T H E U N I V E R S I T Y O F M I C H I G A N

COLLEGE OF ENGINEERING
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Final Report

QUALITY OF CONCRETE USED IN CONSTRUCTION

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1. INTRODUCTION

1.1 GENERAL

Concrete is composed principally of cement, aggregates, and water. It contains some entrapped air and practically all of the concrete used by the Michigan Department of State Highways contains purposely entrained air obtained by use of a combination of air-entraining cement and admixture. Admixtures are also sometimes used for other purposes such as to accelerate, retard, improve workability, reduce mixing water requirements, increase strength, or alter other properties of the concrete.

When freshly mixed, concrete is a very perishable product which must be carefully handled during the early minutes or hours of its life and before hardening sets in; otherwise, its ultimate usefulness will be impaired. Similarly, it must be properly cured in a favorable temperature and moisture environment for the first few days of its life.

The considerable mileage of concrete pavement and hundreds of concrete bridges and other concrete structures now in Michigan testifies to successful surveillance of the concreting operation by personnel of the Michigan Department of State Highways. However, modern developments make it advisable to reassess present practices and to seek improved techniques.

Brief historical background is provided by the observation that, "In 1891 the first portland cement concrete pavement was constructed at Bellefontaine, Ohio. It consisted of an 8-ft wide strip of concrete to provide a solid pavement in front of a line of hitching rails. ... In 1909 the first mile of concrete pavement in the United States was constructed in Wayne County, Michigan and opened to public traffic on July 4th" (1). America's first large-scale multiple span concrete bridge was the Connecticut Avenue Bridge built in Washington, D. C. in 1906. Its overall length is 1,341 ft (2).

The enormous increase in highway construction in Michigan and throughout the nation since the early 1900's has caused a curious partnership to emerge between the suppliers of concrete and those charged with the engineering of the needed facilities. Indeed, innovations in the field of concrete such as announcement of the inverse relationship between concrete compressive strength and the water-cement ratio in 1918 (3), air-entrainment for use in concrete in northern climates (4), and use of the chemical admixtures have been encouraged and the development participated in by consumers as much or to a greater degree than by manufacturers.

Too, the very nature of concrete itself wherein the aggregate components are almost always locally procured and the ingredients combined at or near the job site has always fostered intimate involvement of the highway engineer with the manufacturing process. His knowledge of the local materials stems from lifetime experience. Thus, the consumer-producer relationships in quality-control or quality-assurance which are typical of so many manufactured products are distorted by the fact that the highway engineer himself is often, in essence, a member of the concrete manufacturing team.

1.2 DIVIDED RESPONSIBLITY BETWEEN CONCRETE SUPPLIER AND THE HIGHWAY DEPARTMENT

Shortcomings in the quality of concrete placed on Michigan projects have been discovered occasionally, or have been alleged. Assignment of responsibility for such infractions is a natural consequence so as to resolve the immediate situation and hopefully to forestall similar difficulties in the future.

In view of the involvement of the Department in the manufacturing process as mentioned in the previous section, choice of an appropriate course of action upon discovery of a quality shortcoming in the hardened concrete usually presents an irritating dilemma: the contractor claims use of ingredients tested and approved by the Department and mixed in accordance with the Department's instructions whereas the Department can suspicion a mistake or infraction by the contractor's personnel not detected by the Department's inspectors.

Details of this division of responsibility will be covered later when considering specific construction items.

1.3 SURVEILLANCE OF INSPECTION PROCEDURES BY THE FEDERAL HIGHWAY ADMINISTRATION

On Federal-aid projects, inspection policies are currently outlined in, "Policy and Procedure Memorandum No. 20-6.2," dated April 4, 1972. This document is entitled, "Inspection of construction Projects (Sampling and Testing)" and its purpose is to "prescribe policies, procedures, and guides relating to sampling and testing of materials and construction in connection with the inspection of Federal-aid highway construction projects..." Some of the provisions of this document are specifically applicable to concrete and concrete-making ingredients. MDSH inspection policies which necessarily conform with the Federal Highway regulations will be itemized in later sections.

The Federal Highway regulations in no way assist in solving the basic dilemma on quality-control or quality-assurance of concrete by the Highway Department, namely, the unusual consumer-producer relationship. However, this agency did sponsor an excellent series of articles on "Quality Assurance in Highway Construction" which appeared in Public Roads magazine (5). The latter emphasized the statistical aspects of sampling and testing.

2. PRESENT CONCRETE INSPECTION PRACTICES OF THE MICHIGAN DEPARTMENT OF STATE HIGHWAYS

2.1 DEFINITIONS OF TERMS

Over the years, the Department has established policies in inspection of concrete and its ingredients. These policies conform to the guidelines of the Federal Highway Administration and are enumerated herein using terminology defined by the FHWA in "Policy and Procedure Memorandum No. 20-6.2," dated April 4, 1972. Below are definitions important to understanding of the inspection policies:

Job Control Samples and Tests. Job control samples and tests include all of the samples and tests specified for determining the quality and acceptability of the materials being incorporated or proposed for incorporation in the construction and the quality of the construction work being produced. The test results obtained on the job control samples also serve as the principal basis for determining the acceptability of a completed item of construction.

Progress Record Samples and Tests. Progress record samples and tests are samples taken and tested for the purpose of making an independent spot check on the reliability of the results obtained in job control sampling and testing. The test results obtained on progress record samples do not independently form a basis for determining the acceptability of materials and construction work but supplement job control test results in accomplishing such determinations.

Final Record Samples and Tests. Final record samples and tests are samples taken and tested to determine the in-place characteristics of the materials and to verify conformity with such plans and specifications requirements that are applicable to the completed construction as distinguished from those requirements that are applicable to materials before they are incorporated into the work or to the construction in progress. In this respect final record samples and tests serve the same purpose relative to completed construction as do progress record samples and tests relative to work in progress and materials not yet incorporated.

2.2 INSPECTION OF PORTLAND CEMENT

Cement purchased by contractors having Michigan highway projects originate from about 10 different manufacturers or mills. Manufacturers of cement have found it advantageous for many years to generously support their own mill control laboratories and carry on an aggressive internal quality control program thus ensuring a flow of uniform final product conforming with recognized standards. In recognition of this, the Department adopted a policy in 1962 of accepting certified cement for use without prior State test from those mills having a well established history of compliance with ASTM specifications. Table 1 summarizes the frequency, etc., of progress record samples taken to justify continued use of certified cement in the work.

Experience with the certification scheme has been very satisfactory and few instances of abuse of the privilege of certification have occurred.

From the manufacturers' standpoint, the scheme has distinct advantage:

(1) Customer shipments can be made at once without awaiting completion of prior testing by MDSH,

(2) Silo capacity can be reduced since separate storage of State-tested cement need not be maintained,

(3) No longer maintaining segregated State-tested cement causes the cement company to place even greater emphasis on internal quality control since the entire mill stream is, in effect, subject to random ceck testing by MDSH. Valid claim cannot be made by other cement customers of a superior "special" cement being manufactured for exclusive MDSH use.

Similarly, advantage accrues to the Highway Department in adopting the certification scheme:

(1) Fluctuating contractor demands for State-tested cement no longer causes long work schedules and overtime for State cement testing personnel,

(2) Verifying by MDSH personnel, or representatives, that shipments are made out of State-tested stock at the mill is no longer needed. Furthermore, a modern cement mill makes tracing of a given lot of cement through the intricacies of the conveyor system very difficult,

(3) Contractor claims that the job is being delayed by shortage of State-tested cement is no longer valid,

(4) The progress record samples which are taken by the Department can be relied upon without question to represent that cement entering the work because they are taken directly from deliveries at the job site.

TABLE 1

PRESENT INSPECTION POLICY FOR PORTLAND CEMENT

Tests	Quality Control	Job Control Samples		Progress Record Samples		Final Record Samples	
	Testing by Producer	Sampling Location	Frequency	Sampling Location	Frequency	Sampling Location	Frequency
Physical Normal Consistency Time of Set Air in Mortar Specific Surface Autoclave Expansion Compressive Strength False Set	Yes	(1)	(1)	Random-Job Site (2)	(3)	--	---
Chemical	Yes	(1)	(1)	Random-Job Site (2)	(4)	--	---

(1) Certification of each shipment by supplier.

(2) Spot check of reliability of manufacturer's job control sampling and testing.

(3) For first 10,000 bbl per month . . . . 1 sample per 2,000 bbl or less
next 40,000 bbl per month . . . . 1 sample per 10,000 bbl or less
over 50,000 bbl per month . . . . 1 sample per 25,000 bbl or less

Whenever a major paving project is in progress, additional samples shall be obtained at the rate of one sample per 15,000 - 20,000 bbl.

(4) Normally annually.

2.3 INSPECTION OF AGGREGATES

MDSH inspection policies for aggregates for concrete provide a marked contrast with those for portland cement covered in the previous section due largely to fundamental differences in the two products.

In the first place, the basic quality of an aggregate is very importantly influenced by the geology of the particular pit or quarry in which the producer is operating. Substantial modifications of the product can be accomplishedby washing, screening, crushing, and beneficiation, but the fact remains that he is largely at the mercy of what nature has provided.

Until very recently, aggregate producers have carried on no quality control testing of their own but, rather, have monitored the tests of MDSH or other inspectors stationed at their plants to ascertain the acceptance status of their products. However, several of the larger producers are now engaging their own inspectors to conduct tests of their aggregates destined for general usage and, to some extent, for highway projects.

Table 2 lists the inspections of aggregates carried on by MDSH personnel. The schedule aims to conform with the FHWA guidelines. The twice weekly progress record samples for deleterious particles and sieve analysis of coarse aggregates shown in the table are superimposed on the normal inspection scheme and provide confirmation that the aggregates stored at a ready-mixed plant or paving batching plant do actually conform with the specifications. Contamination or impairment of the grading analysis can be suspicioned between the point of original inspection at the producer's plant and final stockpiling or storage just before entering the mix.

It will be one of the aims of this research to assess whether or not the very considerable annual effort by the Department in behalf of ensuring use of only high quality aggregates in the concrete can somehow be reduced.

2.4 INSPECTION OF MIXING WATER AND ADMIXTURES

Problems associated with monitoring the quality of water used for mixing concrete have practically disappeared in Michigan. Most mixing water originates from municipal drinking water supplies and injurious contaminants are not present. A minimum inspection program is maintained, however, as listed in Table 3.

Widespread use of air-entraining admixtures since the late 1940's has resulted in a settling down of the pattern of usage, and problems in quality control of A.E. admixtures are seldom encountered. The uniformity requirements of ASTM Specification C 260 for Air-Entraining Admixtures for Concrete can be invoked when needed. Occasionally a supplier has wished to furnish A.E.

TABLE 2

PRESENT INSPECTION POLICY FOR CONCRETE AGGREGATES

Tests	Quality Control Testing by Producer	Job Control Samples		Progress Record Samples		Final Record Samples	
		Sampling Location	Frequency	Sampling Location	Frequency	Sampling Location	Frequency
			(a) Coarse Aggregate				
Aggregate Abrasion	No	Producer's plant	Once per production year per source	--	--	--	---
Sulfate Soundness	No	Producer's plant	Once per production year per source	--	--	--	---
Deleterious Particles & Sieve Analysis	No	Producer's plant	Each 300 tons	Producer's plant	One per wk. by central lab.	--	---
	Variable			Producer's plant	One per wk. by Dist. Mat. Insp.	--	---
				Transit mix or other batch plant	Two per wk.* by Dist. Mat. Insp.		
Moisture Content	No	Transit mix or other batch plant	One per day of concrete production	--	--	--	---
Unit Weight	No	Transit mix or other batch plant	Prior to use or change of material	--	--	--	---

*If random sampling at proportioning plant not feasible due to storage of aggregate in inaccessible bins, additional check sample per production week to be taken at producer's plant.

