Forms" operation is shown for "First Lane" where two rows of forms are required and for "Second Lane" where one row is required. The "Combined Form Cost" (average) is used in the estimate. A comparison of form costs should include the operation "Pull and Move Forms."

For this estimate, two additional laborers would be required for fine grading the second lane. This would be due to the hand work involved along the longitudinal construction joint, around the tie bars, etc. This is taken care of in the estimate by the addition of one laborer for the entire operation.

Equipment cost for 12-ft machinery is approximately 12 percent less than the cost of 24-ft machinery. A reduction of $48.00 is accounted for under the "Fine Grade" operation equipment.

The "Mix and Place" operation is affected only by the reduction of 12 percent ($100.00) for the three pieces of paving equipment used.

The longitudinal joint operation will require two additional laborers to install the keyway and tie bars and to straighten out the bent tie bars after the centerline row of forms has been pulled.

Finishing a 12-ft lane requires fewer men than a 24-ft pavement although union regulations in some areas require the same number of finishers for a dual-drum paver, regardless of width of pavement or production. For this estimate the cost shown is for a reduction of two finishers. The operation "Pull and Move Forms" has been adjusted to compensate for the additional forms to be placed. It is not true that the cost of placing forms is 50 percent more for a 12-ft lane than a 24-ft because there are certain operations which can safely handle the increased footage required without any increase in labor or equipment as shown in Table 16.

Bent tie bars will cost $1.00 per cwt more than straight bars, which will result in a $0.0040 increase per sq yd. The metal keyway required for the longitudinal construction joint, provided with holes to accommodate the tie bars, will be considered for this estimate as salvageable material for several uses on this job and will cost $150.00 per 1,000 lineal ft. For this estimate 10,000 ft of this keyway will be required, resulting in a cost of $0.0112 per sq yd.

Table 16 shows that this 9-in. pavement, constructed one lane at a time (12 ft) would cost $0.0403 per sq yd more than if constructed full width (24 ft).

SUMMARY

Table 17 shows the total cost difference between some of the construction and design factors analyzed. Due to the vast number of comparable factors that could be considered, this paper has been limited to a few of the more prominent (Fig. 1). An analysis of this type enables the engineer to select and compare any factor he so chooses.

Recognizing that these pavements have equivalent load-carrying capacities, the wide range of costs as shown in Table 17 certainly warrants similar research of individual projects by highway engineers using local construction practices, labor rates, and material prices. A true engineering design must be based on economy and construction factors as well as structural factors. The engineer should not be satisfied unless he can honestly say he has designed the most economical pavement that will satisfactorily serve the public needs.

America is moving ahead but it must proceed efficiently and economically. The competitive spirit among contractors and equipment manufacturers is devising new methods of placing more and better pavements for less money. Engineers must do their part to utilize these methods and provide the most economical design. Only through research of this type can the engineer justly analyze a concrete pavement design.

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