TABLE 2 (Concluded)

Tests	Quality Control Testing by Producer	Job Control Samples		Progress Record Samples		Final Record Samples	
		Sampling Location	Frequency	Sampling Location	Frequency	Sampling Location	Frequency
(b) Fine Aggregate							
Sulfate Soundness	No	Producer's plant	Once per production year per source	--	--	--	---
Organic Colorimetric	Variable	Producer's plant	Once daily	Producer's plant	Two per mo. by central lab.	--	---
Moisture Content	No	Transit mix or other batch plant	One per 5 hr of production	--	--	--	---
Sieve Analysis	Variable	Producer's plant	Each 300 tons	Producer's plant	Two per mo. by central lab.	--	---
				Producer's plant	One per wk. by Dist. Mat. Insp.	--	---
				Transit mix or other batch plant	Two per wk.* by Dist. Mat. Insp.	--	---
Mortar Strength	No	--	--	Producer's plant	Initial test by central lab. and if organic high		

*If random sampling at proportioning plant not feasible due to storage of aggregate in inaccessible bins, additional check sample per production week to be taken at producer's plant.

TABLE 3

PRESENT INSPECTION POLICY FOR MIXING WATER AND CONCRETE ADMIXTURES

Tests	Quality Control	Job Control Samples		Progress Record Samples		Final Record Samples	
	Testing by Producer	Sampling Location	Frequency	Sampling Location	Frequency	Sampling Location	Frequency
Mixing water	--	Source	One for each project involving concrete (1)	--	--	--	---
Admixtures							
Calcium chloride	Yes	--	--	Job	Prior to initial use of brand on job		
"Chemical" ASTM C 494	Yes	--	--	Producer's plant	Prior to first use of product. Tested by "Recognized lab" (2)	--	---
Air-entraining	Yes	--	--	Producer's plant	Prior to first use of product. Tested by "Recognized Lab" (2)	--	--
Water-reducing	Yes	--	--	Producer's plant	Prior to first use of product. Tested by "Recognized Lab" (2)	--	---
Water-reducing and retarding	Yes	--	--	Producer's plant	Prior to first use of product. Tested by "Recognized Lab" (2)	--	---

(1) Water approved by State Board of Health may be used without testing.
(2) A "recognized" laboratory is any State Highway Laboratory, Federal Highway Administration or cement and concrete laboratory regularly inspected by the Cement and Concrete Reference Laboratory of the National Bureau of Standards.

admixtures of such high concentration that the needed accuracy of dispensing cannot be attained by available automatic equipment, but the problems have not been found insurmountable.

Use of the water-reducing and retarding admixtures in bridge deck construction has generated problems in concrete uniformity, quality control, and Department quality assurance. Reference 6 aimed at providing a better understanding of the lack of compatibility of high dosages of certain admixtures with certain cements. The recommendations of this report with regard to quality assurance by the department are still under study.

2.5 SELECTION OF MIX PROPORTIONS

Since the early 1930's, the Department has informed the contractor of the exact quantity of each ingredient to be incorporated in the concrete batch. Laboratory determinations using the materials shipped from the project are made using a modification of the "mortar voids" method from which the mix proportions are calculated. This is an example of the deep involvement of the Department in the concrete "manufacturing" process.

The laboratory determinations made on the concrete ingredients in preparation for selecting mix proportions include specific gravity of the cement and aggregates and absorption value of the coarse and fine aggregates. Trial mortars are made using job cement and fine aggregate. Density determinations of these mortars made at different sand-cement ratios, when coupled with suitable mathematical manipulations of empirical constants derived from job experience, permits selection of batch quantities.

It the contractor changes the sources of concrete constituents during the progress of the job, revised batch proportions are prescribed based on new laboratory determinations. These records have supplemental value in providing a history of materials sources and mixture proportions for the permanent project files.

Table 4 contains a listing of the several standard classes of concrete employed by the Department in pavements and structures. A fairly wide range of basic characteristics is indicated giving some idea of the diversity of "highway" construction.

In the case of one class of concrete, namely, that for prestressed concrete beams, the supplier selects his own mix proportions subject to Department prescribed restrictions on cement content, air content, slump, and compressive strength. This removes Department need for much troublesome inspection of batching, mixing equipment, etc. The rationale for this difference in Department practice from other classes of concrete is that the concrete is of a single class made repetitively in the beam manufacturer's plant,

TABLE 4

GRADES OF CONCRETE USED BY MICHIGAN DEPARTMENT OF STATE HIGHWAYS

Grade Designation	Coarse Aggregate (1)	Cement Content (sk/cyd)	Air Content (%)	Maximum Slump (in.)	Minimum Design Modulus of Rupture, 28 Days (psi)	Minimum Design Compressive Strength, 28 Days (psi)
40S - Piling	6A,17A	6.5	5 - 8	5 (2)	700	4000
40S - Structural	6AA	6.4	5 - 8	3-1/2	700	4000
35P - HE	6A	7.0	5 - 8	3	725	4500
35P - HE	6A	6.0 (3)	5 - 8	3	650	3500
35T Tremie	6A	6.5	5 - 8	7	650	3500
35P	6A	6.0	5 - 8	3	650	3500
35S	6A,6AA	6.0	5 - 8	3-1/2	650	3500
35S	6A,17A	6.0	5 - 8	3	650	3500
30P	6A	5.5	5 - 8	3	600	3000
30M - Commercial	--	5.5	5 - 8	4	---	--
X - As Specified	--	3.0+	---	--	---	--

(1) As required or permitted.
(2) Slump not less than 3 in.
(3) Type IIIA cement shall be used.

and the restrictions that are made are almost self-enforcing. The interrelationships of the required amount of entrained air, maximum cement content, and required compressive strength makes use of a low slump concrete mandatory by the beam producer. The compressive strength requirements give recognition to the modern view that the probability of a single test specimen falling below any given minimum must be realistically acknowledged, and it therefore specifies that for 5000 psi concrete, "the compressive strength of the three test specimens shall be at least 93% of 5000 psi (4650 psi) with at least one of the three test specimens having a compressive strength of 5000 psi or greater."

2.6 BATCHING AND MIXING

Accurate weighing of the concrete ingredients for each batch and thorough intermingling during mixing are necessary for providing uniformly mixed, high quality concrete. The MDSH standard specifications devote considerable space to specifying the batching equipment, i.e., weigh hoppers, scales, interlocking devices, etc. Additionally, descriptive material regarding mixers and mixer performance requirements are given for large size central mixers. Detailed requirements for concrete mixed in transit mixers are also enumerated.

A delicate division of responsibility characterizes this batching and mixing activity. Prior to beginning the concreting operation, Department representatives examine the batching, mixing, and transporting equipment which the contractor proposes to use. If these items comply with the Department requirements, he uses them subject to batch weight settings prescribed by MDSH personnel. Depending upon fluctuations in the moisture content of the aggregates as periodically determined by the MDSH plant inspector, or if different classes of concrete are being furnished, these scale settings may be revised several times during one day's operation.

Any work on equipment to remedy shortcomings discovered during the progress of the job is, of course, the contractor's responsibility. Whether or not a shortcoming is discovered during concreting may depend upon so many factors that it is difficult to assess, in a given case, whether the Department plant inspector will become aware of the difficulty and demand remedial action. For example, one or two batches might completely lack sand. These would probably be noticed visually at once and corrective action taken. On the other hand, the air-entraining dispenser could fail to function, or could run dry, and not be detected for several batches. Minor discrepancies in batch scale settings could conceivably be undetected for several hours.

2.7 TESTS OF FRESH CONCRETE

From a quality control standpoint, tests performed on the plastic concrete after completion of mixing have very limited value: (1) The major independent test now available for the fresh concrete, namely, the slump test measuring consistency of the mix, is almost meaningless from a diagnosis standpoint; for instance, a dramatic change of slump from the preceding batch may be due to a variety of causes, i.e., improper weighing of water or the aggregates, sudden change in moisture content of the sand, sudden change of grading of aggregates, etc. (2) If the slump test reveals that the mix is too dry, the remainder of the batch not yet discharge can sometimes be corrected by addition of water, however, this risks the chance of an excessively high water-cement ratio and consequent loss of strength; if the mix is too wet, acceptance of the remaining undischarged concrete can be refused, but this may be only a token reprimand since most may have been already discharged before the faulty slump is confirmed. (3) Similar "after the fact" considerations apply to measurement of entrained air. Although the air test normally takes only 3-5 min to perform, discovery of improper air content amy come too late to enable proper remedy. (4) The yield test which entails determining unit weight of the fresh concrete derives its ability to establish exact cement content only from unquestioned accuracy of batching the concrete ingredients (scale weights); as such its real utility can be suspected.

Table 5 lists the frequency of job control and progress record tests on the fresh concrete.

2.8 TESTS OF HARDENED CONCRETE

Concrete becomes "hard" about 3-5 hr after casting and then continues to gain strength thereafter for a long period; the rate of strength gain depending upon the moisture and temperature environment. Any tests performed on the hardened concrete obviously cannot contemplate anything except the most drastic remedial measures if an infraction of the specifications is discovered; for example, penalizing the contractor or in the extreme case complete removal of the defective portion.

2.8.1 Strength Tests—The two distinctly different purposes for which concrete strength test specimens are made should be emphasized: (1) In the first case, the specimens aim to verify the mixture design when using job materials in which case the specimens are cured under standard laboratory conditions of temperature and humidity. Such tests establish what strength the concrete is potentially capable of attaining. (2) In the other case, the test specimens are cured under moisture and temperature conditions aiming to duplicate those on the actual construction job. Often, the latter specimens are stored alongside the structure. It is debatable how successfully small 6- x 12-in. test cylinders or 6- x 6-in. cross-section test beams can be expected to duplicate the moisture and temperature environment of the much larger masses of concrete in the actual structure or pavement. In any event, the reason for low strength, if such is observed, of job cured specimens can only be conjectured unless

TABLE 5

PRESENT INSPECTION OF PLASTIC CONCRETE BY MDSH

Tests	Quality Control Testing by Producer	Job Control Samples		Progress Record Samples		Final Record Samples	
		Sampling Location	Frequency	Sampling Location	Frequency	Sampling Location	Frequency
Yield	No	At placement site	Whenever an overrun is greater than 3% or whenever any underrun cannot be explained	--	--	--	---
Slump	No	At placement site	Once per 2 hr of production if used for structural purposes; or once every 3-4 hr if used in pavement	At placement site	Observed once per production week	--	---
Entrained air	No	At placement site	At start of pour and every third truck or once every hr if used for structural purposes; or once every 2 hr of production if used in pavements	At placement site	Once per structure unit if used for structural purposes; or once per week if used in pavement	--	---

positive evidence is available from companion specimens of the type described in (1) above that the concrete is in fact capable of attaining satisfactory strength.

A running record of strength tests of hardened concrete on a project builds a quality history upon which some assurance of the integrity of future construction can be based. In this sense, undue skepticism of the value of strength tests of the current production, even though learned 7, 14, or even 28 days after placement, is not entirely warranted.

Test beams are now made on MDSH construction jobs and are cured and broken in flexure. Table 6 lists the frequencies of such tests. Flexural tests are still performed on bridge concrete although all designs of bridge members contemplate that the concrete be required to resist compressive stresses only

At the time of the first MDSH field strength tests of concrete in the early 1930's, small portable flexure testers were devised and used experimentally without distinction as to whether the concrete was for a bridge or pavement. In the intervening years, reasonable portable and inexpensive compression testers have become available, and it is difficult in retrospect to understand why the Department has not yet changed to cylinder compression testing of bridge concrete.

TABLE 6

PRESENT INSPECTION OF HARDENED CONCRETE

Tests	Quality Control Testing by Producer	Job Control Samples		Progress Record Samples		Final Record Samples	
		Sampling Location	Frequency	Sampling Location	Frequency	Sampling Location	Frequency
Modulus of Rupture	No	At placement site or batch site	Four beams each, on alternate days if used for pavements; two beams per structure unit or very 200 cyd if for structures	--	---	--	---
Compressive Strength (Prestressed beams only)	Yes*	Manufacturer's plant	Two cylinders each from three batches per beam	--	---	--	---
Core Depth (Pavements only)	No	--	--	--	---	At placement site	One per 1000 ft of pavement

*In presence of MDSH representative.

3. NONCOMPLYING CONCRETE

3.1 GENERAL

As a result of inspections or testing programs concrete used by the Department from a certain pour may be judged to not be in compliance with the applicable specification requirement. Effort is here made to assess the consequences of such noncompliance recognizing the need for enforcement of the specification from a purely legal standpoint and also separately assessing the consequences of such noncompliance from the standpoint of expected impairment of the performance of the structure or pavement. Often the test results fall into a gray area intermediate between unquestioned noncompliance and values considered barely satisfactory. Extenuating circumstances, real or alleged, make administration of a specification difficult when test values fall within this gray area.

There is always the hope that improved testing techniques, greater recognition of inherent material variations, and generally greater sophistication in all aspects of testing will narrow this gray area. In any case, good engineering judgement must prevail in making the final decision. The present report can only hope to outline misconceptions or call attention to current developments whose recognition may improve the decision process.

3.2 SLUMP

The slump test is used to describe the fluidity or consistency of the plastic concrete, the method being given under ASTM Designation C 143 or AASHO Method 119. The fluidity of the fresh concrete will importantly influence its satisfactory placement. For example, concrete placed in a structural member having closely spaced, congested reinforcing bars using hand methods of consolidation will necessarily have to be very fluid to flow into the restricted spaces. A slump of 5-6 in., as undersirable as it may be, might be required to achieve placment in such a case. Such high fluidity will amost certainly promote segregation of the aggregate sizes during placement. On the other hand, pavements with widely spaced reinforcing can be satisfactorily placed with a dry mixture of less than 1-in. slump when powerful vibrators are available to aid consolidation.

A recently issued ACI "Recommended Practice" (7) contains the following statement regarding slump of structural concrete:

> "A 3-in. (8 cm) slump is normally ample for properly vibrated structural concrete in forms. What may be regarded as a need for wetter concrete in many quarters is better satisfied by more

thorough vibration. Actually, concrete for heavy structural members and slabs can be satisfactorily placed at a 2-in. (5 cm) maximum slump when properly vibrated."

Concrete placed by pumping may require a slightly higher initial slump. The same committee report contains the following statement with regard to paving concrete:

"The successful use of mechanical vibrating and finishing equipment in pavement construction requires that the concrete mixture have adequate placeability and finishability. However the slump should not exceed 2 in. (5 cm), to keep segregation and loss of entrained air near the surface at a minimum (and to maintain the highest practible quality of concrete)."

Since the contractor's operations are so importantly influenced by the concrete slump, there is some validity in the view that the Department should abstain entirely from placing restrictions thereon; i.e., restrictions will be largely self-enforcing. Two examples in this regard are slipform paving and pretensioned prestressed beams; in the former, a fairly dry mix must be employed to prevent sloughing of the concrete behind the paver, and in the latter the strict strength requirements of the air-entrained concrete are such that the use of high-slump, weak mixes are automatically ruled out.

Slump is often considered a measure of water content of the concrete since slump can always be increased by addition of water. Increase in slump of a typical concrete from a value of 2 to 4 in. is accomplished by increase of about 9% in the unit water content or about 3 gal/cyd of concrete which would result in increase of w/c of a 6-sack concrete of about 0.045 by weight. This would in turn cause a probably reduction of 28-day compressive strength of about 350 psi (8).

Table 7 has been prepared using data derived from Refs. (9) and (10) and displays compressive strength increments resulting from slumps deviating from those desired if slump changes are assumed due exclusively to changes in water content (calculated here as w/c changes of 6-sack concrete). It will be noted concrete initially of low slump will be more sensitive, strength-wise, to changes in slump than will high slump concrete. In any event, minor batch-to-batch slump variations do not predict important strength changes and consequently do not influence the decision process unless close to the critical strength limit and the concrete is nominally of low slump.

Many investigations of the variability of slump on actual construction operations have been made in recent years, some of which are reported in Part 3 of Ref. (5). Depending upon the project, overall standard deviation averages roughly 0.5 to 0.9 in. Variances due to sampling and testing are greatly overshadowed by "material" variances, indicating that the test itself and sampling

TABLE 7

EXPECTED CHANGE IN COMPRESSIVE STRENGTH DUE TO INDICATED CHANGE IN SLUMP, PSI

(Assuming slump change due exclusively to change in water content of 6-sack A.E. concrete)

Nominal Slump Level (in.)	Measured Slump (in.)								
	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	7.0
1.0	0	-210	-330	-450	-550	-670	-850	-900	-970
1.5	+240	0	-120	-220	-300	-430	-550	-650	-750
2.0	+350	+120	0	-120	-200	-350	-470	-560	-600
3.0	+570	+320	+170	+ 80	0	-100	-250	-350	-450
4.0	+670	+400	+300	+200	+120	0	-120	-220	-320
6.0	+930	+660	+550	+450	+350	+200	+100	0	-100
7.0	+980	+700	+580	+480	+390	+300	+190	+ 90	0

techniques are not important contributors to the observed variability. Rather, most of the slump variability is attributable to aggregate moisture fluctuations, batching errors, or other concrete mixture variations causing a change of slump.

3.3 FLEXURAL STRENGTH

Concrete pavement design procedures invariably use flexural strength as an important factor, thus despite inherent obstacles in proper measurement of flexural strength on an actual construction job, it is understandable that great effort should be spent in attempting to monitor this important item.

In flexural testing of a beam specimen, maximum stress occurs at the outermost fibers whose location, unfortunately, coincides with that portion of the beam which dries first when the test specimen is removed from moist curing. This drying causes substantial differential shrinkage and induces tensile stress which renders an evaluation of the true tensile properties of the concrete almost unattainable. For example, Ref. (11) reports average losses of flexural strength of two different concretes moist cured for 91 days of 8 and 9%, respectively, when exposed in air for only 30 min of drying. One day of drying in air following proper moist curing caused an apparent strength loss of 31 and 35%, respectively.

Controversy arising from observations similar to above led Walker and Bloem to comment in a written discussion of Ref. (12) as follows:

"Mr. Werner and Mr. Goldbeck apparently derived the impression that the paper advocated the abandonment of flexural strength as a basis for concrete pavement design. Such was not the intention. Accepted design theories depend upon a knowledge or assumption of flexural strength for determining load-carrying capacity or selecting required thickness. Tests for modulus of rupture are necessary in establishing concrete proportions required to secure the desired strength level and in comparing strength-producing properties of different concrete ingredients. However, this work should be confined to the laboratory where testing conditions can be meticulously controlled. The test for modulus of rupture is too sensitive to extraneous factors, particularly moisture condition of specimens, to permit its use as a basis for acceptance or rejection of concrete in the field."

Recent evaluation of the results of the AASHO test road (13) again confirm the great significance of flexural strength to rigid pavement behavior; an important conclusion is quoted as follows:

"Eq. 18, relating the ultimate number of axle-load applications, $N_{2.5}$, to the flexural strength of pavement material, f_c,.... suggests that the pavement life should increase in proportion to the fourth power of strength of slab material....."

If it is assumed that reliable means can be developed to assess the true flexural strength of paving concrete, the foregoing relation provides a method of evaluating the consequences of concrete not complying with the project flexural strength requirements. Table 8 has been prepared giving the anticipated life of the pavement corresponding to deficiencies in flexural strength ranging from none to 150 psi and for five design strength levels, namely, 550, 600, 700, and 750 psi. What might be anticipated to be relatively minor deficiencies in strength predict substantial reductions in service life; a 50-psi deficiency causes roughly a 25% reduction and a 100-psi deficiency from design predicts a halving of service life. Any temptation to neglect deficiencies in flexural strength of paving concrete seems entirely unwarranted in light of this data.

As pointed out in previous paragraphs, the extreme sensitivity of the flexural test to seemingly minor infractions of prescribed testing techniques makes it advisable that an entirely new approach to the matter be sought. Suggested modifications of current policies will be detailed later.

3.4 COMPRESSIVE STRENGTH

Compressive strength is an important variable in structural reinforced concrete design since it is assumed that the concrete will be called upon to resist compressive stresses. Except for prestressed bridge beams, the

TABLE 8

PREDICTED PAVEMENT SERVICE LIFE RESULTING FROM DEFICIENCIES IN FLEXURAL STRENGTH

(Life at design strength = 100%)

Deficiency from Design Strength (psi)	Design Flexural Strength (psi)				
	550	600	650	700	750
0	100	100	100	100	100
25	83	84	85	86	87
50	68	71	73	74	76
75	56	59	61	64	66
100	45	48	51	54	56
125	36	39	43	46	48
150	28	32	35	38	41

Department has operated under the assumption that concrete demonstrating satisfactory flexural strength necessarily has acceptable compressive strength; consequently, flexural test beams have been employed on both pavement and structure projects interchangeably.

For a given combination of concrete ingredients and method of making, curing, and testing specimens, compressive and flexural strength of a concrete will simultaneously increase or decrease with changes in water-cement ratio; one can be predicted from the other. However, flexural strength is particularly susceptible to structural strength of the coarse aggregate constituent, and when concrete ingredients are changed predictions of compressive strength from flexural strength are not necessarily valid.

An acceptance procedure for prestressed beams based on compressive testing of 6- x 12-in. cylinders has been successfully employed by the Department, and it will be proposed later in this report that the testing of 6- x 12-in. compression cylinders might well be used for all structural applications where compressive stresses are to be resisted.

With respect to noncomplying concrete, procedures given by ACI 318-71, Building Code for Reinforced Concrete, provide that portions of the structure containing concrete suspected deficient by 500 psi or greater from f'_c will be cored or load tested. "Concrete in the area represented by the core test will be considered structurally adequate if the average of three cores is equal to at least 85% of f'_c and if no single core is less than 75% of f'_c" (Par. 4.3.5.1).

3.5 ENTRAINED AIR CONTENT

Much of the concrete used by the Department is exposed to moisture and frost of the Michigan winters necessitating that it can be protected by containing an adequate system of well-spaced microscopic air voids.

Use of air-entraining cement supplemented, when necessary, by additional air-entraining admixture so as to provide air contents within the limits now generally provided by the standard specifications should insure concrete amply well protected from freeze-thaw action and destructiveness of deicer chemicals.

The newly proposed ACI "Recommended Practice for Concrete Highway Bridge Construction," ACI Committee 345 (38) specifies that concrete made with aggregate of 1-in. maximum size (corresponds with Michigan 6A) contain 6 ± 1% air, not importantly different from the present Michigan requirement of 6.5 ± 1.5% air for both structural and paving concrete.

Concrete containing less than about 5% air will lack adequate weather resistance, and concrete with this maximum size aggregate having air contents in excess of about 8% will be penalized by strength losses of 3-4% for each 1% increase in air. Previous considerations of strength losses permit assessment of the impairment of service life resulting from losses due to excessive air content.

Information in support of the provision of the 9.0 ± 1.5% air requirement for the special concrete to be used in portions of bridge construction for sidewalks, safety and medial curbs, etc., in paragraph 7.01.03 of the 1973 Standard Specifications is somewhat controversial. Bureau of Public Roads data of Grieb, Werner, and Woolf (39) and data of Inge Lyse of Norway (40) seemed to support the need for such high air content to resist deicer chemical damage. However, in the discussion of Ref. (40), Klieger and Mather, who have worked extensively in the field of salt water and deicer exposure, dispute the need of such high air content and are concerned with the very substantial strength loss at the high side of the recommended air content. Work using Michigan materials concluded that, "Increasing the air content from 5.2 to 7.3% improved scaling resistance slightly but further increase of air up to 10.1% appeared to have little benefit" (41). The Michigan work also indicated a loss of compressive strength of approximately 15% for the 10% air concrete with respect to the 5% air concrete. As a compromise between the viewpoints, an air content of 7.5 ± 1.5% is recommended for this special concrete.

4. INSPECTION SYSTEMS AVAILABLE

4.1 GENERAL

In seeking improved inspection procedures, or proposing new systems for insuring use of only high quality concrete by the Department, the concept will be emphasized that every effort should be made to divorce the Department from what may be termed strictly "quality control." Those individuals who most directly exercise control (i.e., those who position the weights on weigh beams at the batch plant, set the timer controlling mixing time, choose the throttle setting for mixing speed, etc.) are in closest physical proximity to the levers, valves, etc., regulating the "quality" of the product and should exercise control. These are contractor or material producer personnel. It is in the latter's hands, for example, to make the first move toward remedying an obvious shortcoming in the product. Judgment of impending trouble and the remedy may take only a few seconds. Department inspectors must necessarily exercise more leisurely "remote control" and really can do no other than accept or reject the product after subjecting it to time-consuming tests. Such tests are often too late to greatly influence the quality of the production stream except for the benefit of subsequent production or to gather data for statistical analysis.

If the validity of this viewpoint be acknowledged, i.e., that those having most immediate contact with the production should exercise control, then several alternative inspection schemes can be critically examined with respect to their ability to accomplish this.

Using a given scheme, the Department should be unwilling to assume too great a consumer risk and thus jeopardize its ability to prevent use of an inferior product. On the other hand, the producer cannot be expected to assume other than minimum losses due to unwarranted rejection of acceptable material or, what is not so often recognized as a producer risk, he cannot often undergo loss because of tardy discovery and subsequent rejection of production later found to be substandard.

4.2 ACCEPTANCE BY CONTRACTOR OR SUPPLIER CERTIFICATION

In this scheme, all aspects of "quality control" are relinquished to the supplier. The Department is responsible for preparation of the specification requirements and acts as a watchdog to later verify compliance with the specifications. Day-to-day control over the production stream, however, is the responsibility of the supplier.

Section 2.2 of this report gave some details of the successful application of the certification scheme allowing portland cement to be incorporated in the work without prior Department test. In considering extending certification to other features of concrete making, several observations should be made:

4.2.1 Cement mills supplying Michigan highway projects have a long history of operating their own quality-control departments. The product is manufactured under close scrutiny using mill laboratories generally outfitted with sophisticated chemical and physical apparatus for rapid quality determinations and in some cases so arranged as to automatically feedback corrections to the manufacturing process. The specification limits for cement have evolved slowly through the past 70 years of ASTM standardization, and the test techniques used by most of the producer and consumer laboratories have themselves been monitored periodically by the Cement and Concrete Reference Laboratory (CCRL), an agency of the National Bureau of Standards. Thus, testing, inspection, and quality control have become an ingrained way of life in the cement industry.

4.2.2 Manufacture of portland cement is a high-volume, essentially one-product business, contrary to today's consumer demands for variety so prevalent in some fields. The manufacturers have successfully avoided a multiplicity of grades, types, and colors, etc., of their products and oppose vigorously special grades. They are thus able to concentrate their entire control effort pretty much on this one product.

4.2.3 An important consideration of a successful certification scheme is the method used by the purchaser to satisfy himself of the continued validity of the certifications. The past 10 years experience has indicated that in the case of portland cement, samples taken randomly from project deliveries and subsequently tested at the Department central laboratory have confirmed the propriety of the certifications. Obviously, each ingredient of concrete and the finished product itself should be given thorough study before proposing certification acceptance.

4.2.4 In contemplating possible extension of the certification scheme to cover acceptance of aggregates for concrete, or acceptance of the mixed concrete itself, attention is called to the fact that suppliers of aggregates and concrete furnishing to Michigan projects range widely in capabilities and size with investments varying from only a few thousand dollars up to large corporations capitalized in the millions. The smallest cement manufacturer today has an investment of at least 40 million dollars with the accompanying expertise capable of undertaking an in-house quality control program which such an investment warrants. Conversely, the smaller aggregate producers and ready-mixed concrete suppliers can be expected to have scarcely more than token knowledge of quality control techniques, and the Department can therefore suspicion their eligibility to certify their output.

One solution for the small organization called upon to certify would be for it to hire a testing organization to examine its product thus establishing a basis for certification. This would unquestionably increase the cost but would benefit the Department in not needlessly tieing up inspection personnel to conduct quality control testing in behalf of a small organization not yet ready itself to furnish proof of strictly an engineered product.

4.2.5 Table 9 evaluates the tests which the Department might use on its own samples to substantiate producer certifications if aggregates or concrete, or both, were to be accepted on this basis. The entries marked, "Dif" are techniques which would temporarily present difficulties to the Department since standard testing procedures are only now being developed or the techniques now exist but are not too familiar to MDSH personnel. As would be expected, most of the traditional tests on aggregates are more expeditiously conducted on samples before placing in the concrete mix. Except for compressive strength of drilled cores (and possibly modulus of rupture as will be detailed later), the tests on concrete employ the freshly mixed concrete with which to commence the tests.

4.2.6 There is temptation to require the supplier to simultaneously provide the certification and a copy of the test results in support of the certification. The test results may be assumed to be in some measure supplanting the need for verification tests. This practice should be discouraged since it stifles producer innovation and fails to recognize that the tests upon which the supplier depends for supporting his certification are not necessarily those which are even available to the consumer, nor are they necessarily the tests which the consumer must use in his quality assurance program. The point is sometimes overlooked that the manufacturer may have more compelling data at his command than is accessible to the purchaser. For example, a manufacturer of galvanized sheet metal may have very reliable knowledge of consuming a certain weight of molten zinc in coating a known number of square feet of base metal and thus have very reliable data on the overall average thickness of galvanizing. A prohibitive number of tests by the purchaser would be required on the finished sheet to establish the same value with equal reliability. Similarly, a concrete paving contractor may have very positive knowledge of the tonnage of portland cement used in paving a certain mileage of pavement of known thickness and width; consequently he will be reliably informed of the overall average cement content of the concrete. An inspection agency would require many expensive tests to establish the same value with equal accuracy.

4.2.7 In summary, acceptance of concrete and concrete ingredients on the basis of certification has much merit. An orderly extension of the present policy of accepting certified portland cement could be undertaken by the Department starting, probably, with fine aggregate as the next candidate for certification (sand now presents few acceptance problems). As producer and Department personnel become accustomed to the new policy, other concrete materials could be phased in to the certification scheme over, for example, a five-year period.

There are many advantages to the certification acceptance scheme:

TABLE 9

EVALUATION OF METHODS AVAILABLE TO VERIFY CERTIFICATIONS

Test	Fine Aggregate			Coarse Aggregate			Mixed Concrete	
	Sampled Before Placing in Concrete	Sampled from Freshly Mixed Concrete	Sampled from Hardened Concrete	Sampled Before Placing in Concrete	Sampled from Freshly Mixed Concrete	Sampled from Hardened Concrete	Sampled from Freshly Mixed Concrete	Sampled from Hardened Concrete
Aggregates								
Organic Matter	Yes	No	No	--	--	--	--	--
Sulfate Soundness	Yes	No	No	Yes	Dif	No	--	--
Loss by Washing	Yes	No	No	Yes	No	No	--	--
Grading Analysis	Yes	Dif	No	Yes	Dif	No	--	--
Mixed Concrete								
Cement Content, sk/cyd	--	--	--	--	--	--	Dif	Dif
Slump	--	--	--	--	--	--	Yes	No
W/C	--	--	--	--	--	--	Dif	Dif
Modulus of Rupture	--	--	--	--	--	--	Yes	Dif
Compressive Strength	--	--	--	--	--	--	Yes	Yes
Air Content	--	--	--	--	--	--	Yes	Dif

CODE: Yes - Conformance with specifications can be confirmed by testing random samples.
No - Not practical or impossible to determine conformance with specifications from random samples.
Dif - Difficult to determine conformance with specifications but technique to do so can be developed.

(1) Control of the product quality is placed with the supplier in whose hands it most logically rests. (This does not infer that the Department is to relinquish its responsibility for setting the level of quality, i.e., the specification limits.) Department control must necessarily be "second hand" due to necessity for post-production testing, whereas the supplier is in immediate command to remedy shortcomings as they develop.

(2) Verification testing by the Department to insure certification validity can be done at district or central laboratory at a place most convenient for testing personnel without the urgency to meet production schedules.

(3) Department field construction personnel are not burdened with materials control testing which is often looked upon as an irksome task incompatible with normal construction inspection.

(4) The supplier can no longer claim job delays due to awaiting Department approval testing.

4.3 CONTRACTOR QUALITY CONTROL UNDER DEPARTMENT SURVEILLANCE

An acceptance scheme now being employed in some instances by the Corps of Engineers, U.S. Army (15), requires that the Contractor secure qualified inspection personnel and carry on a complete quality control program, all phases of which are subject to approval by the Corps. Corps surveillance covers such matters as the Contractor's quality control organization, scholastic background and experience qualifications of the technical personnel, required records to be maintained, etc. It appears that the contractor is required to support a quality control program just about equivalent to that which the Corps would feel needed if it were conducting the inspections itself.

The Corps scheme requires the Contractor's organization to maintain laboratory testing facilities and testing personnel and likewise demands highly qualified Corps personnel to oversee the contractor's quality control efforts. Documentation by Daily Inspection Reports is demanded, and the contractor is generally required to submit test data, etc., on forms prepared by the Corps.

The inspection burden taken on by the small contractor on a minor project under this scheme seems considerable and in this respect is analogous to the previously described certification scheme; however, there is one subtle but basically important difference, namely, that the contractor's control operations are constantly under the watchful eye of the Corps. Indeed, if anything goes "wrong" on the project concerning materials control, the Corps would seem to share responsibility equally, or perhaps even more than the contractor, since the Corps is constantly scrutinizing progress and specifying precisely what tests were to be performed, and how, etc. However, with the certification scheme, and in the extreme case, the supplier or contractor could conceivably not perform any tests during a certain period if he has sufficient confidence in his product to risk the possibility that Department tests would later find him not in compliance. If Department validations confirm his judgment, there has been a definite saving. Equally significant would be the case where he was able to use an abbreviated quality control procedure which by its nature would not be available to the Department. The certification scheme encourages innovation on the part of the supplier or contractor to seek out such "short-cuts."

The Corps plan is ably described and defended in the following quotation (16):

> "The Corps of Engineers has been busy changing its procedures to place responsibility on the contractor for testing and inspection necessary to control the quality of the work. He is required to submit a formal plan indicating what, when, how, and by whom testing and inspection will be done. This procedure allows him to use his own system if we consider it adequate to produce the required results. The Corps will review the contractor's plan and accept it, if it is reasonable. The Corps will provide surveillance to monitor the contractor's testing and inspection for effectiveness, laboratory procedures and equipment calibration, and quality control reports. The Corps also performs verification tests and inspections as needed to assure that the specified quality has been produced before acceptance. Since some work is covered up by other work as the job progresses, this requires some testing and inspection throughout the construction operations, but duplication of effort can be kept to a minimum by surveillance. There is no intention for the Corps to quit inspecting and testing, but these efforts can be reduced to those required to fulfill our responsibility when the contractor does a good job of controlling the quality of his own work. We plan to quit doing the contractor's work for him and make him responsible for the quality he agreed to produce when he signed the contract."

4.4 ACCREDITATION

There is, of course, strong desire on the part of all concerned that only those who are strictly competent should participate in concrete design, testing, mixing, and other phases of concrete construction. Early record that this ideal should be voluntarily achieved is contained in a "Statement of Responsibilities" developed in 1960 by the National Joint Cooperative Committee between the National Ready-Mixed Concrete Association and the Associated General Contractors of American and adopted by those associations. It was reviewed by both associations again in 1965 and republished without change. This interesting document is reproduced in the Appendix.

4.4.1 It was early realized that a purely voluntary, cooperative effort to insure competence in concrete construction such as described above would not be 100% successful, and Roger H. Corbetta, chairman of the board, Corbetta Construction Company, spearheaded a drive aiming to formalize the matter and pleaded for establishment of a "National Regents Board" under joint ASCE, ACI sponsorship to grant "Certificates of Competancy" to qualifying concrete contractors and plants and issue licenses to testing laboratories (17,18). A National Board of Accreditation in Concrete Construction (NBACC) was, in fact, established; however, its efforts languished and as recently as April, 1973 it is reported in the Journal of ACI that the ACI Board of Directors voted to assist reactivating it.

4.4.2 Another activity in the accreditation field is the certification scheme of the National Ready-Mixed Concrete Association in cooperation with the Truck Mixer Manufacturers Bureau and the Concrete Plant Manufacturers Bureau. In 1965, the policy was established that if the production facilities of a ready-mixed concrete organization met certain requirements, it would be entitled to display a "Certificate of Conformance." Inspection to determine compliance is conducted under the direction of a registered professional engineer who must attest that the batch plant, trucks, etc., qualify for such a certificate. Periodic checkups are required (19). The Department could well support this laudable activity by requiring that all plants supplying Michigan projects have the certificate.

4.4.3 The competence of testing organizations undertaking inspection of concrete construction, particularly in the private sector, has sometimes been questioned for very good reason and, after much study, the American Society for Testing and Materials in 1967 established "Recommended Practice for Inspection and Testing Agencies for Concrete, Steel, and Bituminous Materials," issued as Designation E 329. "This recommended practice was circulated for review before acceptance to the American Concrete Institute, American Society of Civil Engineers, American Council of Independent Laboratories, Construction Specification Institute, and a joint AIA-ASCE-ACI Committee on Quality in Concrete" (20). This recommended practice defines duties and responsibilities and establishes minimum requirements for personnel and equipment of public and independent commercial materials inspection and testing agencies engaged in inspection and testing of concrete and steel as used in construction. Inspection of the agency and its personnel at intervals of not more than three years by the Materials Reference Laboratory of the National Bureau of Standards is now required.

It would seem only reasonable that adherence to this recommended practice by any agency undertaking inspection in behalf of the Department should be demanded.

4.5 PERFORMANCE SPECIFICATIONS

Observation is sometimes made that the deep involvement of the Department in the quality control of concrete production could be alleviated by adoption of some sort of performance or "end result" specification in place of the "prescription" type under which the Department is essentially now operating. Reference (21) gives a brief evaluation of the performance type specification:

> "With this type of specification the contractor or producer takes the entire responsibility for supplying an item of construction, or a product, that meets the specification requirements. The specification places no restrictions on the materials to be used or the methods of incorporating them into the completed work or product. This type of specification is suitable for use only if (a) the essential characteristics of the end result are known and are measurable, (b) a quick method of test is available, and (c) deficiencies can be corrected by reprocessing.
>
> "The last is a practical rather than a theoretical condition. The principal objection to this type of specification is that a large quantity of construction or material in place may be found to be defective and no correction is possible. In theory the contractor can be forced to remove and replace the defective item, but in practice this may be unrealistic because of various pressures and exigencies. The situation is embarrassing to both the contractor and the engineer. There is no satisfactory solution and often the substandard work is accepted, with or without a token penalty. For this reason, performance specifications are most suitable for such items as the construction of embankment, where a definite density can be specified, the density of a compacted lift can be readily measured. No restrictions need be placed on the contractor as to moisture content or equipment, because if the required density is not obtained it is not impractical to recompact the material."

It is interesting to note from the same report (21) the contrasting specific reference to production of portland cement concrete as suitable to the "materials and methods specification" often referred to as the "prescription" type:

> "This type of specification is customarily used for most items of highway construction and must be used when (a) the essential characteristics of the completed work are not known or are not measurable, (b) no quick method of acceptance is available, or (c) it is impractical to remove and replace defective work.
>
> "The contractor or producer is directed to combine specified materials in definite proportions, using approved equipment, or to

place a specified material or product in a specified way. Normally the operations must at all times be under the surveillance of inspectors who represent the engineer. Although some specifications hopefully state that the contractor or producer is responsible for the end result, this statement is not usually legally enforceable if the materials and methods requirements have been met.

"Probably the best example of this type of specification is that for the production of portland cement concrete. The component materials—cement, aggregates, water, and air-entraining agents—must be pretested and approved. These materials must be combined in specified proportions, mixed in a certain way. The mixture must meet further requirements as to consistency and air content.

"In this case it is necessary to use the materials and methods specification because quick tests for compressive strength have not been adopted, and because there is no definitive test for the second essential characteristic of concrete, which is durability.

"The weakness of the materials and methods specification is that it may not always produce the desired end result. It is based on past experience, and if variables unknown to the specification writer change under new conditions, the end result may not be satisfactory.

"A common example is subbase material that, although constructed of the specified aggregate, meeting all requirements as to gradation and Atterberg limits, and compacted to the specified density, may not provide a stable working platform for subsequent construction.

"In this situation the engineer is in an awkward position, because any effort to force the contractor to take remedial measures may result in a claim at the end of the job."

Test methods of greater sophistication for rapidly determining concrete quality are constantly under development, some of which will be described later in this report. However, the fact remains that if the above entirely reasonable quoted Miller-Warden criterion is adhered to, namely, that for successful operation of an end results specification deficiencies must be correctable by reprocessing, then hardened concrete scarcely fits this description. The cost of repair or replacement may be exhorbitant, and only limited ability presently exists to even detect that deficiencies are present in the finished product.

4.6 CONSTRUCTION WITH SERVICE LIFE GUARANTEE

Some success has been reported in Europe wherein the contractor posts a bond guaranteeing satisfactory service performance for a specified number of years after completion of the construction project (22). It follows that the contractor will wish to actively participate in the design phase of such a project, including choice of materials, etc., in order to prevent taking too great a risk with unfamiliar type of construction.

In the United States, an analogous type of construction is becoming more prevalent under the designation of "turnkey" operations wherein contractors become designer-builders. This seems more favored on large, complicated projects such as nuclear power plants. In essence, the client states his construction need and has little control or managerial function thereafter until the constructor ultimately turns over the keys to the finished project. The propriety of turnkey operations is now becoming clouded by controversy between architects-engineers-contractors as to their proper spheres of activity. The Consulting Engineers Council is becoming involved in the matter (23,24).

Question can be raised as to the applicability of a service life guarantee to highway bridge or pavement construction in a dynamic society such as in the U.S. Subsequent increase of traffic or allowable loadings, for example, would surely be held to invalidate continued liability on the part of the insuring agency. The service bond concept seems more appropriate to apartment house construction, for example, where there is little likelihood of significant changes later in the type of service demanded.

It is not inconceivable that the service bond concept might be somehow devised to accommodate later changes during the life of the project, but this would require many adjustments on the part of the legal and engineering professions to meet such a challenging departure from customary practice.

4.7 BONUS-PENALTY PLANS

Financial incentives (and penalties) to encourage better bituminous construction have been extensively investigated by Louisiana (25). Obviously, a clear understanding between supplier and purchaser is mandatory if penalty in unit prices will be imposed. Sampling plans, testing variability, normal material variability, etc., must all be carefully evaluated and properly accounted for so that equity to both parties will result. In the field of bituminous pavement construction, this has been reported as successfully accomplished (26), and the following data reported on 16 Louisiana projects:

Total Tonnage of Hot Mix	Tonnage Paid for at 95% of Contract Price	Tonnage Paid for at 80% of Contract Price
544,384	30,211 (5.5%)	7,223 (1.3%)

None was so deficient as to be paid at 50% of unit price or required to be removed.

The tabulation can be interpreted as recording that about 5% of the total tonnage experienced a 5% penalty and about 1% a 20% penalty. No bonus payments were reported nor are contemplated in the more recent versions of the Louisiana specifications.

Terminology has grown in the bituminous paving field so that bonus-penalty plans have become synonymous with "end result specifications." This seems unfortunate because penalties have been exacted, for example, for late completion on many different types of projects for a long time without implication of "end result specifications." Similarly, concrete pavements of insufficient thickness as determined by drilled cores have given rise to penalties for many years. In our opinion, the term, "end result" should apply only where actual performance in service has proved that the choice of materials and design were, or were not, adequate to the need.

A paper by Arena gives further details of the Louisiana practice (26):

> "The end result specification as applied on Asphaltic Concrete mixtures in Louisiana consists of two types of testing, namely, Control and Acceptance Testing. The control testing is the sole responsibility of the contractor; the acceptance testing is the responsibility of the Highway Department.
>
> "The quality control testing as performed by the contractor, or his representative, consists of the initial design of the mix, submittal of a job mix formula, two extracted gradations and asphalt contents per day, ten temperatures per day and an overall general observation to insure the quality of the mix being produced."

The Louisiana "end result" specification plan has some resemblance to the procedure previously identified as "Contractor Quality Control Under Department Surveillance" of the U.S. Corps of Engineers given in Section 4.3, but it emphasizes the sliding scale of unit prices which in turn depend upon the number and magnitude of deficiencies discovered after finish of construction. Surveillance of the contractor's quality control procedures during construction is minimal.

The Louisiana scheme certainly has merit but requires in the case of concrete that the schedule of penalties, lot size, statistical variations, etc., be reevaluated. Furthermore, there are definite limitations to the tests that can be conducted on the finished concrete product unless there is willingness to develop expertise with some of the tests now classed as only on the fringe of "acceptance" tests, for example, air content of hardened concrete by linear traverse techniques (ASTM C 457-71), cement content of hardened concrete (ASTM

C 85-66), and critical dilation of concrete subject to freezing (ASTM C 671-71T). Louisiana is just now experimenting with such a specification for concrete pavement but has found it necessary to independently police minimum cement content and maximum water-cement ratio as before. Penalties are established for surface tolerance and thickness. A "lot" is considered as 4000 lineal feet of 24-ft wide pavement. A "section" is 400 lineal feet of pavement. The State itself makes one slump and air test per section and runs two gradation tests per day "for their information only."

5. COST OF INSPECTION OF CONCRETE

The Michigan Department of State Highways currently contracts for about 3 million sq yd of pavement and roughly 100 bridge structures annually. This amounts to about 1 million cyd of concrete.

In order to arrive at a rough estimate of the expense of concrete inspection which the Department might reasonably allot for this amount of construction, it can be observed that commercial agencies are reported to estimate about 30 cents/cyd as the average cost of cylinder strength testing alone. On this basis, cylinder testing would cost about $300,000 annually to which should be added the cost of aggregate testing, preparation of mix designs, day-to-day air tests, etc. This could easily bring the total inspection cost to one-half million dollars.

If the current price of the concrete material, alone, be assumed to be $20/cyd, this would bring the inspection cost to about 2-1/2% of the gross material price, not an unreasonable percentage.

On this basis, a fairly sizable investment in new equipment, development of techniques, or personnel adjustments could be undertaken by the Department if there were prospect of even a small percentage improvement in such a substantial annual expenditure.

6. IMPROVED TESTING INSTRUMENTS AND TECHNIQUES

Innovations in concrete testing techniques and instruments are constantly under development, some of which might have application to Department of Highways practice. The more important of these are listed below and brief estimate made of their applicability:

6.1 REBOUND HAMMER

This instrument (Figure 1) for nondestructively determining the compressive strength of concrete has also gone under the names of "Schmidt" or "Swiss" hammer and has been in use for about 20 years (27). The rebound of a steel missile, spring-driven, on to a plunger held firmly against and perpendicular to the concrete surface is measured. The instrument has serious limitations in its ability to provide a strict psi reading of concrete strength because, "different surface shpe, texture, aggregate types, condition of cure, or moisture content cause measurable variations in rebound readings." It does appear to aid in distinguishing portions of a structure having marked differences in compressive strength as is sometimes encountered in "post-mortem" examinations but has doubtful utility in acceptance testing. ASTM is now preparing a standard for this method of test which will encourage its wider use.

6.2 WINDSOR PROBE

This device (Figure 2) fires a calibrated projectile into the concrete by detonating a measured explosive charge (28). Depth of penetration of the projectile ("probe") provides a measure of the concrete strength. The penetration is influenced by hardness of the aggregates in the concrete, and five grades of hardness on Moh's scale is provided for in the instrument calibration. The present testers furnished by the manufacturer are usually arranged for firing three probes into the concrete so as to provide an average penetration reading. The test is essentially nondestructive but requires grouting of the three small holes (about 1/4 in. diameter) which remain after removal of the probes. So far as can be determined, the only manufacturer of the equipment is Windsor Probe Test Systems, Inc., P.O. Box 10281, Elmwood, Conn., 06110. The proprietary nature of the system has inhibited its standardization and adoption, particularly by public agencies.

6.3 TENSILE SPLITTING TEST

In this test (Figure 3), a concrete cylinder of the type used in compression tests, is placed with its axis horizontal between the platens of a testing

Figure 1. Rebound hammer for nondestructive measurement of concrete compressive strength. (Courtesy of Soiltest)

Figure 2. Windsor probe. Depth of penetration of projectile fired into concrete indicates compressive strength. (Courtesy of Soiltest)

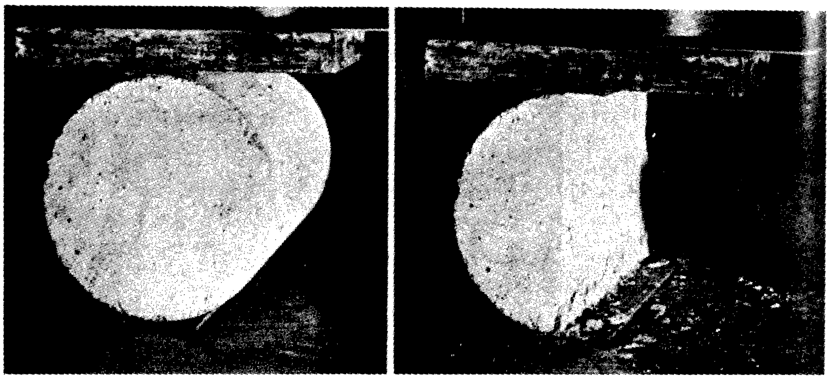

Figure 3. Tensile splitting test of concrete cylinder.

machine, and the load is increased until failure by splitting along the vertical diameter takes place (29). Drilled cores not containing steel reinforcing can similarly be tested for splitting tensile strength. ASTM standardized the procedure for this test under designation C 496 and first issued it in 1962. The test itself was first independently announced in Brazil and in Japan in 1953.

In the 11 years intervening between its first publication by ASTM and the present, the test has been subjected to numerous investigations and a large number of reports issued (30,31,42).

The test has many advantages, probably the most significant being that molded cylinders (or drilled cores) can be used interchangeably for compression or tensile tests, thus are appropriate for MDSH use for either pavements or structures.

Extensive tests by the U.S. Bureau of Public Roads led to the following conclusions (32):

"1. A linear relation exists between the splitting tensile strength and the flexural strength of concrete for a given material and method of curing. The relation between splitting tensile strength and compressive strength of concrete is curvilinear.

"2. The relation between splitting tensile strength and flexural strength varies with the type and maximum size of the coarse aggregate. The relation between splitting tensile strength and compressive strength also varies with the type and maximum size of the coarse aggregate.

"3. For the concrete prepared with the same materials, the ratio of the splitting tensile strength to the flexural strength is constant and is not affected by the cement content of the concrete or the age at test. The ratio of the splitting tensile strength to the compressive strength decreases as the compressive strength increases; therefore, this ratio varies with the cement content or the age at test.

"4. For continuously moist cured specimens, the splitting tensile strength averaged approximately 5/8 of the flexural strength for gravel concrete, 2/3 for limestone concrete, and 3/4 for lightweight aggregate concrete. Because of the nonlinear relation between splitting tensile strength and compressive strength no average ratios can be given.

"5. The splitting tensile strength of the concrete is less affected by drying than the flexural strength. This effect is more pronounced for concrete prepared with lightweight aggregates than for concrete prepared with natural aggregates. The reduction in splitting tensile strength caused by drying tends to be greater than the reduction in compressive strength.

"6. No appreciable difference exists between the unit splitting tensile strength of cylinders 6 in. in diameter and 12 in. in length and cylinders 6 in. in diameter and 6 in. in length."

Acceptance of the test and its use in engineering work is exemplified by its adoption in "Standard Specification for Lightweight Aggregate for Structural Concrete," ASTM C 330. The requirements for nominal torsion and shear stress in ACI 318-71, "Building Code for Reinforced Concrete," likewise tie into the splitting tensile test of concrete containing lightweight aggregate, but Sec. 4.2.9.1 of the Code specifies that, "Tensile splitting tests of field concrete shall not be used as a basis for acceptance." This latter sentence was inserted not because the test is necessarily considered inappropriate for such purpose but to forestall those who were demanding excessive testing by simultaneously requiring split cylinder <u>and</u> compression testing of field specimens.

The information now available is overwhelmingly in favor of the splitting tensile test over the flexural beam test, and its adoption by MDSH will be recommended.

6.4 MISCELLANEOUS STRENGTH TESTS

6.4.1 Pull-Out Test - In this test, a 3/4 to 1-in. diameter bolt with nut threaded on the bottom is embedded in the concrete about 2-1/2 in. at the time of casting and is then pulled out at the test age with a hydraulic jack equipped with gage to read the pulling force. This dislodges a conically shaped piece of concrete much as if an anchor bolt is pulled out of the hardened concrete. The total load on the jack is then treated as uniformly distributed over the surface of the extracted cone from which the unit tensile strength is computed.

Some work on this test has been done by the National Ready-Mixed Concrete Association and by V. M. Malhotra of the Minerals Processing Division, Mines Branch, Ottawa, Canada. It has been reported that the technique is being patented by Owen Richards, 4306 Rosemary St., Chevy Chase, Md., 20015 and seems unlikely as being presently applicable to Highway Department use.

6.4.2 Ring Tensile Test - In this test (Figure 4), hydrostatic pressure is applied against the inside of a concrete ring specimen by inflating a specially molded rubber bladder (33). The forces are strictly radial, and restraints typical of most tensile tests are a minimum. In order to test concrete with 1-in. maximum size aggregate, rather large rings should be employed, and the authors suggest wet screening over a 3/8-in. sieve so that a 6-in. inside diameter ring, such as used with mortar, can still be used. The test removes many of the theoretical objections to most tensile tests but standardization has not yet been undertaken and further consideration by the Department is undoubtedly premature.

6.4.3 Double Punch Tensile Test - In this test (Figure 5), a concrete cylinder is placed vertically between the loading platens of the machine and is compressed by two steel punches whose faces are placed parallel to the bottom and top surfaces of the cylinder (34). The sample splits across many vertical diametral planes similar to the split cylinder test. This test has been proposed for such a short time that it is too early to judge its acceptance.

6.5 OTHER MISCELLANEOUS TESTS

6.5.1 Workability Probe for Fresh Concrete - This instrument (Figure 6) was recently announced as a promising substitute for the slump cone (35). The probe consists of a hollow tube 3/4 in. in diameter and 13 in. long, pointed at the end. The bottom 6 in. of the tube is perforated with slots and holes in a prescribed configuration. When the probe is inserted in the fresh concrete, some of the paste and mortar flows in through the openings and, depending upon the fluidity of the mix, is retained in the probe when it is withdrawn from the concrete. Up to a certain fluidity, the greater the height of retained mortar, the greater the slump. However, when the slump becomes high enough (approximately 7 in.), mortar begins to flow out of the probe when it is withdrawn and the "workability index" measured by the instrument diminishes as the slump increases. This reversal may be the instrument's greatest fault and inhibit its adoption, but it is too early to assess its ultimate success.

6.5.2 Concrete Maturity Meter - The amount of strength acquired by concrete depends importantly upon its age and temperature during curing. In 1956, it was proposed that advantage could be taken of this to develop a "maturity

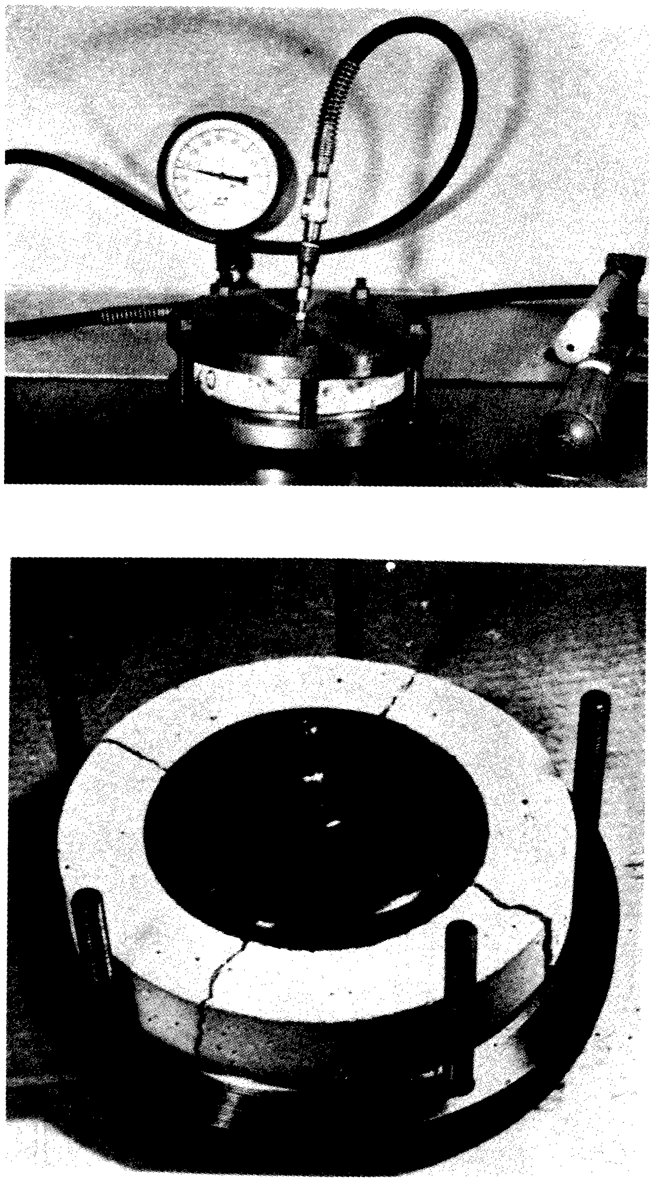

Figure 4. Ring tensile test. Top: Test assembly. Bottom: Ring after test. (From Reference 33)

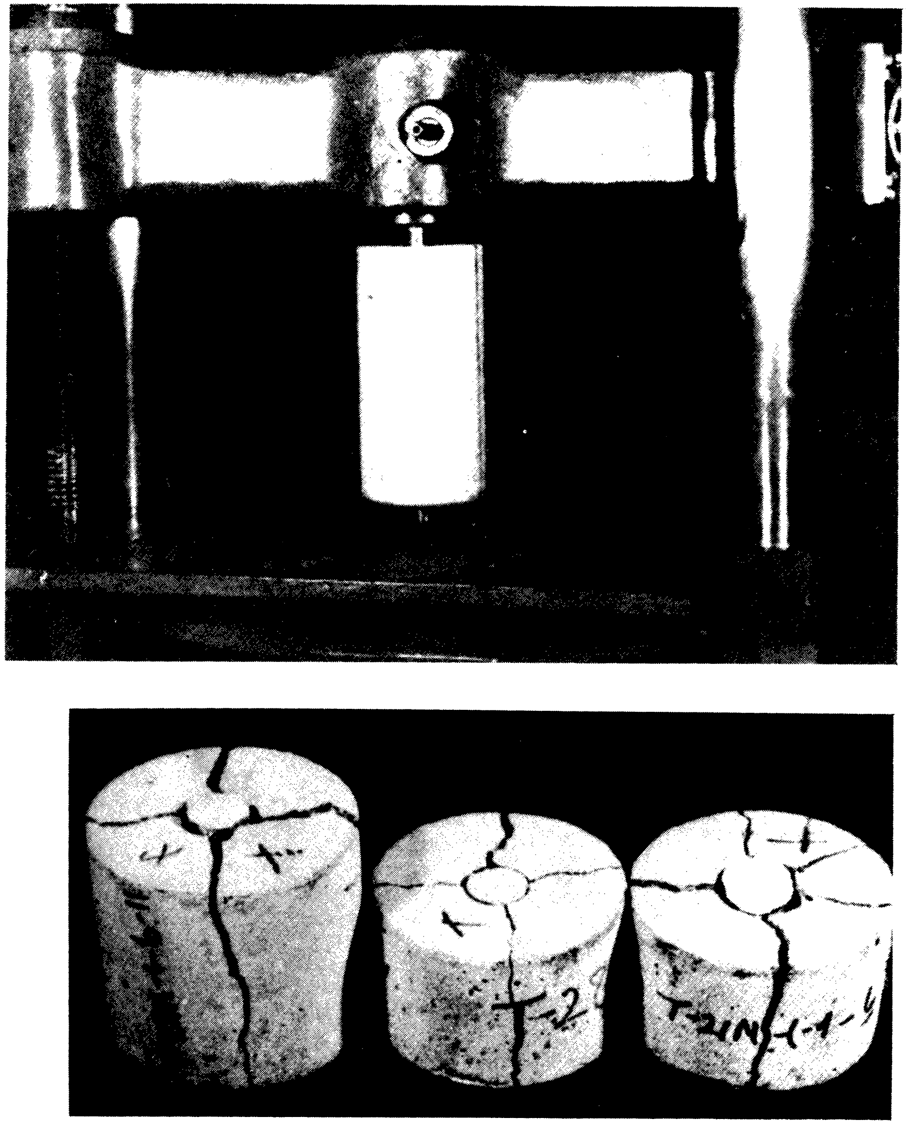

Figure 5. Double punch tensile test. Top: Cylinder undergoing test. Bottom: Cylinders after test. (From Reference 34)

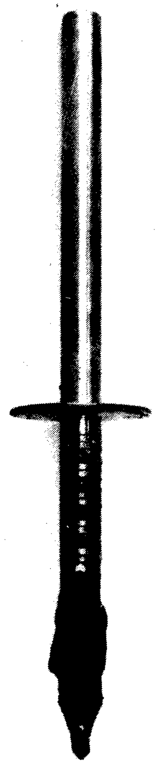

Figure 6. Workability probe for testing consistency of fresh concrete. (From Reference 35)

concept" of concrete, defined as the product of age and temperature (36), and thus enable a prediction of strength at any age. Strengths at very early ages of precast products, strength for form removal and for patching, are of particular interest. An instrument is now being made in Scotland (Figure 7) which employs this concept. A probe is inserted in the concrete at time of casting to measure temperature, and the device cumulatively measures the product of (temperature in degrees centigrade + 10) x age in hours and displays the result continuously on a digital counter. The device is available from Crow Hamilton & Co., Ltd., 47 Haggs Road, Glasgow, S.1. Scotland and might have some use for MDSH for special work but probably not for routine acceptance.

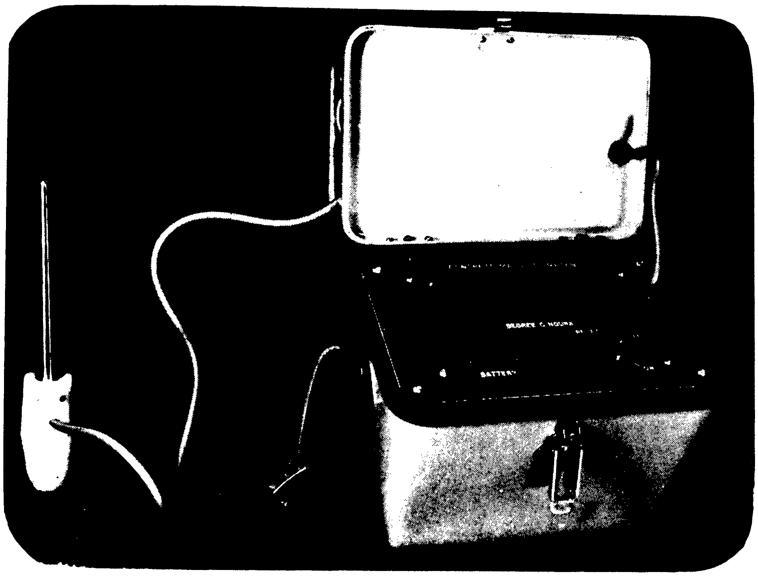

Figure 7. Concrete maturity meter.
(From Manufacturer's Literature)

7. PROPOSED REVISIONS IN MDSH CONCRETE INSPECTION PROCEDURES

7.1 GENERAL

The preceding sections of this report outline current MDSH inspection policies for concrete ingredients and concrete itself and give some historical background of their origin. Potential changes in inspection schemes as well as promising new hardware have been outlined. The presentations are highly selective; exhaustive coverage would be needlessly burdensome.

In making specific recommendations for MDSH inspection changes, the following criteria have been considered:

7.1.1 Improvement in ability to measure a fundamental property of material rather than performance of an identification or index test should be sought. For example, conducting the flexural strength test of paving concrete is an unsatisfactory method of learning its true tensile properties.

7.1.2 Divorcing the Department from quality control effort in behalf of the supplier should be encouraged wherever possible. Manipulation of the levers, gages, weigh beams, etc., which control the quality of the concrete and its ingredients are properly in the hands of the manufacturer, producer, or equipment operator who is closest to the process. The quality control personnel of the supplier, next in line of responsibility and having vested interest in the business venture, should be directing this operation, not MDSH personnel.

7.1.3 Department efforts in assuring that only suitable quality materials or processes are used in the concrete manufacture should be satistically valid with regard to sampling frequency, repetition of tests, etc. Approval of each lot, for example, should be accomplished with suitably balanced and known risk of error on the part of both the Department and producer.

7.1.4 Proposed modifications should be simple and easily understood with the least possible chance of misunderstanding. There should be a suitable transition period into unfamiliar techniques or policies.

7.1.5 Hopefully, inspection costs will be reduced by any modifications which are adopted. Increased costs should be tolerated only upon proof of substantial technical improvement. After all, present policies have withstood the test of time quite successfully.

7.2 CERTIFICATION ACCEPTANCE OF CONCRETE FINE AGGREGATE

It is recommended that fine aggregate for concrete be accepted on the basis of certification in the case of suppliers who have established a reputation for furnishing uniformly acceptable sand. Acceptance of portland cement by the Department on this basis has been carried on successfully for the past 10 years. Extension of the policy by removing the Department from the supplier's quality control of sand would be another salutary step, and it can be hoped that experience with this scheme would ultimately demonstrate the wisdom of carrying it over into acceptance of coarse aggregate.

Fine aggregate has been recommended as the next candidate for certification acceptance because its quality control in recent years has, like portland cement, presented few problems in Michigan.

It is appropriate to here emphasize that the 1972 edition of the AASHO Guide Specifications for Highway Construction recognizes the propriety of certification under Section 106, Control of Material, as follows:

> "106.04 Certification of Compliance. The Engineer may permit use prior to sampling and testing of certain materials or assemblies accompanied by Certificates of Compliance stating that such materials or assembiles fully comply with the requirement of the contract. The certificate shall be signed by the manufacturer. Each lot of such materials or assemblies delivered to the work must be accompanied by a Certificate of Compliance in which the lot is clearly identified.
>
> "Materials or assemblies used on the basis of Certificates of Compliance may be sampled and tested at any time and if found not to be in conformity with contract requirements will be subject to rejection whether in place or not.
>
> "The form and distribution of Certificates of Compliance shall be as approved by the Engineer.
>
> "The Engineer reserves the right to refuse permission for use of materials or assemblies on the basis of Certificates of Compliance."

It is recommended that such check samples as are taken by the Department for confirmation of certification eligibility be forwarded to the central laboratory and thus relieve District personnel of the need for sand testing. This would also no longer require having washing, sieving, organic testing equipment, etc., in the District. Advantages of the certification acceptance scheme would thus become immediately tangible to a greater number of Department personnel and lead to wider acceptance of the scheme. With regard to the latter, there is an understandable, but false, notion that certification means a relaxation of standards because quality control is left to the supplier. Actually, experience can prove the reverse to be true; the possibility of losing eligibility to certify may encourage even greater effort on the part of suppliers to furnish an acceptable product.

7.3 TEST CYLINDERS AS REPLACEMENT FOR TEST BEAMS

Section 6.3 of this report gave some background on use of the cylinder splitting test as a promising replacement for the flexural testing of beams. It is now recommended that the Department convert to testing of 6- x 12-in. standard size cylinders for all projects requiring concrete, i.e., conduct splitting tensile tests of cylinders for pavements and compression tests of cylinders for structures. The advantages of this scheme are many:

(1) Use of cylinders will enable direct measurement of compressive strength for concrete destined for use in structures. This is entirely compatible with the fact that design procedures of the latter contemplate resisting comprssive stresses only.

(2) Identical cylindrical test specimens made from concrete for pavements can be measured for tensile properties with only minor alteration of testing equipment.

(3) Test beams (6 x 6 x 36 in.) now made by the Department weigh approximately 110 lb each whereas 6- x 12-in. test cylinders weigh only 30 lb apiece. Thus, the physical exertion of handling beams is much greater and discourages careful handling which is demanded if meaningful results are to be obtained. It is almost mandatory that handling and testing of beams be a two-man job whereas all phases of cylinder testing can be readily accomplished by one person. The physical exertion in handling test beams is considerable, and many individuals are now cautioned against handling such heavy weights for medical reasons.

(4) Allowing a 6- x 12-in. test cylinder to undergo some surface drying upon removal from moist curing is not nearly as serious in diminishing splitting tensile strength as is similar drying in reducing flexural strength of a test beam. It is unrealistic to expect that all specimens, either cylinders or beams, will always receive optimum treatment, and the choice should obviously favor the specimen less sensivitive to mishandling.

(5) Making trial batches of concrete is much more feasible when using test cylinders, a procedure now rarely employed by the Department. The amount of concrete in a batch required to make even one test beam (3/4 cu ft) discourages such trials.

(6) The small size of test cylinders makes proper curing at early ages much easier and thereby encourages gathering more meaningful strength data.

(7) Molds, curing chambers, testing machines, and capping equipment for cylinder testing are readily available because such specimens are almost universally used in testing for commercial construction.

(8) Cores not containing steel reinforcement which have been drilled from completed pavements can be used directly for determining splitting tensile strength. The results so obtained can then be compared at once with design values or with results from control cylinders made during construction, and without necessity for troublesome conversion factors.

Disadvantages in using splitting tensile tests as a measure of concrete quality are: (1) necessity to establish a new scale of splitting tensile values to be expected with Michigan materials, and (2) necessity to procure certain new testing equipment.

References (31) and (32) provide information on a great number of studies aiming to translate flexural to splitting tensile values, but often the scatter of the data is such that meaningful correlation is doubtful. It seems likely that many investigators were unaware of the extreme sensivity of the flexural test to what might be considered minor surface drying of the test specimen and consequently good correlations could not be expected. A rough approximation, however, is that 350 psi splitting tensile strength is roughly equivalent to 650 psi flexural strength. Since Michigan uses a type of center point loading in flexural testing, prediction of splitting tensile values is even less reliable for MDSH practice.

As a means of rapidly gathering splitting tensile data on Michigan materials, it is recommended that such tests be conducted immediately on drilled pavement coressent to the central laboratory which do not contain reinforcement instead of the usual compression test. This would quickly provide an excellent background of data for instituting splitting tensile advisory limits in the standard specifications.

7.3.1 Costs of Splitting Tensile Tests - Converting to use of test cylinders instead of beams will require procurement of new equipment and conducting an educational program in the revised techniques.

The following estimate is made of the new equipment needed for each MDSH District on the assumption that cylinder testing, at least initially, will be carried on at a central location for all projects in the District:

(1) Compression Tester, with electric pump, 12-in. gage, 250,000-lb capacity, ASMT C 39.
(Soiltest CT-755, $1,555)

(2) Splitting Tensile Aligning Jig (Figure 3, ASTM C 496).
(Estimated price if several purchased, $100 each)

(3) Cylinder Capping Set including vertical capper, capping plate, compound warmer, ladle, cylinder carrier, and supply of capping compound.
(Soiltest CT-56, $266)

(4) Curing Chamber for maintaining 95+ relative humidity at 73F ± 5F, thermostatically controlled.
(Soiltest CT-203, $425)

(5) Supply of nonreusable 6- x 12-in cylinder molds.
(Priced at $0.25 to $0.30 each)

(6) Supply of 1/8-in. plywood bearing strips - 1 x 13 in.

The basic equipment itemized above needed for each District totals $2,300. Nonreusable molds and capping compound for each cylinder amounts to about $0.35. A rough estimate of the annual Department cost for expendable molds and capping compound per year for testing 1 million cyd of concrete is made by assuming a test of four cylinders (two each for two test ages) from each 200 cyd of concrete. This would total about $7,000 per year.

Proposed testing of cylinders at a District Laboratory requires that they be cast on the job, suitably protected against moisture loss and against excessive temperature changes for the first 24 hr, then demolded and moist stored at 73F until tested. This requires transporting the cylinders to the District laboratory sometime after the first 24 hr. Compression cylinders from structures must be capped with quick hardening compound before breaking.

It is difficult to estimate what additional burden this revision in testing practice will impose on District personnel or just how this activity can best be organized. There are presently eight District laboratories in operation, and the ninth may be reactivated when needed (District 4). Conditions may be sufficiently varied from District-to-District that there should be considerable latitude in mode of operation.

The overall reception of this scheme by District personnel is estimated to be highly favorable since the individual specimens are no longer so burdensome, and the work is being done with fairly precise testing equipment under recently developed ASTM testing methods. The temptation to "eyeball" tests using the discredited flexural beams will be replaced by the thoroughly contemporary splitting tensile test and compression test of cylinders. There will not be as great a tendency to treat strength testing activity as a thoroughly distasteful one to be delegated to otherwise unoccupied and inexperienced construction inspection personnel.

7.3.2 Criteria for Improved Strength Testing Using Cylinders - Section 7.1 outlined four conditions which would desirably be fulfilled if changes in inspection schemes were proposed. Adoption of test cylinders in lieu of test beams definitely satisfies the first and last recommendations, namely, (1) that fundamental property measurements should be undertaken instead of conducting index or identification tests, and (2) whatever is proposed should be simple and easily understood, certainly the case for the cylinder test.

The third item regarding statistical validity of the sampling and testing scheme is adequately met in the case of compression testing of cylinders for structures by adherence to Section 15 of ASTM C 94, Standard Specification for Ready-Mixed Concrete. This specification currently requires at least one test (two cylinders) for each 150 cyd of concrete, and this provision has been extensively considered. Experience with the splitting tensile test is less comprehensive, but Kenis mentions an overall coefficient of variation of 8.5% (Disc. of Ref. 32, p. 995). Also, Galloway and Raithby give a value of 5.4% overall coefficient of variation for 608 cylinders from 152 batches from one class of concrete and 6.7% overall from 136 cylinders from 34 batches for another class (37). In view of the fact that variations are not too different from those expected from compression testing about which much is known, sampling frequency should not be significantly different for cylinders which are intended for splitting tension tests.

Experience will aid development of new specification limits based upon 6- x 12-in. cylinders when tested both in compression and in splitting tension so that the Department will rapidly become satisfied that concrete of equivalent quality is being insured under the new testing scheme. Until such time that this assurance is achieved, it seems premature that the Department forego continuation of beam testing even though the latter step should be accomplished as rapidly as possible. Concrete suppliers will quickly become accustomed to the new procedure, particularly ready-mixed concrete suppliers, since the latter have long been furnishing to commercial customers who monitor concrete quality by cylinder testing.

Within a period of 2-3 years after adoption of cylinder testing and simultaneous acceptance of sand on the basis of certification, it would seem likely that the Department could gradually divest itself of other aspects of concrete quality control in behalf of suppliers. For example, selection of mix proportions, water-cement ratio, control of slump and air content, etc, can hopefully be delegated someday to the supplier. As now is the case with portland cement, the Department might then accept concrete on the basis of certification with occasional check test for slump, air, and cylinder strengths.

8. SUMMARY OF RECOMMENDATIONS

8.1 LIST OF RECOMMENDATIONS

Below is a list of the recommendations made in this report together with reference to the particular section in which detailed comments are made:

8.1.1 Table 8 of Section 3.3 provides information on how seemingly minor deficiencies in concrete flexural strength may seriously impair pavement life. A policy is needed which will restore concrete strength testing by the Department to the importance which it deserves. In Section 7.3 it is proposed that the Department discontinue making and testing 6- x 6- x 36-in. test beams for flexural tests and instead cast 6- x 12-in. test cylinders. For paving concrete, the cylinders are turned on their sides and broken in splitting tension and for concrete for structures, the cylinders are capped and broken in compression. Such drilled cores from pavements as are free of reinforcement can likewise be tested for splitting tensile strength.

8.1.2 Replace the special nominal 9% entrained air requirement for safety curbs, etc., in 7.01.03 of the 1973 Standard MDSH specifications with the more reasonable 7.5 ± 1.5% requirement (see Section 3.5). Substantial losses in strength occur at such high air contents and without commensurate increase in durability.

8.1.3 Allow use of concrete sand on the basis of certification from suppliers who have established a record of satisfactory production (Section 4.2.7).

8.1.4 Require that all ready-mixed concrete plants supplying Michigan highway projects possess a current "Certificate of Conformance" under the certification scheme started by the National Ready-Mixed Concrete Association (Section 4.4.2).

8.1.5 Require that any inspection agency performing work for the Department comply with the current version of ASTM E 329, "Recommended Practice for Inspection and Testing Agencies for Concrete, Steel, and Bituminous Materials."

8.1.6 As soon as possible after establishing cylinder testing in standard MDSH practice, reevaluate the certification acceptance scheme for its applicability to coarse aggregate and to mixed concrete.

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The opinions and conclusions expressed or implied are those of the author and are not necessarily those of the Michigan Department of State Highways or the Division of Research Development and Administration, The University of Michigan.

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APPENDIX

STATEMENT OF RESPONSIBILITIES

Scope

Concrete as supplied for construction is a perishable product, requiring the informed cooperation of both the ready-mixed concrete producer and the contractor to assure its satisfactory performance. It is the purpose of this statement to outline the functions of those two parties, and to define their respective areas of responsibility. It is assumed that requirements for the concrete are properly covered in the specifications, and that it is not the function of the contractor or producer to overcome deficiencies or oversights in design of the structure.

General

Concrete construction involves two phases which correspond to the areas of responsibility of the producer and contractor. The production phase belongs to the ready-mixed concrete operator, and encompasses the operations of securing satisfactory ingredient materials, combining them in proper proportions, mixing them into a homogeneous product and delivering the mixture into the hands of the contractor in such condition that it can be satisfactorily placed. The second phase, under the purview of the contractor, includes the movement of the concrete into the forms, its proper placement and consolidation, the finishing operations, and adequate protection and curing to assure developing the quality potential. Transfer of the concrete from the producer's delivery conveyance into the handling equipment of the contractor marks the division between the two areas of responsibility. Specific functions and responsibilities of the two parties are described below.

PRODUCER RESPONSIBILITIES

The ready-mixed concrete producer shall:

1. Use material—aggregates, cement, water and admixtures, if required—meeting the requirements of the specifications and capable of producing concrete of the required quality.

2. Provide adequate personnel and equipment to assure continuous production at a rate to meet the needs of the work. The equipment shall conform to and be operated within requirements of the specifications for such features as accuracy of measurement, rate and amount of mixing and volume rating.

3. Proportion and batch all concrete to meet specification limits. Depending upon the nature of the specifications, the limits to be met may include one or a combination of the following:

   a. Quantity of cement per unit volume of concrete

   b. Ratio quantity of mixing water to quantity of cement

   c. Consistency, usually measured as slump

   d. Air content

   e. Specific ratios or quantities of ingredients

   f. Strength (Note: The producer's responsibility for strength extends only to measurements by recognized methods for evaluating quality of the concrete as delivered.

4. Cooperate with inspection services by making all facilities and operations conveniently accessible for examination and securing of test samples.

CONTRACTOR RESPONSIBILITIES

The contractor shall:

1. Provide the producer in advance with all information necessary to establish mixtures and costs, including: limitations on materials, proportions, strength and consistency; location and nature of project; quantity of concrete required; rate and method of placement; anticipated unusual conditions.

2. Organize concrete placement to permit advance scheduling of deliveries and prompt discharge after delivery.

3. Perform all operations of handling, placement, consolidation, protection and curing in conformance with specification requirements to assure adequate quality of the end product.

4. Cooperate in facilitating inspection and, where required, engage competent personnel for sampling and testing the concrete.

JOINT RESPONSIBILITIES

Except on large projects where specialized inspection forces are provided, concreting operations are not usually under constant surveillance. The producer and contractor must see that satisfactory control is maintained.

It is particularly important to avoid the use of excessive mixing water. The contractor's forces should be informed of the dangers and be firmly disciplined in avoiding high slump. At the same time, the producer should discourage the use of high slump concrete by requiring that extra water, over that needed to produce the specified slump, be noted and signed for. Authoritative cooperation on the part of the contractor is needed to see that this procedure is followed.

Conformance with good practices in controlling the amount of mixing and the elapsed time between batching and discharge requires attention from both contractor and producer. No difficulty is encountered if ordering and delivery schedules are consistent with the capacity of placement facilities.

All parties have an important stake in seeing that concrete testing is properly done. Particularly in the case of strength, errors in measurement can lead to unjustified concern over quality, resulting in costly retesting, delays or replacement. Violations of standard sampling and testing practices should not be tolerated by either the ready-mixed concrete producer or the contractor.

The "Statement of Responsibilities" contained herein was developed by the National Joint Cooperative Committee between the National Ready Mixed Concrete Association and the Associated General Contractors of America in 1960, 1961, and 1962 and adopted by those associations.

It was reviewed by both associations in 1965, found to have stood the test of time, and was republished with no change.